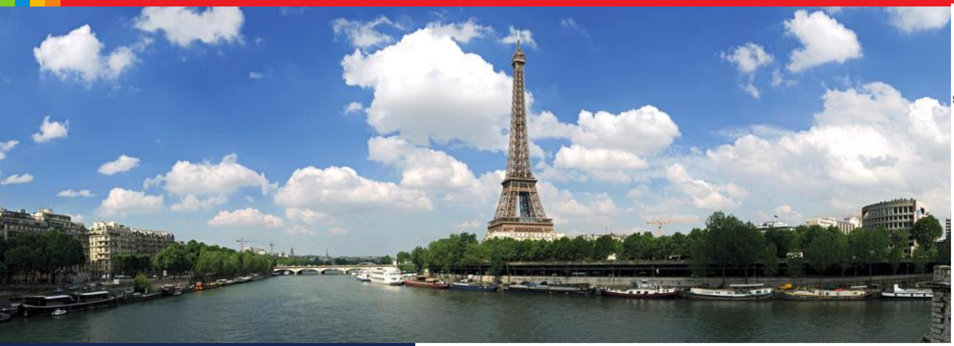
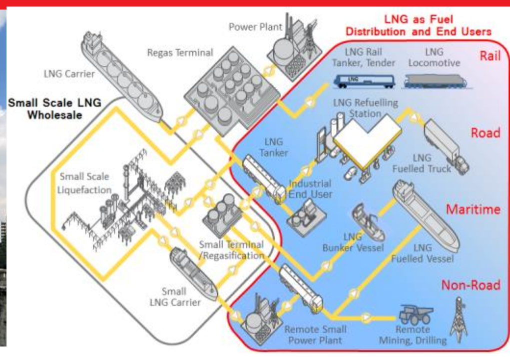
2012-2015 Triennium Work Reports





LNG as Fuel

International Gas Union

Programme Committee D Study Group 2

June 2015

WGCPARIS2015
WORLD GAS CONFERENCE

IGU
INTERNATIONAL GAS UNION
UNION INTERNATIONALE DU GAZ

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Acronyms

Acronym	Term
AAR	American Association of Railroads
ABS	American Bureau of Shipping
ADR	International Carriage of Dangerous Goods by Road
BLEVE	Boiling Liquid Expanding Vapor Explosion
BOG	Boil off gas
BRG	Berkeley Research Group
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Butane
CAA	Clean Air Act
CAGR	Compound Annual Growth Rate
CH_4	Methane
CHP	Combined heat and power
CI	Compression-ignition
CLNG	Center for Liquefied Natural Gas
CN	Canadian National Railway
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CREG	Belgium's Regulatory Commission for Electricity and Gas
DGB	Dynamic Gas Blending
DMA	Danish Maritime Authority
DOE	United Stated Department of Energy
DOT	United States Department of Transportation
EC	European Commission
EC Report	European Commission Report on Climate Action
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EIA	United States Energy Information Administration
EMD	Electro motive diesel
EPA	United States Environmental Protection Agency
ERS	Emergency Release System
EU	European Union
FRA	Federal Railroad Administration
GHG	Greenhouse gas
GIIGNL	International Group of Liquefied Natural Gas Importers
HC	Hydrocarbon
HES	Health, Environment and Safety
HFO	Heavy fuel oil
HPDI	High pressure direct injection
IAPH	International Association of Ports and Harbors'
IEA	International Energy Agency
IEO	International Energy Outlook
IMO	International Maritime Organization
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCNG	Liquefied-Compressed Natural Gas

LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSFO	Light sulphur fuel oil
MARAD	United States Department of Transportation Maritime Administration
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
MEPC	Marine Environment Protection Committee
MGO	Marine gas oil
MN	Methane number
MW	Megawatt
N	Nitrogen
N_2	Nitrogen gas
N_2O	Nitrous oxide
NFPA	National Fire Protection Association
NGFT TAG	Natural Gas Fuel Tender Technical Advisory Group
NGV	Natural gas vehicle
NMHC	Non-methane hydrocarbon
NO	Nitric oxide
NO_2	Nitrogen dioxide
NOx	Nitrogen oxide
NTPC	Northwest Territories Power Corporation
OACI	International Civil Aviation Organization
PLG	Gas liquefied under pressure
PM	Particulate matter
PPE	Personal Protective Equipment
psig	Pounds per square inch gauge
PSV	Platform service vessel
PTS	Port to Ship
PTT	Portable tank transfer
QCDC	Quick Connect Disconnect
SEEMP	Ship Energy Efficiency Management Plan
SI	Spark-ignition
SIMOPS	Simultaneous operations
SO_2	Sulfur dioxide
SOx	Sulphur oxide
STS	Ship to Ship
THC	Total hydrocarbon emission
TTS	Truck to Ship
TPED	Transportable Pressure Equipment directive
UIC	Union Internationale des Chemins de fer
UNFCCC	United Nations Framework Convention on Climate Change
WM	Wood Mackenzie
WPCI	World Ports Climate Initiative

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1. Executive Summary

The International Gas Union (IGU) study, “LNG as Fuel”, explores the evolving role of Liquefied Natural Gas (LNG) as a fuel across all industries that consume hydrocarbon energy—transportation in road, rail, marine, aviation, heavy machinery, mining, drilling, agriculture and remote power generation. Whether principle interests relate to the regulatory or environmental drivers, the economic or commercial incentives, or the health and safety aspects of operations, all participants in this fuel evolution should be aligned for success. The goals of the IGU study on “LNG as a Fuel” are to increase awareness of the rapidly evolving LNG as fuel business and promote informed discussion of tangible next steps for a safe, economic and reliable industry.

A success factor in the evolution of LNG as a fuel is the growth and availability of small scale LNG. The small scale LNG business is rapidly developing across the globe with new regions opening up and new players entering this sector while existing players expand. Compared to the well-established base-load LNG industry, small scale LNG is characterized by different dynamics and drivers. Details of small scale LNG are provided in the IGU study on “Challenges and Opportunities of Small Scale LNG”.

“LNG as Fuel” presents a comprehensive analysis of the use of LNG as the physical form, which is regasified for consumption in natural gas engines and dual fuel (natural gas and diesel) engine applications. This report focuses on the distribution and end users portion of the value chain, Figure 1.

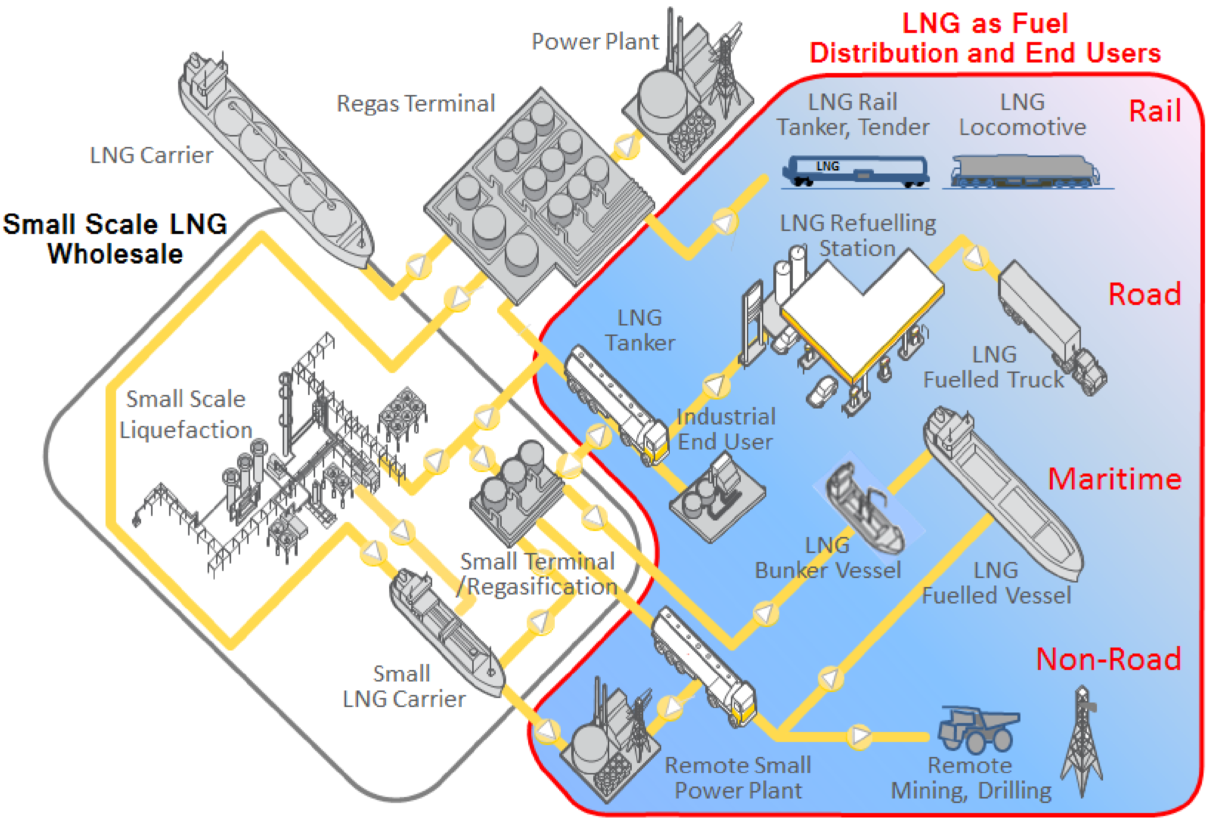

Figure 1 - LNG as Fuel Applications

a. Environmental Drivers

There is growing global interest to reduce emissions with varying levels of commitment regionally. World petroleum and other liquids consumption is forecast to grow by 38% between 2010 and 2040. With the increased consumption comes the associated emissions of energy-related greenhouse gases (GHG), forecast to increase 45% by 2040. The world is on a trajectory toward long-term temperature increase of 3.6˚C, far above the internationally agreed target. As a result the global climate debate is driving change for cleaner burning natural gas and alternate fuels.

The maritime industry accounts for only 2.7% of world CO_2 emissions but causes 14% of the world SOx pollution. A global cap of 3.5% on the sulphur content of marine bunker fuel, effective from January 2012, is scheduled to reduce to 0.5% from January 2020. Within Environmental Control Areas (ECA), the sulphur limit was reduced to 0.1% from 1% effective 1 January 2015. As one solution, the maritime industry has begun studying and implementing LNG as a maritime transport fuel to reduce emissions in response to regulations.

From an environmental emissions perspective, LNG as fuel is a viable mitigant significantly reducing emissions of carbon dioxide (CO_2) up to 20%, sulfur oxide (SOx) up to 100%, nitrogen oxide (NOx) up to 90%, and particulate matter (PM) up to 99%. The maritime industry is the low hanging fruit leading the transition to LNG as fuel, primarily due to global concern about SOx emissions.

The On-Road transportation sector, which is the largest contributor to transportation emissions, has the potential to have the greatest impact on reducing emissions by using LNG as a fuel supply in the heavy vehicle (over 33,000 pounds) segment. Heavy vehicles are characterized by high utilization on defined corridors and regular schedules, which facilitates planning refueling infrastructure.

b. Business Drivers

Market pull from owners and operators of ships, buses, heavy trucks, locomotives and drilling equipment has caused engine manufacturers to begin designing and building a range of natural gas and dual fuel engines for use with LNG. The engine industry seems to be in an evolutionary phase and will need added time to meet the needs of all customers as they evaluate and test these new engines for economical business solutions.

The On-Road transportation sector driven by commercial fleet owners in LNG fueled vehicles has grown significantly over the past decade. In China, major LNG corridors already exist with 1330 LNG stations in place in 2013 and an environmental call to improve air quality by increasing that number to 10,000. In Europe, the Blue Corridors project is underway to build LNG fueling infrastructure and to demonstrate the economic viability of LNG fuel for heavy trucking to encourage growth. The project includes 14 new LNG or LCNG stations along four corridors connecting Europe's South to North and West to East and a fleet of 100 LNG heavy duty vehicles..

The Maritime transportation sector is rapidly developing LNG as fuel capability with 134 LNG fueled ships in operation or on order as of January 2015. By 2020, DNV-GL expects 1000 new buildings to be delivered with natural gas engines, equal to 10-15% of new ships.

Additionally, 600 to 700 ships could be retrofitted to run on LNG. After 2020, DNV-GL estimate 30% of new builds annually (3,600 to 4,500) will be LNG fueled.

The Non-Road transportation sector is making advances using LNG as a fuel supply for mining and drilling operations, remote small-scale power barges, remote community and industrial fuel supplies, railway locomotive test programs, and very long lead time aviation research.

A dilemma exists between the level of LNG demand and the availability of LNG supply and distribution, with owners on both sides of the business depending on the other to anchor new investments. As a result cooperatives and partnerships are being formed to mitigate commercial risks, align business interests and move supply and demand projects forward in parallel. The value can be captured by those willing to take the risk and invest in the future of LNG as fuel.

A potential benefit for all end users may be fuel cost savings of natural gas relative to diesel fuel cost if the advantageous price differential in some regions becomes a sustainable reality. The current oil price cycle poses a challenge for LNG as Fuel applications and is expected to delay greater acceptance and implementation due to owners' preference to use lower cost fuels and utilize abatement measures. Furthermore, if LNG is taxed on a volumetric basis, this could be detrimental for LNG because it has lower energy content per unit volume than diesel.

c. Attention to Safety

The LNG industry has created an enviable track record of safety in operations and transport. Many government and industry entities have shown their support in maintaining that high level focus by publishing a number of excellent guidelines and checklists. However, with a growing number of participants along the value chain, there is a challenge that all parties conform to the same high level of attention to safety. A single LNG incident could impact public perception causing a ripple effect that could negatively impact the broader natural gas industry.

Primary risks associated with LNG as fuel tend to be related to LNG transport and cargo transfer at a smaller scale than current industry norms. Number of LNG tank trucks on roadways, bunker vessels in ports and harbors and methane slippage to the atmosphere during connections are the key areas of interest for heightened safety awareness. Training is the principal means of minimizing the chance of human error. Regular inspection and preventive maintenance should avert use of damaged equipment. Use of interconnector fittings is the existing safeguard to make leak-tight connections.

We, as an industry, need to embrace all new players and ensure that safety information is widely disseminated on all aspects of LNG transfer, transport and dispensing to all stakeholders interested in LNG as fuel. Industry, local government authorities and first responders must coordinate effectively to maintain a high level of awareness of LNG related activities and ensure all stakeholders are engaged in promoting a culture of Safety.

The outlook for LNG as fuel is very positive and continues to gain momentum!

2. Energy Outlook, Emissions and Regulations

This chapter presents the global energy outlook to 2040 for Organization for Economic Cooperation and Development (OECD) and non-OECD countries, energy related CO_2 emissions, and the contribution of the transportation sector[1]. We then look at the evolution of emissions regulations across all sectors of transportation. In particular, we look at the maritime sector to understand the stringent regulations imposed under the International Convention for the Prevention of Pollution from Ships (MARPOL) regarding protection of the marine environment by the International Maritime Organization (IMO), an agency of the United Nations. This background provides the setting for considering use of LNG as an alternative clean fuel that satisfies emissions regulations across all end user sectors identified in the scope of this study.

a. Energy Outlook

The U.S. Energy Information Agency (EIA) International Energy Outlook 2014 (IEO2014) reference case forecasts world petroleum and other liquids consumption will grow by 38% between 2010 and 2040. The growth is driven by strong, long-term economic development in countries outside the OECD, where average annual growth is 2.0%. In particular, non-OECD Asia and the Middle East account for 85% of the total increase in world liquid fuels consumption, Figure 2.

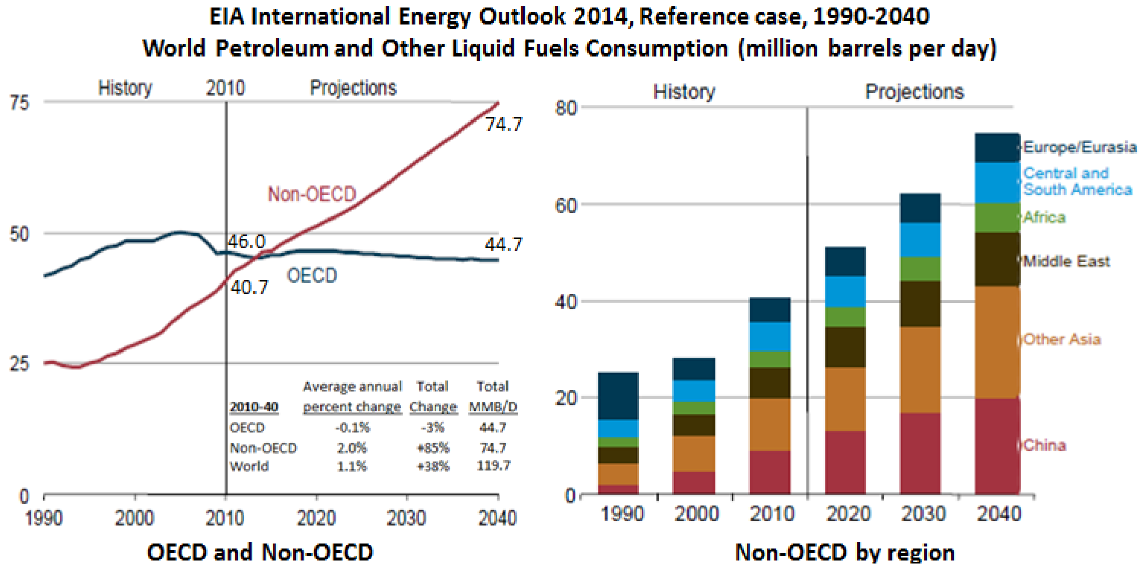

Figure 2 - World Petroleum and Other Liquids Consumption 1990-2040

Consumption of world petroleum and other liquids by end-use sector for OECD countries compared to Non-OECD countries for the reference case is given in Figure 3. Fast-paced economic expansion among the non-OECD regions drives the increase in demand for liquid fuels for personal and freight transport, as well as for energy in the industrial sector[2]. As of 2014, liquid fuels consumption in non-OECD countries exceeds that of OECD countries.

[1] OECD and non-OECD member listing are included in Appendix 9.1.

[2] U.S. EIA International Energy Outlook, 9 September 2014. DOE/EIA-0484 (2014).

Liquids consumption in OECD countries declines slightly, by -0.1% per year over the 2010-2040 time period. In much of the OECD, relatively stable economic growth and static or declining population levels contribute to lower levels of liquid fuels consumption. In addition, many OECD governments have adopted policies that mandate improvements in the efficiency of motor vehicles, and consumers are turning to more fuel-efficient transportation choices in the face of sustained high oil prices[3].

The EIA reports that as China's economy moves from dependence on energy intensive industrial manufacturing to services, the transportation sector becomes the most significant source of growth in liquid fuels use, and the country's liquid fuels consumption more than doubles from its 2010 level. Liquid fuels demand in the Middle East grows substantially due to strong population growth rates, rising incomes and liquids-intensive industrial demand.

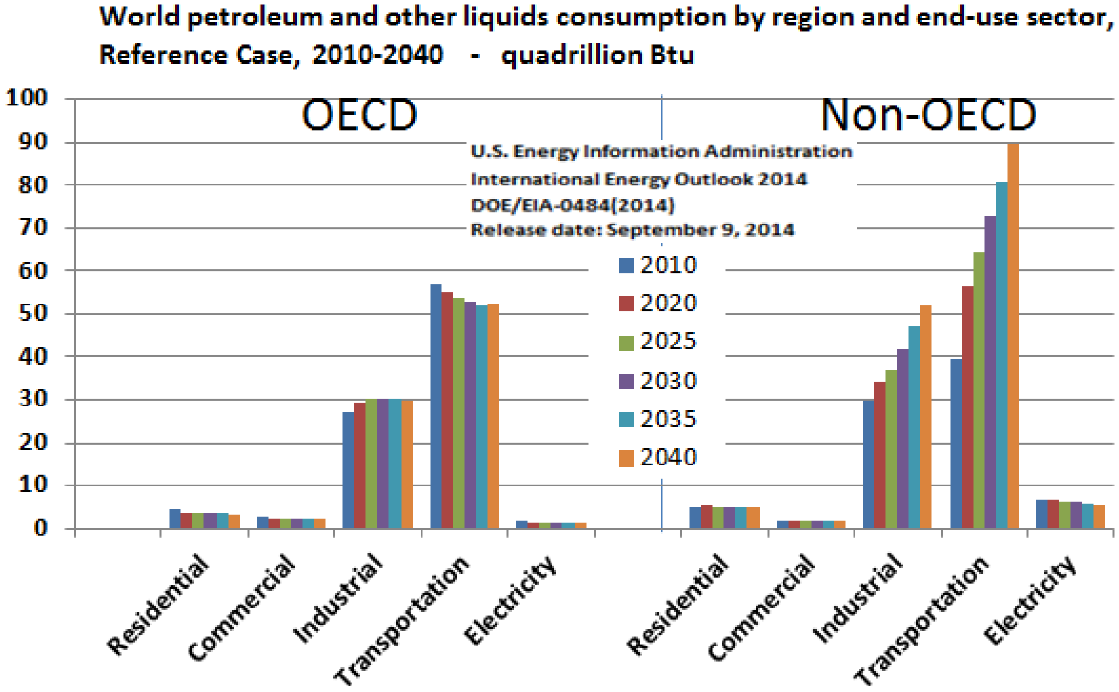

Figure 3 - World Liquids Consumption by End Use Sector

China, India and other Asia account for 60% of non-OECD consumption in 2040, while Africa, other Europe/Eurasia, Brazil, Middle East, other Central /South America and Russia account for the balance.

Petroleum and other liquid fuels remain the largest source of world energy. Liquids consumption increases only in the transportation and industrial sectors, while declining in the residential, commercial and electric power sectors due to rising world oil prices and the ability to switch to alternative fuels. The use of liquid fuels in the transportation sector continues to increase despite rising prices due to transportability and high energy density.

b. Emissions

With the increased consumption of transport fuels comes the associated increase in emissions of energy-related anthropogenic GHG. Within the energy sector, CO_2 resulting

[3] Ibid

from the oxidation of carbon in fuels during combustion dominates the total GHG emissions[4]. The International Energy Agency reports that in the central scenario, the world is on a trajectory consistent with a long-term temperature increase of 3.6˚C, far above the internationally agreed target to hold the increase in global average temperature below 2°C above preindustrial levels. As a result, energy consumption is a critical component of the global climate debate driving the push for change to clean burning natural gas and alternative fuels. This environmental driver along with the need for adequate range between refueling stations sets the stage for LNG as fuel opportunity.

The EIA's International Energy Outlook 2013 (IEO2013) focuses on world CO_2 emissions during 2010-2040[5]. In the Reference case, CO_2 will increase approximately 45%, to 45 billion metric tons in 2040 from 31 billion metric tons in 2010, with the vast majority of growth in Non-OECD countries, Figure 4.

