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

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Keywords: methane, methane emissions, fugitive emissions, methane slippage, boil off, LNG tanker, liquefaction, lifecycle analysis, global warming potential, GWP, GWP_{20}

Abstract

Before 2016, the export of liquefied natural gas (LNG) from the United States was banned, but since that time exports have risen rapidly, fueled in part by the rapid growth in shale gas production. Today the United States is the largest exporter of LNG. This paper presents a full lifecycle assessment for greenhouse gas emissions from LNG. These emissions depend on the type of tanker used to transport the LNG, with emissions far larger when LNG is transported by older, steam-powered tankers burning heavy fuel oil. The largest source of emissions in this case is from venting of methane lost by evaporation from the storage tanks, called boil off. More modern tankers, whether powered by steam or 4-stroke or 2-stroke engines, can capture this boil-off methane and use it for their power, thereby greatly lowering methane emissions. For scenarios for LNG that is transported by more modern tankers, the single largest source of emissions in the full lifecycle are those from the production, processing, storage, and transport of the natural gas that comprises the feedstock for LNG. Fugitive emissions of unburned methane are particularly important, but so are the carbon dioxide emissions from the energy intensive processes behind modern shale gas extraction. In all of the scenarios considered, across all types of tankers used to transport LNG, methane emissions exceed emissions of carbon dioxide from the final combustion of LNG. Carbon dioxide emissions other than from this final combustion are significant, but smaller than the carbon dioxide from the final combustion. While some proponents of LNG have argued it has a climate benefit by replacing coal, the analysis presented here disproves this. Across all scenarios considered, total greenhouse gas emissions from LNG are larger than those from coal, ranging from 24% to 274% 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). Exports doubled between 2019 and 2023, and they are 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).

Proponents of this increase in LNG exports from the United States often claim a climate benefit, arguing that the alternative to the increased export of LNG both to Europe and Asia would be greater use of coal (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 full magnitude of these LNG greenhouse gas emissions are.

There are relatively few previous 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). Some prior assessments did not consider upstream emissions of methane from the production and use of natural gas, and none have considered the emissions of carbon dioxide associated with the production, processing, and transport of natural gas. 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). 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, particularly 4-stroke engines, although increasingly 2-stroke engines are coming into play as well (Bakkali and Ziomas 2019; Pavlenko et al. 2020). Some steam-powered vessels can only burn heavy fuel oil, but other steam-powered tankers as well as all of the tankers powered by 4-stroke and 2-stroke engines can burn fuel oils or LNG. Emissions of both carbon dioxide and methane vary significantly across these different tankers and fuels. For example, older tankers that burn only heavy fuel oils are more likely to vent unburned methane to the atmosphere from LNG that evaporates from the storage tanks, a process called “boil off.” 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 (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 have not been fully explored in earlier lifecycle assessments and is a major focus of the analysis I present here. My analysis relies heavily on two recent, comprehensive assessments of the use of LNG as a marine fuel (Pavlenko et al. 2020; Balcombe et al. 2021).

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 natural gas that is the feedstock for LNG (referred to as upstream and midstream emissions), emissions from the energy used to power the liquefaction of natural gas to LNG, emissions from the energy consumed in transporting the LNG by tanker, emissions from the energy used to re-gasify LNG to natural gas, and emissions from the delivery of gas to and combustion by the final consumer.

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 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 consumed in the liquefaction, tanker transport, and regasification processes. The procedure for estimating quantities for each of these is presented below, and upstream plus midstream emissions are calculated from these total quantities and empirically determined emission factors. The methane emission factor for natural gas is based on a recent synthesis of data from 18 studies that used airplane flyovers of satellites to estimate emissions across the major shale gas field in the United States (Howarth 2022-a, 2022-b). The mean value from these studies weighted by the volume of gas production in each of the fields is 2.6% of natural gas production (Howarth 2022-b). This does not include methane that is emitted from gas distribution systems, which are separately considered. Methane emissions from producing fuel oil are estimated as 0.10 g CH4/MJ (Howarth et al. 2011). For indirect carbon dioxide emission, I use values developed by the State of New York, converting these to metric units and net calorific values: 12.6 g CO2/MJ for natural gas and 15.8 g CO2/MJ for fuel oil (DEC 2021, table A.1).

Liquefaction:

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). Carbon dioxide emissions from the combustion of the gas powering the plants have been measured at many facilities in Australia, the US, 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. 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.

