LNG as a Marine Fuel

LNG Market & Environmental Performance

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EXECUTIVE SUMMARY

How can the maritime industry power such floating giants, the global shipping fleet which enables a complex web of logistics, while eliminating its carbon footprint? Now that is the billion-dollar question for an industry which is responsible for the transport of almost everything that we use. At Ocean Dynamex, we investigate various solutions, and we question every gap to reach out a trajectory that would survive the test of time, economies of scale and compatibility with the future of opportunities. In this report, we provide an insight and foresight for the development of natural gas as marine fuel from the perspectives of environmental, economic and engineering performance.

In search of our answer to this challenging inquiry, we asked four essential groups of questions and explored them in four parts:

- Is it rational to assume the security of natural gas supply at reasonable prices? What is the current and prospective status of natural gas market? How do the biogas and syngas industries influence the nature of this ecosystem?
- Can natural gas really solve the ship emission problem? What is the environmental performance of natural gas? What extent does the methane slip affect the ship emissions with high pressure diesel engines? Is it feasible to store, carry and refuel the liquified natural gas as marine fuel?
- Does natural gas also outperform in terms of life cycle inventory of waste and emissions? Does shipping play a significant role in the well-to-tank emission inventories?
- Is it really necessary to expect a broader network of LNG bunkering for implementing the solution? Once the natural gas is adopted by stakeholders, what would be the pathway where the natural gas evolves to?

Our research team has gathered the knowledge and data from multiple fields to deal with each part, and we illustrated our findings in a concise and comprehensive way to pave the way for improving the decision-making process of stakeholders.

This report comes with original content for the first time in the industry. You will find our LNG bunker price assessments, an approximation of LNG bunker prices, for delivery at certain regions. By this, we would like to improve the visibility into the cost of LNG fuel market and gain predictability. The investment decisions are well affected by the predictability of cost drivers, and therefore, LNG bunker prices is an important component of the analysis. We also created a list of LNG bunkering facilities around the world. For this, hundreds of documents and media releases have been scanned, every port with LNG bunkering trials is reported in the list. In addition to that, some potential new locations are also provided for further considerations.

Among many important results of this report, a number of key takeaways can be reported as follows:

- LNG as marine fuel has the technical characteristics to achieve the level of power generation for ship propulsion. Natural gas has much higher energy content, and it is super clean in terms of black carbon and particulate matters.
- Since LNG is a thin substance, the components of engine room are well maintained compared to fuel oil with thick and sludgy texture. It does not require pre-heating or filtering.
- LNG is very cheap fuel, usually remains below most fuel oil and diesel oil grades.
- By introduction of biomethane and synthetic methane, the environmental performance of natural gas is significantly improved (the well-to-tank).
- By utilizing high pressure two-stroke diesel cycle engines, the methane emission from LNG fuel is extremely low; there is no reason for causing notable amount of methane slip.
- Oil and gas industries invest in emission control through the extraction, production, gathering and transport stages in recent years. Governments and supra-national organizations (e.g. European Union) raise funds to assist the transformation of the oil and gas ecosystems.
- Instead of burning natural gas, it can also be used as an input for LNG fuel cell mechanism in which hydrogen fuel is generated from methane. By upcoming improvements and upgrades, LNG fueled shipping fleet can be installed with LNG fuel cell units to replace auxiliary engines. Similar to solar panels, the cost and efficiency of fuel cell technology improves dramatically with more public interest and entrepreneurial activities in the marine energy space.

Introduction

THE MARITIME INDUSTRY has been evolving since WWI, and the cost of shipping has been significantly reduced. In the success of this great leap, the transition from coal burning steam engines to fuel oil burning steam engines and diesel engines have an essential role. Fuel oil has reduced the need for bunker storage, providing much higher energy content (much higher speed) and easy access to marine bunkers around the world. Therefore, it would be quite valid to state that fuel oil powered the globalization phenomenon. The conventional marine bunker is under the environmental critique due to the fact that it is one of the dirtiest fuels in the world. With the introduction of new regulations, the ecosystem of marine bunkering and the shipping industry are going through a metamorphosis to replace this century-old energy resource with modern and cleaner alternatives.

In 1997, the International Maritime Organization (IMO, a specialized agency of the United Nations) adopted an additional section (ANNEX VI) to the International Convention for the Prevention of Pollution from Ships (MARPOL) to regulate and improve air pollution from ships. Since Annex VI has entered into force in 2005, the air pollution from ships has been investigated and multiple solutions have been discussed. In the latest mandate, all ships in international shipping are required to reduce their Sulphur emission (SO_X) through exhaust gas to 0.50% m/m (mass by mass) (a.k.a. IMO2020 or Sulphur Cap).

the Sulphur Cap has initiated an irreversible momentum into the inevitable metamorphosis.

IMO2020 is a historical move in many ways. It is the first significant implementation of a regulation for the air pollution from ships. Earlier regulations such as the reduction of SO_X emission to 3.5% m/m did not require a large-scale change in the marine bunkering ecosystem. However, the latest regulation on further reduction SO_X emission has massive impacts in the shipping industry as well as the oil industry supplying the traditional fuel oil. The last large-scale regulation on the marine pollution, the double hull rule for tankers (reg. 19 in Annex I of MARPOL), caused the phasing-out of the aged tanker fleet rapidly and literally refreshed the global tanker fleet. Yet another major impact of Sulphur Cap is the economic chain reaction led by the fact that the cost of marine energy is lifted, and in the new normal, there are many alternatives which were not even competitors at all just a few years ago. Since heavy fuel oil (HFO) is very cheap and the entire bunkering ecosystem is designed accordingly, none of such alternatives would be powerful enough to shift the century-old customs of the industry. However, the Sulphur Cap has initiated an irreversible momentum into the inevitable metamorphosis which is going to be followed by much stringent measures and further reduction of other air pollutants (e.g. CO_2) in line with the targets of the United Nations and other global environmental stakeholders.

In the new normal of maritime energy space, various stakeholders joined the race of being the new standard of the industry and replacing the fuel oil. On the other hand, the fundamental features needed to replace the legacy of fuel oil are not easy to be accomplished by most alternatives. There are four principal components of the decision-making process: (1) The solution must be economically viable for an industry going through one of the longest periods of economic recession in the history. That is also a significant requirement as the shipping service is a competition between carriers to offer the best price to customers. Adopting a costly alternative may not be welcomed in such a competitive market. (2) The new fuel or energy resource must be powerful enough to run over 10,000 tonnes of steel on the sea. Therefore, energy content (calorific value) or power generation capacity is a key factor in the wide-spread acceptance of the solution. (3) The alternative must be available and abundant. Nearly 100,000 cargo ships around the globe must be able to access to the alternative fuel for the next decades till a better solution is introduced. (4) The new fuel must be technically feasible to be carried on board ships. There are three aspects of this concern. The alternative method can be fitted to the existing ships or to an average design by relatively minor adjustments. Another issue is that the new method must be safe and secure as e.g. poisonous fuels require additional care and safety standards. Finally, the alternative solution must have a feasible lifetime and be immune to the test of time with the introduction of new regulations and developments in the long-run. That is to say, the solution may be adjusted and calibrated to another energy system in the future with minor structural changes.

Considering above mentioned circumstances, there is no single solution satisfying all of these features that is found in the traditional fuel oil and developed gradually in a period of half a century. On the other hand, there are alternative fuels which have existed for decades and are used for other purposes before entering to the marine bunkering industry. Among them, Liquified

Natural Gas (LNG) is a leading and promising transition fuel with an established ecosystem as an energy resource, many producers and suppliers around the world, abundance of reserves (even more than crude oil) and many other advantages comparing to other solutions which may be viable in the long-run. In this report, LNG and its variants (biogas and syngas) are investigated through the lenses of an economist (Part 1), an environmental engineer and public decision maker (Part 2 & 3) and a ship investor and strategist (Part 4).

In Part 1, we lay down the facts and prospects in the natural gas production and trading, the LNG market, commoditization of LNG, prices of natural gas and price assessment for LNG bunker as well as the penetration of biogas and syngas variants into the LNG fuel market with striking environmental gains.

Part 2 illustrates the green shipping concept and the air pollution phenomenon followed by emission simulations of a select group of ships conducted by an emission inventory methodology adopted by leading public authorities. In this section, we compare LNG fuel with very low Sulphur fuel oil (VLSFO), the modified heavy fuel oil satisfying the Sulphur Cap limits, among various types of ships and routing characteristics.

In Part 3, we go forward to dissect the air pollution from upstream and downstream operations of LNG and variants. While the supply-chain emission may not be estimated accurately due to certain limitations, the presented results would help decision makers to recognize an approximation of emission characteristics of the life cycle of LNG fuel.

In Part 4, we question the availability and survival of the LNG fuel from a strategic viewpoint. Accordingly, we investigate the operational challenges, LNG bunkering infrastructure, the impact of limited implementation or mass use of the LNG fuel and also how the LNG fuel ecosystem would evolve in the long-run. One of the essential questions in this part is how the LNG fuel would complement and pave the way to much cleaner solutions as a transition fuel.

The transformation of the marine energy space is a point of no return. Stakeholders inevitably bite the bullet and adapt to the new normal with potentially fragmented environment, where shipping firms implement solutions based on their fleet and trading characteristics. In contrast to the last century, we will likely observe a period where multiple energy solutions will be utilized at the same time instead of a step-wise evolution. Looking back over the history of the maritime industry, sail ships and steam ships, coal burning and fuel oil burning steam ships, steam ships and diesel engine ships operated simultaneously for at least a decade or more. It is a massive change considering the size of today's world shipping fleet and how it has been optimized and established in a century. In an interconnected world of shipping, marine energy transformation is a problem with concerns on the economy of scale (widespread use and acceptance), performance and survival in an era of rapid changes.

The objective of this report is to gain a closer look into LNG and its variants (i.e. methane) as a marine fuel by addressing major questions related to the environmental and economic aspects. Shipping firms may consider our work as a complementary document to their financial assessments regarding the cost of retrofitting existing ships or ordering new ships at shipyards.

Part 1

Understanding the Natural Gas & LNG Market

LNG as a Commodity

Summary

- LNG is an abundant energy resource with a developing market as a commodity.
- Global natural gas reserve is approx. 7,177 trillion cubic feet, over 700 times more than the global proven crude oil reserve.
- Natural gas is geographically available in most continents, less concentrated and more liberal markets without an OPEC-like organization setting production volume and prices. In contrast to crude oil, the natural gas market does not have price benchmarks adopted by most stakeholders. Prices can differ significantly among regions.
- LNG Marine Bunker is very new, and therefore, its market is not mature and transparent as the traditional marine fuels. However, the price assessment of Ocean Dynamex reflects averages among regions for planning and predictive exercise.
- LNG Marine Bunker is expected to be cheaper than MGO or VLSFO and even cheaper than HFO in certain periods and regions.
- The Biogas Revolution may even improve the environmental performance and bring LNG variants (biomethane, synthetic methane) to the market. Net Zero Emission is achievable with biogas option, in particular cases, negative emission may be gained in the long-run.

The Nature of Natural Gas

NATURAL GAS is a fossil fuel naturally trapped under layers of rock formations deep beneath the earth's surface, and it can be extracted in various ways, as well as naturally coming out of the ground. Therefore, the first discovery of natural gas goes back thousands of years when it accidentally slipped through the earth's surface due to natural seismic movements or human-made excavations.

Natural gas was formed millions of years ago, according to the prevalent theory, it is formed by the decomposition of plants, animals and microorganisms (i.e. thermogenic process) buried in sedimentary rock layers. Compression generated below the earth's crust, and high temperature led to the production of methane (CH_4) (a.k.a. thermogenic methane) as the primary component of natural gas[1]. It has a higher energy content of 55 MJ/kg compared to e.g., heavy fuel oil's energy content of 41.9 MJ/kg (oil product)[2].

As a naturally occurring hydrocarbon, natural gas is a mixture of multiple substances in which methane corresponds to a minimum 75% of its content. In addition to methane content, *ethane, propane, butane, nitrogen, carbon dioxide and traces of some other elements* may compose none to 10% of natural gas (Liu et al., 2020). Therefore, natural gas is classified in two significant grades at the extraction: (1) Wet gas (i.e. natural gas liquids – NGLs) refers to natural gas composed of methane and other substances with the methane concentration of 75-85%. (2) Dry gas is the 'clean' form of natural gas, so that, methane concentration raises over 85%. In both cases, a purification process is needed to achieve much higher methane concentrations. Wet gas or NGLs are usually consumed for household use (heating, cooking) or processed by the petrochemical industry to manufacture plastics and other organic chemicals. On the other hand, dry natural gas is used as fuel for vehicles or burned to generate electricity. Compressed and cooled (dry) natural gas can be stored and transported in liquid form called liquified natural gas (LNG). LNG is cryogenic

in nature and can be formed at the temperature of -162°C, allowing it to shrink up to 600x its volume in the gaseous state.

Natural Gas Production

Conventional (dry) natural gas is found associated with crude oil (associated gas) and naturally comes with crude oil drilling and extraction operations. In some instances, dry natural gas can be extracted a high concentration without crude oil mixture or with minimal oil traces, called non-associated gas. **Unconventional** gas refers to other formations of natural gas such as shale gas or coalbed gas, and it is mainly extracted by using hydraulic fracking in today's natural gas industry (Middleton et al., 2017).

The world natural gas production is led by ten major oil and gas[3] companies:

Gazprom	*BP*	*ConocoPhillips*
ExxonMobil	*Chevron*	*Eni*
China National Petroleum	*Total*	
Royal Dutch Shell	*Equinor*	

Although these firms account for the gas production, Qatargas is apparently the major liquified natural gas (LNG) exporting company in the world. According to the latest data released by Energy Information Agency (EIA) of the U.S., the global natural gas reserve is around 7,177 trillion cubic feet which is significantly higher than crude oil reserve of 9.9 trillion cubic feet[4].

Three countries lead global natural gas production: the U.S., Russia and Iran account for 46% of the world gas production (Fig. 1.1). The vast majority of production is consumed in the domestic markets. According to 2019 statistics, the U.S. produced over 950 billion cubic meters following steady increasing capacity since 2006 (Fig. 1.2).

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Russia's production volume has gained an expansion in the last three years but stands behind the U.S. production yet. The shale gas revolution has lifted the U.S. market to the top by 2011, and the U.S. producers continuously invest in the capacity to retain the leadership of the global market.

Domestic consumption of natural gas in the U.S. market has gradually scaled up due to growing population (while Russia's population is stationary or even declining for many years), coal-to-natural gas conversion in the electricity market as well as industrial consumption for the production of fertilizers, chemicals and pure hydrogen. Especially wet gas is a feasible source of Ethane which extracted from NGLs by a de-ethanization process, and later, Ethane is converted into Ethylene as the raw material of all plastics (Saito & Sekine, 2020; see *side note*).

Ethane is extracted from wet gas and converted to Ethylene for production of plastic material (below figure).

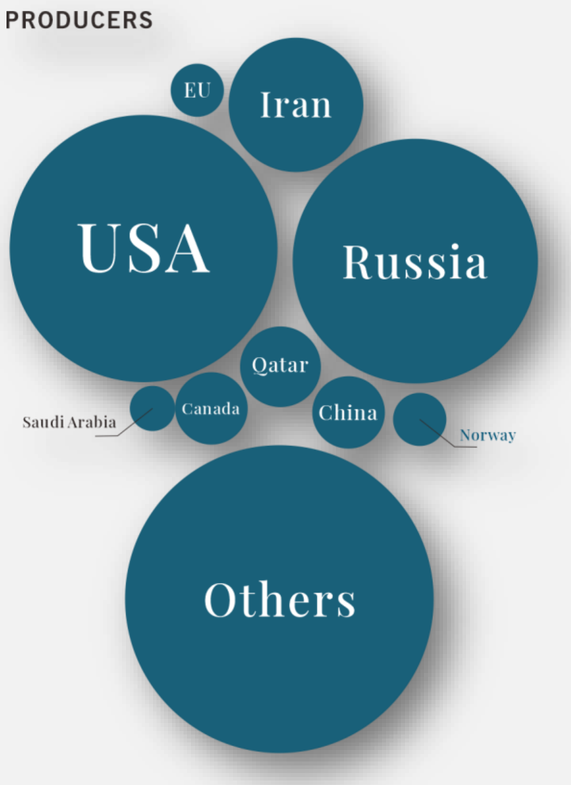
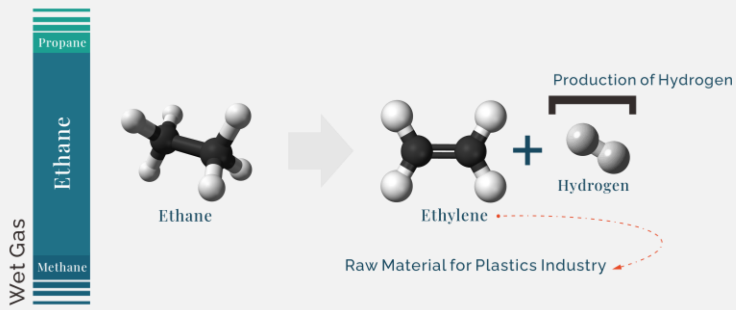


Fig. 1.1. Global natural gas production by volume.
Source: BP Statistical Review of World Energy 2020.



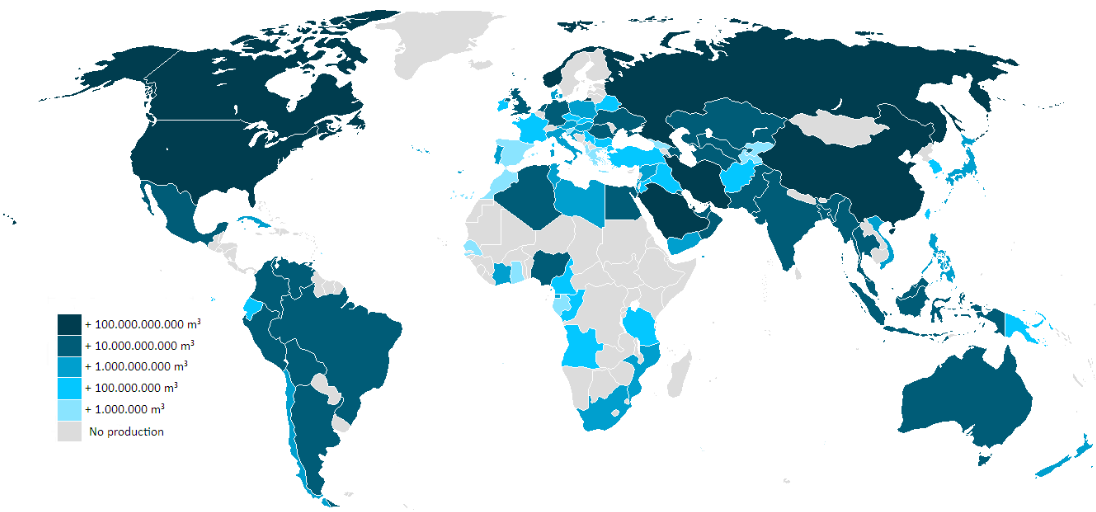


Fig. 1.2. Global natural gas production by volume.
Source: Natural Gas Production of Countries by CIA World Factbook.

Natural gas is transported through pipelines, tank trucks and LNG carrying ships (i.e. LNG carrier). For transportation, the temperature of natural gas is reduced in addition to the pressurization process to convert and store in liquid form (i.e. LNG).

Pipelines are still the major mode of transporting natural gas. However, the majority of LNG exports are transported by LNG carriers, and the LNG shipping is a growing segment in the maritime industry.

Qatar is the leading LNG exporting country with operations mainly governed by the state-owned enterprise, Qatargas (Fig. 1.3). Australia (particularly West Australia) exports almost similar amount of LNG delivered to Asian destinations broadly. The U.S. has developed an enormous LNG export capacity in recent years, and it is steadily stepping up the capacity.

LNG exports are mainly delivered to four Asian countries, namely Japan, China, South Korea and India (Fig. 1.4). Import volume of Japan has increased at avg. 10% in the last decade while South Korea gained limited growth, even declining periods, due to energy source shifts from natural gas to nuclear or coal power in electricity generation. Eventually, the second biggest importer of LNG, S. Korea, lost its position to China, which has grown more than two-fold in the last three years period.

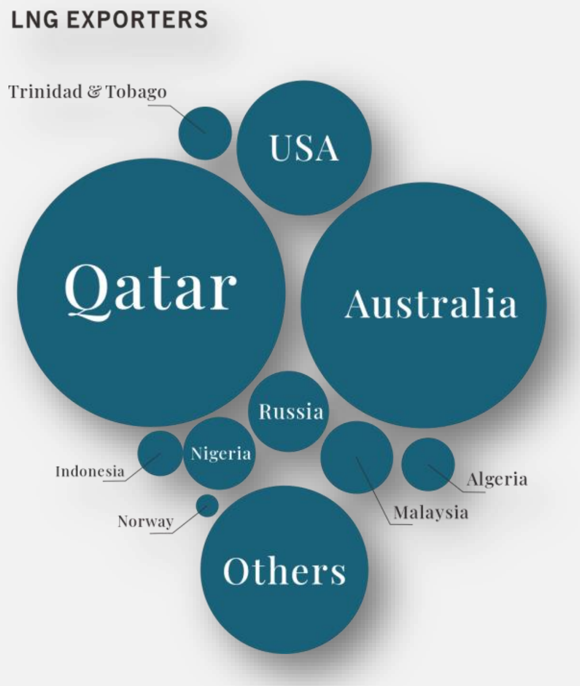


Fig. 1.3. Global LNG exporting countries by volume.
Source: BP Statistical Review of World Energy 2020.

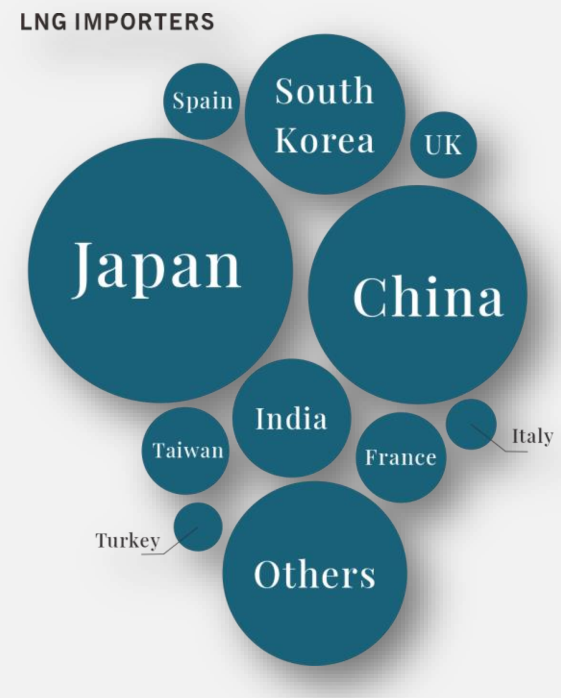


Fig. 1.4. Global LNG importing countries by volume.
Source: BP Statistical Review of World Energy 2020.

The urbanization of China and the demand for a cleaner source of energy restructure the energy use favoring alternative energy resources. In recent years, China transforms its energy generation mix weighting more on the natural gas (both household and electricity generation) in addition to wind and solar power.

A similar trend is observed in India for almost the same reasons. Both China and India traditionally have a coal-intensive energy mix in power generation, and environmental concerns incentivize the use of LNG as a step forward to better air quality in urban areas.

There are established LNG trading routes from Qatar to India (nearest) and North-Eastern Asia. Accordingly, LNG shipping volume in these routes is expected to grow mainly in the Indian market (Fig. 1.5).

Energy transition of India will boost the LNG shipping in the region. India's LNG import volume has increased over 10% since 2008, much larger volumes are expected in the near future.

Fig. 1.5. LNG trade routes (Qatar's exports).
Source: BP Statistical Review of World Energy 2020.

The second-biggest LNG trading cluster is grounded with the Australian export market. With the additional capacity from Malaysia, these two suppliers account for a massive volume to Japan, China and South Korea. The vast majority of Australian LNG exports are shipped from Western Australia ports (Fig. 1.6).

Western Australia is also a hub for the nation's iron ore and coal exports. Iron Ore exports from Western Australia is over 90% of entire Australian iron ore export volume. In this regard, Western Australia is a major port of call for very large Capesize dry bulkers carrying iron ore and coal parcels. In line with the LNG bunker development, some carriers shift to LNG fueled dry bulk carriers operating in Western Australia to China and Japan routes. Blessing of the big trio - natural gas, iron ore and coal in the region – has created a fruitful synergy for cleaner maritime transport[5].