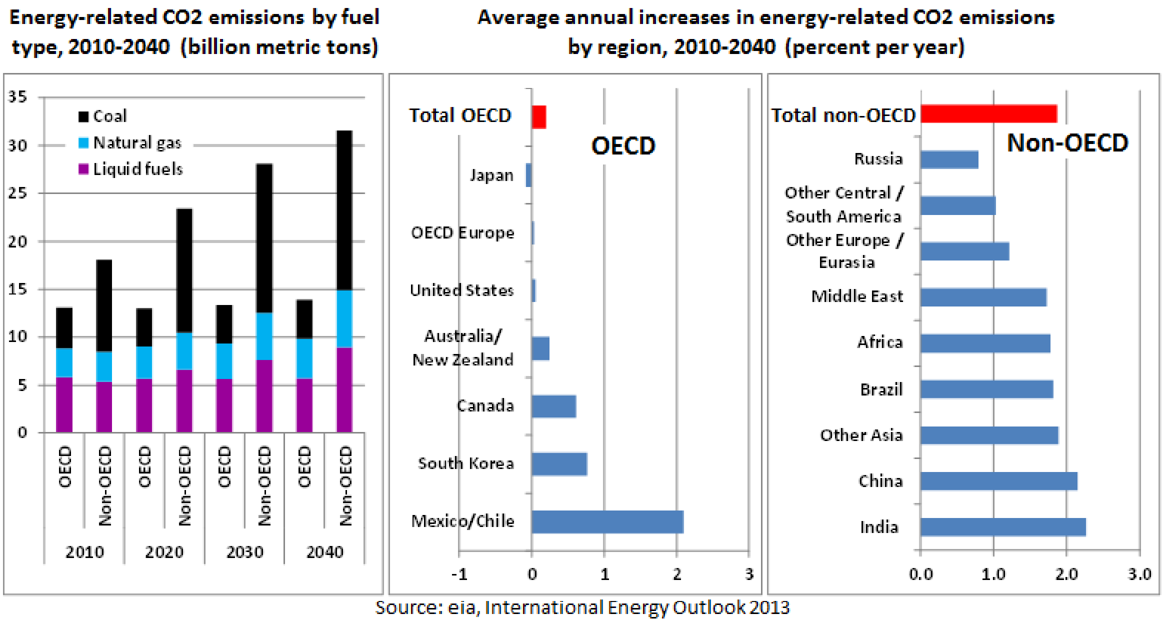

Figure 4 - CO_2 Emissions by Fuel Type and Average Annual Increase by Region

The IEO2013 forecast shows that non-OECD countries account for 94% of the total increase in world energy related CO_2 emissions, with the largest contributors being China, India, Other Asia and Middle East .The total average annual increase in CO_2 emissions in non-OECD countries is 1.9%, while in OECD countries it is 0.2%. Identification of OECD countries and non-OECD countries is given in Appendix 9.1.

The IEO2013 notes that two energy sectors combined are the source of about two-thirds of global CO_2 emissions in 2011: Electricity-and-Heat (42%) and Transport (22%)[6]. Within the transport sector, road transport accounts for 72.3% of emissions followed by marine (9.0%) and aviation (6.6%). LNG as fuel is a viable mitigant significantly reducing emissions of CO_2, NOx, SOx and PM.

[4] IEA Statistics, 2013 Edition, CO_2 Emissions From Fuel Combustion, Highlights.

[5] U.S. Energy Information Administration | International Energy Outlook 2013, Appendix K.

[6] International Energy Agency, 2011 CO_2 Emissions Overview, CO_2 Emissions from fuel combustion

Actions taken to curb energy emissions will be pivotal in determining whether or not environmental goals are reached[7]. Many government initiatives are underway to reduce carbon emissions, including: the U.S. Climate Action Plan, the European discussions on 2030 energy and climate targets, the Chinese plan to limit domestic use of coal, and the Japanese discussions on a plan to limit energy related CO_2 emissions.

Agreement was reached at the United Nations Framework Convention on Climate Change (UNFCCC) 17th Conference of the Parties conference in December 2011, to launch a process to develop a policy with legal force under the Convention applicable to all Parties. An important step forward occurred at the 20th Conference of the Parties in December 2014 through negotiations by over 190 countries[8]. Nations concluded by elaborating the elements of the new agreement, scheduled to be agreed in Paris in late 2015, while also agreeing the ground rules on how all countries can submit contributions to the new agreement during the first quarter of 2015. The Intended Nationally Determined Contributions (INDC) will form the foundation for climate action post 2020 when the new agreement is set to come into effect. During the 20th Conference of the Parties, countries also made significant progress in elevating “adaptation” onto the same level as “action” to cut and curb emissions.

A reference report by the European Commission (EC) Joint Research Centre (JRC) on regulating emissions to air from ships found that designing policy strategy to abate emissions from international maritime transport is complex due to the international regulatory framework that governs the sector[9]. The emissions from marine engines is directly related to total fuel consumption, which depends on multiple factors including hull size, shape and roughness, loading conditions, engine condition, maneuvering time and cargo operations.

DNV-GL reported on the results of multiple researchers and found that in addition to CO_2 emissions, the emissions of SOx and NOx, particularly from the marine transportation sector, are a great concern[10]. SOx emissions cause cooling through effects on atmospheric particles and clouds. NOx emissions increase the levels of the GHG ozone (O_3) and reduce methane (CH_4) levels. These changes cause warming and cooling, respectively, with a net result that is a strong cooling effect. Given the tightening regulations on shipping emissions of SOx and NOx, lower future shipping emissions means lower future cooling effect. Lower cooling effect adds to the problem of global warming.

Lloyds Register reports that marine heavy fuel oil (HFO) with high-sulphur content accounted for 76% of marine bunker fuel in 2010[11]. For economic reasons, the shipping industry commonly consumes HFO, which is the residual end product of the refinery process. While

[7] International Energy Agency World Energy Outlook 2013, Executive Summary.

[8] UNFCCC Press Release, 14. Dec, 2014: Lima Call for Climate Action Puts World on Track to Paris 2015.

[9] European Commission, Joint Research Centre, Institute for Environment and Sustainability, JRC Reference Reports, Regulating Air Emissions from Ships. The State of the Art on Methodologies,Technologies and Policy Options, Apollonia Miola, Biagio Ciuffo, Emiliano Giovine, Marleen Marra. November 2010. [JRC Report]

[10] DNV, Assessment of measures to reduce future CO2 emissions from shipping, Research Innovation Position Paper, May 2010.

[11] Lloyds Register, LNG-fuelled deep sea shipping. The outlook for LNG bunker and LNG-fuelled new-build demand up to 2025. August 2012. [LR Report]

shipping accounts for only 2.7% of world CO_2 emissions, it causes 14% of the world SOx pollution[12].

A comparison of sulphur content of fuels ranging from road diesel to the upper IMO limit for shipping is given in Figure 5[13]. The chart also includes other marine fuel oils, and established and proposed maritime fuel limits. The global average marine HFO oil has approximately 2,700 times more sulphur content than that of conventional diesel for cars at 10 ppm. By comparison, LNG has no sulphur content.

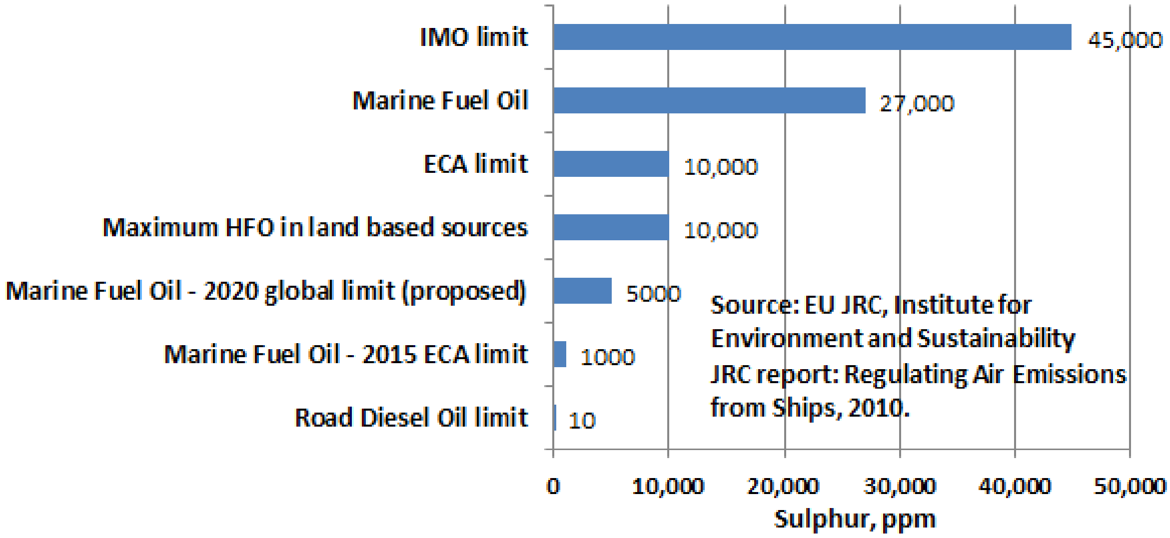

Figure 5 - Relative Sulphur Content of Marine Fuel Oil

Air pollution has significant negative impacts on human health and well-being, which entail substantial economic consequences. A report by the Center for Energy, Environment and Health in 2011 on the health-cost impact of air pollution in Denmark and Europe estimates that the number of premature deaths in Europe due to international ship traffic is around 50,000 cases per year, and will increase in spite of the introduction of the sulphur emission control areas (SECA) [14]. International ship traffic constitutes a major problem for impacts on human health in Europe with economic impact estimated at 58 bn Euros/year in the year 2000 increasing to 64 bn Euros/year in the year 2020, due to a general increase in the ship traffic worldwide. Hence, health and economic impacts are major drivers for timely and effective regulation of emissions to the atmosphere from shipping and other sources.

C. Emissions Regulations

The following sections of this chapter discuss the broad responsibility for regulating emissions from mobile sources around the world. The increasing number of interested parties considering use of LNG as a fuel for transportation, small scale remote power or as remote supply for local gas distribution has prompted several leading organizations to publish studies and guidelines aimed at assisting LNG stakeholders in understanding and

[12] Society for Gas as a Marine Fuel, Introductory Guide, Version 1, September 2014.

[13] JRC Report.

[14] Center for Energy, Environment and Health, Scientific Report No 3: Environment and Health (CEEH), Assessment of Health-Cost Externalities of Air Pollution in Denmark and Europe using the EVA Model System, 2011.

implementing the existing and planned policies and legislation intended to protect air quality. A sample of studies focused on maritime LNG bunkering infrastructure is given in Figure 6.

Reference Document	Source
Bunkering of LNG-fueled Marine Vessels in North America	American Bureau of Shipping (ABS)
Liquefied Natural Gas (LNG) Bunkering Study	U.S. Department of Transportation Maritime Administration (MARAD), DNV-GL
LNG bunkering in the Port of Antwerp	Port of Antwerp
Gas Technology - A Special Report on Gas Solutions (Bunkering)	Lloyd's Register Report
LNG Bunker Checklists (Shore to Ship, Truck to Ship, Ship to Ship)	Int'l Association of Ports and Harbors' (IAPH) World Ports Climate Initiative (WPCI)
Joint Industry Project, LNG Fuel Bunkering in Australia: Infrastructure and Regulations	DNV-GL

Figure 6 - Example of Maritime Studies and Guidance on LNG Bunkering

The U.S. Environmental Protection Agency (EPA) is authorized under the Clean Air Act (CAA), to regulate emissions from mobile sources, which includes a wide variety of vehicles, engines, and equipment[15]. "On-road" or highway sources include vehicles used on roads for transportation of passengers or freight. “Non-road” or off-road sources include vehicles, engines, and equipment used for construction, agriculture, recreation, and many other purposes. Within these two broad categories, sources are further distinguished by size, weight, use, and/or horsepower.

Mobile source sectors regulated by the EPA include: aircraft, heavy duty vehicles, light duty vehicles, locomotives, motorcycles, marine compression-ignition (CI) engines, marine spark-ignition (SI) engines and vessels, non-road CI engines and equipment, non-road large SI engines and equipment, non-road small SI engines and equipment, and recreational engines and vehicles. The Emission Standards Reference Guide on the EPA website provides detailed emission standards for all regulated sectors[16].

Mobile sources pollute the air through combustion and fuel evaporation, contributing to four significant air pollutants: carbon monoxide (CO), hydrocarbons (HC), NOx, and PM. Additionally, air toxics and GHG are emitted. Air toxics are pollutants known or suspected of causing cancer or other serious health or environmental effects. GHG, such as CO_2, trap heat in the earth's atmosphere, contributing to global climate change.

The EPA regulates emissions from mobile sources by setting progressively more stringent emission standards for the specific pollutants being emitted. EPA also sets sulfur standards for gasoline, on-road diesel fuel, and non-road diesel fuel. Once emission standards are set for a particular engine and/or vehicle category, manufacturers must produce engines that meet those standards within the timeframe of the corresponding implementation schedule. The EPA specifies test procedures to measure engine or vehicle emission levels, and uses the test results to determine compliance.

[15] EPA, Emission Standards Reference Guide, Basic Information, Overview of Mobile Sources, www.epa.gov
[16] Ibid

European Union (EU) emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of EU directives staging the progressive introduction of increasingly stringent standards. European emission regulations for new heavy-duty diesel engines are commonly referred to as Euro I through VI; regulations for new light duty vehicles are commonly referred to as Euro 1 through 6. Details on regulations and directives for transport and environment are available on the EC Environment website[17].

Emission standards specify the maximum amount of pollutants allowed in exhaust gases discharged from a diesel engine. The "tailpipe" emission standards were initiated in California in 1959 to control CO and HC emissions from gasoline engines. Today, emissions from internal combustion engines are regulated in tens of countries throughout the world. The regulated diesel emissions include:

- Diesel PM, measured by gravimetric methods. Sometimes diesel smoke opacity measured by optical methods is also regulated.
- NOx composed of nitric oxide (NO) and nitrogen dioxide (NO_2). Other oxides of nitrogen which may be present in exhaust gases, such as nitrous oxide (N_2O), are not regulated.
- HC gases, regulated either as total hydrocarbon emissions (THC) or as non-methane hydrocarbons (NMHC). One combined limit for HC + NOx is sometimes used instead of two separate limits.
- CO

Emissions are measured over an engine or vehicle test cycle which is an important part of every emission standard. Regulatory test procedures are necessary to verify and ensure compliance with the various standards. These test cycles are supposed to create repeatable emission measurement conditions and, at the same time, simulate a real driving condition of a given application; this adheres to the standardized terms of "Repeatability" and "Reproducibility" adopted by many global standardization organizations. Analytical methods that are used to measure particular emissions are also regulated by the standard. The DieselNet website provides information on emissions standards for North America, Europe, Asia, Australia and South America covering On-Highway, Non-road, Marine, Locomotive, and other relevant emissions sectors.

d. On-Road Transport

There has been an evolution of global on-road emissions regulations as illustrated by Cummins Emissions Regulations in Figure 7[18]. North America, Western Europe, Scandinavia and Japan are leading global efforts through enactment of emissions regulations issued in recent years. The EPA and the EU have each issued a series of increasingly stringent emissions rules and GHG regulations with effect from various dates.

[17] European Commission, Environment, Air, Transport & Environment: http://ec.europa.eu/environment/air/transport/index.htm

[18] On-Highway Emissions Regulations, Cummins Emissions Solutions.

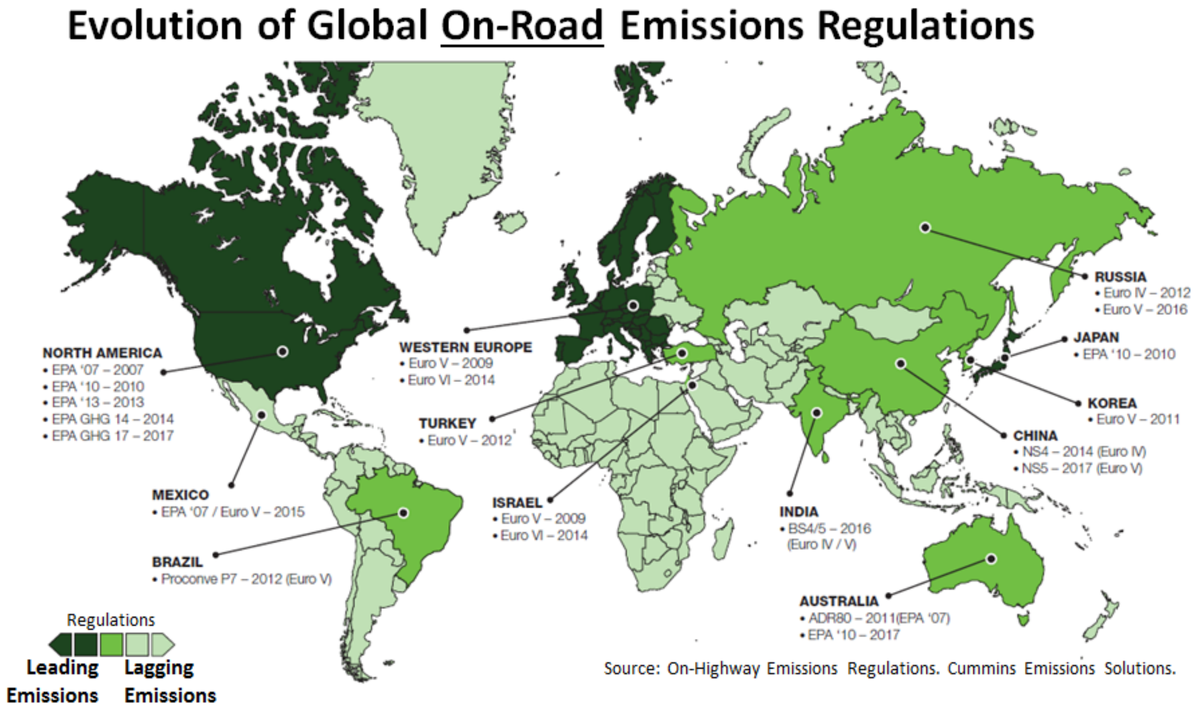

Figure 7 - Evolution of Global On-Road Emissions Regulations

Regulatory limitations on NOx and PM have been reduced in steps over the past decade causing the transportation industry to require cleaner burning fuels or to install filters and equipment to clean the engine exhaust before venting to the atmosphere. Many countries have begun to put regulations into place, often adopted out right or adapted from EPA or EU rules. In particular, note the progressive reduction of allowable NOx and PM levels, measured in units of grams / hp-hour, illustrated in Figure 8, for on-road vehicles.

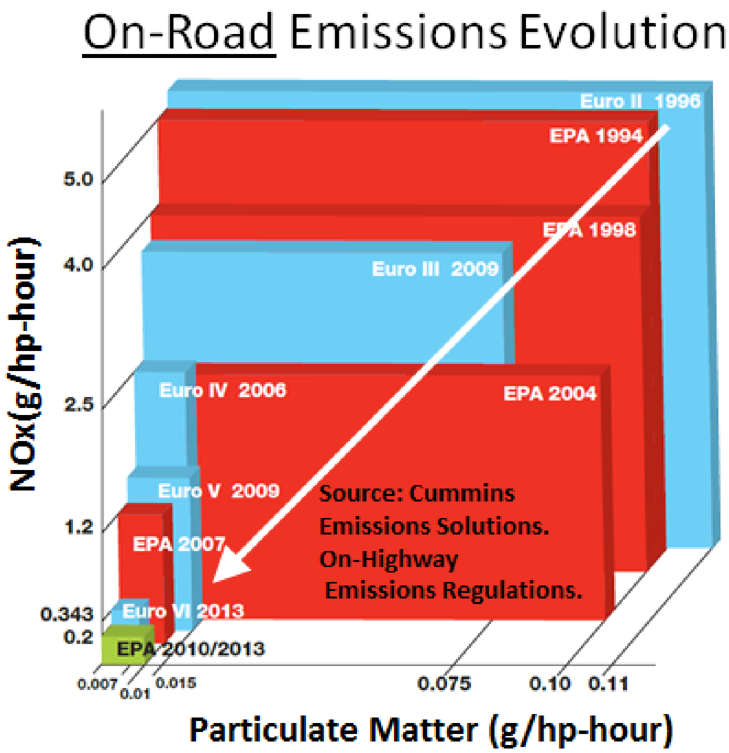

Figure 8 - On-Road Emissions Evolution

e. Maritime Transport

IMO is an agency of the United Nations which has been formed to promote maritime safety. MARPOL 1973/1978 represents the main IMO Convention currently in force regarding protection of the marine environment. Annex VI was added to minimize airborne emissions from ships and their contribution to global air pollution and environmental impact. Annex VI entered into force in 2005, and a revised Annex VI entered into force on 1 July 2010[19].

Annex VI defines two sets of emission and fuel quality requirements, one for Global, and another for ECA, Figure 9[20]. The ECAs for the North Sea and the Baltic Sea are currently adopted for SOx and PM. The ECAs for North America and US Caribbean (including Hawaii, Puerto Rico and U.S. Virgin Islands) are currently adopted for SOx, PM and NOx.

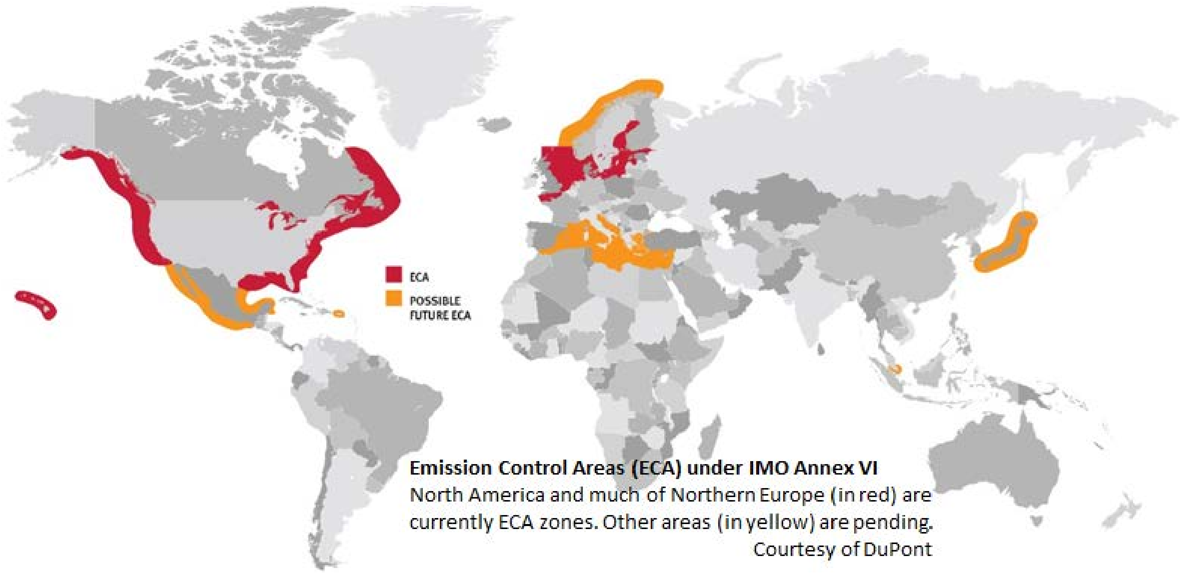

Figure 9 - ECA Areas Where All Ships Must Meet New Emission Limits by 2015

A global cap of 3.5% is applied from January 2012 on the sulphur content of marine bunker fuel to limit emissions of sulphur dioxide (SO_2). The cap is scheduled to reduce to 0.5% from January 2020; however, the date may be delayed to 2025, depending on an evaluation of worldwide refinery status to increase capacity of low sulphur marine distillate fuel by 2018. Within ECAs, the sulphur limits are much more stringent as illustrated in Figure 10. The ECA limit of 1% was reduced to 0.1% from 1 January 2015[21].

[19] International Maritime Organization, Air Pollution and Greenhouse Gas (GHG) Emissions from International Shipping.

[20] DNV GL Efficiency Through Technology Choices, 20 May 2014.

[21] LR Report, LNG-fuelled deep sea shipping, August 2012.