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). Further, some natural gas is vented as unburned methane at LNG liquefaction plants. For this, I use the central value of 0.35% of the LNG formed from Balcombe et al. (2021) who report a range of 0.011% to 0.63%. This corresponds to 3.5 g CO2/kg of LNG liquified.

Some of the LNG that is liquefied is consumed in transporting and handling the LNG before it is consumed by the final consumer, as considered further below. Therefore, emissions of both methane and carbon dioxide from the liquefaction process are larger when expressed per kg of final consumption that per kg of LNG liquefied. In my analyses, this difference is estimated from the total amount of LNG that must be liquefied in order to provide a unit of LNG for final consumption.

Boil off of methane:

Leakage of heat through insulation causes some LNG to evaporate (boil off) as methane gas, and this must be removed from the tanks to maintain pressure. During loading and unloading, an estimated 0.45% of the LNG being loaded is boiled off (Hassan et al. 2009). This is generally used to power operations at the port facilities or flared to the atmosphere. For this analysis, I assume all of the boil off during loading and unloading is released as carbon dioxide emissions, with zero methane emissions. This underestimates methane emissions to some extent, but there are insufficient data available to robustly estimate these. The carbon dioxide emissions from the boil off during loading and unloading is added to the tanker carbon dioxide emissions estimated below, although this is a very small contribution to those emissions.

Boil off also occurs from tankers during transport at rates between 0.1% and 0.17% of the LNG cargo load per day (Gerldmyer et al. 2003; Hassan et al. 2009; BrightHub Engineering 2022). The ambient temperature is important, and rates of 0.1% per day are characteristic at 5^{o} C while 0.17% per day is characteristic at 25^{o} C (Hassan et al. 2009). 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). Boiled off methane can be used to fuel many tankers, and in fact contributes 80% of the fuel used globally by the LNG tanker fleet (IMO 2021). In this analysis, I assume that tankers only vent methane from boil off to the atmosphere when the rate of boil off exceeds the use of boil off as a fuel for the tanker (Bakkali and Ziomas 2019). However, some older tankers are not capable of burning boil off, and for these, I assume all boil off is vented to the atmosphere as unburned methane. While some modern tankers are able to reliquefy methane to LNLG, this is not common, and the necessary equipment is absent from older, steam-powered tankers (Hassan et al. 2009).

Fuel consumption rate and emissions from LNG tankers:

My analysis considers four different types of tankers: 1) steam-powered 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) tankers powered by 2-cycle engines capable of using either diesel oil or boil off. At one time, almost all LNG tankers were powered by steam engines that burned only heavy fuel oil, and some of these are still in operation. However, the LNG tanker fleet today is dominated by steam-powered engines that can burn LNG and 4-stroke engines (Bakkali and Ziomas 2019; Pavlenko et al. 2020). As of 2019, LNG tankers powered by 2-stroke engines were rare although at least one was in construction and another four were planned (Bakkali and Ziomas 2019; Pavlenko et all. 2020).

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. Boil off in excess of the energy needs of the tanker is assumed to be vented to the atmosphere as unburned methane. While some vessels have equipment for reliquefying methane to LNG rather than venting, this is not common, particularly on older steam-powered tankers, which typically vent boil-off methane (Hassan et al. 2009). 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 boil off were not sufficient, many tankers instead are likely to force more boil off for their fuel, at rates greater than the 0.1% to 0.17% per day, in part to meet stringent sulfur emission standards for ships that went into effect in 2020 (Bakkalil and Ziomas 2019). 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 2-cycle engines (Raza and Schoyen 2014; Bakkali and Ziomas 2019). Carbon dioxide emissions from the consumption of the LNG are taken as 2,750 g CO_2/ton of LNG (IMO 2021). Carbon dioxide emissions and fuel oil use for those steam-powered tankers that can only burn heavy fuel oils are scaled to those from LNG-powered tankers, assuming 80 g CO_2/MJ for heavy fuel oil and 55 g CO_2/MJ for LNG (Pavlenko et al. 2020).

Some unburned methane is emitted in the exhaust streams from LNG tankers, particularly from those powered by 4-stroke and 2-stroke engines fueled by LNG. For vessels powered by 4-stroke engines, I assume this methane release is 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, I assume a 3.8% methane emission rate based on data in Balcombe et al. (2022) for a newly commissioned tanker. Note that this is higher than 2.3% 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 is negligible and are ignored in this analysis (Pavlenko et al. 2020).