Fig. 1.6. LNG trade routes (Australian & Malaysian exports).
Source: BP Statistical Review of World Energy 2020.

The emergence of Spot LNG Market

In recent years, the LNG market has gone through a transformation in its market structure. LNG has been sold and transported for wholesale contracts stretching over five years of supply security, and accordingly, LNG has been typically priced for wholesale (larger) volumes. An example would be the long-standing Japan LNG import market. Japan imports LNG from mainly Middle East suppliers for decades, and long-term contracts for consecutive delivery have been fixed during years in addition to spot LNG contracts[6].

On the other hand, spot trading of LNG is a relatively new market. In the last few years, there is a growing spot LNG sales volume with the development of new uses of LNG as well as new regions intending to use LNG. Japan/Korea Marker (Platts) – JKM, National Balancing Point (UK, ICE Futures Europe) – NBP and Title Transfer Facility (Netherlands, ICE-Endex Exchange) – TTF are some indicative pricing schemes or indices to represent spot LNG market in Asia and Europe market. Henry Hub (HH) natural gas prices of the U.S. is used as a benchmark for the North American market while HH prices are set for natural gas (gaseous form) but not liquified form. In this regard, spot LNG prices for North American market are priced on 2.25-3.50$ margin plus 115% HH basis structure in which 15% refers to the cost of procuring feedstock gas including liquefaction process (Fig. 1.7).

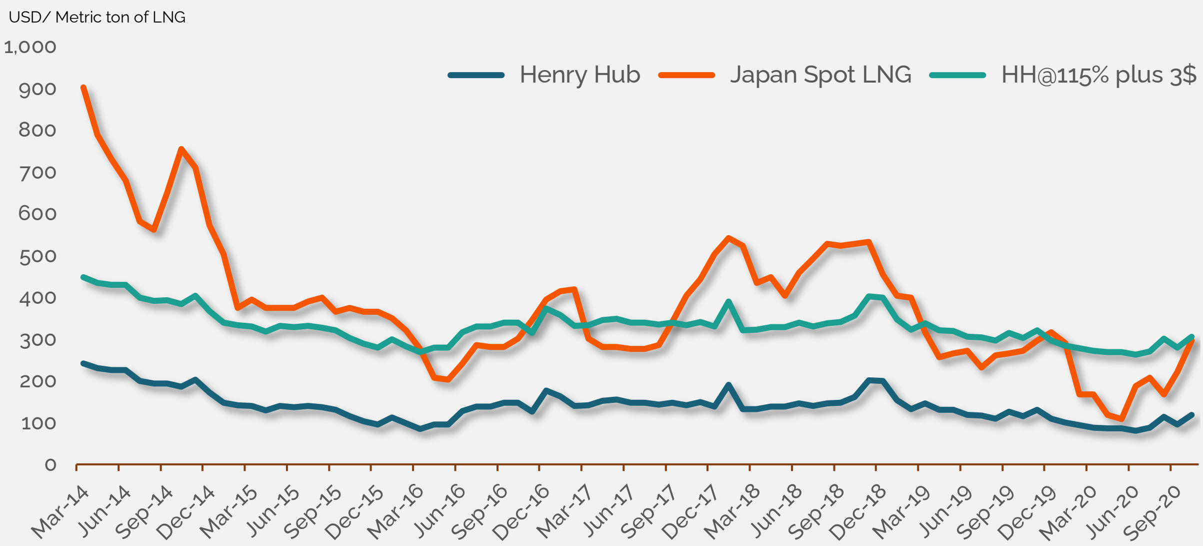


Fig. 1.7. LNG prices; Henry Hub, Japan spot LNG and Henry Hub at 15% plus 3$ margin
(USD per metric ton of LNG; 1 metric ton = 49.6 MMBtu).
Source: METI Japan & EIA US; recreated by metric conversions.

Energy Market Company (EMC) provided an alternative pricing benchmark of Singapore called Sling index - short for SGX LNG Index Group – till the end of 2019. However, Sling did not achieve to be a benchmark in competition with other pricing agencies (e.g. JKM)[7]. Singapore LNG (SLNG) 's aspiration for being a regional hub is backed by significant physical storage capacity building.

Commoditization of LNG

As the liquidity of spot LNG market evolves, the commoditization of LNG has gained market traction, leading to the formation of multiple LNG futures contracts (a.k.a. LNG derivatives) such as ICE JKM, ICE NBP, ICE TTF, ICE Gulf Coast Marker, among others. As of December 2020, the liquidity volume of LNG futures stretches over one month to calendar year maturities.

LNG Prices indexed to Oil Prices

Long-term LNG contracts are still the majority of the market, and these contracts are particularly linked to oil prices through a pricing scheme called oil indexation[8]. Due to the substitute effect, LNG prices are expected to stay lower than oil prices, and that is mostly the situation for decades. Developments in the commoditization of LNG (spot LNG) may cause a slight deviation from the current market mechanism. However, LNG is anticipated a competing commodity, and the oil prices will probably preserve its role as a benchmark.

LNG Marine Bunker Market

LNG use as a marine fuel is indicated to be a leading transition fuel in the shipping industry due to various benefits (See next part for more details) (Thomson et al., 2015; Sames et al., 2011 with GL and MAN B&W; among others). Considering multiple potential pathways to achieve 'net zero-emission', LNG stands as a viable and operationally feasible transition to future solutions (e.g. hydrogen fuel).

On the other hand, LNG bunker's price is an outstanding question since it is less known to the industry. In addition to that, spot LNG sales and commoditization of LNG are a relatively new phenomenon, and the market of LNG is a recent development. In line with the growth of spot LNG market, the transparency and visibility of LNG sales and prices improve. As mentioned earlier, such an evolution of the market also increases the volume of derivatives for future sales.

Generating Proxy LNG Bunker Prices

In this regard, the approximation of LNG bunker prices is performed by conversion to the energy content of IFO380 grade marine fuel plus liquefaction and delivery cost on average[9]. In other words, LNG bunker prices are levelized for the same energy content of IFO380 for direct comparability. Following approximation is executed (US$ basis):

Step 1. Conversion from MMBtu to Gigajoule (GJ); 1 MMBTU = 1.05 GJ

Step 2. Liquefaction and Delivery Cost; $3.5 per MMBtu[10]

Step 3. IFO380 levelization at 40.6 GJ per metric ton

Step 4. Conversion from Gross Calorific Value to Net Calorific Value at 10% increment[11].

Step 5. LNG bunker prices in West Australia (AUS) are assessed at US$1 per MMBtu below the Japan-Korea prices[12].

The price assessments for LNG marine bunker are illustrated in Table 1.1. Based on the approximation methodology mentioned above, natural gas prices are converted to LNG bunker prices of corresponding regions (e.g. Henry Hub refers to the Gulf of Mexico; TTF refers to the Netherlands and other ports in the region).

Table 1.1. LNG Marine Bunker Price Assessments (USD/metric ton).

	Henry Hub	*Japan-Korea*	*NBP*	*TTF*	*AUS*
2018Q1	301	599	508	499	502
2018Q2	290	570	513	517	476
2018Q3	294	659	602	574	557
2018Q4	335	626	555	541	526
2019Q1	293	467	442	438	382
2019Q2	277	387	339	353	309
2019Q3	268	377	367	367	300
2019Q4	269	427	405	400	345
2020Q1	246	326	297	302	254
2020Q2	236	256	250	245	190
2020Q3	250	326	330	325	254
2020Q4	275	531	370	400	441

(Henry Hub, U.S.; Japan-Korea; NBP, U.K.; TTF, Netherlands; AUS, West Australia)

Source: Ocean Dynamex Market Intelligence, EIA, METI, Galp Energia.

Henry Hub prices are significantly lower than most LNG supplying regions, and it is even lower than traditional high Sulphur fuel oil (IFO380) in some periods (Fig. 1.8). Other LNG pricing schemes are also competitive against very low Sulphur fuel oil (VLSFO), particularly marine gas oil (MGO)[13].

Most marine bunker prices released in public outlets represent the commodity prices, excluding the delivery cost (a.k.a. barging cost). The delivery cost can be in the range of $7-10 per metric tonne in busy ports like Singapore with the impact of economy of scale while it can be over $20 per metric tonne in secondary ports and/or for smaller parcels (Panamax Bulker vs Handysize). Accordingly, the gap between LNG bunker prices and the traditional fuels broadens considering other benefits such as environmental gains, technical gains such as no sludge, excellent combustion, much less maintenance of parts (pistons, cylinders, valves), no need for fuel heating, among others. The fuel system will be much cleaner and less wear-out.

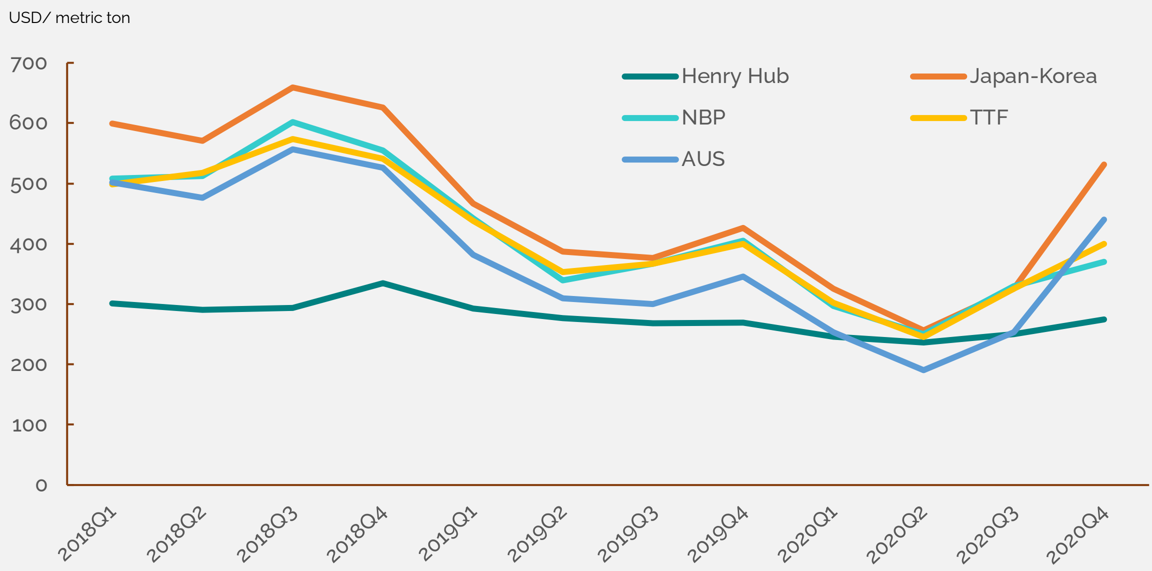


Fig. 1.8. LNG marine bunker price assessments based on a natural gas index (Henry Hub, U.S.; Japan-Korea; NBP, U.K.; TTF, Netherlands; AUS, West Australia) **plus liquefaction, storage and F.O.B. delivery estimations** (calorific value at IFO380 equivalent)**.**
Source: Ocean Dynamex Market Intelligence, EIA, METI, Galp Energia.

In the Wake of Climate Crisis

LNG has several advantages comparing to traditional energy resources and fuels. Higher energy content, lesser air pollutant emission and lower prices are some major distinct merits of LNG. With the rising concerns on environmental decay and climate change, LNG stands on a double-edged sword. LNG is a lot cleaner than most traditional fuels, while methane emission is an outstanding challenge. Fugitive methane emission through the supply-chain beginning from production to consumption is previously recorded as a contrasting factor. On the other hand, there are various measures and technologies to reduce methane emissions, and it is expected to be negligible in the near future. Emission quality, methane slip and other issues will be discussed in the next part of this report.

Twofer with Biogas and Syngas Revolution

Rise of Biomethane

A significant amount of global methane emission is led by agriculture, manure and enteric fermentation (cattle farms). This group of methane emission is around 40% of global methane emission. Therefore, meat and agricultural consumption is the far major source of global methane emission. Another major methane emitter is the landfills of solid waste (as well as liquid household waste). In addition, natural methane emission exists for ages such as wetlands (See Part 2 for more details).

There are also natural methane sinks which negate such impact. In the last century, mining activities, fossil fuel production and consumption as well as agricultural activities, have lifted the bar rapidly causing an imbalance between emissions and sinks. Rising global population demands more food and more energy, which in turn, inflates the methane emission volume.

There are two innovative solutions to transform some of these emission channels for a good reason: Net zero emission, and in certain pollutants, negative emission. In recent years, multiple projects and facilities have established systems collecting methane emission from agriculture, solid waste and other organic substances and channeling into **'biogas' (biomethane)** production. This ecosystem does not only produce less carbon dioxide emitting biogas grades but also reduces methane emission from other sources. In a similar vein, **substitute LNG or synthetic LNG (SNG, also syngas)** produces methane from lignite coal which is usually consumed in power plants for electricity generation or by renewable energy through electrolysis mechanism. By converting lignite coal with methanization, much cleaner energy source is produced which can be used in power plants instead of pure lignite coal which causes massive air pollution. On the other hand, syngas can be produced by much cleaner process by utilizing an electrolysis mechanism which does not only eliminate the air pollution, but much importantly, it captures CO_2 and converts it to syngas in the form of H_2 or, after methanization, CH_4.

Biogas is a mixture of methane, CO_2 and traces of other gases produced by anaerobic digestion of organic matter (easily degraded biomass, e.g. sugars, fatty acids, proteins) in an oxygen-free environment (Molino et al., 2013; Ryckebosch et al., 2011) (Fig. 1.9). Biogas' content is defined by the process used in the production such as landfill gas recovery system, biodigester system or wastewater treatment plant.

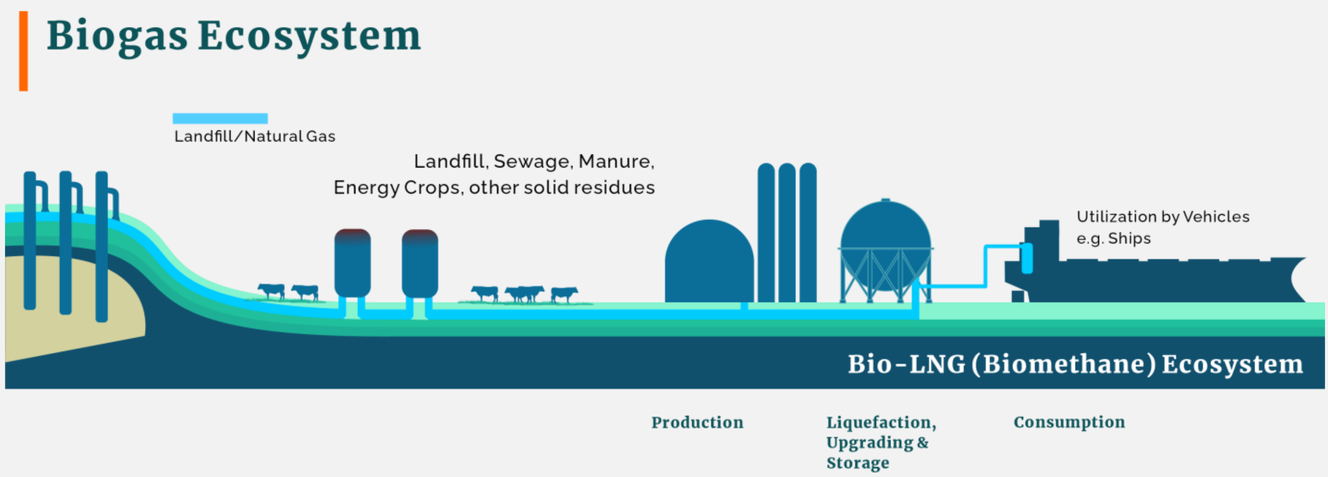


Fig. 1.9. Biogas Production by using landfill, sewage, manure and other solid waste.

Biogas consists of methane and CO_2 where the methane content can be 50-70%. Biogas can be for household and power generation without a preprocessing. However, it needs to be purified for **biomethane** (bio-LNG) stream. Through the upgrading process, biomethane can be produced at 90% methane content.

Biomethane has a lower heating value (LHV) of slightly over 20 MJ/kg before upgrading, and purification process and new technologies improve this further[14]. After upgrading, its energy content is improved to the level of natural gas (45-50 MJ/kg). With this, biomethane is a direct substitute of traditional natural gas and compatible for vehicles and ships. According to various studies, biofuel can dramatically reduce CO_2 emissions at the level of 60-80% (Bouman et al. 2017). Therefore, biofuel and biogas in particular, have a great potential of improving the environmental footprint led by air pollutants.

Synthetic LNG Production with Renewable Energy

One of the production methods of syngas is through a thermochemical gasification process by heating biomass to high temperatures (>700°C) without combustion. The intermediate product is a synthesis gas consisting of methane, hydrogen, carbon monoxide and carbon dioxide. In addition to the lignite coal, other lignocellulosic biomass including energy crops and residues from forestry and agriculture can also be used.

However, there is an alternative method of syngas production with additional environmental benefits which utilizes renewable energy resources such as solar or wind power to convert carbon dioxide to hydrogen and later synthetic methane. The reliance on fossil fuel has led to gradually increasing concentration of atmospheric CO_2, which in turn, has contributed to global warming. The conversion of CO_2 into synthetic fuels is a promising solution to reduce carbon dioxide emissions and generate useful energy rich fuels.

The mechanism of synthetic methane by renewable energy works in two stages (Fig. 1.10): (1) First, carbon dioxide from capturing facility or exhaust gas (e.g. power plant flue gas) is converted to carbon monoxide, hydrogen and oxygen by introducing water and running an electrolysis process with renewable power generators. (2) Second, carbon monoxide (and/or carbon dioxide as in the first stage) and hydrogen are converted to methane and water by a chemical process called 'the Sabatier reaction'. During the second stage, a metal catalyst (fixed-bed reactors) is introduced to execute the chemical reaction. This process is also known as **catalytic hydrogenation or methanation.**

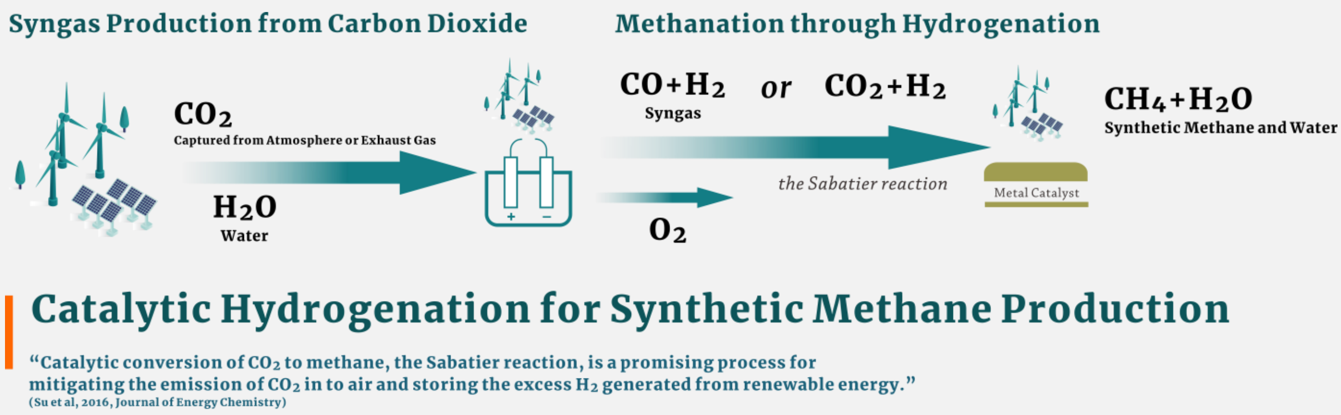


Fig. 1.10. Syngas and Synthetic Methane Production by using renewable energy and exhaust gas.
Source: Su et al. (2016), Miguel et al. (2015).

The hydrogenation is not a new idea, and it has been developed by Paul Sabatier (1854-1941, Nobel Prize in Chemistry) a century ago (Rönsch et al., 2016). The process was not feasible for mass production due to various limitations and lack of efficiency (energy used to execute the reaction). In recent years, the synthetic methane production has developed significantly with the presence of much efficient use of renewable energy production and improvements in the mechanism. There are multiple industrial solutions offered by private entrepreneurs and engineering firms.

Another critical component of the mechanism is the carbon capture from existing exhaust gas outlets or directly from air. The direct CO_2 capture from ambient air is still a developing methodology with various proposals (e.g. Sen et al., 2020; Zhu et al., 2020; among others). However, utilizing exhaust gas (flue gas) is an established method offered by industrial electrolysis companies.

In the next few decades, the Power-to-Gas (PtG) process will play a significant role in the future energy system. By utilizing above mentioned concept, renewable electric energy will be stored in the form of methane via electrolysis and subsequent methanation (Götz et al., 2016).

Considering that the storage and transport of hydrogen requires much lower temperatures and larger volume, methanation also improves the efficiency of the fuel supply-chain.

Conclusion

The rise of natural gas and variants such as biogas and syngas offer a new era to the energy ecosystem of the world. By blending with renewable energy resources, natural gas can be produced from already methane emitting sources (biogas), or it can be used as a medium for storing renewable energy and consuming in the form of synthetic methane.

The global reserve of the natural gas is significantly more than crude oil, and it is diversified in multiple continents and countries which ensures easier access to the energy resource. In recent years, the commoditization of LNG has developed gradually with more visibility, transparency and efficient pricing. In contrast to early 2010s, the LNG market has more established structure supported by various price benchmarks and ever-increasing volume of LNG trading.

In brief, the market for LNG as a commodity explicitly supports the LNG marine bunker market and new projects to facilitate its implementation and broader use particularly in larger cargo ships.

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[7] https://ca.reuters.com/article/idUSKCN1UP052
[8] https://timera-energy.com/oil-price-plunge-and-the-lng-market/
[9] Our approach will be an adaptation of the method proposed by FortisBC, a Canadian LNG supplier. For more details: https://shipandbunker.com/news/world/772235-ship-bunker-fortisbc-begin-first-published-posting-of-lng-bunker-prices

[10] Steuer (2019) presents an estimation of liquefaction and LNG shipping to Japan-Korea from West Canada in an Oxford University report. The estimated prices are C$3.5 for liquefaction and C$1 for shipping per MMBtu. Similarly, LNG shipping between Australia-Japan is estimated around $1 per MMBtu. These cost items can change due to the region, the technology and capacity utilization of facility. Most LNG bunker barges would not sail over 30 nautical miles comparing to a transatlantic voyage (Canada-Japan) over 4,000 nautical miles. Therefore, LNG bunker delivery should be much less than such estimations. However, LNG bunkering as a new business channel will require an initial capital investment for equipment, bunker barges and shore facility. We still implement C$1 (US$0.78) per MMBtu for delivery cost as a worst-case scenario. Finally, the total cost of C$4.5 (US$3.5) has been applied in our price assessment.

[11] The calorific value is reduced by various reasons. Conversion ratio is not clear and depends on multiple factors. 9% reduction in calorific value would require 10% increment on prices to retain the same amount of power generation. Our assumption will be 10% price increment for this study.

[12] See footnote 6.

[13] Marine bunker prices can be quite different in e.g. Europe and Asia. Readers can compare their corresponding regions from publicly available resources. Interpretations are for global averages in this study.

[14] https://f3centre.se/en/fact-sheets/biogas-biomethane-sng/

Part 2

Environmental Gain with LNG Fuel

Emission Inventory Assessment

Summary

- LNG is an abundant energy resource with various technical and environmental advantages. LNG is carried by ships and has been consumed around the world for decades. Its infrastructure as a commodity is well established, and the industry is well developed.
- LNG has a higher energy content compared to HFO (1.2×), Methanol (2.4×) and Ammonia (2.6×), so that, less fuel is consumed with LNG in mass amount.
- Among many potential options, LNG is the only alternative combining higher energy content, lower fuel price, lower toxicity, lower environmental footprint and reasonable volume factor.
- LNG fuel reduces particulate matter, black carbon and Sulphur content; it reduces CO_2 over 20% and NOx over 90%.
- Methane emission is a bigger problem than the public perception. There are various sources of methane emissions that people cannot control yet such as sporadic events (wild fire) or food industry (cattle farming).
- An emission inventory simulation has been performed for Capesize dry bulk carrier, VLCC oil tanker and Post-Panamax containership in major trading routes to illustrates the emission content.
- By using High-Pressure Dual Fuel Engines, the fugitive methane emission from LNG fuel is almost comparable to VLSFO. The difference may arise at low speed (e.g. ports) which can easily be eliminated by switching to 100% pilot fuel (e.g. MGO) during low-speed operations.

