DOI: 10.36163/aon-2024-0003

DEVELOPMENT OF LIQUEFIED NATURAL GAS EXPLOITATION IN MARITIME TRANSPORT

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ABSTRACT

With the development of new technologies and the possibility of various alternatives, LNG continues to evolve and its applications are increasing year on year. This article presents a literature analysis of the use of liquefied natural gas worldwide. Currently, due to the introduction of the Sulphur Directive, alternatives are being sought to reduce environmental pollution. The article describes the volume of toxic compounds released into the atmosphere.

By developing the use of LNG, the magnitude of the benefits of the low-sulphur fuel is understood. Its range of advantages has led to the use of the raw material in maritime transport as a marine fuel. The paper describes the supply chain models that can be used for the different volumes of LNG use.

Keywords: liquefied natural gas, LNG-powered ships, transportation safety, environmental protection

1. INDRUCTION

Liquefied natural gas (LNG) is a raw material that has been liquefied by cooling it to -162°C. In this case, the volume of the gas is reduced 600 times. In practice, this means that LNG occupies a volume 3 times smaller than the same volume of natural gas in its compressed state (usually at a pressure of 20 MPa). [38] This significantly reduces the cost of storing and transporting LNG. LNG is colorless, odorless, non-corrosive and non-toxic. Natural gas requires cryogenic tanks for storage and transportation due to its low temperature. [16, 25, 36]

The characteristics of LNG are: [21, 24, 34, 35]

1. It consists primarily of methane with a small amount of other hydrocarbons, water, carbon dioxide, nitrogen, oxygen and some sulfur compounds. In a process known as liquefaction, natural gas is cooled below its boiling point, removing most of these compounds. The remaining gas is LNG, consisting mainly of methane with small amounts of other hydrocarbons. [10]
2. LNG as a fuel is more economical than traditional fuel. LNG has a higher energy density than CNG and thus has significant potential in CNG market segments that require vehicles to travel longer distances. [6]

3. Most of the world's LNG supply comes from countries with large natural gas reserves. These countries include Algeria, Australia, Brunei, Indonesia, Libya, Malaysia, Nigeria, Oman, Qatar and Trinidad and Tobago. There are 91 LNG receiving terminals around the world. LNG is transported by double-hulled vessels specially designed to transport LNG at low temperatures. LNG is distributed from natural gas wells from pipelines, renewable natural gas sources and condensation. [11]
4. LNG is delivered from liquefaction plants primarily in tanks that transport the fuel to the station, where it is then dispensed to power vehicles. Natural gas can be stored in various forms. Most commonly in underground pressure storage in three types of facilities. Typically, small oil or gas fields are used because they are more readily available. In some countries, natural gas in the form of LNG is stored in aboveground storage tanks. LNG is also used in heating systems, as well as in power generation or other industrial applications. [1, 30]
5. LNG/CNG is the cleanest fossil fuel. LNG is a source of competitively priced energy that can help meet future economic needs around the world.

An important factor in the LNG distribution process is the LNG supply chain. [17] The separation of three models of the LNG distribution chain provides a basis for the analysis of the separate phenomena occurring in each model or the preparation of concepts and technical projects with a specific scope identified in the models. There are different modes of transportation in each group.

2. IMPLEMENTATION OF THE SULFUR DIRECTIVE

New regulations for the Baltic Sea region, in line with the standards of the International Convention for the Prevention of Pollution from Ships (MARPOL - Marine Pollution), provide for a tenfold reduction in the sulfur content of bunker fuel. The previous standard, in effect until January 1, 2015, allowed a 1% concentration of this substance. However, since the Baltic region is part of the SOx Emission Control Areas (SECA), according to the new standards set by the IMO, the maximum sulfur concentration in fuel should now not exceed 0.1%. [12, 19] Maritime vessels that provide their services in these areas must make significant changes to their fuel systems to meet the new regulations. These changes could include switching to a more expensive fuel with reduced sulfur content, such as Marine Gas Oil, by installing a fuel “scrubber” on the vessel, or switching entirely to LNG propulsion. [2]

The full impact of this directive is not yet known. The implementation of restrictive regulations may also trigger the development of new technologies in fuel production and a whole new way of thinking about green fuel consumption.

