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MODELLING AND ANALYSIS

The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States

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Abstract

Liquefied natural gas (LNG) exports from the United States have risen dramatically since the LNG-export ban was lifted in 2016, and the United States is now the world's largest exporter. This LNG is produced largely from shale gas. Production of shale gas, as well as liquefaction to make LNG and LNG transport by tanker, is energy-intensive, which contributes significantly to the LNG greenhouse gas footprint. The production and transport of shale gas emits a substantial amount of methane as well, and liquefaction and tanker transport of LNG can further increase methane emissions. Consequently, carbon dioxide (CO_2) from end-use combustion of LNG contributes only 34% of the total LNG greenhouse gas footprint, when CO_2 and methane are compared over 20 years global warming potential (GWP_{20}) following emission. Upstream and midstream methane emissions are the largest contributors to the LNG footprint (38% of total LNG emissions, based on GWP_{20}). Adding CO_2 emissions from the energy used to produce LNG, total upstream and midstream emissions make up on average 47% of the total greenhouse gas footprint of LNG. Other significant emissions are the liquefaction process (8.8% of the total, on average, using GWP_{20}) and tanker transport (5.5% of the total, on average, using GWP_{20}). Emissions from tankers vary from 3.9% to 8.1% depending upon the type of tanker. Surprisingly, the most modern tankers propelled by two- and four-stroke engines have higher total greenhouse gas emissions than steam-powered tankers, despite their greater fuel efficiency and lower CO_2 emissions, due to methane slippage in their exhaust. Overall, the greenhouse gas footprint for LNG as a fuel source is 33% greater than that for coal when analyzed using GWP_{20} (160 g CO_2-equivalent/MJ vs. 120 g CO_2-equivalent/MJ). Even considered on the time frame of 100 years after emission (GWP_{100}), which severely understates the climatic damage of methane, the LNG footprint equals or exceeds that of coal.

KEYWORDS
global warming potential, GWP_{20}, lifecycle analysis, LNG, methane emissions

1 | 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.[1] In 2022, the United States became the largest exporter of LNG globally.[2] Exports of LNG doubled between 2019 and 2023, and if allowed by the United States government to continue, were predicted to double again over the next 4 years.[3] As of 2023, the LNG exported from the United States represented 21% of all global LNG transport.[4] In January of 2024, U.S. 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.[5] An earlier version of the analysis I present 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.[6]

Proponents of increased exports of LNG from the United States to both Europe and Asia have often claimed a climate benefit, arguing that the alternative would be greater use of coal produced domestically in those regions,[3,7] with increased emissions of carbon dioxide. 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.[8–11] As a greenhouse gas, methane is more than 80 times more powerful than carbon dioxide when considered over a 20-year period,[12] 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 regasify it. The liquefaction process alone is highly energy-intensive.[13,14] A lifecycle assessment is required to determine the full magnitude of these LNG greenhouse gas emissions. My analysis builds on earlier lifecycle assessments for LNG.[15–21] Of these, only those since 2015 have analyzed LNG export from the United States, and their focus was on export to China. My focus here is on exports from the United States to Europe as well as to China, using the most recent data on methane emissions from shale gas development in the United States.

Most natural gas production in the United States is shale gas extracted using 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.[22,23] It is the rapid increase in shale gas production in the United States that has allowed and driven the increase in export of LNG.[3] 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 the greenhouse gas emissions associated with 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.[22,23]

The types of ships used to transport LNG have been changing in recent years,[24–26] and more than 85% of the global fleet is composed of tankers less than 20 years old.[4] As of the beginning of 2024, this fleet consisted of 701 tankers, only 21 of them older than 30 years, and 359 new tankers were under construction.[4] Several different modes of propulsion are common in LNG tankers, including steam power and four- and two-stroke engines. The vast majority of these tankers can be powered either burning "boil-off" or other fuels, such as diesel or heavy fuel oil. Boil-off is the evaporative loss of methane due to some heat leakage through insulation and into the tanks that hold LNG. The only common tankers that cannot use boil-off methane for their fuel are slow-speed diesel vessels that instead capture and reliquefy their boil-off. These make up approximately 7% of the global fleet, although no new ones have been delivered since 2015, in part because of difficulty in meeting new emission standards.[4] Steam-powered vessels compose 31.5% of the global fleet. They are relatively inefficient, and so are considered a "superseded technology."[4] Another 28% of the fleet is made up of tankers powered by electric motors with electricity provided from four-stroke generators that can burn two or more fuels.[4] These are more efficient than steam-powered vessels but have high maintenance costs. Among the newest propulsion technologies is the use of two-stroke engines powered by either boil-off or diesel fuel.[4] Dual-fuel two-stroke tankers have greater fuel efficiencies and so are likely to become more common in the future.[25,26]

Emissions of both carbon dioxide and methane vary significantly across these different types of tankers.[27] Tankers powered by four- and two-stroke engines are more efficient than are steam-powered tankers, and so have lower carbon-dioxide emissions.[24,26] However, when these four- and two-stroke vessels burn boil-off, some unburned methane slips through and is emitted in the exhaust gases.[26,28] Steam-powered tankers emit virtually no methane in their exhaust gases which may

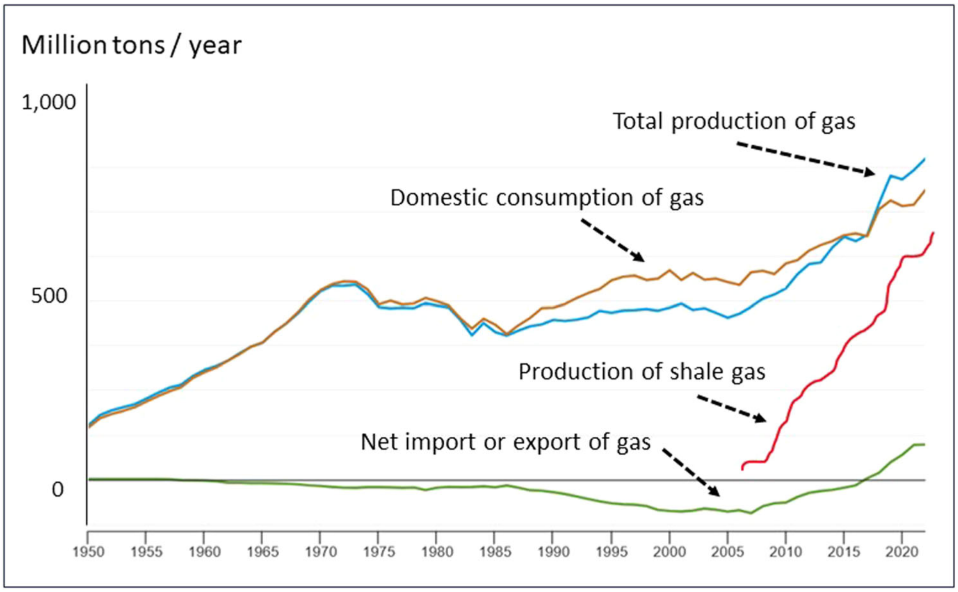

FIGURE 1 Trends in natural gas production in the United States from 1950 to 2022, showing total production of gas (conventional plus shale), production just of shale gas, domestic consumption, and the net import or export of gas. Almost all of the increase in natural gas production since 2005 has been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

partially offset their higher emissions of carbon dioxide. These differences in emissions from tankers are a major focus of this analysis, which considers four different types of tankers: (1) steam-powered vessels, (2) tankers that are powered by four-cycle engines, (3) more modern tankers powered by two-cycle engines, and (4) tankers that are unable to burn the boil-off of LNG and are powered primarily by diesel oil. My analysis relies heavily on three recent, comprehensive assessments of the use of LNG as a marine fuel.[26–28]

I present a detailed lifecycle assessment for the LNG system that estimates emissions from the production of shale gas feedstock through combustion by the final consumer. My analysis focuses on 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.[26,29] 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 regasify 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.[30]

As with some other prior lifecycle assessments for LNG, I explicitly compare the emissions from LNG to those for coal.[17,19–21] Additionally, I compare the greenhouse gas footprint of LNG with the those of oil and natural gas used domestically and with that for electric-driven heat pumps.