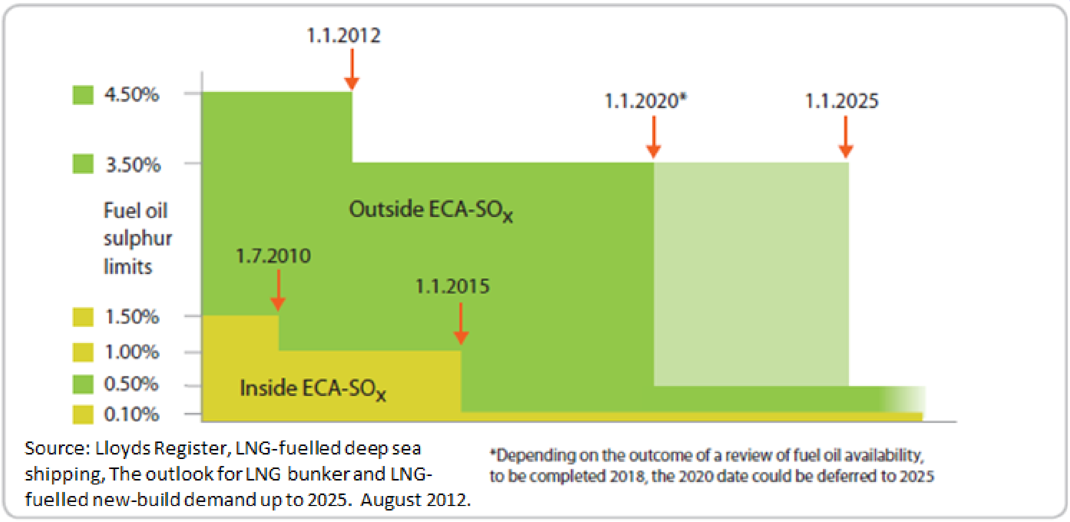

Figure 10 - MARPOL Annex VI Sulphur Limits and Timelines

DNV-GL report that approximately 40% of the world fleet enters ECA waters during a year, with half of those vessels spending more than 5% of their time. This means that ECA requirements must be part of fleet owners' planning. From 2016, all new ships must comply with the Tier III NOx requirements to reduce by approximately 75%, when operating in the North American/US Caribbean ECA. This requirement is expected to be extended to the Baltic Sea and North Sea ECAs.

Proposed ECAs are being considered for other areas, i.e. Northern Norway, Mediterranean, Japan and Mexico, Figure 9. The influence of Annex VI requirements on current and potential ECAs has started to impact demand for clean maritime fuel, alternative technologies to clean-up diesel emissions, dual fueled engines and pure natural gas fueled engines.

The ABS study on Bunkering of Liquefied Natural Gas-fueled Marine Vessels in North America provides a structured process for implementing an LNG fuel supply project with regard to seeking compliance with local regulations. ABS chapters 3, 4 and 5 provide details of the regulations and guidance on implementation. This study is an excellent resource intended to help operators and owners of gas-fueled vessels, LNG bunkering vessels, and waterfront facilities who need background information and guidance to address North American (U.S. and Canada) federal regulations, state/provincial and port requirements, international codes, and standards and potentially waterway requirements or restrictions as well as unique issues such as regional and local restrictions on storing LNG.

f. Maritime Abatement Measures

DNV-GL has divided abatement measures into four main categories, Figure 11[22].

- Technical measures aimed at reducing power requirement or improving fuel efficiency.
- Operational measures aimed at improving performance through maintenance and operations.

[22] DNV, Assessment of measures to reduce future CO2 emissions from shipping, Research Innovation Position Paper, May 2010.

- Structural measures improving efficiency by altering the way two or more counterparts interact.
- Alternative fuels and / or power sources aimed at reducing emissions.

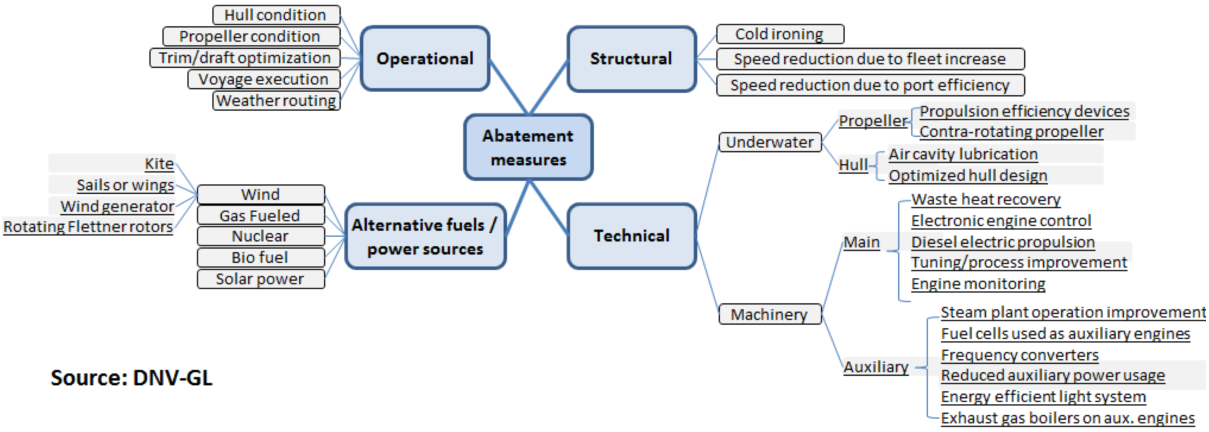

Figure 11 - Overview of CO_2 Abatement Measures in Shipping

Technical measures generally have a substantial investment cost and potentially very significant emission reduction effects. Many technical measures are limited to application on new ships, due to the difficulties or high costs of retrofitting existing ships. Operational measures are easier and less costly to implement. Structural measures are mixed depending on level of control to affect efficiency improvements. Fuel measures tend to be more complex and costly to pursue.

Marginal abatement cost is the cost of avoiding the next one tonne of CO_2 emissions through application of a specific measure. DNV-GL shows the marginal abatement costs in Figure 12, based on the average abatement cost for all ship segments for opportunities to reduce emissions from shipping in 2030.

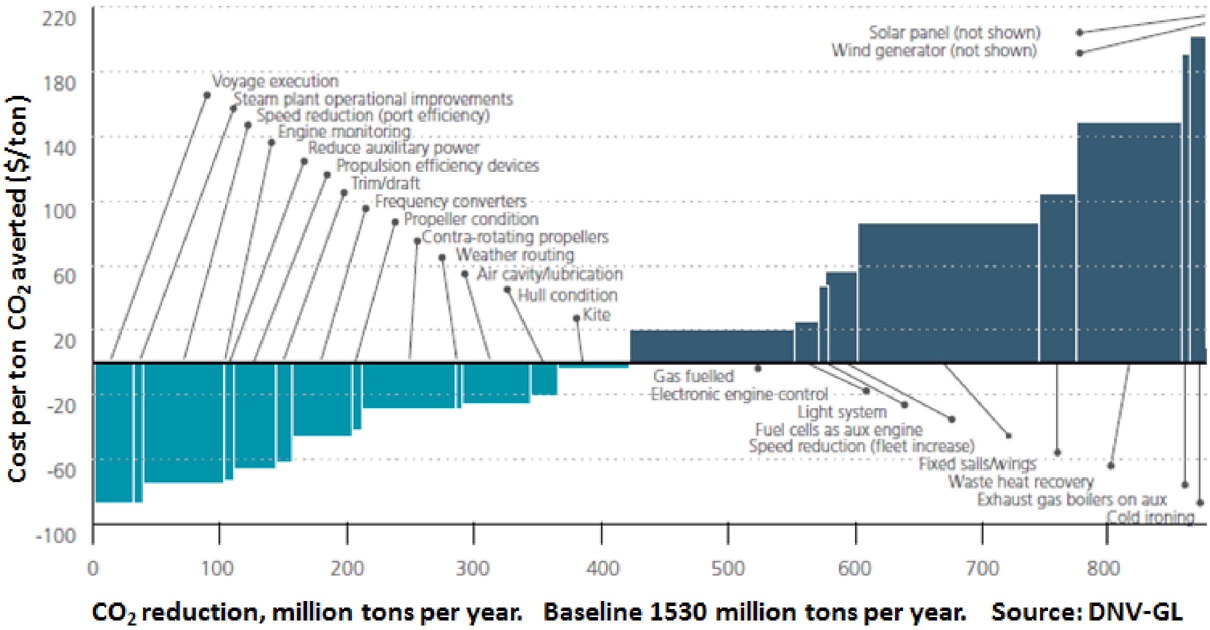

Figure 12 - Marginal Abatement Cost Per Reduction Measure for the Fleet in 2030

The width of each bar represents the potential to reduce CO_2 emissions from shipping, while the height represents the average marginal cost of avoiding one tonne of CO_2 emission through that option, assuming that all options to the left are already applied. The graph is arranged from left to right with increasing cost per tonne CO_2 averted. Where the bars cross the x-axis, the options start to have a net cost increase, instead of a net cost reduction.

i. Scrubber Abatement Technology

Sulphur abatement technology for removal of SOx and PM, successfully used by refineries for decades, is a relatively new use for shipping. When the sulphur restrictions were first announced, uncertain retrofit cost coupled with uncertain technical and cost efficient operations seemed to make scrubbers an option of last resort for the existing fleet and a poor alternative for new builds.

However, a recent study found that the marine industry has changed its initial sceptical view about scrubber technology[23]. Many new contracts with scrubber companies are being announced by operators of ferries, cruise ships and cargo vessels. The study observed that a ship outfitted with a scrubber can have a payback period of one to three years depending on the amount of time a ship spends in an ECA, current fuel price differentials, amount of fuel consumed, scrubber costs and other factors. For ships traveling more than 30% of the time in an ECA, adoption of emission abatement technology is reported to be increasing. Installation is easiest on new builds, but can be performed as a retrofit requiring dry-dock, which can take six months to a year before a system is fully installed, tested and accredited.

ii. Alternative Marine Fuels

Low sulphur fuel oil (LSFO) is an alternative to HFO. LSFO is a marine distillate which includes marine diesel oil (MDO) and marine gas oil (MGO). Operating on LSFO would comply with sulphur limitations but would not reduce CO_2 or PM. A comparison of marine fuel options with Annex VI restrictions on fuel oil sulphur content is given in Figure 13.

<table>
<tr><th>Marine Fuel Option</th><th>LNG</th><th>Marine Distillate</th><th>HFO</th></tr>
<tr><td>CO2 removal</td><td>Up to 20%</td><td>None</td><td rowspan="4">Requires abatement</td></tr>
<tr><td>SOx removal</td><td>Up to 100%</td><td>MDO: up to 98%</td></tr>
<tr><td>NOx removal</td><td>Up to 90%</td><td rowspan="2">Requires abatement</td></tr>
<tr><td>PM removal</td><td>Up to 99%</td></tr>
<tr><td>Future potential</td><td>Further CO_2 reduction</td><td colspan="2">Mature technology</td></tr>
<tr><td>Infrastructure</td><td>Early Stages</td><td>Requires increased refinery capacity</td><td>In place</td></tr>
<tr><td>Cost of use</td><td>LNG storage tank, incremental fuel price, incremental cargo space</td><td colspan="2">Cost of abatement technology</td></tr>
<tr><td rowspan="2">Challenges</td><td rowspan="2">Bunker space, cryogenic equipment, possible methane slippage</td><td colspan="2">Abatement maintenance, disposal</td></tr>
<tr><td>Refinery investment, capacity, varied blends</td><td>Abatement technologies</td></tr>
<tr><td colspan="4">Adapted from Lloyds Register, LNG-fuelled Deep Sea Shipping, August 2012</td></tr>
</table>

Figure 13 - Options for Compliance with Annex VI Restrictions

[23] The Motorship, Choice of sulphur emissions abatement technology depends on payback time, 11 Jul 2014. G. Billemeyer and M. Davidson, Belco Technologies Corp.

In 2020, when the IMO global cap of 0.5% sulfur is scheduled to be enforced, demand for marine distillate could be as high as 200-250 million tonnes per year, up from current refinery capacity level of about 30 million tonnes. However, the high cost of making the fuel and the consequence of a market price higher than LNG or HFO, makes the future demand level uncertain. This raises the question whether the refineries would be willing to invest tens of billions of dollars on new capacity to meet potential demand.

Recognizing that future LSFO supply is uncertain, IMO said it would study global availability. However, the study is scheduled to start in 2016 and will take two years to complete. The timing of results may create a timing challenge for ship owners to make the necessary changes and leave insufficient time for refineries to increase LSFO production capacity by 1 January 2020. The outcome of the IMO investigation could be a delay of enforcement of the 0.5% sulfur limit up to 5 years, until 2025. Refer to section 6.e.3 Alternative Marine Fuel Availability for further discussion.

Lloyds Register conducted a survey of ship owners on deep sea trades and found that ship owners view MDO/MGO as a short term solution, abatement technologies as a medium term option, and LNG fueled engines as a viable long term option, particularly for liner trades. Lloyds Register concludes that use of LNG as a bunker fuel for ships represents a real alternative to conventional marine HFO because of the absence of SOx content in emissions (depending on engine type).

iii. Efficiency Measures

MARPOL Annex VI Chapter 4 introduced two mandatory mechanisms to reduce emissions of GHGs from international shipping and ensure an energy efficiency standard[24, 25]. The first mechanism is the Energy Efficiency Design Index (EEDI) for new ships stipulating minimum energy efficiency standards. Ship designers and builders may choose the technologies needed to satisfy the EEDI requirements. The IMO may waive the requirement to comply with the EEDI for certain new ships, such as those already under construction. The second mechanism is the Ship Energy Efficiency Management Plan (SEEMP) for operators of all ships to improve the energy efficiency. These regulations apply to all ships of 400 gross tonnage or larger that enter into force from 1 January 2013.

g. Non-Road Transport

There has also been an evolution of global non-road emissions regulations as illustrated by Cummins Emissions Solutions in Figure 14.

[24] IMO, Mandatory energy efficiency measures for international shipping, IMO environment meeting, briefing 42, July 15, 2011.

[25] DieselNet, IMO Marine Engine Regulations, http://www.dieselnet.com/standards/inter/imo.php#nox

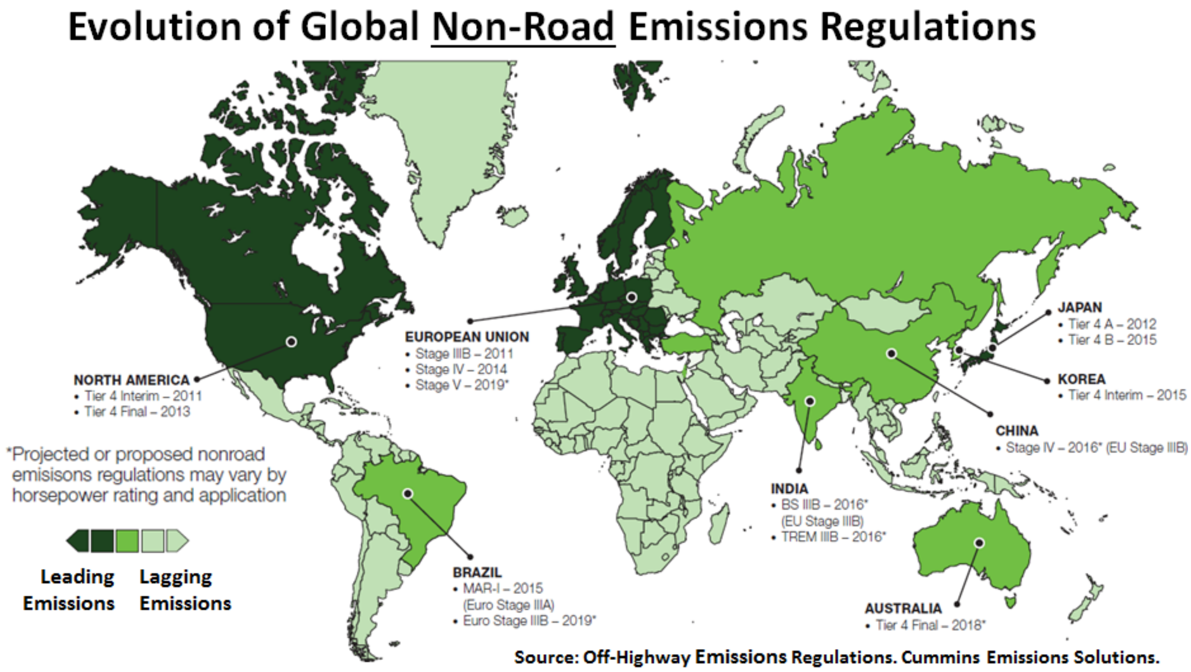

Figure 14 - Evolution of Global Non-Road Emissions Regulation

Note the progressive reduction of PM and NOx emissions, measured in units of grams / hp-hour, as illustrated in Figure 15.

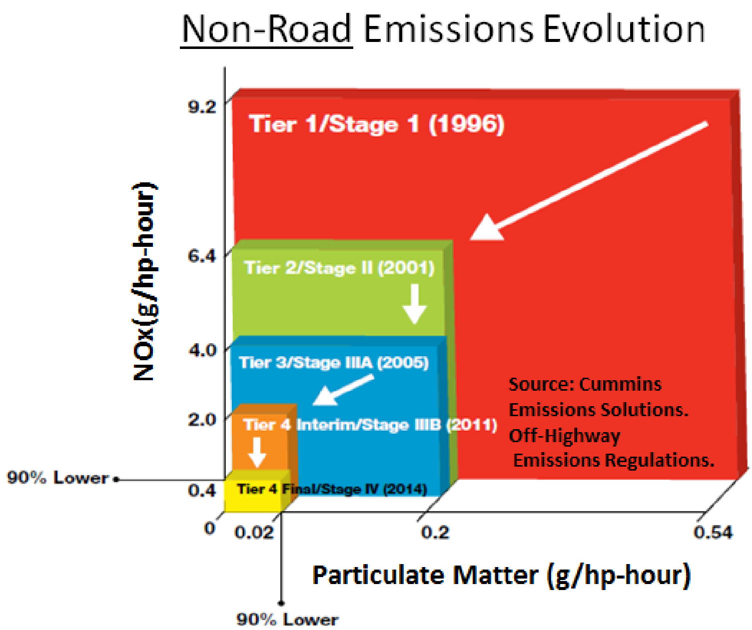

Figure 15 - Non-Road Emissions Evolution by Country

The 2014 non-road regulations in North America, Europe and Japan call for PM and NOx levels to be reduced by more than 90 percent from current levels for most power categories. The use of advanced engine technology and exhaust after-treatment is required to achieve these near-zero emissions levels in a broad range of applications. Furthermore, non-road emissions regulations require both engine and after-treatment to be certified compliant as a single emissions system, replacing engine only-measured tailpipe- emissions.

EPA standards for non-road engines and vehicles are given on the EPA website[26]. Guidance is given for:

- Aircraft -- exhaust emission standards
- CI engines -- exhaust emission standards
- Large SI engines -- exhaust and evaporative emission standards
- Locomotives -- exhaust emission standards
- Marine CI engines -- exhaust emission standards
- Marine SI engines and vessels -- exhaust emission standards
- Recreational engines and vehicles -- exhaust emission standards
- SI engines 19 kilowatts (kW) and below -- exhaust emission standards
- SI engines 19kW and below, recreational engines and vehicles, and marine SI engines -- evaporative emission standards

EC standards on the Environment are given on the EC website and are discussed in the Handbook on the Implementation of EC Environmental Legislation, Overview on Air Quality[27].

h. Rail Transport

Worldwide, railways generate 3% of transport CO_2 emissions, while sustaining more than 9% of total transport activity[28]. Emission standards for European railway locomotives have been established by the International Union of Railways (Union Internationale des Chemins de fer, UIC), a Paris-based association of railway companies[29]. The emission standards are binding to member railways covering all five continents and are specified in UIC Leaflet 624, Exhaust emission tests for diesel traction engines, last updated in February 2012.

The UIC emission standards apply to diesel engines for railway traction, with the exception of engines for special locomotives (e.g., refinery or mine locomotives) and traction engines with an output of less than 100 kW. The standards apply to all engines used in new locomotives or for repowering of existing locomotives. The UIC reports annually on railway emissions.

A quarter of the world's railway lines are electrified; in Europe, more than 50% of railway lines are electrified; in North America nearly none. Considering the energy chain behind electricity, the UIC and IEA report that in 2010 natural gas fueled 22% of the world electricity mix (compared to coal at 40%) from which the railways draw power. Among the countries, the electricity mix in Russia was gas 50% (coal 16%), Japan 34% (coal 34%), EU 10% (coal 15%) and China 2% (coal 78%).

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[26] EPA, Emission Standards Reference Guide, Nonroad Engines and Vehicles: http://www.epa.gov/otaq/standards/nonroad/

[27] Handbook on EC Environmental Legislation, Overview, Air Quality: http://ec.europa.eu/environment/air/pdf/air.pdf

[28] Railway Handbook 2013, Energy Consumption and CO_2 Emissions, UIC and iea,

[29] International: UIC Locomotive Emission Standards, DieselNet.

According to the United Nations Statistics Division, railroads worldwide burned an estimated 9 billion gallons of diesel in 2012[30]. Of this, the U.S. EIA report that seven U.S. Class 1 railroads consumed more than 3.6 billion gallons of diesel fuel.

Emission standards for U.S. railway locomotives have been established by the EPA. The standards are specified in a three part program that, when fully implemented, will dramatically reduce PM emissions up to 90% and NOx emissions by as much as 80% from diesel locomotives of all types: switch engines, line haul and passenger rail[31]. The standards are based on the application of high-efficiency catalytic after-treatment technology for engines entering service in 2015 and later. The EPA standards will also apply to existing locomotives when they are rebuilt for extended service. Additionally, requirements are in place to reduce idling and related emissions for new and rebuilt locomotives.

i. Aviation

According to the EC report on Climate Action, direct emissions from aviation account for about 3% of the EU's total GHG emissions and about 13% of transport emissions globally[32]. The large majority comes from international flights. Aircraft emit significant quantities of NOx that promote the formation of ozone and also emit black carbon. Because these gases and light-absorbing aerosols are emitted at high altitudes, their impact is thought to be especially large[33]. According to the EC report, CO_2 emissions from aviation are expected to grow around 3-4 per cent per year. By 2020, global international aviation emissions are projected to be around 70% higher than in 2005; by 2050, they could grow by a further 300-700%.

A worldwide agreement was reached within OACI (International Civil Aviation Organization) on October 4th 2013 to limit from 2020 the CO_2 emissions worldwide for Air Traffic. The detail of the mechanism will be finalized in 2016. This could be a driver for alternative fuels and LNG.

[30] Westport in R&D Project for Natural Gas-Fueled Locomotives, Alternative fuels could alter cost, GHGs for freight and passenger trains. Dec. 8, 2011. Robert Brooks | American Machinist.

[31] US Environmental Protection Agency, Nonroad Engines, Equipment and Vehicles; Locomotives, Exhaust Emission Standards, http://www.epa.gov/otaq/standards/nonroad/locomotives.htm

[32] European Commission, Climate Action, Reducing emissions from aviation, latest update 22 September 2014. http://ec.europa.eu/clima/policies/transport/aviation/index_en.htm.

[33] IPCC, Climate Change 2007, Chapter 5, Transport and its infrastructure, Section 5.2.2 Transport in the future.

3. Fuel Options and Engines

The evolution of natural gas as fuel dates back to World War I, when gasoline was scarce worldwide and coal gas was used out of necessity to fuel vehicles. Although limited by the capacity, practicality and safety of mounting uncompressed gas storage bags to vehicles, and by the limited range of travel with few refueling options, these gas-bag vehicles proved the feasibility of utilizing HC gas as a transport fuel, Figure 16.

