Analysis of Liquefied Natural Gas as a Marine Fuel in the United States

Published April, 2024

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Acronyms & Abbreviations

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2- or 4-S	Two- or four-stroke engine
AFR	Air-to-fuel ratio
AIS	Automatic Identification System
AR6	IPCC Sixth Assessment Report
Atm	Atmospheric pressure (14.696 PSI)
ATSDR	Agency for Toxic Substances and Disease Registry
BC	Black Carbon
BCF	Billion Cubic Feet
BOG	Boil-Off Gas
BTU	British Thermal Unit
CAPEX	Capital Expenditure
CCST	Carbon Capture
CDC	Centers for Disease Control and Prevention
CEJST	Climate and Economic Justice Screening Tool
CH_2O	Formaldehyde
CH_4	Methane
CII	Carbon Intensity Indicator
CIMC	China International Marine Containers
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent units
CPP	Clean Power Plan
CSA	Clean Shipping Alliance
DOE	Department of Energy
DWT	Deadweight Tonnage
ECA(s)	Emissions control area(s)
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ETS	Emission Trading System
EU	European Union
FSRU	Floating Storage Regasification Unit
Gal	Gallon
GGFR	Global Gas Flaring Reduction Partnership
GHG	Greenhouse Gas
GHG(s)	Greenhouse gas(ses)
GHG4	Fourth IMO Greenhouse Gas Study
GJ	Gigajoule
GT	Gross Tonnage
GT	Gross tonnage
$GWP_{20/100}$	Global warming potential (20 or 100-year)
HPDF	High-Pressure Dual-Fuel
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
kg	Kilogram (1,000 g)
km	Kilometer (1,000 m)
kW	Kilowatt (1,000 W)
LBSI	Lean-burn spark ignition
LH_2	Liquid hydrogen

LNG	Liquefied natural gas
LNG	Liquefied Natural Gas
LNGBV(s)	Liquefied natural gas bunkering vessel(s)
LPDF	Low-Pressure Dual-Fuel
LPG	Liquefied Petroleum Gas
m^3	Cubic meter
MARPOL	International Convention for the Prevention of Pollution from Ships
MGO	Marine Gas Oil
MJ	Megajoule
MMBTU	Million British Thermal Units
MMT	Million Metric Tons
MRV	Monitoring, Reporting, and Verification
MTPa	Million tons per annum (year)
MTSA	Maritime Transportation Security Act
MW	Megawatt
NEI	National Emissions Inventory
NH_3	Ammonia
NIMBY	Not In My Back Yard
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen Oxides
OGV(s)	Oceangoing vessel(s)
OPEX	Operating Expense
PM	Particulate Matter
PSI	Pounds per Square Inch
RED	Renewable Energy Directive
ROPAX	Roll-on/Roll-off Passenger
RORO	Roll-on/Roll-off
SVI	Social Vulnerability Index
TCF	Trillion cubic feet
TEU	Twenty-Foot Equivalent Unit
TtW	Tank-to-wake/wheel
UHC	Unburned Hydrocarbons
UNGD	Unconventional natural gas development
USACE	United States Army Corps of Engineers
USC	United States Code
VOC	Volatile Organic Compound
WB	World Bank
WtT	Well-to-tank
WtW	Well-to-wake/wheel

LNG Properties and Conversions

Storage Temperature (LNG)	-162°C
Storage Pressure (LNG)	1 atmospheric pressure (atm) or 15 pounds per squar inch (psi)
1 cubic meter LNG (m^3)	615 cubic meter natural gas (m^3)
1 cubic meter LNG (m^3)	264.172 gallons LNG (gal)
1 cubic meter LNG (m^3)	0.448 metric tonnes LNG (mt)
1 metric tonne LNG (mt)	53.57 million British Thermal Units (MMbtu)
1 billion cubic feet per day (Bcf/d)	7.59 million tonnes per year (Mtpa)
1 million tonnes per year (Mtpa)	48.7 billion cubic feet per year (Bcf/y)
1 million tonnes per year (Mtpa)	1.379 billion cubic meters per year (Bcm/y)
1 trillion cubic feet (Tcf)	1000 billion cubic feet (Bcf)
1 MJ	847.81712 BTU

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Introduction

International and domestic shipping are responsible for emissions of over 1 billion metric tonnes of carbon dioxide (CO_2) every year (Faber et al., 2020). In July 2023, the International Maritime Organization (IMO) set a goal of reaching net-zero greenhouse gas (GHG) emissions from international shipping by 2050 compared to the 2008 baseline (Marine Environment Protection Committee, 2023a), but the range of plausible scenarios in the Fourth IMO GHG (*GHG4*) study projects CO_2 emissions to increase from about 90% of 2008 levels in 2018 to 90-130% of 2008 levels by 2050 (Faber et al., 2020). That is, *GHG4* shows projected emissions to either stay flat (relative to 2018 levels), or increase, therefore missing projected IMO goals by 2050.

Liquified Natural Gas (LNG) is emerging as an alternative fuel to conventional bunkers, as it emits lower criteria air pollutants (SOx and NOx), and its stack emissions of GHGs are lower.1 According to GHG4, consumption of LNG by international shipping increased by around 28-29% from 2012 to 2018. In 2022, 51% of newbuild vessel orders by tonnage were LNG dual fueled (397 orders of 36.4m GT).2

Box 1: Introduction to Liquefied Natural Gas
Liquefied natural gas (LNG) is produced through liquefaction of natural gas, which is predominately made up of methane (CH_4), by cooling natural gas down to around -162°C. The energy density of LNG is ~50 MJ/kg in its liquefied state, making it a useful energy carrier for use in combustion engines or directly as a commodity for commercial, industrial, and power generation needs. LNG has been promoted as an alternative fuel choice to substitute for conventional marine fuels, such as heavy fuel oil or marine diesel oil.

LNG has a lower carbon-to-hydrogen ratio and nitrogen content than conventional marine fuels, and LNG combustion emits lower levels of particulate matter (PM) and black carbon (BC) and is near sulfur-free. However, LNG combustion greatly increases emissions of formaldehyde (CH_2O), carbon monoxide (CO) and unburned hydrocarbons (UHCs) over diesel fuel.

While LNG has received interest for its ability to meet present regulated criteria pollutant emissions standards (e.g., SO_x), LNG is not a low-GHG fuel. LNG is almost entirely composed of methane, which is a potent GHG. Unburned methane that escapes into the atmosphere along the LNG supply chain can represent a significant contributor to GHG inventories.

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[1] https://www.wartsila.com/insights/article/mind-the-methane-gap

[2] https://insights.clarksons.net/green-technology-tracker-january-2023/

However, due to concerns about its methane emissions, the viability of LNG as a low-GHG fuel has been called into question.[3] The LNG landscape—from fuel production and bunkering to vessel operations and environmental considerations—is rapidly evolving. This report provides a detailed review of the existing literature on LNG as a marine fuel, including discussion of policies and regulations; LNG engine technologies and emissions; the global and U.S. LNG vessel fleets; production, import and export of LNG; and the health and equity implications of LNG. The main chapters are supported by additional detail in the Supplemental Information sections found at the end of the report.

Background

LNG plays a pivotal role in the global energy sector. Transoceanic trade of natural gas has grown rapidly over the past decade, and LNG has seen growing interest and use as an alternative fuel for the maritime sector. Methane emissions from international shipping increased by around 150% between 2012-2018, primarily attributed to the increase in use of LNG as a propulsion fuel (Faber et al., 2020). To support this increased use of LNG, supporting production and distribution infrastructure rapidly expanded and investments are growing.

Methane emissions, including those from ships, have substantial implications for climate change and warming impacts. Methane is 27-30 times more potent than carbon dioxide (CO_2) as a greenhouse gas over a 100-year timeframe (United States Environmental Protection Agency, 2016b); and is 82.5 times more potent than CO_2 over the near-term (Table 1).

Table 1. GWP_{20} and GWP_{100} estimates for carbon dioxide and methane from the U.S. Environmental Protection Agency (EPA) and the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6)

	U.S. EPA	IPCC AR6
CO_2 $GWP_{20 \text{ and } 100}$	1	1
CH_4 GWP_{20}	81 - 83	82.5
CH_4 GWP_{100}	27 - 30	29.8

(Forster et al., 2023; United States Environmental Protection Agency, 2016b)

Global warming potential (GWP) also accounts for indirect effects, such as methane's role as a precursor to ozone which, when present in the troposphere, absorbs outgoing radiation (heat). Methane is typically reported in CO_2 equivalent emissions (CO_2e) weighted by GWP (e.g., 1 kg CH_4 = 82.5 kg CO_2e (IPCC AR6, GWP_{20})) to standardize discussion of the climate effects of warming emissions and allow direct comparison with other greenhouse gasses. Reports of methane weighted by GWP_{20} or GWP_{100} may be different based on the year and source of their GWP number.

The United States (U.S.) has been the world's top producer of natural gas since 2011 and has been a net exporter since 2017 (Maizland & Siripurapu, 2022). The contribution of methane from U.S. natural gas

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[3] See, for example https://www.nrdc.org/sites/default/files/sailing-nowhere-liquefied-natural-gas-report.pdf, https://www.transportenvironment.org/discover/methane-escaping-from-green-gas-powered-ships-fuelling-climate-crisis-investigation/

operations is approximately 164.9 million metric tonnes CO_2e, accounting for 25.4% of total methane emissions in the U.S. (United States Environmental Protection Agency, 2022). While methane emissions are often referred to as slip or leaks, some emissions occur from purposeful venting, such as for routine maintenance or maintaining storage pressures. Methane emissions from LNG increase with transportation distance due to venting or burning of daily boil-off gas (BOG) generation (Al-Breiki & Bicer, 2021). Thus, its global export has increased methane released to the atmosphere before it even fueled a vessel.

Whether through uncombusted methane released in exhaust gasses or venting of boil-off gas to maintain storage pressures, leaks occur throughout LNG's supply and consumption. The LNG fuel value chain "encompasses the production, processing, and conversion of natural gas to LNG, its long-distance transportation, and regasification, as it travels from the wellhead to end-users" (Office of Fossil Energy, 2020). Emissions occurring over the entire fuel value chain, from production to use, are referred to as well-to-wake (WtW) emissions. As much as 4% of natural gas produced by shale fracking is lost to leakage before consumption as fuel (Howarth, 2019). While the exact measurements are uncertain, it seems rates are higher than the estimations. Given the high warming potential of methane compared to CO_2, it is crucial to reduce methane leakage from LNG infrastructure and optimize LNG technologies (Alvarez et al., 2012).

The LNG supply chain involves the following:

1. Natural gas is extracted from subsurface reservoirs, such as salt formations and depleted aquifers, and transported via pipelines to processing facilities to remove impurities (U.S. Energy Information Administration, 2015).

2. Processed natural gas is transported to liquefaction sites via pipelines, where it is supercooled to -260°F (-162°C), transforming the gas into a liquid state and becoming LNG. At this stage, LNG is approximately 1/600th the volume that it was in its gaseous state, which increases transport capacity and feasibility (Office of Fossil Energy, n.d.).

3. LNG is moved to storage tanks, typically transported by LNG carriers, to be transferred at the destination.

4. At this stage, LNG can be stored, regasified via heating for use, or transported via truck, ship, and rail to the end consumer.

Given the evolving international climate goals, treaties, and subsequent regulations, LNG life cycle emissions will struggle to align with targets. In addition to the global warming implications of LNG use, other impacts involving human health and environmental justice exist. For example, methane emissions from increased LNG consumption can increase background ozone concentrations, which can harm human health at ground level. Also, during natural gas production, additional criteria pollutants can contaminate the air and water, posing risks to communities residing in proximity to natural gas extraction and liquefaction sites (W. Peng et al., 2020). Further exploration of the health repercussions of LNG is necessary to formulate regulatory policies in the maritime sector.

Policy & Regulation

Regulatory agencies across the globe are increasingly focused on GHG emission reductions. Regulations for global warming mitigation have long focused on CO_2 emissions. However, methane is the second most abundant anthropogenic GHG after CO_2 (United States Environmental Protection Agency, 2016a). The maritime industry is beginning to incorporate methane emissions into their regulatory frameworks, but policies and regulations are in early development. For the maritime sector, policy decisions and implementation timelines can shape choices in engine, fuel, and exhaust after-treatment and guide infrastructure development.

This section includes information on domestic and international policies and regulations that have implications for maritime methane emissions and thus LNG-fuel use.

U.S. Blueprint for Transportation Decarbonization

The U.S. has not mandated a national climate target within its domestic regulations, however, in 2021 the U.S. re-joined the Paris Agreement and committed to achieve at least a 50% reduction in net GHG emissions by 2030 (United Nations Climate Change, n.d.). In January 2023, a collaboration of U.S. federal agencies[4] released a joint strategy to transform and decarbonize the transportation sector by midcentury, including the domestic and oceangoing U.S. fleets (United States Department of Energy et al., 2023). The federal GHG reduction goals for maritime include:

1. Ensure that 5% of the global deep-sea fleet are capable of using zero-emission fuels by 2030, with at least 200 of these ships using these fuels for their primary propulsion across the main shipping routes;
2. Ensure 10 large trade ports, that cover at least three continents, can supply zero-emission fuels by 2030;
3. Support more research and design of sustainable fuels and technologies, increase investment in domestic landside infrastructure, and incentivize U.S. commercial operators to move toward lower emissions; and
4. Collaborate with other countries in IMO policy processes to achieve zero emissions of international shipping by 2050.

The current strategies in this collaborative blueprint support the near-term opportunities of sustainable liquid fuels in the maritime sector (primarily LNG and biofuels), over that of battery/electric or hydrogen propulsion (including hydrogen for ammonia and methanol), for which they consider that more research and advancements are required (United States Department of Energy et al., 2023). Maritime shipping is recognized as having the lowest carbon-intensity compared to other transport modes, and the

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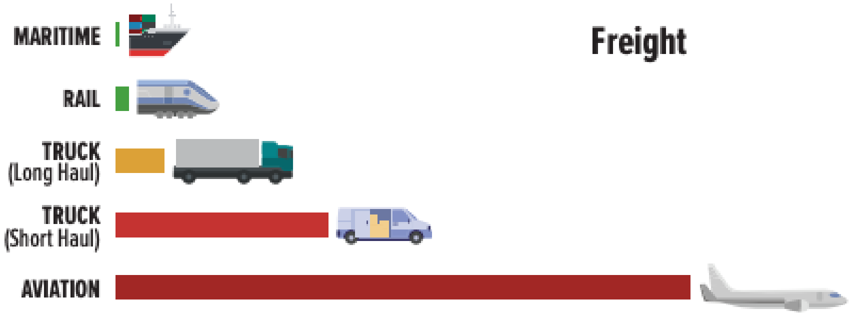
[4] Department of Energy, Department of Transportation, Environmental Protection Agency, and Department of Housing and Urban Development

administration’s plan states that “a system that prioritizes the low-carbon-intensity options has fewer emissions overall” (Figure 1).

Figure 1. Emissions by Mode of Transportation



Average pounds of GHG emissions per passenger mile or freight ton-mile using for existing fossil fuel technologies.

Comparative emissions per passenger-mile or freight ton-mile by freight transport mode- Freight, sourced from The U.S. National Blueprint for Transportation Decarbonization; informed by GREET model and EPA data.

The strategy urges regulations that increase the rate of adoption of low-GHG capable transportation, particularly for maritime due to the long lifespan of the fleet. The Blueprint cites the Inflation Reduction Act and Port Infrastructure Development Program as two in-place packages of federal subsidies to develop zero-emission infrastructures at ports, but requests resources be allocated to incentivize clean vessel upgrades/retrofits.

The Global Methane Pledge

The U.S. and EU jointly launched the Global Methane Pledge in 2021, which was signed by 111 nations. This pledge called on participants to develop or update a national methane reduction action plan before the 27th United Nations Climate Change conference of Fall 2022. The pledge does not specify additional actions or steps participants are expected to take. It is non-binding but was set to motivate a global reduction in methane emissions by ≥30% by 2030 (compared to 2020 levels). The Global Methane Pledge is broad but has implications for maritime methane emissions and thus LNG-fuel usage. To date, no country has demonstrated significant progress toward achieving these goals (Climate & Clean Air Coalition, 2021, 2023).

U.S. Clean Shipping Act

In 2023, the U.S. Clean Shipping Act was introduced in Congress and would set a plan to eliminate GHG emissions from all shipping companies and their vessels engaging in business with the United States. It proposes GHG intensity standards for fuels, including methane, as well as the well-to-wake and indirect emissions of the source. For each calendar year, the act proposes that vessels must report the amount of the fuel consumed and the total GHG emissions measured in CO_2e (GWP$_{100}$) for “any voyage of a vessel for the purpose of transporting passengers or cargo for commercial purposes” that enters or leaves the U.S. The emissions monitoring framework and reporting requirements will be based on existing EU and IMO schemes. If accepted, its reduction scheme will establish a baseline of the average GHG intensity of the fuel used by all vessels on covered voyages in 2024 and reduce emissions by at least 20% from 2027, at least 45% from 2030, at least 80% from 2035, and 100% from 2040 onwards (House of Representatives, 2023).

Methane Regulations in the European Union

EU Monitoring, Reporting, and Verification System

The EU Monitoring, Reporting, and Verification (EU MRV) requires ships >5,000 gross tonnage calling at EU ports to calculate and disclose annual CO_2 emissions, fuel consumption, and energy efficiency in a public database. Voyage-level monitoring is then aggregated and reported annually (Erbach, 2020). Emissions of methane and nitrous oxides, another potent GHG, will be added to the EU MRV reporting requirements in 2024 and the minimum gross tonnage will drop from 5,000 to 400 GT beginning in 2025 (European Parliament & Council of the European Union, 2023).

Fit for 55 & FuelEU Maritime

"Fit For 55" is a legislative package containing 12 items that aim to reduce GHG emissions by 55% by 2030 in the EU (compared with 1990 levels). Of the 12 items in Fit For 55, four are directly relevant to the maritime industry. Beginning January 2023, maritime bunker fuels sold in the EU and used on voyages within the EU will no longer be tax-exempt. The new structure will tax fuels that pollute the most at the highest rate, ranging between €0.15-10.75/GJ. Additionally beginning in 2023, an updated version of the EU emissions trading scheme (ETS) will require all vessels navigating to and from European ports to purchase allowances for each ton of CO_2 they emit, which will ultimately be determined by market pricing for carbon emissions. The scheme will be slowly scaled-up to its full capacity in 2025. Discussions are still ongoing about when the tax would fall onto the shipping company versus the chartering entity (Furustam, 2022).

Another EU regulation, the FuelEU Maritime regulation, has been introduced that will increase the availability of alternative fuels and electrified equipment at ports within the EU. This currently proposed regulation will support increasing the availability of LNG for bunkering at EU ports (Furustam, 2022). The FuelEU Maritime regulation is due to come into effect in 2025. FuelEU Maritime focuses on reducing the GHG-intensity from the maritime industry, including CO_2, CH_4, and NO_x emissions, through low-GHG fuels with specific consideration of the so-called "well-to-wake" (or full life cycle) emissions. The inclusion of methane will be significant in motivating technological advances to improve efficiency and to reduce methane slip. The FuelEU GHG intensity reduction targets are outlined by the following schedule: 2% from 2025, 6% from 2030, 14.5% from 2035, 31% from 2040, 62% from 2045, and 80% from 2050 (compared to a reference value of 91.16 gCO2e/MJ). The FuelEU methane slip factors for vessels engines using fuels such as LNG are 0.2% for high-pressure dual fuel 2-Stroke (2-S), 1.7% for low-pressure dual fuel 2-stroke (2-S), 3.1% for low-pressure dual fuel 4-stroke (4-S), and 2.32% for lean-burn spark ignition 4-S. These values are calculated at 50% of the engine load (European Commission, 2021).

The International Maritime Organization, MARPOL Annex VI

The IMO has worked to address GHG emissions from ships, consistent with the Paris Agreement global average temperature targets. The initial GHG strategy of 2018 proposed a 40% reduction in carbon intensity (e.g., CO_2 per transport work) by 2030, as well as an effort to move to a 70% reduction in carbon intensity by 2050 relative to 2008 levels, and a 50% reduction in total annual GHG emissions by 2050 relative to 2008 levels (Marine Environment Protection Committee, 2018).

The revised 2023 IMO Strategy on Reduction of GHG Emissions from Ships has introduced “indicative checkpoints” that call for reducing total GHG emissions between 20-30% by 2030 and between 70-80% by 2040, relative to 2008 rates (Marine Environment Protection Committee, 2023a). The revised strategy also aims for 5-10% of fuels used by international shipping to be zero or near-zero-GHG emission fuels by 2030 and for net-zero-GHG emissions by 2050. The IMO’s Life Cycle Analysis (LCA) Guidelines[5] include methane slip from LNG engines in the life cycle emissions table and the revised GHG strategy includes direction to “consider and analyse [sic.] measures to address emissions of methane.” The revised strategy is not legally binding, however, the measures used to implement it can be. The IMO’s Marine Environment Protection Committee has until 2025 to set mid-term measures and 2028 for long-term measures, for which methane will likely be addressed (Marine Environment Protection Committee, 2023b).

The International Convention on the Prevention of Pollution from Ships (MARPOL) Annex VI also introduced the Energy Efficiency Design Index (EEDI) to set efficiency requirements for ship newbuilds of ≥400 gross tons, beginning at and after 2013. EEDI seeks to reduce CO_2 emissions through requirements in efficient technology onboard. It was expanded in 2021 with the Energy Efficiency Existing Ship Index (EEXI), which came into effect in 2023. EEXI set requirements for existing ships to meet carbon standards through engine upgrades and other enhancements to vessel efficiency and operations. Lastly, the Carbon Intensity Indicator (CII) was introduced to grade ships from A to E on their efficiency and determine the level of annual improvements, although there are limited repercussions for low-graded ships. These carbon standards do not directly address methane slip, but including it in the IMO’s future considerations of EEDI/EEXI/CII would be beneficial in light of the growing uptake of LNG fuel (International Maritime Organization, n.d.).

LNG Engine Types

Regulations that set emissions standards, particularly those targeting NO_x, have produced an LNG fleet that has 80% of its vessels powered by low-pressure dual fuel (LPDF) engines (Kuittinen et al., 2023). This is largely attributed to modern lean-burn spark ignition and low-pressure dual fuel engines that satisfy IMO NO_x Tier III regulations without aftertreatment exhaust technologies. However, these engines have consequently higher methane emissions, as shown in Table 2 (Eilts, 2018).

Detail on LNG engine types can be found in Supplemental Information (SI) 1.

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[5] MEPC.376(80)

Table 2. Comparison of marine LNG engine types and characteristics

Engine Type	Lean-Burn Spark Ignition (LBSI)	Low-Pressure Dual Fuel (LPDF)		High-Pressure Dual Fuel (HPDF)
Power Stroke	Four-stroke		Two-stroke	
Power Range	Medium- & High-speed 0.5-8 MW	Medium-speed 1-18 MW	Slow-speed 5-63 MW	Slow-speed >2.5 MW
Fuel Cycle(s)*	Otto	Otto (gas mode) & Diesel (diesel mode)		Diesel
Ignition Process	Spark plug ignition of air-gas mixture	Constant volume homogeneous air-gas mixture		High-pressure compression-ignition
Pilot Fuel	No	Yes		
Nitrogen Oxides Performance	Tier III			Tier II

*Diesel-cycle systems inject fuel at high pressures, for which heat is generated in the charge to ignite the fuel. Otto-cycle uses constant volume combustion of an air-fuel mixture at low pressures, with use of a spark plug or pilot fuel ignition.

(Schuller et al., 2021; Ushakov et al., 2019)

LNG-compatible marine engines can be categorized as either four-stroke lean-burn spark ignition engines (LBSI 4-S) or dual fuel engines, which include high-pressure two-stroke (HPDF 2-S) and low-pressure two- or four-stroke engines (LPDF 2-S or 4-S). Dual fuel engines operate using “primary” fuel (e.g., LNG), with a secondary “pilot” fuel, which is usually marine diesel. LBSI engines run on LNG only while dual fuel engines are capable of running on multiple fuel sources and can rapidly switch between fuels.

LNG Retrofit

Existing internal combustion engines can be modified and retrofitted to burn LNG as an alternative fuel choice to conventional marine fuels. Vessel retrofits require investment in new vessel infrastructure and additional space for cryogenic fuel storage and delivery. LNG retrofit is time-intensive, and Clarksons research reports that six specialist LNG building yards are fully booked until 2027 (Clarksons, 2023). Retrofits primarily emphasize enhanced combustion efficiency, with targeted adjustments to the start of combustion, air-fuel ratio, injectors, or other mechanical components.

LNG can be used in conventional diesel internal combustion engines, with relatively minor modifications, as the basic mechanical components are similar. The capital expense (CAPEX) to retrofit a two-stroke engine and fuel system to run on LNG for a large crude oil tanker is around $30.3 million, or approximately $1,000/kW, assuming a 30,000 kW engine (SEA-LNG, 2022). Norway’s Det Norske Veritas estimates that the cost of retrofitting a ship for LNG should not exceed 25% of the cost of a newbuild vessel to be economically viable (Chryssakis, 2023). In 2023, the average price of a newbuild LNG carrier was around $260 million (Synder, 2023b; The Maritime Executive, 2022b). The median combined power of existing main and auxiliary engines is around 26,500 kW. Therefore, retrofitting 26,500 kW of total engine power at a cost of $26.5 million (10.2% of new build price) could be considered economically viable.

Retrofitting an LNG vessel to be able to run on zero- or near-zero alternative fuels is addressed later in the report in the discussion on the LNG value chain where LNG as a transition maritime fuel end use is examined.

Engine Type Emissions and Efficiency

An exhaust emissions trade-off exists between NO_x and UHCs when selecting a marine engine, due to differences in the air-fuel ratio (See Section SI 1). Engine tuning to meet regulatory requirements for NO_x typically does not consider CH_4 and CO, for which there have been limited international regulations until recently.

Otto-cycle gas combustion (LBSI and LPDF) have higher methane slip but lower NO_x than Diesel-cycle (HPDF) engines (Stiesch, 2022). However, HPDF engines do meet IMO Tier III NO_x limits without additional technologies for exhaust treatment (Table 3).