2 | 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 approximately 10% greater than when using gross calorific values.[10,29,31] LNG and heavy fuel oils are assumed to have energy densities of 48.6 and 39 MJ/kg, respectively.[32] 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.[12] Specifying the time frame for comparison is necessary because methane has a far shorter residence time in the atmosphere. The use of GWP_{100} is more common than GWP_{20}, although evidence shows GWP_{100} underestimates the climatic impact of methane, and GWP_{20} is increasingly being favored in many lifecycle assessments.[9,11,20,26,28,33–35] For ease of calculation, this analysis assumes that shale gas and LNG are composed just of methane, ignoring other gases. Table 1 briefly summarizes some of the input parameters for the lifecycle assessment that are detailed below.

TABLE 1 Summary of some of the major input parameters used in liquefied natural gas (LNG) lifecycle assessment.

Stage	Equation	Parameter value	References
Upstream and midstream			
• Methane	Equation (1)	2.8% of production	Sherwin et al.[30]
• CO_2	Equation (2)	612 g CO_2/kg LNG	DEC,[36] Table A.1
Downstream methane	Equation (3)	0.0032 kg/kg LNG	Alvarez et al.[37]
Liquefaction			
• Methane	Equation (4)	3.5 g CH_4/kg LNG	Balcombe et al.[28]
• CO_2	Equation (5)	270 + 57 + 18 g CO_2/kg LNG	Tamura et al.[16] and Okamura et al.[15]
Tankers			
• Methane slip	Equation (6)	0%, 3.8%, or 6.4% of fuel burn	Pavlenko et al.,[26] Balcombe et al.,[34] and Comer et al.[38]
• Fuel consumption	Equations (7) and (8)	108, 130, or 175 tons/day	Raza and Schoyen[39] and Bakkali and Ziomas[24]
• Boil-off	Equation (9)	0.00135 kg CH_4/kg/day	Hassan et al.,[40] Huan et al.,[25] and Rosselot et al.[27]
• Cargo volume	–	68,000 tons LNG	Raza and Schoyen[39]
• Voyage times	–	21.4, 38, or 70 days roundtrip	Oxford Institute for Energy Studies[41]

Note: See text for detailed derivations and discussion.

2.1 | 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 system. 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 methane and g of carbon dioxide/kg of LNG burned by the final consumer:

$$CH_4 = [(0.028)*(1.028)*(1000\,g\,CH_4/kg)*\mathbf{LNG.\,tot}] + [\mathbf{Fuel.\,oil}*(3.9\,gCO_4/kg\,oil)], \quad (1)$$

$$CO_2 = [(612\,g\,CO_2/kg\,LNG)*\mathbf{LNG.\,tot}] + [\mathbf{Fuel.\,oil}*(616\,g\,CO_2/kg\,oil)], \quad (2)$$

where **LNG.tot** is the total mass of methane gas consumed or emitted, including not only from the final combustion of the regasified LNG 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. **Fuel.oil** is the quantity of heavy fuel oil or diesel consumed by ships (for those ships that use these 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 **Fuel.oil** are shown in Equations (3) and (11).

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.[30] Here, we use their estimates for the Permian Basin, and weigh the upstream emissions by the portion of energy produced as natural gas compared with oil, as recommended by Sherwin et al.[30] Details are provided in Supporting Information Table A. The vast majority of LNG exports from the United States are from Texas and Louisiana.[2] The Permian Basin (west Texas and southeastern New Mexico) 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 the proximity of these fields to the LNG export terminals.[42–44] Methane emissions from producing fuel oil are estimated at 0.10 g CH_4/MJ.[10,45] With an energy density of 39 MJ/kg, this is equivalent to 3.9 g CH_4/kg fuel oil (Equation 1). 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 for fuel oil[36] (Supporting Information

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, hydraulically fracture the wells, and process, store, and transport the fuels.

The total mass of methane burned to make carbon dioxide or emitted as methane over the entire lifecycle for LNG is calculated in Equation (3):

$$\mathbf{LNG.tot} = (1\,\text{kg}/\text{kg LNG}) + \mathbf{LNG.liq} + \mathbf{LNG.ship} + \mathbf{Vent.boil.off} + (0.0032\,\text{kg}/\text{kg LNG}), \quad (3)$$

where 1 kg/kg LNG is the quantity of LNG burned by the final consumer. **LNG.liq** is the total mass of LNG consumed or emitted during the liquefaction process, **LNG.ship** is the mass of LNG 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 LNG emitted as methane to the atmosphere by tankers that reliquefy boiled-off methane (due to imperfect capture of this methane) 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 gas 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.[37] Emissions in the destination country would be substantially higher for the case of delivery of gas to homes and commercial buildings for heating.[46]

The calculation for **LNG.ship** is shown in Equation (8). The calculation for **Vent.boil.off** is described in Equation (10). **LNG.liq** is calculated by summing the mass of gas burned to produce the CO_2 emissions for liquefaction shown in Equation (4) (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) (converted to units of kg/kg LNG).

2.2 | 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.[13] 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.

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

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

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 in Equation (3), 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.[37]

In Equation (4), 3.5 g CH_4/kg LNG is the total rate of release of unburned methane during liquefaction and for regasification based on the mean from the review by Balcombe et al.[28] Note that a recent paper[47] reported a lower value, which may represent a best case of what is possible, since they required the cooperation from owners of the LNG facilities.[48] The higher value from Balcombe et al.[28] seems likely to be more representative of standard industry performance. For Equation (5), the values 270, 57, and 18 g CO_2/kg LNG are, respectively, the quantities of carbon dioxide emitted from burning gas to power liquefaction, 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 CO_2/kg LNG liquefied.[15,16] Here, I use the mean estimate of 270 g CO_2/kg LNG liquefied, which is equivalent to 9.8% of the natural gas being liquefied This is comparable to the value used by Balcombe et al.[28] in their lifecycle assessment and is at the very low end of emission estimates provided by Pace

Global[14] for guidance for new plants built in the United States: 260–370 g CO_2/kg LNG liquefied. My estimate is, therefore, conservative. In addition, carbon dioxide present in unprocessed natural gas, which sometimes contains significant quantities of carbon dioxide, is emitted to the atmosphere as the methane in natural gas is liquefied. These emissions are estimated as 23 to 90 g CO_2/kg LNG liquefied.[15,16] Here, I use a mean estimate of 57 g CO_2/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 CO_2/kg LNG, and a mean estimate of 18 g CO_2/kg.[15,16]

2.3 | Volume of LNG tanker cargo and length of tanker voyages

Emissions of both carbon dioxide and methane from LNG tankers depend on the size of the tanker and the length of cruises. Most LNG tankers have total capacities between 125,000 and 150,000 m^3. In this analysis, I use a value of 135,000 m^3, or 67,500 tons LNG.[39] 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.[39] 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 United States (9070 km each way, Sabine Pass, TX to the UK) and the longest regular commercial route from the United States (27,961 km each way, Sabine Pass, TX to Shanghai[41]). Most of the LNG exports from the United States are from the Sabine Pass area, so these distances well characterize US exports.[3] Considering the average speed of 19 knots (35.2 km/h),[41] these cruise distances correspond to times of 19, 10.7, and 35 days each way, respectively, or 38, 21.4, and 70 days roundtrip. Note that the travel distances for LNG tankers have been increasing over time.[49] 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.[50]