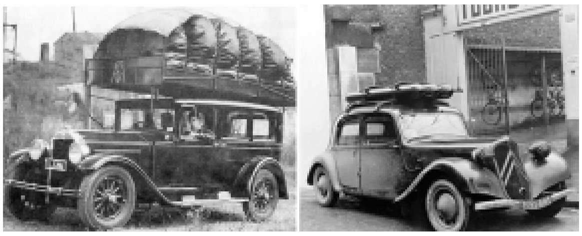

Figure 16 - WW I and WW II Era Gas Fueled Vehicles. Courtesy Low-Tech Magazine

During World War II, compressed natural gas (CNG) for transport was made feasible through the introduction of gas cylinders, commonly mounted on the roof of vehicles or in the cargo space. Otherwise, oil based liquid petroleum products have been the fuels of choice worldwide for mobile applications, offering high density energy in safe and easily transportable liquid form. The fuels most commonly used include gasoline, diesel, jet fuel, residual fuel oil and liquid petroleum gases.

LNG as a transportation fuel supply began to interest fleet owners following implementation of EPA and EU standards for diesel emissions in the On-Road and Off-Road sectors starting about year 2000. Many nations have adopted these standards or implemented their own in recent years. Similarly in the maritime sector enforcement of MARPOL Annex VI from 2005 setting emissions and fuel quality requirements in ECA waters and globally, prompted ship owners to begin considering LNG as a fuel supply. The LNG is regasified to natural gas before consumption in a gas engine. A discussion of end user applications across all sectors is given in Chapter 4.

a. Fuel Energy Content

The amount of energy provided and the pricing basis for a given quantity of fuel are important considerations that should be understood for new fuel.

Oil based fuel products, such as diesel and gasoline, are typically sold on a volumetric basis (for example per gallon or per liter) for a given specification of that fuel. In comparison, LNG has historically been sold on an energy content basis, for example price per MMBtu.

A number of factors need to be examined when considering the pricing basis for new fuels such as LNG. The key issue is that for a given quantity of fuel the density and calorific value (i.e. the amount of energy per unit volume) will determine the amount of energy available and therefore the distance a vehicle can travel. The weight, size and cost of the fuel storage tank are also important considerations for the end user as fuels that require large or heavy tanks can reduce the space available to transport passengers and / or cargo, or weigh down a vehicle making it less efficient.

The chart in Figure 17 compares energy content per unit volume with the per unit weight for several transportation fuels, not including the storage tanks or associated equipment.

Storage tanks for compressed fuels are typically heavier pressure-rated containers than tanks for chilled liquefied fuels.

Compared to gasoline and diesel, other options may have more energy per unit weight, but none have more energy per unit volume. Natural gas, either as LNG or CNG, is lighter than gasoline but has lower density per unit volume.

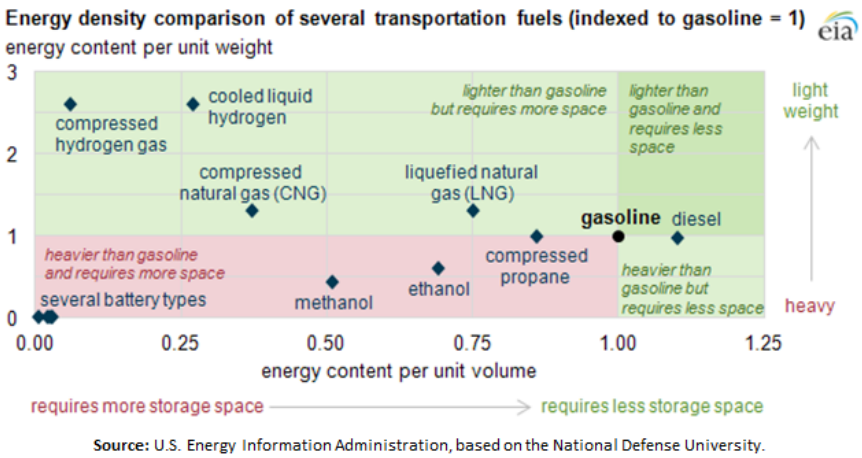

Figure 17 - Energy Density Comparison of Transportation Fuels

b. Vehicle Range

The widespread use of gasoline and diesel is largely explained by energy density and ease of onboard storage. The energy per unit volume is a key determinate to the distance a vehicle can travel before needing to be refueled. LNG has lower energy density per unit volume than diesel and therefore has a lower range than diesel, but higher range than CNG. A comparison of fuel volume and range for diesel, LNG and CNG is given in Figure 18.

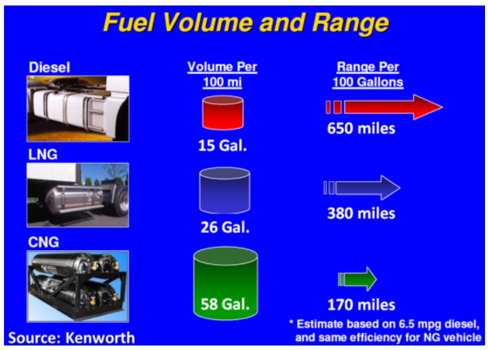

Figure 18 - Fuel Volume and Range Comparison

The density of LNG, and therefore the amount of energy in the equivalent volume of fuel, is related to the temperature and pressure in the tank. LNG at lower temperature and pressure will provide an increased range for the vehicle and a longer hold time in the fuel tank[34] . For example, a truck fueled with LNG at 50 pounds per square inch gauge (psig) has range up to 740 miles and a hold time up to 10 days, compared to a super warm tank of LNG at 225 psig, which has a range up to 620 miles and one day hold time, Figure 19.

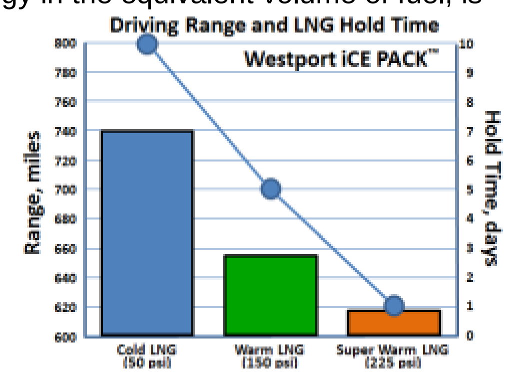

Figure 19 - LNG Driving Range and Tank Holding Time

[34] Westport Ice Pack LNG Tank System, Leverage the Benefits of Cold LNG.

c. LNG Quality

Variations in LNG quality could cause inefficiencies and equipment performance issues for the end user. Although a number of guidelines exist for fuel composition for natural gas engines, there are few standards in existence.

The principal constituent of natural gas is methane (CH_4) with smaller quantities of other components including heavier HC, hydrogen sulfide (H_2S) and inerts (e.g. CO_2 and nitrogen (N)). The natural gas is treated to remove impurities and gas liquids, then liquefied through a refrigeration process to approximately -260˚F (-162˚C) to yield LNG. Typically LNG consists of 83% to 97% CH_4 with small amounts of ethane (C_2H_6), propane (C_3H_8), butanes (C_4H_{10}) and trace amounts of nitrogen gas (N_2).

The design of the liquefaction plant, usually based on the specification required by the end user, will determine the composition and quality of LNG produced. LNG quality therefore varies depending on the source of the LNG (i.e. which liquefaction plant it is produced by), as well as transportation time, during which the composition can change slightly due to the evaporation or boil off of lighter components.

LNG quality is typically described using a measure of energy content (e.g. gross calorific value), the combustion characteristics of the LNG (e.g. Wobbe Number, Soot Index, or Incomplete Combustion Factor) and the impurities contained in the LNG (e.g. % sulphur, CO_2, N_2).

Gross heating value is a key measure of LNG quality since LNG is sold on an energy basis. The range of gross heating value (and other key quality parameters) for a variety of different sources of LNG is given in Figure 20, showing a range of 39.92 MJ/m^3 to 46.24MJ/m^3. Further information is given in Appendix 9.h, LNG Quality and Methane Number.

LNG CHARACTERISTICS

The average composition is chosen as being representative among compositions reported by the different receiving terminals.

Origin	Nitrogen N2 %	Methane C1 %	Ethane C2 %	Propane C3 %	C4+ %	TOTAL	LNG Density (1) kg/m³	Gas Density (2) kg/m³(n)	Expansion ratio m³(n)/m³ liq	Gas GCV (2) MJ/m³(n)	Wobbe Index (2) MJ/m³(n)
Australia - NWS	0.04	87.33	8.33	3.33	0.97	100.0	467.35	0.83	562.46	45.32	56.53
Australia - Darwin	0.10	87.64	9.97	1.96	0.33	100.0	461.05	0.81	567.73	44.39	56.01
Algeria - Skikda	0.63	91.40	7.35	0.57	0.05	100.0	446.65	0.78	575.95	42.30	54.62
Algeria - Bethioua	0.64	89.55	8.20	1.30	0.31	100.0	454.50	0.80	571.70	43.22	55.12
Algeria - Arzew	0.71	88.93	8.42	1.59	0.37	100.0	457.10	0.80	570.37	43.48	55.23
Brunei	0.04	90.12	5.34	3.02	1.48	100.0	461.63	0.82	564.48	44.68	56.18
Egypt - Idku	0.02	95.31	3.58	0.74	0.34	100.0	437.38	0.76	578.47	41.76	54.61
Eqypt - Damietta	0.02	97.25	2.49	0.12	0.12	100.0	429.35	0.74	582.24	40.87	54.12
Equatorial Guinea	0.00	93.41	6.52	0.07	0.00	100.0	439.64	0.76	578.85	41.95	54.73
Indonesia - Arun	0.08	91.86	5.66	1.60	0.79	100.0	450.96	0.79	571.49	43.29	55.42
Indonesia - Badak	0.01	90.14	5.46	2.98	1.40	100.0	461.07	0.82	564.89	44.63	56.17
Indonesia - Tangguh	0.13	96.91	2.37	0.44	0.15	100.0	431.22	0.74	581.47	41.00	54.14
Libya	0.59	82.57	12.62	3.56	0.65	100.0	478.72	0.86	558.08	46.24	56.77
Malaysia	0.14	91.69	4.64	2.60	0.93	100.0	454.19	0.80	569.15	43.67	55.59
Nigeria	0.03	91.70	5.52	2.17	0.58	100.0	451.66	0.79	571.14	43.41	55.50
Norway	0.46	92.03	5.75	1.31	0.45	100.0	448.39	0.78	573.75	42.69	54.91
Oman	0.20	90.68	5.75	2.12	1.24	100.0	457.27	0.81	567.76	43.99	55.73
Peru	0.57	89.07	10.26	0.10	0.01	100.0	451.80	0.79	574.30	42.90	55.00
Qatar	0.27	90.91	6.43	1.66	0.74	100.0	453.46	0.79	570.68	43.43	55.40
Russia - Sakhalin	0.07	92.53	4.47	1.97	0.95	100.0	450.67	0.79	571.05	43.30	55.43
Trinidad	0.01	96.78	2.78	0.37	0.06	100.0	431.03	0.74	581.77	41.05	54.23
USA - Alaska	0.17	99.71	0.09	0.03	0.01	100.0	421.39	0.72	585.75	39.91	53.51
Yemen	0.02	93.17	5.93	0.77	0.12	100.0	442.42	0.77	576.90	42.29	54.91

(1) Calculated according to ISO 6578 [T = -160ºC] (2) Calculated according to ISO 6976 [0ºC / 0ºC, 1.01325 bar]. **Source: International Group of Liquefied Natural Gas Importers (GIIGNL)**

Figure 20 - Gross Heating Value for a Variety of LNG Sources

d. Methane Number

When natural gas is used to run an internal combustion engine, quality variations can induce knock occurrence. Methane Number (MN) is a measure of resistance of fuel gases to engine knock, a phenomenon where the air-fuel mixture detonates instead of burning slowly when triggered by the ignition system. This detonation produces shock waves that could lead to increasing emissions, decreasing engine efficiency and damage to the engine. To ensure efficient engine operation the MN of the LNG should at least equal to the minimum MN specified for the engine. MN is analogous to Octane Number for petrol engines. . Further information is given in Appendix 9.h.

MN has a scale from 0 to 100. Pure methane is the knock resistant reference fuel with a MN of 100; pure hydrogen is the knock sensitive reference fuel with a MN of 0**. MN is not a thermodynamic property of gas that can be measured by a standard formula, and resistance to knock is also engine dependent**. There is no standard calculation method for MN and the multiple methods currently in use by industry yield different results as shown in Figure 21. The difference could be more than 5; therefore, a MN specification should also state the corresponding calculation method.

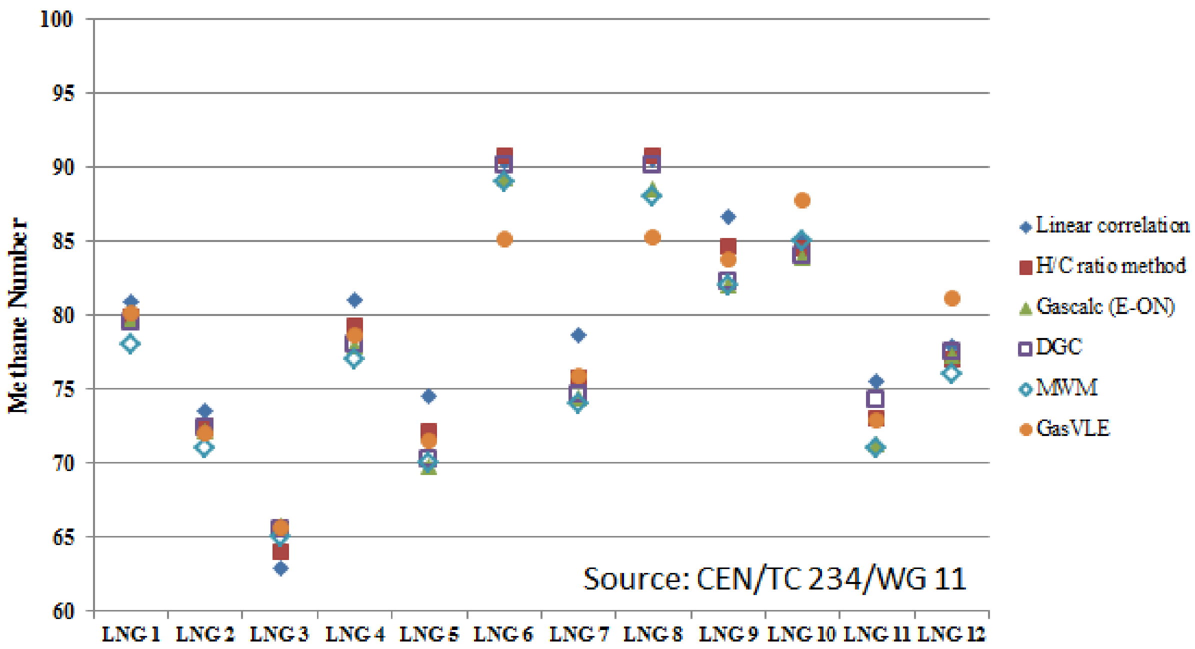

Figure 21 - Methane Number of LNGs Using Different Methodologies

There is currently no regulatory requirement for a minimum MN for LNG fuel, but not all LNG is equally suitable for all engines as LNG is produced from diverse sources all over the world with varying composition and MN. This represents a challenge that will need to be addressed by the supply, engine and regulatory stakeholders as the industry develops.

Scientific and technical studies and experiments have been conducted with a view to develop a new method to assess resistance of fuel gases to engine knock. These developments could be an enabler for both LNG fuel suppliers and users.

e. Safety Considerations

Although use of LNG and CNG as fuel for fleet applications is similar, the general properties affecting safety are different. LNG is a more refined and consistent product than CNG without the corrosive issues associated with water vapor and contaminants. LNG has no natural odor; therefore personnel would not detect a leak unless large enough to create a condensation cloud or localized frost. It is essential that HC gas detectors be placed in areas where LNG is being transferred or stored.

LNG won't burn until it becomes natural gas vapor. Natural gas has narrow flammability limits, combusting in air/fuel proportions of 5 to 15%. Below 5% the mix is too lean to burn, and above 15% the mix is too rich. CH_4 auto ignition temperature is 1004°F, significantly higher than gasoline (495°F) or diesel (600°F). As such, open flames and sparks can ignite natural gas; however, many hot surfaces such a muffler will not ignite natural gas. The flame front on burning methane in an open, unconfined environment has a relatively slow flame speed of about 4 mph.

f. Engine Types

There are two types of natural gas fuelled engines: SI engines ignite the gas using a spark plug, while CI engines ignite by compression of diesel during the combustion cycle. These types of engines are further classified as shown in Figure 22. Further information is given in Appendix 9.g on Engine Considerations.

Ignition Type	Technology	Notes
Spark plug	Stoichiometric	Natural gas only, ignited by a spark plug. Uses exactly the required amount of air to burn the available fuel.
Spark plug	Lean burn	Natural gas only, ignited by a spark plug. Uses more than the required amount of air to burn the available fuel.
Compression	Dual fuel	Engines operate on both natural gas and diesel fuel simultaneously, the majority of fuel burned being natural gas. Diesel fuel auto ignites under compression and then ignites the natural gas.
Compression	High Pressure Direct Injection	Fuelled by diesel and natural gas. Diesel pilot injection is used to ignite the gas.

Figure 22 - LNG Engine Ignition and Technology Types

SI engines are dedicated gas engines fueled by natural gas sourced from LNG or CNG storage tanks. SI engines are widely used in a variety of applications, as discussed in Chapter 4, End User Sectors[35]. The engine technology, based on the type of air-fuel ratio used, is either stoichiometric or lean burn. Stoichiometric engines use exactly the required amount of air to burn the available fuel, whereas lean engines consume more air than is required to burn the fuel resulting in less NO_X emissions and more efficient combustion producing more power. Lean burn and stoichiometric engines tend to be spark ignited Otto cycle engines typically based on diesel engines with modified engine management system, ignition system and gas supply. These engines are typically used for light to medium duty applications as they lack the power and torque characteristics required to move very heavy loads.

Spark-ignited engines require warming the LNG to more than 100 psi prior to dispensing, otherwise, adding colder LNG would cause tank pressure to decrease and affect engine performance. Warming the LNG increases fueling time. However, newer technology for LNG

[35] Resource Guide for Heavy-Duty LNG Vehicles, Infrastructure, and Support Operations, Prepared by Kevin L. Chandler Matthew T. Gifford Brian S. Carpenter , Battelle ,505 King Avenue , Columbus, Ohio 43201

fuel tank and engine systems provides an advantage by allowing colder LNG at lower pressure to be dispensed. Tank pressure fluctuation is not an issue as fuel pressure is regulated by the engine.

CI engines run on a combination of natural gas and diesel fuel and are typically based on modified diesel engines, usually post-production or as a retrofit kit. The dual fuel engine provides the advantage of allowing the operator to run on diesel only if no natural gas is available or to run the engine with natural gas injected into the air inlet manifold, displacing approximately 50% to 70% of the diesel. The High Pressure Direct Injection (HPDI) engine runs on natural gas injected directly into the cylinder using a combined diesel/gas injector and at a gas:diesel ratio of 95:5. Typically, CI dual fuel engines are used in heavy duty, high horsepower applications.

g. Natural Gas Engine Manufacturers

Growing interest in natural gas as a sustainable and cost competitive fuel has prompted end users to begin to replace diesel fueled equipment across a wide range of applications. Market pull has caused many engine manufacturers to design and build a wide range of natural gas and dual fuel engines for the vehicles, vessels and locomotives that move people and goods, as exemplified in Figure 23. Further information on engine manufacturers is given in Appendix 9.f Original Equipment Manufacturers – Engines.

OEM	Gas Focus	Road	Non Road	Remote Power	Rail	Marine
Caterpillar	• Dual fuel engines for rail, maritime, mine haul trucks • NG engines generator sets for drilling and remote power • Next Generation LNG fueled locomotives • Acquired MAK, Progress Rail Services & Electro-Motive Diesel		X	X	X	X
Cummins	• NG engines, 150 to 400 hp, certified with 3-way catalyst, meet/ exceed U.S. EPA, California Air Resources Board, and EURO emissions standards • Over 34,000 Cummins natural gas engines are in service worldwide		X			
GE	• Jenbacher gas engines, drilling / industrial gen-sets • Waukesha gas-fueled engines, generator sets, combined heat and power (CHP) modules, Organic Rankine Cycle systems / auxiliaries range 0.12 to 9.5 • Evolution series locomotives		X	X	X	
MAN	• Commercial heavy road vehicle engines • Power, Agriculture, Marine dual fuel	X	X	X		X
Mitsubishi	• Gas fueled power generation • Gas-fuelled engines and related systems for marine			X		X
Rolls Royce	• MTU high-speed engines and propulsion systems for ships, heavy road, defense vehicles and energy industry • Bergin medium speed engines SI engines for marine and land uses.	X	X	X	X	X
Volvo	• In 2014 Volvo Penta will release 5 Tier 4 Final-compliant industrial engines • Bi-fuel 16-litre Tier 4 Interim engine for oil & gas and mobile operations • One of Europe's largest suppliers of NG buses	X	X	X		
Wärtsilä	• Gas power plants • Gas-fuelled engines and related systems for marine • Medium-scale LNG infrastructure development		X	X		X
Westport-Cummins	• Design NG engines and LNG Fuel Systems for HD trucking • NG/LPG engines and fuel systems for light-duty market • WiNG™ Power Sys.for Ford F-250/550 Super-Duty trucks in US & Canada	X			X	

Figure 23 - Example of Original Equipment Manufacturers for NG Engines

h. Research and Long Lead Development

The US EIA consider freight rail a potential additional source of natural gas use in Annual Energy Outlook 2014 (AEO2014). Transition from diesel to natural gas as a fuel for freight locomotives will depend on economics, infrastructure needs, and railroads' decisions with regard to risk and uncertainty. Locomotive stock has a 30-year design life. Research and development of LNG fueled locomotives and tenders are being conducted in North America, Brazil, Russia, India and Australia. Although field testing is underway in several locations, replacing stock would likely occur in coordination with normal replenishment cycles.

LNG for potential use as aviation fuel is an even longer research opportunity. Russia began working on the use of liquid hydrogen (LH_2) and LNG for various gas-turbine engines as early as 1968. In 1988, the first test flight of a jet aircraft burning LH_2 was conducted, and in 1989 a modified jet engine using LNG as fuel was tested. The LNG fueled aircraft made 100 flights[36]. However, little progress has since been made.

The U.S. National Aeronautics and Space Administration (NASA) sponsored concept studies for "N+3" airliners (three generations from today's Boeing 737 and 777 aircraft) that would be flying around 2030-35. Boeing, Lockheed Martin and Northrop Grumman submitted N+3 reports in 2010. NASA observed that many technologies were not addressed and therefore awarded a year-long extension to Boeing to perform an "N+4" study to help identify which of the potential technologies warranted further research, as lead time to get a technology ready for the industry is about 20 years[37]. Liquefied natural gas propulsion was one of the technologies selected. The study concluded that while LNG might not seem an obvious choice for a future aviation fuel, it offers lower fuel burn and emissions as well as potential cost and availability benefits.

The Intergovernmental Panel on Climate Change (IPCC) points out that technology development in aviation has to overcome several major hurdles before a technology could be adopted. A new technology must demonstrate proven benefits, reliability against the overriding safety requirements, and a product lifetime that has 60% of aircraft in service at 30 years age[38] . As a result, change is slower in the aviation industry than is seen in other transport sectors.