Green Shipping in a Nutshell

BY THE INCREASING AWARENESS and demand for Green Shipping, the maritime industry has begun a long-lasting journey to explore, develop and implement cleaner fuels and alternative energy systems. It is estimated that shipping emissions account for 3% of the world's air emissions, and this number will hit 6% by 2020 and 15% by 2050 (Helfre, Boot, 2013).

Anthropogenic emission could alter the chemical composition of air. Consequently, those harmful air emissions that are produced during ship cruising or even hoteling in a port could be easily spread to the land area under the action of sea breeze, thus aggravating air pollution issues and cause human health problems. For example, about 95% of particulate matter (PM) generated from ship engine's combustion are less than 2.5μ in diameter, which is particularly detrimental to respiratory system. Furthermore, other pollutants like CH_4 and CO_2 could impose great environmental issues and worsen the ecosystem. Therefore, various solutions are being discussed by stakeholders.

Some significant air pollutants from ships include carbon dioxide (CO_2), Sulphur oxide (SO_X), nitrogen oxide (NO_X), particulate matters (PM), carbon monoxide (CO) and methane (CH_4).

In these circumstances, **the Decarbonization of Shipping** is set as an ultimate objective of the maritime industry by IMO and other key industry representatives under the broader concept of **Green Shipping**. Ship emissions lie at the heart of the problem as the major driver of the carbon footprint led by the shipping operations. Potential measures to decarbonize the seaborne transport include the use of cleaner fuels, the use of exhaust gas filtering devices (i.e. scrubbers), improvements in the efficiency of propulsion system and ship design, embedding renewable energy resources, discovering and recovering the energy loss, improvements in the shipping and port operations, among others. For example, on the efficiency management aspect, the Energy Efficiency Design Index (EEDI) is mandatory for all new ships as of July 2011 with the adoption of amendments to MARPOL Annex VI (MEPC 62). A Ship

Energy Efficiency Management Plan (SEEMP) must be prepared by carriers to manage and improve visibility into the efficient use of energy resources on board[1].

IMO embraces the implementation of counter-measures to achieve Greenhouse Gas (GHG) emission targets. The initial GHG strategy aims at a reduction in carbon intensity of international shipping by at least 40% by 2030, encouraging efforts towards 70% by 2050, compared to 2008 levels. In addition to that, total annual GHG emissions from the global shipping operations should be reduced by at least 50% by 2050 compared to the figures of 2008[2]. The Sulphur mandate has been adopted by January 2020 to reduce SO_X emissions to the level of 0.50% m/m, and this regulation has ignited a chain reaction in the industry regarding the fuel choice, power systems and feasibility of alternative solutions in the new normal. The fuel cost of shipping has raised with the requirements of the Sulphur Cap which in turn created a cost range of feasibility where more solutions can intervene and flourish. Another significant result of this regulation and subsequent recommendations of IMO is that the maritime industry needs to expand its strategic horizon up to 30-40 years down the road for managing its operations proactively and being prepared on the green shipping agenda.

The average economic lifetime of a cargo ship is around 30 years for the majority of the world shipping fleet in the light of vast historical records[3]. In other words, the orderbook of new building ships in the next decade will need to be compliant with the strategic horizon stretching to 2050. The shipping companies are apparently not accustomed to such long-term planning, and it is quite unique experience for the industry. With the extended horizon, the maritime industry focuses on the long-term solutions which can survive through upcoming regulations of the emission control.

"Achieving net-zero emissions means our economy either emits no greenhouse gas emissions or offsets its emissions, for example, through actions such as tree planting or employing technologies that can capture carbon before it is released into the air." [3]

Net-Zero Emissions by 2050, Government of Canada

The most prominent and rapid applications of Green Shipping is the choice of cleaner fuel or installing an exhaust gas cleaning equipment. The latter solution, also called scrubbers, is an additional mechanism installed as a part of ship exhaust gas system. While several statistics have been reported, approximately 20-30% of cargo ships in different segments are estimated to be retrofitted or will be installed with an exhaust cleaning equipment by 2021. Scrubbers can be a solution particularly for cargo ships in a certain age group which will operate a significant period to pay off the carriers' capital investment. However, scrubber systems are not error-free, and the disposal of cleaning sludge is an ongoing debate. In addition, scrubbers are not a long-term solution yet considering the ambitions of IMO and other decision makers.

With the fact that a long-term solution for net zero or zero emissions is still an emerging agenda, a total lifecycle solution including the propulsion system, fuel

Biomethane and synthetic methane have potential of achieving net zero and negative emission (certain pollutants) in the well-to-tank, total life cycle assessment.

characteristics and the fuel supply-chain must be developed and implemented (lifecycle assessment will be discussed in the next part). Therefore, IMO and many countries have adopted policies for net zero emission legislation by 2050. The Government of Canada and the European Union are some early examples with prescriptive policies leading the industries for finding and valuing solid measures to achieve the net zero emission target[4,5].

Modern ships are equipped with combustion (diesel) engines generating a high level of propulsion power, and the replacement of this amount of power generation with other forms of energy systems is not efficient and powerful enough to run the current volume of shipping operations (particularly long-distance shipping). In this regard, the fuel conversion with potentially net zero emission features will be the first major revolution for the industry. Among various proposals, Liquified Natural Gas (LNG) has properties combining both power requirements and environmental targets. In addition to the conventional LNG, biogas and synthetic methane developments draw a much plausible future with net zero and negative emission (certain pollutants) prospects. The prospect of the evolution of LNG (combustion) ecosystem to LNG fuel cell is another promising future in securing the environmental objectives by 2050.

In this part, we will investigate the LNG as a marine fuel, air pollution problem, regulatory requirements and finally emission inventories for sample ships and routes.

Emergence of LNG as a Marine Fuel

In the circumstances of a challenging fuel choice problem, LNG is a prominent alternative till a more viable option is discovered. LNG transportation infrastructure and relevant facilities have been operating for decades, and there is an established know-how with the LNG transport and consumption. In recent years, major shipping hubs such as Singapore, Shanghai, Rotterdam, Houston (among others) have established LNG bunkering facilities. Simultaneously, spot LNG market develops gradually which also improves the development of LNG bunkering services.

Among other alternatives, LNG stands out in three essential features:

(1) LNG is one of the cleanest' viable' fuels in the market. Black carbon, PM and Sulphur emissions are at negligible level. CO_2 emission is reduced 20-30% (EPA U.S., 2020; IMO GHG Study, 2020). Although methane emission is frequently pointed out, the CO_2 equivalent of methane slip is extremely low (GWP_{25} or GWP_{100}[6]). By utilizing high-pressure diesel engines, the methane slip from combustion is reduced to extremely low levels (Lighthouse, 2020). Due to its purity as a material (compared to fuel oil), the engine room and equipment are

exposed to a clean fuel which improves the lifetime of the entire engine room facility and reduces the workload of engineers.

(2) LNG is much cheaper than most fuels (See Part 1).

(3) LNG has a naturally higher calorific value (energy content, MJ/kg) compared to conventional marine fuels, methanol and liquid ammonia. Each carbon atom is saturated with four hydrogen bonds in a methane molecule. This chemical structure allows excellent combustion compared to heavier fuels. Also, it is not toxic and corrosive as liquid ammonia[7].

In Table 2.1, various fuel choices and coal as reference are listed with their calorific value (*MJ/kg*), density at the storage conditions and the volume of storage required to retain same energy content as the traditional heavy fuel oil (HFO). In two extremes, liquid ammonia and liquid hydrogen suffer from the volume expansion problem. For generating required power, these two fuels will occupy min. three-fold of the space for traditional fuels. Methanol also requires 2.5 times larger storage space on board. The energy content of Methanol is almost half of any traditional fuels in the market.

Table 2.1 Energy content of various fuels at Lower Heating Value (LHV) and the volume required to achieve same energy output as Heavy Fuel Oil (HFO).

	MJ/kg	Density (kg/m³)	Volume Comparison (approx.)
Liquid Ammonia (anhydrous ammonia)	18.8	600-650	3.3
Methanol	20	792	2.5
Coal	26	800-929	1.8
Heavy Fuel Oil (HFO)	39.4	990	1.0
Very Low Sulphur Fuel Oil (VLSFO)	42	940	1.0
Marine Diesel Oil (MDO)	42	890	1.0
Marine Gas Oil (MGO)	43	860	1.1
Liquified Petroleum Gas (LPG)	45.5	500-550	1.6
Liquified Natural Gas (LNG)	48.6	430-470	1.8
Liquid Hydrogen	120	71	4.6

Source: Compiled from various resources; approximations[8].

On the other hand, traditional marine fuels (HFO, VLSFO, MDO and MGO), LPG and LNG still ensure a balance of energy content and density (volume factor below 2.0), so that, the volumetric challenge is minimal and viable (particularly ships over 40k DWT). The density of Hydrogen (capacity of storage) can be improved with higher compression techniques at 300-700 bar while density gain is minimal at around 10-30 kg/m^3. The trade-off between density gain and toleration of higher pressure is a challenging point. Kawasaki Heavy Industries has launched the world's first ocean-going liquid hydrogen carrier, *Hydrogen Frontier*, and its specifications released in public outlets indicate that the low pressure and regular density level have been targeted[9]. In these circumstances, hydrogen fuel requires significantly larger storage space (5x) for regular cargo ships. Although hydrogen fuel can be viable for small boats and watercrafts, cargo ships sailing days and weeks would need extremely large fuel tanks, additional insulation and yet willingness to pay twice of any traditional fuel with the current technology of hydrogen production (Table 2.2).

Commodity prices may differ according to the region, parcel size and timing, but Table 2.2 illustrates average prices for compressed liquid fuels in December 2020 based on multiple resources. LNG is significantly cheaper than most fuels (including MGO and in most times VLSFO). Currently, the cheapest LNG fuel can be provided in North American ports due to low natural gas prices (Henry Hub).

Table 2.2 Prices for compressed tank fuels.

	Price [a] USD/mton
Liquid Ammonia	$490
Liquified Petroleum Gas (LPG)	$450 ($400-$600)
Liquified Natural Gas (LNG)	$350-$380
Liquid Hydrogen	$1000-$1500

Source: Compiled from various resources, EIA, METI, Argus Media, GlobalPetrolPrices.com; approximations.
[a] As of December 2020, average or estimations.

Cleaner Engine Room, Safer Transport

One of the prominent advantages of LNG fuel is the fact that LNG is a sludge-free fuel. This feature of LNG brings a number of technical benefits including (but not limited to) reduced maintenance and part replacements (pistons, cylinders, valves, among others), removal of fuel heating process and corresponding equipment, cleaner fuel system and lesser wear-out in the system equipment (no corrosion, no particulate).

In addition to that, methane as a chemical substance is much pure and saturated fuel. It is a colorless, odorless[10], neither corrosive nor toxic but flammable gas. It is combustible if the volume concentration of natural gas is the range of 5-15% in air[11]. The difficulty of achieving combustion is an advantage in terms of safety, and it is resolved by using pilot fuel and other calibrations in dual fuel engines. Methane is water insoluble, and therefore, it quickly evaporates and disappears (no residue behind) even if there is a spill. In the history of LNG shipping since the 1960s, LNG ships completed over 35,000 voyages without a significant spill, loss of cargo, or environmental incident.

None of maritime related incidences (e.g. grounding) have ever caused containment failures or cargo spills. Due to strict containment rules (multiple walls) and insulation of roughly 2.5 meters between hull and tanks, LNG ships are known as one of the safest seagoing structures in the world.

Impact of Biomethane and Synthetic Methane Development

The penetration of biogas and synthetic methane into the LNG fuel ecosystem will improve the well-to-tank environmental performance significantly (See Part 3). Although the final product, methane, does not change much after upgrading process, the well-to-tank emission inventory plays a significant role in two ways. First, the recycling of methane emission from other sources such as landfill or manure negates the impact of fugitive methane emission at the final disposal (i.e. air emission). Second, the reuse of methane emission ensures the potential of net zero emission. The characteristics of biogas and syngas ecosystem will be discussed in Part 3.

In contrast to various merits of using LNG as fuel, the fugitive emission (methane slip) is criticized as an adverse effect. For a complete account of the environmental concerns about the LNG fuel, the air pollution phenomenon, methane emissions in general and recent regulations in the maritime industry has been reviewed in this part. In addition, an emission inventory assessment has been presented at the end of this part. The lifecycle analysis and supply-chain emissions will be evaluated in Part 3.

Air Pollution

Air pollution is the phenomenon arisen from anthropogenic (human-driven) and connatural (driven by other species or geology) processes. An air pollutant is classified as 'pollutant' due to its impact on the health conditions of human and other species. Such adverse impact can be observed through the direct exposure to poisonous gases or indirectly by chain reactions as in the greenhouse effect.

For example, carbon dioxide (CO_2) is a natural component of fresh air and essential for living creatures. On the other hand, the mixture of oxygen, carbon dioxide and nitrogen (among others) stand on a viable balance supporting the ecosystem of living creatures. An unusual rise of CO_2 concentration in air has certain side-effects, particularly the heat trapping property blocks the solar radiation from escaping back to space[12]. This property is traditionally found in agricultural greenhouse structures to retain heat and moisture; accordingly, the greenhouse effect is named after.

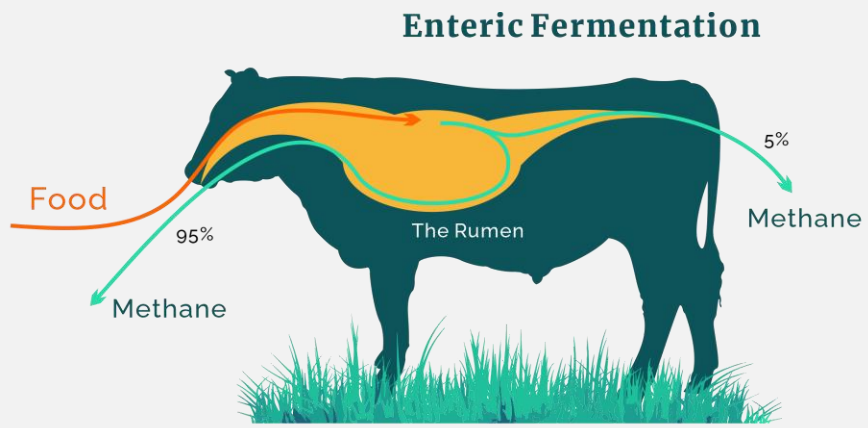
Anthropogenic sources of air pollution are well known to general public while the connatural sources of air pollution (or release of certain gaseous substances) are less reported in mass media. According to multiple scientific studies, some animals such as beavers contribute to the air pollution and greenhouse effect (Whitfield et al, 2015; Weyhenmeyer, 1999). Geologic emission is also a natural source of air pollution led by tectonic movements around the earth's crust (Ciotoli et al, 2020; Himmler et al, 2019; Etiope and Klusman, 2002). The discovery of natural gas seepage in rural areas is very common as tectonic shifts generate new gates for natural gas reserves. Furthermore, natural wetlands covering approx. 12.1 million km^2 area (roughly the size of Greenland) is one of major sources of methane emission estimated at 30% of global methane emission[13]. In this regard, methane emission is a natural and ongoing process in many distant valleys of the earth.

Methane emission is a natural and ongoing process in many distant valleys of the earth.

In balancing the connatural methane emission, there are channels that methane sinks back to the ground or converted to other substances by various chemical reactions. For example, methanotrophic bacteria that reside within soil use methane as a source of carbon in methane oxidation transforming methane to carbon dioxide and water (Heilig, 1994). According to the United Nations Framework Convention on Climate Change (UNFCC), methane would have 12-15 years of lifetime before sinking and resolving. Its greenhouse impact is estimated to be over 50 times more than carbon dioxide in 20 years period[14] (GWP_{20}).

Among anthropogenic sources of air pollution, there are many essential components that support and enable the modern life. Paddy rice fields are known to be responsible for roughly 20% of human driven methane emissions (Heilig, 1994). Livestock production (cattle farms, poultry farming) adds up another 20% due to enteric fermentation (ruminants) and animal waste (Fig. 2.1).

Another major source of emissions is the biomass burning, mainly bushfires and other types of forest fires. Indonesian deforestation for palm plantation[15] and Mexican sugarcane burning (Flores-Jimenez et al, 2019) are some examples of human driven wood fires leading inflated emission budget. Crop burning is a major environmental debate in Mexico, and it is performed across more than 90% of the country's entire crop area. Accordingly, methane emissions are also generated by sugarcane burning (ibid.) Savanna biome in South Africa faces a similar situation as well[16].



Over 20% of Global Methane Emission

"Livestock production is the largest anthropogenic source in the global methane budget, mostly from enteric fermentation of domestic ruminants." (Chang et al, 2019, Nature Communications)

Fig. 2.1 Ruminant husbandry and enteric fermentation account for over 20% of global anthropogenic methane emission, the largest source of methane emission.
Source: Chang et al, 2019; Hammond et al, 2016.

Recent bushfires in Australia released more than half of the nation's annual emission inventory[17]. Wildfires around the world (California, Australia, Siberian Russia, among others) are among the leading drivers of CO_2, CO and CH_4 (methane) emissions (Fig. 2.2).

Fig. 2.2 Bushfires in California, U.S, and Australia caused massive CO_2, CO and CH_4 emissions for weeks during 2019-2020 period.
Photo Credit: Pexel.

10-15% of global methane emission is generated by landfills.

Yet another principal source of methane emission is the anaerobic decomposition of organic waste in landfills[18]. 10-15% of global methane emission is generated by landfills (Kumar et al, 2004; Scharff and Jacobs, 2006), and landfills are the third largest source of anthropogenic methane in the United States. The United Nations and the European Union have adopted protocols to require quantification of methane emission from landfills (ibid.)

According to the Global Methane Initiative, an organization on the recovery and use of biomethane, the U.S., China, Mexico, Russia, Turkey, Indonesia, Canada, U.K., Brazil and India are top ten countries with the highest landfill methane emission[19], and therefore, these countries have great potential of biomethane production from landfill gas recovery (Fig. 2.3).

Landfill Gas Collection to Biomethane Process

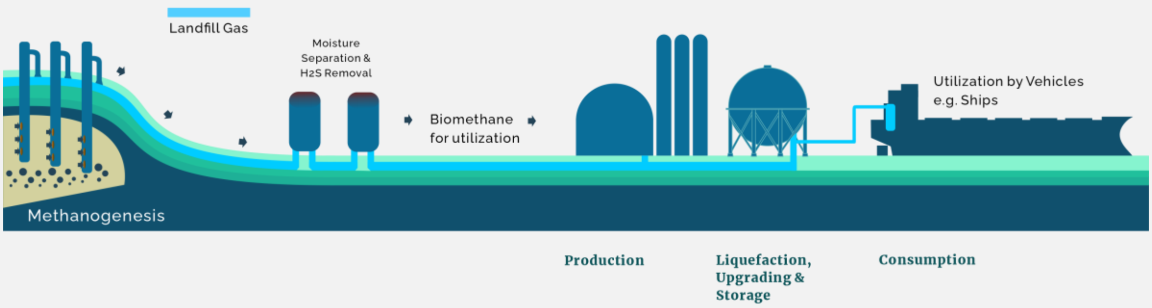


Fig. 2.3 Landfill gas collection, processing and biomethane production.

Biomethane produced from landfill gas can be utilized in power plants, industrial facilities as well as fueling vehicles including commercials ships. Technology Readiness Level (TRL) for biomethane utilization in ships is reported at highest degree, TRL 9, indicating that "actual system proven in operational environment"[20].

Air Pollution Control in the Maritime Industry

According to multiple estimations, the shipping industry (mainly ship and port operations) causes around 3% of global GHG emission (Smith et al., 2014, the Third IMO GHG Study). The aviation industry is estimated to be 2% of the global emission, and land transport (road and rail) accounts for 19%. Transportation in general produces roughly a quarter of global emission inventory, and it is a priority of national and international regulators to reduce emissions from transport vehicles. Major air pollutants from ships include carbon dioxide (CO_2), Sulphur oxide (SO_X), nitrogen oxide (NO_X), particulate matters (PM and black carbon), carbon monoxide (CO) and methane (CH_4). Among the ship emission inventory, CO_2 is over 98% of entire air pollution budget (Liu et al, 2020). Methane and non-methane volatile organic compounds (NMVOCs; benzene, xylene, alcohols) are less than 0.03% (3‱, per ten thousand).

Accordingly, the maritime industry attracts a great attention from environmental interest groups and major regulators such as the International Maritime Organization (IMO). IMO has implemented many regulations in its history to improve safety and security of shipping operations as well as marine environment protection. Solid waste management (garbage disposals, sludge disposals, noxious liquids) has been regulated decades ago, and it functions fairly under the limitations of control and monitoring. The International Convention for the Prevention of Pollution from Ships (a.k.a. MARPOL) first entered into force in 1983, and since then, new regulations have been developed and mandated gradually with the emergence and awareness on other environmental contents. Each type of disposal has been classified in an annex where the latest one, ANNEX VI, has been adopted in 2005 regarding the air pollution (Prevention of air pollution from ships). The Marine Environment Protection Committee (MEPC) of the IMO is responsible for the investigation, research and development of new regulations as well as revising previous directives. In addition, the regulatory function of the IMO, there is a significant coercive capacity through the system of port state control (PSC) mechanism which randomly inspects ships calling corresponding ports and forces ship operators to implement IMO regulations accurately. In brief, IMO regulations have an unavoidable enforcement capacity over ships navigating between international ports[21].

Initial regulations on the air pollution have been enforced by defining the emission control areas (ECAs)[22] where ships are limited to certain type of fuel to reduce emission inventory. Latest regulation enforced by the IMO, also known as IMO2020, requires a Sulphur emission limit of 0.50% (mass by mass) which eventually entails either the change of fuel type or utilization of exhaust gas cleaning equipment called scrubber. Shipping industry has been well optimized and standardized in the last century, and therefore, the relative cost of shipping at the final product (e.g. an item at a supermarket) is extremely low. However, above mentioned circumstances have brought a new type of uncertainty to the industry with a fuel choice problem connected to the cost and operation of facilities on board. The impression with scrubbers is a bit problematic. A scrubber uses a mechanism to filter exhaust gas with water which produces a sort of sludge water with contamination inside. In most scrubber systems, the sludge water is dumped to sea. In a recent study, the International Council on Clean Transportation (ICCT) advised prohibition of scrubbers as they do not really improve the environmental concern[23].

Fig. 2.4 Current and prospective emission control areas (ECAs).

That being said, most carriers have preferred a fuel change option which is mainly the low Sulphur fuel oils (LSFOs) in the current market. Yet another great deal with LSFOs has arisen from the black carbon loophole. LSFOs reduces the Sulphur content significantly while the black carbon (particulate matter as – uncombusted – contamination) can be even more than traditional fuels[24, 25] due to combustion problems.

Emission Inventory Analysis for Major Shipping Routes

In this report, three representative shipping routes for Capesize, VLCC (Very Large Crude Carrier) and Container ships have been studied, and emission inventories are presented. For each type of ship, critical specifications of ships and routes are given prior to the emission simulations.

Methodology

Emissions produced from a given source depends on the amount of fuel consumed and the specifics of that fuel's combustion (Liu and Duru, 2020). In other words, the amount of fuel consumption is defined by the engine power, specific fuel consumption (SFC) and operating time at these specific factors. The fuel combustion characteristics are quantified by an emission factor that reflects the volume of the exhaust gases after combustion. The ship emission formula is presented as in Eq. (1) (The Third IMO GHG Study, Smith et al., 2014):

$$E_{i,j,k,l,m} = \sum_{i=1}^{n} VAN_j \times P_{j,k} \times LF_{j,k,l} \times T_{j,k,l} \times EF_{i,j,k,l} \times \frac{LLAF_{j,k}}{10^6} \qquad \text{Eq. (1)}$$

where *i,j,k,l,m* and *n* represents the pollutant (either CO_2, SO_X, NO_X, PM, CO or CH_4), the ship types (either container ship, dry bulk carrier, tanker, freighter or passenger ship), the engine types (either main engine, auxiliary engine or auxiliary boiler), the fuel types (either residual fuel oil, marine distillate/gasoline oil, low Sulphur fuel oil or liquified natural gas), the operating modes (either cruising, maneuvering, or berthing) and the number of AIS report intervals, respectively. *E* is the calculated emission (*t*); *VAN* is the total ship arrivals in the emission accounting year; *P* is the engine power (*kW*); *LF* is the load factor; *T* is the operating time (*h*); *EF* is the emission factor (*g/kWh*); *LLAF* is the low load adjustment factor. This formula can be applied in the ship traffic (vessel movements in a port area) or in tracking a particular ship through a voyage. When it is applied to a single ship sample (as in this report), *VAN* would be excluded from the formula.