It is worth noting that growing environmental awareness and the need to reduce greenhouse gas emissions are making LNG an increasingly important part of the future energy landscape. However, the challenges associated with its extraction, transportation and liquefaction require appropriate regulation and technology to ensure the sustainable use of LNG for the environment. LNG has the potential to revolutionize energy, transportation and industry. Its versatility and environmental benefits make it a key component in combating climate change and improving quality of life. LNG has a more favorable environmental impact than traditional fossil fuels, mainly due to its greenhouse gas emissions. [18] Scientific studies have shown that burning LNG generates significantly less carbon dioxide (CO_2) per unit of energy compared to other fossil fuels. This is due, among other things, to LNG's more efficient combustion process and its lower carbon content (Table 1).

Table 1. Carbon dioxide emissions from combustion of different types of fuel (source:18)

Types of fuels	***Emissions CO_2***
Fuel oil	*3,1 t*
Coal	*2,7-2,8 t*
Natural gas	*1,85 t*
Biomass	*0*

Considering the environmental factor, it is important to note that LNG consists mainly of methane. The global economy is focused on minimizing methane emissions during extraction, production and transportation processes, as methane is a potent greenhouse gas. Innovative technologies and monitoring can help reduce these emissions. Therefore, it is becoming right to use LNG in many branches of the world's economies.

3. BENEFITS OF LNG

LNG is an extremely important feedstock for the rapidly growing energy sector. Its main advantage is its high density, which makes it a very efficient and economical energy source. It is also one of the cleanest fuels, as the liquefaction process removes most impurities. This process makes LNG an attractive choice for reducing harmful emissions and combating climate change.

Its main advantages also include low greenhouse gas emissions. LNG is more environmentally friendly than traditional fossil fuels such as coal or oil. Its combustion generates much less CO_2 and other harmful substances, which contributes to reducing climate change. In addition, LNG is an efficient source of energy. [13] It can be used to produce electricity as well as heat, allowing cogeneration and increasing the efficiency of energy processes. [5, 31]

LNG is a versatile fuel and can be used in various sectors, from energy to industry and transportation. This results in the possibility of wide application of the raw material. The development of the global economy and concern for the environment has led to the use of clean fuels, which potentially leads to an increase in natural gas consumption. [15, 28] The inability of many countries to meet the demand for natural gas at the expense of domestic energy reserves makes it necessary to supply gas from imports. On the other hand, the remoteness of gas production areas from markets requires adequate transportation. [29] Above that:

1. LNG production has grown from small facilities covering “peak” gas consumption loads to large production complexes. The capacity of LNG production lines increased from 0.3 million tons in 1964 to 7.8 million tons in 2008.
2. Since the 1990s, various projects have emerged to use LNG as a motor fuel for water, rail and even road transportation.
3. rocket engines using LNG + liquid oxygen as fuel are being developed.
4. At the end of 2022, the European Union has become the world's top LNG consumer, overtaking China, Japan and South Korea.
5. LNG exports from the United States to Europe in 2022 increased 2.5 times to 117.4 million cubic meters.

LNG is a versatile raw material that has been widely used in various areas of the economy: [8, 40]

1. Power generation. LNG is often used in power generation. LNG-fueled power plants are becoming increasingly popular due to their efficiency and lower environmental impact compared to traditional coal-fired power plants. In addition, LNG can also be used in cogeneration, which allows simultaneous generation of heat and electricity, increasing energy efficiency.

2. Transportation. LNG is increasingly being used in transportation, especially in marine and heavy road transport. Ships and trucks fueled by LNG emit significantly less harmful substances than those fueled by traditional fuels. This contributes to reducing the environmental impact of transportation and improving air quality. In addition, LNG refueling networks for passenger vehicles are also being developed, opening up new prospects for green transportation.
3. Industry. The crude is used for such purposes as the production of insulation materials, cooling in industrial processes or as a fuel in manufacturing processes. Its flexibility and low greenhouse gas emissions make it an attractive solution for many companies seeking to reduce their environmental impact.
4. Off-grid energy systems. LNG can also play a key role in providing energy in remote and hard-to-reach areas, especially where traditional energy infrastructure is lacking. In such cases, liquefied natural gas can be used to generate electricity and heat, allowing people to enjoy modern conveniences.