Articles on aviation research are given in Appendix 9.e, Off-Road, Power Generation and Aviation LNG as Fuel.

[36] NK-88 by Kuznetsov Engine Design Bureau, http://ram-home.com/ram-old/index.html

[37] LNG Propulsion - A Cool Idea? Graham Warwick, Mar 19, 2012: MRO Links website, Aviation Week.

[38] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007, Chapter 5, Transport and its infrastructure, Section 5.3.3 Aviation.

4. End User Sectors

This chapter discusses the evolution of demand for natural gas as fuel from early road transport techniques to the introduction and growth of CNG technology, leading to the current application of LNG as fuel supply for road and non-road applications using natural gas engines and dual-fuel engines. LNG is a means of storing clean burning natural gas in a liquefied form with higher energy density than CNG with less total weight, thereby enabling increased vehicle range and time between refueling. The LNG is regasified before consumption in a natural gas or dual fuel engine. Examples of end user applications, current testing programs and research in future possibilities are presented.

a. Road Transport

The latest estimate of total vehicles in the world is about 1.3 billion[39]. About 80% of these vehicles are found in eighteen countries: U.S., China, India, Japan, Indonesia, Germany, Brazil, Italy, France, Russia, U.K., Spain, Mexico, Thailand, Vietnam, Taiwan, Poland and Malaysia, Figure 24. Sixty-six countries account for the remaining 20% of vehicles. The United States is estimated to have over 253 million vehicles, about 20% of the world total[40]. Over the last decade the total number of natural gas vehicles (NGV) in the world increased significantly to an estimated 17.7 million vehicles as of June 2013[41]. Growth has been led by Asia-Pacific countries with a 35% annual growth rate[42]. The increase has been predominately in light vehicles due to natural gas engine technology and government supported establishment of CNG fueling infrastructure.

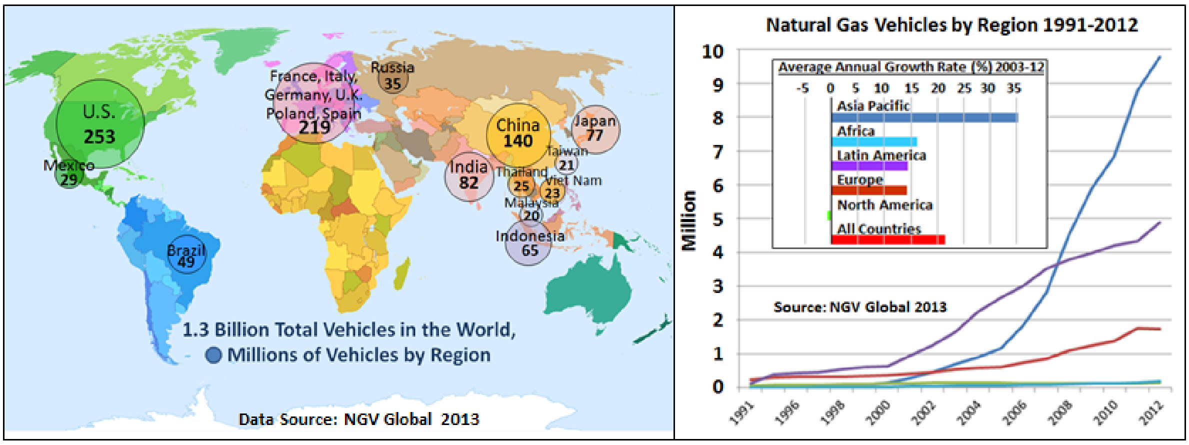

Figure 24 - Total Vehicles in World and Growth of NGVs

[39] NGV Global, NGV Knowledge Base, Current NGV Statistics as a Percentage of Total Vehicles, Nov. 2013 as of Dec 2012.
[40] U.S. Department of Transportation, Bureau of Transportation Statistics, Table 1-11.
[41] NGVA Europe, Worldwide NGV Market Share, latest update in June 2013.
[42] NGV Global, Current Natural Gas Vehicle Statistics, Last updated Nov 2013, Data as at Dec 2012.

The US Department of Energy (DOE) reports that heavy duty trucks travel the greatest annual distance while transit buses and refuse trucks consume the highest volumes of fuel[43]. These vehicles generally travel hub and spoke from a central depot, or point to point along established freight corridors. These vehicles are particularly well suited for conversion or replacement by LNG fueling systems for economic and environmental benefits. Central depots and established freight corridors are ideal for dedicated LNG fueling stations.

Interest by commercial fleet owners in LNG fueled vehicles has grown significantly over the past decade, due to ongoing emissions concerns, improved spread between lower priced natural gas and higher priced diesel fuel, and operational efficiencies. The interdependent relationship between having enough customer base to justify investing in LNG fueling infrastructure versus having enough infrastructure to justify investing in LNG fueled vehicles has led to a number of industry consortiums and government supported initiatives to move both opportunities forward. Progress has been made in development of technology, codes and regulations, and coordinated fueling infrastructure.

The AEO2014 forecasts U.S. natural gas consumption in transportation to increase sharply by 2040, Figure 25, spurred by relatively low natural gas prices[44]. CNG and LNG will account for about 3% of total U.S. energy transportation consumption. Although a relatively small share, it marks the beginning of natural gas consumption, primarily by medium-duty trucks using CNG and heavy-duty trucks using LNG[51].

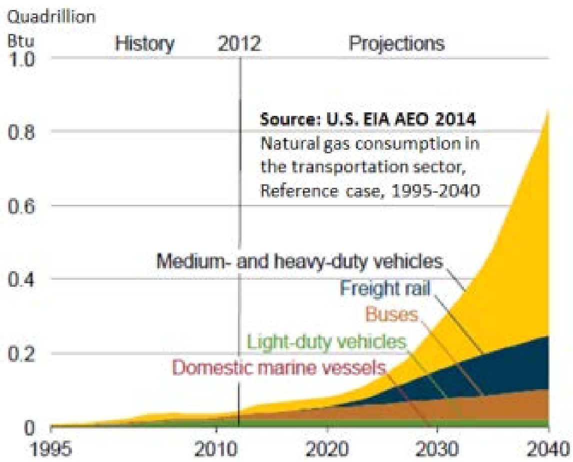

Figure 25 - Natural Gas Consumption in Transportation

The IEA reports that in 2012, road transport account for just 1.4% of global natural gas demand, up ten-fold since 2000. The IEA expects this share to almost double by 2018, with China's growth dwarfing other countries. Although, NGVs remain a small share of total vehicles in the world, environmental drivers and fuel cost savings will continue to be drivers for change over time[45].

b. Maritime Transport

DNV-GL performed a comprehensive simulation of the world merchant fleet up to 2020[46]. In the most likely scenario, 1000 new buildings are expected to be delivered with natural gas engines, equal to 10-15% of new ships. Additionally, 600 to 700 ships could be retrofitted to run on LNG. The regulatory drivers are the 0.1% ECA sulphur limit in force from 1 January 2015, and the 0.5% global sulphur limit from 1 January 2020, as well as the international ship EEDI which came into force on 1 January, 2013. As discussed in Chapter 2, the

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[43] US DOE Alternative Fuels Data Center, Average annual fuel use by major vehicle categories, July 2013 Update.

[44] U.S. EIA, Annual Energy Outlook 2014, release April 2014, Transportation.

[45] IEA Energy Issue 5, 4Q2013, Ministerial 2013, Global Synergy for Tomorrow's Energy, A different gas fills more tanks.

[46] Shipping 2020, DNV GL, September 2012.

economic viability of various emission abatement technologies depends heavily on the relative price levels of fuels and where the vessels travel. DNV-GL found LNG is a cost-efficient option for vessels spending more than 30% of their sailing time in ECAs.

Lloyd's Register Marine in collaboration with the Energy Institute at the University College London published a 2014 report on Global Marine Fuel Trends 2030[47]. Overall fuel demand doubles by 2030, with the HFO continuing to be the primary fuel with share in the status quo case comparable to 2010 levels. Other fuel options will see a higher rate of growth to meet this demand. LNG is forecast to reach a maximum 11% share in 2030. Small ships will see the highest LNG uptake. Ships are long-lived investments; fleet change to new technologies will evolve over the longer term as older vessels are retired and new builds are required.

Norway has led the move to LNG fueled ships with construction of the first vessel in 2001, and by March 2014, a fleet of 42 LNG fueled vessels has been built[48]. Most are small ferries that shuttle supplies to offshore oil platforms. As of January 2015, DNV-GL reports there are 57 LNG fueled ships in operation and 77 on order worldwide, for a total of 134 LNG fueled ships[49]. Another 100 ship orders are estimated yet to be placed. The types of LNG fueled vessels include:

- Car shuttle-ferry
- Platform Service Vessel (PSV)
- Product Tanker
- Container Vessel
- Ro-Pax
- Gas Carrier
- Dry Cargo
- Passenger shuttle-ferry
- MR - tanker
- Escort tug
- Chemical tanker
- Dry Cargo / Fish Forage Carrier
- High-speed PAX catamaran
- Patrol Vessel
- Ro-Ro Cargo Vessel
- Oil Tank Barge
- Passenger vessel
- Inland waterway vessel
- Fishing vessel
- LNG Hybrid Power Barge

A sample of published articles on orders for LNG fueled ships is given in Appendix 9.d, Maritime Transport LNG as Fuel Programs. These programs include: Argentina, Canada, China, Denmark, Italy, Finland, Germany, Japan, Netherlands, Norway, Qatar, Singapore, Sweden, Thailand, U.K., Uruguay, and USA, among a rapidly growing list of LNG users.

A major concern of ship owners that impacts adoption of LNG as fuel technology is uncertainty about the availability and timing of LNG bunkering infrastructure worldwide. A 2014 survey of 22 ports by Lloyd's Register, indicates 59% of ports already provide LNG bunkering infrastructure or have specific plans, Figure 26[50]. Furthermore, 55% indicate the port is participating in the International Association of Ports & Harbors (IAPH) project to develop guidelines for LNG bunkering in ports.

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[47] Global Marine Fuel Trends 2030, Lloyd's Register Marine, University College London, March 2014.

[48] DNV GL, LNG, Energy of the Future, Lars Petter Blikom, 25 April 2013.

[49] Ship list – Vessels in operation and vessels on order, DNV-GL, 16 January 2015.

[50] Lloyd's Register LNG Bunkering Infrastructure Survey 2014. The outlook of Ports on provision of LNG bunkering facilities.

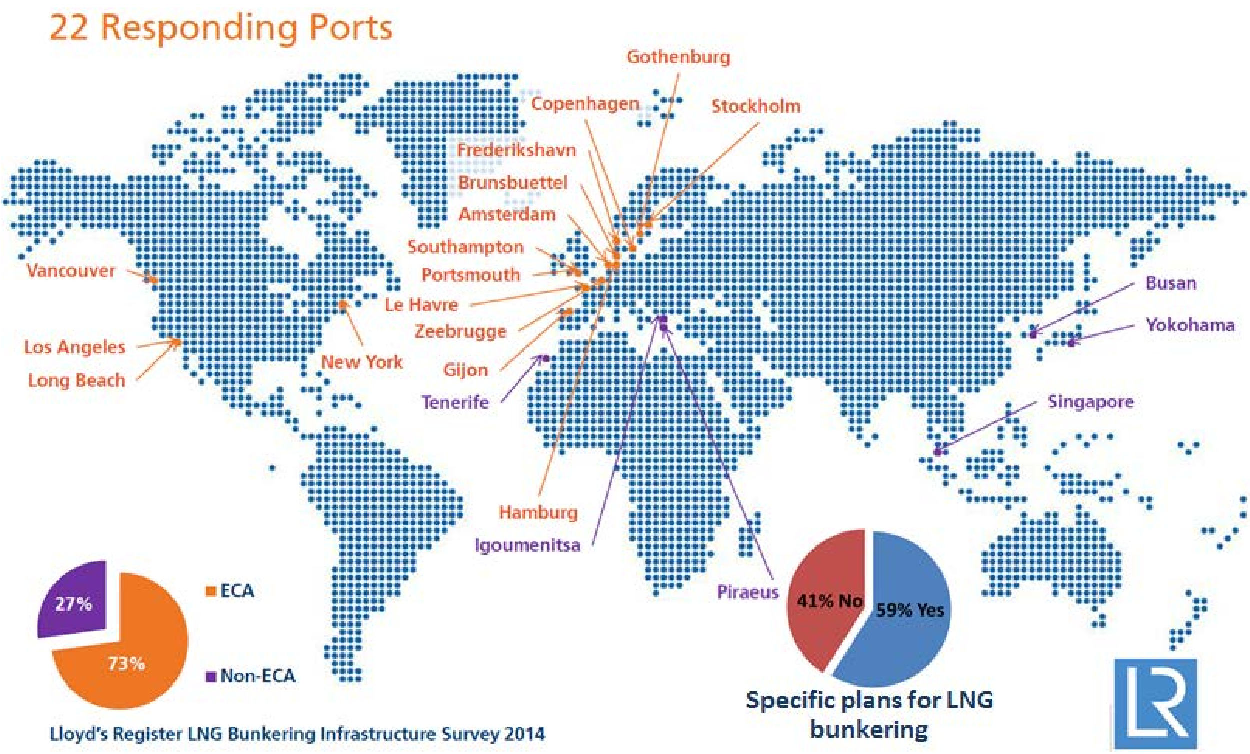

Figure 26 - Lloyd's Register LNG Bunkering Infrastructure Survey 2014

European ports have done the most work in response to ECA emissions and sulphur limits[51]. The Ports of Rotterdam and Zeebrugge will propose LNG bunkering with bunkering vessels that are under construction[52]. Studies are underway for LNG bunkering at other ports including Port Antwerp, Port of Dunkirk, Port Ferrol, Port Roscoff, Port Santander and Port of Hamburg[53]. The Port Authorities for the Port of Rotterdam and the Port of Gothenburg have formed an alliance to establish LNG infrastructure by 2015. The Port of Antwerp Port Authority appointed ship owning company EXMAR as its strategic partner to provide LNG bunkering[54]. The Port of Rotterdam is working with Shell, Gasunie and VOPAK, while the Port of Zeebrugge is working with GDF Suez, NYK and Mitsubishi[55]. DNV-GL and partners are working on a LNG bunker barge concept for Norway[56]. Qatar, Singapore, Japan, Thailand, China, UAE, USA and Canada among others are assessing LNG bunkering infrastructure[57, 58].

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[51] Port of Rotterdam Authority, press release 10 October 2012.

[52] Gasunie and Vopak sign agreement with Shell as launching customer for LNG Break Bulk terminal, 23 Aug. 2012: http://www.gasunie.nl/en/news/gasunie-en-vopak-tekenen-overeenkomst-met-shell-als-launching-cus#sthash.3A3DhHi8.dpuf

[53] Pioneering role in LNG bunkering, http://www.portofantwerp.com/en/everythingispossible/port-antwerp-pioneers

[54] Port of Antwerp Gets Practical About LNG Bunkering. September 18, 2013: MarineLink.com

[55] GDF SUEZ signs an agreement with NYK and Mitsubishi to develop LNG as marine fuel worldwide, 1 July 2014, http://www.gdfsuez.com/en/journalists/press-releases/gdf-suez-signs-an-agreement-with-nyk-and-mitsubishi/

[56] Large Volume LNG Bunker Barge Concept Unveiled. June 10, 2013 | Norway: NGV Global News.

[57] Global Transport Sector Looks To Ride Natural Gas Boom, Reuters News, H. Gloystein, J. Saul, Feb. 4, 2014.

[58] Asia to Drive LNG Bunker Adoption, Ship & Bunker - Asia/Pacific News, 21 January 2014.

c. Floating Power Generation

Floating power generation is well established, stretching back to the 1930s when adapted ships were used in the US to provide additional summer power to southern coastal resorts before moving to northern locations in winter to back up power in case of storms. During the 1990s, power barges became a popular way of providing energy to developing nations, with equipment suppliers like General Electric, Westinghouse, Wärtsilä, and MAN offering various sizes and configurations. Today there are over 75 power barges operating around the world in locations as diverse as Bangladesh and New York City.

A decision to utilize power barges is influenced by three factors:

- Poor infrastructure - Deployment to areas with port locations close to end users reduces shore-side cabling and additional infrastructure requirements for power feed into the local network.
- Poor credit ratings or stability – Deployment to countries deemed too risky to invest in fixed infrastructure may attract a mobile barge option to reduce the level of risk.
- Expedited interim provision - Deployment in regions experiencing leaps in demand for commercial scale power or emergency relief while longer term solutions are procured.

i. Small-scale Power Demand

Demand for floating power is continuing to expand as energy hungry, middle class societies continue to emerge across developing nations. In addition to the stranded markets, such as island states, a significant increase in demand can be expected across the rapidly developing economies such as Brazil, Russia, India, China, Indonesia and the Philippines. Quick deployment of additional power assets is needed to cover the rise in population and industry in historically remote areas.

A number of LNG import schemes are specifically tailored to deliver re-gasified LNG to land based gas fired power stations. Often the power project and import terminals become too large for the local consumption, or too complex to achieve financial closure, hindering progress and project realization.

Emerging economies and isolated island states are experiencing unstable and/or expensive power supply situations and seek immediate solutions to sustain economic development. A second tier of industrialized countries is also emerging in the industry and power sector, dependent upon competitive pricing of fuels.

It is a difficult task to get a full overview of potential gas to electrical power opportunities world-wide in the capacity range for a power barge (i.e. 50 – 300 MW). For instance, there is a vast number of existing diesel-engine based electricity generation units spread across the globe in developing countries today that burn HFO or diesel at a substantial premium to natural gas.

If the LNG supply chain is sufficiently large (accumulation of generating capacity) or the LNG source is close enough to the power plant, the viability of switching to LNG should be attractive. The opportunity to combine floating power generation with an integrated LNG storage system directly in the area where the requirements exists, could be very attractive and offer clear economic, commercial and social benefits.

ii. Indonesia example

A DNV-GL led Joint Interest Project (JIP) in 2010 looked into small scale LNG opportunities in SE Asia and reported that in the Eastern part of Indonesia 70 small power plants (100 MW and below) could be built/converted to natural gas, Figure 27.

The study found the opportunity for additional installed power generation by 2020 in Indonesia is 47,000 MW, of which 8,300 MW is small scale. By installing this capacity, total capacity in Indonesia would be 75,000 MW by 2020, only 33% of the estimated installed capacity in Malaysia.

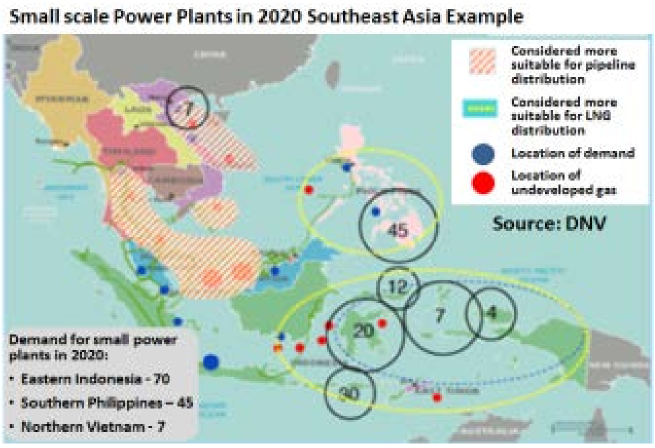

Figure 27 - Indonesian Example of Small Scale Power Plants in 2020

iii. Philippines example

The Philippines is an island state with a rapidly growing economy. At a compound annual growth rate (CAGR) of 6-7% power demand is quickly outstripping supply in all parts of the archipelago. Electricity prices are among the highest in the world. A deficit of 3000 MW is forecasted by 2015. Preliminary analysis shows that a 125,000 m^3 LNG floating storage offloading unit acting as a central hub could be put in place at a competitive cost.

In this scenario, the hub could receive long-haul LNG from a medium size carrier (40,000m^3). Coupled with 2 small scale LNG carriers (15,000 m^3), a short sea distribution network could be established using 25 LNG power barges with a generating capacity of 50 MW each, Figure 28. The competitiveness of the production of electricity from natural gas would depend on an efficient operation of the logistics and LNG fuel cost.

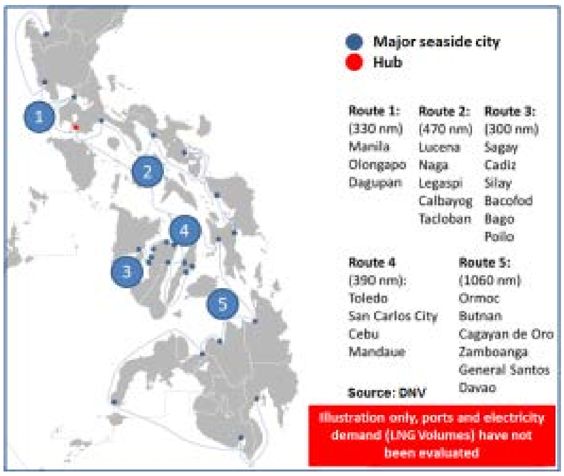

Figure 28 - Philippines Example of Potential Small Scale Power Plants in 2020

d. Non-Road Applications

Non-road refers to uses such as mining trucks, drilling operations, agriculture, industry and municipalities. Following are examples of LNG as fuel in non-road applications. End users are recognizing the cost savings and emissions reduction advantages that LNG as fuel provides.

i. Mining Trucks

From 1 January 2014, non-road engines with output over 75 kW in the US and 130 kW in the EU will have to meet US Tier 4 Final and EU Stage IV requirements, respectively, to reduce NOx and PM emissions by 99% over pre-legislation levels. Natural gas fueled engines and dual fueled engines for heavy trucking, locomotives and maritime vessels have been adapted to off-road uses.

The top ten mining companies utilize more than 28,000 heavy mine haul trucks (>100 tonnes) worldwide, consuming over two billion gallons of diesel annually[59]. Many mining operations have begun to utilize LNG as fuel. For example, Westport and Caterpillar are co-developing HPDI for off-road engines, including large mine trucks, with 95% substitution of diesel with natural gas. Shell Canada is testing a new engine and fuel mix using LNG that could reduce operating costs and emissions from oil sands mining in northern Alberta[60]. Pertamina is working with PT Mandiri Indominco on a LNG fuel program for inpit dump trucks at a major coal mine in Kalimantan[61, 62]. GFS added dual-fuel LNG conversion systems for the Komatsu 830 and 930 mine haul truck and Caterpillar 777 and 793 mechanical drive trucks. These off-road trials of LNG as fuel are setting the stage for a significant increase in applications worldwide. Additional information on non-road LNG is given in Appendix 9.e, Off-Road, Power Generation and Aviation LNG as Fuel.

ii. Drilling Operations

LNG is increasingly being used to fuel natural gas engines and dual fuel engines for drilling rigs, generator sets, high pressure pumping equipment and heavy trucks that support the well related operations, Figure 29. The high pressure injection pumps for well stimulations and completions are particularly power intensive requiring large fuel supply for short periods. A massive amount of machinery may be required to deliver the high pressure, high volume fluid injection rates necessary to fracture rock formations in deep wells. LNG provides a significant cost savings over diesel fuel in this type of operation.