2.4 | 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 largely from the incomplete combustion of fuel by four-cycle and two-cycle tankers, with release of unburned methane in the exhaust gases. As noted in the introduction, my analysis considers four different types of tankers: (1) steam-powered vessels, (2) tankers that are powered by four-cycle engines, (3) modern tankers powered by two-cycle engines, and (4) tankers that are unable to burn the boil-off of LNG and that are powered by diesel oil. Here, 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 heavy fuel oil and/or diesel oil, consumption of these fuels tends to be very low compared with LNG,[24,34,39] except in those rare times when LNG prices are high relative to fuel oils.[51] And while it might be expected that tankers would burn fuel oil if the rate of unforced boil-off were not sufficient, most 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.[24]

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 LNG burned by the final consumer.

$$CH_4 = [\mathbf{LNG.\ ship} * \mathrm{Slip} * 1000] + \mathbf{Vent.\ boil.\ off}, \tag{6}$$

$$CO_2 = [\mathbf{LNG.\ ship} * (44\,\mathrm{g}\ CO_2/\mathrm{mol}) / (16\,\mathrm{g}\ CH_4/\mathrm{mol}) * 1000\,\mathrm{g}\ CH_4/\mathrm{kg}\ CH_4] + [\mathbf{Fuel.\ oil} * (80\,\mathrm{g}\ CO_2/\mathrm{MJ\ oil}) * (39\,\mathrm{MJ}\ /\mathrm{kg\ oil})], \tag{7}$$

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 value of 80 g CO_2/MJ is the carbon-dioxide emission factor per unit of energy for fuel oil[26] and 39 MJ/kg is the energy density for fuel oil.

For vessels powered by four-stroke engines, I assume **Slip** is 0.064 (6.4%) of the LNG burned by the tanker, the average value measured by Comer et al.[38] in a recent campaign using drones, helicopters, and on-board measurements at sea. This is significantly higher than the values assumed by Balcombe et al.[28] and by Pavlenko et al.[26] For tankers powered by two-stroke engines burning LNG, I assume a 0.038 methane slip rate based on data in Balcombe et al.[34] for a newly commissioned tanker. Note that this is higher than 0.023 reported in Balcombe et al.[28] or values reported in Pavlenko et al.,[26] due to emissions of unburned methane from electric generators, which are necessary for tankers powered by two-stroke engines. Methane emissions in the exhaust of steam-powered tankers are negligible, as are emissions from burning diesel,[26] and are ignored in this analysis.

Equation (8) provides the estimation for LNG consumed by tankers that burn LNG, normalized to the mass of LNG delivered.

$$\mathbf{LNG.\ ship} = \mathbf{Days} * (\mathbf{LNG.\ fuel}/60,800,000\ \text{kg LNG}), \tag{8}$$

where **Days** is the number of days for a roundtrip cruise to and from the liquefaction 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/day for steam-powered tankers, 130 tons LNG/day for ships powered by four-cycle engines, and 108 tons LNG/day for ships powered by modern two-cycle engines.[24,39]

The unforced boil-off of methane during the voyage is calculated in Equation (9).

$$\mathbf{Boil.\ off} = (0.00135\ \text{kg}\ CH_4/\text{kg LNG/day}) * \mathbf{Days} * (1000\ \text{g}\ CH_4/\text{kg}\ CH_4), \tag{9}$$

where **Boil.off** is the evaporation from the tankers' LNG tanks during the voyage that occurs from thermal seepage through the insulation of the tanks' insulation. The value of 0.00135 kg CH_4/kg LNG/day is the average rate of boil-off of methane, equivalent to 0.135%/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%/day at ambient temperatures of 5°C and as high as 0.17%/day at temperatures of 25°C.[25,27,40,52] 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. 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.[40]

$$\mathbf{Vent.\ boil.\ off} = 0.0035 * \mathbf{Boil.\ off} * \%\mathbf{Reliq}, \tag{10}$$

where **%Reliq** is the percentage of **Boil.off** that is not used as fuel by the tanker, but rather is reliquefied. Note that in the past, some tankers simply vented all of the boiled-off methane.[40,52] Even today, most tankers are not equipped to reliquefy boil-off, but these only vent boil-off in excess of their use for fuel. The assumed fraction of methane emitted during reliquefaction, 0.0035, is the same as assumed for shore-based liquefaction plants discussed above.

The quantity of fuel oil or diesel burned by ships, for those ships not burning LNG, is calculated by Equation (11).

$$\mathbf{Fuel.\ oil} = (167,000\ \text{kg oil /day}) * \mathbf{Days}/(60,800,000\ \text{kg LNG}), \tag{11}$$

where 167,000 kg oil/day is the rate at which a tanker burns fuel oil and 60,000,800 kg LNG is the quantity of LNG delivered per average cruise. The value of 167,000 kg oil/day is based on data in Bakkali and Ziomas[24] which indicated an equivalent fuel burn rate of 115 tons LNG/day for slow-speed diesel tankers, assuming 80 g CO_2/MJ for fuel oil and 55 g CO_2/MJ for LNG.[26]

2.5 | 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,[37] or 0.0032 kg methane/kg LNG consumed. As noted above, emissions would be higher for gas used to heat homes and commercial buildings.[46]

When the gas is burned by the final consumer, I use carbon-dioxide emissions of 2750 g CO_2/kg 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 CO_2/MJ for natural gas[31] and is also the value assumed by the IMO[53]) for burning LNG in tankers. Methane is never burned with 100% efficiency, and so there is likely some slippage of unburned methane from the combustion. However, I am aware of no data on this for electric-power plants, and assume no slippage in this analysis, to be conservative.

2.6 | Comparison to natural gas, diesel oil, coal, and heat pumps

The emission factors for methane and carbon dioxide for natural gas that are used domestically (i.e., not converted to LNG) are calculated in Equations (12) and (13), in units of g CH_4 or g CO_2/MJ of energy produced.

$$CH_4 = (0.0312)*(1.0312)*(55\,g\ CO_2/MJ)*(mol/44\,g\ CO_2)*(16\,g\ CH_4/mol), \tag{12}$$

$$CO_2 = (55\,g\ CO_2/MJ) + (12.6\,g\ CO_2/MJ), \tag{13}$$

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[30] and 0.0032 (0.32%) for downstream emissions (Supporting Information 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[54] (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[36] (Supporting Information Table A-1, converted to net calorific and metric units).

The emission factors of methane and carbon dioxide for coal that is used domestically (not transported long distances by ship) are shown in Equations (14) and (15).

$$CH_4 = 0.21\,g\ CH_4/MJ, \tag{14}$$

$$CO_2 = (99\,g\ CO_2/MJ) + (3.4\,g\ CO_2/MJ), \tag{15}$$

where 0.21 g CH_4/MJ is the emissions factor for methane from the production of coal in the United States based on IPCC data[29] (converted to net calorific values), 99 g CO_2/MJ are the direct emissions when the coal is burned[54] (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[36] (Supporting Information 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.[17] 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)[55] and for average mining operations in Poland (0.19 g CH_4/MJ).[56]

The emission factors of methane and carbon dioxide for diesel oil that is produced domestically are shown in Equations (16) and (17).

$$CH_4 = 0.40\,g\ CH_4/MJ, \tag{16}$$

$$CO_2 = (75\,g\ CO_2/MJ) + (15.8\,g\ CO_2/MJ), \tag{17}$$

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[54] (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[36] (Supporting Information Table A-1, converted to net calorific and metric units). The methane emission factor is from data presented in Supporting Information Materials for Sherwin et al.[30] and is based on oil production from the Permian Basin, apportioning upstream methane emissions to the percent of energy produced that is oil compared with 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-equivalent/kWh, or 70 g CO_2-equivalent/MJ.[57] The average ground-source heat pump has a Coefficient of Performance (COP) of 4.8.[58] The emissions for using a heat pump are estimated by dividing the average grid emissions by the COP.