One of the disadvantages of using LNG is infrastructure costs. Building infrastructure to produce, store and transport the crude is expensive. It requires investment in LNG terminals and a specialized transport fleet. Which is a very big inconvenience for some countries because LNG is still dependent on crude supplies, which can create risks related to geopolitical tensions and natural gas prices on the world market. [9]

4. DIRECTIVE LNG DISTRIBUTION LOGISTICS CHAIN MODEL

The import of liquefied natural gas by specialized marine vessels is a transportation technology implemented in many countries. It was initiated in 1965, when the first shipment of LNG from Algeria to the UK was launched. Maritime transportation makes it possible to import gas from a variety of sources located in different parts of the world, which guarantees security of supply, despite the higher costs compared to land transport via pipelines for closer sources of supply. The prerequisite for such deliveries is the possession of a maritime fleet with adequate parameters adapted to shipping conditions in different parts of the world and LNG receiving terminals. [3]

Transport and transmission of gas can be carried out in liquid (LNG) or compressed (CNG) form. The available literature presents analyses that show that transportation of natural gas over distances exceeding 2,500 kilometers is more cost-effective using LNG carriers than transporting compressed gas by pipeline. During transportation by sea, 2% of the cargo is lost due to vaporization. The vaporized gas can be used in the ship's propulsion and power systems, which reduces transportation costs. LNG transported in a liquefied state has a 25% market share in the global trade. A trend of increasing demand for LNG is observed in the market [20] (Table 2).

Table 2. Changes in global LNG volumes by sea (source: 14)

Year	***Transportation volume, million tons***	***Growth rate compared to the previous year, %***
1994	*99*	-
1995	*103*	*4,04*
1996	*110*	*6,8*
1997	*120*	*9,09*
1998	*120*	*0*
1999	*130*	*8,33*
2000	*142*	*9,23*
2001	*143*	*0,7*

Year	***Transportation volume, million tons***	***Growth rate compared to the previous year, %***
2002	*149*	*4,2*
2003	*161*	*8,05*
2004	*169*	*4,97*
2005	*180*	*6,51*
2006	*200*	*11,11*
2007	*210*	*5*
2008	*215*	*2,38*
2009	*222*	*3,26*
2010	*262*	*18,02*
2011	*288*	*9,92*
2012	*237,7*	*-17,42*
2013	*236,8*	*-0,38*
2014	*250*	*5,57*
2015	*244,8*	*-2,08*
2016	*258*	*5,39*
2017	*293,1*	*13,6*
2018	*316,5*	*7,98*
2019	*354*	*11,58*
2020	*356,1*	*0,59*
2021	*372,3*	*4,55*
Average annual growth rate in year 1994–2021		*5,2*
Average annual growth rate in year 2008–2021		*4,5*

LNG is a large natural gas resource, which ensures a stable supply of the resource. This helps secure energy supply and reduce the risk of uncertainty in supply. Accordingly, the LNG supply chain is a succession of stages of interrelated operations that form a network based on technical infrastructure and technological operations. The size of the installation and the distribution area were taken as the basis for the description of the LNG distribution chain model, which also takes into account the division of operations by range of operations. International LNG distribution is carried out according to the following technologies within the logistics chain: [39]

- gas at the terminals is purified and liquefied;
- natural gas extracted from the fields is delivered by pipeline to terminals located on the coast;
- gas is pumped from tanks to gas carriers via heat-insulated pipelines;
- gas is delivered by gas tankers to receiving terminals equipped with unloading facilities, storage and regasification tanks with the raising of its pressure before feeding it into distribution pipelines supplying gas to end users [26, 27].

Gas liquefaction facilities and regasification terminals can be divided in terms of size and volume of gas transported into:

- large-volume - (above 300 tons of LNG/day) for international and intercontinental deliveries by sea,
- medium - (up to 300 tons of LNG/day) of regional importance, usually linked to the LNG distribution network by pipeline or overland transport (by rail or truck),
- small - (up to 20 tons of LNG/day) of local importance linked to the distribution network by land transport (mainly by car) [41, 41].

Taking the above division as a basis, three models of the LNG distribution logistics chain were defined:

1. Large-volume (large). Macrologistic - linked to the processes taking place within the global and national economy, consisting of the following chain elements:

1.1. gas field;

1.2. gas liquefaction - gas liquefaction plant;

1.3. LNG marine terminal - loading;

1.4. transportation by sea - gas carrier;

1.5. LNG marine terminal - unloading;

1.6. regasification;

1.7. gas storage and distribution by pipeline.

2. Medium-tonnage (medium). Mesologic - related to the processes within the economic department, consisting of the following elements of the chain:

2.1. distribution pipeline;

2.2. gas liquefaction plant;

2.3. overland transportation - by rail;

2.4. gas regasification plant;

2.5. distribution pipeline.