Figure 29 - LNG Fuel Supply for Drilling Operations; courtesy Prometheus Energy

[59] Westport's New VP Will Focus on Natural Gas for Mining and Rail. Sept. 18, 2013. Vancouver BC: NGV Global News.
[60] Shell Canada /Caterpillar to Explore LNG for Mining Trucks. December 16, 2013, Calgary AB: NGV Global News.
[61] Indonesia: Pertamina Pioneers Utilization of LNG for Transportation, Aug 7, 2012: LNG News World.
[62] Pertamina to Supply LNG to Indominco. Lili Sunardi, Arsyad Paripurna, December 9 2013: Bisnis Indonesia.

What differentiates well completion operations from mining or other remote operations is the requirement for a high rate of LNG vaporization for short time periods. In these situations, the combination of a LNG trailer with a high volume vaporizer trailer work well together to deliver the necessary flow rates to fuel multiple natural gas engines operating simultaneously. For routine well site and drilling operations, use of integrated remote LNG storage and vaporization trailers provide the best solution, Figure 30.

Figure 30 - Remote LNG Trailers and Vaporizers; courtesy Linde

Several examples of LNG use in drilling operations are discussed in Chapter 7, Value Proposition and further described in Appendix 9.e.

iii. Remote Inland Communities

Similar to remote maritime power supply, a number of remote inland communities have recognized the economic and environmental benefits of trucking LNG for local gas distribution and power generation. For example, in the Northwest Territories of Canada, twenty-one communities worked together with Northwest Territories Power Corporation (NTPC) to purchasing LNG in lieu of diesel fuel to run their power plant. As diesel fuel and transportation costs rose, the alternative of trucking LNG became economically viable. NTPC constructed a LNG storage facility and began trucking LNG from Vancouver, BC to the remote city of Inuvik in January 2014 to offset half the diesel requirement. NTPC plans to expand the program across the Northern Territories[63]. Two additional LNG facilities are expected in northern British Columbia and Alberta by 2016[64].

e. Rail Transport

Since the late 1980's the U.S. rail industry has been evaluating and testing dual fuel and gas fuel for locomotives. AEO 2014 forecasts freight rail to be a growing LNG market sector beginning in 2020, when current locomotive test programs have been completed. By 2040, LNG may gain 35% of the US rail fuel market share in the reference case. Even in the low case, LNG may supply 16% of rail transport fuel. More information on Railroad LNG Test Programs is given in Appendix 9.c.

[63] Inuvik's LNG facility 'breaks trail' in the North, Maria Church, January 13, 2014: Northern Journal.

[64] LNG deliveries start to fuel Inuvik power plant in Canada's far north. January 16, 2014: Arcticgas.gov

Canadian National Railway (CN) is developing a HPDI locomotive to displace up to 95% of the diesel, Figure 31. Two Electro Motive Diesel (EMD) locomotives will be demonstrated in 2014; commercial production is expected in 2017. CN is also testing the viability of low-pressure LNG-diesel conversion using Caterpillar's Dynamic Gas Blending (DGB) technology[65]. LNG is regasified through a heat exchanger aboard the tender and natural gas flows through a flexible hose from the tender to the locomotive.

Figure 31 - EMD LNG Locomotive; courtesy Canadian National Railway

U.S. railroad BNSF started a pilot program in 2013 with three locomotives each from GE and Caterpillar, Figure 32[66]. GE has also developed the NextFuel natural gas retrofitting kits to enable existing Evolution Series locomotives to operate on 100% diesel or up to 80% natural gas, with Tier 3 compliance. BNSF expects to make a decision regarding conversion of its fleet of over 7000 locomotives at the conclusion of the test program.

Figure 32 - LNG Locomotives; courtesy GE and Caterpillar

Development of an industry-standard LNG fuel tender is being led by the American Association of Railroads' (AAR) Natural Gas Fuel Tender Technical Advisory Group (NGFT TAG). The group has met with locomotive, engine, freight and tank wagon manufacturers, and the Federal Railroad Administration (FRA) to develop fuel tender performance standards[67]. A wide range of requirements must be satisfied including: safety, exhaust emissions performance, range, high horsepower, high tractive, fuel economy and reliability[68].

Operational challenges include duplicative fuel depots, the interconnected network of freight railroads serving multiple states or countries, increasing numbers of run-through trains and the complication of distributed power locomotives located within long freight trains[69].

[65] Westport Delivers First LNG Tender, Rich Piellisch, HHPInsights.com, April 9, 2014.
[66] BNSF to test LNG as fuel in freight locomotives, Railway-technology.com, 8 March 2013.
[67] LNG: Fuel of the future? International Railway Journal, Kevin Smith, December 09, 2013.
[68] An Evaluation of Natural Gas-fueled Locomotives, November 2007, BNSF Railway, Union Pacific Railroad, The Association of American Railroads, California Environmental Associates.
[69] LNG: Fuel of the future? International Railway Journal, Kevin Smith, December 09, 2013.

5. LNG Distribution

LNG distribution is the logistical arrangement to deliver natural gas in condensed liquid form to customers as discussed in Chapter 4 on End User Sectors. LNG distribution is flexible with several alternative means of transport, but a common trait for all alternatives is the production of boil-off gas, i.e. the reversion of LNG back to its natural gaseous state, which needs to be taken into account when planning any logistical chain.

LNG may be distributed from a LNG terminal or small scale LNG plant by transport over land or by sea. LNG may be transported in insulated cryogenic tanks by truck, rail, ship or a combination of these to deliver LNG to end users. A LNG fuelled vessel may be bunkered by port-to-ship (PTS), truck-to-ship (TTS), ship-to-ship (STS) transfer or by portable tank transfer (PTT). The International Organization for Standardization (ISO) has established standards for ISO-containers transporting cryogenic liquids.

The point where distribution by one method is preferred to distribution by another method is not easily answered since it depends on the circumstances of each particular end user, location and means of access available. However, a general assessment as a function of volume and distance is illustrated in Figure 33.

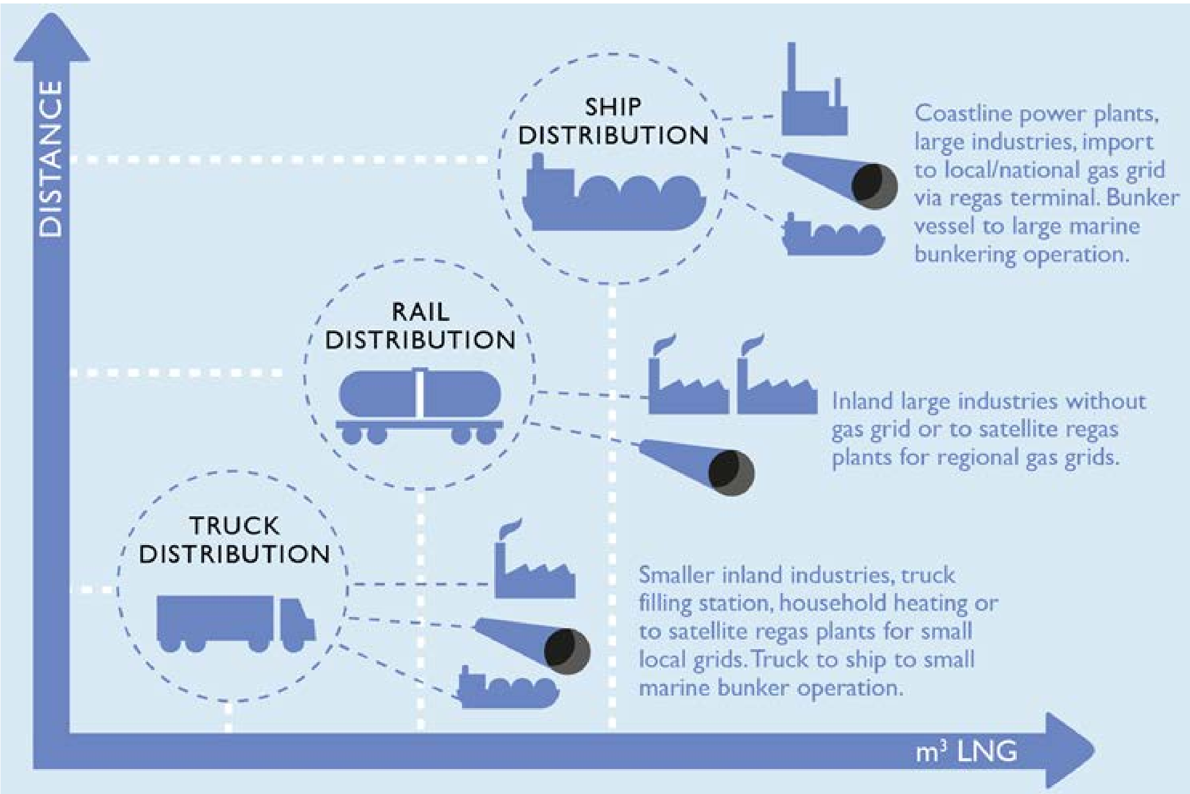

Figure 33 - LNG distribution options; courtesy Swedegas AB

This chapter presents a description of various methods of LNG distribution.

a. Port Infrastructure

Large LNG import terminals are built to import LNG via large specialized LNG carriers, store the LNG in purpose-built LNG tanks while maintaining the molecules in liquid form and regasify the LNG for distribution through the natural gas pipeline grid and/or distribute the LNG when required. LNG distribution by truck has a long history. For example, in Spain LNG has been distributed by truck since the 1970's; during 2012 over 45,000 truck cargos were loaded, which equates to approximately one conventional LNG cargo per month[70].

Many LNG import terminals are evaluating the concept of "break bulk" where large LNG storage volume is broken into smaller distributable parcels via land and/or sea. This is economically feasible since the large investment for infrastructure, such as LNG storage tanks and berth facilities, has already been made. The incremental costs for small scale bunker jetties and truck or railcar loading racks for small parcel send out capabilities creates interesting business opportunities. Lately, there has been increased activity to build more LNG distribution infrastructure for bunkering and trucks as a result of market demand. This is particularly the case in Europe where there are numerous small scale LNG facilities under construction or being planned, as shown in Figure 34[71]. These facilities are either at existing large scale terminals (for break bulk) or as separate smaller redistribution terminals, especially in Scandinavia.

#	Terminal	Country
1	Zeebrugge	Belgium
2	GATE/LBBR	The Netherlands
3	Isle of Grain	UK
4	Milford Haven	UK
5	Teesside	UK
6	Sines	Portugal
7	Swinoujscie	Portugal
8	Barcelona	Spain
9	Huelva	Spain
10	Cartagena	Spain
11	Sagunto	Spain
12	Bilbao	Spain
13	Mugardoz	Spain
14	Livorno	Italy
15	Panigaglia	Italy
16	Porto Viro	Italy
17	Fos Cavaou	France
18	Fos Tonkin	France
19	Montoir de Bretagne	France
20	Fredriksstad	Norway
21	Snöhvit/Melköya	Norway
22	Risavika	Norway
23	Lysekil	Sweden
24	Nynäshamn	Sweden
25	Revithoussa	Greece
26	Marmara Ereglisi	Turkey
27	Aliaga Izmir	Turkey
28	Musel	Spain

Figure 34 - LNG terminals in Europe; adapted from Energigas Sverige AB

The table in Figure 34 lists the location of existing European import terminals and the map shows locations. Among the European import terminals, 22 offer truck loading services and another two have plans to do so in the future. Nine terminals have facilities for marine

[70] Source: Enagas, Spain

[71] Gas Infrastructure Europe, SSLNG map database, March 2014

distribution to load small LNG feeders and bunker barges. Another nine terminals have plans to do so. Today no European import terminal offers direct loading of freight railcars at the terminal but five terminals are looking into the possibility to offer this option or service. A complete list of import terminals globally is available in the IGU World LNG Report.

b. Maritime LNG Distribution

Norway has been at the forefront of LNG distribution by sea on LNG fueled ferry services dating back to 2000. Initially, the Norwegian government only allowed loading of LNG on vessels that did not transport passengers. However, beginning in 2014 LNG bunkering of Fjord Line cruise ships with passengers on board was permitted. Bunkering of Viking Line cruise ships in Stockholm was approved with passengers on board in 2013. This action highlights the changing environment of safety regulations and public acceptance of LNG as a viable and safe fuel option.

The growth of LNG distribution by sea has started to gain traction on a global basis. In anticipation of imminent LNG use in the United States, the U.S. Coast Guard has asked for public comments as a proactive step in establishing two guidelines:

- Guidance Related to Vessels and Waterfront Facilities Conducting LNG Marine Fuel Transfer Operations and Guidelines for LNG Fuel Transfer Operations
- Training of Personnel on Vessels Using Natural Gas as Fuel

As discussed in the Chapter 2 on regulations, LNG growth is being driven largely by MARPOL Annex VI, which will reduce SOx, NOx and PM emissions in ECA zones and globally. An increasing number of ports are evaluating or developing LNG infrastructure in anticipation of the need for LNG as fuel to help meet the new stringent environmental caps. In addition, LNG break bulk distribution is being developed using small LNG carriers, such as at Gate Terminal in the Netherlands, to deliver smaller quantities of LNG to storage and/or end users not connected to a gas grid.

The global market for small-scale LNG carriers is at the moment small and has historically been controlled by a few players. There are currently 10 LNG carriers with capacity below 10,000 m^3 in the global LNG fleet and most of these are multi-gas carriers to allow for greater commercial flexibility.

The historic requirement for small-scale deliveries of LNG by ship has been limited by the relatively high cost of small parcels of LNG and the difficulty in securing them. Now, through a combination of government and IMO incentives and new avenues of supply, the demand for small-scale LNG carriers is growing. With anticipated growth in LNG as a fuel there will be an associated growing need to provide flexible bunkering solutions (as with other ship fuels) and this will translate into an increasing demand for small-scale LNG carriers and bunkering barges.

A comprehensive study headed by the Danish Maritime Authority (DMA) was released in 2012 and concluded that Northern European ECA alone will require 24 bunker barges by 2020, growing to 35 by 2030, Figure 35. Currently, four bunker barges have been ordered, are under construction or are in service in Europe. The price of marine fuel will be a determining factor on the demand side (number of LNG fuel capable vessels), and it is very likely that new build ships sailing in or into the ECAs will have dual fuel capability to hedge the fuel price.

Forecast of Bunker Vessels for Northern European ECA			2020	2030
Maritime demand to be supplied by small and medium terminals, vessels and trucks (tonnes)			3,630,000	6,212,780
Number of terminals	Medium size (case II)		9	11
	Small size (case III)		23	38
Number of bunker vessels	Total		**24**	**35**
	by capacity	1000 m^3	19	28
		3000 m^3	3	5
		4000 m^3	1	1
		10,000 m^3	1	1
Number of trucks	capacity	50 m^3	6	8

Figure 35 - Forecast of Bunker Vessels for Northern European ECA

c. LNG Bunkering Methods

LNG bunkering, the fueling of ships with LNG as the energy source, can be performed by four methods: PTS, TTS, STS and PTT.

i. Port-to-Ship

The most common form of PTS distribution is from an on-shore LNG storage tank to a vessel via a pipeline and a ship jetty using flexible hose, Figure 36. The connection between the onshore LNG tank and the ship allows flexibility to load various vessels (fit for purpose concept). An alternative for ships regularly departing from the same port and consuming substantial volumes of LNG is installation of fixed onshore LNG bunkering infrastructure including distribution and monitoring systems with local expertise in place, Figure 37. This system is fixed and limited to specific vessels (fit for use concept).

Figure 36 - PTS Bunkering using Flexible Hose; courtesy Micro Motion and Emerson

Figure 37 - PTS Bunkering Fixed Pipe Arrangement; courtesy Gasnor and Rolls Royce

The disadvantages of fixed onshore bunkering include potential berth congestion, potential misalignment of coupling systems and priority of large scale LNG import/exports activity versus small-scale operations. Fixed onshore distribution requires constant monitoring and technical support to manage the LNG transfer.

ii. Truck-to-Ship

TTS distribution is probably the most flexible form as the vessel is not required to moor at a dedicated LNG dock for the transfer and the LNG truck can move to the transfer location at the required time, Figure 38. Given the limited size of the truck´s tank, a disadvantage is highlighted when a large vessel bunkering may require multiple trucks to fill its fuel tank, causing delays to the vessel's schedule and introducing more operational risk. TTS distribution does offer a good alternative for smaller vessels that do not have fixed routes and need to bunker at a variety of ports, which frees up their operational capacity and range. Also, during the buildup phase of LNG bunker demand, it may be hard to justify investment in a bunker barge; therefore, the truck bunker solution offers a potential cost efficient start up solution.

Figure 38 - Truck-to-Ship Bunkering; courtesy Gasnor

iii. Ship-to-Ship

STS distribution requires the most monitoring and equipment; however, it is an essential method. The vast majority of bunkering today is performed by ship-to-ship transfer. It is expected that a majority of maritime LNG bunkering will be performed the same way. This method is most suitable for large ships and for ships with no particular port of call.

The majority of LNG bunkering vessels planned and/or ordered is for 6000 m^3 or less storage capacity. However, when economically justified, much smaller bunker vessels can provide a more customized solution. For example in Stockholm, the AGA Seagas bunker barge is 157 feet long (48 meters), and can transport 187 m^3, or about 60-70 tons of LNG at one time. Since approval for bunkering with passenger onboard, 2013 through November 2014, more than 500 successful bunkering operations have been performed. The AGA Seagas is shown in Figure 39 bunkering its daily committed customer, the passenger ferry M/S Viking Grace.

Figure 39 - AGA's Seagas Bunkering Ferry Grace; courtesy Viking Line, WPCI, photo K. Gabor

iv. Portable Tank Transfer

This form of LNG distribution utilizes refueling via portable tanks (ISO containers) that can be directly driven onto or lifted on and off a vessel. The amount of LNG will depend on the number of portable tanks the vessel is capable of storing. The inherent advantage of this system is the flexibility offered to configure LNG capacity based upon the voyage and the number of tanks required. The portable tank system can be transported by other means like truck and rail as well as being utilized by many different industries which augments its economic viability. The disadvantages of the system are the need for compatibility between tank design and vessel; multiple tanks will require multiple connections which increase operational and methane slippage risks. Multiple tanks at multiple locations will require careful scrutiny of standards. The physical transfer operation demands increased monitoring and could also increase bunkering time.

d. Maritime Technical Challenges

i. Transfer at Sea

Transfer at sea poses unique technical challenges due mainly to the relative motions between the bunkering vessel and the receiving vessel. Secure mooring arrangements are critical. The relative motions introduce pressure variations in the flow lines and the constant movement between the vessels stresses the flow line and/or loading arms and the couplings. Rigid loading arms offer a more secure method to handle the pressure and movement during loading operations; however, the arms have a limited operating envelope and need acceptable metocean conditions for safe fluid transfer operations. Flexible hoses may offer the greatest range of motion and ability to handle bunkering connections on a wider range of different receiving vessels, but the range of movement and pressure must be constantly managed.

ii. Boil Off Gas Handling

BOG handling is another important factor to consider in the logistics and scheduling of LNG cargo distribution. Whereas crude and its derivatives can remain on the water in a fungible state for extended periods, LNG will gradually warm up and revert back to its natural gas state increasing pressure and temperature inside the storage tank. BOG must be continuously managed for economic and safety reasons. This is done by recondensing or consuming the BOG in the vessels engine or utility systems (i.e. power generation). The vessel must have a safety relief system (incineration, flaring/venting). LNG distribution requires specialized equipment and processes to maintain the cold state of the liquefied gas. The impact of BOG is given in Figure 40, which shows reduced delivery of LNG as a function of distance traveled[72].

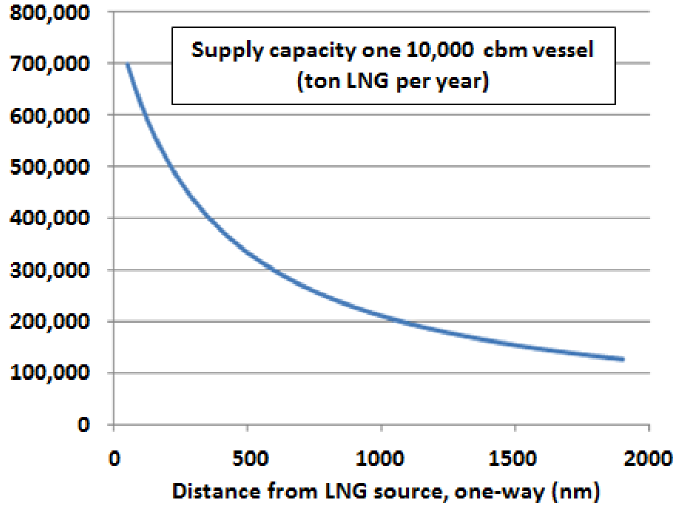

Figure 40 - LNG Quantity Delivered verses Distance; courtesy I.M. Skaugen SE

iii. Small-scale LNG Tanks

A third factor of importance in small-scale sea transport (LNG carriers) and using LNG as fuel for any type of vessel is the type of tanks to be used. There are several types of LNG tanks regulated by IMO as illustrated in Figure 41.

Figure 41 - Types of LNG Storage Tanks

The two types of main containment tank, A - Atmospheric and C - Pressurized, are suitable for small-scale use but have different operational and economic parameters that must be evaluated. Ship owners want to optimally utilize the vessel hull shape, deck space and carrying capacity. An atmospheric tank can be designed to use the hull space more optimally than a pressurized tank, and can therefore carry more LNG in the space it occupies. A comparison of space and volume between IMO Type A and C tanks is given in Figure 42. A pressurized tank can allow pressure to build up and therefore has improved capability to

[72] IM Skaugen SE, Small Scale LNG – Multigas Carriers, Transport Capacity. www.skaugen.com

manage BOG. However, refilling a pressurized tank cannot be done without first depressurizing the tank and managing the vented gas.

Cost of construction is also a key element and several tank technology companies have developed small-scale tank systems to reduce construction cost, new insulation methods to limit BOG or are adapting current designs.

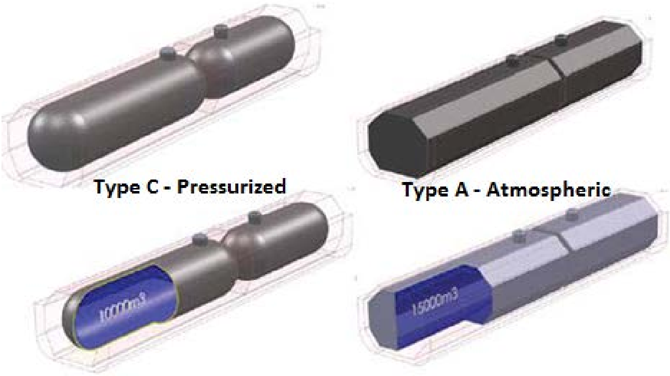

Figure 42 - Space and Volume Comparison of IMO A and C Tanks; courtesy Torgy

As this industry grows it will be interesting to see which tank type will be the preferred "standard", or if both types will find its place in small-scale distribution and bunkering.

iv. Sloshing

Also important to consider in sea transport is sloshing within the storage tanks due to vessel movement in harsh sea conditions[73]. Sloshing is the irregular movement of liquids within the containment system due to:

- Environmental conditions
- Floating structure (shape and dimensions)
- Number, size and geometry of LNG tanks
- Filling level of the LNG tanks
- Coupling between motions of the floating structure and LNG
- Hydro-structural interaction

Partially filled LNG tanks increases the possibility of damage from sloshing. The potential of sloshing must be actively managed by understanding the limits of the containment system and constantly monitoring key parameters which includes: pressure, LNG levels, BOG, minimum and maximum fluid levels in the tank, minimum and maximum levels needed across all tanks. Additionally, proficient testing of the integrity of the containment material and system should be performed at regular intervals.

e. LNG Distribution by Road

LNG can be transported by road to customers not served on a gas grid. The distribution chain starts with a truck filling bay at the (import) terminal. Time for filling a normal sized truck of 50 m^3 is approximately 1 hour. An example of a truck filling can be seen in Figure 43.