3 | RESULTS AND DISCUSSION

3.1 | Boil-off and LNG consumption by tankers

The rate of LNG used to power tankers is compared with unforced boil-off in Table 2, for those tankers that can burn 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,[40] is always less than the fuel required for tankers powered by steam turbines and four-stroke engines. This is also true for tankers powered by modern two-stroke engines at the lower temperature. My analysis therefore assumes that these tankers force additional boil-off to meet their fuel needs,[24] and this additional forced boil-off is included in the overall lifecycle assessment for each type of tanker. For tankers powered by modern two-stroke engines at the higher temperature, the 115 tons LNG/day as unforced boil-off exceed the fuel requirement of 108 tons LNG/day, although not by much (Table 2). These tankers are likely to be equipped with equipment to reliquefy boil-off in excess of their fuel needs. Consequently, I assume that no boil-off from these tankers is vented to the atmosphere and that all is captured.

TABLE 2 Comparison of rate of unforced boil-off and fuel needs to power different types of liquefied natural gas (LNG) tankers.

	Tons LNG/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 four-stroke engines burning LNG	130
Boil-off required for tanker powered by two-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.

3.2 | Comparison of emissions of CO_2 from final combustion to methane and indirect CO_2 emissions

Table 3 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 direct emissions as the gas is burned by the final consumer to produce electricity. These emissions are also summarized in Figure 2 for the shortest and longest voyage times as well as average voyage time, 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 3, methane emissions are compared with carbon dioxide using GWP_{20}.[12] Total emissions are comparable across all four scenarios using different types of tankers, ranging from 7370 to 8028 g CO_2-equivalent/kg LNG consumed for the average roundtrip voyage length of 38 days (Table 3). Results using GWP_{100} rather than GWP_{20} are presented in a later section of this paper. As discussed in Section 2, many researchers increasingly favor GWP_{20} for lifecycle assessments, since this better capture the effects of methane on the climate system.[11,20,26,28,33–36]

The direct 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 35%–37% of total greenhouse gas emissions across the four scenarios (Table 3). The largest component of the emissions is from upstream and midstream sources, from producing, processing, storing, and transporting natural gas. The combined emissions for both carbon dioxide and methane from upstream and midstream sources contribute 46%–48% of total emissions for delivered LNG (Table 3). 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, and make up 9.4%–9.9% of total emissions across the scenarios (Table 3). Methane emissions from upstream and midstream sources are larger (expressed as carbon-dioxide equivalents), contributing 36%–38% of total emissions for delivered LNG (Table 3).

The liquefaction process is an important source of emissions of both carbon dioxide and methane, reflecting the large amount of energy needed to super cool methane to liquid form and the release of some unburned methane at liquefactions facilities (Table 3). 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 four scenarios, ranging from 8.6% to 9% of total emissions (Table 3).

Tanker emissions are the most variable of the emissions across the scenarios considered, ranging from 3.6% of total emissions in the case where LNG is moved by tankers burning diesel oil to 8.1% when LNG is moved by tankers powered with four-stroke engines when both carbon dioxide and methane are considered (Table 3). The emissions of carbon dioxide by tankers are 2.4% of total emissions for two-stroke-engine tankers, 2.8% for four-stroke-engine tankers, 3.9% for steam-powered tankers, and 4.4% for tankers powered by diesel engines (Table 3), reflecting the different fuel efficiencies of these modes of propulsion. However, the two least efficient types of tankers have zero methane slip emissions, while the more efficient tankers powered by two- and four-stroke engines emit significant methane, 2.8% and 5.3%, respectively, of total emissions for delivered LNG (Table 3). These methane emissions, which result from slippage of methane emitted unburned in the exhaust stream,[26,28,33] more than offset the lower carbon-dioxide emissions. Note that my analysis assumes no methane

TABLE 3 Full lifecycle greenhouse gas emissions for liquefied natural gas (LNG) for four different scenarios for shipping by tanker, using world-average voyage times (38-day roundtrip).

	Carbon dioxide g CO_2/kg	Methane g CH_4/kg	Methane g CO_2-equivalent/kg	Total combined g CO_2-equivalent/kg
Steam-turbine tankers powered by LNG				
Upstream and midstream emissions	768 (9.9%)	36.1	2982 (38%)	3750 (48%)
Liquefaction	383 (4.9%)	3.9	320 (4.1%)	703 (9.0%)
Emissions from tanker	301 (3.9%)	0	0 (0%)	301 (3.9%)
Final transmission and distribution	0 (0%)	3.2	264 (3.4%)	264 (3.4%)
Combustion by final consumer	2750 (35%)	0	0 (0%)	2750 (35%)
Total	**4202** (54%)	**43.2**	**3566** (46%)	**7768**
Four-stroke engine tankers powered by LNG				
Upstream and midstream emissions	753 (9.4%)	35.4	2920 (36%)	3673 (46%)
Liquefaction	375 (4.7%)	3.8	314 (3.9%)	689 (8.6%)
Emissions from tanker	223 (2.8%)	5.2	429 (5.3%)	652 (8.1%)
Final transmission and distribution	0 (0%)	3.2	264 (3.3%)	264 (3.3%)
Combustion by final consumer	2750 (34%)	0	0 (0%)	2750 (34%)
Total	**4101** (51%)	**47.6**	**3927** (49%)	**8028**
Two-stroke engine tankers powered by LNG				
Upstream and midstream emissions	741 (9.6%)	34.9	2876 (37%)	3618 (47%)
Liquefaction	369 (4.8%)	3.7	309 (4.0%)	678 (8.8%)
Emissions from tanker	186 (2.4%)	2.6	212 (2.8%)	397 (5.2%)
Final transmission and distribution	0 (0%)	3.2	264 (3.4%)	264 (3.4%)
Combustion by final consumer	2750 (36%)	0	0 (0%)	2750 (36%)
Total	**4046** (52%)	**44.4**	**3661** (48%)	**7707**
Diesel-powered tankers				
Upstream and midstream emissions	693 (9.4%)	32.6	2689 (36%)	3381 (46%)
Liquefaction	345 (4.7%)	3.5	289 (3.9%)	634 (8.6%)
Emissions from tanker	326 (4.4%)	0.2	15 (0.2%)	340 (4.6%)
Final transmission and distribution	0 (0%)	3.2	264 (3.6%)	264 (3.6%)
Combustion by final consumer	2750 (37%)	0	0 (0%)	2750 (37%)
Total	**4114** (56%)	**39.5**	**3256** (44%)	**7370**

Note: Methane emissions are shown both as mass of methane and mass of CO_2-equivalents based on GWO_{20}. Values are per final mass of LNG consumed. Numbers in parentheses indicate the percent for each component of the total CO_2-equivalents.

emissions from imperfect capture of boil-off used for fuel. I conclude that modern two- and four-stroke powered tankers may emit 30%–215% more total emissions than do steam-powered tankers, despite the lower fuel efficiencies and higher carbon-dioxide emissions for steam. Methane slip makes up 53% of the total tanker emissions for tankers powered by two-stroke engines and 66% for those powered by four-stroke engines. Similarly, Rosselot et al.[27] concluded that methane slip made up 54% of total emissions for a very modern tanker powered with a two-stroke engine