Table 3: Emission profiles of LNG-fueled marine engines

Engine Type	**LBSI 4-S**	**LPDF 4-S**	**LPDF 2-S**	**HPDF 2-S**
Percent of Fleet	< 2%	~54%	~25%	15%
E2/E3 Weighted* CH_4 Slip (g CH_4/kWh)	2.0-5.5	2.0-13.5	2.1-3.5	0.2-0.3
<25% Load CH_4 Slip (g CH_4/kWh)	6.4-42.0	6.1-123.0	2.8-7.2	N/A
>75% Load CH_4 Slip (g CH_4/kWh)	2.5-5.0	2.6-10.1	1.9-2.9	N/A
Average CH_4 Slip (gCO_2e/kWh, GWP_{100})	60.0	119.0	64.0	7.0
Total GHG WtW Emissions (gCO_2e/kWh, GWP_{100})	624.0-N/A	685.0-786.0	594.0-655.0	533.0-547.0

Upstream GHG emissions of U.S. Natural Gas: 28.8-68.4 gCO_2e/kWh, GWP_{100}

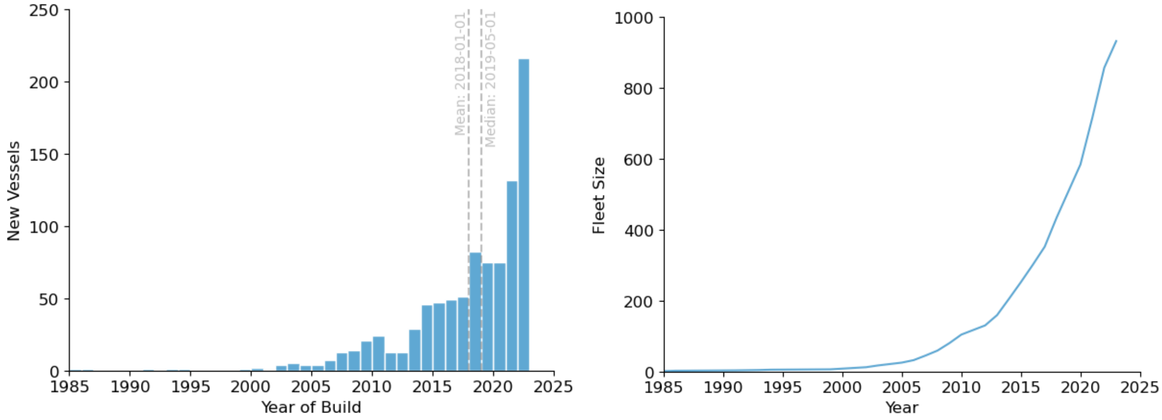
*The use of IMO E3/E2 test cycles in reporting of methane slip is debated. These rely on uniform modes of engine power & speed with a specified weighting, which cannot represent the true operating conditions of every vessel. E2 cycles are for “constant-speed main propulsion” whereas E3 cycles are for "propeller-law-operated main and auxiliary engine" application (ISO 8178).

(Argonne National Laboratory, 2022; International Maritime Organization, 2022; International Organization for Standardization, 2020; Kuittinen et al., 2023; Littlefield et al., 2022; Pavlenko et al., 2020; Schuller et al., 2021)

The Global LNG Vessel Fleet

Growth of the global LNG fleet has been rapid, with 54% of IMO numbers in the current active fleet registered in or after 2019. Over 90% of the LNG fleet was built in or after 2010, and the mean vessel age, as of writing, is 5.4 years (Figure 2).

Figure 2. New Vessels and LNG Fleet Size



Bar plot showing new vessels by year of build (left) and line plot showing cumulative LNG fleet size (right).

There are 904 active vessels propelled by LNG as a primary fuel, with an additional 28 vessels that were propelled by boil-off gas (BOG) from LNG cargo. BOG results from LNG vaporization within cryogenic storage tanks and increases internal pressure, requiring release. Venting these vapors releases methane emissions directly to the environment, and some LNG carriers have been equipped to power steam turbine propulsion engines with the BOG that would otherwise be considered lost cargo of the fuel they are transporting. There were 244 vessels that listed LNG as a secondary fuel, as well as 240 conventionally fueled LNG tankers.

LNG tankers make up 45.5% of the vessels in the LNG-fueled fleet (55.2% by deadweight), indicating the demand for natural gas imports and exports in the global energy trade. The conventionally fueled LNG tanker fleet (17.9 years) is older than the LNG-fueled tanker fleet (5.4 years), with an observable preference for LNG-fueled tankers beginning in 2010. In 2023, the combined gas carrying capacity of all vessels in service/commissioned is 105.4 million cubic meters (m^3).

Containerships represented approximately 1% of the LNG fleet in 2021 but were the third largest population in the mid-2023 fleet at 6.4% (12.1% by deadweight). The orderbook reflects an additional 183 LNG-fueled containerships that will enter the fleet in coming years, more than quadrupling its current population and increasing deadweight by a factor of 2.87.

The LNG orderbook reflects a substantial increase in sizable LNG-fueled vessels entering the fleet. There is a trend toward larger and higher-powered vessels in recent years, observable in the active and ordered fleet, for which a higher fuel consumption – and likely total emissions – can be expected. Low-pressure dual fuel engines, which emit the highest methane emissions and higher life cycle GHG emissions than conventional fuels based on GWP_{20}, make up 80% of current engines in the fleet. Consequently, LNG as an alternative marine fuel chosen to meet the regulatory requirements on CO_2, NO_x, and SO_x, and the current fleet of engines, may be increasing emissions of methane to the atmosphere.

The growth of LNG use within the maritime industry has highlighted the limited regulatory oversight of methane emissions. Long-term investments in vessels and infrastructure that have been made could work against global emission trajectories. The following sections provide insight into the natural gas markets and LNG investments in the United States.

Additional detail on the fleet is available in SI 2.

The Jones Act & U.S. LNG Fleet

LNG produced in the U.S. cannot be transported by water between U.S. ports or terminals, or bunkered, without a Jones Act-compliant vessel. The Merchant Marine Act of 1920[6], commonly referred to as the Jones Act, regulates maritime commerce in U.S. waters and between U.S. ports (U.S. House of Representatives, 2022). The Jones Act mandates that all goods shipped between U.S. ports must be transported by vessels that are U.S.-flagged, -owned, -crewed, -registered, and -built. The Jones Act was established to promote a network of U.S. domestic shipbuilding and shipping after World War I. Restrictions on vessels engaged in coastwise trade and commodity movements are not solely an LNG problem, but rather an issue for domestic bunkering that will continue to be a hurdle for the domestic production of alternative fuels. Rising costs and limited supply, further exacerbated by the Russian invasion of Ukraine, has led to renewed criticism of the Jones Act due to the limitations it has placed on the domestic natural gas industry (Cyran, 2022).

The Jones Act does not apply to the entire U.S.-flagged fleet, only to vessels involved in domestic shipping. Jones Act-compliant vessels represent around 50% of the total U.S.-flagged fleet (Maritime Administration, 2021). As of 2023, there are no U.S.-flagged LNG carriers in operation. Eight prior U.S.-flagged LNG carriers changed to foreign flags, and therefore can no longer transport LNG within the U.S., or were scrapped in the 1990s (Maritime Administration, 1999). Presently the U.S., despite being the world's top producer of natural gas since 2011, has been simultaneously importing LNG for its own maritime use due to the cost restrictions of a U.S.-built LNG carrier (Cyran, 2022; Maizland & Siripurapu, 2022). The U.S. only has three shipyards capable of building Jones Act-compliant vessels, in stark contrast with the thousands of shipyards in Japan and China (Grabow et al., 2018).

The top global LNG shipbuilders include CIMC (China), Keppel Offshore and Marine (Singapore), and Hudong Zhonghua Shipbuilding (China), with a total market share of about 90% (Hosokawa & Kawasaki, 2022). However, the U.S. cannot utilize these manufacturers for their Jones Act fleet. A newbuild LNG carrier is estimated to cost $260 million in the 2023 global market, with the cost of shipbuilding increasing (Synder, 2023b; The Maritime Executive, 2022b). U.S.-built tanker costs have been estimated to be four times greater than the global price of a similar vessel (Grabow, 2019). Furthermore, the

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[6] 46 USC § 50101.

average cost of operating a U.S.-flagged vessel was previously reported to be 2.7 times higher than that of a foreign-flagged vessel with projected growth of that gap (Maritime Administration, 2011). Thus, it is more economical to have foreign-flagged LNG tankers complete voyages to U.S. harbors to import the fuel, than to ship domestic LNG resources.

The U.S. Government Accountability Office found that the high costs to build and crew a Jones Act-compliant LNG carrier would increase the cost of transporting LNG to further harm the competitiveness and demand of LNG in the global market. A 2015 estimate suggested that the high investment and operation costs of a Jones Act-compliant LNG tanker could increase the cost of export by 25%, making U.S. LNG less competitive on the market and reducing demand (Fleming, 2015).

U.S. LNG-Fueled Ship Orders

LNG's return on investment to shipowners and operators has a payback period between one to three years (SEA-LNG, 2019). The additional capital and operating costs for new-build Jones Act-compliant vessels would be unfavorable to the terms of this payback period. The 2023 LNG-fuel orderbook grew to 46% of the active LNG-fueled fleet, with a significant population of LNG tankers on order (See Section SI 2: LNG Orderbook Fleet). In 2023, the U.S. Coast Guard reported 20 LNG-fueled vessels out of 177 total vessels in the U.S.-flagged oceangoing fleet (excluding bunkering vessels, the National Defense Reserve Fleet, and those operating exclusively on inland waterways) (Bureau of Transportation Statistics, 2019; United States Coast Guard et al., 2023).

There has been a clear downward trend in the U.S. merchant fleet, comprising an increasingly smaller percentage of the growing global fleet. In 1960, the U.S. fleet represented 17% of the world fleet, but the nation's fleet has been reduced to represent less than 0.2% in 2023, as vessel operators prefer foreign "flags of convenience" (Bureau of Transportation Statistics, 2019; Premack, 2021). Although a limited population, U.S.-flagged vessels are anticipated to increasingly uptake alternative fuel choices to meet forecasted environmental regulations, due to the nation's position on the imperative for international shipping to reach zero-GHG emissions by 2050. Moreover, the U.S.-flagged fleet predominantly operates within U.S. waters and therefore are subject to emission regulations in coastal emission control areas (ECAs) (J. Taylor et al., 2022). ECAs have motivated the movement to uptake alternative fuels and emissions abatement technologies to achieve lower NO_x and SO_x emissions.

There are two Jones Act-compliant, 5,000 twenty-foot-equivalent units (TEUs), LNG-fueled containerships built for the U.S. fleet that operate from Hawaii, the *MV Janet Marie* and *MV George III* (Larkin, 2022). The *MV George III* cost $225 million to build when contracted in 2017, but estimated costs would be upwards of $300 million to replicate today (Richardson, 2022). The U.S. Coast Guard has previously made the determination that retrofitting an older Jones Act-compliant vessel for LNG at a foreign shipyard would not compromise its status of compliance (Washburn, 2021). This appears to have set a precedent allowing foreign retrofit of U.S. vessels to meet environmental regulation (SO_x and NO_x) without compromising their status. Two additional U.S.-flagged container ships signed contracts in 2022 for the retrofit of dual fuel LNG engines; based on a similar conversion the cost of retrofit has been estimated at $35 million individually (42,000kW HPDF 2-S engine, ~$830/kW) (MAN Energy Solutions, 2022b; The Maritime Executive, 2022a).

Conclusions for the LNG Fleet

Regulations and underlying micro- and macroeconomic factors have motivated ship operators to begin to transition away from conventional fuels. LNG has grown in usage as a marine fuel due to relative abundance of the fuel and compliance with global and regional SO_x and NO_x regulations. The rapidly growing LNG-fueled fleet has largely selected engines that meet NO_x standards with a tradeoff of higher methane emissions, which are presently subject to limited regulatory oversight.

Challenges posed by the Jones Act have limited investments in the domestic maritime fleet. These restrictions are not exclusive to LNG, but rather represent a broader issue for domestic fuel bunkering and alternative fuel markets, as the U.S. does not have the capacity to ship its own domestic products. The subsequent sections consider the expansion and domination of the U.S. natural gas trade. The U.S. market will not only contribute to the global availability and pricing of LNG as a marine fuel but also the nation’s investments will play a vital role in the long-term global energy landscape.

LNG Storage and Bunkering in the U.S. and Canada

LNG is experiencing rapid growth that has increased the need for specialized storage and operating infrastructure to deliver LNG fuel to ships. The first U.S. commercial liquefaction facility was built in 1941. By 2019, there were 10 coastal ports offering LNG bunkering, and by 2023, LNG can be bunkered at 185 ports worldwide (Clarksons, 2023; Parfomak et al., 2019). Europe and Asia were the early adopters of LNG bunkering, but LNG bunkering is growing in North America, as shown in the introductory timeline above.

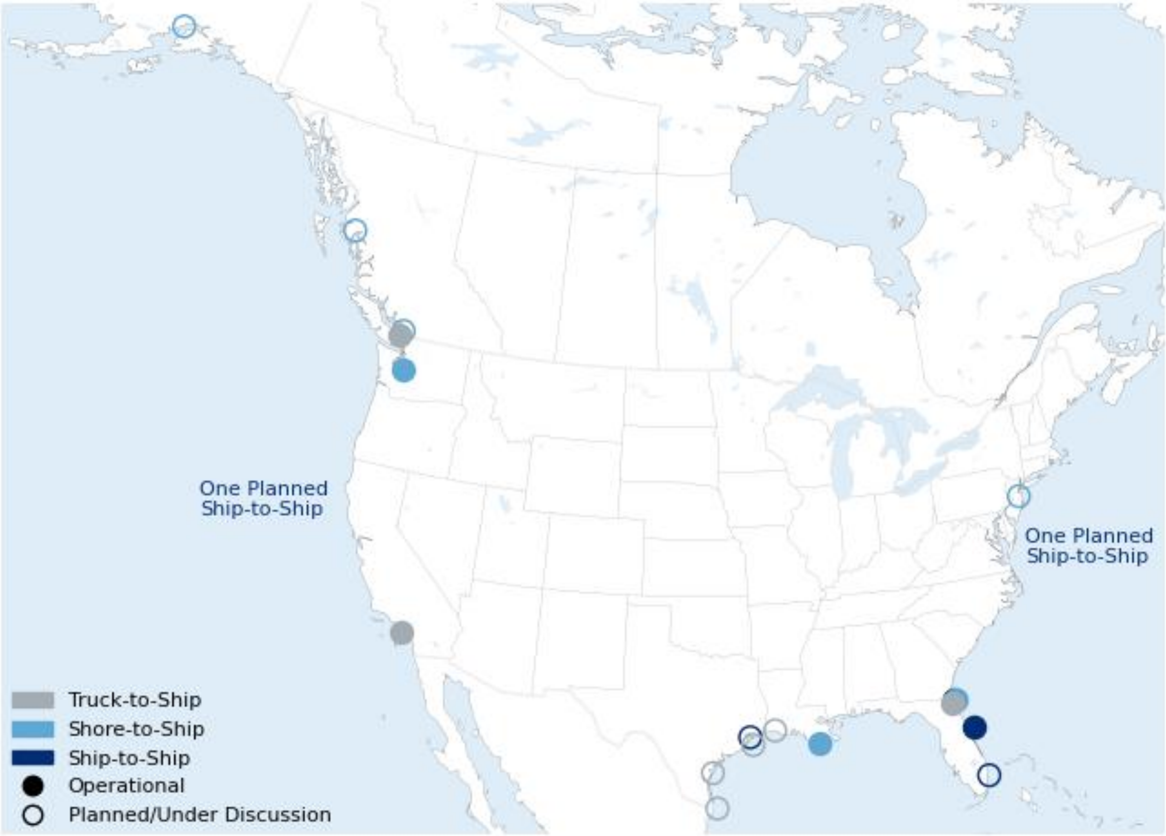
The first North American (U.S./Canada) port to offer LNG bunkering was Port Fourchon, Louisiana, in 2013. There are currently 19 existing or planned LNG bunkering operations at 15 ports in North America (SEA-LNG, 2023a). Of these 19 bunkering operations, 9 are operational and 10 are planned or under discussion. Three modes of LNG bunkering are offered in North America:

- Truck-to-Ship (3 operational, 4 planned)
- Shore-to-Ship (3 operational, 1 planned)
- Ship-to-Ship (3 operational, 5 planned)
- It is also possible, though less common, to bunker LNG by transferring portable tanks (ISO containers) from land to on-board vessels.

As shown in Figure 3 and Table 4, the majority of ports with LNG bunkering are located in the Gulf of Mexico and the Pacific Northwest. Early investments focused on growth in Jacksonville, Florida, and Port Fourchon, Louisiana, and the majority of planned bunkering operations are found in the Gulf of Mexico. JAX LNG and Eagle LNG have established the largest LNG bunkering operation of any U.S. port with their base in Jacksonville, Florida. Their facilities have the capability to serve domestic and international vessels. JAX LNG is the long-term LNG fuel supplier to the world’s first LNG dual fuel container ships, the *Isla Bella* and the *Perla del Caribe*, that are operated by TOTE Maritime Puerto Rico (*JAX LNG*, 2023; Wheeler et al., 2020). Truck-to-Ship bunkering remains the most common LNG-bunker facility type, potentially due to the low investment costs associated with it; however, recent investments in Shore-to-Ship and Ship-to-Ship bunkering signal a move toward larger-scale LNG bunkering operations that can better satisfy the needs of larger oceangoing vessels (OGVs).

Additional information on port bunkering operations and modes of bunkering can be found in SI 3. Regulatory information for LNG bunkering, storage, and transportation can be found in SI 6.

Figure 3. LNG Bunkering Operations in the U.S. and Canada



Map showing planned and existing bunkering locations in the U.S. and Canada. Filled circles show operational facilities, open circles show facilities in the planning/discussion stage.

The ports of Los Angeles and Long Beach in California are in the top five largest and busiest ports in the U.S. However, LNG bunkering capabilities at the ports are limited. In 2021, Eagle LNG identified that vessels traversing Asian shipping lanes on the Trans-Pacific trade would choose to bunker in Asia as they would have enough fuel for the roundtrip (Fisher, 2021). Demand for LNG bunkering infrastructure at the ports of Los Angeles and Long Beach is highly influenced by fuel prices, especially in their ability to sell LNG at a price comparable to the Southeastern U.S., for which there is a lower markup due to surrounding natural gas production. Recent updates to the Port of Long Beach's Master Plan that suggest future expansion of LNG bunkering at the port has been met with community backlash (Long Beach Post Partner, 2023).

The development of bunkering infrastructure is dependent on the needs of individual ports and their stakeholders. In most cases, LNG bunkering combines on-site storage facilities with off-site liquefaction plants, small-scale LNG plants with liquefaction capabilities, and/or LNG bunkering vessels (LNGBVs) that transport and store LNG from offsite liquefaction plants.

Table 4: Table of existing and planned LNG bunkering operations

Type	Port	Status	Start Date	Bunker Operator	Bunkering Capacity
Ship-to-Ship	Port Canaveral	Operational	2023	Shell	5,500 m^3
	Port of Jacksonville	Operational	2018	Polaris New Energy	2,200 m^3
	Port Miami	Operational	2023	Shell	4,000 m^3
	Galveston	Planned	2024	Pilot LNG	18,000 m^3 storage; 0.65 Mtpa
	TBD East Coast	Planned	2024	Fincantieri Bay Shipbuilding for Crowley/Shell	12,000 m^3
	TBD West Coast	Planned	2024	Vard Marine for Centerline Logistics	6,000 m^3
	Port Everglades	Planned	2023	Shell	5,500 m^3
Shore-to-Ship	Tacoma	Operational	2022	Puget Sound Energy	12,000 m^3
	Port Fourchon, Louisiana	Operational	2013	Harvey Gulf	1,020 m^3; transfer rate 2.08 m^3/minute
	Jacksonville - Talleyrand Marine Terminal	Operational	Jan 2019	Eagle LNG	1,890 m^3 storage tank and loading jetty
	Vancouver	Planned	2024	Seaspan	TBD
	Port of New York and New Jersey	Under discussion	TBD	TBD	TBD
Truck-to-Ship	Vancouver	Operational	TBD	Fortis BC	78 m^3/hour/truck
	LA/Long Beach	Operational	Q3 2022	Clean Energy Fuels Corp.	1,140 m^3
	Jacksonville - Dames Point Terminal	Operational	2018	Jax LNG	Liquefaction plant capacity 450 m^3 per day; two storage tanks net capacity 7,570 m^3.
	Port Isabel Logistical Offshore Terminal, Inc. (PILOT)	Planned	2022	Stabilis Solutions, Inc.	Scalable
	Corpus Christi, Texas	Planned	TBD	Stabilis Solutions, Inc.	Scalable
	Galveston	Planned	Q2 2022	Stabilis Solutions, Inc,	Scalable
	The Cameron Parish Port, Harbor & Terminal District (CPP)	Planned	End 2021	Stabilis Solutions, Inc.	Scalable

Approximately 70% of the global LNGBV fleet has a capacity of 5,000 m^3 and above (Synder, 2023a). Fueling rates are significantly faster than truck-to-ship, but half the speed of shore-to-ship, at 1,000 m^3/hour (Satta et al., 2021). A cruise ship requires around 2,000 m^3 for a seven-day itinerary (MarineLink, 2022; Professional Mariner, 2021). With up to 12,000 m^3 capacity, the largest LNGBVs can refuel multiple large OGVs before returning to an LNG terminal to refuel.

As of summer 2023, the global operational LNG bunkering and bunkering-capable fleet reached around 31 vessels, with an additional 15 vessels on the orderbook. Their capacity is rising to accommodate a larger fleet of LNG-fueled ships, with the active fleet average rising to 7,700 m^3 by end-2022, up from 6,900 m^3 in 2021, and the orderbook of future LNGBVs averages 9,800 m^3 (International Gas Union, 2023). However, investment costs in LNGBVs are high, with builds of a standard cargo capacity of 7,500 m^3 costing approximately $50 million (Bureau Veritas, 2022).

The U.S. LNGBV fleet must be Jones Act compliant in order to transport and bunker domestic LNG between U.S. ports. To date, the U.S. LNGBV fleet is Jones Act compliant, as there is no efficient alternative, or loophole, for ship-to-ship bunkering (Table 4). While LNGBVs can travel to serve a larger region, these vessels are not used for, or capable of, transporting bulk quantities of LNG for import/export across transoceanic journeys. The cost to build a compliant vessel is high and may hinder the ability of U.S. operators to match their supply of LNGBVs to the demand of the growing global LNG-fueled fleet looking to bunker in U.S. waters and ports.

Table 5: U.S.-Flagged Jones Act Compliant LNGBVs

Service Date	Vessel Name	Home Port	Operating Area	Capacity (m^3)	Notes
2018	Clean Jacksonville	Jacksonville	Florida & Southeast U.S.	2,200	The world's first LNG inland bunker barge[7]
2021	Q-LNG 4000 (Q4K)	Canaveral	Florida & Caribbean	4,000	The first U.S. offshore bunkering barge. Refills its LNG at Elba Island, GA facilities[8]
2022	Clean Canaveral	Canaveral	Florida, Southeast U.S., Gulf Coast	5,500	Completed first ship-to-ship transfer July 2023[9,10]
2023	Clean Everglades	Jacksonville	Florida, Southeast U.S., Gulf Coast	5,500	Anticipated late 2023 launch[11]
	Unnamed	Tacoma	Northwest U.S. & Western Canada	TBD	LNG facilities were delayed due to ongoing government discussions, permitting delays, and environmental opposition; came online summer 2021[12]
2024	Unnamed	TBD; Built by Vard Marine for Centerline Logistics	U.S. West Coast	6,000	Anticipated 2024 launch[13]
	Unnamed	TBD; Built by Fincantieri Bay Shipbuilding for Crowley/ Shell	U.S. East Coast	12,000	Anticipated 2024 launch[14]
	Unnamed	Galveston	Texas & Gulf Coast	18,000	Anticipated 2024 launch. Located on Pelican Island, adjacent to the Houston Ship Channel[15]

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[7] https://seasidelng.com/operations/

[8] https://professionalmariner.com/first-lng-bunkering-barge-in-us-begins-work-in-port-canaveral/

[9] https://seasidelng.com/operations/

[10] https://shipandbunker.com/news/am/760207-lng-bunkering-first-at-port-canaveral

[11] https://seasidelng.com/operations/

[12] https://shipandbunker.com/news/am/844695-gac-puget-lng-aim-to-launch-tacoma-gas-bunker-supply-operation

[13] https://professionalmariner.com/centerline-vard-to-design-lng-bunker-barge/

[14] https://www.marinelink.com/news/crowley-lng-bunker-barge-sport-tge-marine-497175

[15] https://www.rivieramm.com/news-content-hub/news-content-hub/us-continues-to-up-its-lng-bunkering-game-68045

United States Natural Gas Terminals

The U.S. Energy Information Administration (EIA) identifies eight natural gas terminals in the U.S. with three dedicated to exports, two dedicated to imports, and three with dual-functionality (U.S. Energy Information Administration, 2023b). Facilities are located in Texas, Louisiana, Georgia, Maryland, Massachusetts, and offshore in the Massachusetts Bay. There are two additional import terminals in Puerto Rico, identified in Table 6.[16]

Sabine Pass, Louisiana, has the largest storage capacity of natural gas at 16.9 billion cubic feet (Bcf). For comparison, the average U.S. export terminal is capable of storing 11.7 Bcf. Facilities with export functionality all have concurrent liquefaction operations for overseas shipping. Sabine Pass (3.0 Bcf/d) is capable of approximately three times the liquefaction potential of the next largest operation (1.2 Bcf/d) in Corpus Christi, Texas, and the remaining facilities have production rates less than 0.7 Bcf/d. Facilities with import functionality have concurrent regasification operations for overseas receiving, with a max capacity of 1.6 Bcf/d at Elba Island, Georgia, and an average capacity of 1.2 Bcf/d.