Engine Power

The maximum continuous rated power (*MCR*) of main engines used in the calculation. MCR values can be found in the corresponding engine manufacturer's manuals or ship particulars if reported. As for auxiliary engines and boilers, such information could not be found from a public database. This is because neither IMO nor classification societies require ship owners to release this information (Liu and Duru, 2020). Under this premise, the default auxiliary engine and boiler loads by operating modes are extracted from the IMO GHG Studies (2014, 2020) used as applicable proxies.

Load Factor

The load factor for main engine is calculated using the Propeller Law, where the ratio of the actual speed is compared to the designed maximum speed of the vessel (Ryder and Chappell, 1980; Wang and Meng, 2012; Liu and Duru, 2020), shown as Eq. (2). The load factor is capped to a maximum value of 1.0 so that there is no calculated engine load factor greater than 100%.

$$LF = \left(\frac{V}{V_d}\right)^3 \qquad \text{Eq. (2)}$$

where *LF* is the load factor; *V* represents the actual sailing speed (nautical miles); V_d represents the maximum design speed (nautical miles).

Emission Factor and Low Load Adjustment Factor

Emission factor for each exhaust pollutant is directly linked to the fuel type, engine type, and Sulphur content. Emission factors were gathered from multiple documents and reported in *Appendix A* (EPA U.S., 2020; IMO 2020)[27]. The low load adjustment factors (LLAF) were applied to the main engines for below 20% load levels due to the combustion inefficiency (Table 2.3).

Emission Factor for Methane (CH_4)

The emission factor for methane is a frequently debated topic, and multiple estimations can be found in various reports. In latest inventory guidance of the EPA U.S. (2020), the hydrocarbon (HC) emissions for LNG fuel is reported at 0.0 g/kWh (less than 0.1 g/kWh) for high pressure (compression ignited) two-stroke diesel cycle engines. The same report also indicates that methane emissions would be around 2% of hydrocarbon emissions. In this regard, multiple documents published by independent organizations and academic papers have been investigated to reflect emission factors as accurate as possible. This report assumes only high pressure (compression ignited) two-stroke diesel cycle engines in its sample.

Table 2.3 Low load adjustment factors.

	Low Load Adjustment Factor					
Load	*CO_2*	*NO_X*	*SO_X*	*PM*	*CO*	*CH_4*
2%	1.00	4.63	1.00	7.29	9.70	21.18
3%	1.00	2.92	1.00	4.33	6.49	11.68
4%	1.00	2.21	1.00	3.09	4.86	7.71
5%	1.00	1.83	1.00	2.44	3.90	5.61
6%	1.00	1.60	1.00	2.04	3.26	4.35
7%	1.00	1.45	1.00	1.79	2.80	3.52
8%	1.00	1.35	1.00	1.61	2.45	2.95
9%	1.00	1.27	1.00	1.48	2.18	2.52
10%	1.00	1.22	1.00	1.38	1.97	2.18
11%	1.00	1.17	1.00	1.30	1.79	1.96
12%	1.00	1.14	1.00	1.24	1.64	1.76
13%	1.00	1.11	1.00	1.19	1.52	1.60
14%	1.00	1.08	1.00	1.15	1.41	1.47
15%	1.00	1.06	1.00	1.11	1.32	1.36
16%	1.00	1.05	1.00	1.08	1.24	1.26
17%	1.00	1.03	1.00	1.06	1.17	1.18
18%	1.00	1.02	1.00	1.04	1.11	1.11
19%	1.00	1.01	1.00	1.02	1.05	1.05
20%	1.00	1.00	1.00	1.00	1.00	1.00

Due to various limitations of 'precision' and changes in the fuel and engine systems, emission inventory methods are subject to revisions. In this report, we studied accurate and unbiased results by considering multiple factors instead of targeting the precision, which is extremely difficult to retain by its nature. The fact is that most trusted resources in the ship emission also represent averages and approximations. On site measurements of a specific ship can always be different than those approximations due to above mentioned circumstances.

More details on the methodology can be found at Liu and Duru (2020), EPA U.S. Port Emissions Inventory Guidance (2020)[26], the fourth IMO Greenhouse Gas Study (2020)[27], among others[28].

Emission Inventory for Capesize Dry Bulk Carriers

For the assessment of emission inventories in Capesize Dry Bulkers, three major routes are selected for the empirical simulation (Table 2.4). A 180k DWT Capesize bulker in operation of iron ore shipments is simulated for three corresponding routes at navigation speed of 12 nautical miles.

Emission factors for main engines and auxiliary engines are provided in Appendix A for different engine load particulars. Carbon dioxide (CO2), Sulphur oxide (SOX), nitrogen oxide (NOX), particulate matters (PM), carbon monoxide (CO) and methane (CH4) emissions are estimated based on emission factors and emission inventory methodology proposed by Liu and Duru (2020).

Table 2.4 Specifications of routes and average fuel consumption (entire trip) **during simulations** (180k DWT Capesize Bulk Carrier)**.**

			VLSFO Fuel (*mt*)[a]		LNG Fuel (*mt*)[a]	
Round Trip	*Speed*	*Distance (mile)*	*Total*	*Per Day*	*Total*	*Per Day*
Tubarao (Espírito Santo)-Rotterdam	12	9,996	875	21	726	17
Tubarao (Espírito Santo)-Kashima (Japan)	12	23,638	3,139	36	2,605	30
Hedland (Australia)-Tianjin (China)	12	7,749	750	23	622	19

[a] Main engine specs: Two-stroke high pressure low speed dual fuel (diesel cycle) at the power of 18,660 kW. Fuel consumption at 30% MCR (12 knots): VLSFO, 29 mton/day; LNG, 24 mton/day[29]. The fuel consumption in the table represents the average consumption of the entire trip.

Emission Inventory for Tubarao (Espírito Santo) – Rotterdam Trip

The emission inventory for Tubarao (Espírito Santo) – Rotterdam round trip has been calculated for a 180k DWT Capesize dry bulker based on given technical specifications at Table 2.4. The calculation reflects a complete round trip including loading port operations (Tubarao), sailing to the discharging port (Rotterdam), discharging port operations and final return voyage back to Tubarao (excluding the next round of loading port operations). Typical cargo for given route specifications is iron ore. In this simulation, the 180k DWT Capesize vessel spends seven days at ports and 35 days in sailing between ports (Table 2.5). Total time spent for this round trip is estimated at 42 days.

Table 2.5 180k DWT Capesize, Tubarao-Rotterdam round trip; sailing/port days.

	Tubarao - Rotterdam
Days in port	7
Days in sailing	35
Total days for one round trip	42

The emission inventory results for VLSFO and LNG are illustrated in Table 2.6. As expected, carbon dioxide accounts for over 90% of emissions. Methane emission from the round-trip calculation is slightly over 80 kg comparing to 2,770,000 kg for LNG fuel. By levelization on CO_2 at GWP_{20} (global warming potential in 20 years; 84 times for methane), methane emission reaches to 6,820 kg for LNG and 0.2% of all CO_2 emissions. Other pollutants also account for a small fraction of CO_2 emissions (Fig. 2.5).

To simulate rising methane emission rates due to ship-specific conditions (such as engine or fuel problems) or miscalculations (debating emission factor for methane) with LNG fuel, we also calculated three inflated numbers for 10 times, 20 times and even 100 times more methane emission than the base inventory calculation. In the worst scenario (100x), methane emission can reach 8,120 kg while this scenario is way higher than most reputable benchmarks as mentioned in the methodology. In such a devastating amount, levelized methane emission (GWP_{20}) may be equal to a quarter of total CO_2 emissions. Comparing to other pollutants, methane emission can be just same levels of them (Fig. 2.6).

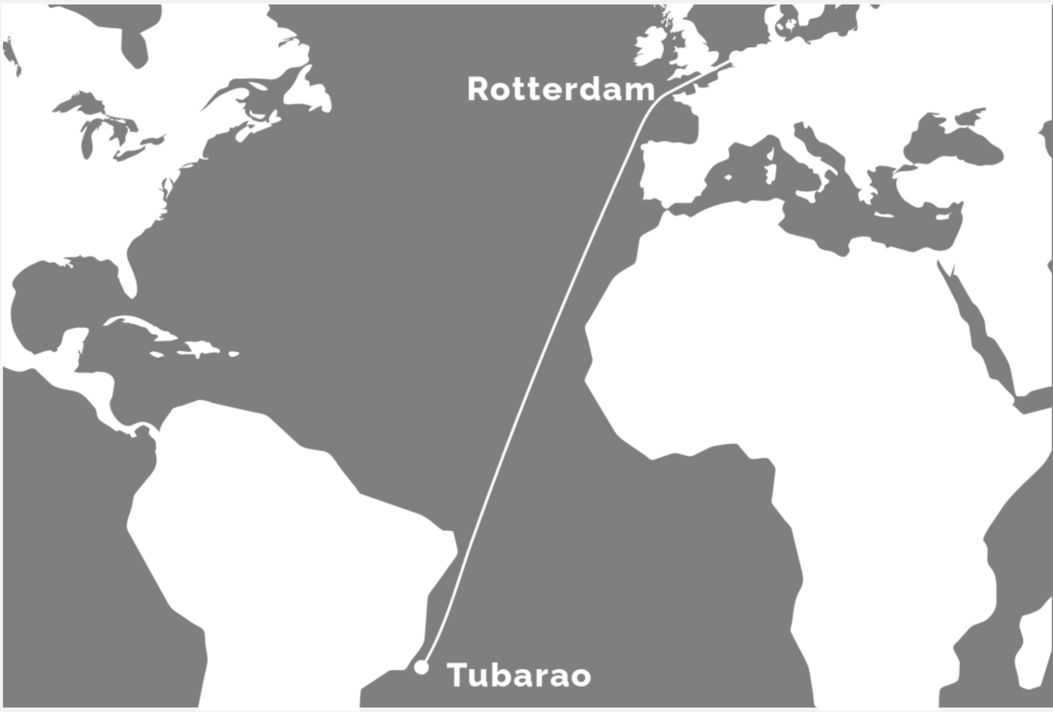


Table 2.6 180k DWT Capesize, Tubarao-Rotterdam round trip; emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	3,642	2,770	
NO_X	102	8	
SO_X	12	0	
PM	2	0	
CO	9	9	
CH_4 (*methane*)	0.08	0.08	
CO_2 eq. GWP 20 years	*6.40*	*6.82*	*0.2% of CO_2 inventory*
CH_4 10x		*0.81*	
CH_4 20x		*1.62*	
CH_4 100x		*8.12*	*GWP_{20}; 24.6% of CO_2*
Total	3,767	2,787	

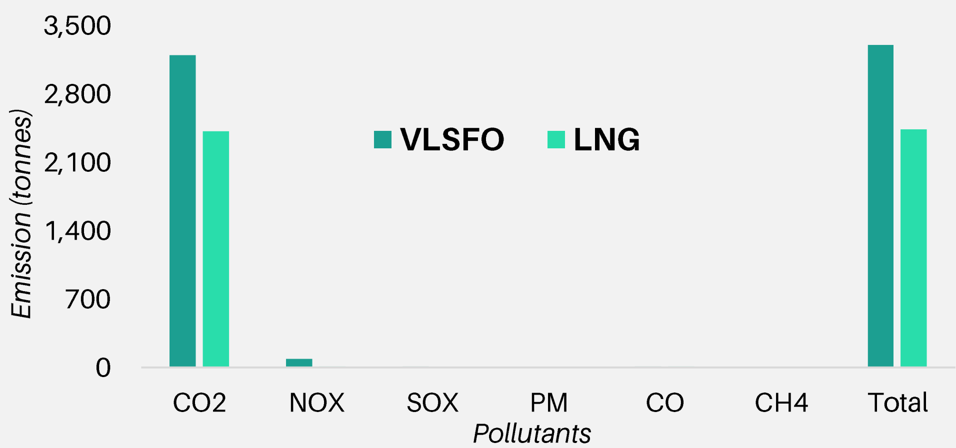


Fig. 2.5 180k DWT Capesize, Tubarao-Rotterdam round trip; emission inventory.

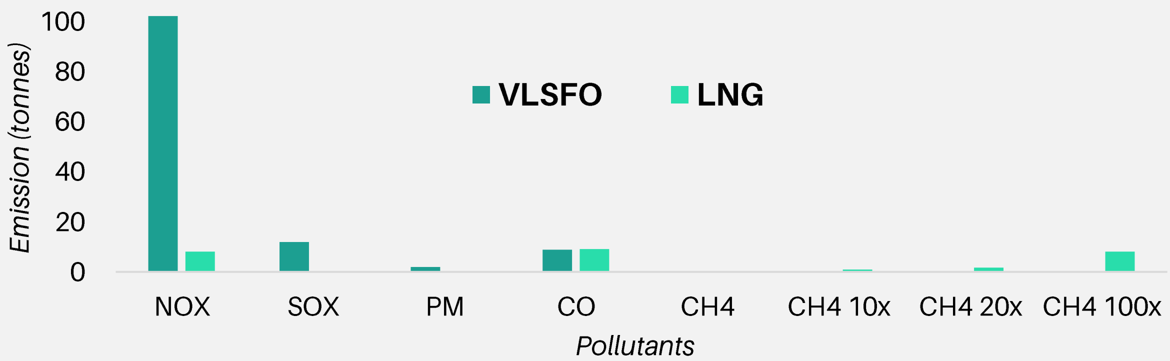


Fig. 2.6 180k DWT Capesize, Tubarao-Rotterdam round trip; emission inventory without CO_2.
Note: CH_4 10x, 20x and 100x values are only calculated and reported for LNG fuel.

Emission inventory simulations for other routes are given in the following infographics. Numerical results from each simulation can be interpreted as in above sample assessment.

Emission Inventory for Tubarao (Espírito Santo) – Japan (Iron ore)

180k DWT Capesize, Round Trip

Through Cape Town

Sailing/port days.

Tubarao	Tubarao - Japan
Days in port	5.5
Days in sailing	82
Total days for one round trip	87.5

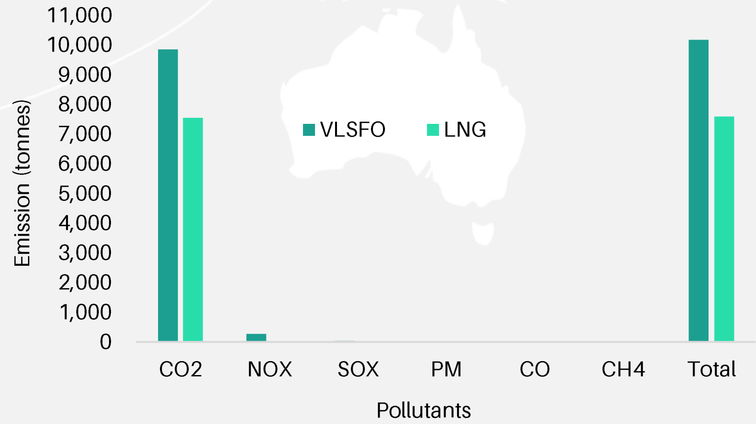


Fig. 2.7 Emission inventory.

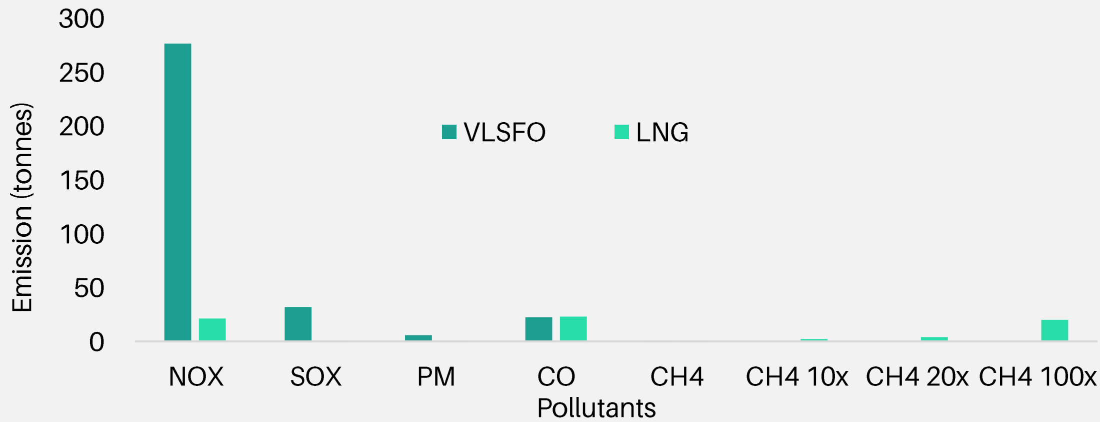


Fig. 2.8 Emission inventory without CO_2.

Table 2.8 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	9,846	7,542	
NO_X	277	21	
SO_X	32	0	
PM	6	0	
CO	22.7	23.1	
CH_4 (*methane*)	0.19	0.20	
CO_2 eq. GWP 20 years	*15.96*	*16.80*	*0.2% of CO_2 inventory*
CH_4 10x		*1.98*	
CH_4 20x		*3.96*	
CH_4 100x		*19.80*	*GWP_{20}; 22.1% of CO_2*
Total	10,183	7,587	

Emission Inventory for Hedland (Australia) – Tianjin (China)

180k DWT Capesize, Round Trip

Table 2.9 Sailing/port days.

	Hedland-Tianjin
Days in port	4.1
Days in sailing	28
Total days for one round trip	32.1

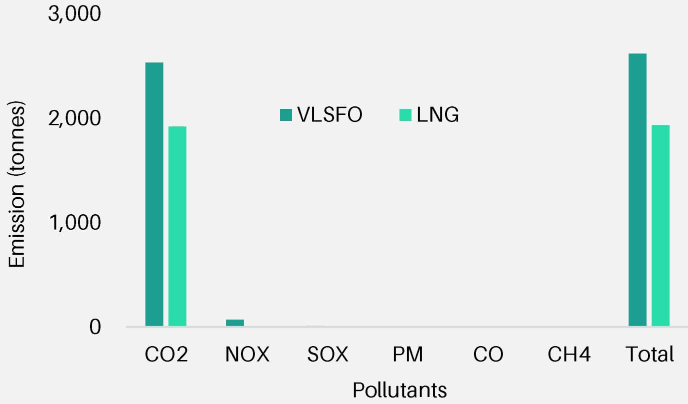


Fig. 2.9 Emission inventory.

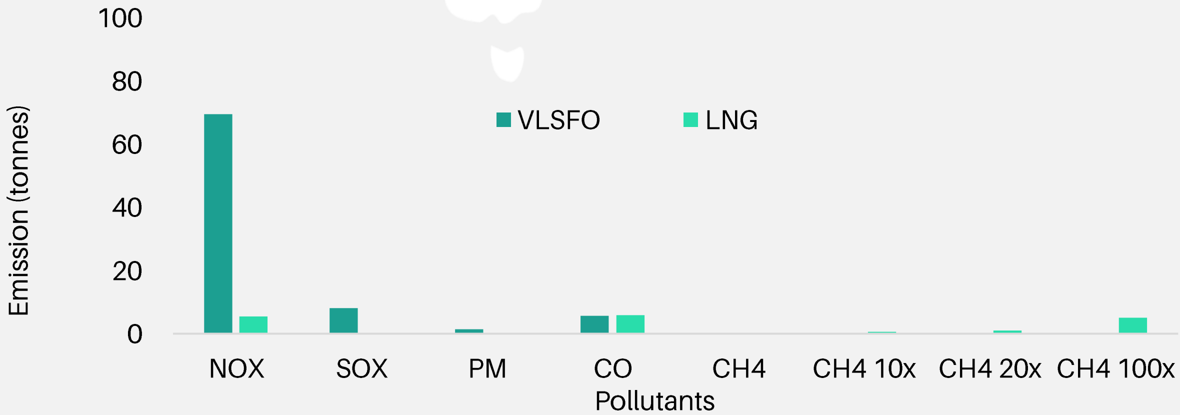


Fig. 2.10 Emission inventory without CO_2.

Table 2.10 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	2,531	1,921	
NO_X	70	5	
SO_X	8	0	
PM	1	0	
CO	5.7	5.9	
CH_4 (*methane*)	0.05	0.05	
CO_2 eq. GWP 20 years	*4.2*	*4.2*	*0.2% of CO_2 inventory*
CH_4 10x		*0.50*	
CH_4 20x		*1.01*	
CH_4 100x		*5.04*	*GWP_{20}; 22.1% of CO_2*
Total	2,616	1,932	

Emission Inventory for VLCC Tankers

For the assessment of emission inventories in VLCC tankers, three crude oil routes are selected for the empirical simulation (Table 2.11). A 310k DWT VLCC tanker in operation of crude oil shipments is simulated for three corresponding routes at navigation speed of 13 nautical miles.

Table 2.11 Specifications of routes and average fuel consumption (entire trip) **during simulations** (310k DWT VLCC Tanker)**.**

			VLSFO Fuel (*mt*)[a]		LNG Fuel (*mt*)[a]	
Round Trip	*Speed*	*Distance (mile)*	*Total*	*Per Day*	*Total*	*Per Day*
Ras Tanura (MEG)-Qingdao (China)	13	12,424	1,754	37	1,455	31
Ras Tanura (MEG)-Houston (USG)	13	25,202	4,416	48	3,666	40
Houston (USG)-Singapore	13	26,834	5,597	57	4,646	48

[a] *Main engine specs: Two-stroke high pressure low speed dual fuel (diesel cycle) at the power of 24,254 kW. Fuel consumption at 38% MCR (13 knots): VLSFO, 49 mton/day; LNG, 41 mton/day*[30]*. The fuel consumption in the table represents the average consumption of the entire trip.*

Emission Inventory for Ras Tanura (MEG) – Qingdao (China)

310k DWT VLCC, Round Trip

Table 2.12 Sailing/port days.

	Ras Tanura-Qingdao
Days in port	4.5
Days in sailing	43
Total days for one round trip	47.5

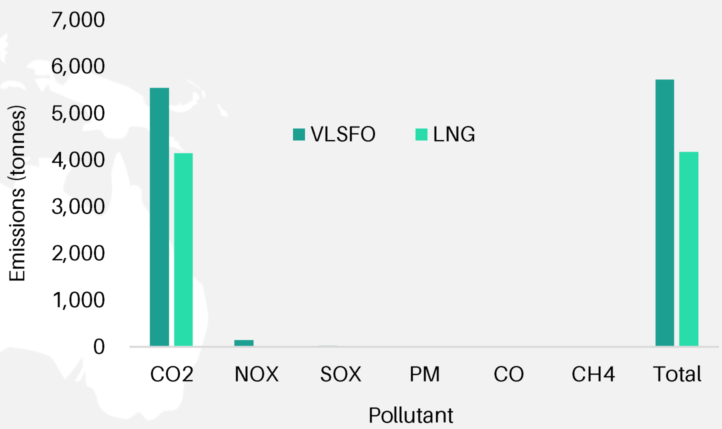


Fig. 2.11 Emission inventory.

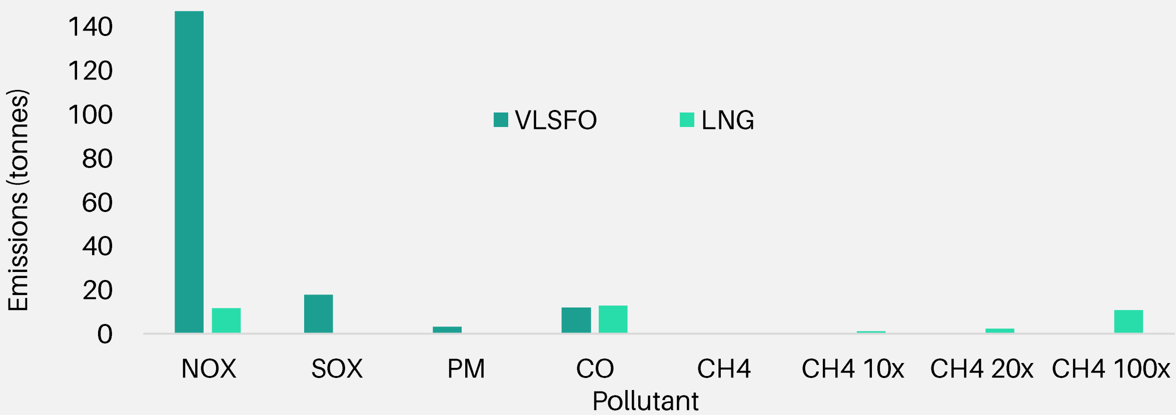


Fig. 2.12 Emission inventory without CO_2.