Volume of LNG cargo and length of tanker voyages:

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).

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 my baseline analysis, I consider 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).

When the gas is burned by the final consumer, I assume carbon dioxide emissions of 2,750 g CO2/ton 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 coal:

To compare the greenhouse gas footprint of LNG to that of coal, I use values from Howarth (2020) for carbon dioxide emitted during combustion of coal (99 g CO2/MJ) and for upstream fugitive methane emissions associated with coal (0.20 g CHk4/MJ), converted to net calorific values. For the indirect emissions of carbon dioxide from the production and transportation of coal, I use the value developed by the State of New York (3.1 g CO2/MJ), converted to metric units and net calorific values (DEC 2021, Table A-1).

Results and Discussion

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 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 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 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, steam-powered tankers that cannot use LNG for fuel are older and 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).

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 (including from loading and unloading), emissions associated with the final transmission to consumers, and emissions as the gas is burned by the final consumer. These emissions are also summarized in Figure 1, 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 1 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 steam engines burning heavy fuel oil are far larger than for the other three scenarios. This is largely due to the venting to the atmosphere of unburned methane from boil. 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 23% of total greenhouse gas emissions (expressed as carbon dioxide equivalents) and up 63% of total carbon dioxide emissions (not including methane) for the case where LNG is transported by steam-powered 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 approximately 37% of total greenhouse gas emissions and 67% of all carbon dioxide emissions (Figure 1, Table 2). Even larger than the carbon dioxide emissions from combustion of the LNG by the final customer, though, are upstream and midstream emissions from producing, processing, storing, and transporting natural gas (Table 2). This is true across all scenarios, with these emissions composing 29% of total emissions for the scenario where tankers burn heavy fuel oil and approximately 44% 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 natural gas extraction and processing systems, but methane emissions from upstream and midstream sources are several times higher across all scenarios (Table 2).

The liquefaction process is an important source of emissions of both carbon dioxide and methane, with methane emissions being somewhat larger (when expressed as carbon dioxide equivalents; Table 2). These liquefaction emissions are the second largest source of emissions, after the upstream and midstream emissions, 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 steam-engine tankers that burn heavy fuel oil, but emissions from tankers are relatively small in the other scenarios (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 more modern 4-stroke and 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, with these emissions (expressed as carbon-dioxide equivalents) being larger than carbon dioxide emissions from the exhaust of these vessels (Table 2). These methane emissions 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.

Methane emissions from the final transmission of gas to the consumer are relatively small, 3.5% or less of total lifecycle greenhouse gas emissions across 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). This corresponds to a range of 1,400 to 2,890 g CO_2-equivalents per kg LNG burned, increasing the total greenhouse gas footprint of LNG by up to 38% above the values shown in Table 1. 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).

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 1 and Table 2. See Supplemental Tables A and B 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 steam-powered tankers than 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 A, Supplemental Table B). 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 1) hold across the cases for shorter and longer voyages.

Figure 2 compares the greenhouse gas footprint of LNG in different tanker-delivery scenarios to those of coal and natural gas that is not liquefied, using global average tanker voyage distances and GWP_{20} for comparing methane to carbon dioxide. Coal and natural gas have very similar footprints, as we have previously demonstrated (Howarth and Jacobson 2021), indicating that natural gas does not have an inherent climate advantage over coal (Gordon et al. 2023). The footprint for LNG is greater than that of either coal or natural gas even in the case of short cruises using tankers that are powered by LNG, where the LNG emissions are 24% larger than for coal. 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 2).

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 1 and 2, 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 1), 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 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 2) since methane emissions from coal are less than from natural gas and LNG. Even so, greenhouse gas emissions from LNG are at least as much as from coal, in the scenario with short voyages and tankers burning LNG, to considerably worse than coal, for the scenario of long voyages by tankers burning heavy fuel oil (Supplemental Figure B). Even when using GWP100, LNG is never preferable to coal from the standpoint of greenhouse gas emissions.

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^{o} C of the total global warming to date since the late 1800s, compared to 0.75^{o} C for carbon dioxide (IPCC 2021). And 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.

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. 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.

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 2).