Methane emissions from the final transmission of gas from the regasification terminal to the consumer are relatively small, only 264 g CO_2-equivalent/kg LNG delivered, for all the different tanker scenarios, ranging from 3.3% to 3.4% of total emissions (Table 3). This is because my analysis focuses on the use of LNG to produce electricity, and the transmission pipelines that

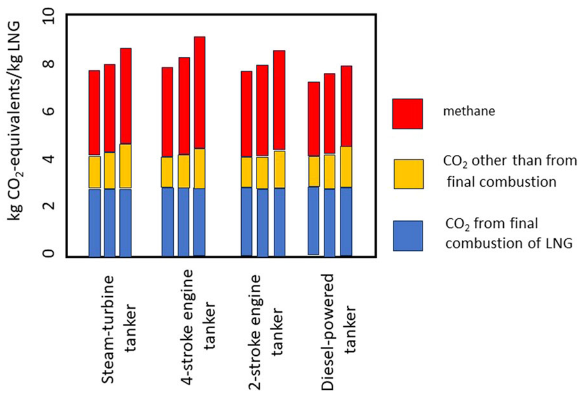

FIGURE 2 Full lifecycle greenhouse gas footprints for LNG expressed per mass of LNG burned by the final consumer, comparing four scenarios where the LNG is transported by different types of tankers. For each type of tanker, scenarios are shown for shortest voyage times (bars to the left), average voyage times (center bars), and longest voyage times (bars to the right). 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. GWP_{20}, 20-year global warming potential; LNG, liquefied natural gas.

deliver gas to such facilities generally have moderately low emissions.[37] 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%–3.5% of the gas delivered to customers leaks to the atmosphere unburned (see summary in Howarth[46] and references therein). This corresponds to a range of 1400–2890 g CO_2-equivalent/kg LNG delivered, increasing the total greenhouse gas footprint of LNG by up to 35% above the values shown in Table 3. Emissions from distribution systems are not as well characterized in either Europe or Asia as in the United States,[46] although one study suggests emissions in Paris, France are in the middle range of those observed in the United States.[59]

3.3 | 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 Table 3. See Figure 2 and Supporting Information Tables B and C for detailed 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 boil-off from LNG is used to power tanker transport (Figure 2 and Supporting Information Tables B and 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 3) hold across the cases for shorter and longer voyages. In all cases, total greenhouse gas emissions exceed the direct carbon-dioxide emissions when the LNG is burned by the final consumer, by 2.6–2.8-fold for the shortest cruises (Supporting Information Table B) and by 2.8–3.2-fold for the longest cruises (Supporting Information Table C). Upstream and midstream emissions, particularly for methane, are a dominant feature across all time frames and transport by all types of tankers.

3.4 | Comparison to natural gas, diesel oil, coal, and heat pumps

Figure 3 compares the greenhouse gas footprint of LNG for the shortest and longest voyage distances 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 4 also shows this comparison with LNG tankers for the average tanker-cruise length, using the average emissions across the three scenarios for transport of LNG by tankers burning LNG boil-off for their fuel. The carbon-dioxide emissions just from combustion are substantially greater for coal, 99 g CO_2/MJ versus 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 versus 83.1 g CO_2/MJ for LNG (Table 4). This is because of greater energy costs and, therefore, higher emissions of carbon dioxide for developing and transporting the LNG compared with coal. Methane emissions for LNG are substantially larger than for coal, 76.5 g CO_2-equivalent/MJ for LNG compared with only 17.3 g CO_2-equivalent/MJ for coal (Table 4). As presented in Section 2, this result for methane emissions for coal is quite

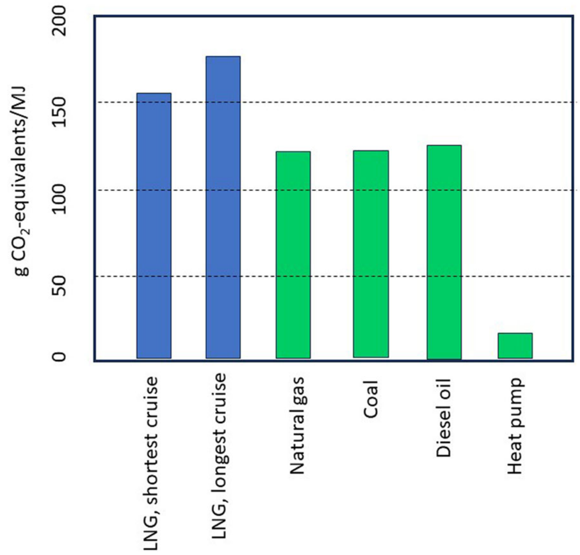

FIGURE 3 Full lifecycle greenhouse gas footprint for LNG for both short and long cruises compared with coal used domestically, diesel oil used domestically, natural gas used domestically, and electric-power ground-source heat pump powered by the average European electric grid. The LNG values are the means for the three types of tankers that burn LNG for fuel. Methane emissions are converted to carbon-dioxide equivalents using GWP_{20}. Note that values are expressed per unit of heat energy for each fuel for delivery to an electric generation plant. This does not include methane emissions from urban distribution systems that deliver to buildings for heat. Emissions for LNG and natural gas used domestically would both increase substantially for this use of gas. See text. GWP_{20}, 20-year global warming potential; LNG, liquefied natural gas.

robust across regions, including China and Poland.[55,56] Consequently, total greenhouse gas emissions are 33% larger for LNG than for coal for the cases of average tanker-cruise lengths, 160 g CO_2-equivalent/MJ for LNG versus 120 g CO_2-equivalent/MJ for coal (Table 4).

Natural gas used domestically in the United States (i.e., 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.[11] Neither natural gas nor coal used domestically in the United States has a large climate advantage over the other.[8] The greenhouse gas footprint for diesel oil from the Permian Basin is also similar to that of coal (Figure 3 and Table 4). However, the footprint for LNG is greater than that of coal, diesel oil, or natural gas even in the case of the shortest cruises. The greenhouse gas footprint for LNG is 28% greater than that of coal for the shortest cruises and 46% greater for the longest cruises (Figure 3).

Also shown in Figure 3 are the greenhouse gas emission estimates 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. Overall 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 energy mix, emissions would be relatively low for the heat pump: 55 g CO_2-equivalent/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.

3.5 | Comparison with prior studies

My estimates for the greenhouse gas footprint for LNG exports are at the upper end of those presented in previous studies. Rosselot et al.[20] provide estimates for LNG exported from the United States to China, based on scenarios where the LNG is produced from a gas field in East Texas with relatively low upstream methane emissions and from a gas field in the Permian Basin with higher methane emissions. Using data from their Figure S-5, I calculate total emissions of 95 g CO_2-equivalent/MJ for the East Texas LNG and 175 g CO_2-equivalent/MJ for the LNG produced with gas from the Permian, based on GWP_{20}. These values are 40% lower and 9% higher, respectively, than my estimate of 160 g CO_2-equivalent/MJ (Table 4). Note that Rosselot et al.[20] concluded that LNG produced from gas fields with high methane emissions would be worse than coal from a climate perspective, in agreement with my conclusion. Abrahams et al.[21] show total precombustion emissions (i.e., all emissions other than final combustion) as 86 g CO_2-equivalent/MJ when using GWP_{20} (their Table S7). Adding in the emissions for final combustion of 55 g CO_2/MJ (Table 4), total emissions are 141 CO_2-equivalent/MJ, or 12% lower than my estimate. Gan et al.[18] show the noncombustion emissions of exporting LNG to be in the range of 25–90 g CO_2-equivalent/MJ (their Figure S1, using GWP_{20}). Given combustion emissions of 55 g CO_2/MJ, total emissions would be 80–145 g CO_2-equivalent/MJ, or 9% to 50% less than my estimate. The Gan et al.[18] estimates are based on the GREET model maintained by the US Department of Energy. The NETL[17] report also uses

TABLE 4 Greenhouse gas emissions for liquefied natural gas (LNG) exported from the United States compared with those for diesel oil and coal produced domestically near the final site of consumption.