Table 6: Active U.S. LNG Import and Export Terminals

Terminals	Function	Regasification Capacity (Bcf/d)	Liquefaction Capacity (Bcf/d)
Cameron, Louisiana	Export	–	0.60
Cove Point, Maryland	Import/Export	1.8	0.70
Elba Island, Georgia	Import/Export	0.33	1.6
Corpus Christi, Texas	Export	–	1.2
Everett, Massachusetts	Import	0.70	–
Freeport, Texas	Import/Export	1.7	0.70
Northeast Gateway, Connecticut	Import	0.40	–
Sabine Pass, Louisiana	Export	–	3.0
Ponce, PR	Import	–	–
San Juan, PR	Import	–	–

Everett and Northeast Gateway, each located in the Northeastern U.S., received 93% of the nation's LNG imports in 2022, entirely from Trinidad and Tobago. The remaining 7% of LNG-specific natural gas imports came from Canada in containerized trucks. Imports of LNG represented 25.27 Bcf, while exports of LNG represented 3.87 trillion cubic feet (Tcf). Imports of LNG represent 35% and exports represent 100% of U.S. natural gas trade by tanker in 2022 (U.S. Energy Information Administration, 2023a).

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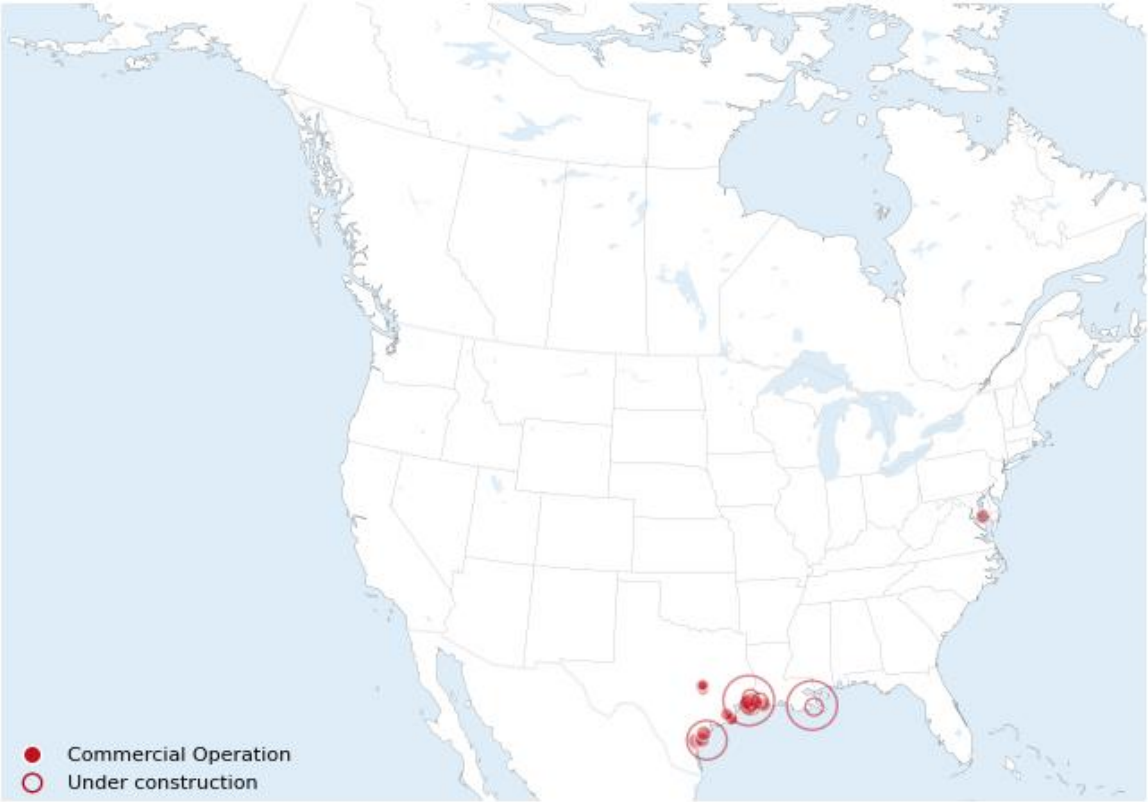
[16] Current & earlier iterations of https://www.energy.gov/fecm/articles/lng-monthly-2023

U.S. Liquefaction Capabilities

Since 2016, when the U.S. began exporting LNG, 28 U.S. liquefaction projects have reached final investment decision.[17,18] Of the 28 projects, 20 are operational and 8 are under construction or being commissioned. These 28 projects include 11 facilities, shown in Figure 4. An additional 10 projects are pending final investment decision, including the expansion of U.S. LNG production to Mississippi (Gulf LNG) and Alaska (Alaskan LNG) (Donaghy, 2023; Office of Resource Sustainability, 2023). One of these projects, Rio Grande LNG Phase 1, is expected to reach a final investment decision in 2023 (BloombergNEF, 2023). Five gulf-based projects are proposed and under review, including 2 offshore projects and 3 projects located in Louisiana. An additional 26 LNG export locations have been stalled, mothballed, retired, or canceled (Donaghy, 2023).

Figure 4: Liquefaction Facilities in the U.S.



Map showing operational and under construction liquefaction facilities in the U.S. Filled circles show operational facilities, open circles show facilities under construction or planning. Circle size correlates to liquefaction capacity. Coordinates have been adjusted slightly to visually identify facilities that are close together.

The U.S. has a total baseload liquefaction capacity of ~10.8 Bcf/d with a peak capacity of ~13.0 Bcf/d. The average commercial facility-level baseload is around 0.54 Bcf/d. The U.S. will be significantly

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[17] U.S. International Energy Agency, Data and Statistics. https://www.iea.org/data-and-statistics

[18] Global Gas Infrastructure Tracker, Global Energy Monitor, July 2022. https://globalenergymonitor.org/projects/global-gas-infrastructure-tracker/

increasing per-train baseload capacity in the coming years with projects underway.[19] Currently commissioned and under construction projects have a planned average baseload capacity of ~1.00 Bcf/d with a minimum of 0.66 Bcf/d in Calcasieu Pass and a maximum baseload of 1.58 Bcf/d in Plaquemines Phase 1 and Port Arthur Phase 1. With the addition of these projects, the total U.S. baseload capacity is brought to ~18.7 Bcf/d and peak capacity to ~22.1 Bcf/d.

The push for the construction of new LNG production facilities propelled the U.S. to become the world's largest exporter of LNG in the first half of 2022, and subsequently dropping to the third largest exporter, behind Qatar and Australia, at year end after exports declined in the second half of the year (York, 2023). The increase in LNG exports by the U.S. in 2022, compared to 2021, far exceeded that of any other country and can be attributed to operations at Calcasieu Pass and Sabine Pass coming online (International Gas Union, 2023).

The majority of North American LNG terminals are located near the Gulf of Mexico. According to Global Energy Monitor LNG terminal data, there are only two small Canadian LNG export terminals in operation: Fort Nelson LNG Terminal (0.02 Mtpa) and Tilbury Island LNG Terminal (0.03 Mtpa). An additional, larger terminal, LNG Canada Terminal (14 Mtpa), is scheduled to finish construction in 2025. The first LNG export terminal to be located on the North American West Coast will be Costa Azul Export Terminal north of Ensenada, Mexico, which is currently under construction and set to start operations in 2024. Several proposed LNG export projects in Mexico would source their gas from U.S. natural gas production (Donaghy, 2023).

The addition of Costa Azul, which is in relatively close proximity to Southern California, could reduce the transportation markup of LNG bunkering prices for the Western U.S. If Mexico's natural gas prices are competitive and can be transported over a shorter distance, California bunkering prices may become more domestically competitive. Additionally, LNG imported from Mexico would not require a Jones Act compliant vessel to transport or bunker it for U.S. ships, thus reducing the CAPEX of bunkering infrastructure and potentially motivating more domestic competition.

U.S. Import & Exports of Natural Gas

The U.S. has been a net exporter of natural gas since 2017 and was the fastest growing LNG exporter from 2018-2022. Export volumes of natural gas by tanker increased by approximately 21x between 2016 and 2022 (Figure 5). Import volumes have conversely decreased, though appear linear when compared to the scale of exports (Figure 5). EIA reports that the increased 2018 import demand could be attributed to weather extremes. Colder winter weather than 2017 increased consumption of natural gas as a home heating fuel, while 2018 also experienced record-high summer temperatures to increase demand for air conditioning and, therefore, electricity fueled by natural gas (Kopalek, 2019). DOE import and export data do not include volumes transported by pipeline. Data for 2023 are incomplete, available to March, and therefore are not represented in any analysis per year.[20] Exports reached 3.86 trillion

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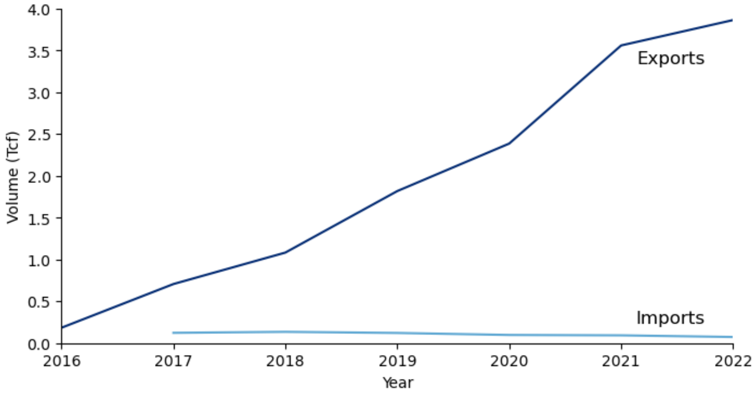
[19] An LNG "train" refers to the liquefaction facility, including gas treatment and separation, compression, and refrigeration.

[20] 2023 data reveals imports at 0.04 Tcf and exports at 1.77 Tcf up to March / Current & earlier iterations of https://www.energy.gov/fecm/articles/lng-monthly-2023

cubic feet (Tcf) in 2022, up from 0.18 Tcf in 2016. Imports declined from 0.134 Tcf in 2018 to 0.073 Tcf in 2022. Net exports of LNG for the U.S. grew from 0.58 Tcf in 2017 to 3.79 Tcf in 2022.

Figure 5: U.S. Import & Export Volumes of Natural Gas

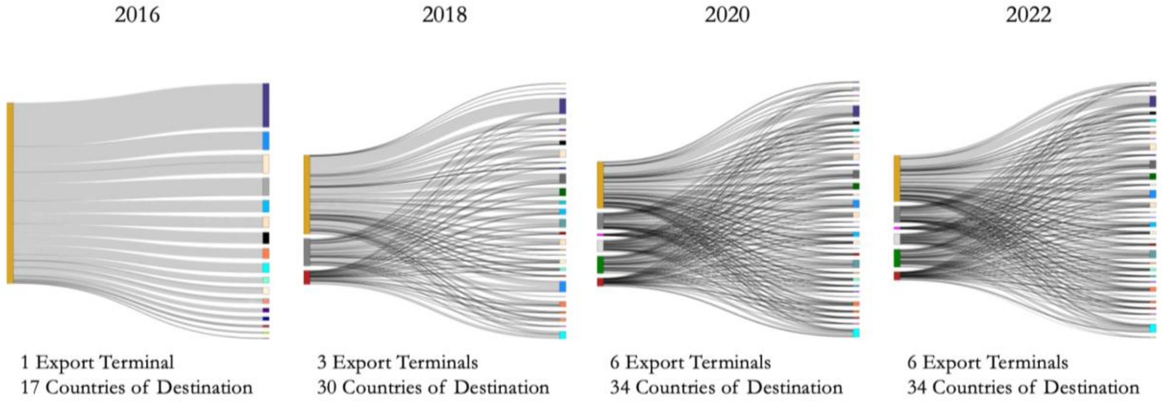


Line plot showing U.S. import and export volumes of Natural Gas by Tanker (Tcf) since 2016.

U.S. Export Terminals

The U.S. has grown as a net exporter, largely due to the growth in export terminal capacity. Sabine Pass, Louisiana, was the only U.S. terminal exporting natural gas in 2017. By 2022 there were six facilities, although three terminals represented over 80% of the U.S. natural gas export volume for 2022: Sabine Pass, Louisiana (38.2%), Cameron, Louisiana (25.3%), and Corpus Christi, Texas (19.5%). France and the U.K. were consistently in the top three countries of destination for these major export terminals; the Netherlands, Japan, or Spain can be interchanged for the remaining position for each respective terminal. By 2022, exports of U.S. natural gas were shipped to 33 countries, with over a third (39.4%) of the volume received by countries importing less than 5% of the total U.S. volume. The growth, increased complexity in the export market, and volume of these exports is shown in Figure 6.

Figure 6: Natural Gas Export Volumes Between Terminal and Country of Destination



Sankey plot showing natural Gas export volumes between terminals by country of destination. Plots show the increase in complexity of the natural gas export market.

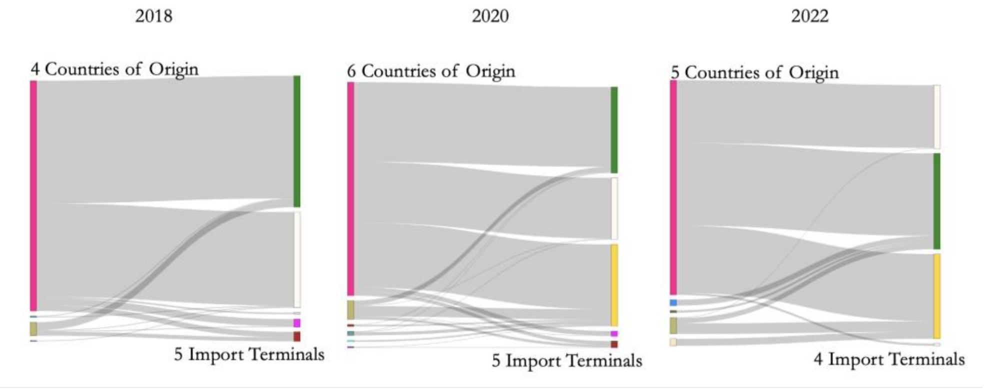
U.S. Import Terminals

Everett, Massachusetts, is consistently the largest import terminal within the contiguous United States across the six years analyzed. While U.S. exports and their infrastructure have been growing, imports have seen a more turbulent market. However, the volume of natural gas imported to the U.S. by tankers has been trending downwards. The majority of this volume is received from Trinidad and Tobago. The growth, complexities, and volume of these imports can be observed in Figure 7.

The Northeast Gateway, an import-only facility, has mostly sat idle since 2010, minus relatively small shipments of LNG in 2019 and 2022. Other U.S. import facilities have sat completely idle or have been decommissioned since around 2010, such as the Gulf Gateway and Neptune terminals. Initial investment in these import facilities were undercut by the growth of cheaper domestic natural gas supplies (Fitzgerald, 2013; Maritime Administration, 2022).[21]

Puerto Rico imports 100% of its natural gas consumption, as it does not have its own reserves (and thus, no exports). Ponce, on the southern shore of Puerto Rico, has imported larger volumes of natural gas by tanker than Everett, Massachusetts, since 2018. In 2022, Ponce received 49.3% of the total U.S. import volumes, compared to Everett's 28.2%. The two Puerto Rico terminals accounted for almost 70% of import volumes that year. Distribution from the U.S. to Puerto Rico by tanker is made more costly by the Jones Act. DOE data consider flows to Puerto Rico as domestic and so, these shipments are not represented in Figure 7. Puerto Rico receives 87% of its imports from Trinidad and Tobago, 6% from Nigeria, and the remaining 7% from a mix of small global imports with no distinct region.

Figure 7: Natural Gas Import Volumes Between Terminal and Country of Destination



Sankey plot showing natural Gas import volumes between terminals by country of destination. Plots show lower market complexity than for exports (Figure 6)

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[21] DOE reports no data for these and other inactive facilities / Current & earlier iterations of https://www.energy.gov/fecm/articles/lng-monthly-2023

LNG Vessel Movements & U.S. Terminals

There are 407 unique tankers transporting U.S. exports and 58 unique tankers transporting U.S. imports reported by DOE across the 2016-2022 timeframe. Of the import tankers, 46 also transported exports of natural gas (79% of import tankers). In 2016 one tanker, the *Clean Ocean*, exported nearly 6.8% of all exports, and just 10 tankers accounted for over 50% of exports. Growth in the population of export tankers means the volume exported by the top 10 tankers has rapidly declined. (Table 7).

Table 7: Annual U.S. Natural Gas Exports by Tankers

Year	Tanker Population*	Export % by Top 10 Tankers	Top Tanker	Top Tanker Export %
2016	37	50.39%	Clean Ocean	6.76%
2017	98	30.48%	Creole Spirit	4.17%
2018	123	21.01%	Maria Energy	2.67%
2019	168	14.70%	Hyundai Peacepia	1.83%
2020	209	11.01%	Adriano Knutsen	1.53%
2021	278	8.62%	Adriano Knutsen	1.00%
2022	275	9.35%	Traiano Knutsen	1.05%

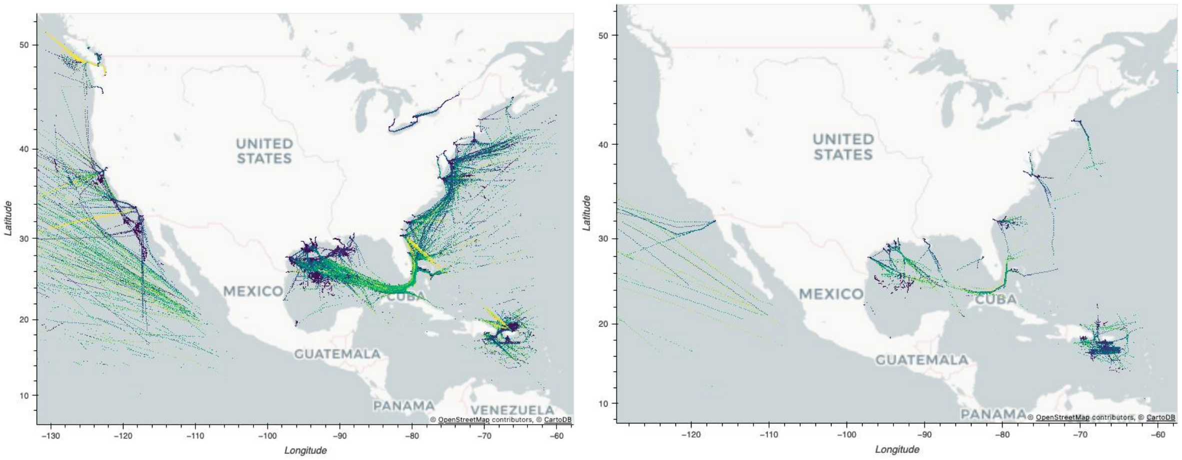
*Tankers represented and named for U.S. exports, not total global population of LNG tankers

AIS data for the entire global LNG fleet were observed within U.S. waters for all of 2022. These results identified 340 unique LNG-fueled vessels operating in U.S. waters, tankers or otherwise. There were an additional 49 conventionally fueled LNG carriers observed.

More detail is available in Section SI 4: Analysis of Vessel Movements.

LNG vessels were observed operating on the West Coast, East Coast, Gulf of Mexico, and the Great Lakes. There was significant LNG vessel activity around Puerto Rico, with high-speed vessel movements to Jacksonville. LNG-fueled non-carrier ships traversed U.S. waters more broadly than LNG carrier vessels, which were generally limited to ports in the Gulf; Savannah, Georgia; the Chesapeake Bay; Boston, Massachusetts; and southern Puerto Rico (Figure 8).

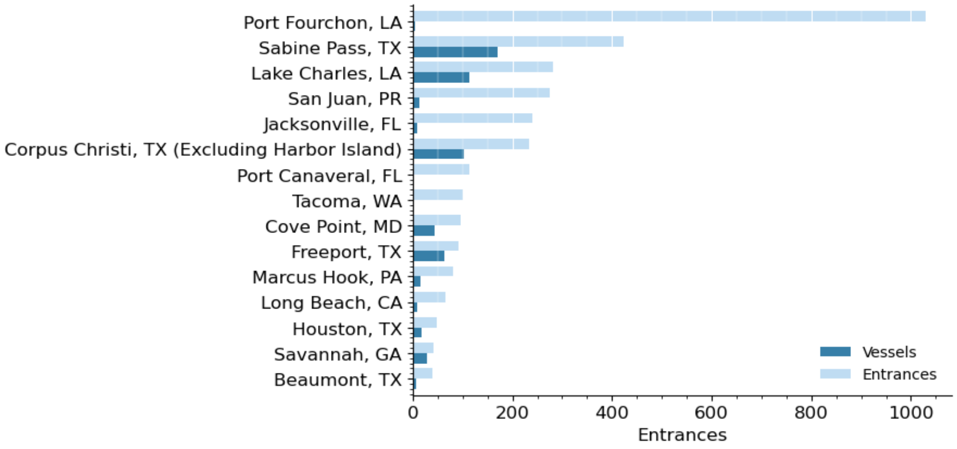
Figure 8: Traffic density of LNG-powered vessels and LNG-carriers



Traffic density of LNG-powered vessels (left) and LNG-carriers (right) operating in U.S. waters. Lighter colors represent higher speeds.

Port Fourchon had by far the largest number of LNG vessel entrances (1,030), from a very small (n=5) number of vessels. Further analysis of these vessels and their movements shows that all vessels are offshore support vessels owned by Harvey Gulf International Marine,[22] and their movements are generally localized to oil and gas infrastructure just offshore of Port Fourchon. The next most frequently called upon ports are Sabine Pass, Texas; Lake Charles, Louisiana; San Juan, Puerto Rico; and Jacksonville, Florida (Figure 9).

Figure 9: Entrances by LNG-powered vessels and LNG-carriers



Bar plot showing count of entrances and unique vessels for LNG-powered and LNG-carrier vessels calling at the top 15 ports in 2022.

Additional details on vessel movements can be found in SI 4.

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[22] *Harvey Energy, Harvey Liberty, Harvey Power, Harvey America, Harvey Freedom*

Conclusions for the U.S. Natural Gas Market

LNG has grown significantly as a marine fuel, with bunkering growing from 10 ports in 2019 to reach 185 ports worldwide in 2023. Investments in ship-to-ship bunkering reflect a shift toward substantial, long-term commitments by the U.S. and other nations. The U.S. has made significant investments in domestic natural gas production and expansion of its infrastructure, propelling it to the top global exporters. However, the Jones Act potentially limits the U.S. from bunkering its own natural gas and participation in the export market.

The Liquefied Natural Gas Value Chain

The "value-chain" of LNG includes the entire natural gas supply chain from production at the wellhead to the final consumer. The value chain includes production, processing, liquefaction, transportation, regasification, and end-uses (Figure 10). Natural gas extracted at the wellhead is processed to remove impurities and transported to liquefaction facilities by pipeline. At the liquefaction facility natural gas is converted to a liquid (LNG) by cooling to -162℃. After liquefaction, LNG is transported via truck, rail, or ship to receiving terminals, where it is regasified and stored before distribution to end-users.

Figure 10: LNG Value Chain

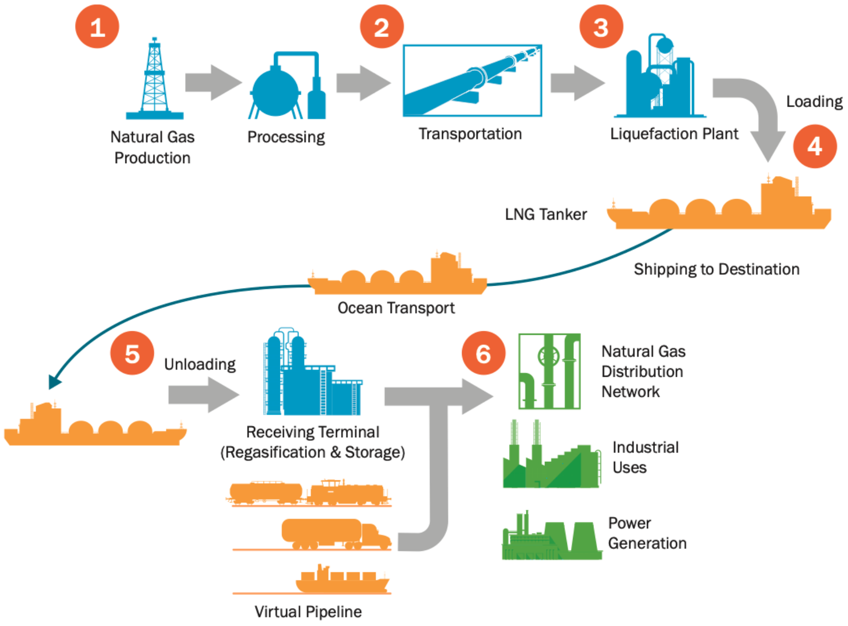


Diagram of the LNG value chain from production to end-use (Office of Fossil Energy, 2020).

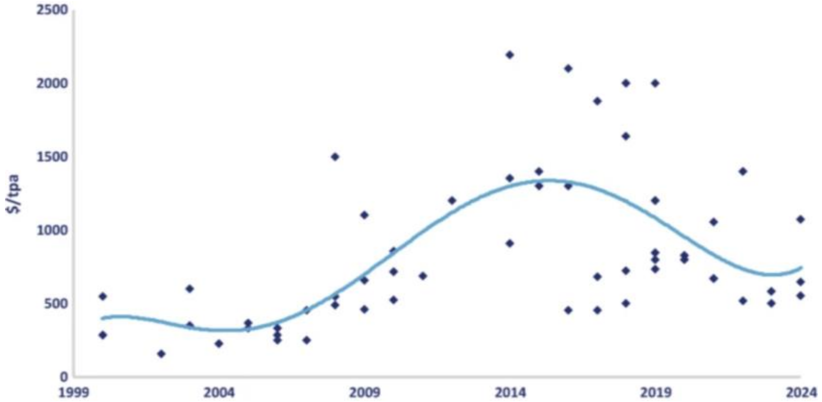
More detailed information on the LNG value chain can be found in SI 5.

Value Chain Financial Investments in LNG

Natural gas must travel from the well pad for processing, and in some cases for liquefaction, where pipelines are not feasible or do not exist. A natural gas pipeline is estimated to cost around $5.34 million per mile,[23] and offshore pipelines are around double that cost (Petak et al., 2017). In 2022, there were approximately three million miles of mainline and other pipelines in the U.S. to link natural gas production areas, storage facilities, and consumers (U.S. Energy Information Administration, 2022).