Figure 43 - Truck Loading at Terminal; courtesy dourogás

[73] Source: www.marin.nl/web/Research-Topics/Loads-responses/Sloshing.htm

The LNG cargo is transported to the end user's site. The maximum distance for transport depends primarily on the end user's economic capability to pay the added transportation cost. A competitive distance is typically up to 700 km, and recently has been demonstrated under special circumstances to range up to 2500 km.

Another critical factor to consider is the buildup of BOG in the cryogenic tank as it is gradually warmed to ambient temperature which increases internal pressure and risk to the tank. BOG must be considered in the engineering and design of the tank. An example of a LNG trailer being loaded is shown in Figure 44.

Figure 44 - LNG trailer with 56 m^3 Capacity; courtesy Indian Oil

The LNG cargo is usually delivered to local or satellite storage for subsequent distribution as LNG or as natural gas. This technique is adapted from the air gases industry, which has liquefied gases for several decades for industry and hospitals. Satellite storage typically ranges in capacity from 2 m^3 to 1500 m^3, and several tanks may be used together. A vaporizer system uses air-to-air or air-to-water heat exchange to regasify the LNG. Figure 45 illustrates a satellite plant for a local gas grid consisting of two pressurized storage tanks and an air-to-air vaporizer.

Figure 45 - Satellite Plant with Regasification Unit; courtesy sonorgás

i. LNG and LCNG Refueling Stations

LNG from local storage may be distributed through a LNG dispenser directly to fuel tanks on LNG fueled vehicles such as heavy trucks and buses. Alternately, the LNG may be dispensed in a process known as Liquefied-Compressed Natural Gas (LCNG) whereby the LNG is pumped to high pressure in its liquid form then flowed through a vaporizer to regasify the gas at high pressure to fill CNG storage tanks, as shown in Figure 46. Both techniques rely on LNG as the storage state of natural gas with the difference being that LCNG regasifies before filling the vehicle´s CNG tank and that for LNG the regasification is done on the vessel or vehicle itself before feeding into the engine.

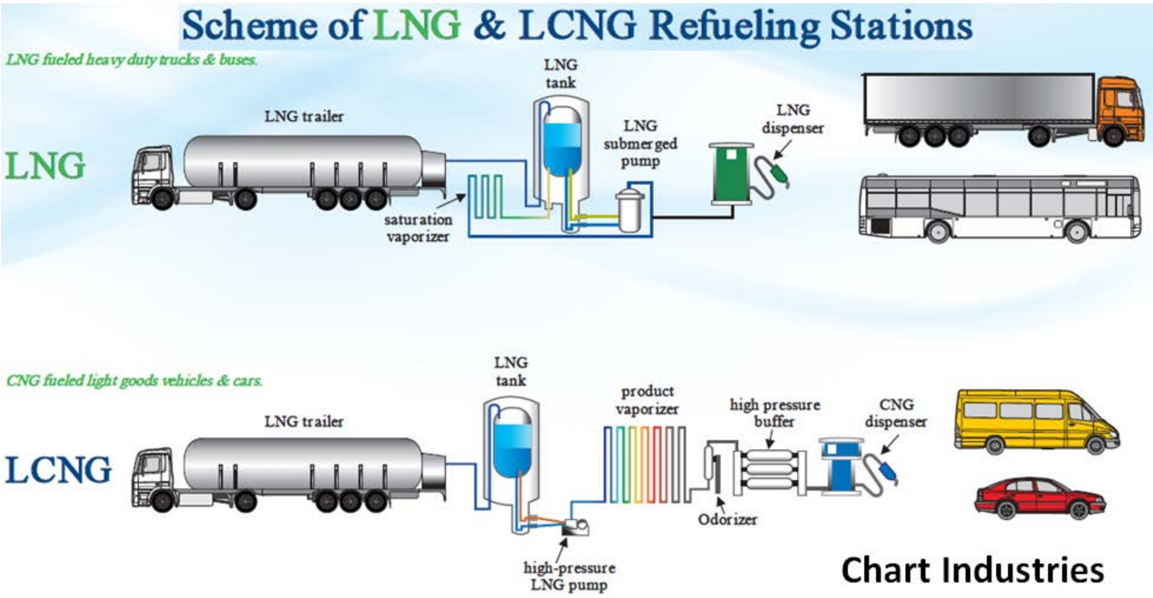

Figure 46 - LNG and LCNG Refueling Stations

NGVA Europe has identified a total of 1433 LNG and 441 LCNG stations worldwide as of September 2013, with China leading the way at 1330 LNG stations and 400 LCNG stations[74. 75].

ii. Virtual Pipelines

ISO containers, discussed in section 5.g, are the most suitable means of transport for LNG virtual pipelines, i.e. systems of regular transport of LNG from a source, such as an LNG liquefaction plant or marine terminal, to a consumer, such as a power plant, a large vehicle fueling network or a ship bunkering terminal. For example, a LNG virtual pipeline using 40 ISO containers in circulation with delivery of 100 containers per months has been in operation since the spring of 2014 between the LNG marine terminal at Sines, Portugal, and a remote 20 MW power plant on the island Madeira. The ISO containers are transported from the terminal over 150 km road to Lisbon port then shipped 1000 km to the island of Madeira for onward road transport to the power plant, Figure 47.

Figure 47 - Virtual Pipeline Sines-Madeira (road-ship-road); courtesy Gaslink

74 NGVA Europe, NGVs and refuelling stations Worldwide, last updated 23 September 2013.

75 NGVA Europe, NGVs and refuelling stations Worldwide, last updated 23 September 2013.

In another example, China's LNG road network is often referred to as a "virtual pipeline" covering approximately 1000 km from Western China to the East Coast. In November 2014, China LNG Group entered into a preliminary agreement with Sinopec Fuel Oil Sales Corp., which would build new LNG fueling stations at existing retail-fuel stations along two major highways in eastern China and for the supply of LNG[76].

iii. Blue Corridors Project

In Europe, the LNG Blue Corridors project unites the expertise of industrial partners and research institutes in LNG transport and infrastructure technology. It is in the first phase of the staged roll out of LNG refueling stations and broad market development for heavy duty vehicles using LNG as fuel. Four LNG Blue Corridors cover the Atlantic and the Mediterranean regions connecting Europe's South to North and West to East, Figure 48[77]. The project will include building 14 new LNG or LCNG stations and building up a fleet of about 100 LNG heavy duty vehicles which will operate along the corridors.

As of June 2014, development of the Blue Corridor LNG fueling infrastructure is well underway with three stations open, five under construction and two additional sites approved. The project will run for 4 years and will connect over 12 Member States and align itself with existing demonstrations running at national levels. The project involves cooperation between heavy duty vehicle manufacturers, fuel suppliers, fuel distributors and fleet operators.

Figure 48 - Map of Four European LNG Blue Corridors

iv. Mobile LNG Distribution

Mobile LNG fueling capabilities are well suited for remote, non-stationary equipment such as mining and drilling operations. Mobile units are completely self-contained with instrument controls, pump, single hose filling, auto-shutoff, and electronic metering that complies with the most stringent weight and measurement requirements. The fueling procedures are similar to heavy truck fueling with a grounding cable attached between the fueling unit and the equipment, and a hose nozzle mechanically secured to the fuel tank.

Large dual fuel mine haul trucks of 100 tonne or more are designed with specific fuel pod configurations and refueling receptacles located according to customer requirements. The LNG fuel tank and the diesel fuel tank are typically designed to be refilled on the same 12-hour duty cycle. The LNG storage pod is filled using a pressurized hose and quick-disconnect coupling that allows for a safe and rapid fueling operation, Figure 49.

[76] China LNG: Signed Preliminary Liquefied-Natural-Gas Agreement with Sinopec Unit, Dow Jones Institutional News, Wayne Ma, 26 November 2014.

[77] NGVA Europe, LNG Blue Corridors Project Progresses As First Refuelling Points Open This April, 14 March 2014.

LNG fueling may be performed in parallel with diesel fueling. The fueling facility may be permanent, temporary or mobile depending on the duration of mining operation[78].

Figure 49 - LNG Fueling of Mining Truck; courtesy HPP Insight, Alpha Coal West

f. LNG Distribution by Rail

LNG has been transported by rail since the early 1970's, using flat railcars carrying ISO containers or specially designed LNG tank railcars, Figure 50. Loading of LNG is carried out at the terminal storage tank by connecting adjustable loading arms or flexible hoses to the tank on the railcar or to the ISO container. Connection using loading arms has the advantage of reduced risk of accidental damage, whereas connection using flexible hose is likely to be less expensive and in most cases the preferred method. In the case of an ISO container, it could be lifted onto the railcar before or after loading of the LNG depending on the loading bay configuration.

Figure 50 - LNG Iso-Container railcars and Tank Car; courtesy JAPEX, Chart

VTG Aktiengesellschaft in Germany, a wagon hire and rail logistics company, is collaborating with Chart Ferox, a worldwide manufacturer of storage, transport, and distribution systems for liquefied air and natural gases, to build two prototype units for the safe and economical carriage of LNG by rail[79]. VTG and Chart are developing a new modern LNG freight railcar with 111 m^3 capacity that will be presented during Transport Logistic 2015 exhibition in Munich, Germany. VTG already today have one freight railcar that has

[78] GFS Corporation, Natural Gas and Diesel Conversion Systems. www.gfs-corp.com

[79] VTG and Chart Ferox Build Rail Tank Cars for LNG Transportation, LNG World News, May 27, 2014.

stood the test of time and miles distributing ethylene on North America's railroads, this model, the SR 603, can also be used for distributing 64,637 kg of LNG[80].

Unloading the LNG requires that the customer have storage capacity on site to receive the cargo. Customer's storage capacity would be based on fuel consumption, BOG, rail delivery frequency and reliability, and potential interruptions in the LNG supply chain. The main differences between the two rail distribution methods are summarized in Figure 51[81].

Tank railcar	ISO Container railcar
Larger capacity, Chart SR603 with approximately 116m^3 capacity (64,637 kg LNG), reduces transportation cost and handles fewer parcels.	A standard 89 ft flat railcar holds two 40 ft containers each with ~42 m^3. The ISO containers are used as storage at the customer's site.
Requires direct access by rail track to terminal storage and customer storage	Direct access by rail not required, can be transported by truck to customer's site
No back-up in case of accident, the freight railcar would need to be emptied on site	Trucks could transport the containers by alternate route
Large end users are experienced at receiving Liquefied Petroleum Gas (LPG) and oil by freight car	Would use the terminal truck loading bay; separate rail loading bay not needed
No lifts needed which eliminates a risk	Likely easier to handle cross-border, when changing to different railway dimensions

Figure 51 - Comparison of LNG Freight Rail Cars and ISO Container on Rail Cars

The rail industry is also testing and evaluating LNG as fuel for locomotives, particularly in North America, which consumes over half the annual diesel consumption by railroads worldwide. The EIA forecasts growth in LNG as locomotive fuel after 2020. Several tank manufacturers produce LNG tender cars, a special railcar that carries the fuel to be used by the locomotive engine, like the one shown in Figure 52. Features such as industry standard design and intelligent fueling controls will allow tenders from all major North American manufacturers to be interchangeable[82]. Development of an industry-standard cryogenic fuel tender is under the auspices of the AAR, and the NGFT TAG is tackling regulatory and safety issues.

Figure 52 - LNG Locomotive and Tender; courtesy Canadian National Railway

g. ISO Intermodal Containers

Fuel tenders can also be configured using ISO containers mounted on a railcar, which can be easily removed when empty and replaced with a full tank transported by truck. The fuel tender may be refueled by truck or switched out. The most modern refueling equipment in a commercial application will provide a refueling time of 30 to 45 minutes.

80 Chart Industries, product sheet for LNG Tank Car SR-603.

81 Swedish Gas Technology Centre, M. Ragnar, publication 2014:295, Rail transportation of liquid methane in Sweden and Finland

82 Westport LNG Tender.

The International Organization for Standardization (ISO) has established regulations for a specialized tank to transport LNG worldwide. The regulations define the size, strength and durability requirements to guarantee that the container can withstand extreme environments endured during transport as well as possess the structural integrity needed to be lifted by cranes or other heavy equipment. The ISO Intermodal Container for LNG is manufactured in 20 ft. and 40 ft. lengths and is suitable for transport by truck, rail or ship[83]. LNG tank containers are designed to store LNG for longer periods of time with higher working pressures. For example, Chart Industries makes 20 and 40 ft. containers with the following specifications:

Type / Code	Nominal Capacity Liters	Working Pressure psig	Holding Time days
20 ft / EN	20,080	145 - 348	52 - 75
20 ft / ASME	20,000	100 - 230	44 - 65
40 ft / EN	43,500	145	65
40 ft / ASME	43,500	100	53

Figure 53 - LNG ISO Intermodal Container Specifications; courtesy Chart Industries

h. LNG Storage and Transport Tanks

Discussion of LNG distribution is not complete without the basic understanding of LNG storage tanks. LNG requires specialized cryogenic materials in the manufacture of equipment used for storage and transfer[84]. The low temperature of LNG affects the strength characteristics of many materials making them potentially unsafe for their normal intended use. For example, carbon steel loses ductility at low temperature and can fracture.

LNG bulk transport tanks have the following basic components:

- Inner pressure vessel made from nickel steel or aluminum alloys exhibiting high strength characteristics under cryogenic temperatures
- Several inches of super-insulation, e.g. aluminized mylar or perlite, in a vacuum environment between the inner pressure vessel and the protective outer jacket
- Outer vessel jacket made of carbon steel and not normally exposed to cryogenic temperatures
- Control equipment for loading and unloading (piping, valves, gages, pump, etc.)
- Safety equipment (pressure relief valves, burst disk, gas detectors, safety shut off valves, etc.)

The double wall metal tanks and structural supports make the LNG tank extremely robust to physical damage and the effects of external fire. LNG trailers built in the U.S. comply with the Department of Transportation (DOT) design standards for cryogenic liquids, or with the Transportable Pressure Equipment directive (TPED) and ADR in Europe[85, 86]. A LNG

[83] IHS GlobalSpec,ISO Containers Information.

[84] http://www.chebeague.org/fairwinds/risks.html

[85] DOT CFR49 specifications– 49 CFR parts 173.318 and 178.338 (MC-338).

[86] European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).

transport tank is stronger and more resistant to tank rupture than a non-cryogenic transport tank (e.g., LPG or gasoline) in the event of an accident.

The vacuum insulation enables the internal tank pressure to remain within acceptable operating pressure limits for a range of days depending on the type of tank. Typical LNG road trailer or ISO container has a non-venting ("holding") time around 60 to 80 days. Although vacuum insulation reduces heat transfer, there will be BOG, raising the vapor pressure inside the inner tank. LNG cylinder tanks have operating pressures up to 24 bar (approximately 350 psi), iso-containers range from 10 to 24 bars, and LNG trailers often have lower operating pressure, such as 3 - 7 bars[87]. A pressure release device will safely vent gas to the atmosphere if the pressure exceeds a set limit. A secondary pressure release device is commonly set 30-50% above the primary device release pressure and provides redundancy. Under normal operations, no venting takes place when using cryogenic bulk means of transport.

LNG fuel tanks on a vehicle or vessel are significantly more complicated to design and manufacture with the additional requirement to regasify the LNG. These vehicles and vessels weigh more and cost an order of magnitude more than a single-walled diesel tank[88]. Similarly, the natural gas engine and the dual fuel engine are more complex. Therefore, LNG fueling systems are most suitable for commercial transport, predominately for heavy duty vehicles weighing approximately 15 tonnes or more, and for heavy maritime vessels such as platform support vessels, barges, passenger ferries or larger vessels.

Compatibility is a consideration for long distance transport accessing public LNG fueling stations. Fleet operators must verify compatibility of the LNG fuel dispensing equipment, i.e. the nozzle and mechanical grip mechanism, and the LNG fuel quality and temperature against the requirements of the vehicle in addition to verifying there is adequate public access to LNG on the route.

[87] Chart Industries, LNG Engineered Tanks, Vertical and horizontal tanks for storage of liquefied LNG and hydrocarbons.

[88] Using LNG as a Fuel in Heavy-Duty Tractors, National Renewable Energy Laboratory, NREL/SR-540-24146, July 1999.

6. Value Proposition

This study has discussed the major considerations for LNG as fuel: environment, regulations, engines and fuel options, demand, infrastructure and distribution. This information is important to land and sea transport fleet owners and end users to help evaluate investment in the technology to retrofit and/or replace existing equipment and place orders for new equipment to meet growth requirements while complying with increasingly stringent emissions regulations. This section discusses the value proposition issues and provides examples of the savings and benefits reported by end users.

a. LNG Demand Drivers

LNG production has more than doubled during the past 10 years, driven by supply growth and the competitiveness and environmental advantages of natural gas. The major commercial uses are power generation as well as heating and industrial processes such as fertilizer production. In the past decade, LNG as a transportation fuel supply has become an economically viable alternative. This has contributed to a growing international and spot market LNG trade, and the construction of new LNG terminals in many parts of the world, especially in Europe and Asia. Improved access to LNG by new and notably smaller players in the LNG distribution and end user chain has driven demand in the transport sector.

Substantial new liquefaction capacity is under construction in Australia and will start coming on stream during the next few years. Large shale gas production in North America is leading to a number of LNG liquefaction projects. Newly discovered large gas reserves offshore East Africa and in the Eastern Mediterranean may also become new sources of LNG supply. A forecast of world LNG supply and demand by the Berkeley Research Group (BRG) is given in Figure 54.

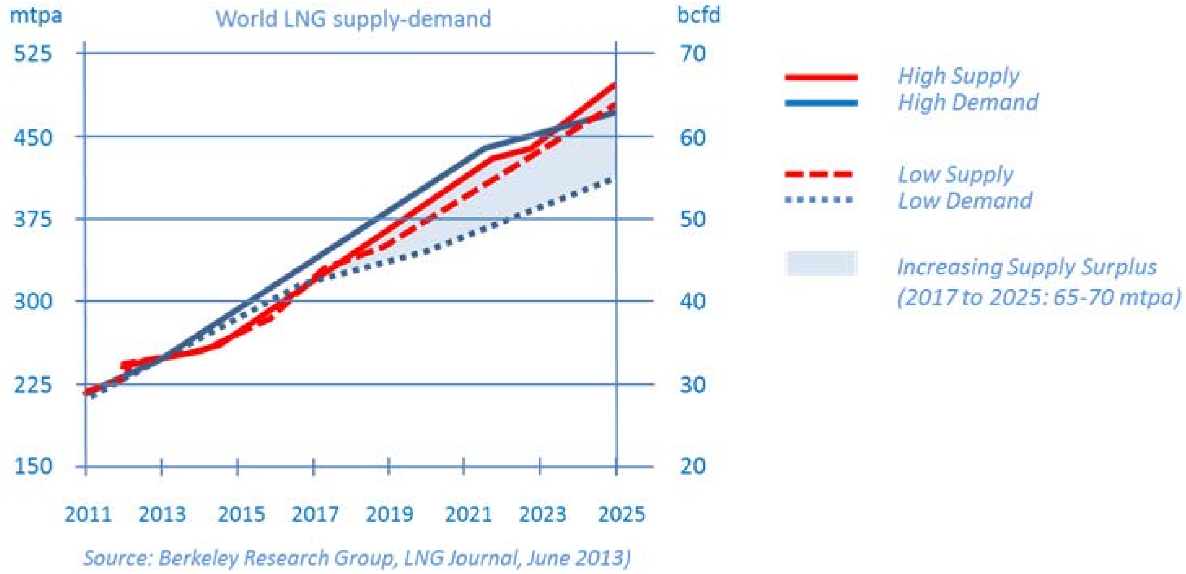

Figure 54 - World LNG Supply Demand Forecast

Although LNG retail pricing is regional, it is influenced by the global balance of LNG supply and demand. In the BRG forecast, the range of supply (High – Low) is dependent in part on level of restrictions placed on North American LNG exports. The range of demand will depend in part on the pace and level of Japan's nuclear reentry and on the success of China's shale gas development. The timing of new LNG commercial project startups will impact pricing, which will affect imports to Japan and China. The expected lower price of North American exports could put downward price pressure on other non-North American LNG projects increasing risk of timing delay and / or lower output from planned projects. The shaded area in Figure 54 indicates surplus supply expected after 2017, which could be as much as 65-70 mtpa LNG. As lower LNG prices compete with other higher priced sources of energy demand for LNG will grow.

b. Historical Fuel Prices

Regardless of location, fuel costs have historically been on the rise. For consumers, the economic driver is the price at the fuel pump, which for diesel has increased at a world average rate of 11.4% per year over the time period 2002-2012, Figure 55[89].

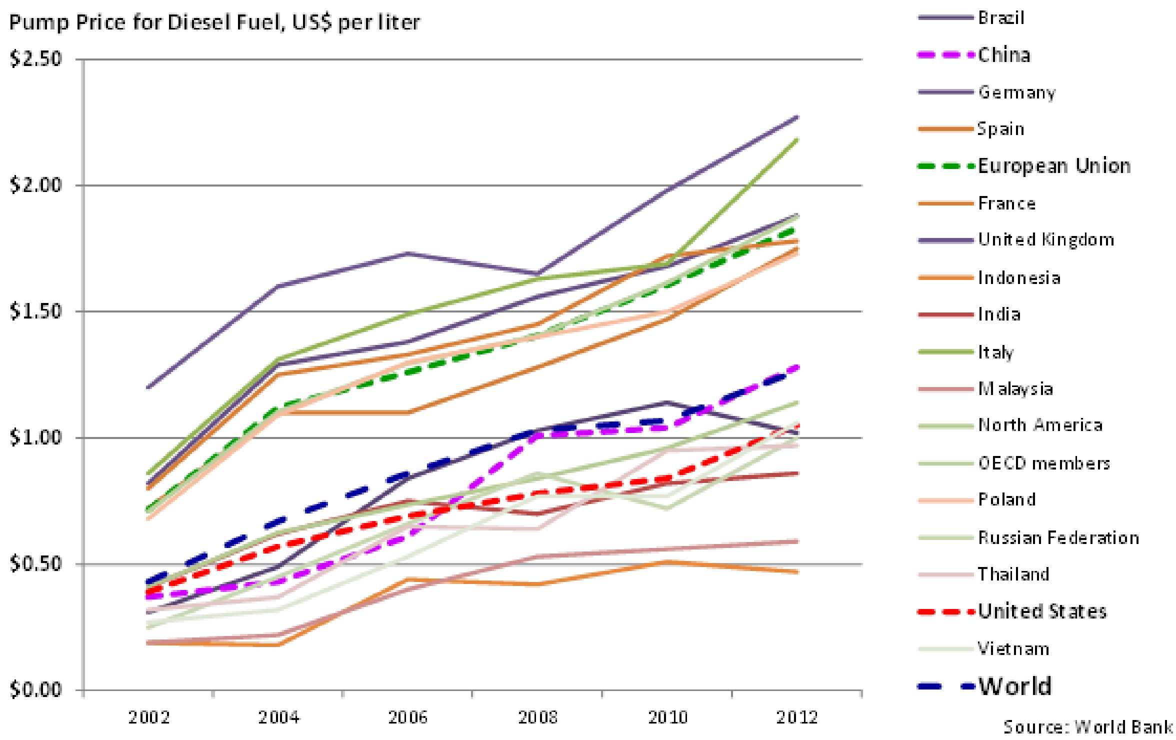

Figure 55 - Pump Price for Diesel Fuel, US$ per liter, 2002 – 2012

In the United States, the surplus of natural gas has created a margin between the average retail prices of gasoline and diesel versus the price of natural gas, which has become substantial and sustained, Figure 56.