	Carbon dioxide g CO_2/MJ	Methane g CH_4/MJ	Methane g CO_2-equivalent/MJ	Total combined g CO_2-equivalent/MJ
Average for LNG				
Upstream and midstream emissions	15.5	0.73	60.1	75.6
Liquefaction	7.7	0.078	6.5	14.2
Emissions from tanker	4.9	0.053	4.4	9.3
Final transmission and distribution	0	0.066	5.4	5.4
Combustion by final consumer	55.0	0	0	55.0
Total	**83.1**	**0.93**	**76.5**	**160**
Diesel oil				
Upstream and transport emissions	15.8	0.40	33.0	48.8
Combustion by final consumer	75.0	0	0	75.0
Total	**90.8**	**0.40**	**33.0**	**123.8**
Coal used domestically				
Upstream and transport emissions	3.4	0.21	17.3	20.7
Combustion by final consumer	99.0	0	0	99.0
Total	**102.4**	**0.21**	**17.3**	**119.7**

Note: LNG estimates are the averages for the three scenarios shown in Table 2 for tankers that are fueled by LNG, using world-average voyage times (38 days). 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.

the GREET model, and produces similar results: 102 g CO_2-equivalent/MJ for total emissions using GWP_{20} (calculated from information in Table S4 of Rosselot et al.[20]), a value near the middle of those from Gan et al.[18] and 36% lower than my estimate.

A key reason that some of these other studies find that total emissions are lower than what I report here is their use of lower estimates for upstream and midstream emissions of methane. Specifically, the studies by Gan et al.[18] and NETL[17] use the default methane estimates in the GREET model, which are derived from inventory estimates from the US Environmental Protection Agency. The EPA inventory estimates in turn are based on unverified self-reporting from the oil and gas industry, and are clearly too low compared with data derived from independent sources published in the peer-reviewed literature.[46] My study relies on the most robust estimates available for estimates of methane emissions from upstream and midstream sources.[30]

For estimation of total emissions from coal, my estimate of 119.7 g CO_2-equivalent/MJ is well within the range presented in other studies, such as the estimate of 106.6 g CO_2-equivalent/MJ used by NETL[17] and the estimate of 125 g CO_2-equivalent/MJ from Abrahams et al.,[21] using GWP_{20}.

3.6 | GWP time frame—Sensitivity and significance

My analysis is sensitive to the global warming potential that is used, as seen in the online only Supporting Information Figures A and B. Using GWP_{100} of 29.8 instead of GWP_{20} of 82.5,[12] as was used in Figures 2 and 3, decreases the methane emissions expressed as carbon-dioxide equivalents by a factor of 2.77 (i.e., 82.5/29.8). 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 all four of the scenarios when using GWP_{100} (Supporting Information Figure A). Similarly, the greenhouse gas footprints of LNG and natural gas that is not liquefied decrease relative to coal when viewed through the lens of GWP_{100} (Supporting Information Figure B and Figure 3) since methane emissions from coal are less than from natural gas and LNG. Total greenhouse gas emissions from LNG estimated using GWP_{100} are equal to those for coal in the scenario with short voyages but are still greater (by 12%) for the longest cruises (Supporting Information Figure B). That is, even using GWP_{100}, the greenhouse gas footprint of LNG is always as large as or larger than that of coal. The greenhouse gas footprint of LNG is always substantially worse than that of natural gas used domestically, whether estimated with GWP_{20} or GWP_{100} (Figure 3 and Supporting Information Figure B). This must be true, since the LNG is made from natural gas but requires substantial energy to liquefy and transport to market.

3.7 | Concluding thoughts

Much of my analysis focuses on comparing the influence of different types of tankers on the LNG greenhouse gas footprint. Surprisingly, tanker type has relatively little influence, since tankers that are more fuel efficient and therefore have lower carbon-dioxide emissions have greater methane slippage in their exhaust. There are relatively few measurements of methane slippage, and I agree with others that it should be a priority to further explore slippage rates.[34,38] The effect of tanker speed on emissions could also be further explored. In this analysis, I use average speeds for the world's LNG tanker fleet in recent years, but slower speeds lead to substantially greater efficiencies, reducing emissions of both carbon dioxide and methane.[27] Nonetheless, emissions from tankers are a small part of the total for LNG.

The largest contributions to the greenhouse gas footprint for LNG exported from the United States are the upstream and midstream emissions from shale gas, particularly for methane. It should come as no surprise, therefore, that studies that assume lower methane emissions conclude that the overall LNG footprint is less than in my analysis. This is certainly the case for those assessments that rely on the GREET model and use the default methane emission factors from that model.[17,18] As noted above, the values used in the GREET model are based on unverified industry reporting to the US Environmental Protection Agency, and these estimates have been repeatedly found to be too low (see review by Howarth[46]). My methane emission factor is derived from the very latest data set from a large body of independent observations (Sherwin et al.[30]) and far better reflects the current state of the science.

Some LNG assessments compare methane and carbon dioxide using GWP_{100} rather than GWP_{20},[17–19] although Rosselot et al.[20] used GWP_{20} as do many studies specifically focused on LNG tanker emissions.[25–28,34] Again, it should not be surprising that those analyses that rely on GWP_{100} report lower total 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 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."[60] 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 with 0.75°C for carbon dioxide.[12] 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.[61] Reducing methane emissions rapidly is increasingly viewed as critical to reaching climate targets.[62,63] In this context, many researchers call for using the 20-year time frame of GWP_{20} instead of or in addition to GWP_{100}.[26,28,33–35] GWP_{20} is the preferred approach in my analysis presented in this paper, as was the case for our earlier lifecycle assessment of blue hydrogen.[11] Using GWP_{20}, LNG always has a larger greenhouse gas footprint than coal.

Increasingly, leaders on global climate policy are calling for a rapid move away from all fossil fuels, including natural gas and not just coal.[64,65] With an even greater greenhouse gas footprint than natural gas, ending the use of LNG should be a global priority. I see no need for LNG as an interim energy source, and note that switching from coal to LNG requires massive infrastructure expenditures, for ships and liquefaction plants and the pipelines that supply them. A far better approach is to use financial resources to build a fossil-fuel-free future as rapidly as possible.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