The operational costs of LNG transport by vessel carrier are competitive with gaseous pipeline transport for distances greater than 1,860-4,350 miles, dependent on the pipeline tariff. This is largely due to the cost to liquefy and maintain the fuel in its liquid state. Liquefaction costs vary from approximately $200/ton per year to over $2,000/ton per year (tpa). Global development of new LNG infrastructure has driven up demand for engineering, procurement, and construction services and the average cost of liquefaction plants has increased since 2000 (Figure 11) (Molnar, 2022).

Figure 11: Per-unit liquefaction investment costs



Line plot showing Unit investment costs of LNG liquefaction projects (2000–2024) by Molner, 2022.

Natural Gas Energy Investments

IEA publishes the World Energy Investment annual report and supporting data to update recent years of energy investments and capital flows across the globe, and quarterly market reports are shared in the global gas outlook (International Energy Agency, 2023c, 2023b). IEA notes that the last few years represent a period of extreme disruption within the energy sector, including the impacts of COVID-19 and the Russia-Ukraine conflict. IEA calculations of investments in natural gas for North America (Canada, Mexico & U.S) are shown in Table 8 along with global investments.

Global fossil fuel investments in 2023 are projected to exceed targets for net zero emissions by 2050 by more than double that recommended by this climate scenario. Fossil fuel companies saw extraordinarily high profits in 2022 compared to the average in recent years, with the largest share of profits and investments observed in the upstream oil and gas industry. Growth in natural gas infrastructure was not halted by high gas prices as a result of the Russia-Ukraine conflict. Rather, loss of Russian natural gas

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[23] Central x 0.65, Midwest x 1.20, Northeast x 1.68, Offshore x 1.00, Southeast x 0.80, Southwest x 0.74, and Western x 0.94 / https://www.api.org/~/media/files/policy/infrastructure/api-infrastructure-study-2017.pdf

supply led to higher global investments in natural gas production, as well as import and export capacities. An increase of six trillion cubic feet (Tcf) of liquefaction capacity is projected from global projects under development.

Table 8: IEA Energy Investments for Natural Gas

	Total investment (Billion $2022)			
Natural Gas Industry Investment	**2020**	**2021**	**2022**	**2023**
North American Fuel	56	60	68	64
Global Fuel	224	232	260	276
North American Power*	12	12	13	12
Global Power*	47	57	64	64

*Oil and natural gas are reported under the same category of power investment by IEA

Total U.S. production of natural gas increased by 3.7% in 2022 but is expected to slow down in 2023 (Table 9). This is partially attributed to limited export outlets, as other nations have import infrastructure under development, especially for transoceanic shipments of LNG. The U.S. experienced a moderate (4%) decline in LNG exports for the first quarter of 2023, compared to the first quarter of 2022, following an eight-month outage of the Freeport, Texas, facility caused by a large fire.[24] However, the U.S. is anticipated to drive the growth in LNG supply in 2023 (in addition to growth in Trinidad and Tobago).

Table 9: IEA Natural Gas Consumption and Production in the U.S.

	Natural Gas Consumption (Tcf)				**Natural Gas Production (Tcf)**			
	2020	**2021**	**2022**	**2023**	**2020**	**2021**	**2022**	**2023**
United States	30.7	30.9	32.5	31.8	33.7	34.8	36.0	36.7
North America	38.1	38.5	40.4	40.4	40.4	41.8	43.4	44.1
Global	138.6	145.1	142.9	142.7	138.7	145.5	145.0	145.0

Global Investments in LNG

While the U.S. is building out LNG export infrastructure, Europe is aggressively investing in LNG import infrastructure. As of 2022, the EU was the largest global LNG importer, with France as the top importing country within the EU. In 2022, LNG imports into Europe increased by around 60% compared to 2021, almost doubling the LNG imports from the U.S. (Cooper, 2023). The EU currently has an import capacity of around 157 billion cubic meters per year (bcm/y) and, partially due to the Russian invasion of Ukraine, the EU has increased investments in LNG infrastructure in recent years (European Council, 2022). The

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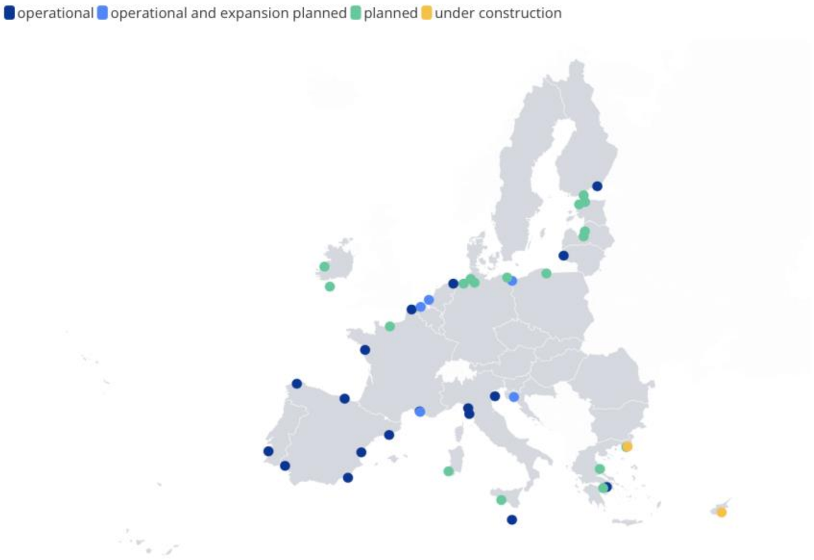
[24] The fire was caused by ignition of natural gas that had leaked from the pipe systems. The Pipeline and Hazardous Material Safety Administration released a report that primarily blamed inadequate operating and testing procedures, with poor attention to maintenance of the control room alarm systems.

infrastructure expansion seeks to increase the availability of imports from the U.S., Qatar, and other non-Russian exporting countries. Germany is seeing the most dramatic increase in investment in LNG infrastructure, with a projected investment of at least €9.8 billion by 2038. Before 2022, Germany had zero LNG import capacity (Eckert, 2023). Predicted costs are already looking to exceed the allocated funding by 2038 (BMWK-Federal Ministry for Economic Affairs and Climate, 2023).

Some experts warn that planned European import capacity will far exceed projected LNG demand by 2030, leading to massive excess import capacity. European import capacity could reach 400 bcm/y by 2030. Yet projections for LNG demand are anticipated to be as low as 150-190 bcm/y for the same year, according to forecasts by The Institute for Energy Economics and Financial Analysis and S&P Global Commodity Insights (IEEFA, 2023). The countries with the largest estimated excess import capacity are Spain (50 bcm/y), Turkey (44 bcm/y), and the U.K. (40 bcm/y) (IEEFA, 2023).

Figure 12: LNG infrastructure in the EU



Source: European Commission, Gas Infrastructure Europe

Map showing operational, planned, and under construction LNG infrastructure in the EU as of December 2022. Source: European Commission.

Germany’s LNG fixed infrastructure plans have lengthy timelines so they may consider future applicability for hydrogen and/or hydrogen derivatives. The LNG terminal at Wilhelmshaven has been designed as a green gas terminal for synthetic methane produced from green hydrogen. Investments in six Floating Storage and Regasification Units (FSRU) terminals have and will provide energy support for the winter of 2022/23 and the winter of 2023/24. However, contracts were deliberately designed as charter/rental rather than purchase to cover fixed terminal construction timelines and so that FSRUs can be dropped if demand shifts (BMWK-Federal Ministry for Economic Affairs and Climate, 2023).

Global natural gas demand is projected to continue growing, increasing by 1,435 bcm by 2050, largely due to demand-growth in Asia Pacific, Middle Eastern, and African countries driven by rising populations, urbanization and economic activity (Gas Exporting Countries Forum, 2022). However, the U.S. Biden Administration has similarly acknowledged that building export terminals and securing long-term supply contracts for natural gas could lock in more years of fossil fuel consumption and GHG emissions than allocated in climate agreements. The U.S. continues to promote carbon capture and sequestration methods as a partial solution to these emissions, given it does not address methane (Schonhardt & Waldburn, 2022).

Although the total U.S. domestic demand for natural gas is anticipated to decrease post-2030, it is forecasted to hold demand to 2050 within the transport sector and blue hydrogen generation from natural gas sources. The Inflation Reduction Act will further secure natural gas in the U.S. energy mix, with financial incentives for carbon capture technologies and its role in blue energy production investments. Additionally, global carbon markets and the Global Methane Pledge could likely incentivize the expansion of methane abatement and carbon capture technologies, as well as blue hydrogen to maintain the role of natural gas in the global energy transition (Gas Exporting Countries Forum, 2022). The U.S. and other experts have argued that Europe is overly confident in its ability to bring hydrogen to scale on its proposed timelines as a replacement for natural gas (Schonhardt & Waldburn, 2022).

The U.S. can plausibly be expected to provide natural gas to Europe beyond 2030 for direct consumption and for blue energy production from natural gas. The European Commission's REPowerEU plan targets investments for 20 million tonnes of hydrogen by 2030, with a 50/50 split in domestic production and imports of hydrogen energy (European Commission, 2022). Research by Ryland Energy in Norway found that Europe is on track to produce 3 million tons/year of green hydrogen by 2030 but would require 54 million tons/year to replace natural gas and fossil fuel reliance. They state that while hydrogen is unlikely to outright replace these energies, that mixing hydrogen with natural gas could be a transitional step to reducing GHGs (Rystad Energy, 2022). However, hydrogen-blending is likely not compatible with existing natural gas infrastructure that was built without an energy-transition in mind and must be evaluated on a case-by-case basis. Addressed in subsequent sections, LNG infrastructure is not easily transitioned to other low-GHG fuels; very conservative estimates exist for repurposing existing natural gas pipelines for hydrogen-natural gas blends, even in low concentrations (<10%) (Topolski et al., 2022). Thus, a full transition to hydrogen transportation is infeasible, as well as incompatibilities with other low-GHG fuels.

Additional information about the risk to investment in LNG can be obtained from SI 5.

LNG as a Maritime Transition Fuel

LNG is a growing fuel choice for marine transportation, promoted as a “transition fuel” with the dependability of a fossil fuel with reduced CO_2 emissions, while also being cheaper than fuels derived from renewable energies. Additionally, LNG has negligible sulfur content, supporting low SO_x emissions, in compliance with MARPOL VI regulations and sulfur emission control areas. The Danish Maritime Authority estimated an increase of nearly 140% in the use of LNG for adherence to sulfur emission control areas-limits from 2013-2020 (World Ports Climate Initiative LNG Working Group, 2013).

While the full life cycle of LNG and its fugitive methane emissions may offset total GHG savings, LNG is being embraced at a much faster pace than other alternatives. Norway's Det Norske Veritas indicated that LNG is leading the fuel transition with 81% of total new orders, 74% of these orders were for container vessels and pure car and truck carriers. This brought the total count of LNG-fueled ships to 876, whereas the second leading alternative fuel choice of methanol only has a total of 82 vessels in operation and on order (DNV, 2023).

Investment in low-emission fuels were found to be behind climate goal trajectories, with a need to rise from $18 billion in 2022 to an average of $150 billion per year over the remainder of this decade (International Energy Agency, 2022). The Biden Administration has pledged to halve emissions by 2030, compared to 2005 levels. Despite this and other supplementary climate goals, U.S. emissions grew by another 36 Mt to 4.7Gt in 2022, as natural gas emissions increased by 89Mt to overtake the 69 Mt emissions decline of coal (International Energy Agency, 2023a). Following decades of rising emissions, the IEA challenged that new investments in gas and other fossil fuels were to stop immediately, if nations were to meet Paris Agreement goals (Bouckaert et al., 2021). Therefore, emission trends and global climate goals are experiencing a disconnect, for which more significant action needs to be taken to prevent climate warming beyond 1.5°C by 2050.

The Russian invasion of Ukraine has motivated infrastructure investments for greater fossil fuel production, including LNG, to support current markets. LNG investments must focus on tackling fugitive methane emissions rather than production expansions, with IEA adding that there should be an industry-wide "zero tolerance approach to methane leaks." Methane abatement would require an estimated investment of $11 billion per year, with a return of an additional 80 billion cubic meters of gas to global markets and a net income of about $20 billion (based on gas prices in 2022), thus satisfying both environmental and economic goals (International Energy Agency, 2022).

Conversion of LNG Infrastructure

Retrofitting LNG storage tanks for other fuels is essential to its future fuel transition, as it is the most expensive technology in its fuel chain (≥50% of CAPEX) (Riemer et al., 2022). Storage tank functionality is key to the efficiency of the terminal, especially in regard to boil-off rates. In recent years, LNG terminals have been built throughout Europe & Asia with the branding of being "hydrogen-ready," meaning they could eventually be used for hydrogen fuels as both fuels are stored under cryogenic conditions. Liquefied hydrogen requires a better insulated system relative to LNG storage and is not compatible with certain materials that would be present in LNG facilities not built for future transition (International Energy Agency et al., 2022). LNG is also often discussed as a transitory fuel for ammonia. However, conversion of either existing or planned LNG infrastructure for alternative fuels is challenging and requires significant modifications (International Energy Agency et al., 2022). With the challenges of infrastructure conversion, in addition to uncertainty about the readiness of hydrogen and ammonia as marine fuels, there is concern that LNG infrastructure will become abandoned assets in future GHG-neutral energy systems.

Only about 50% of LNG capital expenditures could be reused for liquid hydrogen and that number decreases if hydrogen-compatible materials were not used in the initial construction, such as with older terminals (Samuel & Fakhry, 2023). Liquid hydrogen (LH_2) requires more extreme cryogenic temperatures and greater insulation than for LNG storage (-253°C LH_2 vs. -162°C LNG) with a higher boil-off rate that will increase if components of the terminal are not compatible. LH_2 storage tanks are estimated to make up 95% of the total costs of all equipment at an import terminal (IRENA, 2022). Moreover, the investment costs of LH_2 compatible tanks will be 45-50% higher compared to LNG tanks (Riemer et al., 2022). Less favorably, the energy stored by LH_2 in the same volume tank would be 60% lower due to its lower volumetric density (International Energy Agency et al., 2022).

Ammonia (NH_3) is toxic, with strict safety requirements that require specific materials at construction. The additional CAPEX to build an "ammonia-ready" LNG terminal are less than the costs associated with retrofitting an existing LNG terminal (International Energy Agency et al., 2022). Retrofitting a terminal can be quite expensive, with up to 20% of the capital expenditure spent to modify an existing LNG facility, in contrast to the 7-12% spent to build "ammonia-ready." The costs for an "ammonia-ready" storage tank and BOG system are the most significant investments (Ghasemi, 2023; International Energy Agency et al., 2022).

Additionally, the energy capacity of a retrofit ammonia terminal will be less than that of an LNG terminal. The volumetric capacity of a tank filled by LNG would be reduced to two-thirds when replaced by ammonia and its energy capacity reduced by 60% (making the energy capacity comparable to LH_2 in the same sized tank) (International Energy Agency et al., 2022).

LNG facilities that were not built with a transition in mind, for hydrogen or ammonia, would be costly in its conversion. There are many factors contributing to the intricacy of retrofitting LNG terminals to support other fuels. Additionally, it will require careful evaluation and planning in early stages that will be necessary in regard to safety, environmental, and economical scales to determine suitable locations.

Conversion of LNG Vessels

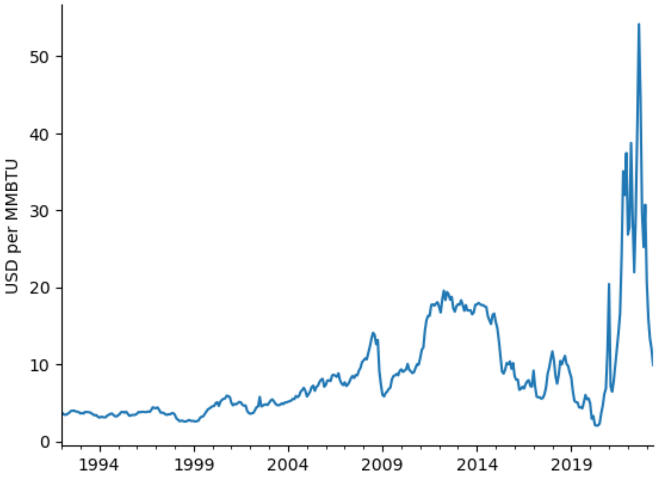
There is minimal experience on how to retrofit today's newbuild LNG vessels for later low-GHG fuels. Hydrogen- and ammonia-primary powered ships are not yet widely considered feasible, thus further complicating these predictions.

In a scenario based on the lower bounds of fuel price predictions coupled with a carbon-tax, analyses found that bio-fuels were more cost-effective than electro-fuels for reducing emissions (Lagemann et al., 2022). Across scenarios, the researchers found methanol retrofits were the lowest cost; however, they may not be cost-effective when considering the cost-emissions compromise under a carbon-tax system. Hydrogen retrofit would require a significant reduction in storage system costs to be feasible in any scenario. Under multiple scenarios, ammonia was found to be the best retrofit solution(Lagemann et al., 2022). Similar to other LNG infrastructure, vessel designs to ease future retrofit and conversion are in the works (Gallucci, 2022). Ammonia is considered easier to store than hydrogen or LNG and two- and four-stroke ammonia-ready engines will be available before 2030 (DNV, n.d.; Lindhardt et al., 2023). 58 vessels are listed as "ammonia-ready" on the 2023 orderbook, implying preparation in the shipbuilding process for future conversion, when the supporting technologies and infrastructures are available (Ovrum et al., 2023).

LNG Costs in the Context of Alternative Fuels

Fuel price is ranked as an important driving factor by most shipping-related stakeholders. A stakeholder review conducted during a dip in LNG price (2018), found that despite LNG only being favored for its fuel price, and not for other factors, it was ranked highest overall stakeholder choice over hydrogen, methanol, or biofuels (Hansson et al., 2019). Natural gas and LNG prices have been volatile and high in recent years, based on its historical standards, although prices are returning to competitive levels below $10 per million British thermal units (MMBtu) (Figure 13). LNG prices averaged $892/metric ton (mt) from January through June 2023 at the Port of Rotterdam (compared to MGO at $767/mt) (Russell, 2023).

Figure 13: Price of LNG (1992 - 2023)



Line plot showing the price of LNG ($/MMBTU) from 1992 to 2023 (International Monetary Fund, 2023)

Additional details on LNG in the context of alternative fuels can be found in SI 7.

Conclusions for Value Chain Investments

Considering the substantial investments already committed toward natural gas, it is imperative that the LNG industry evolve cleaner and more sustainable practices. This includes but is not limited to investing in emissions abatement technologies, preparing infrastructure for future energy transitions and/or powering alternative fuel production. This must be done in tandem with research and development to improve the feasibility of zero- or near-zero-GHG fuels, especially in regard to lower energy densities, higher costs, and, except for production from 100% renewable energy, upstream fossil fuel reliance. In addition to the large-scale climate implications of the natural gas market, there are potential localized impacts from extraction to end-use that will be explored over the following sections.

Health and Equity Impacts of LNG

As global trade volume increases, concerns regarding the health and environmental repercussions of emissions from shipping vessels have surged (Endresen et al., 2008; Gopikrishnan & Kuttippurath, 2021; Winebrake et al., 2009). Air pollution is one of the leading causes of death worldwide, causing disproportionate harm in developing industrial nations, and is estimated to have caused over six million deaths in 2019 alone (The Institute for Health Metrics and Evaluation, 2019). Increases in maritime trade, with the use of highly polluting ship fuels, has led to significant impacts on public health due to localized air pollution of ports and waterways in populated areas (Sofiev et al., 2018). Prominent governing bodies, including the IMO and EU, have adopted regulations to address air quality issues arising from the maritime sector. Particularly noteworthy is IMO's MARPOL Annex VI, which regulated emissions of NO_x and SO_x from ships, and more recently efforts to address GHGs (International Maritime Organization, 2019).

Limits on NO_x and SO_x emissions have compelled ships to shift from conventional fuels like heavy fuel oil, which has significant associated SO_x emissions, toward fuels that align with MARPOL Annex VI requirements. Compliant fuels include ultra-low sulfur fuel oil (<0.1% S), very low sulfur fuel oil (<0.5% S), and LNG (<0.004% S), among others. These policies have succeeded in reducing SO_x concentrations in some inland areas, but the benefits are not always fully realized partly because of complex atmospheric chemistry interactions (Akimoto & Tanimoto, 2022; Van Roy et al., 2023).

LNG has gained significant attention in the maritime sector, owing to its high energy density, compliance with MARPOL Annex VI SO_x regulations, and expanding operating and bunkering infrastructure. However, regulations that consider the life cycle impacts of LNG on GHGs and on the health of local and global populations have not been implemented. The IMO has only started developing such regulations and aims to have them in place in the next two to three years.

Methane emissions, which can result from the production and consumption of LNG, are linked to significant impacts on air quality by influencing concentrations of ground-level ozone (Fiore et al., 2002). Additionally, harmful criteria pollutants are released during natural gas extraction, processing, and liquefaction, potentially impacting the air and water quality of nearby communities.

LNG production and impacts on local communities can also give rise to environmental justice and equity issues. Communities near LNG production facilities may face health consequences resulting from exposure to pollutants, economic impacts due to fluctuations in property value, and socio-economic and cultural changes arising from their proximity to emerging natural gas projects. LNG production has been linked to instances of environmental injustices tied to ethnicity, culture, gender, and income, discussed further below.

This section provides an overview of the science connecting methane emissions and human health and provides context for discussion of methane emissions related to shipping activity from an environmental justice perspective. The section concludes with discussion of estimates of criteria pollutant emissions related to LNG production.

The Potential Impacts of LNG on Health

Transitioning from marine diesel fuel to natural gas was shown to result in significant reductions in particulate matter, black carbon, SO_x, NO_x, and CO_2; however, these benefits come with health and environmental tradeoffs. Other air pollutants, such as formaldehyde, carbon monoxide, and methane, significantly increase with natural gas production and use (Adgate et al., 2014; W. Peng et al., 2020). Methane emissions have substantial impacts on ground-level ozone (O_3), a pollutant harmful to human health. To understand the full scope of the health impacts of LNG, more thorough investigations of the public health implications of transitioning to a methane-intensive fuel source are necessary.

Air Quality Impacts: LNG Methane Emissions and Ozone Formation

Methane is released to the atmosphere throughout the life cycle of LNG, from leaks throughout the supply chain as well as methane slip directly from the engine (Balcombe et al., 2022; Thomson et al., 2015; Ushakov et al., 2019). Emissions from methane slip in LNG engines can vary and are influenced by engine type, load, exhaust temperatures, and other factors, discussed in Section SI 1: Engine Type Emissions and Efficiency. As much as 99% of tank-to-wake methane emissions from dual fuel LNG carriers can be attributed to methane slip, and approximately 56% of total TtW GHG emissions, measured by GWP20 (Balcombe et al., 2022).

There is no clear consensus in the literature around the net health impacts of natural gas as a substitute for conventional fuels, with many studies finding local and regional air quality benefits of switching to LNG, such as reduced NO_x and $PM_{2.5}$ emissions (Balcombe et al., 2022; Li et al., 2021; W. Peng et al., 2020). Reductions in NO_x can have complex interactive effects on methane. NO_x reductions can cause a decrease in atmospheric concentrations of hydroxyl radicals (OH). OH plays an important role in reducing methane concentration by transforming methane molecules into other compounds, typically CO_2 and H_2O (methane oxidation). Consequently, NO_x reductions can lead to an increase in the atmospheric lifetime of methane due to lower oxidation rates by OH, which carries implications for global warming and air quality (Akimoto & Tanimoto, 2022). Research indicates that NO_x reductions associated with COVID-19 lockdowns could explain most of the increase in atmospheric methane during that period (Stevenson et al., 2021).

A longer atmospheric lifespan of methane would lead to greater climate warming due to the potency of methane as a GHG versus what it eventually transforms to, usually CO_2 and H_2O, when it undergoes oxidation. Increasing methane lifetime can result in additional impacts on health through its contribution to climate warming.

More information on these interactions can be found in Section SI 8: Health and Equity Implications Stemming From LNG.

Many studies that indicate air quality benefits from increased LNG usage focus on the immediate impact of methane emissions on air quality in close proximity to their source, without quantifying the long-term impact of methane emissions on concentrations of other harmful gasses. Methane is an ozone precursor, a harmful air pollutant with impacts on human health. Definitive studies have demonstrated a link between methane concentrations, ozone, and human and environmental health impacts, dating back to the early 2000s (Fiore et al., 2008; West et al., 2006).

Methane oxidation is responsible for a majority of tropospheric ozone formation (West & Fiore, 2005). Ground-level ozone—even in low concentrations—has significant impacts on air quality and public health. Ozone exposure causes and exacerbates respiratory issues, including asthma, and has been linked to cardiovascular disease and premature death (Ebi & McGregor, 2008). Ozone-attributable mortality increased by 46% from 2000 to 2019 (Malashock et al., 2022). Ozone pollution is also detrimental to crop production and reduces land carbon sinks by reducing plant primary productivity (Mar et al., 2022). The association between NO_x emissions and ozone formation was part of the rationale for the relevant limitations outlined in MARPOL Annex VI.

Changes in methane concentrations produce gradual and globally distributed changes in ozone levels. By contrast NO_x emissions, which are regulated, have rapid and local impacts on ozone levels (West & Fiore, 2005). Modeling studies estimate that reducing methane emissions by 50% almost halves occurrences of high ozone spells (>70 parts per billion by volume) in the U.S., as well as significantly reducing climate warming (Fiore et al., 2002). Despite the science being long established and air quality precedence being set by MARPOL Annex VI, global air quality controls address ozone pollution but do not regulate methane emissions directly as a source of ozone formation.