A broader conclusion is the need to move away from any use of LNG as a fuel as quickly as possible, and to immediately stop construction of any new LNG infrastructure. Those proponents of exporting LNG from the United States are wrong when they assert a climate benefit for the use of LNG over coal (Sneath 2023; Joselow and Puko 2023). In fact, the LNG greenhouse gas footprint is larger than that of coal (Figure 2), and short-term energy needs such as those caused by the Russian invasion of Ukraine are better met by reopening closed coal facilities, on a temporary basis, than by expanding LNG infrastructure. Any new LNG infrastructure will become a stranded asset as society moves away from all fossil fuels. In recent years, many have recognized that we need to move away from natural gas, as well as coal, to address the climate emergency (Gaventa and Patukhova 2021; Figueres 2021). With an even greater greenhouse gas footprint than natural gas, ending the use of LNG must be a global priority.

Acknowledgements
I thank Roxanne Marino for valuable discussions leading to this manuscript. This work was supported by a grant from the Park Foundation and by an endowment given by David R. Atkinson to support the professorship at Cornell University held by Robert W. Howarth.

Disclosure statement

The author confirms that he has no conflicts of interest that would adversely influence this research. The research was supported by a grant from the Park Foundation and by an endowment given by David R. Atkinson to support the professorship at Cornell University held by Robert W. Howarth.

Data availability

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

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Figure legends

Figure 1. 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 2. Full lifecycle greenhouse gas footprint for coal and natural gas 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.

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.

Supplemental Figure B. Full lifecycle greenhouse gas footprint for coal and natural gas 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_{100}. See text.

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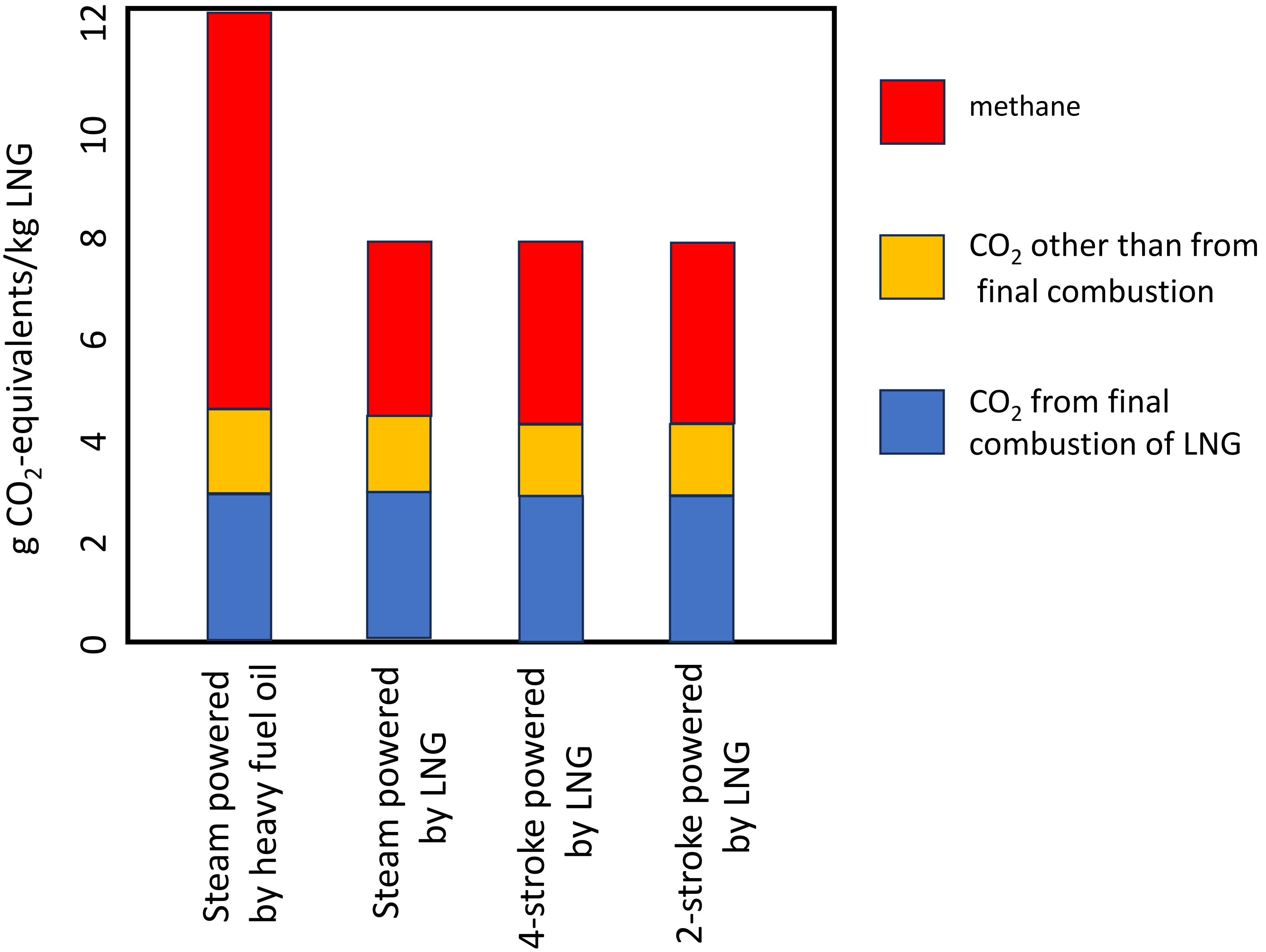
Table 1. Comparison of rate of unforced boil off and fuel needs to power different types of LNG tankers.