3. Low-volume (small). Micrologistic - linked to processes within the company, consisting of the following elements of the chain:

3.1. storage tanks;

3.2. land transportation - by road;

3.3. regasification plant;

3.4. distribution pipeline.

The technology of gas preparation and transportation takes place in several stages. The large-tonnage models describe the entire path of gas from its extraction, to the entry of gas into the distribution network. The medium-tonnage and low-tonnage models describe the logistical processes that take place from the moment the gas is unloaded at a gas terminal on the coast, delivered by various modes of transport and distributed locally.

The development of LNG use in shipping is manifested in: [7, 33]

1. Lower air pollutant emissions: LNG is a relatively clean fuel compared to traditional fossil fuels such as diesel or gasoline. LNG-fueled vehicles emit significantly less air pollutants such as nitrogen oxides (NOx) and particulate matter, helping to improve air quality in urban areas.

2. Reduction of carbon dioxide (CO2) emissions: Liquefied natural gas has a lower carbon content than traditional fuels, resulting in lower CO2 emissions when burned. This in turn supports the goals of reducing greenhouse gas emissions and fighting climate change.
3. Cost savings. While investments in LNG infrastructure may be costly initially, using this fuel can save money in the long run. LNG prices can be more stable than those of traditional fuels, and the energy efficiency of LNG-powered vehicles can bring financial benefits to transportation operators.
4. Noise reduction: LNG-powered vehicles often generate less noise compared to vehicles with internal combustion engines, which has a positive impact on the noise environment in urban areas and on transportation routes.
5. Diversification of energy sources. The use of LNG in transportation contributes to the diversification of energy sources in the transportation sector, which can increase resilience to fluctuating fuel prices and reduce dependence on a single type of fuel.

LNG-based maritime transportation has significant benefits for environmental aspects and energy efficiency compared to traditional marine fuels. The impact of LNG-based maritime transportation relative to environmental aspects and energy efficiency is also manifested in:

1. Energy efficiency: LNG, as an energy-efficient feedstock, allows the reduction of carbon dioxide (CO_2) emissions per transport unit. The introduction of this fuel stimulates the development of modern technologies such as advanced gas engines, contributing to the efficiency of the maritime fleet.
2. Regulatory compliance: LNG-based marine transportation meets current and future regulatory standards, enabling vessel operators to comply with stringent emissions requirements.
3. Diversification of supply sources: the transition to LNG supports the diversification of marine fuel supply sources, contributing to the energy independence of the transportation sector.
4. Investment in infrastructure: the implementation of LNG-based marine transportation requires investment in infrastructure, such as LNG liquefaction terminals and an expanded distribution network. These investments have the potential to support local economies and create jobs.

In summary, LNG-fueled maritime transportation is an effective alternative to traditional marine fuels, marking a new era in sustainable transportation. The ultimate success of this transformation depends on a comprehensive industry approach, effective regulation and systematic investment in technology and infrastructure development. [4]

5. CONCLUSIONS

Maritime transport remains one of the most efficient and economical means of intercontinental freight transport. Therefore, in order to ensure environmental safety, restrictions or new solutions are being developed to eliminate the problem.

There is a steadily growing interest in the use of LNG as a fuel for marine vessels. This is happening against the backdrop of a general increase in attention to environmental issues and regulatory pressure to reduce emissions from shipping. One of the key benefits of using LNG is lower emissions compared to traditional fuels such as oil and diesel. The use of LNG can help reduce emissions of sulfur dioxide (SOx), nitrogen oxides (NOx) and particulate matter in the air.

Investment in new technologies is leading to the reorganisation of fleets and infrastructure in favour of LNG. This may involve the construction of new ships, the conversion of existing ships to use LNG, or the development of infrastructure to support the delivery of LNG to ports. LNG is used as a fuel for a variety of marine vessels, including container ships, tankers, bulk carriers and passenger ships. It should be noted, however, that the introduction of LNG in the transport sector poses some challenges, such as the need to develop refuelling infrastructure and adapt existing or purchase new vehicles, which can be costly. In addition, the sustainable use of LNG requires close monitoring and optimisation of processes to minimise potential negative environmental impacts. [32]

Work is constantly underway around the world to improve technologies for extracting, transporting and storing the resource. Also, it is worth noting that at various stages of gas deployment there is the possibility of using alternative gas transportation technologies: CNG - compressed gas; NGH - gas in the form of gas hydrate; GTL - gas in liquid form; GTW - gas for electricity. [23, 37]

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