Prevailing emissions policies that refer to methane focus on GHG reductions. Some regulations can be construed to acknowledge the impact on air quality. For example, the proposed U.S. Clean Shipping Act of 2023 (CSA), can be interpreted to consider the air quality implications in the assessment of the proposed GHG intensity standards. Section 212.A.B. of CSA stipulates that when assessing the economic and technological feasibility of the GHG-intensity standard, the administrator must consider "the net reduction of emissions of greenhouse gasses and potential adverse impacts on public health, safety, and the environment, including with respect to air quality, water quality, and the generation and disposal of solid waste."[25] In the case of CSA, methane is included in the definition of GHGs. A stronger foundation for this interpretation could be established with additional research involving estimating shipping industry-specific methane emissions and the long-term impact on air quality. Due to the many contributing factors to tropospheric ozone concentration and large uncertainties linked to methane changes from shipping activities, conducting a proper attribution study to evaluate the impact of LNG consumption on long-term ozone levels is challenging. Fortunately, Earth system models can be used to

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[25] H.R.4024, Clean Shipping Act of 2023, 118th Congress https://www.congress.gov/bill/118th-congress/house-bill/4024/text?s=1&r=4

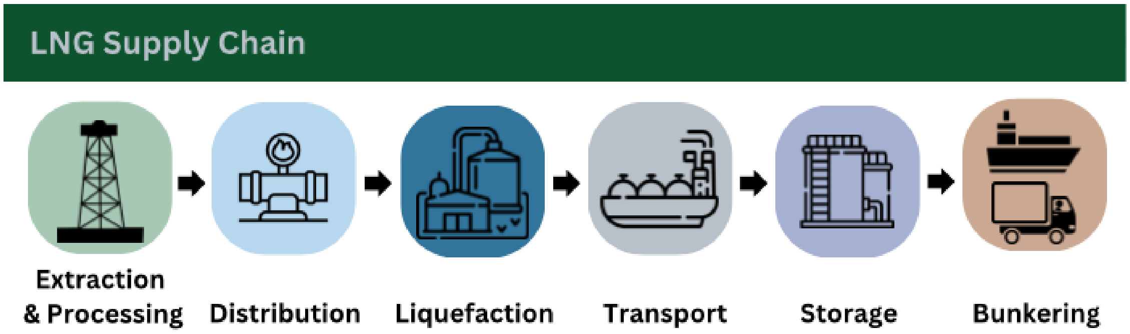
isolate methane controls and simulate several emissions scenarios. This approach can offer insight into understanding how/if changes in methane emissions from LNG-fueled ships impact ground-level ozone.

Studies have assessed human health impacts of LNG maritime transport, without specific focus to methane (Aseel et al., 2021). Other studies have mentioned the impact of methane slip on ozone, but in the context of its contribution to climate change, rather than health impacts (Pavlenko et al., 2020). To the authors' best knowledge, no existing studies have quantified the effects of methane emissions from LNG-shipping on tropospheric ozone and subsequently connected it to human health. This type of investigation could help inform future regulations on methane emissions in the maritime industry and align methane controls with GHG regulations, as well as existing MARPOL Annex VI regulations on NO_x and SO_x.

Environmental Justice Concerns

The combustion of LNG generally has globally distributed risks, whereas the upstream (well-to-tank) emissions from processes to produce LNG can have a more localized effect. Communities in close proximity to natural gas extraction sites, liquefaction facilities, and LNG terminals can be exposed to a variety of economic, political, and health risks. Health and equity issues are prevalent throughout the entire LNG supply chain, which is simplified and presented in Figure 14.

Figure 14: LNG Supply Chain from Wellhead to Bunkering



Simplified flow diagram of the LNG supply chain, showing the pathways from extraction at the wellhead to bunkering (EERA).

Health Risks and Environmental Justice: Natural Gas Extraction

Natural gas development has been linked to water and air contamination, increased risk of cancers in children, and heightened levels of respiratory disease (Apergis et al., 2021; C. J. Clark et al., 2022).

A systematic literature review on the environmental and health impacts of Unconventional Natural Gas Development (UNGD), which accounted for 89% of total U.S. natural gas production in 2022, identified 685 peer-reviewed studies relevant to impact assessment of UNGD (Center for Sustainable Systems, 2023; Energy Information Administration, 2023a). Hydraulic fracturing, also known as "fracking," is a type of UNGD that plays a large role in LNG production. UNGD can be discerned by three categories of impact: public health, water quality, and air quality. Of the articles analyzed, 84% of public health studies identified negative impacts on health, 87% of air quality studies found a positive relationship with increased air pollution, and 69% of water quality studies identified connections to water contamination (Hays & Shonkoff, 2016). Thereby, the majority of current research supports that UNGD projects can be detrimental to the health of individuals located near extraction sites, encompassing impacts on water, air quality, and general health.

Mental health conditions, such as anxiety and depression, have been linked to communities in close proximity to natural gas wells. Many mental health impacts were driven by perceived danger or feelings of uncertainty, including feelings of powerlessness and uncertainty of the health impacts. Additional studies also cited effects due to increased light and noise pollution (Malin, 2020) and heighted mental and physical health issues in pregnant women living near extraction sites (J. A. Casey et al., 2019; Malin, 2020). A Canadian study found higher levels of fracking-related chemicals in areas near the homes of pregnant and Indigenous women, which would substantiate these anxieties (Caron-Beaudoin et al., 2022).

“Boomtowns” are fracking town communities that undergo quick economic expansion as a result of new gas extraction activity in the area. The expansion of fracking operations can lead to positive impacts, such as increased employment, a surge in population, and increased economic activity. However, accompanying negative impacts include housing shortages, infrastructure strain, boom-bust cycles, and increased social vulnerabilities for low-income groups, especially women. Communities subject to boom-bust cycles are often connected to elevated crime rates and drug use, compounding the risks posed to vulnerable communities in the area (Lehman & Kinchy, 2021; McHenry-Sorber et al., 2016; Ruddell et al., 2014).

Health Risks and Environmental Justice: Production, Storage, and Bunkering

LNG has some favorable environmental qualities when compared to conventional fuels, including comparatively low SO_x emissions. However, emissions of detrimental pollutants stemming from LNG production might be higher than initially anticipated (Sierra Club, 2022b). LNG liquefaction facilities emit harmful pollutants, including methane, dust, CO_2, CO, SO_2, ammonium (NH_4^+), and hydrogen sulfide (H_2S). Inhalation of these pollutants can cause respiratory disease, cardiovascular damage, and other health conditions to local communities. A study done in China found that the assessed environmental benefits of transitioning from coal to gas have been overestimated due to the exclusion of pollution occurring from the liquefaction process. The environmental benefits of transitioning from coal to gas, while still positive, were substantially decreased when emissions from liquefaction were considered (Yuan et al., 2020). Consequences of liquefaction include increased emissions from electricity generation, natural gas flaring, and methane leaks (Abrahams et al., 2015).

The absence of robust estimates of emissions from LNG is reflected in U.S. operations. For example, due to underestimating potential emissions for the Corpus Christi LNG terminal in Texas, one of the largest LNG facilities in the U.S., it has consistently exceeded approved emission levels for pollutants, including for carbon monoxide and volatile organic compounds (VOCs). Despite local pushback, the Texas Commission on Environmental Quality has chosen to grant substantial raises in the plant's pollution thresholds, including a quota of around 353 tons of VOCs annually, twice the initial limit, and over 40% increase in the limits for four other pollutants. Emission limits were set based on estimates provided by the parent company of the operation, Cheniere, which has claimed that in order to meet the original limits the plant would undergo frequent shutdowns. Local populations bear the brunt of the miscalculation of emissions, increased pollution limits, and degraded air quality (Groom & Volcovici, 2022; Sierra Club, 2022a).

A significant proportion of the emissions at LNG terminals occur when excess gas at the plant is flared. Flaring may be performed for various reasons, including insufficient local demand, commencement of extraction before development of a pipeline, when infrastructure is inadequate to manage episodes of peak production, and in emergency and operational situations where pressure builds up and needs to be released. In addition to the GHGs, pollutants harmful to human health like soot can be released when gas is burned during flaring.

Flaring is also an environmental and economic concern, accounting for approximately 0.6% of total anthropogenic emissions and billions of dollars of economic loss each year (~$15 billion in 2022) (The World Bank, 2023). Around 500 Mt CO_2e was emitted in 2022 due to flaring, according to the IEA (International Energy Agency, 2023d; Schulz et al., 2020). Additional emissions of NO_x and VOCs occur due to operating activities such as loading and off-loading tankers and increased usage of diesel-fuel operating vehicles (Afon & Ervin, 2008; Surapaneni & Morse, 2019).

Accidents at LNG facilities can also pose a threat to workers and bystanders. Cryogenic leaks expose workers to risk of frostbite or damage to the lungs from inhaling fumes (Yue et al., 2020; Zwęgliński, 2022). Safety incidents are rare in the U.S. due to extensive safety precautions and careful equipment engineering. During an explosion at Freeport LNG in 2022,[26] only two individuals were reportedly injured due to the explosion, who happened to be swimming nearby. (Verma et al., 2022). Oil and gas workers are exposed to a heightened risk of death in the workplace. Hazards such as explosions, fires, and leaks have been reported in the U.S. and Canada (Environmental Health and Toxicology Branch & Biological Risks and Occupational Health Branch, 2015).

Community Impacts of LNG Infrastructure Development

The U.S. has benefited from a national boom in LNG production, becoming a net exporter of natural gas in 2017 and one of the top three LNG-exporting countries by 2022 (Energy Information Administration, 2023b). The precise local economic effects of constructing a new LNG facility are somewhat uncertain. A study commissioned by the service provider of a since-canceled LNG project in Maine explored the economic impacts of constructing the terminal and found that the construction project could bring millions of dollars in labor income to the area and stimulate the local economy (Gabe, 2014). On the other hand, a study conducted by an Australian public policy think tank identified significant negative local economic impacts of new LNG infrastructure. The study found that the construction of a new LNG plant in Gladstone, Australia, could result in the loss of thousands of jobs, millions of dollars in manufacturing activity, reduced affordability of housing, and hardship to small and medium sized businesses (Grudnoff, 2012). Another study even suggested that the construction of another LNG plant in Australia could have disrupting effects to the social balance of the community due to an influx of male

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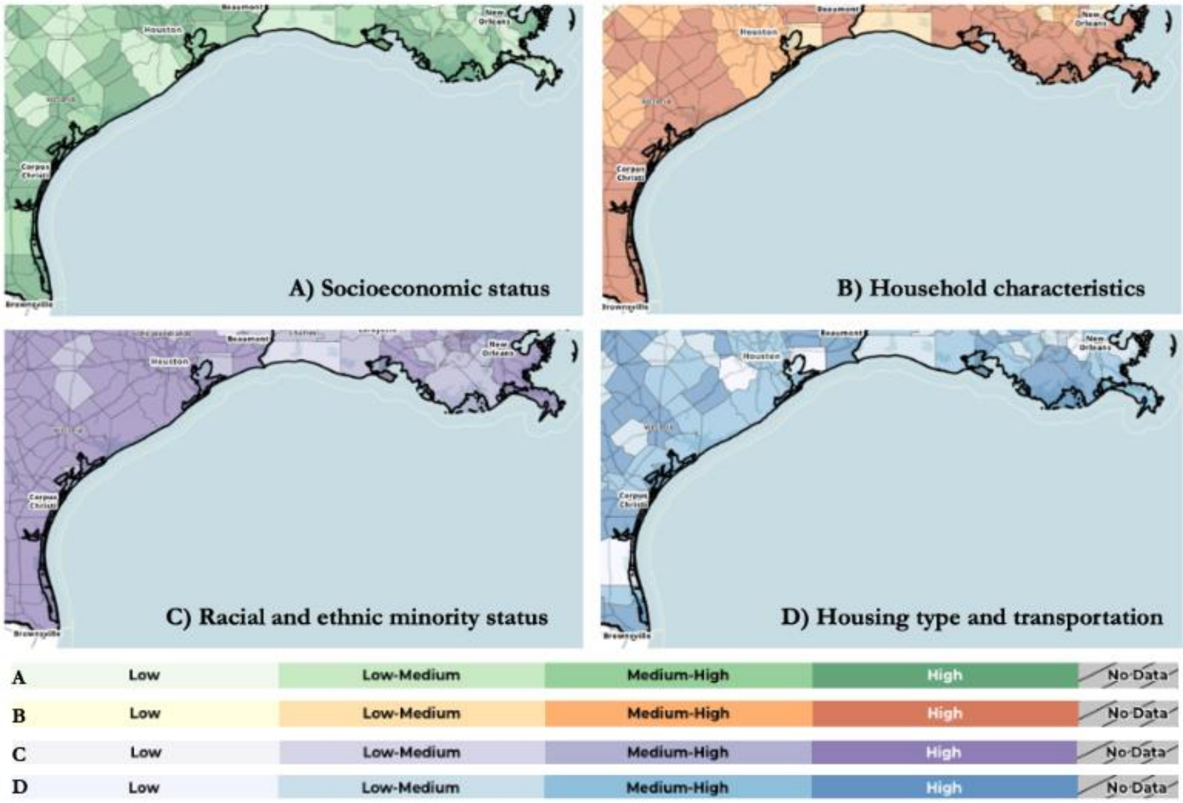
[26] One of the largest LNG plants in the U.S. for imports and exports

construction workers (A. J. Taylor & Carson, 2014). Conflicts of interest can arise due to the backing of these studies by either LNG companies or environmental organizations.

The construction of new LNG facilities has been connected to equity and justice issues, a common result of natural resource development in general (Malin et al., 2019). A majority of existing and planned U.S. LNG projects are positioned along the Gulf Coast, which has prompted concerns about the livelihood of these local communities.

According to the Center for Disease Control and Agency for Toxic Substances and Disease Registry Social Vulnerability Index (SVI),[27] Gulf Coast communities show higher vulnerability relative to some other regions of the U.S. Many counties near LNG terminals, such as Corpus Christi, have "high" levels of vulnerability across all four vulnerability categories: socioeconomic status, household characteristics, racial and ethnic minority status, and housing type and transportation, shown in Figure 15. A look at the distribution of overall SVI throughout the U.S. identifies the Gulf Coast as a relatively high area of vulnerability. Although the selection of sites for these LNG terminals is often driven by factors like shipping lane accessibility, market demand, and proximity to natural gas reserves and production, the placement of these terminals can spark environmental justice and equity concerns.

Figure 15: Social Vulnerability Index in the Gulf Region



Social Vulnerability Index (SVI) by county and socioeconomic status, household characteristics, racial and minority status, and housing type in the Gulf Coast, 2020 data.

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[27] CDC/ATSDR Social Vulnerability Index. Data last reviewed December 1, 2022. https://www.atsdr.cdc.gov/placeandhealth/svi/interactive_map.html

Several proposed and existing LNG export facilities are situated near impoverished communities. According to Oil and Gas Watch, over 40% of residents within three miles of the proposed Commonwealth LNG site on the west side of the Calcasieu Ship Channel live below the poverty level (Oil and Gas Watch, 2023). In Cameron Parish, where there are three terminals, more than 14% of residents live below the poverty line, and two-thirds of residents within a block of the Plaquemines plant live below the poverty line (McDaniel et al., 2023; Younes & Bittle, 2023). The vulnerable communities living in these areas may be disproportionately impacted by the existence of the new plants, lacking the resources to resist or mitigate the potential impacts.

The arrival of new LNG plants can worsen health disparities, barriers to accessing jobs, and general economic well-being. Disadvantaged members of these communities, due to their socio-economic status, may have less ability to cope with the environmental impacts of nearby natural gas extraction or LNG production, resulting in disproportionate exposure to pollution and hazardous materials. Research has demonstrated a decline in housing prices following the establishment of noxious plants in close proximity, which could pose economic challenges for those living in vulnerable communities who may otherwise choose to relocate away from the vicinity of LNG facilities (D. E. Clark & Nieves, 1994; Meyer et al., 2006).

Community Resistance to LNG Infrastructure Development

Insufficient communication with communities concerning the potential impacts of LNG plants, coupled with limited community engagement in decisions regarding their establishment, can lead to cultural injustices as well. A proposed LNG terminal in North Port St. Joe, Florida, reportedly threatened the community's way of life and cultural integrity. The community has a history of environmental and economic injustices, notably highlighted by the decline of the area following the closure of a contaminating paper mill in 1999. Plans to reinvigorate the area with improved infrastructure, real estate opportunities, and a Black history museum, were supported by over $850,000 in funding for health and housing from the EPA and Biden Administration, following Hurricane Michael in 2018. In the beginning of 2023, a suggested LNG plant in the vicinity of the former paper mill jeopardized these endeavors, potentially affecting their initiatives to rejuvenate the community and allocate resources to nature-based strategies for mitigating the effects of hurricanes. This case serves as an example of the inequitable nature of such LNG investments, affecting marginalized communities that have previously fallen victim to environmental injustices driven by industrial activities. Similar instances have risen within Indigenous communities, who have been impacted by oil and gas extraction on their land (Lau, 2022).

Active community resistance and campaigning have successfully thwarted the expansion of LNG infrastructure. In the instance of North Port St. Joe, the community's opposition, involving extensive activism and legal action, played a role in halting the proposed plant (Green, 2023). Additional efforts to cancel or slow down LNG expansion have been seen throughout the U.S. and Canada, including in Georgia, Louisiana, Maryland, Oregon, and British Columbia, driven by local NGOs and community-based organizations with heavy support from larger environmental coalitions (Global Energy Monitor, 2021). Community resistance is primarily demonstrated through protests and legal proceedings, often led by NGOs and members of the local community. The instances cited primarily align with "not-in-mybackyard" (NIMBY) campaigns but efforts along the Gulf coast and west coast signify a shift toward "not-in-anyone's-backyard" opposition to LNG expansion, contributing to the resistance developing in response to broader fossil fuel development (Boudet, 2011).

National Emissions Inventory: LNG Production Emissions

The U.S. National Emissions Inventory database includes measurements of air emissions sources for several LNG terminals. Table 10 shows 2020 emissions related to health and climate forcing associated with four large LNG terminals in the United States.

Table 10: Annual Emissions at four large LNG facilities (EPA NEI 2020)

Site Name	CO_2 (Tons)	Methane (Tons)	NO_x (Tons)	$PM_{2.5}$ (Tons)	SO_x (Tons)	VOCs (Tons)
Cameron LNG	3,660,323	2,069	1,203.53	159.50	8.91	120.56
Corpus Christi LNG	1,956,500	886	1,080.46	36.03	11.04	46.50
Cove Point LNG	1,234,763	204	160.30	18.75	1.14	16.45
Sabine Pass LNG	4,516,574	1,313	2,887.32	96.24	0.98	165.60

In 2020, the four LNG terminals listed were responsible for approximately 5,332 tons of NO_x emissions, which is equivalent to 0.23% of total NO_x from on road mobile source emissions (2.345 million tons) and about 1.25% of NO_x emissions from all fires (425,509 tons). The $PM_{2.5}$ emissions reached about 310.5 tons, which equates to 0.39% of total $PM_{2.5}$ from on road mobile source emissions (79,621 tons) and approximately 2.47% of total $PM_{2.5}$ from the oil and gas sector. Total CO_2 emissions from these terminals equate to about 0.7% of CO_2 emissions from industry in 2020 (1,465 MMT CO_2e) (U.S. Environmental Protection Agency, 2023).

Cameron LNG, Corpus Christi LNG, and Sabine Pass LNG are all located in areas that are in the 95th-100th national percentile of “toxic releases to air,” according to EPA EJScreen. These areas have more favorable air quality $PM_{2.5}$ and ozone levels, falling below the 80th national percentile in both of these categories. Each of these three terminals is situated in a location with flood risks exceeding the 90th national percentile, which makes the terminals relatively vulnerable to the impacts of severe weather conditions. Cameron Parish, the locale of Sabine Pass and Cameron LNG, ranks low in overall SVI, while surrounding counties Jefferson Parish and Vermilion Parish have a high SVI. On the other hand, San Patricio County, where Corpus Christi LNG is located, receives medium-high to high SVI ratings across all categories.

Conclusions on LNG, Health, and Environmental Justice

Reductions in methane emissions have a two-fold benefit: climate change mitigation and improved air quality. Yet air quality governance has not recognized this directly. Existing regulations considering methane primarily focus on warming rather than air quality. While regulating emissions from LNG production rightly falls under stationary source regulations, understanding the contribution of the LNG value chain to air quality and climate change is imperative to driving the adoption of methane emissions policies in the maritime space. Moreover, consideration of other resulting emissions will help address environmental justice concerns.

Tight restrictions and monitoring requirements for criteria pollutants from LNG production phases may help assuage environmental justice concerns related to pollution exposure. Further technological developments could limit emissions across the supply chain and reduce environmental and health burdens on local communities. Additional policy may seek to address the socioeconomic impacts that may be experienced by communities nearby LNG terminals.

Conclusion

The natural gas industry has experienced a significant boom, rapidly growing to compete with conventional fossil fuels in and beyond the energy and maritime sectors. However, research has been revealing that the GHG reduction potential of LNG does not align with ambitious climate targets. Although natural gas reduces CO_2, NO_x, $SO_{x,}$ and other pollutants, its UHC emissions diminish its impact with its high global warming potential. Moreover, LNG fuel has a conflicting NO_x-UHC trade-off, for which current NO_x regulations have led the LNG fleet to overwhelmingly choose LPDF engines, with higher life cycle emissions than conventional fuels (attributed to methane slip). Thereby unintentionally working against climate warming prevention efforts.

Recognition of methane in regulatory frameworks is on the horizon and will play a pivotal role in either deterring LNG use or motivating a concerted effort to reduce GHGs in LNG technologies (engine designs, paired exhaust aftertreatment, storage and reliquefaction, etc.). In addition to the environmental impacts, better regulations can help to mitigate the localized effects of natural gas on communities and their health. Community activism and push-back against natural gas infrastructure indicates a desire to move toward cleaner alternatives.

The economic commitments made by the United States' and other substantial global economies in natural gas risks loss of investment return, in the case of infrastructure abandonment, as the rapid growth to meet short-term demand conflicts with energy transition timelines that align with climate targets. Especially as LNG continues to be marketed as a "transition fuel", necessary attention should be made to infrastructure designs preparing for conversion to low-GHG energies. This includes upstream production and downstream vessel adaptations.

Political intervention, not only to better regulate methane but also to improve the economic viability of near-zero and zero-GHG fuels is imperative to match 2030 and 2050 climate timelines. This could take form in penalties to polluters through emissions pricing or subsidies to support production of energy alternatives—or a combination of both. Until such measures are taken, the economic viability of natural gas will secure its future as the primary conventional fuel substitute, despite its shortcomings in meeting international climate objectives. Furthermore, significant research and development must be made to bring low-GHG alternatives production to scale; to provide sufficient supply and offset differences in energy density.

Supplemental Information

Photo: Alamy Stock

SUPPLEMENTAL INFORMATION

SI 1: LNG Engines

Low-Pressure Dual Fuel

LPDF engines utilize the Otto-cycle when burning LNG, which relies on constant volume combustion of an air-fuel mixture with a much lower combustion ratio compared to Diesel-cycle operation, resulting in a jump in pressure with ignition. The air-to-fuel ratios (AFR) influence the combustion power and emissions. Low AFR (rich burn) results in low NO_x emissions and higher power, but consequently higher methane slip with more unburned fuel. High air to fuel mixtures (lean-burn) can be more fuel efficient but can also result in high levels of UHCs due to an unsteady nature of combustion from too lean conditions (Ushakov et al., 2019).

Methane emissions for LPDF engines are highest at low operational loads due to its air-fuel ratio (Grönholm et al., 2021). Low loads have more cold space within the combustion chamber where fuels are not completely oxidized (i.e., quenching), which leads to methane slip (Jensen et al., 2021). Low engine load has a greater effect on methane slip for LPDF four-stroke engines than for LPDF two-stroke engines (Balcombe et al., 2022).

High-Pressure Dual Fuel

Diesel-cycle HPDF engines inject natural gas directly into the combustion chamber at high pressure, rather than pre-mix fuel with air. They have higher compression ratios, temperature, and pressure, which results in near complete combustion of the fuel and insignificant UHC emissions (i.e., methane slip). Empty volume in the engine increases methane slip rates for LPDF engines, whereas the compression stroke of HPDF engines prevents the possibility of methane slip (Grönholm et al., 2021).

A comparison of marine engine emissions suggested that only HPDF 2-S, reduced life cycle GHG emissions when using LNG compared to conventional fuels (GWP_{20}) (Pavlenko et al., 2020). However, HPDF engine emissions have only been reported on by engine manufacturers, with no test-bed or at-sea independent studies to date (Kuittinen et al., 2023). Furthermore, low load operations of HPDF may result in 65-85% higher NO_x (Nemati et al., 2022).

Modern two-stroke HPDF engines have negligible methane slip levels over the engines' load range (0.2-0.3 gCH_4/kWh) (MAN Energy Solutions, 2022a). HPDF engines can be modified for improved efficiency and lower methane; however, manufacturers do not consider it to be a cost-competitive solution. Instead, manufacturers are focused on improving the Otto-cycle combustion to meet present and future emissions standards of all GHGs (Stiesch, 2022).

Lean-Burn Spark Ignition

LBSI engines operate solely on the Otto-cycle. A spark plug, rather than a pilot fuel, ignites the air-fuel mixture to push the piston. Low load operations impact combustion efficiency for LBSI, as with both HPDF and LPDF engines. However, LBSI engines had less methane slip at low loads than for LPDF. Methane slip for an LBSI engine was reported as high as 1,176 gCO_2e/kWh at 10% load, which is still significantly less than LPDF 4-S engines with reported emissions up to 3,444 gCO_2e/kWh (IPCC AR6, 28 GWP_{100}) (Kuittinen et al., 2023).

LBSI engines have been shown to operate in leaner conditions (high AFR) compared to in manufacturer testing, resulting in higher UHCs in true operation (Stenersen & Thonstad, 2017). Methane slip from LBSI engines may be improved with changes to piston design, as well as reducing crevice volume and optimizing flame quenching to reduce cold space. Pairing LBSI engines with an oxidation catalyst aftertreatment reduced methane slip by 70% in manufacturer testing. The first operational test installation on board a vessel will start in 2023 (Stiesch, 2022).