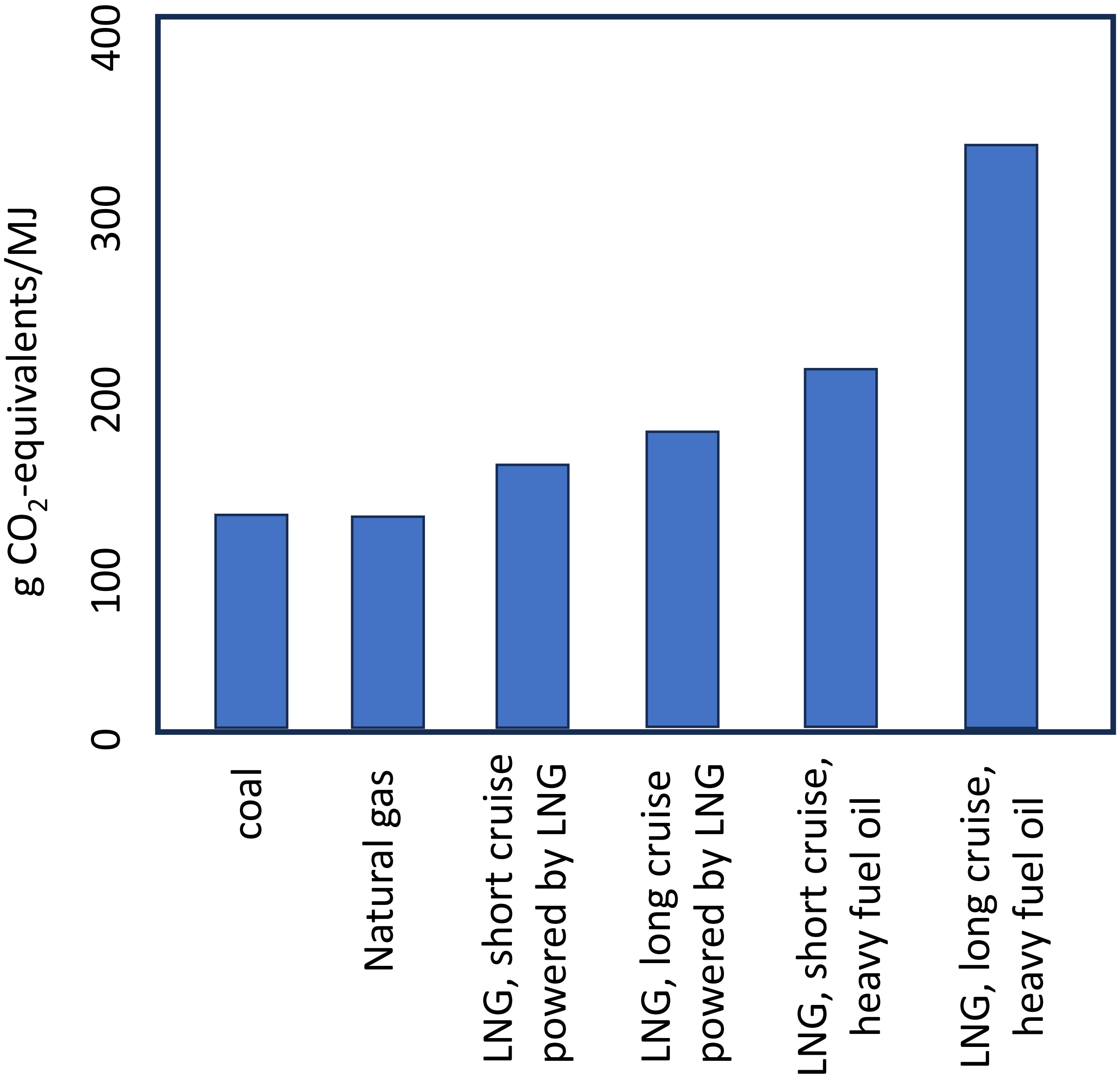
	Tons LNG per day
Unforced boil off, ambient temperature of 5^o C	67.5 [a]
Unforced boil off, ambient temperature of 25^o C	115 [a]
Steam-powered tanker burning LNG	175
Tanker powered by 4-stroke engines burning LNG	130
Tanker powered by 2-stroke engines burning LNG	108