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

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REFERENCES

1. DiSavino S. After six decades, US set to turn natgas exporter amid LNG boom. *Reuters*. 2017. Accessed October 16, 2023. https://www.reuters.com/article/us-usa-natgas-lng-analysis/after-six-decades-u-s-set-to-turn-natgas-exporter-amid-lng-boom-idUSKBN1700F1
2. EIA. *The United States Became the World's Largest LNG Exporter in the First Half of 2022*. Energy Information Agency, US Department of Energy; 2023. Accessed October 17, 2023. https://www.eia.gov/todayinenergy/detail.php?id=53159
3. Joselow M, Puko T. The next front in the climate fight: U.S. exports of natural gas. *Washington Post*. October 17, 2023. Accessed October 17, 2023. https://www.washingtonpost.com/climate-environment/2023/10/17/natural-gas-exports-climate-activists/?utm_source=newsletter&utm_medium=email&utm_campaign=wp_climate202&wpisrc=nl_climate202
4. IGU. *World LNG Report*. International Gas Union; 2024. Accessed August 20, 2024. https://www.igu.org/resources/2024-world-lng-report/
5. Carbon Brief. What does Biden's LNG "pause" mean for global emissions? *Carbon Brief Oil Gas*. 2024. Accessed March 1, 2024. https://www.carbonbrief.org/qa-what-does-bidens-lng-pause-mean-for-global-emissions/
6. Clarke A. How one methane scientist influenced Biden's pause on LNG approvals. *Bloomberg*. February 29, 2024. Accessed March 1, 2024. https://www.bloomberg.com/news/features/2024-02-29/biden-lng-approval-pause-influenced-by-cornell-methane-scientist
7. Sneath S. LNG export terminals belching more pollution than estimated. *The Lens*. Accessed August 25, 2023. https://thelensnola.org/2023/07/31/lng-export-terminals-belching-more-pollution-than-estimated/?fbclid=IwAR0zBDGWl9AGe446XX1NcWk7CXsr0DTAPHsow8Xdr-n7Ai58nCIchbxpsGVo
8. Gordon D, Reuland F, Jacob DJ, Worden JR, Shindell D, Dyson M. Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates. *Environ Res Lett*. 2023;18:084008. doi:10.1088/1748-9326/ace3db
9. Howarth RW. A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. *Energy Sci Eng*. 2014;2:47-60. doi:10.1002/ese3.35
10. Howarth RW, Santoro R, Ingraffea A. Methane and the greenhouse gas footprint of natural gas from shale formations. *Clim Change*. 2011;106:679-690. doi:10.1007/s10584-011-0061-5
11. Howarth RW, Jacobson MZ. How green is blue hydrogen? *Energy Sci Eng*. 2021;9:1676-1687. doi:10.1002/ese3.956
12. IPCC. Climate change 2021: the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, et al., eds. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press; 2021:2391. doi:10.1017/9781009157896
13. Hwang Y, Al-AbulKarem A, Mortazavi A, Radermacher R. Chapter 5—Natural gas liquefaction cycle enhancements and optimization. In: Mokhatab S, Mak J, Valappil J, Wood D, eds. *Handbook of Liquefied Natural Gas*. Elsevier; 2014:229-257. doi:10.1016/B978-0-12-404585-9.00005-2
14. Pace Global. *Life Cycle Assessment of GHG Emissions from LNG and Coal Fired Generation Scenarios: Assumptions and Results*; 2015. Accessed October 16, 2023. https://www.ourenergypolicy.org/wp-content/uploads/2015/10/PACE_Report.pdf
15. Okamura T, Furukawa M, Ishitani H. Future forecast for life-cycle greenhouse gas emissions of LNG and city gas 13A. *Appl Energy*. 2007;84:1136-1149.
16. Tamura I, Tanaka T, Kagajo T, et al. Life cycle CO_2 analysis of LNG and city gas. *Appl Energy*. 2001;68:301-319.
17. NETL. *Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States: 2019 Update*. National Energy Technology Laboratory, US Department of Energy; 2019. Accessed March 21, 2024. https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf
18. Gan Y, El-Houjeiri HM, Badahdah A, et al. Carbon footprint of global natural gas supplies to China. *Nat Commun*. 2020;11:824. doi:10.1038/s41467-020-14606-4
19. Nie Y, Zhang S, Liu RE, et al. Greenhouse-gas emissions of Canadian liquefied natural gas for use in China: comparison and synthesis of three independent life cycle assessments. *J Clean Prod*. 2020;258:120701. doi:10.1016/j.jclepro.2020.120701
20. Rosselot KS, Allen DT, Ku AY. Comparing greenhouse gas impacts from domestic coal and imported natural gas electricity generation in China. *ACS Sustainable Chem Eng*. 2021;9:8759-8769. doi:10.1021/acssuschemeng.1c01517?rel=cite-as&ref=PDF&jav=VoR
21. Abrahams LS, Abrahams C, Griffin WM, Matthews HS. Life cycle greenhouse gas emissions from U.S. liquefied natural gas exports: Implications for end uses. Environ. Sci. Technol. 2015;49:3237-3245. doi:10.1021/es505617p
22. Howarth RW. Ideas and perspectives: Is shale gas a major driver of recent increase in global atmospheric methane? *Biogeosciences*. 2019;16:3033-3046. doi:10.5194/bg-16-3033-2019
23. Howarth R. Methane and climate change. In: Stolz JF, Michael Griffin W, Bain DJ, eds. *Environmental Impacts from Development of Unconventional Oil and Gas Reserves*. Cambridge University Press; 2022.
24. Bakkali N, Ziomas L. *Forced Boil Off of Gas: The Future of LNG as a Fuel for LNG Carriers*. McKinsey; 2019. Accessed September 10, 2023. https://www.mckinsey.com/industries/oil-and-gas/our-insights/forced-boil-off-gas-the-future-of-lng-as-a-fuel-for-lng-carriers
25. Huan T, Hongjun F, Wei L, Guoqiang Z. Options and evaluations on propulsion systems of LNG tankers. In: Serpi A, Porru M, eds. *Propulsion Systems*. IntechOpen Books; 2019. doi:10.5772/intechopen.82154
26. Pavlenko N, Comer B, Zhou Y, Clark N. *The Climate Implications of Using LNG as a Marine Fuel*. International Council