Table 2.13 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG
CO_2	5,545	4,147
NO_X	147	12
SO_X	18	0
PM	3	0
CO	12	13
CH_4 (*methane*)	0.10	0.11
CO_2 eq. GWP 20 years	*8.4*	*9.2*[a]
CH_4 10x		*1.09*
CH_4 20x		*2.18*
CH_4 100x		*10.89*[b]
Total	5,725	4,172

[a] 0.2% of CO_2 inventory
[b] GWP_{20}; 22% of CO_2

Emission Inventory for Ras Tanura (MEG) – Houston (USG)

310k DWT VLCC, Round Trip

Table 2.14 Sailing/port days.

	Ras Tanura-Houston
Days in port	4.0
Days in sailing	88
Total days for one round trip	92.0

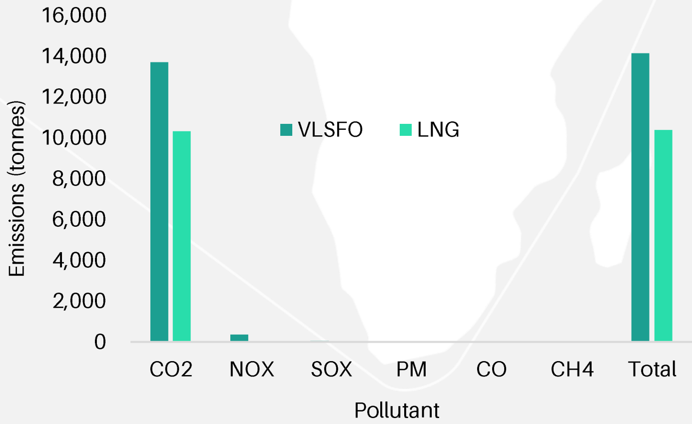


Fig. 2.13 Emission inventory.

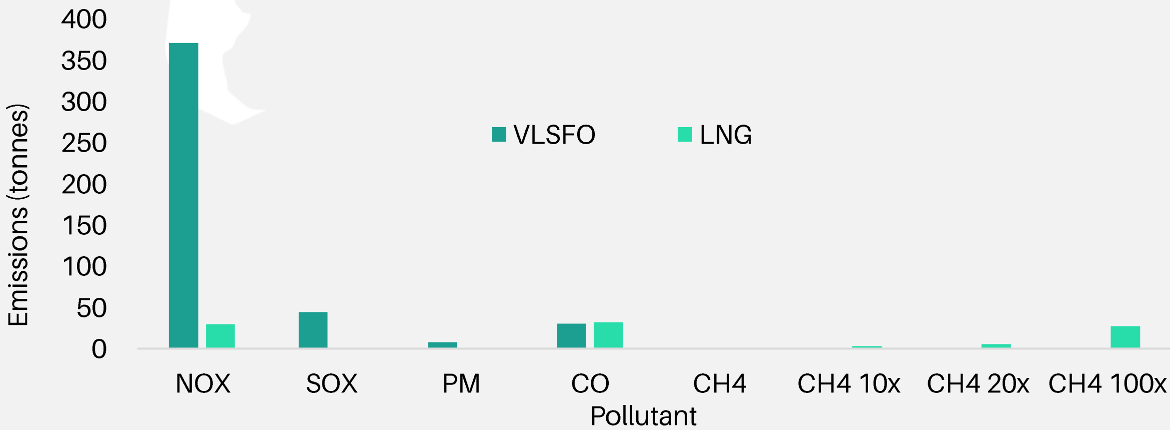


Fig. 2.14 Emission inventory without CO_2.

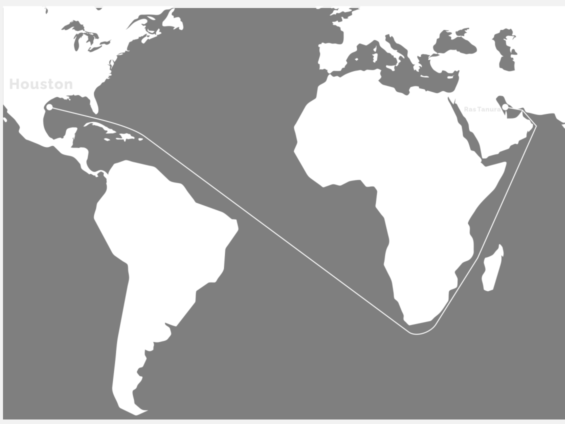


Table 2.15 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	13,693	10,334	
NO_X	371	29	
SO_X	44	0	
PM	8	1	
CO	30.5	31.7	
CH_4 (*methane*)	0.26	0.27	
CO_2 eq. GWP 20 years	*21.6*	*22.8*	*0.2% of CO_2 inventory*
CH_4 10x		*2.71*	
CH_4 20x		*5.43*	
CH_4 100x		*27.13*	*GWP_{20}; 22% of CO_2*
Total	14,147	10,396	

Emission Inventory for Houston (USG) – Singapore

310k DWT VLCC, Round Trip

Table 2.16 Sailing/port days.

	Houston-Singapore
Days in port	4.8
Days in sailing	93
Total days for one round trip	97.8

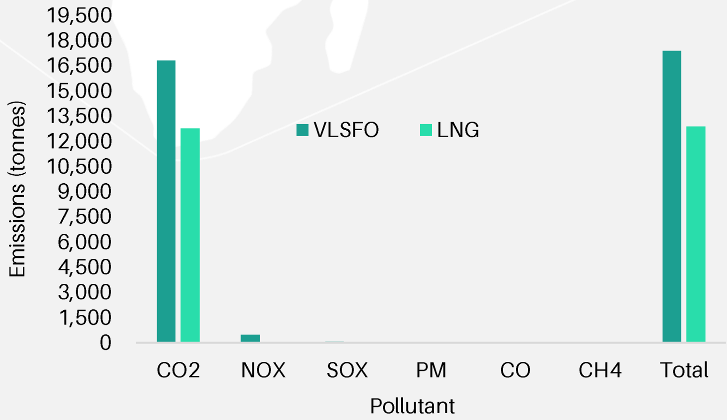


Fig. 2.15 Emission inventory.

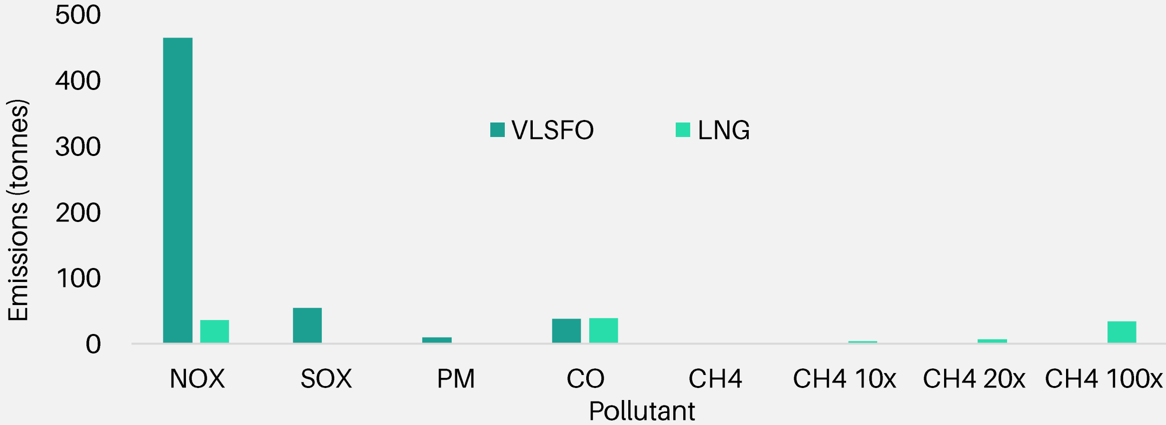
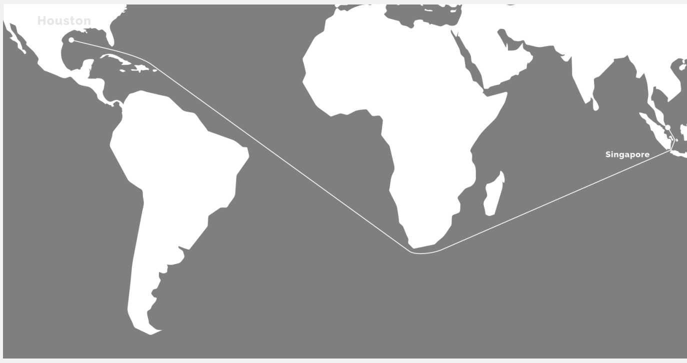


Fig. 2.16 Emission inventory without CO_2.

Table 2.17 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	16,814	12,789	
NO_X	465	36	
SO_X	54	0	
PM	10	1	
CO	38.2	39.2	
CH_4 (*methane*)	0.32	0.34	
CO_2 eq. GWP 20 years	*27.2*	*28.2*	*0.2% of CO_2 inventory*
CH_4 10x		*3.36*	
CH_4 20x		*6.72*	
CH_4 100x		*33.58*	*GWP_{20}; 22% of CO_2*
Total	17,382	12,866	



Emission Inventory for Container Ships

For the assessment of emission inventories in containerships, three containership routes are selected for the empirical simulation (Table 2.18). A 9,000 TEU container ship is simulated for three corresponding routes at navigation speed of 17-18 nautical miles.

Table 2.18 Specifications of routes and average fuel consumption (entire trip) **during simulations** (9,000 TEU Container ship)**.**

			VLSFO Fuel (*mt*)[a]		LNG Fuel (*mt*)[a]	
Round Trip	*Speed*	*Distance (mile)*	*Total*	*Per Day*	*Total*	*Per Day*
Tokyo, Nagoya, Kobe, Busan, Xingang, Qingdao, Shanghai, Ningbo, Keelung, Xiamen, Hong Kong/Yantian, Kaoshiung, Cai Mep, Singapore, Colombo, Le Havre, Antwerp, Rotterdam, **Hamburg**	17	28,639	11,413	70	9,473	58
Kaoshiung, Hong Kong/Yantian, Xiamen, Keelung, Ningbo, Shanghai, Qingdao, Xingang, Busan, Kobe, Nagoya, Tokyo, Long Beach/Los Angeles, Jacksonville, Savannah, Charleston, Norfolk, New York, **Boston**	18	28,724	12,552	80	10,418	66
Hamburg, Bremerhaven, Rotterdam, London Gateway, Southampton, Le Havre, Halifax, New York, Philadelphia, Baltimore, Norfolk, Charleston, Savannah, Jacksonville, Port Everglades, **Miami**	18	12,173	7,556	72	6,271	60

[a] *Two-stroke high pressure low speed dual fuel (diesel cycle) at the power of 48,000 kW. Fuel consumption at 60% MCR: Route 1 - VLSFO, 124 mton/day; LNG, 100 mton/day. Route 2 - VLSFO, 108 mton/day; LNG, 87 mton/day. Route 3 - VLSFO, 108 mton/day; LNG, 87 mton/day*[31]*. The fuel consumption in the table represents the average consumption of the entire trip.*

Emission Inventory for Tokyo – Hamburg

9,000 TEU Containership, Round Trip

Table 2.19 Sailing/port days.

	Tokyo-Hamburg
Days in port	37
Days in sailing	127
Total days for one round trip	164

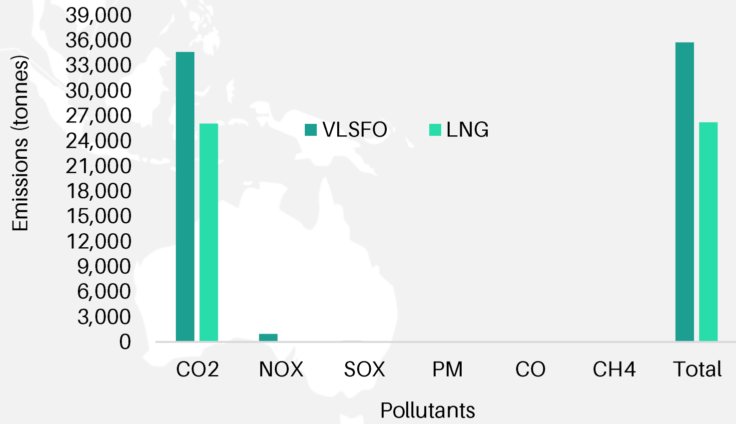


Fig. 2.17 Emission inventory.

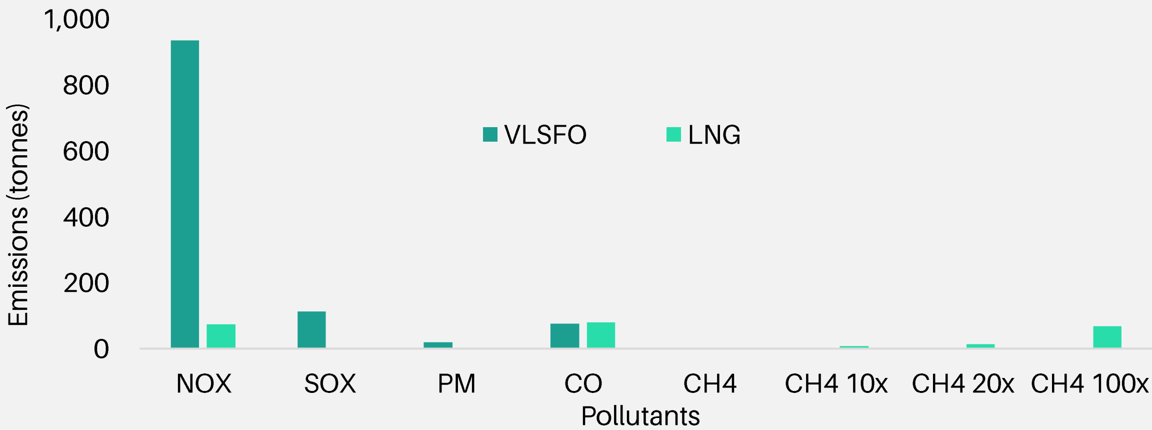


Fig. 2.18 Emission inventory without CO_2.

Table 2.20 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	34,656	26,078	
NO_X	934	74	
SO_X	112	0	
PM	20	2	
CO	77	80	
CH_4 (*methane*)	0.65	0.68	
CO_2 eq. GWP 20 years	*54.2*	*57.5*	*0.2% of CO_2 inventory*
CH_4 10x		*6.85*	
CH_4 20x		*13.70*	
CH_4 100x		*68.48*	*GWP_{20}; 22% of CO_2*
Total	35,800	26,235	

Emission Inventory for Kaoshiung – Boston

9,000 TEU Containership, Round Trip

Table 2.21 Sailing/port days.

	Kaoshiung - Boston
Days in port	40
Days in sailing	117
Total days for one round trip	157

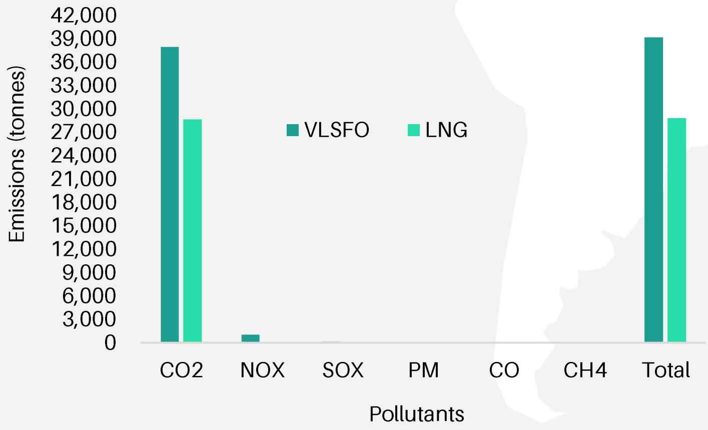


Fig. 2.19 Emission inventory.

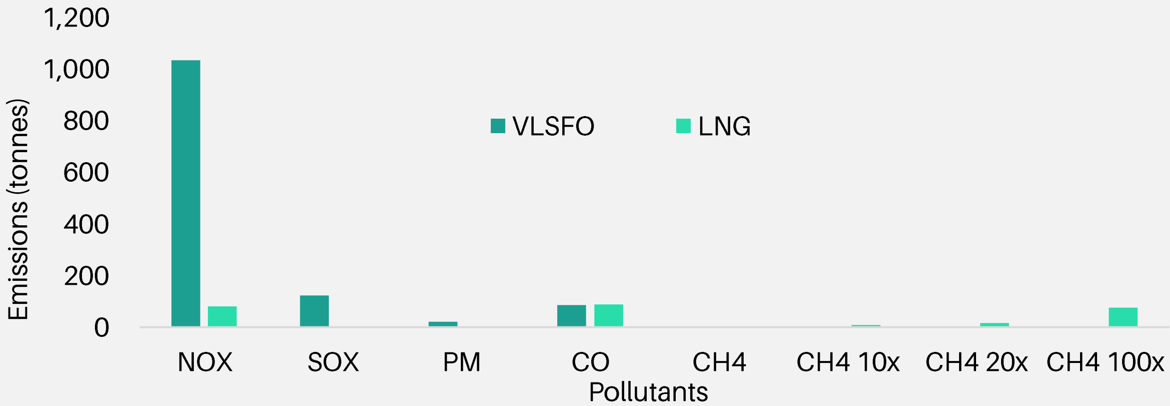


Fig. 2.20 Emission inventory without CO_2.

Table 2.22 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	37,953	28,681	
NO_X	1033	82	
SO_X	123	0	
PM	22	2	
CO	84.8	87.9	
CH_4 (*methane*)	0.72	0.75	
CO_2 eq. GWP 20 years	*60.2*	*63.2*	*0.2% of CO_2 inventory*
CH_4 10x		*7.53*	
CH_4 20x		*15.06*	
CH_4 100x		*75.31*	*GWP_{20}; 22% of CO_2*
Total	39,216	28,853	

Emission Inventory for Hamburg – Miami

9,000 TEU Containership, Round Trip

Table 2.23 Sailing/port days.

	Hamburg - Miami
Days in port	34
Days in sailing	71
Total days for one round trip	105

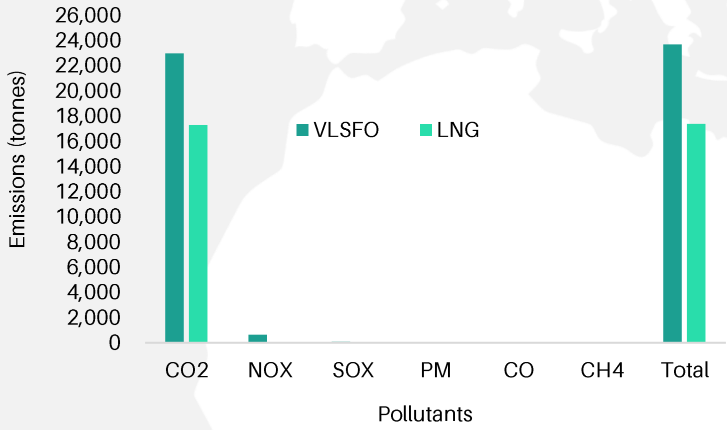


Fig. 2.21 Emission inventory.

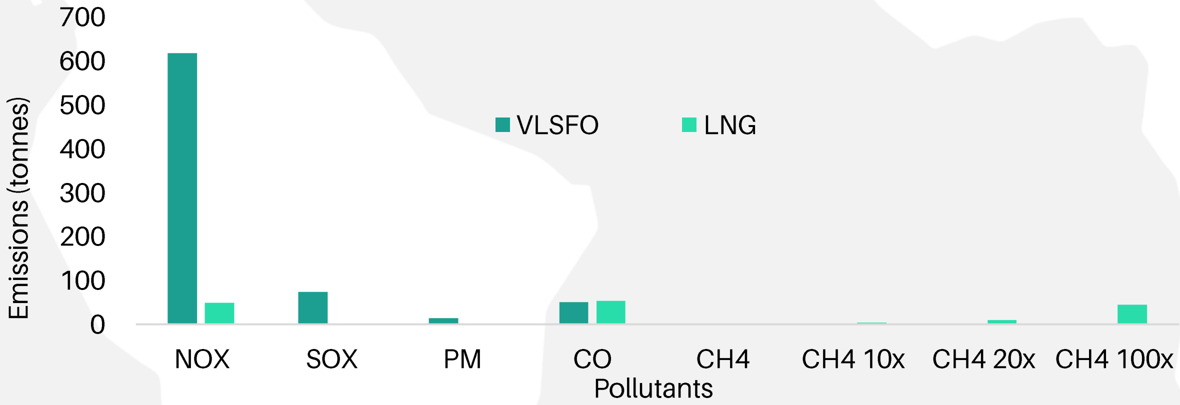


Fig. 2.22 Emission inventory without CO_2.

Table 2.24 Emission inventory.

Pollutants (*tonnes*)	VLSFO	LNG	
CO_2	22,960	17,265	
NO_X	618	49	
SO_X	74	0	
PM	13	1	
CO	50.7	52.9	
CH_4 (*methane*)	0.43	0.45	
CO_2 eq. GWP 20 years	*36.0*	*38.1*	*0.2% of CO_2 inventory*
CH_4 10x		*4.53*	
CH_4 20x		*9.07*	
CH_4 100x		*45.34*	*GWP_{20}; 22% of CO_2*
Total	23,716	17,369	

Conclusion

In this part, we explored the principles of green shipping with a particular focus on the air pollution aspect. The Sulphur mandate and subsequent recommendations caused a paradigm shift in the maritime industry and changed the regular practices. In contrast to the context of a decade ago, several fuel options and energy systems lay down a new normal and direction of evolution. Ship investors need to expand their horizons and make decisions having long-term impact.

According to the technical assessment of various fuel choices, LNG significantly stands out, and it is the major contender with environmental, operational and economic advantages. By utilizing high pressure diesel engines, the emission characteristics of LNG fuel is much better than most fuels.

With multiple simulations, we observe that the methane emission problem is minimal, and it can be reduced further in operational level with a balanced use of LNG fuel and pilot fuel.

LNG fuel is a leading solution for larger tonnage as the economic and environmental advantages are more visible. LNG fueled dry bulk carriers, tankers are containerships are already operating, and there are outstanding deliveries in the next decade which is expected to rise further.