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
Steam tankers powered by heavy fuel oil				
Upstream & midstream emissions	736	32.2	2,657	3,393
Liquefaction	425	4.2	347	772
Emissions from tanker	425	51.3	4,232	4,657
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,336**	**90.9**	**7,500**	**11,836**
Steam tankers powered by LNG				
Upstream & midstream emissions	718	32.5	2,681	3,399
Liquefaction	430	4.4	363	793
Emissions from tanker	300	---	---	300
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,198**	**40.1**	**3,308**	**7,506**
4-stroke engine tankers powered by LNG				
Upstream & midstream emissions	700	31.7	2,615	3,315
Liquefaction	435	4.3	355	790
Emissions from tanker	217	2.5	206	423
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,102**	**41.7**	**3,440**	**7,542**
2-stroke engine tankers powered by LNG				
Upstream & midstream emissions	691	31.3	2,582	3,273
Liquefaction	430	4.2	347	777
Emissions from tanker	179	2.6	215	394
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,050**	**41.3**	**3,408**	**7,458**


g CO_2-equivalents/kg LNG
0
2
4
6
8
10
12
Steam powered by heavy fuel oil
Steam powered by LNG
4-stroke powered by LNG
2-stroke powered by LNG
methane
CO_2 other than from final combustion
CO_2 from final combustion of LNG