on Clean Transportation; 2020. Working paper 2020–02. Accessed October 16, 2023. https://theicct.org/sites/default/files/publications/Climate_implications_LNG_marinefuel_01282020.pdf
27. Rosselot KS, Balcombe P, Ravikumar AP, Allen DT. Simulating the variability of methane and CO_2 emissions from liquefied natural gas shipping: a time-in-mode and carrier technology approach. *ACS Sustainable Chem Eng*. 2023;11:15632-15643. doi:10.1021/acssuschemeng.3c042
28. Balcombe P, Staffell I, Kerdan IG, Speirs JF, Brandon NP, Hawkes AD. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. *Energy*. 2021;227:120462. doi:10.1016/j.energy.2021.120462
29. Howarth RW. Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York. *J Integr Environ Sci*. 2020;17:69-81. doi:10.1080/1943815X.2020.1789666
30. Sherwin ED, Rutherford JS, Zhang Z, et al. US oil and gas system emissions from nearly one million aerial site measurements. *Nature*. 2024;627:328-334. doi:10.1038/s41586-024-07117-5
31. Hayhoe K, Kheshgi HS, Jain AK, Wuebbles DJ. Substitution of natural gas for coal: climatic effects of utility sector emissions. *Clim Change*. 2002;54:107-139.
32. Engineering ToolBox. *Fuels—Higher and Lower Calorific Values*. EngineeringToolBox.com; 2003. Accessed October 9, 2023. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
33. Fesenfeld LP, Schmidt TS, Schrode A. Climate policy for short- and long-lived pollutants. *Nat Clim Change*. 2018;8:933-936. doi:10.1038/s41558-018-0328-1
34. Balcombe P, Heggo DA, Harrison M. Total methane and CO(2) emissions from liquefied natural gas carrier ships: the first primary measurements. *Environ Sci Technol*. 2022;56:9632-9640. doi:10.1021/acs.est.2c01383
35. Ocko IB, Hamburg SP, Jacob DJ, et al. Unmask temporal trade-offs in climate policy debates. *Science*. 2017;356:492-493. doi:10.1126/science.aaj2350
36. DEC. *Statewide Greenhouse Gas Emissions Report*. New York State Department of Environmental Conservation; 2021. Accessed October 16, 2023. https://www.dec.ny.gov/energy/99223.html#Report
37. Alvarez RA, Zavala-Araiza D, Lyon DR, et al. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*. 2018;361:186-188. doi:10.1126/science.aar7204
38. Comer B, Beecken J, Vermeulen R, et al. *Fugitive and Unburned Methane Emissions from Ships (FUMES): Characterizing Methane Emissions from LNG-Fueled Ships Using Drones, Helicopters, and On-board Measurements*. International Council on Clean Transportation; 2024. Accessed August 21, 2024. https://theicct.org/publication/fumes-characterizing-methane-emissions-from-lng-fueled-ships-using-drones-helicopters-and-on-board-measurements-jan24/
39. Raza Z, Schoyen H. A comparative study of the northern sea route (NSR) in commercial and environmental perspective with focus on LNG shipping. In: *6th International Conference on Maritime Transport, Barcelona, Spain*; 2014. Accessed October 16, 2023. https://www.researchgate.net/publication/272828954_A_COMPARATIVE_STUDY_OF_THE_NORTHERN_SEA_ROUTE_NSR_IN_COMMERCIAL_AND_ENVIRONMENTAL_PERSPECTIVE_WITH_FOCUS_ON_LNG_SHIPPING
40. Hasan MMF, Zheng AM, Karimi IA. Minimizing boil-off losses in liquefied natural gas transportation. *Ind Eng Chem Res*. 2009;48:9571-9580. doi:10.1021/ie801975q
41. Oxford Institute for Energy Studies. *The LNG Shipping Forecast: Costs Rebounding, Outlook Uncertain*. Oxford Institute for Energy Studies; 2018. Accessed October 16, 2023. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/02/The-LNG-Shipping-Forecast-costs-rebounding-outlook-uncertain-Insight-27.pdf
42. EIA. *EIA Expects U.S. Natural Gas Production to Rise as Demand for Exports Grows*. Energy Information Agency, US Department of Energy; 2022. Accessed March 28, 2024. https://www.eia.gov/todayinenergy/detail.php?id=51558
43. EIA. *High Natural Gas Production and Storage Injections in September Drove U.S. Prices Down*. Energy Information Agency, US Department of Energy; 2022. Accessed March 28, 2024. https://www.eia.gov/todayinenergy/detail.php?id=54499
44. EIA. *U.S. Natural Gas Production and LNG Exports Will Likely Grow Through 2050 in AEO2023*. Energy Information Agency, US Department of Energy; 2023. Accessed March 28, 2024. https://www.eia.gov/todayinenergy/detail.php?id=56320
45. NETL. *Petroleum-based Fuels Life Cycle Greenhouse Gas Analysis—2005 Baseline Model*. National Energy Technology Laboratory, US Department of Energy; 2008. Accessed September 4, 2019. https://openei.org/wiki/NETL_-_PetroleumBased_Fuels_Life_Cycle_Greenhouse_Gas_Analysis_2005_Baseline_Model
46. Howarth R. Methane emissions from the production and use of natural gas. *EM Mag*. 2022:11-16. Accessed October 16, 2023. https://www.research.howarthlab.org/documents/Howarth2022_EM_Magazine_methane.pdf
47. Innocenti F, Robinson R, Gardiner T, Howes N, Yarrow N. Comparative assessment of methane emissions from onshore LNG facilities measured using differential absorption Lidar. *Environ Sci Technol*. 2023;57:3301-3310. doi:10.1021/acs.est.2c05446
48. Frank J. Study suggests LNG production facilities should monitor methane emissions—just like the rest of the gas supply chain. *EDF Blog*. February 16, 2023. Accessed May 28, 2024. https://blogs.edf.org/energyexchange/2023/02/16/study-suggests-lng-production-facilities-should-monitor-methane-emissions-just-like-the-rest-of-the-gas-supply-chain/
49. Timera Energy. *LNG Shipping Distances Drive Up Costs*; 2019. Accessed October 16, 2023. https://timera-energy.com/lng-shipping-distances-drive-up-costs/
50. Williams C 2023. Cheniere shunning Panama Canal for longer LNG routes to Asia. Reuters. Accessed October 16, 2023. https://www.reuters.com/business/energy/cheniere-shunning-panama-canal-longer-lng-routes-asia-2023-07-11/
51. Jaathan J, Khasawneh R. Update 1-off the boil: LNG tankers burn more oil as gas prices soar. In: *Utilities—Natural Gas*. Reuters; 2021. Accessed October 16, 2023. https://www.reuters.com/article/global-tankers-lng/update-1-off-the-boil-lng-tankers-burn-more-oil-as-gas-prices-soar-idUSL1N2Q50U0

52. BrightHub Engineering. *Dual-Fuel Engines in LNG Tankers*; 2022. Accessed October 12, 2023. https://www.brighthubengineering.com/naval-architecture/111619-propulsion-methods-for-modern-lng-tankers/
53. IMO. *Energy Efficiency of Ships. MEPC 77/6/1*. Marine Environmental Protection Committee, International Maritime Organization; 2021. Accessed September 10, 2023. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC%2077-6-1%20-%202020%20report%20of%20fuel%20oil%20consumption%20data%20submitted%20to%20the%20IMO%20Ship%20Fuel%20Oil%20Consumption%20Database%20in%20GISIS.pdf
54. EIA. *Carbon Dioxide Emissions Coefficients*. Energy Information Agency, US Department of Energy; 2016. Accessed October 11, 2019. https://www.eia.gov/environment/emissions/co2_vol_mass.php
55. Wang K, Zhang J, Cai B, Yu S. Emission factors of fugitive methane from underground coal mines in China: estimation and uncertainty. *Appl Energy*. 2019;250:273-282. doi:10.1016/j.apenergy.2019.05.024
56. Patynska R. Methodology of estimation of methane emissions from coal mines in Poland. *Stud Geotech Mech*. 2014;XXXVI(1):89-101. doi:10.2478/sgem-2014
57. European Environment Agency. *Greenhouse Gas Emission Intensity of Electricity Generation in Europe*. European Union; 2023. Accessed May 28, 2024. https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1?activeAccordion=546a7c35-9188-4d23-94ee-005d97c26f2b
58. Heat Pumps. *The Latest Heat Pump Statistics (Updated May 2024)*. Heat Pumps of London; 2024. Accessed May 28, 2024. https://www.heatpumps.london/blog/everything-you-need-to-know-about-heat-pumps
59. Defratyka SM, Paris JD, Yver-Kwok C, Fernandez JM, Korben P, Bousquet P. Mapping urban methane sources in Paris, France. *Environ Sci Technol*. 2021;55:8583-8591. doi:10.1021/acs.est.1c00859
60. IPCC. Climate change 2013. The physical science basis. In: *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Change*; 2013. Accessed August 9, 2023. https://www.ipcc.ch/report/ar5/wg1/
61. Ritchie PDL, Alkhayuon H, Cox PM, Wieczorek S. Rate-induced tipping in natural and human systems. *Earth Syst Dyn*. 2023;14:669-683. doi:10.5194/esd-14-669-2023
62. Nzotungicimpaye CM, MacIsaac AJ, Zickfeld K. Delaying methane mitigation increases the risk of breaching the 2°C warming limit. *Commun Earth Environ*. 2023;4:250. doi:10.1038/s43247-023-00898-z
63. Collins WJ, Webber CP, Cox PM, et al. Increased importance of methane reduction for a 1.5 degree target. *Environ Res Lett*. 2018;13:054003. doi:10.1088/1748-9326/aab89c
64. Figueres C. Gas, like coal, has no future as the world wakes up to climate emergency. *South China Morning Post*. August 29, 2021. Accessed August 9, 2023. https://www.scmp.com/comment/opinion/article/3146479/gas-coal-has-no-future-world-wakes-climate-emergency
65. Gaventa J, Pastukhova M. Gas under pressure as IEA launches net-zero pathway. *Energy Monitor*. May 18, 2021. Accessed August 9, 2023. https://energymonitor.ai/policy/net-zero-policy/gas-under-pressure-as-iea-launches-net-zero-pathway

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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