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[2] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx
[3] Review of Maritime Transport 2020, UNCTAD.
[4] https://www.canada.ca/en/environment-climate-change/news/2020/11/government-of-canada-charts-course-for-clean-growth-by-introducing-bill-to-legislate-net-zero-emissions-by-2050.html
[5] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_335
[6] Global Warming Potentials; https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf
[7] A serious danger of ammonia is that if it is mixed with bleach, the chemical reaction releases the toxic chlorine gas, which can be deadly.
[8] https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html
[9] "Japan launches first liquid hydrogen carrier ship" at https://www.ft.com/content/8ae16d5e-1bd4-11ea-97df-cc63de1d73f4
[10] Since natural gas is an odorless and colorless substance, leakage may not be detected in closed spaces by human senses. Therefore, household gas supply is odorized by network provider. LNG is carried in tanks opening to main decks (open space) on ships. LNG bunker tanks are usually designed over the board as well. In open space conditions, methane is lighter than air and does not hang on low altitudes. Considering the latest technology and equipment with LNG transport, the danger of asphyxiation is negligible. In addition to that, a major LNG tanker spill has never occurred in the history.
[11] https://www.afcintl.com/pdfs/applications/combustibles.pdf
[12] https://climate.nasa.gov/faq/19/what-is-the-greenhouse-effect/
[13] https://www.usgs.gov/center-news/understanding-and-predicting-wetland-methane-emissions?qt-news_science_products=7#qt-news_science_products
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[15] https://edition.cnn.com/interactive/2019/11/asia/borneo-climate-bomb-intl-hnk/
[16] https://earth.esa.int/documents/973910/992126/bob1.pdf
[17] https://www.bloomberg.com/news/articles/2019-12-24/bushfires-release-over-half-australia-s-annual-carbon-emissions
[18] https://www.epa.gov/lmop/basic-information-about-landfill-gas#methane
[19] https://www.globalmethane.org/documents/landfill_fs_eng.pdf
[20] https://www.greencarcongress.com/2020/04/20200421-lr.html
[21] Cabotage (domestic) shipments are regulated by the nation. Most nations enforce similar regulatory standard as the IMO's requirements.
[22] Also Sulfur Emission Control Areas (SECAs) which reduces the Sulphur limit to 0.1% (below 0.5% of global limit).
[23] https://theicct.org/publications/air-water-pollution-scrubbers-2020
[24] https://lloydslist.maritimeintelligence.informa.com/LL1130672/VLSFO-blends-face-a-prohibition-push-after-black-carbon-emissions-study
[25] https://www.rivieramm.com/news-content-hub/news-content-hub/why-new-05-sulphur-fuels-may-produce-higher-black-carbon-emissions-60260
[26] https://www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance
[27] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx
[28] Also https://www.danishshipping.dk/en/services/beregningsvaerktoejer/download/Basic_Model_Linkarea_Link/806/energy-demand-and-emissions-of-marine-engines-september-2015.pdf
[29] Particulars of given sample of ships are selected based on a sample collected by AIS (Automatic Identification System) during the period of conducting this study. Engine shaft power is for Specified Maximum Continuous Rating (SMCR). In practice, the ship speed may be adjusted to the market conditions. This study represents the realistic case based on the current ship movement statistics. In comparative analysis, a standard condition has been implemented for both fuel simulations. There is no condition or engine specification gap in VLSFO and LNG simulations.
[30] See footnote 28.
[31] Specifications are compiled from various resources.

Part 3

Emissions from the LNG Supply-Chain

Well-to-Tank Emission Inventory

Summary

- LNG has various advantages in terms of reduced emissions, higher energy content, among others. However, the well-to-tank emission performance is a critical question to answer.
- Lifecycle assessment is a method in environmental engineering to illustrate all stages from soil to soil/air, production to final disposal of materials. In this part, LCA has been conducted for conventional LNG with limitations.
- The conventional natural gas (also oil) industry has a higher amount of methane emission budget than an LNG fueled global shipping fleet. Accordingly, stakeholders invest in mitigating the methane emission from the oil and gas industry.
- Biomethane and synthetic methane are projected to be major game changers in the ecosystem with potential of net zero emission.

Lifecycle Assessment

COUNTER-MEASURES have been implemented to reduce the environmental footprint and greenhouse impact of systems and facilities for many years. On the other hand, such measures also face severe criticism due to the fact that some solutions simply relocate the production site of the environmental side effect, exporting overseas or transforming the footprint from one type of waste to another. For example, electric cars are frequently questioned regarding the source of electricity. If the electricity is generated by using coal-burning thermal power plants, the environmental cost would be even higher than traditional cars.

In addition, the production and disposal of battery packs are two controversial components. In a similar vein, wind turbines are criticized because turbine blades are difficult to dispose of in an environmentally friendly way[1]. By electrification of vehicles, we implicitly agree that e.g. nuclear power is the cleanest option to tackle the footprint problem. Instead of hiding any aspects of the entire ecosystem, lifecycle assessment investigates every step of material production, transportation, manufacturing, use, disposal, and recycle or return to nature (dissolution in soil).

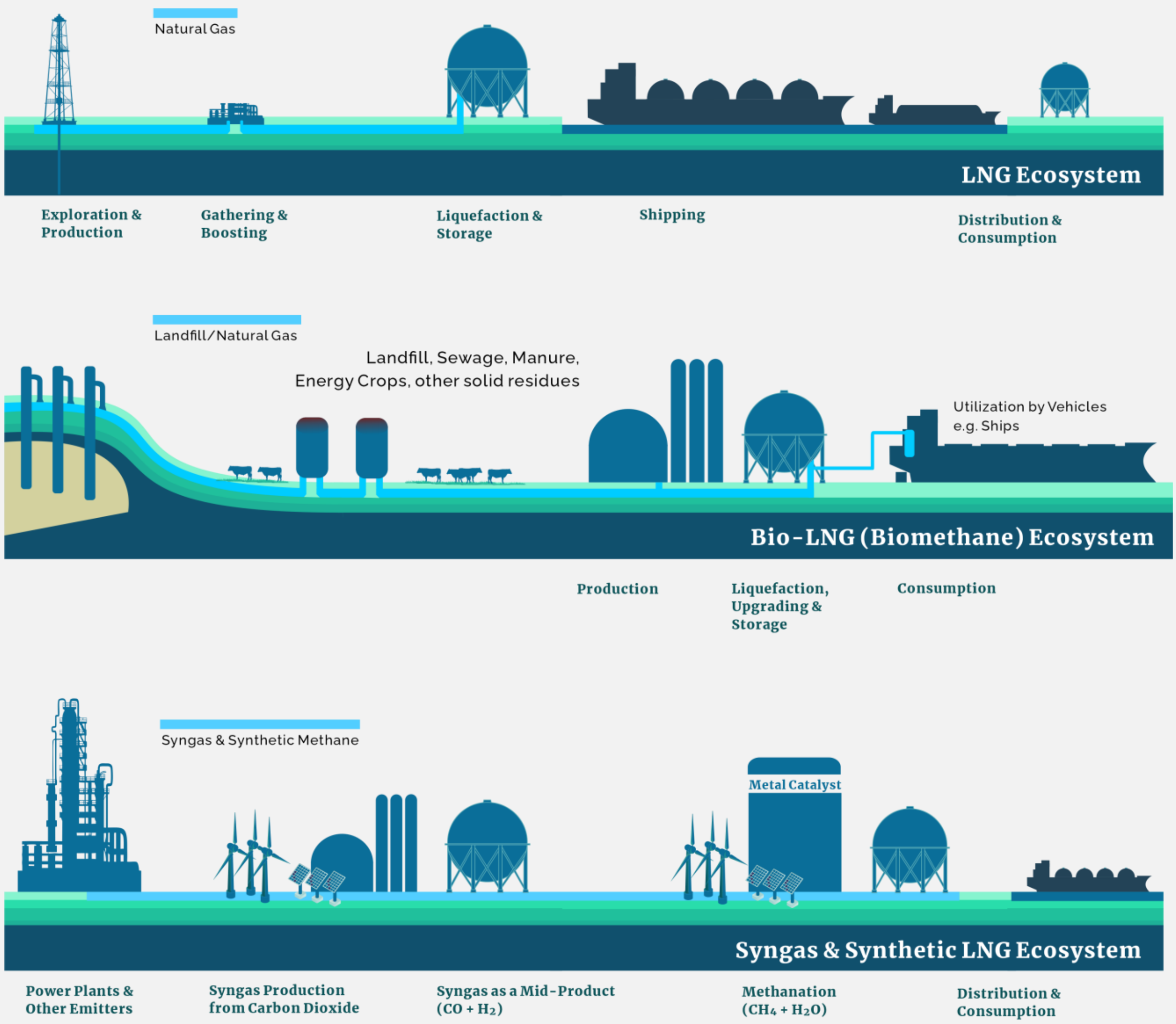
Life Cycle Assessment (LCA) is an approximation of the environmental phenomenon.

Lifecycle assessment or analysis (LCA) refers to evaluating all activities of environmental impact from unearthing raw materials to the final return of residuals to nature. LCA requires a complex research activity including the collection of data, finding 'generalizable' factors and representative figures, assumptions on certain components or processes and multiple causal structures (reasoning). Therefore, there is inherent uncertainty in LCA, so that, it is also a rough approximation of the environmental phenomenon instead of a precise accounting of all aspects.

LCA and Total Emission Analysis for LNG Fuel

Our analysis will investigate the total emission inventory throughout the production, distribution and use of LNG fuel as a marine bunker. In addition to that, Bio-LNG (biomethane) and Synthetic LNG will be studied to shed light on the emission gain and neutrality compared to traditional LNG fuel.

Three LNG ecosystems will be reported in this analysis: (1) Conventional LNG, (2) bio-LNG and (3) synthetic LNG (Fig. 3.1).



Note: The Syngas ecosystem is illustrated in multiple stages for visual comprehension. Production and Methanation processes are usually one single unit in the current applications of synthetic LNG production.

Fig. 3.1 LNG Ecosystems for traditional, bio-LNG and synthetic LNG.

Most LNG ecosystems are composed of four major stages: (1) Production (upstream), (2) liquefaction and storage (upstream), (3) transport (shipping, pipeline – midstream) and (4) distribution and consumption (downstream). In certain ecosystems, LNG may be distributed and consumed in the production facility's location, and the transport operation may not be necessary.

In a recent study, Alvarez et al. (2018) recalculated the amount of methane emission throughout the natural gas production and supply-chain (Fig. 3.2). In this study, the methane emission has been estimated in five stages of the process. The vast majority of fugitive methane emission is recorded before liquefaction and distribution.

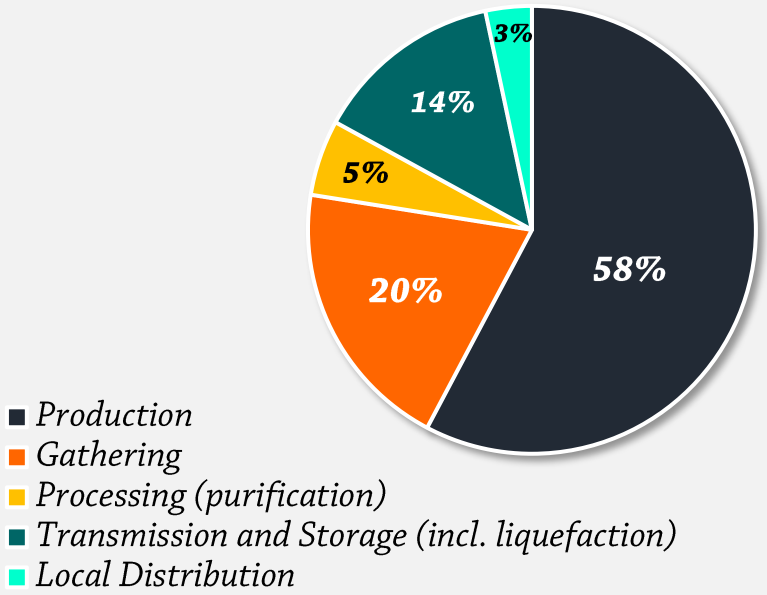


Fig. 3.2 Methane emission in the natural gas industry (Alvarez et al., 2018).

The fugitive methane emission problem in the natural gas industry is mainly led by equipment leaks and unburned methane in the exploration, drilling, extraction and gathering stages.

Production

Exploration, drilling, unearthing, bioprocessing and methanation are operations throughout the production stage of various LNG ecosystems. During these operations, there are channels of anthropogenic and natural (biogenic and seismic) air emissions as well as reduction or conversion of emissions and solid waste. For example, exploration, drilling and unearthing of natural gas from earth's crust are not entirely insulated operations, so that, some of the natural gas extraction is released to the atmosphere which is called '**methane slip**' (a.k.a. fugitive methane emission). Methane slip is not an exceptional side effect of natural gas; actually, it is already observed in traditional oil exploration and in the refinery ecosystem for more than a century. Yet another major source of fugitive methane emission is from coal mining operations. The discovery or awareness of the methane slip may be relatively new, but the phenomenon has a long history in line with the discovery and extraction of crude oil. In addition to that, there are channels other than oil and gas industries such as seismic movements that unearth preserved natural gas.

According to EPA U.S. (2010), earlier estimations of GHG emissions from oil and gas industries were understated due to unknown or unmonitored sources. Following additional sources of inventory are reported:

- *Condensate and petroleum storage tanks*
- *Natural gas well workovers*
- *Natural gas well completions*
- *Natural gas well liquid unloading*
- *Centrifugal compressor wet seals*
- *Flares*
- *Scrubber dump valve emissions through tanks*
- *Onshore combustion emissions*

In recent years, a significant investment has been directed to minimize (if not terminate) the methane slip in the oil and gas exploration industries. The Canadian Federal Government has introduced an exceptional program (December 2020) called **'Emission Reduction Fund – Onshore Program'** which particularly targets the methane slip in the Canadian oil and gas facilities[2]. With this funding scheme, the Canadian Government offers $675 million total budget to be provided upon project proposals to reduce methane slip (5-year payback period). An equivalent of this initiative has been introduced much earlier by the Environmental Protection Agency (EPA) of the U.S. called **'the Natural Gas STAR Program'**.

On the other hand, bioprocessing and methanation in bio-LNG and synthetic-LNG introduce a different mechanism promising '**net-zero emissions**'. In these biogas ecosystems, the methane emission from landfill, manure, lignite coal, power plant emissions and solid or liquid waste is transferred to a collection facility in order to convert the emission into liquified storable natural gas. Therefore, the biogas ecosystem does not only process waste or other materials for generating safer and cleaner waste but also reduces the methane emission for reuse. In a similar vein, modern syngas production facilities convert carbon dioxide emissions from industrial facilities into synthetic methane by using renewable energy resources. In other words, renewable energy is stored in the form of synthetic LNG. These methodologies are eligible to be classified as net zero-emission systems.

Liquefaction & Storage

Methane (CH_4) is a smaller molecule compared to Propane (C_3H_8), Butane (C_4H_{10}) and many other gaseous fuels (except hydrogen). The liquefaction of methane requires high positive pressure (compression at approx. 7 bar or 102 psi) and cooling below -150°C which then can be stored in specially designed and insulated tanks. In such facilities, pressurized methane as a thin material may not be preserved correctly, meaning that methane traces could slip through piping, pressure control mechanisms, loading and discharging operations (another source of fugitive methane emission)[3]. In gaseous form (at room temperature), methane can be easily insulated as it is distributed in cities for household consumption. Liquid methane is naturally regasified and pumped to the network.

Transportation

Although it is a relatively minor point of fugitive methane emission, the transportation and shipping of LNG causes approx. 15% of the fugitive methane emission. Transmission between regions, loading-discharging at ports, and other operations cause methane slip at minimal levels. Transportation is usually the last stage of natural gas in the liquid form. Therefore, the methane emission after this stage is at a negligible level. In gaseous form (low pressure), methane can be well insulated in the system.

Distribution and Consumption

At the final point of use, a negligible amount of methane emission is released within the network of natural gas distribution. Regasification reduces the methane's pressure and temperature before circulation in the network, but traces of emission are unavoidable. In the industrial consumption, fugitive methane emission happens in the storage or piping system as well as combustion engines. For example, low-pressure diesel engines cause such methane slip (unburned methane) during its operation. High-pressure diesel engines would have much-limited slippage as it is calibrated for pressurized injection and combustion. The insulation (piston rings, gaskets) is also capable of preserving most of the methane molecules.

Emission Inventory Analysis for Total LNG Ecosystems

Emission inventory for the LNG supply-chain (well-to-tank) is a challenging task due to the variety of systems, capacity, design and the network size. In different countries, there will be different structures, pipelines, gathering and boosting stations, among others. The volume and number of such components can dramatically change the well-to-tank calculations. A generic estimation that is applicable for all cases and conditions is infeasible. Therefore, the well-to-tank inventories must be investigated in a narrow focus with particular cases. Instead of a generalization, a sample of emission budget for a natural ecosystem would shed light on the potential volume of GHG in the system.

The EPA of the U.S. collects annual emission inventories of the entire energy ecosystem units known as the Greenhouse Gas Reporting Program (GHGRP), and the dataset is publicly available at the Facility Level Information on GHGs Tool (FLIGHT). The EPA collects the data from individual facilities and suppliers of fossil fuels and industrial gases including sources and suppliers in 41 industrial categories[4]. The EPA also recognizes that a complete picture of emissions cannot be defined by GHGRP, but it is still a major input for environmental assessments.

In our sample analysis, we selected each unit of the natural gas ecosystem from actively operating facilities in the Gulf of Mexico (Corpus Christi-Houston Corridor) representing an average capacity[5] for the reference year of 2019. For the investigation, six essential stages of natural gas supply have been considered: (1) Offshore production unit[6], (2) gathering and boosting, (3) gas plant and processing, (4) transmission and compression (e.g. pipelines), (5) liquefaction and shipping terminal operations and finally (6) local distribution at the destination (e.g. LNG bunker barges, city gas network)[7].

In this simulation, one unit per stage of the natural gas ecosystem has been selected to reduce subjective selections. In the industrial practice, a gathering and boosting station would be collecting natural gas from multiple production units. In the later stage, multiple stations would be connected to a single LNG marine terminal (after completing other stages in between, e.g. processing) (Fig. 3.3).

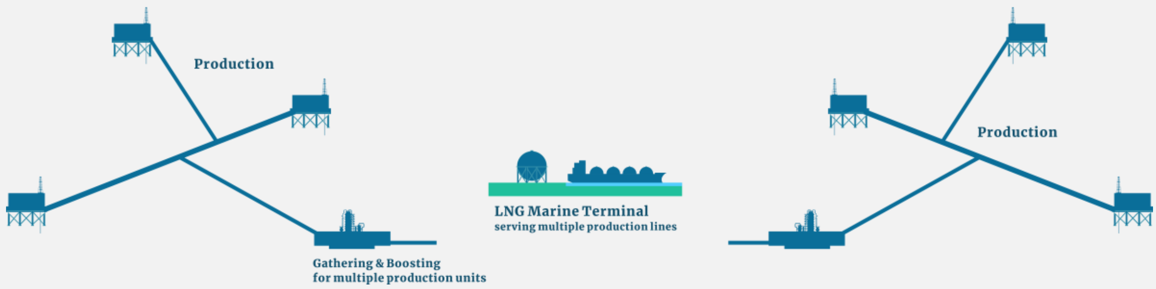


Fig. 3.3 Multiple production units are served by a single gathering and boosting station. Multiple gathering and boosting stations can also be served as a single marine terminal.

In this regard, the presented data can be multiplied for the desired level of production capacity. For example, the CO_2e (carbon dioxide equivalent) emission inventory for the offshore unit is approximately 90,000 metric tonnes (including CO_2, CH_4 and N_2O). This inventory volume can be multiplied to reach higher capacity supply-chain (for three production units, 270,000 metric tonnes). The EPA calculates the CO_2e values based on GWP_{100} (100 years); for example, CH_4 (methane) emissions must be multiplied by 25 (EPA U.S., 2020). In Figure 3.4, CO_2e values for six stages of the LNG supply chain is presented. The vast majority of emissions are in the form of CO_2. The highest volume of fugitive methane emission has been recorded at the gathering and boosting stations as 13% of CO_2 inventory.

On the other hand, the largest cumulative emission is found in the liquefaction, and marine terminal as this stage of the supply-chain gathers natural gas from multiple production lines, generating a high volume of LNG handling. Liquefaction and marine terminal accounts for approx. 3.5 times of a gathering and boosting station.

Local distribution is the second largest for the fugitive methane emissions. Considering the distribution network, area and length of piping, devices working in the network (e.g. household). In this simulation, local distribution refers to the city gas network (an anonymous county in the Texas State of U.S.) In the shipping industry consumption (as fuel), local distribution should be replaced with the LNG consumption as marine fuel (for analysis, see Section 2).

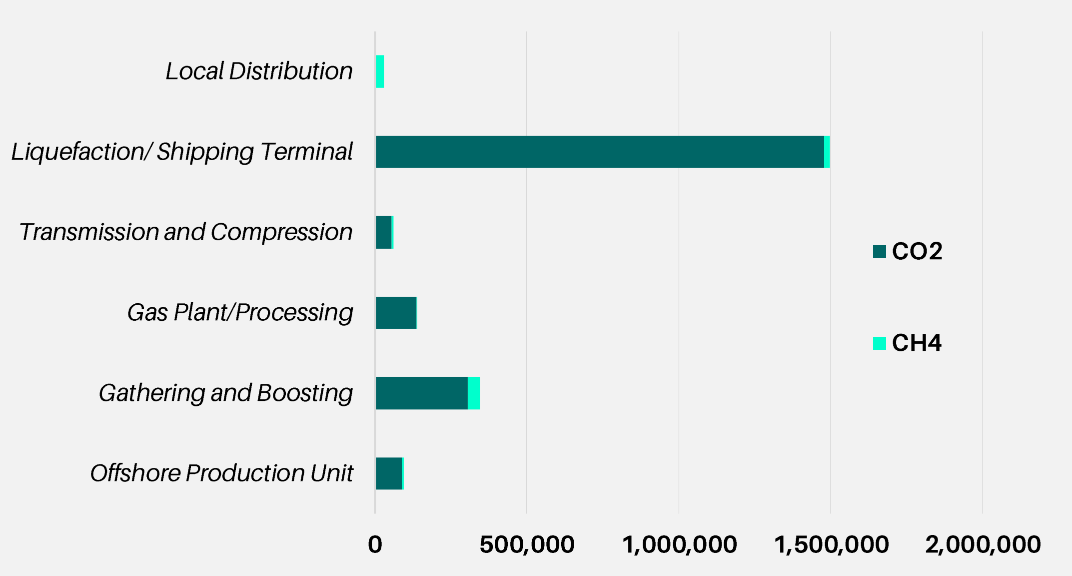


Fig. 3.4 Emission inventory for LNG supply-chain (metric ton).

Note: N_2O data is not presented as its volume is extremely low and not visible.
Source: The Facility Level Information on GHGs Tool (FLIGHT), EPA; a sample of supply-chain units from Corpus Christi-Houston region.

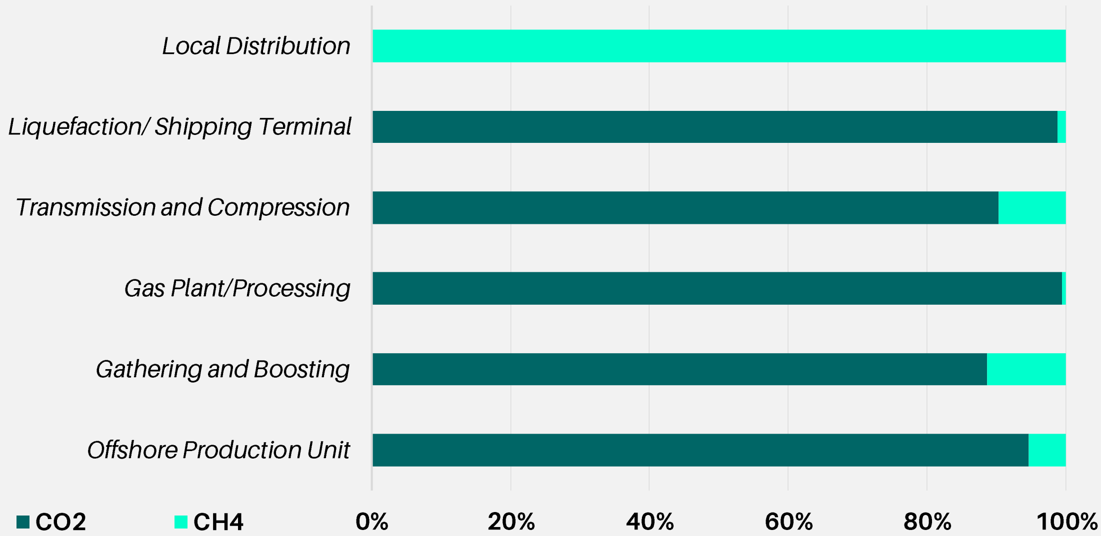


Fig. 3.5 Emission inventory for LNG supply-chain (pollutant ratio).
Note: N_2O data is not presented as its volume is extremely low and not visible.
Source: ibid.

For an illustration, the Containership Route 1 (see Part 2) can be compared to the supply-chain units. The annualized emissions from the route (one ship) are very close to transmission and compression stage in terms of CO_2 inventory while CH_4 emission is extremely low and NO_x emission is much higher (due to combustion engine). Above mentioned well-to-tank emission inventory is given for only a single channel of supply-chain and assuming a single offshore unit.

Well-to-Tank emission inventory is well above the total ship emissions from the global fleet. Public funds are provided to oil and gas industry to develop and implement technologies for emission containment.

The rig count of operating offshore units is around 450 by 2020 with 60% utilization rate[8]. Accordingly, the emission inventory from upstream and midstream operations would be minimum 100 times of given numbers. The methane emission of such size equals to the methane emission from a minimum of 100,000 Post-Panamax containerships. The entire global shipping fleet is around 98,000 including all types and sizes (e.g. small size ships)[9].