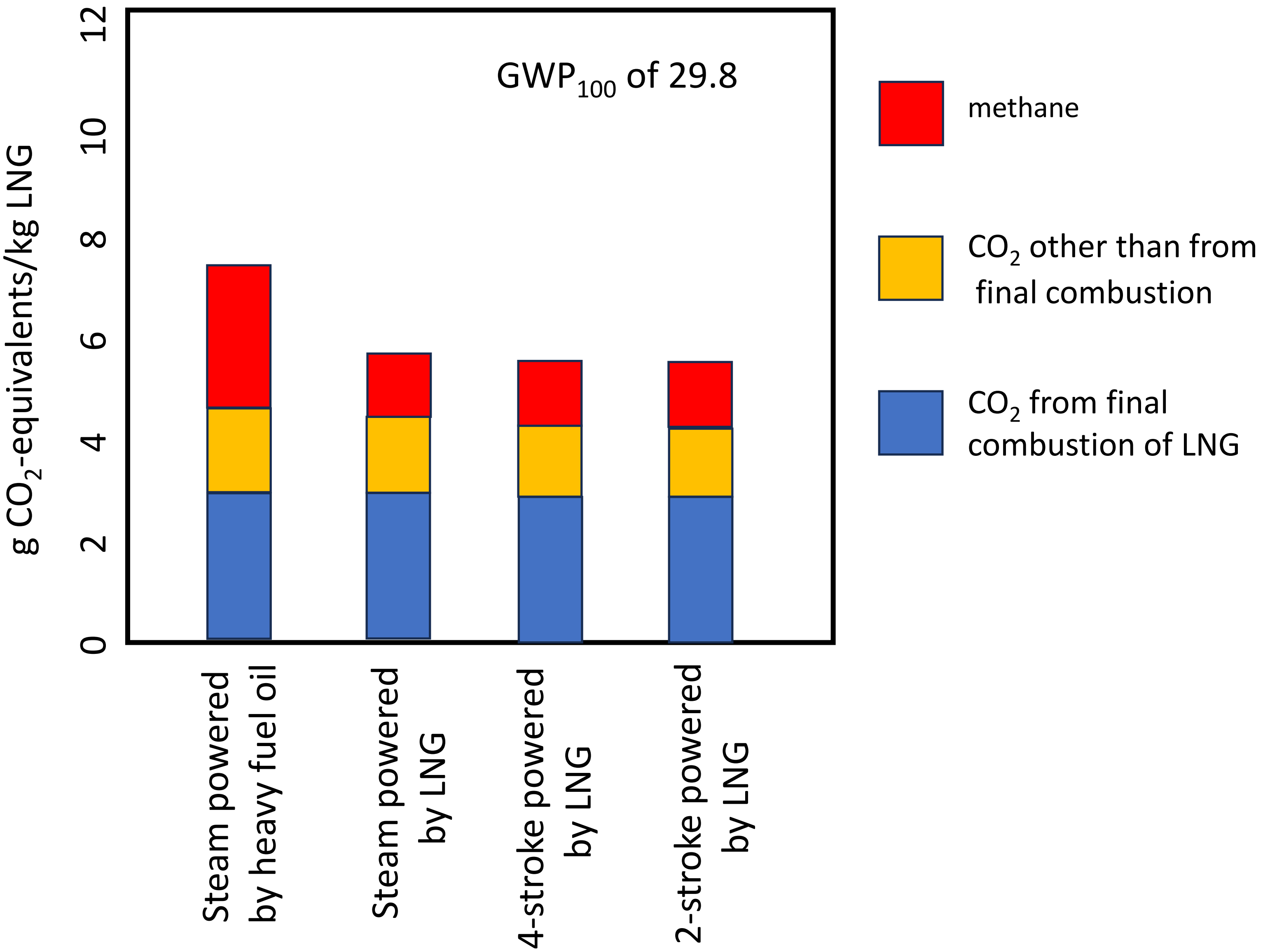

g CO_2-equivalents/MJ
0
100
200
300
400
coal
Natural gas
LNG, short cruise powered by LNG
LNG, long cruise powered by LNG
LNG, short cruise, heavy fuel oil
LNG, long cruise, heavy fuel oil

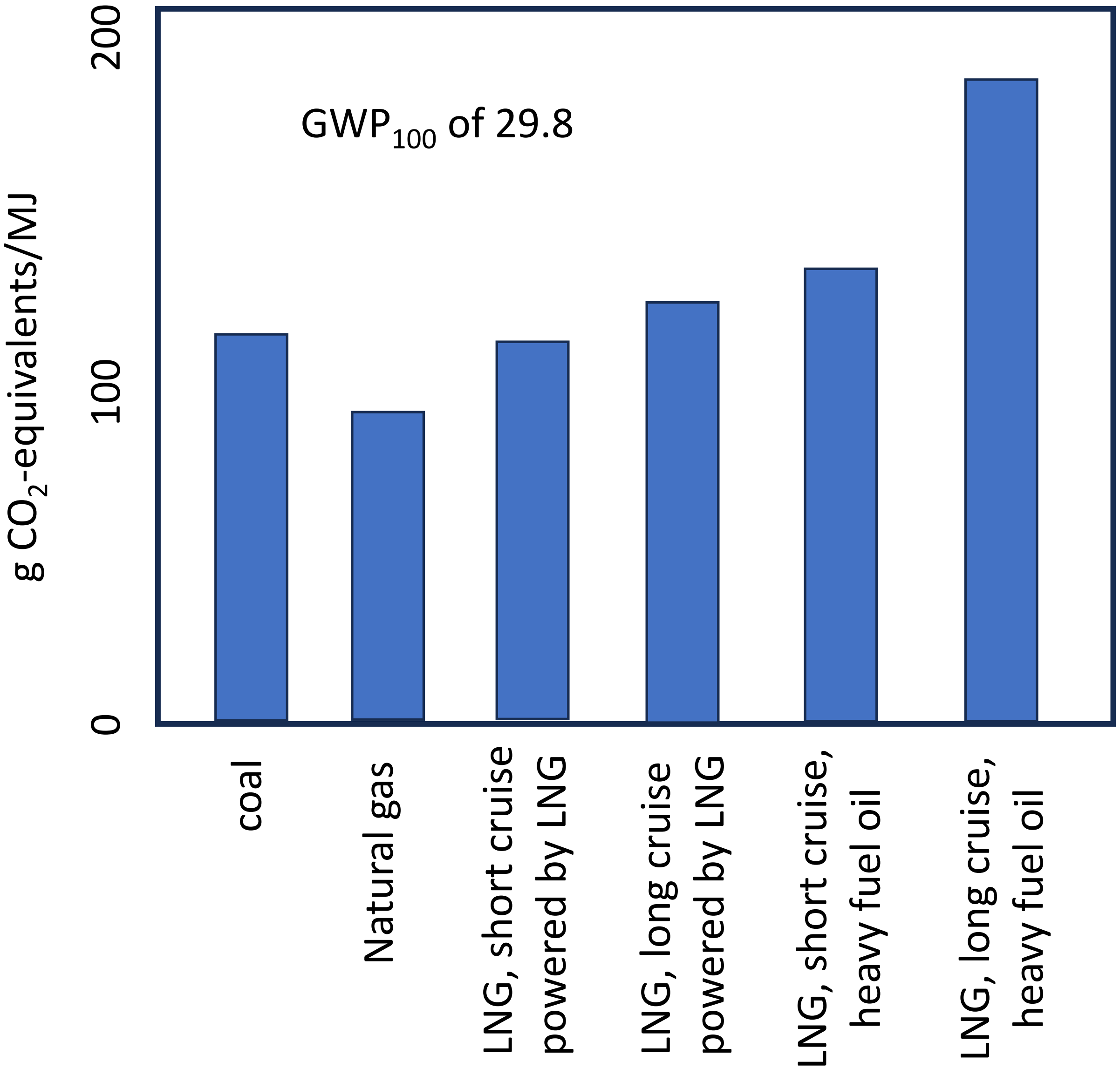
Supplemental Table A. Full lifecycle greenhouse gas emissions for LNG with four different scenarios for shipping by tanker, using shortes voyage times. Methane emissions are shown both as mass of methane and mass of carbon dioxide equivalents based on GWO_{20}. Values are per final mass of LNG consumed.