Engines of the Global LNG Fleet

At present, the LNG population has adopted LPDF engines by a majority and these engines are receiving a much greater focus in the literature. LPDF four-stroke engines make up more than half of the LNG-fueled vessels in operation (Kuittinen et al., 2023). The majority of LNG vessels to date are operating in Norwegian waters, where a levy on NO_x emissions has been established since 2008 (2023 rates of 24.46 NOK/kgNO_x equivalent to 2.31 \$/kgNO_x) (The Norwegian Tax Administration, 2023). This has set a financial motivation to choose engines with the lowest NO_x, which consequently have higher methane emissions. The well-to-wake (WTW) emissions of LPDF 4-S engines are higher than for LPDF 2-S and LBSI at 685 g CO_2e/kWh total GHGs, of which ~17% is methane slip (GWP_{100}) (Schuller et al., 2021).

LPDF 2-S engines comprise approximately a quarter of the LNG-fueled vessels (Kuittinen et al., 2023). LNG-fueled LPDF 2-S engines emit around 594g CO_2e/kWh WtW GHG emissions, of which ~11% resulted from methane (GWP_{100}) (Schuller et al., 2021). LBSI engines represent less than 2% of the LNG engine fleet (Kuittinen et al., 2023). LBSI 4-S engines running on LNG are estimated to emit 624g CO_2e/kWh well-to-wake (WtW) GHG emissions, with 60g CO_2e/kWh (9.6% of total) attributed to methane slip (Schuller et al., 2021). The LBSI population includes high-speed engines, which in general have lower efficiency and were not included in these estimates.

HPDF 2-S engines are approximately 15% of the LNG-fueled vessel population (Kuittinen et al., 2023). Containerships, for which low-speed two-stroke HPDF engines are typically favored, represented only 6.4% of the LNG-fueled fleet discussed in the following data analysis. Thereby, the operational parameters of the current LNG fleet may be skewed toward engines that emit higher methane. The estimated WtW GHG emissions of HPDF 2-S engines are 533g CO_2e/kWh when fueled by LNG, with only 1% due to methane (GWP_{100}) (Schuller et al., 2021).

SI 2: LNG Fleet and Orderbook

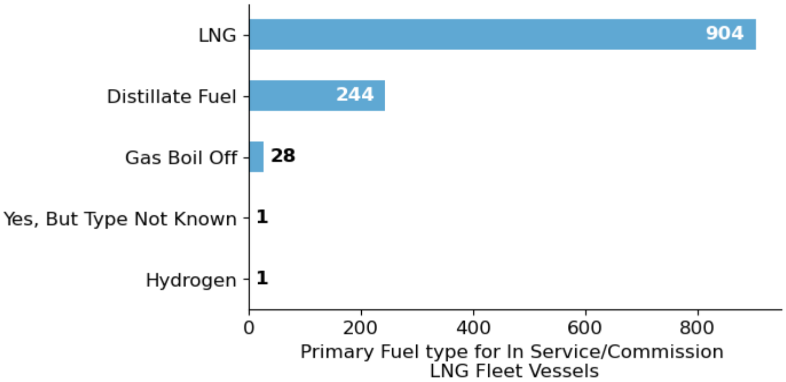
The Global LNG Fleet

EERA analyzed data on the liquefied natural gas (LNG) vessel fleet available from S&P Global's Seaweb portal.[28] Data available in Seaweb include ship details and technical specifications for over 200,000 vessels over 100 gross tons (GT). For this study, we identified all cargo-carrying vessels that were listed as having a primary or secondary fuel type of "Lng" [sic.] or "Gas Boil Off," both of which refer to LNG vessel operations. Furthermore, we identified and queried all vessels with a ship type listed as "LNG Tanker," which includes LNG tankers, bunkering tankers (LNG/Oil), and combination gas tankers (LNG/LPG).

As of this writing, in total these queries yielded 2,020 vessels, of which 1,178 are listed as "In Service/Commission," 567 as on "On Order/Not Commenced," 181 as either "Keel Laid" or "Under Construction," and 94 in some combination of laid up, launched, or under conversion.

Notably, not all of the vessels returned in our queries are specifically propelled by LNG. Focusing on "In Service/Commission" vessels, shown in SI 2: Figure 1, 76.7% list LNG as its primary fuel, and 2.4% list gas boil-off as the primary fuel.[29] The remaining 20.7% of vessels returned list distillate fuel as their primary fuel. All of the vessels that list distillate primary fuels are LNG Tankers that transport, but do not consume, LNG. Secondary fuels are almost entirely (94%) conventional bunker fuels, including distillate fuel (74.0%) and residual fuel (20.0%). One vessel, Hydrotug 1, which operates at the Port of Antwerp, is primarily fueled by hydrogen with LNG as a secondary fuel (CMB.TECH, 2023; Port of Antwerp-Bruges, 2022).

SI 2: Figure 1: Primary Fuel Type for LNG Vessels



Bar plot showing primary fuel type for LNG fleet vessels identified as In Service/Commission in October 2023

Fleet Characteristics

Considering only those vessels listed as "In Service/Commission," we have analyzed detailed vessel characteristics from the Seaweb dataset. We begin by focusing on vessels that use "LNG" or "Gas Boil

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[28] S&P Global's Seaweb Portal, the industry's largest maritime database / https://maritime.ihs.com/Areas/Seaweb

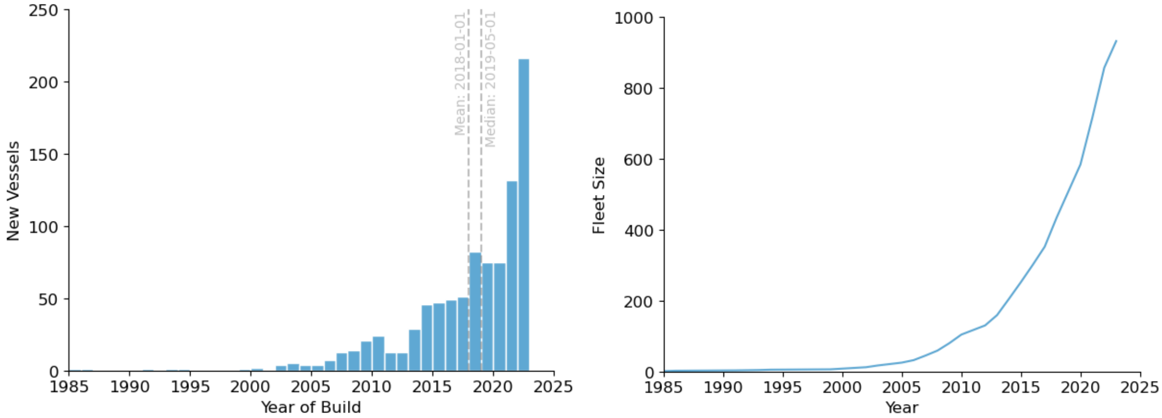
[29] Gas boil-off from LNG storage that has been captured and converted to fuel / https://www.mckinsey.com/industries/oil-and-gas/our-insights/forced-boil-off-gas-the-future-of-lng-as-a-fuel-for-lng-carriers

Off" as their primary fuel, which we will refer to as LNG-fueled vessels for simplicity, then we consider vessels that transport, but do not consume, LNG.

LNG-Fueled Vessels

The Seaweb dataset identifies 932 unique IMO numbers for in-service/commission vessels operating on LNG or boil-off gas (BOG) as a primary fuel. Growth in these vessels has been rapid, with 54% of IMO numbers registered in 2019 or after. Over 90% of those vessels were built on or after 2010 (852 vessels), with rapid, exponential, growth seen in the fleet starting in the early 2000s.

SI 2: Figure 2: LNG-Fueled Vessel Fleet Growth



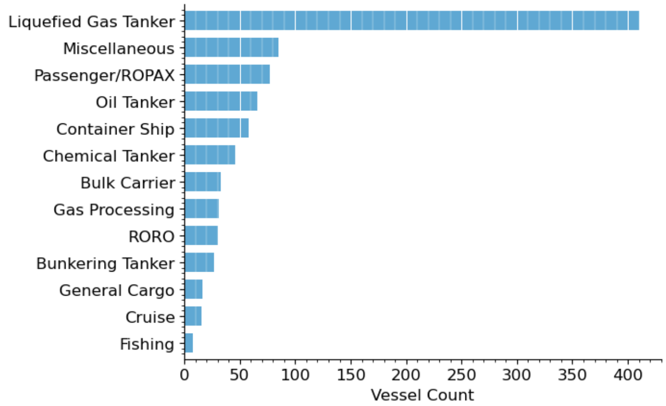
Bar plot showing new vessels by year of build (left) and line plot showing cumulative LNG fleet size (right).

Of the LNG fleet population, the mean vessel build year was 2018 and the median build year was 2019. The oldest vessel in the LNG fleet, the Ostfriesland, a passenger/Ro-Ro vessel flagged and operating in Germany, is 38 years old.

Vessel Type

The largest fraction of LNG vessels by type is liquefied gas tankers, which account for 45.5% of the current fleet. Passenger/ROPAX vessels account for 8.5% of the fleet and container ships account for just 6.4% (SI 2: Figure 3). The overwhelming majority of LNG tankers signifies the large market for natural gas imports and exports in the global energy trade, for which this energy will primarily be consumed by non-maritime sectors. Tankers often use a portion of their cargo for self-propulsion, particularly captured BOG that could otherwise be lost revenue. Signifying the growth of LNG fuel in the shipping industry, container and cargo ships had represented only 1.3% of LNG use in 2021 (Marine Environment Protection Committee, 2022).

SI 2: Figure 3: LNG Vessel Type

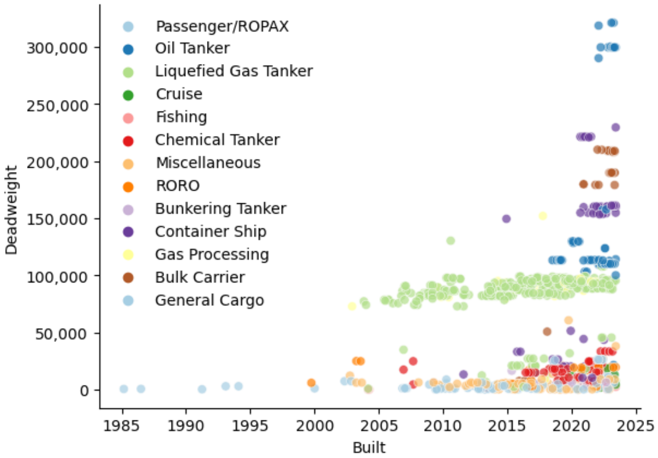


Bar plot showing count of vessels by type for LNG fueled in service/commission vessels.

Deadweight

Deadweight tonnage of LNG vessels, like other vessels in the global fleet, varies greatly. There is a trend toward larger LNG vessels in recent years, though clear classifications persist (SI 2: Figure 4). Sizes of liquefied gas tankers, for example, are consistently around 91,400 DWT, with 50% of those vessels being between 84,000 - 94,700 DWT. Container vessels, which are generally relatively recent additions to the global fleet, have a wider range in deadweight tons, with a median size of 160,000 DWT. Bunkering tankers are among the smallest vessels in the fleet, with a median size of 5,800 DWT.

SI 2: Figure 4: LNG Vessel Deadweight Tonnage and Year of Build

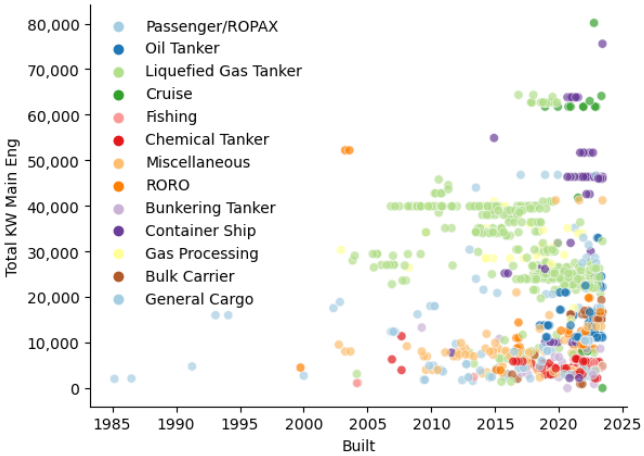


Scatterplot showing LNG vessels by year of build, deadweight, and vessel type. Data show clusters of similarly sized (DWT) vessels by type.

Larger vessels tend to have a higher fuel consumption, and thus total emissions, compared to smaller ones. Moreover, understanding the DWT of the LNG-fueled weight can provide some insight into the preference for onboard technologies, as well as preferences for methods of fuel bunkering. As discussed in preceding sections, the flexibility and flow rates of ship-to-ship bunkering are an ideal infrastructure for large vessels.

Main Engine Power

SI 2: Figure 5: LNG Vessel Main Engine Power and Year of Build

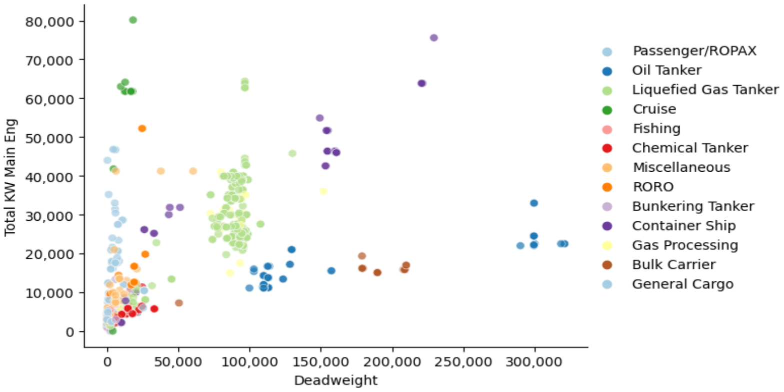


Scatterplot showing LNG vessels by year of build, main engine power (kW), and vessel type.

Cruise ships are among the most powerful vessels in the fleet, with median main engine installed power around 61,800 kW, followed by container ships at 46,360 kW (SI 2: Figure 5). While there is a trend toward higher powered vessels in recent years, deadweight and vessel type are stronger indicators of vessel power demands, as shown below.

Groupings of vessels by type, DWT, and power are clearly visible in SI 2: Figure 6, including for liquefied gas tankers, container ships, and oil tankers. These groups are likely reflective of vessel classes and vessels designed with specific operational parameters in mind, such as terminal berth constraints or draft limits. Moreover, the clear operational parameters of each grouping reflect earlier sentiments about engine technologies representing the vessel-types in the fleet, with regard to speed and power requirements.

SI 2: Figure 6: LNG Vessel Main Engine Power and Year of Build



Scatterplot showing LNG vessels by deadweight, main engine power (kW), and vessel type.

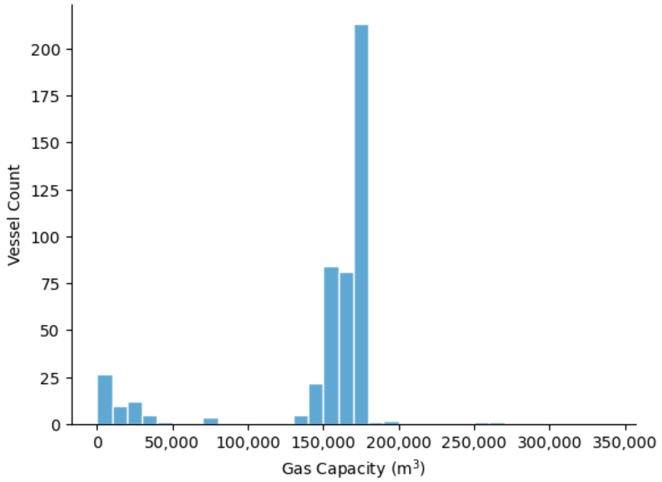
Gas Capacity

Gas capacity scales linearly with vessel deadweight tonnage, with gas capacity estimated at 1.83 m^3 per DWT (Adj. $R^2 = 0.998$, $p < 0.001$). Gas capacity falls into two main size bins, less than 50,000 m^3, and 130,000 - 180,000 m^3 (SI 2: Figure 7).

Of the 55 smaller capacity vessels (<50,000 m^3 gas capacity), 26 (47%) are bunkering tankers and the remaining 29 vessels (53%) are LNG or LPG (liquefied petroleum gas) tankers. Of the 415 larger vessels 383 (92.3%) are LNG tankers, 30 (7.2%) are gas processing vessels, and 2 (0.5%) are floating storage and offloading vessels.

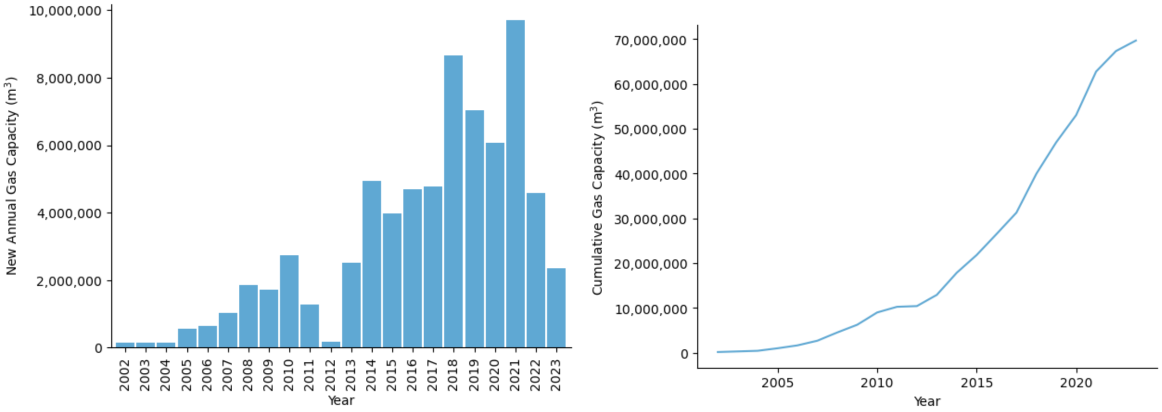
The capacity of the fleet has grown 7.8x from 8.95 million m^3 of gas capacity in 2010 to 69.66 million m^3 in 2023 (SI 2: Figure 8). All years since 2002 have seen growth in gas capacity, with the largest annual additions occurring in 2021 (9.70 million m^3) and 2018 (8.67 million m^3). The growth of the fleet's gas capacity is primarily attributed to tankers involved in the global energy trade of natural gas. The population of bunkering tankers is directly linked to the growth of LNG as a marine fuel.

SI 2: Figure 7: LNG Vessel Gas Capacity



Bar plot showing gas Capacity (m^3) of LNG vessels. Data are grouped into two main categories, less than 50,000 m^3, and greater than 130,000 m^3.

SI 2: Figure 8: LNG Fleet and Newbuild Vessel Gas Capacity

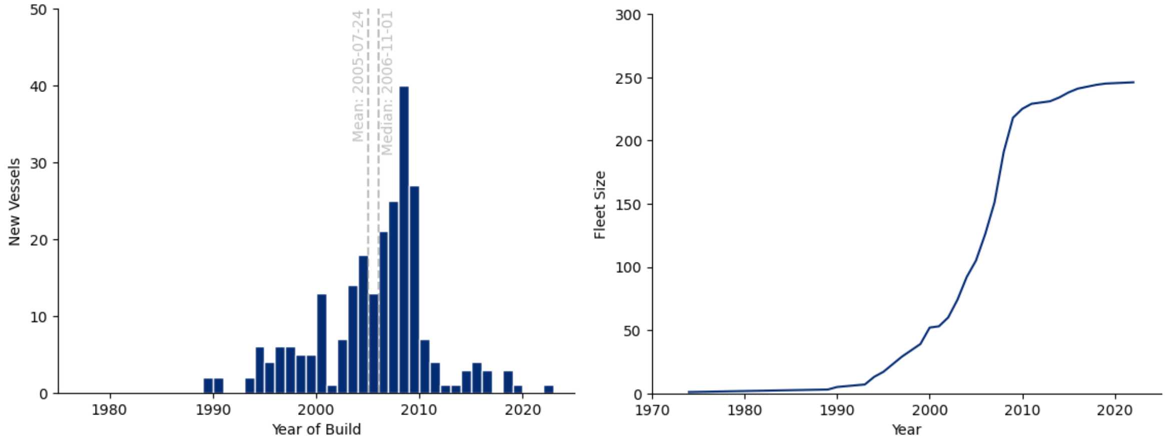


Bar plot showing new annual fleet gas capacity (m^3) (left) and line plot showing cumulative LNG fleet gas capacity (m^3) (right)

Conventionally Fueled Carriers of LNG

The Seaweb data show 246 vessels that are in-service/commissioned but do not list either LNG or gas boil-off as their primary fuel. Of these vessels, all but two are listed as primarily running on distillate fuel and 96% list residual fuel as the secondary fuel. Almost all (97.6%) of these vessels are LNG Tankers, with the others (5 vessels) listed as bunkering tankers (and one Tug).

SI 2: Figure 9: Non-LNG-fueled LNG carriers, LNG Fleet and Newbuild Vessel Gas Capacity

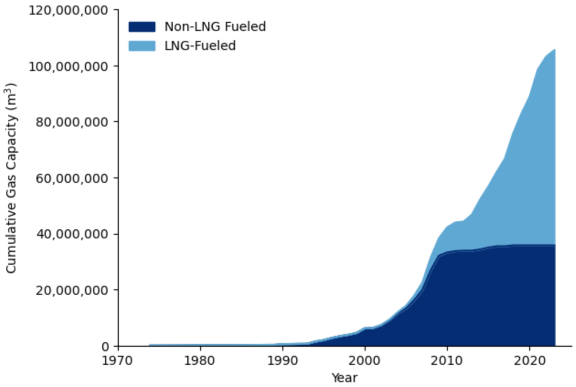


Bar plot showing new vessels by year of build (left) and line plot showing cumulative fleet size (right) for non-LNG-fueled LNG carriers.

The non-LNG-fueled LNG carrying fleet is older than the LNG-fueled fleet, with nearly 90% of vessels built prior to 2010 (SI 2: Figure 9). The mean age of the non-LNG-fueled LNG carrying fleet is 17.9 years, and the oldest vessel, the LNG bunkering tanker Seagas, was built in 1974 (flagged and operating in Sweden).

The total gas carrying capacity of the non-LNG-fueled LNG carrying fleet is 35.75 million m^3, just under 90% of which was added prior to 2010 (SI 2: Figure 9). Comparing the LNG-fueled and non-LNG-fueled fleets. As shown in SI 2: Figure 10, almost all capacity added after 2010 is by LNG-fueled vessels. In 2023, the combined gas carrying capacity of all vessels in service/commissioned is 105.4 million m^3.

SI 2: Figure 10: LNG Fleet Gas Capacity



Area plot showing cumulative LNG fleet gas capacity (m^3) for LNG-fueled and non-LNG-fueled LNG fleet vessels.

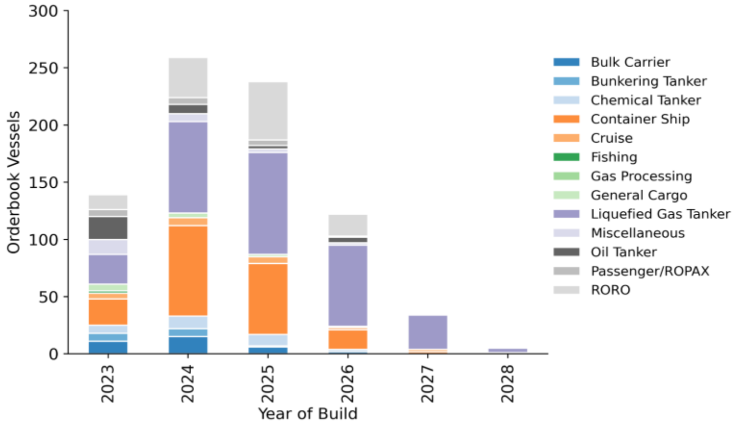
LNG Orderbook Fleet

Based on Seaweb data, there are currently 567 vessels on order/not commenced, with another 97 keels laid, 84 vessels under construction, and 77 launched, bringing the total number of vessels in the LNG orderbook to 825, an increase of 88.5% over the current LNG-fueled fleet. Almost all (99.4%) of the vessels in the LNG orderbook list LNG as a primary fuel, with 3 vessels listing hydrogen as a primary fuel and 2 listing distillate. Of the fuels listing LNG as the primary fuel, 98% are dual fuel, listing distillate fuel as the secondary fuel.

Orderbook Vessel Types

Liquefied gas tankers comprise the largest fraction of vessels on order, accounting for 37.5% of orders (300 vessels) between 2023 and 2028 (SI 2: Figure 11). Container ships (22.9%, 183 vessels) and Ro-Ro vessels (14.9%, 119 vessels) account for the next two largest categories. Together, the top three categories account for three quarters (75.3%) of all vessel orders over the next five years.

SI 2: Figure 11: LNG Orderbook Vessel Types



Annual LNG orderbook vessels by type of vessel and anticipated year of build

Orderbook Deadweight and TEU Capacity

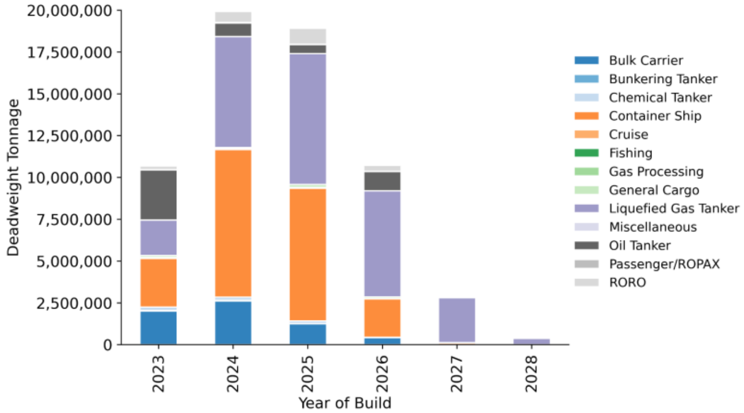
The largest vessels on order, by mean deadweight tonnage, are bulk carriers (mean: 185,492 DWT), followed by oil tankers (mean: 152,712 DWT) and container ships (mean: 120,493 DWT). All vessel types exhibit a wide relative range in terms of DWT on order, reflecting targeted vessel designs for specific routes and purposes. Summary statistics for orderbook vessel deadweight tonnage are shown in SI 2: Table 1.