Table 3.1 Annualized emission inventory from Containership Route 1 (CO_2e GWP100; metric ton).

	CO_2	CH_4	NO_X
Containership Route 1 (annual) (See Part 2)	58,040	38	1,651
Containership Route 1 (annual) × 100 Ships	5,803,977	3,810	165,102

Emission Inventory in Biomethane and Synthetic LNG

With the rise of biogas and synthetic gas production, the environmental footprint is reversed by reusing emissions from one emitting unit as a consumption fuel on another unit. In biomethane production, natural and anthropogenic methane emissions from agriculture, manure, landfills and other waste groups are collected, processed and liquified for reuse as fuel in both land and sea transportation (also power plants). A similar mechanism can be found in synthetic methane production. In lignite coal ecosystem, a massive amount of black carbon, PM, CO, CH_4 and other emissions are saved, methane is produced in methanation process for utilizing in power plants and as fuel in combustion engines.

Furthermore, the syngas production from carbon dioxide emissions or carbon capture by utilizing renewable energy sources promises a net zero emission structure. If carbon capture systems reach their potential, then it can be even negative emission process. The climate target for 2050 by the European Union consists of pathways embracing net negative emissions to achieve climate-neutral economy[10]. Bio-LNG and synthetic-LNG offer a net-zero emission structure in cumulative figures. Considering the reduction in methane emissions, it is actually 'negative methane emission' cycle[11].

Based on the production capacity of bio-LNG and synthetic-LNG plants, the rate of such conversion process will execute a reverse cycle in reducing the greenhouse effect. The emissions from LNG fuels (such as marine fuel) will be negated by shifting from traditional LNG to biogas or synthetic LNG. In a recent study published at a journal of the Royal Society of Chemistry, Zhang et al. (2020) investigated the GHG reduction of biogas and reported 27-62% reduction comparing to conventional natural gas when used in passenger vehicles.

A list of biogas and syngas production plants is given in Appendix C. Considering the higher adoption in the containership segment and potential of containerized LNG refueling concept, the nearest container ports are also provided for further analysis.

Conclusion

We presented some proxy estimations for further consideration by decision makers on the well-to-tank emission inventories. Our numerical results for Corpus Christi-Houston region represent units in a single supply-chain route from an offshore rig to marine exporting terminal.

By a generic approximation, it is crystal clear that even if we assume all ships in the global fleet are Post-Panamax container ships with higher speed and higher fuel consumption, the methane emission from shipping operations is well below the methane emissions from the global oil and gas industry. Considering that more than half of the world shipping fleet is at medium or below tonnage segments, methane emissions from ships would be further less than above inflated amount.

By implementing biomethane and synthetic methane as marine fuel, the net zero emission and net zero methane emission can be gained, and negative emission may be achieved by new technologies and efficiencies in the biogas/syngas production and carbon capture systems.

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[3] Equipment leaks, unburned methane, gas vented during the process, among others.
[4] https://www.epa.gov/ghgreporting/learn-about-greenhouse-gas-reporting-program-ghgrp
[5] Reader must note that the emission inventory for an entire ecosystem (point-to-point) has uncertainties even for a specific chain of facilities. Our illustration is for the sake of giving an idea of emissions. For this kind of investigation, the variance in data is an unavoidable fact.
[6] In this report, offshore production has been chosen as it is typical for the sample region. Alternatively, onshore production can be implemented.
[7] Identity of facilities will be kept anonymous. Interested readers can check EPA's FLIGHT database and observe similar facilities.
[8] https://www.offshore-mag.com/drilling-completion/article/14182376/ihs-markit-worldwide-offshore-rig-count-and-utilization-rate
[9] https://stats.unctad.org/handbook/MaritimeTransport/MerchantFleet.html
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Part 4

LNG Fuel Operations

A Transition Fuel to Meet with Future Compliance

Summary

- There is an existing network of LNG bunkering facilities around the world offering natural gas at competitive prices for the maritime industry.
- LNG has a long history of transport around the world, and therefore, its infrastructure is well established. With some modifications and improvements, the LNG bunkering market is scalable for larger volumes.
- LNG fuel is not just a matter of solving today's clean fuel problem. LNG fuel is about adopting a long-term objective and a viable pathway evolving to fuel cell systems.
- The pathway for the LNG fuel cell option requires minimal effort comparing to pure hydrogen bunkering.

LNG Bunkering and the Future of LNG

REGARDING THE LNG FUEL retrofitting or LNG fuel design of new ships, a major question for most carriers is the practical and operational feasibility of LNG fuel and bunkering. In the last century, traditional fuel oil and its distillates have been utilized in almost all kinds of seagoing vessels, and the supply of traditional fuels has become available around the world. In every major corner of maritime trading routes, a bunkering hub has evolved, so that, the economy of scale and the economy of network have been gained. Therefore, marine bunkers can be found at competitive prices in certain regions, channels and ports.

Although marine bunkers can be supplied in almost all ports, it is very common practice of operators to schedule bunkering operations at transits, channels or competitive ports to reduce fuel cost and achieve better pricing. Singapore, Gibraltar, Turkish Straits, Suez Canal or Cape Town are some examples of bunkering hubs. Operators tend to plan their bunkering needs according to anticipated routes and transits. Most ships can sail over a month without refueling, and that is a period long enough to plan for calling at bunkering hub during its voyages. Bunkering may be provided in loading or discharging ports, but operators would prefer refueling during a transit for better economy of fuel cost.

LNG bunkering is currently offered in most channels and ports. With growing number of bunkering infrastructures, LNG fuel supply is not a bottleneck.

With the development of LNG fuel alternative in response to the environmental concerns and regulatory requirements of air pollution, LNG fuel availability needs to be established in above mentioned bunkering hubs at the first place. It may not be an urgent need to build facilities in satellite ports while transits, channels and ports with high volume of cargo traffic should lead in LNG bunkering infrastructure.

In fact, most bunkering hubs and major ports have already invested in LNG bunkering facilities, vast majority of them have begun offering LNG bunkering in one of bunkering methodologies (sea barges, tank trucks or shore pipeline). Similar to traditional fuels, LNG burning ships can also sail over a month (even two months based on fuel capacity and voyage characteristics), and therefore, LNG fuel supply is not a bottleneck for ships navigating in major shipping routes.

Furthermore, LNG fuel will most probably complement the efforts on the fuel cell technology. By using LNG Fuel Cell methodology, Methane is converted to Hydrogen fuel and injected to fuel cell system to generate DC power. The LNG fuel cell is actually the reverse mechanism of synthetic methane production. In synthetic methane, renewable energy is converted to methane and oxygen by using carbon dioxide and water. In the LNG fuel cell, this process is reversed, and carbon dioxide and water are generated in addition to the DC power. The evolution prospects will also be discussed in this part.

LNG Bunkering Infrastructure

In the last few years, the number and capacity of LNG bunkering facilities around world have grown exponentially. In almost every month, a new LNG bunkering facility is offered, and the current number of active or prospective LNG fuel available ports reached to 134 in addition to two countries with strong commitments. For example, Trinidad & Tobago as a major LNG exporting country is located at the junction of North America-South America trade routes as well as some of Americas-West Africa trading connections. Accordingly, the nation targets to be a hub in the region[1].

In Table 4.1, a list of ports with LNG bunkering facilities (or ongoing facility building) is presented. LNG fuel is extremely abundant in most European ports, mainly Northern Europe, and North Eastern Asia follows with multiple LNG bunkering ports. There are several LNG bunkering facilities in North East American continent including the Great Lakes region (Fig. 4.1).

Major LNG exporters such as Qatar, Australia, U.S. and Russia also develop projects to increase their operations and market share in the LNG bunkering business. By taking the cost advantage, LNG producers can position their ports as LNG bunkering hubs. As discussed in Part 1, North American ports are able to offer much lower prices in the LNG bunker compared to European ports.

Table 4.1 List of ports with LNG bunkering facility.

Ports with LNG Bunkering Facility		
Aarhus	Hou	Quebec City
_Algeciras_*	Huaian	Risavika
Aliaga	Huelva	_Roscoff_*
Almeria	Incheon	Rostock
Antwerp	Isle of Grain	Rotterdam
Aqaba	Jacksonville	Ruwais
Barcelona	South Florida	Sagunto
Bilbao	King Bay, Karratha	Santander
Bjugn	Kingisepp	_Santo Domingo_*
Bodø	Klapeida	Sarnia
_Brazil_*	Kochi	Savannah
Bremen	Kollsnes	Seattle*
Brunsbuttel	La Spezia	Shanghai
Buenos Aires	Lødingen	Sines
Busan	Lubeck	Singapore
_Canakkale_*	Lysekil	Pskov
Cartagena	Malmö	Snurrevarden
Chongqing	Marmara Ereglisi	_Sohar_*
Coast Center Base	Marseille	St. Petersburg
Coega	Melaka (Malacca)	Stockholm
Cologne	Melkøya	Suqian
Copenhagen	Mina Al Ahmadi	Swinoujscie
_Corpus Christi_*	Mississippi	Szczecin
Doesburg	Mongstad	_Tacoma_*
Dubai	Montego Bay	_Tadoussac_*
Duluth	Montoir-de-Bretagne	Tallinn
Dunkerque	Montreal	Tjeldbergodden
Emden	Moskenes	Tokyo
Ferrol	Mugardos	Tornio
Fjordbase	Nagoya	_Trinidad & Tobago_*
Florø	Nanjing	Turku
Fourchon	New York	Ust-Luga
Freemantle, Perth	Newcastle	Valencia
_Galveston_*	Ningbo	Vancouver
Ghent	Ora	Vestbase
Gibraltar	Panama City	Wuhan
Gothenburg	Pasir Gudang, Johor	_Wuhu_*
Halhjem	Pilbara, Hedland	Xi River
Hambantota	Polarbase	Xuzhou
Hamburg	Pori	Yancheng
Hamilton	Port Canaveral	Yokohama
Hammerfest	Port of Brest	Zeebrugge
Helsinki	Primorsk	Zhoushan
Himeji/Kobe	Pyeongtaek	Zhuhai Gaolan
Hirtshals	Qatar	

*In progress.
LNG bunkering facility can be in the form of ship-to-ship (STS), truck-to-ship (TTS) or pipeline-to-ship (PTS). More details can be found in APPENDIX B.
Source: Compiled from various resources, media releases and official websites of ports and terminals. For commercial purposes, the latest status of the LNG bunkering service must be confirmed with ports and suppliers.

Australian LNG Bunkering Operations for Ore and Coal Carriers

Australia is the second biggest exporter of LNG in the world. By utilizing this advantage, it would like to be an LNG supplier for the largest dry bulk carriers calling at Australian ports for iron ore and coal loading. In a recent deal, major ore mining and trading company, BHP Billiton, awarded Shell to supply LNG fuel for its ore carrier fleet between Western Australia and China[2]. Port of Pilbara (Hedland) announced the availability of LNG fuel supply in the terminals of the port authority[3]. The synergy evolving in the Western Australian maritime ecosystem significantly incentivizes the use of LNG as marine fuel. Australian LNG prices are slightly lower than Japan-Korea prices due to the lack of shipping cost premium (approx. $0.50-0.80 per MMBtu)[4]. Therefore, LNG bunker prices in Australian ports are estimated to be $20-60 (USD/mton) lower than North Eastern Asia rates (See Part 1 for LNG bunker price assessments).

Lack of LNG Bunkering in Remote Ports

Is it really a challenge if LNG burning ships need to call at remote ports?

LNG fuel retrofitting and new buildings are usually suggested to larger tonnage which can accommodate extended volume of bunker tanks, LNG facility and gain more economies of fuel cost (due to higher consumption rate). Most of these ships do not visit ports in remote locations or ports with minor trading volume. In brief, the majority of target tonnage for LNG fuel sails and visits ports and channels with LNG bunker supply.

However, in the worst scenario, if those ships need to call at ports without LNG bunker supply and are significantly distant to the nearest LNG bunker supplying location, LNG fueled ships can still burn traditional fuels and are installed with dual fuel engines. In other words, LNG fueled ships are not expected to have shortage of fuel when ports supply traditional marine fuels. In a recent work, Tan et al. (2020) investigated this phenomenon for operational feasibility of LNG bunkering in container ships with bunkering ports without LNG fuel supply. Due to the bunker storage capacity available on ships, the switch to traditional fuel is found minimal. In addition, this study sheds light to the planning for LNG storage tank size. With a pre-studied tank size, LNG fueled ships are not expected to rely on traditional fuels except the pilot fuel which is consumed in trace amounts in high pressure dual fuel engines to achieve combustion quality.

Fig. 4.1 LNG Bunkering Facilities around the World.

LNG Bunkering Facility

Regions with LNG bunker facility

New Normal in the Marine Energy Space

With recent regulations and new emission targets, finding alternative fuels and energy sources has become a primary topic of the industry, and it will most probably stay in the agenda through to the next decade. In contrast to conventional operations, the 'new normal' brings a mixture of solutions, and it mandates a transition period in which the shipping industry would search and implement net zero emission solutions. Due to basic principles of energy creation, zero emission or zero waste solution seems impossible in the short-run.

For the anticipated transition period, the industry needs to adopt a solution which reduces a significant volume of poisonous emissions, black carbon and particulate matter as well as a solution which can be upgraded to future solutions with minimal transition cost. In addition, this solution must be practical for large carriers which need much higher energy content.

LNG as a marine fuel satisfies these expectations in various ways. As indicated in the previous parts, LNG eliminates almost all black carbon, PM, NO_x and SO_x, also reduces CO_2 more than 20%. LNG facilities at shore and on board can be redesigned and reused for other similar fuels such as hydrogen. By additional insulation, calibration and retrofitting, LNG ecosystem can be adapted to hydrogen ecosystem which makes it a leading transition solution (Hydrogen Council, 2020). In this regard, LNG is thought to be the pathway for the future of hydrogen powered engines and fuel cell systems[5].

"In the future, many LNG import terminals will almost certainly allow for the import of both LNG and liquid hydrogen,"

Rob Butler, Baker Botts

Synergy with LNG & Hydrogen Future

Most hydrogen is produced via steam-methane reforming, a method of production for methane to hydrogen chemical process, in the United States[6]. Under high temperature (700°C+) and pressure (44-360 psi), natural gas (methane) is converted to hydrogen and CO which is then also be converted to hydrogen and CO_2. The first step is called steam-methane reformation while latter part is called water-gas shift reaction (Minutillo, 2020). Finally, CO_2 and hydrogen would be generated by the process (see below reaction summary) (Fig. 4.2).

Steam-methane reforming reaction	$CH_4 + H_2O \rightarrow (heat) \rightarrow CO + 3H_2$
Water-gas shift reaction	$CO + H_2O \rightarrow CO_2 + H_2 + heat$
Final output	$\rightarrow CO_2 + 4H_2 + heat$

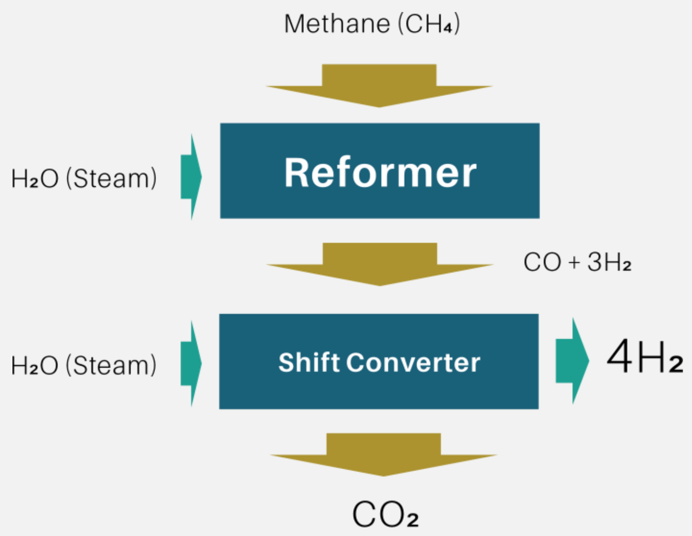

Fig. 4.2 LNG to H_2 conversion process.

In this circumstance, the LNG and Hydrogen fuels share a common future where they symbiotically develop and evolve. The LNG-Hydrogen Ecosystem is another great reason of choosing LNG fuel as the transition material. The Hydrogen Council, one of the leading institutions in the hydrogen industry, recognizes the LNG and bio-LNG revolution as a primer for the future of hydrogen adaptation (Hydrogen Council, 2020).

From LNG Combustion to LNG Fuel Cell

Another potential pathway for LNG-Hydrogen Ecosystem is the implementation of the LNG fuel cell for powering ships. In fact, fuel cells are not a new idea, and they have been experimented with the 1960s (McConnell, 2010). The SiNavy proton-exchange membrane fuel cell (PEMFC) has been providing air-independent propulsion power in non-nuclear submarines since 1997 (ibid.)

Among various types of fuel cell techniques, the LNG fuel cell particularly stands out due to the qualities and availability of natural gas (Van Biert et al., 2016). Natural gas fuel cell systems for residential use reached up to 60% efficiency (Payne et al., 2009), and the efficiency improves gradually.

In the LNG fuel cell solution, LNG retrofit or a new LNG fuel ship is further retrofitted with a fuel cell mechanism by replacing auxiliary engines for electricity generation. Currently, this concept has limited applications in the maritime industry, but it is well expected to be in the market for mass applications. There are examples of industrial use such as data centers[7] and cruise ships[8]. MSC Europa with the world's first LNG-fuel cell operated on board is expected to be delivered in 2022.

LNG fuel is used for hydrogen production in the fuel cell, and later, hydrogen is utilized for electricity generation (Fig. 4.3). Generated DC power can be converted to AC power with an additional unit. Considering the requirements and difficulties with hydrogen storage and transport, hydrogen production from natural gas in the LNG fuel cell mechanism on board is significantly favorable concept rather than storing and utilizing pure hydrogen supplied externally and building a network of hydrogen bunkering for this purpose.

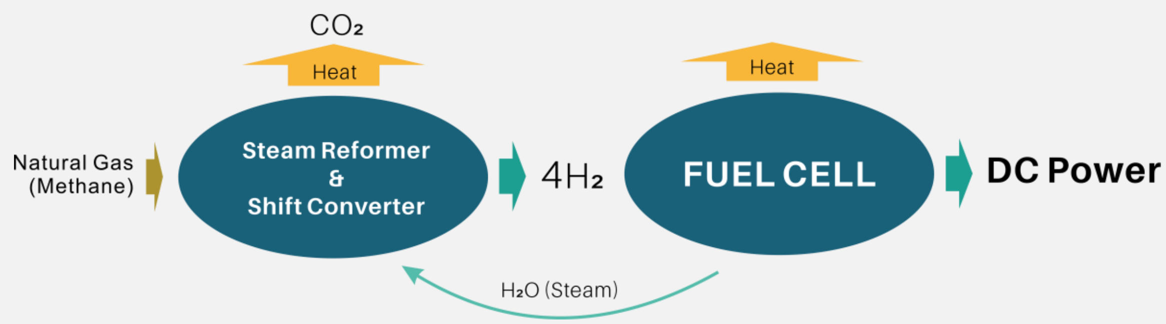

Fig. 4.3 LNG to DC Power by hydrogen fuel cell process.

In terms of air emissions, the difference comes from the lack of internal combustion mechanism. Fugitive methane emissions in LNG fueled ships are mostly generated in the combustion chamber where methane slip, and unburned methane is released with the exhaust gas. With high pressure diesel engines, fugitive methane emissions has been extremely reduced (Lindstad et al., 2020). The fuel cell does not cause such fugitive emissions, and the only gaseous emission is the CO_2. As in Fig. 1.10, CO_2 emission will be recirculated into syngas process by using water to generate more hydrogen fuel.

Conclusion

The new energy space brings many alternative solutions for ship investors and operators. Decision-making in such a perplexing environment is not a one-shot move anymore. Stakeholders need to lay down a clear pathway directing stages to reach a long-term objective. In this regard, we deal with a chain of applications, each naturally transforms to the next stage.

LNG fuel and the LNG fuel cell ecosystem with biogas and syngas integrations demonstrate one of the most viable and coherent pathways for the maritime industry to achieve environmental objectives for 2050 and onward. It is a clean, economically feasible, and most importantly, minimal effort solution to our global climate emergency.

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APPENDIX A

Emission Factors with Low Load Adjustment

PM

	Main Engines (MEs)					Auxiliary Engines (AEs)					Auxiliary Boilers (ABs)				
Load	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG
5%	3.46	1.83	0.76	0.46	0.07	3.51	1.59	0.78	0.44	0.07	1.95	1.00	0.76	0.39	0.07
10%	1.96	1.04	0.43	0.26	0.04	1.99	0.90	0.44	0.25	0.04	1.10	0.57	0.43	0.22	0.04
20%	1.42	0.75	0.31	0.19	0.03	1.44	0.65	0.32	0.18	0.03	0.80	0.41	0.31	0.16	0.03

SO_X

	Main Engines (MEs)					Auxiliary Engines (AEs)					Auxiliary Boilers (ABs)				
Load	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG
5%	18.83	3.49	3.31	0.66	0.00	21.92	4.06	3.88	0.77	0.00	29.46	5.45	5.36	1.08	0.00
10%	12.55	2.33	2.21	0.44	0.00	14.62	2.71	2.59	0.51	0.00	19.64	3.64	3.57	0.72	0.00
20%	10.29	1.91	1.81	0.36	0.00	11.98	2.22	2.12	0.42	0.00	16.10	2.98	2.93	0.59	0.00

NO_X

	Main Engines (MEs)					Auxiliary Engines (AEs)					Auxiliary Boilers (ABs)				
Load	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG
5%	18.10	16.04	15.60	15.60	2.38	14.70	13.02	12.76	12.76	2.38	2.10	1.86	1.83	1.83	2.38
10%	18.10	16.04	15.60	15.60	1.59	14.70	13.02	12.76	12.76	1.59	2.10	1.86	1.83	1.83	1.59
20%	18.10	16.04	15.60	15.60	1.30	14.70	13.02	12.76	12.76	1.30	2.10	1.86	1.83	1.83	1.30

CO

	Main Engines (MEs)					Auxiliary Engines (AEs)					Auxiliary Boilers (ABs)				
Load	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG
5%	5.46	5.46	5.46	5.46	5.46	4.29	4.29	4.29	4.29	5.46	0.78	0.78	0.78	0.78	5.46
10%	2.76	2.76	2.76	2.76	2.76	2.17	2.17	2.17	2.17	2.76	0.39	0.39	0.39	0.39	2.76
20%	1.40	1.40	1.40	1.40	1.40	1.10	1.10	1.10	1.10	1.40	0.20	0.20	0.20	0.20	1.40

CO_2

	Main Engines (MEs)					Auxiliary Engines (AEs)					Auxiliary Boilers (ABs)				
Load	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG
5%	620.62	620.62	588.79	588.79	457.00	722.54	722.54	690.71	690.71	457.00	970.71	970.71	922.97	922.97	457.00
10%	620.62	620.62	588.79	588.79	457.00	722.54	722.54	690.71	690.71	457.00	970.71	970.71	922.97	922.97	457.00
20%	620.62	620.62	588.79	588.79	457.00	722.54	722.54	690.71	690.71	457.00	970.71	970.71	922.97	922.97	457.00

CH_4

	Main Engines (MEs)					Auxiliary Engines (AEs)					Auxiliary Boilers (ABs)				
Load	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG	HFO	VLSFO	MDO	MGO	LNG
5%	0.07	0.07	0.07	0.07	0.07	0.04	0.04	0.04	0.04	0.07	0.01	0.01	0.01	0.01	0.07
10%	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.00	0.00	0.00	0.00	0.03
20%	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01

Source: EPA U.S., 2020; IMO 2020; compiled from various resources. Please refer to Part 2 - Methodology for details.