	Carbon Dioxide	Methane		Total combined
	g CO_2/kg	g CH_4/kg	g CO_2-eq/kg	g CO_2-eq/kg
Steam tankers powered by heavy fuel oil				
Upstream & midstream emissions	706	31.9	2,632	3,338
Liquefaction	414	4.1	338	752
Emissions from tanker	239	29.0	2,393	2,632
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,109**	**68.2**	**5,627**	**9,736**
Steam tankers powered by LNG				
Upstream & midstream emissions	690	31.2	2,574	3,264
Liquefaction	428	4.2	347	775
Emissions from tanker	169	---	---	169
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,037**	**38.6**	**3,185**	**7,222**
4-stroke engine tankers powered by LNG				
Upstream & midstream emissions	679	30.1	2,483	3,162
Liquefaction	422	4.1	338	760
Emissions from tanker	122	1.4	116	238
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**3,973**	**38.8**	**3,201**	**7,174**
2-stroke engine tankers powered by LNG				
Upstream & midstream emissions	674	30.0	2,475	3,149
Liquefaction	419	4.1	338	757
Emissions from tanker	101	1.4	116	217
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**3,944**	**38.7**	**3,193**	**7,137**

Supplemental Table B. 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
Steam tankers powered by heavy fuel oil				
Upstream & midstream emissions	745	32.7	2,698	3,443
Liquefaction	439	4.3	355	794
Emissions from tanker	783	94.5	3,347	8,579
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,717**	**134.7**	**11,113**	**15,830**
Steam tankers powered by LNG				
Upstream & midstream emissions	771	34.9	2,879	3,650
Liquefaction	478	4.7	388	866
Emissions from tanker	554	---	---	554
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,553**	**42.8**	**3,531**	**8,084**
4-stroke engine tankers powered by LNG				
Upstream & midstream emissions	739	33.4	2,756	3,495
Liquefaction	459	4.5	371	830
Emissions from tanker	399	4.6	380	779
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,347**	**45.7**	**3,771**	**8,118**
2-stroke engine tankers powered by LNG				
Upstream & midstream emissions	723	32.7	2,698	3,421
Liquefaction	450	4.5	371	821
Emissions from tanker	329	4.7	388	717
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,252**	**45.1**	**3,721**	**7,973**


g CO_2-equivalents/kg LNG
0
2
4
6
8
10
12
GWP$_{100}$ of 29.8
methane
CO_2 other than from final combustion
CO_2 from final combustion of LNG
Steam powered by heavy fuel oil
Steam powered by LNG
4-stroke powered by LNG
2-stroke powered by LNG


GWP$_{100}$ of 29.8
g CO_2-equivalents/MJ
0
100
200
coal
Natural gas
LNG, short cruise powered by LNG
LNG, long cruise powered by LNG
LNG, short cruise, heavy fuel oil
LNG, long cruise, heavy fuel oil