SI 2: Table 1: Summary statistics for orderbook vessel deadweight tonnage

Ship Type	Count	Mean DWT	Std.	Min. DWT	25%	50%	75%	Max. DWT
Bulk Carrier	34	185,492	55,933	5,560	207,000	209,800	210,000	210,000
Bunkering Tanker	15	5,751	2,744	1,500	4,000	5,300	7,450	12,351
Chemical Tanker	30	19,213	12,306	6,600	9,000	17,999	22,554	50,000
Container Ship	183	120,493	54,293	21,023	82,000	131,000	160,000	230,000
Cruise	23	10,486	5,402	1,000	6,250	10,509	13,500	19,750
Fishing	2	8,650	-	8,650	8,650	8,650	8,650	8,650
Gas Processing	1	95,000	-	95,000	95,000	95,000	95,000	95,000
General Cargo	12	26,533	27,185	7,800	8,700	17,500	26,000	82,000
Liquefied Gas Tanker	300	86,500	14,427	1,280	81,000	92,312	93,000	128,845
Miscellaneous	25	903	2,580	-	-	-	351	12,000
Oil Tanker	36	152,712	102,409	4,998	112,820	114,000	300,000	320,000
Passenger/ROPAX	19	5,687	3,262	600	3,448	5,805	8,475	11,742
RORO	119	18,124	2,676	5,385	18,000	18,600	19,000	23,942

In total, the LNG orderbook will add 63.5 million DWT to the fleet, roughly equivalent to the DWT of the existing LNG-powered fleet (existing fleet = 63.7 million DWT). Liquefied gas tankers alone account for 25.9 million DWT (40.9%), followed by container ships (22.1 million DWT, 34.8%) and bulk carriers (6.3 million DWT, 9.9%). The orderbook is projected to add an additional 10.7 million DWT in 2023, 20.0 million DWT in 2024, and 18.9 million DWT in 2025. Though orderbook numbers decline after 2025, that is likely more reflective of orders simply not having been placed yet, rather than declining future demand.

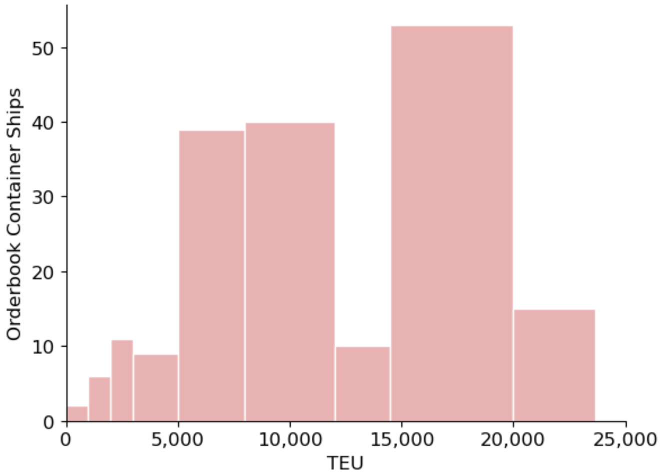
SI 2: Figure 12: LNG Orderbook Deadweight by Vessel Type



LNG orderbook vessel total deadweight tonnage by type of vessel and anticipated year of build.

In total, the LNG orderbook will add containership capacity of 2.06 million TEUs across 183 vessels. SI 2: Figure 13 shows the distribution of containership orders by vessel size. Bin edges in the histogram shown in SI 2: Figure 13 correspond to IMO Size Bins 1-9, with the right edge of the largest bin defined by the largest vessel on order in IMO Size Bin 9 (23,660 TEU).

SI 2: Figure 13: LNG Orderbook TEUs



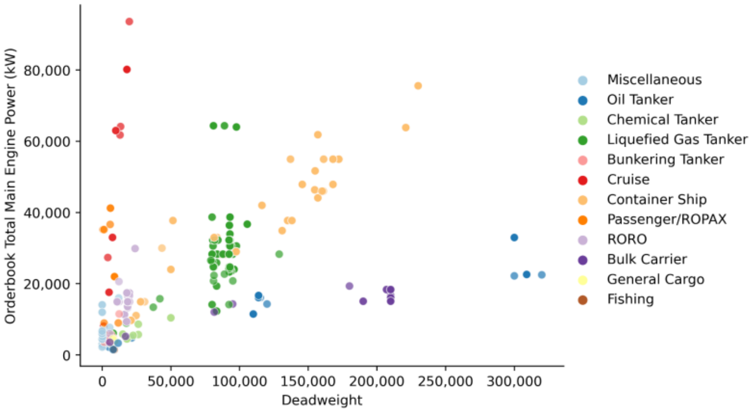
LNG fueled container ship on order, by IMO TEU size bin (1 - 9)

There are currently 68 New Panamax (vessels in bins 8 and 9) on order, which together account for 47.2% of the total TEUs in the orderbook. Bins 5 and 6 comprise the majority of remaining TEUs ordered (14.1% and 19.1%, respectively), together accounting for 33.2% of TEUs ordered.

Orderbook Main Engine Power

As for the current fleet, cruise ships are among the most powerful vessels on order. The data show a positive linear relationship between deadweight and main engine power for cruise ships, though the vessels ordered are generally smaller (< 50,000 DWT) (SI 2: Figure 14). Power also scales positively and linearly with deadweight for container ships and oil tankers. Container ships have a higher power to weight ratio than most other cargo carrying vessel types, which is in keeping with known trends and reflects the industry, which can require fast movement of containerized goods. Liquefied gas tankers show a relatively narrow range in deadweight tonnage, but a wide range in main engine power. This is likely reflective of vessels with similar gas carrying capacity requirements but differing routes and time constraints, with lower powered vessels transiting more slowly than higher powered vessels.

SI 2: Figure 14: LNG Orderbook Deadweight and Main Engine Power



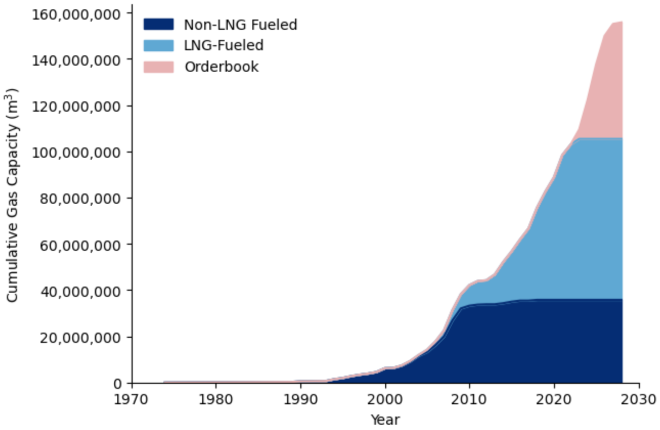
Scatterplot of orderbook LNG vessels by deadweight, main engine power (kW), and vessel type.

Orderbook Gas Capacity

The LNG orderbook includes 316 vessels listed with gas carrying capacity. Of these vessels 294 are LNG tankers, 12 are LNG bunkering tankers, and the remainder are a combination of liquefied gas carriers and bunkering tankers (e.g., LPG, CO_2 etc.). All of the bunkering tankers have gas carrying capacities below 20,000 m^3. The median capacity for an LNG tanker on order is 170,520 m^3. Curiously, there are 191 LNG tankers on order with a listed gas capacity of 170,520 m^3. These vessels appear to be linked to a large push by QatarEnergy for newbuild LNG tankers (J. Casey, 2022).

In total, the current LNG orderbook will add 50.4 million m^3 of gas carrying capacity to the global fleet in the next five years, an additional 29.5% increase in capacity from 2023 through 2028 for a total of 221.3 million m^3 (SI 2: Figure 15).

SI 2: Figure 15: LNG Orderbook Gas Capacity



Cumulative area plot showing orderbook LNG gas capacity compared to the non-LNG and LNG-fueled vessel fleets.

Conclusions from the Orderbook

The LNG orderbook reflects a substantial increase in LNG-fueled vessels entering the fleet in the coming years. The significant growth of container ships on the orderbook (22.9%, 183 vessels) with large DWT and engine power may be outpacing the investments in bunkering infrastructure to meet their needs. Approximately 40% of vessels on the orderbook will have gas carrying capacities, but less than 1% of the total orderbook will be bunkering vessels. This likely indicates that global LNG port infrastructure is still in the early stages of adoption, for which truck-to-ship and shore-to-ship are more prevalent. Whereas bunkering vessels, for ship-to-ship fuel transfer, are considered the best choice for refueling large ships, like the growing containership population.

SI 3: LNG Storage and Bunkering

Port Bunkering Operations

There are three basic bunkering methods: Truck-to-Ship, Ship-to-Ship, and Shore-to-Ship (Park & Park, 2019). Truck-to-Ship bunkering involves using tank trucks to refuel vessels. Truck-to-Ship bunkering offers low investment and operating costs and increased mobility; however, Truck-to-Ship bunkering is not a good candidate for serving large ships due to its small operating capacity (40-80 m^3). Ship-to-Ship bunkering takes place between two ships at anchorage or at port, which offers flexible fueling arrangements. Ship-to-Ship bunkering may entail the usage of barges, tankers, and other floating vessels. Ship-to-Ship bunkering is a preferred option for large vessels due to its greater fueling capacity (1,000 to 10,000 m^3). Shore-to-Ship bunkering occurs at a station, import/export terminal, or intermediary tank. While Shore-to-Ship offers the most efficient fueling in terms of bunkering rate (up to 3,000 l/min), it offers the least flexibility in fueling location. Both Ship-to-Ship and Shore-to-Ship bunkering have higher investment costs than Truck-to-Ship bunkering (International Association of Ports and Harbors, 2023; Y. Peng et al., 2021).

Truck-to-Ship Bunkering

Truck-to-ship bunkering supplies LNG directly to vessels from truck-mounted cryostorage tanks using specialized hose and transfer equipment. Truck-to-ship bunkering delivers on-site LNG to the vessel with relatively low investment costs and limited infrastructure needs. It offers flexibility to the bunkering location at port, as trucks can typically access any berth or pier for bunkering. However, trucks have a limited capacity of 40-80 m^3 and a minimal flow rate around 50 m^3/hour, making it impractical for large OGVs that would require multiple trucks and significant time (International Association of Ports and Harbors, 2023; Satta et al., 2021).

In 2017, a small container ship called the *Wes Amelie* was retrofitted to a dual fuel LNG-capable engine, with a 500 m^3 pressurized LNG fuel tank. When bunkering at the Port of Rotterdam the following year, it required two bunker trucks to simultaneously deliver LNG at a rate of 40 metric tonnes per hour and a total of six LNG bunker trucks to complete bunkering for 120 metric tonnes of LNG fuel. At the time, it was considered a record speed for LNG bunkering, taking approximately three hours (Manifold Times, 2018).

Shore-to-Ship Bunkering

Shore-to-ship bunkering flow rates are significantly faster than truck-to-ship (International Association of Ports and Harbors, 2023). It can deliver large volumes of LNG through onshore tanks with a capacity between 500-30,000 m^3, and its fueling rates reach up to 2,000 m^3/hour. However, it has high investment costs for its infrastructure and equipment and does not allow for simultaneous operations, such as cargo-unloading, during the bunkering operation (Satta et al., 2021). Its installation can be invasive for the port, if building out a permanent pipeline distribution network that requires substantial infrastructure planning. During shore-to-ship bunkering, the ship must be berthed at specific port locations, subject to established timetables and restrictive quay access lanes that may not serve the needs of large OGVs. Thereby, some ports may choose to deploy temporary or portable tanks or may resort back to a preference for trunk-to-ship bunkering. Permanent shore-to-ship infrastructure allows for high capacities and flow-rates, with greater efficiency. Shore-to-shore would make economic sense to a large port that can connect itself to the supply of a nearby terminal.

Ship-to-Ship Bunkering

Ship-to-ship is a location-flexible and time-advantageous choice for large-scale operations, and often the most feasible option for large OGVs. Ship-to-ship bunkering is typically performed in-port, but may occur at anchorage, allowing vessel owners to utilize wait-time in the port queue to refuel before unloading cargo. Furthermore, LNGBVs moored alongside vessels at the quayside may reduce shoreside impacts to cargo handling or circumvent safety restrictions by port authorities regarding simultaneous bunkering and passenger transfer, such as for cruises.

Ship-to-ship bunkering comes with a risk of collision between the bunkering vessel and the refueling ship, the port infrastructure, or other ships within the port. Especially for off-shore fueling, this risk can be heightened by adverse weather conditions (Satta et al., 2021). Furthermore, the human error of ship-to-ship bunkering was found to be reasonable with room for improvement (Uflaz et al., 2022). During ship-to-ship bunkering, the threat of an accident can lead to fatalities or total loss of vessel and its cargo, largely due to risk of ignition. Despite this, a survey of industry experts and stakeholders ranked ship-to-ship bunkering as the preferred choice for shipyard safety (Lee et al., 2021).

If not ignited, LNG fuel spills rapidly vaporize in the presence of water, accelerating the release of uncombusted methane to the environment. High concentrations may cause localized respiratory effects. Ship-to-ship bunkering is imperfect but less detrimental to the sea environment than a conventional oil spill. Nonetheless, a portion of the methane may dissolve into the marine environment with unknown long-term consequences dependent on the temperature of the water, microbial community, weather, and extent of the spill or leak (Reddy, 2022). Most marine life can perceive the heightened methane concentrations and swim away, however concentrations above one milligram per liter may result in disorientation and to prolonged exposure of 1-2 days can cause death (Novaczek, 2012).

Approximately 70% of the global LNGBV fleet has a capacity of 5,000 m^3 and above (Synder, 2023b). Fueling rates are significantly faster than truck-to-ship, but half the speed of shore-to-ship, at 1,000 m^3/hour (Satta et al., 2021). A cruise ship requires around 2,000 m^3 for a seven-day itinerary (MarineLink, 2022; Professional Mariner, 2021). With up to 12,000 m^3 capacity, the largest LNGBVs can refuel multiple large OGVs before returning to an LNG terminal to refuel.

As of summer 2023, the global operational LNG bunkering and bunkering-capable fleet reached around 31 vessels, with an additional 15 vessels on the order book (see SI 2: Table 1). Their capacity is rising to accommodate a larger fleet of LNG-fueled ships, with the active fleet average rising to 7,700 m^3 by end-2022, up from 6,900 m^3 in 2021, and the orderbook of future LNGBVs averages 9,800 m^3 (International Gas Union, 2023). However, investment costs in LNGBVs are high, with builds of a standard cargo capacity of 7,500 m^3 costing approximately \$50 million (Bureau Veritas, 2022).

Ship-to-Ship LNG Bunkering Vessels

Many ports rely on truck-to-ship bunkering during early infrastructure planning and later transition to shore-to-ship or ship-to-ship bunkering with LNG bunkering vessels. In addition to permanent bunkering depots, ships can call at ports with mobile bunkering vessels. LNG bunker vessels began early operation out of the Amsterdam-Rotterdam-Antwerp region, the North Sea, and the Baltic Sea, but since 2017 their numbers have grown substantially across the sector. In 2019 there were only six LNG bunkering vessels across the globe (SEA-LNG, 2023a). Rotterdam hosted its first ship-to-ship LNG bunkering operation in October 2018 and now has nine LNG bunkering vessels operating in the port, including three stationed on a permanent basis (The Maritime Executive, 2020). Due to the mobility of LNGBVs, one bunker vessel/barge can be called to serve multiple ports in a region, so long as there is a site to refill its LNG-cargo. This can offset the risk of its high investment cost, as the supply can travel to meet demand while providing bunkering capabilities to multiple ports under a singular infrastructure investment.

There are large capital investment costs associated with the specialized infrastructure required for fixed LNG bunkering. These vessels require minimum equipment of a cargo containment system, boil-off gas handling systems, and LNG transfer systems. While not required, LNGBV builds can also include dynamic positioning systems to assist in bunkering gas-fueled ships when not moored at the quayside. This system allows refueling at anchorage, to serve vessels waiting to berth or in need of emergency refueling, as well as provides safety measures to quickly move away from the refueling vessel in case of an emergency shut down and disconnection of transfer hoses (Synder, 2020). Furthermore, refueling beyond the quayside on long voyages can save vessel owners, especially containerships, thousands of dollars in costly port fees and lost travel time with reduced port stops.

The number of containerships waiting for a dock at U.S. ports more than doubled from pre-COVID-19 pandemic levels, peaking at more than 150 ships in early February 2022 and returning to this level again by July. Two-thirds of the congested vessels were in queue for the ports of Los Angeles and Long Beach (Miller, 2022). Bunkering vessels capable of offshore refueling before entering the port, may reduce time spent at berth with efficient use of time in the queue to begin addressing congestion with a competitive solution. However, due to the high costs of investment and operation of vessels that meet U.S. compliance to deliver domestic LNG, these additional features may exceed budgets.

U.S. LNG Bunkering Vessels

Only since 2018 have U.S.-flagged LNGBVs entered the fleet, to support ship-to-ship bunkering of U.S. LNG, which are outlined below. Compared to the mean capacity of an LNG carrier at 174,000 m^3, these LNGBVs are significantly smaller, though the capacity of these Jones Act-compliant bunkering vessels is growing over time (Bureau Veritas, 2020). LNGBVs are concentrated in the Southeast U.S. and Gulf Coast, closer to sites of domestic production.

U.S. Natural Gas
Infrastructure Timeline

An overview of significant historic and proposed infrastructure events for Liquefied Natural Gas

- **1941** First U.S. commercial liquefaction facility is built
- **1959** LNG is carried overseas by ocean-going vessel
- **1960-70s** Growth of U.S. LNG facilities and carriers, primarily for import
- **2011** U.S. becomes top natural gas producer
- **2015** First bunkering of an offshore vessel in North America
- **2016** First exports of LNG from the lower 48 states
- **2016** U.S. begins truck-to-ship LNG bunkering
- **2018** U.S. begins ship-to-ship LNG bunkering
- **2018-22** U.S. becomes fastest growing LNG exporter
- **2021** First U.S. offshore bunkering barge
- **2021** U.S. West Coast facility online; Future export plans
- **2022** First Jones Act LNG-fueled ship serves Hawaii
- **2022** Nine U.S. LNG bunkering operations online
- **2025-27** Planned U.S. blue hydrogen facilities in TX & CA
- **2030** First export facility planned outside the lower 48

SI 4: AIS Analysis of Vessel Movements

Vessel movements for the LNG vessels (including LNG-fueled and LNG carriers) identified in Section SI 2: LNG Fleet and Orderbook were analyzed using AIS data for all of 2022 from the Marine Cadastre.[30] In total 389 unique vessels were observed operating in U.S. waters, of which 340 (87.4%) were vessels powered by LNG, and 49 (12.6%) were LNG carriers, not powered by LNG.

LNG vessels were observed operating on the West Coast, East Coast, Gulf of Mexico, and the Great Lakes. Additionally, there is significant LNG vessel activity around Puerto Rico, with high-speed vessel movements to Jacksonville. LNG-powered vessel movements are more widespread than LNG carrier vessel movements, which are generally limited to ports in the Gulf; Savannah, GA; the Chesapeake Bay; Boston, MA; and southern Puerto Rico.

AIS data show 398 unique vessels, based on unique MMSI numbers, that collectively called at 62 ports or regions in the U.S. and Puerto Rico. Based on AIS movements, analyzing vessels stopped (speed over ground ≤ 0.5 knots) within 0.5 nautical miles of a known port facility,[31] EERA identified 3,632 total port entrances by LNG-fueled vessels and carriers in 2022.

Port Fourchon had by far the largest number of LNG vessel entrances (1,030), from a very small (n=5) number of vessels. Further analysis of these vessels and their movements shows that all vessels are offshore support vessels owned by Harvey Gulf International Marine,[32] and their movements are generally localized to oil and gas infrastructure just offshore of Port Fourchon.

The next most-frequently called upon ports are Sabine Pass, TX; Lake Charles, LA; San Juan, PR; and Jacksonville, FL. On the Gulf Coast near Port Arthur, TX, Sabine Pass is home to two facilities that vessels call at, Golden Pass and Sabine Pass LNG terminals. Lake Charles LNG terminals are located on the Calcasieu River, close to the confluence with the Gulf Intracoastal Waterway.

San Juan, PR, and Jacksonville, FL, are interconnected, with a high number of entrances at both ports associated with the frequent movements of comparatively few vessels between the two ports. Over the course of 2022, we observed 202 voyages between Jacksonville and San Juan.

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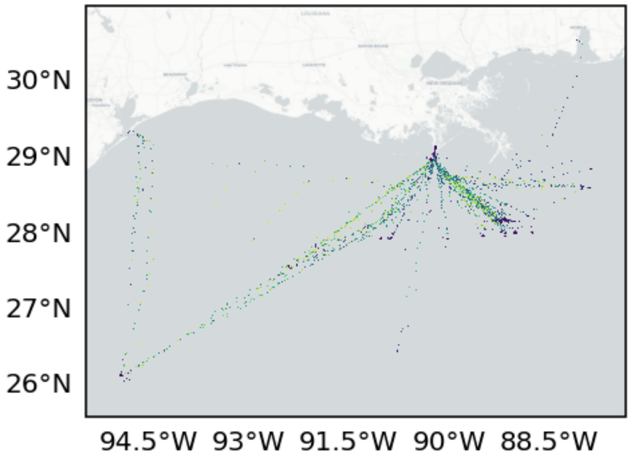
[30] Marine Cadastre, U.S. Coast Guard Navigation Center, 2022 AIS data. https://marinecadastre.gov/ais/

[31] U.S. Department of Transportation: ArcGIS Online, Bureau of Transportation Statistics. https://data-usdot.opendata.arcgis.com/datasets/usdot::docks/about, selected facility types = ['Dock', 'Marina', 'Tie Off']

[32] Harvey Energy, Harvey Liberty, Harvey Power, Harvey America, Harvey Freedom

SI 4: Figure 1: AIS Positions for Vessels Calling at Port Fourchon



AIS map showing movements of five Harvey Marine offshore support vessels, home ported in Port Fourchon, servicing local oil and gas infrastructure. Lighter colors show faster speeds.

Analysis of consecutive entrances (SI 4: Table 3) shows that, for the majority of observed voyages, vessels clear a port, and the next observed entrance will be to the same port. Analysis of voyage durations indicates that in many cases vessels are departing ports in the U.S., calling at distant ports overseas (outside the AIS data extent) over an extensive period of time, then returning to the original port. The median time between entrances is just 18 hours for Port Fourchon, indicating those vessels engage in frequent trips to local offshore oil and gas infrastructure. The median time between entrances on the San Juan - Jacksonville run is around 3.5 days,[33] while vessels visiting Sabine Pass and Lake Charles will typically return after around 40-44 days later, indicating more distant voyages overseas.[34]

DOE vessel movement data show LNG exports from six terminals (SI 4: Table 1) and imports to four terminals in 2022 (SI 4: Table 2). As discussed previously, exports are significantly larger than imports, both in terms of voyage volumes exported and total export volumes.

Total calls and the number of unique vessels calling at export terminals was generally significantly higher than for import terminals, and average export voyage volumes were around 3,074,000 Mcf , compared to import voyage volumes which on average ranged from 279,000 Mcf to 1,118,000 Mcf.

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[33] Four vessels each made around 100 voyages between Jacksonville, FL and San Juan, PR. The *Isla Bella* (103 voyages, container ship, TOTE), *Taino* (102 voyages, container/ro-ro ship, Crowley), *Perla del Caribe* (101 voyages, container ship, TOTE), and *El Coqui* (98 voyages, container/ro-ro ship, Crowley).

[34] We are unable, with the data available, to identify overseas destinations.

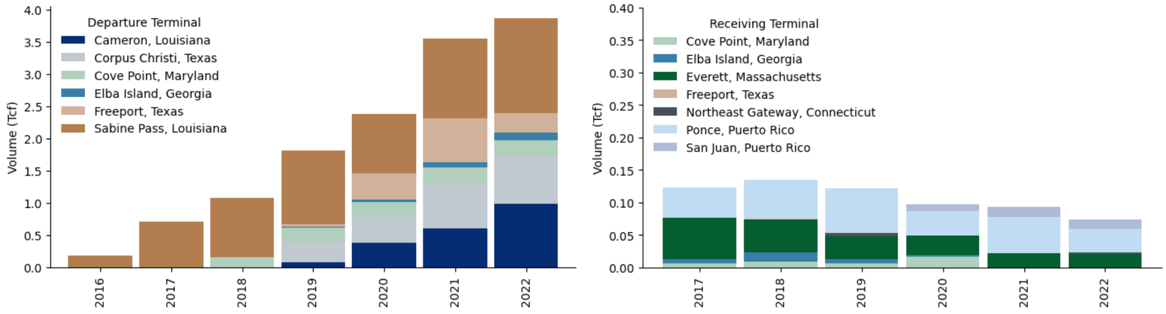
SI 4: Table 1: Export terminal summary statistics (2022)

Departure Terminal	Calls	Unique Vessels	Mean Voyage Volume (Mcf)	Total Export Volume (McF)
Cameron, Louisiana	331	114	2,955,000	978,237,000
Corpus Christi, Texas	235	96	3,205,000	753,285,000
Cove Point, Maryland	86	45	2,859,000	245,914,000
Elba Island, Georgia	36	27	3,012,000	108,437,000
Freeport, Texas	97	63	3,103,000	301,008,000
Sabine Pass, Louisiana	446	175	3,307,000	1,475,029,000

SI 4: Table 2: Import terminal summary statistics (2022)

Receiving Terminal	Calls	Unique Vessels	Mean Voyage Volume (Mcf)	Total Import Volume (McF)
Everett, Massachusetts	11	6	1,881,000	20,696,000
Northeast Gateway	2	1	1,420,000	2,840,000
Ponce, Puerto Rico	28	10	1,289,000	36,096,000
San Juan, Puerto Rico	49	6	279,000	13,651,000

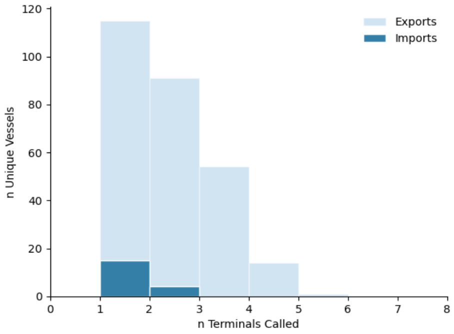
SI 4: Figure 2: Annual Export and Import Volumes by Terminal



Export (left) and import (right) volume of LNG per year by terminal (tcf)

Most LNG importing and exporting vessels called at just one or two terminals in 2022 (SI 4: Figure 5), indicating that vessels operate on liner schedules or are limited to specific terminals based on contracts, or constraining terminal and vessel parameters.