APPENDIX B

List of LNG Bunkering Locations

City/Port	Country	City/Port	Country	City/Port	Country
Buenos Aires	*Argentina*	Zhuhai Gaolan Port	*China*	Montego Bay	*Jamaica*
Freemantle, Perth	*Australia*	Aarhus	*Denmark*	Himeji/Kobe (Tank Truck)	*Japan*
King Bay, Karratha	*Australia*	Copenhagen	*Denmark*	Nagoya (Tank Truck)	*Japan*
Newcastle	*Australia*	Hirtshals	*Denmark*	Tokyo	*Japan*
Pilbara, Hedland	*Australia*	Hou	*Denmark*	Yokohama	*Japan*
Antwerp	*Belgium*	Santo Domingo⁎	*Dominican Republic*	Aqaba LNG Terminal	*Japan*
Ghent	*Belgium*	Tallinn	*Estonia*	Mina Al Ahmadi	*Kuwait*
Zeebrugge	*Belgium*	Helsinki	*Finland*	Klapeida	*Lithuania*
*Unknown**	*Brazil*	Pori	*Finland*	Pasir Gudang, Johor	*Malaysia*
Hamilton	*Canada*	Tornio	*Finland*	Melaka (Malacca)	*Malaysia*
Montreal	*Canada*	Turku	*Finland*	Doesburg (Inland)	*Netherlands*
Sarnia (Inland, Lake)	*Canada*	Dunkerque	*France*	Rotterdam	*Netherlands*
Tadoussac*	*Canada*	Marseille	*France*	Bjugn	*Norway*
Vancouver	*Canada*	Montoir-de-Bretagne LNG terminal	*France*	Bodø	*Norway*
Quebec City	*Canada*	Port of Brest (Tank Truck)	*France*	Coast Center Base	*Norway*
Chongqing (Inland)	*China*	Roscoff⁎	*France*	Fjordbase	*Norway*
Huaian (Inland)	*China*	Bremen	*Germany*	Florø	*Norway*
Nanjing	*China*	Brunsbuttel	*Germany*	Halhjem	*Norway*
Ningbo	*China*	Cologne (Inland)	*Germany*	Hammerfest	*Norway*
Shanghai	*China*	Emden	*Germany*	Kollsnes	*Norway*
Suqian (Inland)	*China*	Hamburg	*Germany*	Lødingen	*Norway*
Wuhan	*China*	Lubeck	*Germany*	Melkøya	*Norway*
Wuhu*	*China*	Rostock	*Germany*	Mongstad	*Norway*
Xi River	*China*	Gibraltar LNG terminal	*Gibraltar*	Moskenes	*Norway*
Xuzhou (Inland)	*China*	Hong Kong/Macao⁎	*Hong Kong*	Ora (Inland)	*Norway*
Yancheng	*China*	Kochi	*India*	Polarbase	*Norway*
Zhoushan	*China*	La Spezia	*Italy*	Risavika	*Norway*

*In progress.

City/Port	Country	City/Port	Country
Snurrevarden	*Norway*	Sagunto LNG terminal (Tank Truck)	*Spain*
Tjeldbergodden	*Norway*	Santander (Tank Truck)	*Spain*
Vestbase	*Norway*	Valencia (Tank Truck)	*Spain*
Sohar*	*Oman*	Hambantota	*Sri Lanka*
Panama City	*Panama*	Gothenburg	*Sweden*
Swinoujscie (Tank Truck)	*Poland*	Lysekil	*Sweden*
Szczecin	*Poland*	Malmö	*Sweden*
Sines	*Portugal*	Stockholm	*Sweden*
Qatar	*Qatar*	*Unknown**	*Trinidad & Tobago*
Kingisepp	*Russian Federation*	Aliaga (Tank Truck)	*Turkey*
Primorsk	*Russian Federation*	Canakkale*	*Turkey*
Pskov (Inland)	*Russian Federation*	Marmara Ereglisi (Tank Truck)	*Turkey*
St. Petersburg	*Russian Federation*	Dubai Jebel Ali LNG Terminal (FSRU)	*United Arab Emirates*
Ust-Luga	*Russian Federation*	Ruwais LNG Terminal (FSRU Excelerate)	*United Arab Emirates*
Singapore	*Singapore*	Isle of Grain LNG terminal (Tank Truck)	*United Kingdom*
Coega	*South Africa*	Corpus Christi*	*United States*
Busan	*South Korea*	Duluth (Inland)	*United States*
Pyeongtaek (Tank Truck)	*South Korea*	Fourchon (Harvey Gulf)	*United States*
Incheon (Tank Truck)	*South Korea*	Galveston*	*United States*
Algeciras*	*Spain*	Jacksonville	*United States*
Almeria	*Spain*	South Florida	*United States*
Barcelona LNG terminal (Tank Truck)	*Spain*	Mississippi (Tank Truck)	*United States*
Bilbao	*Spain*	New York	*United States*
Cartagena	*Spain*	Port Canaveral	*United States*
Ferrol	*Spain*	Savannah	*United States*
Huelva LNG terminal (Tank Truck)	*Spain*	Seattle*	*United States*
Mugardos	*Spain*	Tacoma*	*United States*

*In progress.

APPENDIX C

List of Biogas and Syngas Production Plants

Country	Biogas or Syngas Plant	Since	Capacity (m3/h)	Nearest Container Port
Austria	Asten/Linz	2010	450	LINZ
	Bruck an der Leitha	2007	500	PETRONELL CARNUNTUM
	Engerwitzdorf	2010	175	LINZ
	Margarethen am Moos	2013	400	PETRONELL CARNUNTUM
	Vienna Pfaenau	2014	150	PETRONELL CARNUNTUM
	Wiener Neustadt	2011	120	FISCHAMEND DORF
Belgium	Merksplas	2018	60	RAVELS
Denmark	Bogense	2015	1,100	KLINTEBJERG
	Fredericia	2013	150	FREDERICIA, VEJLE
	Hammel	2016	524	STUDSTRUP
	Hashoj / Dalmose	2011	125	STIGSNAES
	Hemmet	2015	520	HVIDE SANDE
	Hjørring	2014	1,100	HIRTSHALS
	Hjørring	2015	200	HIRTSHALS
	Holsted	2014	2,500	ESBJERG, FANO
	Horsens	2014	1,400	VEJIE
	Lintrup	2016		ESBJERG, FANO
	Midtfyn	2016	160	BOEJDEN, FAABORG
	Skive	2014	600	SKIVE
	Vaarst	2015	1,000	AALBORG, GRONLANDSHAVNEN
	Vrå	2016	3,000	HIRTSHALS
	Broby	2016	1,600	BOEJDEN, FAABORG
	Kalundborg	2018		KALUNDBORG
	Esbjerg Ø	2018	2,600	ESBJERG, FANO
	Trige	2019	900	AARHUS
	Svendborg	2019		SVENDBORG
Estonia	Kunda	2018	550	KUNDA
Finland	Espoo	2012	450	HELSINKI
	Nykarleby/Jeppo	2014	240	PIETARSAARI
	Virolahti	2015		HAMINA
	Oulu	2017		OULU
France	Mortagne-sur-Sèvre	2014	112	NANTES
	Sourdun	2014	143	NOGENT-SUR-SEINE

Hénin-Beaumont	2015	367	AUBY
Saints	2017	204	BONNEUIL
Noyen-sur-Seine	2017	184	NOGENT-SUR-SEINE
Nangis	2019	153	BONNEUIL, NOGENT-SUR-SEINE
Boutigny	2019	143	PARIS
Golbey	2018	184	MARCKOLSHEIM
Thoiry	2018	112	PORT MARLY, NANTERRE
Vaulx-en-Velin	2018	71	LYON
Marseille	2019	296	MARSEILLE
Inzinzac-Lochrist	2019	82	LORIENT
Machecoul-Saint-Même	2019	128	NANTES
Saint-Selve	2020	510	BORDEAUX
Chaumes-en-Brie	2013	148	BONNEUIL
Wannehain	2015	102	TOURNAI (DOORNIK), ANTOING
Liffré	2015	82	TOURNAI (DOORNIK)
Benet	2017	92	LA PALLICE
Cestas	2018	143	BORDEAUX
Milizac	2018	71	BREST
Vert-le-Grand	2018	255	BOULOGNE BILLANCOURT
Wahlenheim	2019	102	GREFFERN RHEINMUNSTE
Saint-Léonard	2019	230	LE HAVRE
Soudan	2019	179	NOGENT-SUR-SEINE
Les Mureaux	2019	99	NEUILLY-SUR-SEINE
Haraucourt-sur-Seille	2019	306	METZ
Saint-Cyr-l'École	2019	68	BOULOGNE BILLANCOURT
Andelnans	2015	178	WEIL AM RHEIN, MULHOUSE
Strasbourg	2015	190	STRASBOURG
Brie-Comte-Robert	2017	158	BONNEUIL
Pommeuse	2018	204	BONNEUIL
Scherwiller	2018	163	MARCKOLSHEIM
Châteaulin	2018	357	MOULIN MER
Celles-sur-Belle	2019	102	LA PALLICE
Marœuil	2019	204	AUBY
Ay-sur-Moselle	2019	37	METZ
Einville-au-Jard	2020	153	METZ
Lille	2011	673	LAMBERSART
Méry-sur-Seine	2015	138	NOGENT-SUR-SEINE
Locminé	2017	122	VANNES

	Barberey-Saint-Sulpice	2017	143	NOGENT-SUR-SEINE
	Étréville	2018	357	PORT JEROME
	Pleudihen-sur-Rance	2019	70	SAINT BRIEUC
	Saint-Denis-sur-Coise	2019	153	LYON
	Le Poiré-sur-Vie	2019	306	LA BARRE DE MONTS
	Apprieu	2019	102	LYON
	Ivry-le-Temple	2019	153	NEUILLY-SUR-SEINE
Germany	Falkenhagen/Brandenburg (synthetic methane)	2013		BERLIN
	Werlte (synthetic methane)	2013		BREMEN
	Straubing (synthetic natural gas)	2017		REGENSBURG
	Aicha (Osterhofen)	2012	660	PASSAU
	Aiterhofen / Niederbayern	2009	1,100	PASSAU, STRAUBING
	Altenstadt/Hessen	2012	770	FRANKFURT AM MAIN
	Anklam	2013	770	LADEBOW
	Apensen/Grundoldendorf	2012	385	STADERSAND
	Arnschwang	2010	770	REGENSBURG
	Badbergen	2005	220	VAHLDORF
	Badeleben	2014	220	VAHLDORF
	Barleben	2012	413	HOHENWARTHE
	Beetzendorf	2015	385	VAHLDORF
	Berlin-Ruhleben	2013	303	BERLIN
	Biburg	2013	350	KELHEIM
	Börger	2011	500	KALUNDBORG
	Bruchhausen-Vilsen	2011	385	ESBJERG
	Brumby	2013	770	VAHLDORF
	Coesfeld / Höven	2013	330	COPENHAGEN
	Dargun	2010	1,375	KOEGE
	Darmstadt-Wixhausen	2008	165	FRANKFURT AM MAIN
	Darmstadt-Wixhausen II	2011	330	FRANKFURT AM MAIN
	Drögennindorf	2010	385	UELZEN
	Dümmer	2018	630	AARHUS
	Eggolsheim (Kreis Forchheim)	2013	385	BAMBERG
	Eich in Kallmünz	2010	385	REGENSBURG
	Eimbeckhausen	2011	350	STOECKEN, BUNKERSTATION LOHNDE
	Einbeck	2009	550	HILDESHEIM
	Ettlingen	2008	330	KARLSRUHE
	Frankfurt am Main	2018	660	FRANKFURT AM MAIN
	Gardelegen	2013	385	WITTINGEN

Geislingen	2014	385	STUTTGART
Gellersen (Kirchgellersen)	2013	358	UELZEN
Genthin	2016	550	VAHLDORF
Giesen	2012	193	SALZGITTER
Godenstedt	2012	330	STADERSAND
Gollhofen-Ippesheim	2011	770	BAMBERG
Gommern	2017	700	HOHENWARTHE
Gröbern	2015	605	DRESDEN
Gröden	2013	358	DRESDEN
Hamburg	2011	275	STADERSAND
Hankensbüttel / Emmen	2011	385	WITTINGEN
Hardegsen	2009	303	HILDESHEIM
Heidenau (Heidkoppel)	2013	385	STADERSAND
Hellerwald / Boppard	2013	770	KOBLENZ
Hohenhameln-Mehrum	2012	358	SALZGITTER
Ilsede Solschen	2017	700	SALZGITTER
Industriepark Höchst	2011	825	FRANKFURT AM MAIN
Jameln	2006	50	UELZEN
Karben	2012	385	FRANKFURT AM MAIN
Klein Schulzendorf / Trebbin	2012	413	POTSDAM
Klein Wanzleben	2012	770	VAHLDORF
Kleinlüder bei Fulda	2012	550	HAINBURG
Kleinlüder bei Fulda II	2013	310	HAINBURG
Koblenz	2018	280	KOBLENZ
Köckte	2013	358	WITTINGEN
Kroppenstedt	2014	770	VAHLDORF
Lenzen	2016	770	UELZEN
Leuben	2012	770	DRESDEN
Lüchow	2009	385	UELZEN
Maihingen	2008	330	STUTTGART
Malstedt	2011	385	STADERSAND
Marktoffingen	2013	193	STUTTGART
Müden (Aller)	2011	385	WITTINGEN
Mühlacker	2007	550	STUTTGART
Niederndodeleben I	2009	770	SALZGITTER
Niederndodeleben II	2014	770	SALZGITTER
Oberriexingen	2011	523	STUTTGART
Oebisfelde-Weferlingen	2013	770	WITTINGEN

	Pessin	2015	385	BERLIN
	Platten	2016	770	TRIER
	Raitzen	2015	660	DRESDEN
	Reimlingen	2015	770	STUTTGART
	Roßwein/Haßlau	2011	385	DRESDEN
	Sachsendorf	2013	358	VAHLDORF
	Sachsendorf II	2012	430	VAHLDORF
	Sagard (Rügen)	2012	715	MUKRAN
	Schwandorf	2011	1,100	REGENSBURG
	Seelow	2011	770	KOSTRZYN
	Semd (Groß Umstadt)	2010	220	FRANKFURT AM MAIN
	Stresow	2011	358	VAHLDORF
	Stülpe	2014	520	POTSDAM
	Torgelow	2018	700	WOLGAST
	Vahldorf	2019	800	VAHLDORF
	Vahldorf/Jersleben	2019	700	VAHLDORF
	Weikersheim	2015	385	BAMBERG
	Wolfshagen	2014	770	BERLIN
	Wolnzach (Hallertau)	2012	1,210	KELHEIM
	Zeven	2009	138	STADERSAND
	Zeven II	2012	138	STADERSAND
Ireland	Kildare	2020	400	DUBLIN
	Este (PD)	2019	2,000	PORTO VIRO
	Rende	2019	600	CORIGLIANO CALABRO
	Faenza	2019	2,000	RAVENNA
	Guglionesi	2019	500	VASTO
	Codigoro	2020	600	PORTO VIRO
	Bottrighe	2020	450	PORTO VIRO
Netherlands	Almere	2017	510	ALMERE STAD
	Alphen aan den Rijn	2019	180	DEN HAAG
	Alphen aan den Rijn	2014	630	DEN HAAG
	Alphen-Chaam	2019	270	BERGEN OP ZOOM
	Bemmel	2017	900	GENDT, PANNERDEN
	Beverwijk	2012	180	BEVERWIJK
	Boornbergum	2020	44	BURGUM
	Bunschoten- Spakenburg	2010	720	EEMDIJK
	De meerlanden	2010	420	AMSTERDAM
	Den Bommel	2015	24	BRUINISSE

	Den Hoorn	2019	720	HOEK VAN HOLLAND
	Dinteloord	2011	1,320	BERGEN OP ZOOM
	Deurningen	2018	44	HENGELO
	Groningen	2009	900	WILHELMSHAVEN
	Harderwijk	2019	960	HARDERWIJK
	Hengelo	2015	36	HENGELO
	Hensbroek	2012	498	HOORN
	Hoorn	2020	26	HOORN
	Jelsum	2017	168	HARLINGEN
	Kampen	2019	36	KORNWERDERZAND
	Leeuwarden	2018	510	HARLINGEN
	Marssum	2018	210	HARLINGEN
	Merselo	2018	44	MAASHEES
	Middenmeer	2012	720	DEN OEVER
	Mijdrecht	2008	36	AMSTERDAM
	Oude-Tonge	2018	300	BRUINISSE
	Vierverlaten	2012	1,320	WILHELMSHAVEN
	Vlaardingen	2018	210	HOEK VAN HOLLAND
	Vriezenveen	2018	36	ALMELO
	Waalwijk	2015	600	WAALWIJK
	Westpoort Amsterdam	2011	81	AMSTERDAM
	Weurt	2012	318	GENDT, PANNERDEN
	Woudenberg	2019	210	BAARN
	Zeewolde	2019	210	ALMERE STAD
Norway	Oslo	2009	375	OSLO
	Stavanger (SNJ)	2009	325	STAVANGER
Sweden	Bjuv	2007	500	HOGANAS
	Alvesta	2015	400	GOTEBORG
	Borås	2002	450	GOTEBORG
	Borås	2012	300	GOTEBORG
	Botkyrka	2009	800	GOTEBORG
	Eskilstuna	2003	250	KOPING
	Eslöv	2018	350	LANDSKRONA
	Falkenberg	2009	750	FALKENBERG
	Gävle	2017	650	GAVLE
	Gävle	2011	140	GAVLE
	Goteborg	2007	1,000	GOTEBORG
	Helsingborg	2002	350	HELSINGBORG

	Helsingborg	2008	650	HELSINGBORG
	Helsingborg	2014	1,400	HELSINGBORG
	Helsingborg	2008	140	HELSINGBORG
	Huddinge	2015	2,000	STOCKHOLM
	Kalmar	2008	300	KALMAR
	Kalmar	2014	700	KALMAR
	Morrum	2015	400	ELLEHOLM
	Karlskoga	2013	900	KRISTINEHAMN
	Karlstad	2010	200	KARLSTAD
	Kristianstad	1999	90	AHUS
	Kristianstad	2006	300	AHUS
	Laholm	2007	300	HALMSTAD
	Lidingö	2010	500	STOCKHOLM
	Lund	2010	100	LANDSKRONA
	Malmö	2008	300	MALMO
	Norrköping	2005	130	NORRKOPING
	Skellefteå	2007	250	RONNSKAR
	Skellefteå	2018	700	RONNSKAR
	Skövde	2012	700	OTTERBACKEN
	Stockholm	2000	300	STOCKHOLM
	Stockholm	2000	300	STOCKHOLM
	Stockholm	2003	400	STOCKHOLM
	Stockholm	2006	1,410	STOCKHOLM
	Stockholm	2016	1,500	STOCKHOLM
	Trelleborg	2014	2,200	TRELLEBORG
	Trollhättan	2007	400	VANERSBORG
	Trollhättan	2002	400	VANERSBORG
	Ulricehamn	2003	20	GOTEBORG
	Upplands-Bro	2018	1,800	STOCKHOLM
	Vårgårda	2014	500	VANERSBORG
	Västerås	2004	700	VASTERAS
	Västerås	2014	800	VASTERAS
Switzerland	Pratteln	2006	165	BASEL
	Reinach	2015	20	BASEL
	Niedergösgen	2018	160	BASEL
	Turgi	2017	55	BASEL
United Kingdom	Southwold	2014	33	IPSWICH
	Aston Clinton	2016	990	LONDON

Aspatria	2016	550	SILLOTH
Red Lodge	2016	1,000	IPSWICH
North Water Bridge	2016	550	ABERDEEN
North Cave	2017	500	HULL
Bridgham	2016	500	IPSWICH
Castle Eaton	2013	550	SHARPNESS
Coston	2014	700	IPSWICH
Hampton Bishop	2011	550	NEWPORT
Abronhil	2011	495	GRANGEMOUTH
Graythorp	2017	550	HARTLEPOOL
Cliffs End	2013	550	WHITSTABLE
Cuckold’s Green	2014	1,100	IPSWICH
Clyst St Mary	2015	550	TEIGNMOUTH
Euston	2015	616	IPSWICH
Avonmounth	2012	1,375	SHARPNESS
Chapeldonan	2009	2,750	AYR
Hackthorn	2014	495	BARROW HAVEN
Sand Hutton	2016	250	HULL
Chatteris	2015	550	IPSWICH
Burton Agnes	2016	550	HULL
Nocton	2015	550	BOSTON
Hempton	2015	550	KINGS LYNN
Hibaldstow	2014	550	BARROW HAVEN
Farley Hill	2016	550	LONDON
Shurlock Row	2016	550	LONDON
Sleaford	2015	826	BOSTON
New Holkham	2014	550	KINGS LYNN
Ipsden	2014	600	LONDON
Kinglassie	2016	500	PERTH
Coupar Angus	2014	605	PERTH
Leeming	2015	550	HARTLEPOOL
Barking	2017	1,100	SILVERTOWN
Monk Fryston	2016	550	HULL
Newton Aycliffe	2013	660	HARTLEPOOL
Ealand	2014	275	BARROW HAVEN
Bournemouth	2017	571	SOUTHAMPTON
Wormit	2016	550	DUNDEE
Old Mickle-eld	2015	550	HULL

	Merton	2013	550	LONDON
	Rogate	2016	550	SOUTHAMPTON
	Rufford	2016	500	BOSTON
	Milngavie	2016	220	GLASGOW
	Middlesbrough	2015	495	HARTLEPOOL
	Chittering	2014	1,100	IPSWICH
	Lindholme	2013	495	BARROW HAVEN
	Bassetlaw	2016	495	BARROW HAVEN
	Bishop's Cleeve	2015	550	SHARPNESS
United States	Livermore			OAKLAND
	South San Francisco			SAN FRANCISCO
	Pixley			SAN FRANCISCO
	Perris			LONG BEACH
	Sacramento			STOCKTON
	Dubuque			CHICAGO
	Fair Oaks			GARY HARBOR
	Canton			CLEVELAND
	Walnut			LOS ANGELES
	Staten Island			NEW YORK
	Edinburg			BROWNSVILLE
	Houston			HOUSTON
	Charleston			CHARLESTON
	Illinois (synthetic natural gas)			CHICAGO
	Illinois (synthetic natural gas)			CHICAGO
	New York (synthetic natural gas)			NEW YORK
	Texas (synthetic natural gas)			HOUSTON

Source: Compiled from various resources. Given data is subject to change and may be the updated status after the publication of this report. The nearest container port data has been generated from spatial estimations.

APPENDIX D

LNG Bunkering Facilities in North America

LNG Bunkering Facilities in Europe

LNG Bunkering Facilities in Asia & Australia

ABBREVIATIONS

ABs	Auxiliary Boilers
AC	Alternating Current
AEs	Auxiliary Engines
AIS	Automatic Identification System
BTU	British Thermal Units
C_3H_8	Propane
C_4H_{10}	Butane
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DC	Direct Current
DWT	Deadweight Tonnage
ECAs	Emission Control Areas
EEDI	Energy Efficiency Design Index
EIA	Energy Information Agency
EMC	Energy Market Company
EPA	Environmental Protection Agency
FLIGHT	Facility Level Information on GHGs Tool
GHG	Green House Gas
GHGRP	Greenhouse Gas Reporting Program
GT	Gross Tonnage
GWP	Global Warming Potential
HC	Hydrocarbon
HFO	Residual/Heavy Fuel Oil
HH	Henry Hub
ICCT	International Council on Clean Transportation
ICE	Intercontinental Exchange
IMO	International Maritime Organization
JKM	Japan/Korea Marker (Platts)
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LLAF	Low Load Adjustment Factor
LNG	Liquified Natural Gas
LSFOs	Low Sulphur Fuel Oils
LSHFO	Low Sulphur Heavy-Fuel Oil
MARPOL	International Convention for the Prevention of Pollution
MCR	Maximum Continuous Rating
MDO	Marine Distillate Oil
MEPC	Marine Environment Protection Committee
MEs	Main Engines
MGO	Marine Gasoline Oil
MSC	Mediterranean Shipping Company
MMBtu	Million Btu
NBP	National Balancing Point
NGL	Natural Gas Liquids
NMVOCs	Non-Methane Volatile Organic Compounds
NO_X	Nitrogen oxide
OPEC	The Organization of the Petroleum Exporting Countries
PEMFC	Proton-Exchange Membrane Fuel Cell
PM	Particulate Matters
PSC	Port State Control
PtG	Power-to-Gas
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SFOC	Specific Fuel Oil Consumption
SLNG	Singapore LNG
SNG	Substitute LNG or Synthetic LNG
SO_X	Sulphur Emission
TRL	Technology Readiness Level
TTF	Title Transfer Facility
UNFCC	United Nations Framework Convention on Climate Change
VLCC	Very Large Crude Carrier
VLSFO	Very Low Sulphur Fuel Oil

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Contact Editor of this Report:

Dr Okan Duru

Director of Research
E-mail: okan.duru@oceandynamex.com
Ottawa ON, Canada

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