SI 4: Figure 3: AIS Positions for Vessels Calling at Port Fourchon



Histogram plot showing the count of unique vessels by number of ports called for import and export vessels.

SI 4: Table 3: Count and median time of LNG voyages between the United States and Puerto Rico

Port A	Port B	Voyages	Entrance ΔT (h)
Port Fourchon, LA	Port Fourchon, LA	995	18
Jacksonville, FL	**San Juan, PR**	202	80
San Juan, PR	Jacksonville, FL	202	88
Sabine Pass, TX	**Sabine Pass, TX**	197	1,000
Lake Charles, LA	Lake Charles, LA	126	1,062
Tacoma, WA	Tacoma, WA	97	168
Corpus Christi, TX	**Corpus Christi, TX**	93	812
Port Canaveral, FL	Port Canaveral, FL	89	96
Marcus Hook, PA	Marcus Hook, PA	50	692
Corpus Christi, TX	**Sabine Pass, TX**	47	1,036
San Juan, PR	**San Juan, PR**	46	235
Sabine Pass, TX	Lake Charles, LA	45	1,100
Sabine Pass, TX	**Corpus Christi, TX**	44	1,007
Lake Charles, LA	**Sabine Pass, TX**	40	1,098
Long Beach, CA	Honolulu, HI	39	151
Oakland, CA	Long Beach, CA	38	50
Honolulu, HI	Oakland, CA	35	137
Corpus Christi, TX	Lake Charles, LA	30	931
Cove Point, MD	**Cove Point, MD**	28	1,285
Freeport, TX	**Freeport, TX**	28	897
Lake Charles, LA	**Corpus Christi, TX**	24	968
Freeport, TX	**Sabine Pass, TX**	20	1,622
Plaquemines, LA, Port of	Plaquemines, LA, Port of	20	4
Beaumont, TX	Beaumont, TX	19	120
Jacksonville, FL	Jacksonville, FL	17	261
Port Canaveral, FL	**San Juan, PR**	17	71
Houston, TX	Houston, TX	17	873
San Juan, PR	Port Canaveral, FL	16	96
Pascagoula, MS	Pascagoula, MS	16	16
Freeport, TX	Lake Charles, LA	15	1,095

Count of LNG powered and carrier voyages and median time difference (hours) between ports in the United States and Puerto Rico based on consecutive observed entrances. Top 30 port pairs. Blue denotes different consecutive ports; **bold** text denotes ports with import/export terminals.

SI 5: LNG Value Chain

LNG Storage and Transportation

Most LNG is transported by large oceangoing vessels, carriers or tankers, that are equipped with cryogenic tanks. Large storage tanks at LNG terminals maintain a liquid-state while holding tens-to-hundreds of thousands of gallons in conditions below -83°C. While liquid natural gas requires less volume than in its gaseous state, the onboard LNG fuel tanks and systems still require three to four times more space than marine gas oil (Harris et al., 2022). This is primarily due to the cryogenic conditions it must be kept under, making LNG a "boiling cryogen" in extremely cool conditions (-162°C). At its boiling point, its temperature does not change with increased heat, as it is cooled by evaporation. This process is called "auto-refrigeration", for which the pressure must be maintained with the release of its vapors. During storage, heat penetration occurs because of the temperature differences between the tank and environment, which causes its evaporation and the generation of BOG.

The only cost-effective method of transporting natural gas in its gaseous state is by pipeline, which theoretically hinders its global export potential. During liquefaction, its volume is reduced more than 600 times, resulting in better storage efficiency in more efficient transport of large quantities (U.S. Energy Information Administration, 2023a). The liquefaction process focuses on compressing, condensing, and lowering the pressure and temperature of the main constituent of natural gas, methane. It is estimated to consume about 2900 kilojoules per kilogram (kJ/kg) of energy for liquefaction, with ~2070 kJ/kg dissipated as heat and 830 kJ/kg stored in the LNG (Franco & Casarosa, 2014).

Storage and regasification consume approximately 27% of the total costs incurred along the LNG value chain (Qyyum et al., 2018). Effective storage of LNG is crucial to its efficiency, due to its boil-off rate, reducing the supply and increasing GHGs. There are few studies looking at the upstream emissions of LNG operations, however, production, distribution, transmission, and storage are estimated to account for 52% of the life cycle methane emissions (United States Environmental Protection Agency, 2022). The boil-off rate depends on storage pressure, thermal insulation, LNG composition, as well as the amount of LNG left in the tank. However, even the most efficient insulation today cannot entirely prevent heat from continually seeping into the container, with boil-off rates often starting at 0.1% of cargo/fuel per day (Wärtsilä, n.d.). If improperly managed, excess pressure due to BOG can risk structural damage to the tanks and create safety issues from leaks, such as fire or explosion (Miana et al., 2016).

In addition to increasing the global warming potential of the fuel, a consequence of this vaporization is the reduced fuel quality of LNG, as the most volatile compounds (nitrogen and methane) are lost first in its boil-off (Miana et al., 2016; Qu et al., 2019). Some LNG carriers have been equipped with reliquefaction plants, specialized capture systems that collect and condense the boil-off vapors and inject the LNG back into the tanks (Lowell et al., 2013). Reliquefaction can conserve fuel to reduce costs and increase efficiency across most voyages; however, the costs of reliquefaction offset the cost-advantages of "slow steaming" practices (speeds ≤ 12 knots) (You et al., 2023). Additionally, liquefaction systems have been considered impractical aboard non-carrier ships due to the large space and equipment required, which are in addition to the already increased storage requirements of LNG. These systems could be better suited during the early stages of storage and liquefaction.

Value Chain Financial Investments in LNG

The LNG value chain begins with the extraction and production of natural gas from subsurface reservoirs, which requires large capital outlay and experienced labor. There are substantial factors related to constructing a well and jumpstarting production, including but not limited to: leasing drilling rights from the property owner; engineer work, well stimulation, construction of the well pad; construction of access roads; equipment transportation; permitting applications; and other various labor.

The trend toward drilling longer horizontal wells is growing, as longer laterals can cut costs by 15-20% (Rassenfoss, 2022). The cost of a single horizontal, unconventional shale gas well is estimated at around $6-8 million in the Northeastern U.S. Beyond the initial CAPEX, average post-production costs in Pennsylvania are approximately $0.80 per thousand cubic feet of natural gas produced (Marcellus Shale Coalition, 2020). Lease operating expenses add up to an additional $1-3.5 million over the life of a 20-year well, and similar costs may be incurred for gathering, processing, and transport t(U.S. Energy Information Administration, 2016).

The natural gas must travel from the well pad for processing, and in some cases for liquefaction, to continue its travel where pipelines are not feasible or do not exist. A natural gas pipeline, based on the 30-inch average diameter, is estimated to cost $5.34 million per mile with regional cost multipliers associated with building a pipeline in the U.S (Petak et al., 2017).[35] Offshore pipelines are around double the cost per mile of onshore pipelines (Petak et al., 2017). In 2022, there were approximately three million miles of mainline and other pipelines to link natural gas production areas, storage facilities, and consumers (U.S. Energy Information Administration, 2022).

The cost of LNG transport by carrier is only competitive with its gaseous pipeline transportation for distances greater than 1,860-4,350 miles, dependent on the pipeline tariff. This is largely due to the cost to liquefy and maintain the fuel in its liquid state. Behind the upstream development of natural gas, liquefaction terminals are the next most expensive piece of the LNG value chain for both initial investment and long-term operation. LNG liquefaction costs vary from approximately $200/ton per year to over $2,000/ton per year (tpa). Due to the simultaneous development of new LNG infrastructure across the globe driving up demand for concurrent engineering, procurement, and construction services, the average cost of liquefaction plants has increased since 2000 (Molnar, 2022).

Risk to Investment in LNG

By 2050, an additional need for 200 million tons of liquefaction capacity is anticipated on a global scale with the majority expected to be supplied by growth in the U.S. (Agosta et al., 2021). The export capabilities of the U.S. have been a significant investment for the nation's natural gas industry. The present global energy shortages, largely impacted by the Russia-Ukraine conflict, have increased the export demands of U.S. LNG, such that the U.S. is on track to become the world's largest exporter of LNG in 2023 (Harrison & Farrer, 2023). Russia cut pipeline deliveries of natural gas to the EU by

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[35] Central x 0.65, Midwest x 1.20, Northeast x 1.68, Offshore x 1.00, Southeast x 0.80, Southwest x 0.74, and Western x 0.94 / https://www.api.org/~/media/files/policy/infrastructure/api-infrastructure-study-2017.pdf

approximately 80% in 2022 and in turn drove up its price, which incentivized global investors to build up non-Russian gas supplies (International Energy Agency, 2023c). The continued growth of liquefaction capabilities in the U.S. helped balance the global supplies of LNG to offset this turmoil (Shell plc, 2023).

Investments in the U.S. natural gas sector come with risk to investing in large-scale, capital-intensive supply projects and export terminals to meet current demand and growth, with the uncertain and possible decline of long-term demand. Particularly, the demand from Europe is questionable due to the continent's strong climate goals, which may have cascading impacts on LNG due to its association with methane emissions (International Energy Agency, 2023c). The EU climate and energy security policies anticipate demand for natural gas to be reduced by at least 40% through 2030, which could cause a decrease in LNG demand after 2023 (Alam et al., 2023).

Market predictions suggest that the U.S. could more than double current LNG exports over the next decade, with over $100 billion put toward LNG production in the next five years (Harrison & Farrer, 2023). The significance of this becomes clearer considering that more than a billion dollars had been made in LNG investments in Jacksonville alone by 2020 (Wheeler et al., 2020). As the global LNG trade is expected to rise, the U.S. and Qatar are anticipated to supply the majority of this new LNG production and export (International Gas Union, 2022). This requires significant capital investments, particularly regarding the transport of natural gas, which can account for over 50% of the costs occurring through the value chain of its international trade (Molnar, 2022). Investments are continuing to be made to meet demand; however, highlighting the larger risk of these investments long-term, the EU will be making competing investments in other energies to meet climate goals. Subsequent or simultaneous investment in technologies to decarbonize natural gas may be required to support long-term demand.

Long-term utilization of infrastructure is not the only risk identified with the fast growth of LNG facilities. There has been significant inflation in the cost of U.S. Gulf Coast projects in the last five years. Project timeline and/or budget overruns are common, demand for qualified labor exceeded supply, there has been competitive pressure from market saturation, and there are low rates of return that have made it challenging to secure financing (Harrison & Farrer, 2023). This in turn generates promising incentives to mitigate emissions across the value chain, through requiring a premium charged to consumers to generate higher returns. Developers for new investment are focusing on sourcing feed gas from projects with certifiably low upstream emissions (i.e., responsibly procured gas) and from renewable natural gas sources (Harrison & Farrer, 2023).

A global motivation to switch to low-GHG and renewable energy sources will require adaptation of the natural gas industry. This includes investments in carbon capture and storage, LNG tank efficiency, boil-off gas capture and reliquefaction, and infrastructure built to be transitioned for compatibility with additional future fuels. These are imperfect solutions at their present design.

Carbon capture will help to further reduce CO_2 but will not minimize methane emissions. Numerous carbon capture technologies are cited as a solution to reducing GHG emissions, yet the technology remains in the research and development phase and has not yet been brought to the commercial market (Khosroabadi et al., 2021). A carbon capture technology under development by the DOE claims it can reduce capture costs (per metric ton of CO_2) significantly, however, it's worth noting they underestimated their baseline compared to the International Renewable Energy Agency report (Jiang et al., 2023). BOG reliquefaction technologies have been experiencing rapid design improvements and attention due to the growing transoceanic LNG trade. Its largest challenges have to do with reducing its energy consumption and costs, as well as optimizing on-board spatial requirements (Yin & Ju, 2022). The complications of infrastructure transitions are later discussed.

SI 6: LNG Regulations

Regulations for LNG bunkering, storage, and transportation

The U.S. regulatory framework for LNG bunkering covers the requirements to transfer fuel between vessels and/or shore structures and how waterfront facilities handle LNG. Additionally, there are international guidelines (e.g., Society of International Gas Tanker and Terminal Operators; Society of Gas as a Marine Fuel) and regulations (e.g., International Maritime Organization) that discuss proper equipment and operation of LNG-fueled ships (SI 6: Table 1). IMO regulation applies to all vessels, regardless of size and addresses:

a) Hardware: liquid and vapor transfer systems

b) Operational procedures

c) Requirement to provide an LNG bunker delivery note.

d) Training and qualifications of personnel involved.

e) Requirements for facilities to meet applicable ISO standards and local codes.

(International Organization for Standardization, 2021)

Existing LNG terminals, such as Port Fourchon, Louisiana, were designed to meet LNG-specific operational and safety standards enacted by the National Fire Protection Association (NFPA), which can apply to facilities with LNG storage in containers and trucks transporting LNG. NFPA standards include:

a) Temperature specifications for materials in contact with LNG

b) Design requirements for filling to prevent combination of other materials (bottom and top filling)

c) Standards for foundations of tank systems situated near each other.

d) Liquid density requirements (density of the liquid shall be presumed to be the actual mass per unit volume at the minimum storage temperatures)

(National Fire Protection Association, 2023)

Additionally, the U.S. Coast Guard (USCG) has established safety requirements for planned LNG bunkering terminals. LNG bunkering terminals will be required to adhere to the requirements of the Maritime Transportation Security Act (MTSA), which compels LNG terminals to submit facility security plans and assessments to the USCG. These must be approved by USCG before operation of the terminal (Zhang & Ahmad, 2020).

In 2017, the first floating LNG terminal launched. Today natural gas can be produced, liquefied, stored, transported, and re-gasified entirely by offshore waterborne vessels. These floating natural gas liquefaction vessels (FLNGs) and floating storage and regasification units (FSRUs) replicate the traditional activities of onshore LNG facilities. These vessels have potentially been used as a workaround to compliance with the complex multitude of agency requirements.

SI 6: Table 1: Regulatory Entities for U.S. LNG Operations

LNG Ports & Terminals	LNG Vessels
International Maritime Organization (IMO) Federal Energy Regulatory Commission (FERC) U.S. Maritime Administration (MARAD) U.S. Coast Guard (USCG) U.S. Environmental Protection Agency (EPA) Army Corps of Engineers (USACE) Pipeline and Hazardous Materials Safety Administration (PHMSA)	International Maritime Organization (IMO) U.S. Coast Guard (USCG) U.S. Environmental Protection Agency (EPA) Army Corps of Engineers (USACE) American Bureau of Shipping (ABS)

SI 7: LNG as a Transition Fuel

As the uptake of LNG continues to accelerate, the construction costs associated with building LNG plants may pose a significant challenge in meeting the increasing demand. According to construction and energy experts, since 2020 there has been a substantial increase of 20% in material prices, while the costs of gas compressors have risen by 30%; moreover, Russia's invasion of Ukraine has contributed to a shortage of metals needed for LNG projects and is expected to further escalate costs by an additional 10% (de Luna, 2022). Aforementioned, IEA argues that addressing fugitive emissions in the LNG life cycle should be prioritized over building additional plants.

Material price rises also impact efforts to reduce clean energy technology costs, with lithium and cobalt more than doubling in 2021 and copper, nickel, and aluminum increasing by 25-40% (International Energy Agency, 2022). Furthermore, higher costs of natural gas will impact those of alternative fuels that rely on natural gas in their production (i.e., steam methane reforming (SMR) and the conversion of natural gas). Low- and no-GHG alternative fuels are likely to remain more expensive than fossil fuels, without policy intervention.

Methanol

Methanol (CH_3OH or MeOH) is currently available to be bunkered and consumed as a shipping fuel, with the potential to be a low-carbon fuel when considering the upstream and full life cycle GHG reductions. Compared to LNG, methanol fuel systems are less costly, easier for the shipyard to fit, require less vessel space, less expensive to bunker, and considered easier to operate (DNV, 2023; Harris et al., 2022). Methanol is presently available in over 120 major ports and can utilize the bunkering infrastructure of conventional marine fuels with minor modification (Marquez et al., 2023). It is considered to be well-proven for use on ships in dual fuel two-stroke engines (Alfa Laval et al., 2020). However, methanol produced with natural gas as feedstock emits 30% more GHGs than LNG across its life cycle (Al-Breiki & Bicer, 2021).

At Rotterdam's bunkering hub, methanol was trading at lower prices than LNG, on a dollar-per-ton basis, as well as when incorporating the relevant energy density factor (Marquez et al., 2023). It has been reported that the investment cost for new-build methanol vessels is similar to that of conventionally fueled vessels. While an LNG engine is estimated to add 22% to the costs of a new vessel, a methanol-fueled engine adds around 10% (Harris et al., 2022). However, methanol is a hydrocarbon and therefore is not low-carbon at consumption, which can be counterproductive to long-term climate needs.

Ammonia

Ammonia (NH_3) is a carbon- and sulfur-free fuel at consumption. Comparing the production and transportation pathways of other alternative, low-carbon fuels, ammonia was found to be 31-32% cheaper than hydrogen and 15-18% cheaper than methanol (Republic of Korea, 2021; Zhao et al., 2019). Ammonia has cost penalties during combustion due to having a lower energy density of 12.7 Megajoules per liter (MJ/L). LNG has nearly double the energy density (22.5 MJ/L) which supports its cost-efficiency at consumption. However, ammonia can be stored and transported under less-extreme temperature and pressure conditions (-33°C at atmospheric pressure), which may contribute to upstream cost savings translated to lower bunkering prices (Alfa Laval et al., 2020).

The costs of ammonia (as well as hydrogen) are complex due to the many assumptions that are made to compensate for under-developed protocols and technologies for its fuel use. A comparative study of fuels reported the estimated bunkering prices of LNG ($692.0/MT), ammonia ($539.3/MT), liquid hydrogen ($2,738.2/MT), and MGO ($599.0/MT), placing ammonia as the cheapest fuel to bunker. Nevertheless, due to its lower energy density, LNG was the most efficient energy based on the daily fuel gas consumption cost (You et al., 2023). The International Maritime Organization previously agreed to price/tax greenhouse gas emissions by 2030, for which a future carbon levy would be favorable to the consumption costs of ammonia in competition with other fuels (Francis, 2023).

Biofuels

Hydrocarbon-biofuels closely resemble the fossil fuels they substitute, with similar safety procedures, combustion traits, and handling characteristics. For consideration as an alternative fuel, the bulk of its emissions are offset by its upstream carbon sequestration, for which the Kyoto Protocol considers it carbon-neutral (Kouzelis et al., 2022). However, the EU Renewable Energy Directive (RED II) guidelines largely limit sustainable biofuels to waste biomass as the feedstock due to indirect land use change, for which the change risks negating the greenhouse gas savings (European Commission, 2023). At present, biofuels are often blended with conventional fuels to improve their emissions profiles.

Biofuels can be difficult to compare to other marine fuels, since there are multiple production pathways from different feedstocks that are going to affect energy density, emissions, cost, ease of retrofit, and more. Long-term per metric tonne bunker cost estimates of biofuels (to 2040) were between 967-1,157 $/MT, with biodiesel and corn ethanol between 500-750 $/MT (Tan et al., 2021). While technically a biofuel, biomethanol is more typically considered a green methanol pathway and has competitive price estimates of 561 $/MT in 2018 and 415 $/MT in 2030 (Lloyd's Register & University Maritime Advisory

Services, 2019). With aforementioned values of LNG fuel between 692-892 $/MT, there are cost-competitive biofuel feedstocks for which reliable feedstock sourcing should improve prices over time.

The estimated global supply of biofuels by 2050 is not anticipated to be large enough to decarbonize multiple sectors, especially not with GHG-neutral feedstocks. The shipping industry would require 20-50% of the anticipated supply if it was to decarbonize primarily using biofuels, including both sustainable and economical feedstocks (Sekkesæter et al., 2023).

Cost of Vessel Regulatory Compliance

The production of low-GHG fuels has been highly intertwined with a fossil fuel reliant energy grid. Under the upcoming additions to the EU regulatory framework, a comparison of LNG against other alternatives found that gray methanol and ammonia (sourced from natural gas energy) were more than twice as costly to achieve compliance, particularly in the first 15 years of the vessel's life (SEA-LNG, 2023b). However, this comparison assumed LNG use in HPDF 2-S engines, which represent a minority of the LNG-fueled fleet and do not meet NO_x regulations without aftertreatment technologies (these additional costs were not included). Thus, it is fair to be skeptical. Accurate cost comparisons are difficult, as there are many wide and varying assumptions made under the relatively new attention of these fuels. While exact values are unclear, prices of low-GHG fuels are likely to remain higher than LNG and other fossil fuels under known regulations on the horizon.

Alternative Fuels Public Health Impacts

Some alternative fuels, such as certain biofuels, can offer reductions in harmful pollutants, such as particulate matter and carbon monoxide when compared to traditional fuel sources, while other fuels, such as ammonia, can introduce new environmental and health hazards, including disruptions to the nitrogen cycle (McCormick, 2007; Smith et al., 2013; Wolfram et al., 2022). Due to complex interactions in atmospheric chemistry and the dynamic nature of the climate system, the introduction of novel pollutants as a result of the growing adoption of an alternative fuel source can have rippling effects throughout the Earth system. In the case of LNG, the emissions associated with increased production and consumption of the fuel can have adverse impacts on human and environmental health and climate.

SI 8: Health and Equity Implications Stemming From LNG

Additional Impacts: Climate Change, Methane, and Ozone

The impacts of methane on health and the environment are also realized through several feedback mechanisms related to its role in intensifying climate change. As a greenhouse gas, increased methane emissions worsen climate change. Since ground-level ozone production typically increases during hot sunny days, an increase in frequency and intensity of heat waves may also result in periods of elevated ozone levels (Knowlton et al., 2004; Utembe et al., 2018). For example, the European heatwave of 2003 triggered high ozone levels, causing over 400 excess deaths recorded in a two-week period due to exposure to ozone and particulate matter (Fischer et al., 2004; Stedman, 2004).

The impact of climate change on total surface ozone concentration is less certain due to increases in water vapor, which can act as a sink for ozone. However, a 2004 study found that climate change alone could increase the frequency and intensity of ozone episodes in the U.S. and estimated a 4.5% increase in ozone-related acute mortality in the 2050s across the NY Metro region studied (Johnson et al., 2002; Knowlton et al., 2004). Observational studies have confirmed that ozone concentrations in New York City are sensitive to heat spells, which change in frequency and intensity as a consequence of climate change (Moshary et al., 2020; Wu et al., 2019). This implies that increased methane emissions can introduce further consequences for local and regional ozone episodes through their influence on climate.

Warming temperatures can additionally increase methane emissions from natural sources, such as wetlands, with natural emissions influenced by changes in climate (Voosen, 2022). This means that even small-scale increases in methane emissions from LNG can amplify overall methane emissions due to a range of positive feedback loops within the Earth system.

Alongside the potential implications of methane for air quality, its contribution to GHG concentrations has other consequential impacts on the health and safety of humans, including increased intensity of extreme weather events and impacts on food security. These factors underline the importance of methane controls in managing public health exposure linked to multiple risk factors.

From a climate change mitigation perspective, regulations addressing methane emissions in shipping are underdeveloped when compared to CO_2 regulations. Methane and ozone are two of the most important GHGs responsible for anthropogenic climate forcing, so implementing aggressive emissions governance can be significantly beneficial to reducing GHG forcing (NASA Aura, 2011).

SI 9: Relevant Data Sources

EPA National Emissions Inventory (NEI)

The NEI[36] is a database maintained by the EPA that tracks and provides information about the emissions of air pollutants from various sources across the country, including criteria pollutants, criteria precursors, and hazardous air pollutants. The NEI is released every three years and is based on a combination of state, local, tribal, and federal data. The NEI includes five data categories: point sources, nonpoint sources, onroad sources, nonroad sources, and fire sources. Data queries have the capability to extract specific information related to geography, types of pollutants, and particular sectors.

Climate and Economic Justice Screening Tool (CEJST)

The CEJST[37] categorizes burdens to highlight disadvantaged areas of the U.S. The categories are based on a range of data, including social, economic, and physical sources. Examples of categories are Climate Change, Energy, Health, Housing, Transportation, and Workforce Development. Disadvantaged communities are determined by percentile-based indicators within each category, grouped by census tract.

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[36] https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei

[37] https://screeningtool.geoplatform.gov/en/methodology

CDC/ATSDR Social Vulnerability Index (SVI)

The SVI[38] is used to quantify the social vulnerability of communities in the U.S. in the context of external forces of human health, including natural and human-caused sources. SVI is broken up into five themes: socioeconomic status, household characteristics, racial and ethnic minority status, housing type and transportation, and overall SVI. SVI is calculated by census tract and county.

World Bank Global Gas Flaring Reduction Partnership (GGFR)

The World Bank (WB) compiles annual data on gas flaring, including details about flare locations, flare size, and field type, the Global Gas Flaring Reduction Partnership (GGFR).[39] Additionally, the WB conducts assessments of the emissions produced through gas flaring and offers estimates of the economic loss connected to resources lost through observed flaring.

EPA EJScreen

EJScreen[40] is an environmental justice mapping tool based on socioeconomic, health, and other indicators of vulnerability. EJScreen allows users to examine potential exposure to hazards, such as ozone, lead paint, and wastewater discharge. This tool can provide valuable insights into environmental justice by combining indicators of vulnerability with exposure to hazards.

IEA Methane Tracker

The IEA Methane Tracker[41] is an interactive database of national and regional estimates of methane emissions. The database includes breakdowns of methane emissions from energy sources and information on abatement options.

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[38] https://www.atsdr.cdc.gov/placeandhealth/svi/index.html

[39] https://www.worldbank.org/en/programs/gasflaringreduction/global-flaring-data

[40] https://www.epa.gov/ejscreen

[41] https://www.iea.org/data-and-statistics/data-tools/methane-tracker

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