[89] World Bank, Data, Pump price for diesel: http://data.worldbank.org/indicator/EP.PMP.DESL.CD?page=1

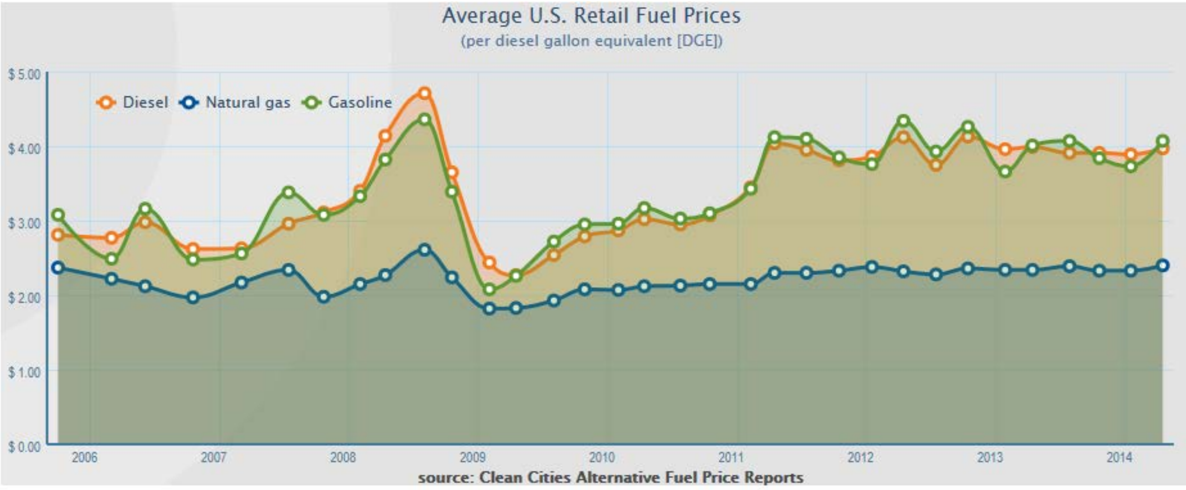

Figure 56 - Average U.S. Retail Fuel Prices

If the BRG surplus scenario becomes a reality, aided by the North American LNG exports of low cost natural gas, the delivered price into Asia could be impacted over the next 5-10 years.

c. Current Price Challenges

Current oil price cycle poses a challenge for LNG as Fuel applications and is expected to delay greater acceptance and implementation due to owners' preference for lower cost fuels and abatement measures.

d. Value Proposition for Road Applications

The chicken and egg dilemma exists between the end users' need for land based LNG distribution networks to be in place and the suppliers' / distributors' requirement for demand to be in place before suppliers commit to infrastructure investments. LNG suppliers, distributors, end users, manufacturers and government agencies are collaborating to coordinate development plans and incentives for LNG / LCNG fuel supply infrastructure, including remote delivery services, to support fleet owners in their areas of operation.

Wood Mackenzie (WM) reports that China will remain the single largest market for gas in transport due to favorable economics of low cost LNG fueled vehicles, strong vehicle market growth and financial support from regional governments keen to reduce emissions in cities where particulate pollution and smog is a growing problem[90]. Growing market interest was shown at the 15th China International NGV and Gas Station Equipment Exhibition in May 2014, when Yantai Jereh Oilfield Services launched the “More LNG stations for Green China” project, appealing to industry to build 10,000 LNG fueling stations in China to provide cleaner sky and fresher air for future generations.

Orders for LNG fueled vehicles are continuing to be placed. China's Beijing Public Transport Group recently ordered 3100 LNG fueled buses. China LNG announced in November 2014 that it would help convert heavy trucks to use LNG as fuel and would provide financial leasing services for the purchase new LNG heavy trucks. China LNG also said it would provide indirect investment to as many as 200,000 LNG heavy trucks by 2020 to help

[90] Wood Mackenzie, Global gas demand in the transport sector could grow to over 160 bcm, news release 29 January 2014

support demand for Sinopec's LNG sales at new LNG fueling stations along two major highways in eastern China[91].

Fleet operators favor LNG as fuel due to easier refueling, increased energy storage and lighter weight than CNG systems with multiple tanks. The incremental costs of LNG fueled trucks is low in China, about US$10,550, relative to US and Europe at US$80,000[92, 93]. Furthermore, LNG fuel pricing in China is set by regulation making the business decision a response to environmental concerns and regulations without the fuel price risk.

In the US and Europe, WM observes LNG as fuel growth is presently slow due to higher costs for natural gas engines and LNG fuel tanks, where incremental costs can exceed US$80,000 per truck, consumer inertia and the lack of distribution infrastructure. WM forecasts stronger demand growth post-2020, as natural gas fuel station corridors get built and as innovators and early adopters seed the market. WM believes growth in small-scale LNG supply facilities will be an enabler of the transport sectors in China and North America, reflecting geography, market access and LNG availability. Europe’s transport sector will be the largest market for break-bulk distribution from existing large scale import terminals in Northwest and Southern Europe.

Zeus Intelligence (Zeus) reported basic economic analysis for LNG fueled trucks compared to the diesel trucks from a costs and savings perspective. An obstacle to switching to LNG is the high incremental costs for cryogenic fuel tanks and gas fueled engines. C.R. England estimates an LNG fueled truck has an incremental cost to a diesel truck of about US$80,000. Assuming a base cost of US$100,000 for a heavy truck (over 33,000 pounds), the total cost for a LNG fueled heavy truck is estimated at approximately US$180,000. Assuming typical annual mileage, the analysis shows the payback period on the incremental investment is about 1.6 years in the base scenario at a savings margin of US$1.50/DGE, Figure 57.

Economic Analysis for LNG Fueled Trucks, US$	**Conservative**	**Base**	**Optimistic**
Diesel price per gallon	$3.00	$4.00	$5.00
LNG price per DGE	$2.50	$2.50	$2.50
Fuel price differential per DGE	$0.50	$1.50	$2.50
Incremental costs	$80,000	$80,000	$80,000
Total costs	$180,000	$180,000	$180,000
Miles per year	180,000	180,000	180,000
Fuel consumption per year	33,333	33,333	33,333
Fuel savings per year	$16,667	$50,000	$83,333
Fuel savings per mile	$0.09	$0.28	$0.46
Payback period for incremental costs, yrs	4.8	1.6	0.96
Payback period for total costs	10.8	3.6	2.16
Source: Data from C. R. England and Zeus Intelligence			

Figure 57 - Economic Analysis for LNG Fueled Trucks

[91] China LNG signed preliminary LNG agreement with Sinopect unit, DJ Inst. News 26 Nov. 2014.
[92] ZEUS, LNG-Fueled Vehicle Report, Development of LNG Fueling Stations in China vs. in U.S., January 30, 2014.
[93] Costs and Savings for LNG Fueled Trucks - Zeus LNG-Fueled Vehicle Report, August 2013.

According to Zeus, technology in natural gas engines and fuel tanks is continually improving which will reduce the incremental investment in new LNG fueled trucks enabling smaller companies to make the change. New trucks can be ordered in either LNG/natural gas or dual fuel engine designs.

Retrofitting existing fleet vehicles is a less expensive way to enter the market, with estimated costs of US$25,000 to US$40,000 per vehicle (tax impact or incentives not considered). A retrofitted truck also has dual fuel capability to switch between LNG when available and diesel when not available.

On a related note, the method of determining LNG pump price and the associated basis for taxation does not follow a standard convention as it does for diesel fuel. It varies from municipality to municipality. The issues concern pricing and taxation on a volumetric basis versus an energy content basis, whether the tax is levied at the fuel depot or at the pump, and whether LNG is taxed at the same rate as diesel fuel. The energy content for a given volume of LNG is dependent on the source of supply, fuel composition, methane number, temperature and pressure of the LNG in storage at the time of sale. If LNG is taxed on a volumetric basis, this could be detrimental for LNG because it has lower energy content per unit volume than diesel and could vary from station to station depending on source and local conditions. Levying tax on an energy basis would require more sophisticated measurement equipment and methodology, which are yet to be resolved.

e. Value Proposition for Maritime Applications

As discussed in Chapter 2, the world shipping industry will be challenged to respond to MARPOL Annex VI limitations for sulfur in ECAs and on global deep sea voyages. Many ship owners will employ a range of abatement measures while others will convert or replace existing engines with LNG-fuelled engines. The value proposition will depend heavily on the relative price of fuels.

i. Outlook for LNG Fueled Shipping

In DNV-GL's report Shipping 2020, scenario D assumes the LNG price is 30% lower than HFO[94]. In this scenario, DNV-GL foresee 1000 newbuildings will be delivered with gas fuelled engines over the period 2012-2020; about 10–15% of the expected newbuildings, Figure 58. These vessels will have either a pure gas fueled engine or a dual-fueled engine with the flexibility to run on liquid fuel as well. In addition, approximately 600–700 ships could be retrofitted with dual fuel engines. After 2020, DNV-GL estimates 30% of all new builds annually will be LNG fueled. This means a market potential for 3600 to 4500 new buildings per year.

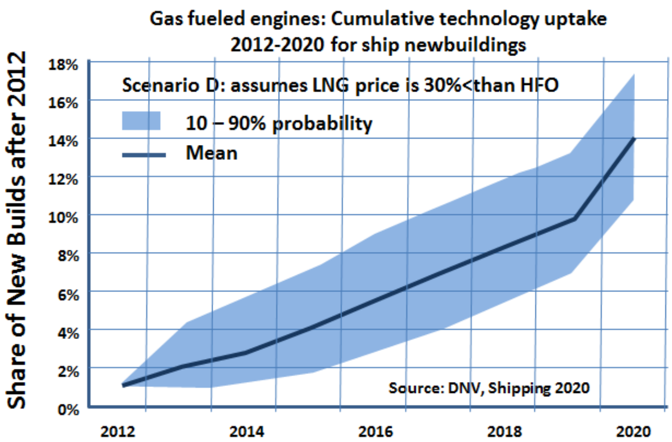

Figure 58 - New Shipping with Gas Fueled Engines

[94]Shipping 2020, DNV GL, September 2012.

ii. Prospects and Challenges

DNV-GL recognizes that there are promising prospects for LNG as a marine fuel and also many challenges as summarized in Figure 59, which demonstrates the interdependencies among value chain components.

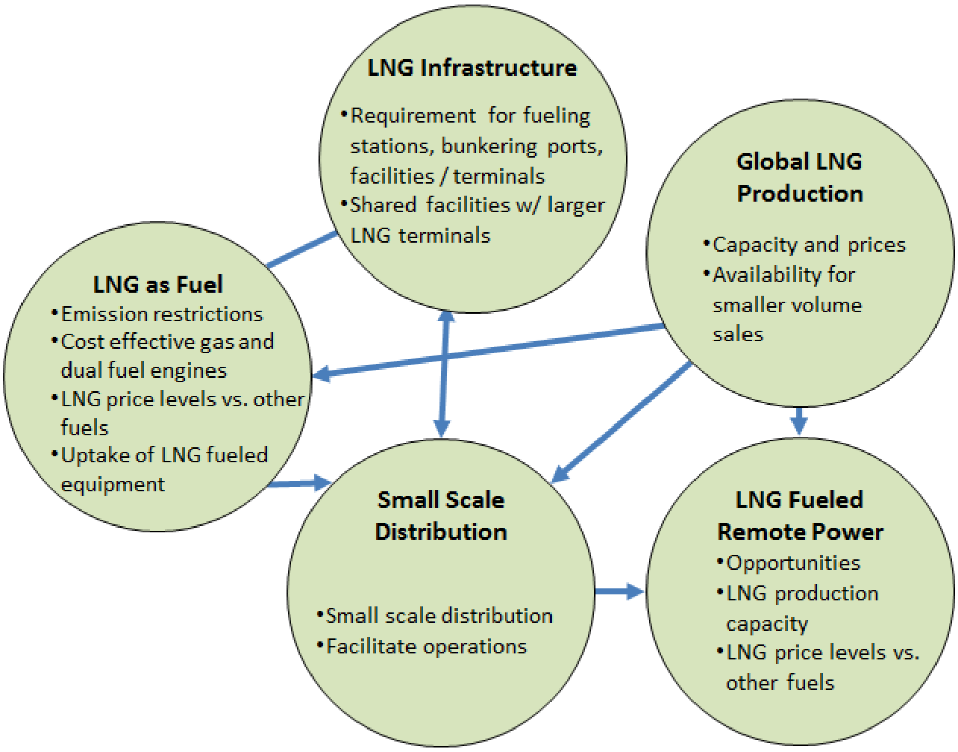

Figure 59 - Prospects and Challenges for LNG as a Fuel; courtesy Methane Strategies

iii. Alternative Marine Fuel Availability

IMO global restrictions on maritime fuel sulphur content for deep sea voyages reduced from 4.5% to 3.5% as of 1 January 2012 and is scheduled to reduce again to 0.5% from 1 January 2020. This means massive changes for bunker operations with massive impact on demand for alternative fuel supplies.

LSFO of 0.5% sulfur content or less relies primarily on availability of MDO and currently makes up less than one-quarter of all marine fuels. LSFO is not viewed as an economically attractive alternative because of its higher cost than conventional marine HFO. At current LSFO price levels, refineries do not find it profitable to invest in new capacity. The investment required to meet future demand for LSFO, which could be as high as 200-250 million tonnes per year, is estimated at close to 100 billion USD. Lead time is approximately seven-year for refineries to undertake capacity expansion projects.

Recognizing that future LSFO supply is uncertain, IMO said it would investigate global availability. However, the study is scheduled to start in 2016 and will take two years to complete. Timing of results is too close for ship owners to make the necessary changes. Industry studies suggest the study should begin earlier. The outcome of the IMO investigation, whenever it is concluded, could be a delay of the 0.5% limit up to 5 years, until 2025.

LNG as a marine fuel would meet the new sulphur limitations. Poten & Partners have forecast a range of demand for LNG by 2025, based on the timing of enforcement, Figure 60.

The High case assumes enforcement of the global sulphur limitation by 2020 is unchanged causing the shipping industry to take action now. The base case assumes enforcement is delayed 5 years to allow refineries more time to invest in LSFO facilities. The Low case shows expected LNG demand as marine fuel if there was no global sulfur restriction. Poten & Partners expect that the LNG supply industry can easily meet the incremental demand for maritime use of LNG as fuel regardless of demand timing.

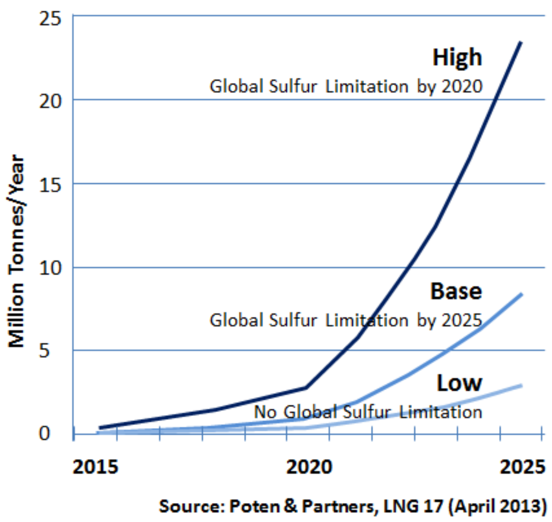

Figure 60 - Potential Demand for Maritime LNG by 2025

f. Value Proposition for LNG as Fuel Non-Road Applications

i. Drilling

Linde analyzed "The Case for LNG Fueling Solutions for Drilling and Completion" and drew the following conclusions[95]:

- [Industry is] undergoing a fundamental shift to LNG use in traditional off-road diesel applications.
- Interest in LNG is at least partly strategically driven. Operating companies have been able to demonstrate leadership to their stakeholders by embracing this "new" fuel. Similarly, O&G service companies recognize that their market position can be enhanced by serving the interests of the operators.
- There is sufficient momentum for significant conversion from diesel to LNG so that once end users spend the nominal amounts to convert to dual-fuel or dedicated LNG engines, they are not likely to switch back to diesel even with fuel cost parity.
- Reducing emissions using LNG can be a tool to avoid future constraints on regional drilling activity.

LNG has now been used for drilling operations across the United States for several years. Prometheus Energy report LNG as fuel replaces approximately 1,500 gallons of diesel per day, per rig; or over 500,000 gallons annually per rig[96]. Ensign Drilling operates 15 rigs exclusively on LNG in the United States and reports 60 percent lower fuel costs with LNG instead of diesel[97].

[95] Linde Group, White Paper. The Case for LNG Fueling Solutions for Drilling and Completion.
[96] Prometheus Energy co-develops world's first LNG-fueled electric drilling rig...
[97] Seneca/Ensign rigs switch to LNG for power in Marcellus, Posted on 29 November 2012, drillilngcontractor.org

ii. Mining

Mining operations consume large volumes of diesel fuel. GFS Corporation provides conversion technology for mine haul trucks in the 100 ton and up class. GFS converted Alpha Coal West's fleet of Caterpillar 793 mine haul trucks at the Eagle Butte Mine to dual-fuel technology, which enables the trucks to operate on a mixture of natural gas (regasified from LNG) and diesel fuel. A haul truck normally consumes 800 gallons of diesel fuel per day. LNG usage ranges from 50% to 60% over the complete duty-cycle of the haul truck. At 50% usage, 400 gallons of diesel consumption is replaced by 640 gallons of LNG.

The savings generated are directly related to the cost differential between LNG and diesel fuel on an energy equivalent basis. GFS report that at diesel cost of US$26.00 per MMBtu (US$3.51 per gallon) and LNG cost of US$12.00 per MMBtu (US$1.00 per gallon), the approximate savings is US$800 per day or close to US$290,000 per year per truck. Extended to a fleet of 25 trucks, the annual savings are in excess of US$7MM. In addition to direct fuel cost savings, the 25 truck fleet consumes over 3.6 million gallons less diesel fuel annually.

High pressure direct injection technology is being developed by Westport and Caterpillar for off-road engines, including mine haul trucks. HPDI will displace up to 95% of diesel with natural gas for even greater savings and emissions reduction.

iii. Remote Industry and Power

LNG fueled industrial applications have been reported in the literature for both urban and remote power generation. Most common examples cited in the literature are related to power generation for electricity distribution and other off-the-grid industrial and manufacturing uses, as discussed in the Chapter 4. The economic and environmental benefits are similar to other LNG as fuel non-road applications.

g. Value Proposition for LNG as Fuel Rail Applications

The EIA consider freight rail a potential additional source of natural gas use in AEO2014. Any transition from diesel to natural gas as a fuel for freight locomotives will depend on economics, infrastructure needs, and railroads' decisions with regard to risk and uncertainty. For AEO2014, alternative cases were developed that anticipate varying degrees of natural gas penetration into the U.S. freight rail market. In the high Rail LNG case, natural gas is used to meet nearly 100% of freight rail energy demand by 2040, while in the reference case it gains 35% of the rail fuel market by that date, and in the low case only 16%. However, because the transportation sector is a relatively small consumer of natural gas compared to other sectors, the seemingly dramatic fuel switch in the high case for freight rail is a relatively minor change in overall U.S. natural gas consumption.

In the reference case, the discounted fuel cost savings using LNG as a fuel compared to diesel over the period from 2020-40 is more than US$1.5 million for each locomotive and tender, Figure 61, recovering the US$1 million incremental cost of equipment. The discounted savings increases to approximately US$2.5 million in the high case, and falls short of recovering costs in the low case.

While economic calculations of fuel savings verses upfront cost are simple, the operational, financial, regulatory and mechanical challenges for railroads are more complex. CN, Union

Pacific Burlington Northern Santa Fe and Norfolk Southern among others are working on developing and evaluating LNG fueled locomotives and tenders.

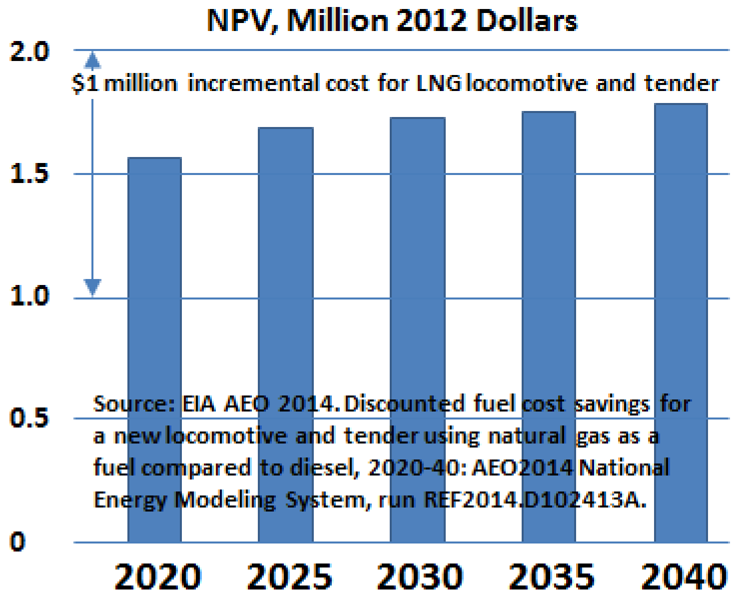

Figure 61 - Discounted Fuel Cost Savings LNG vs. Diesel for Rail

7. Health, Environment and Safety

The LNG industry has established an excellent HES record over the past 50 years with more than 135,000 LNG carrier voyages covering more than 151 million miles without a significant loss of containment either in port or on the high seas[98]. This record is due to continuous safety management efforts with emphasis placed on[99]:

- Training and competency development of personnel,
- Establishment of rigorous and well developed procedures,
- Proactive early detection of potential hazards, and
- Application of preventive and/or corrective methods to eliminate such hazards.

The physical and chemical properties of LNG are well understood. Knowledge of these properties and the potential risks and hazards associated with handling LNG has been incorporated into all aspects of technology, design and operations. The industry has well defined standards, codes and regulations that are widely disseminated to all parties engaged in LNG related activities.

These HES resources are written based on the collective expertise of the LNG industry, and are periodically reviewed and updated in light of advances in technology and changes in regulations. With the advent of 'small-scale' LNG facilities and distribution it is essential that the knowledge and best practices are disseminated to all new participants entering the LNG supply and distribution chain, including end user interfaces with the public.

Transport and storage have been discussed in Chapter 5, LNG Distribution. Health and environment have been discussed in the Chapter 2, Energy Outlook, Emissions and Regulations. This chapter focuses on the Safety related to:

- Bulk transfer and distribution (truck trailers, ISO-containers, bunker vessels, rail tenders, and storage tanks)
- Bunkering of ships (tank to ship, truck to ship, ship to ship, ISO-containers)
- Dispensing to road and non-road fuel tanks (LNG and LCNG stations, mining, drilling, industry)

HES interests also include: operational standards and procedures for bulk transport of LNG by road, vessel or railcar; the robustness of mobile tanks to withstand impact from collision or being dropped; the dispensing of LNG on site; as well as the preparedness of first responders to manage incidents and the potential loss of containment.

Transfer activities require making interconnections and disconnections at numerous interfaces along the LNG supply chain, Figure 62. Improper connection can result in leakage of LNG, increasing the potential for ignition and, depending on location in an open or closed space, increasing the risk of asphyxiation or vapor cloud ignition. Methane slippage from

[98] http://www.api.org/policy-and-issues/policy-items/lng-exports/~/media/Files/Policy/LNG-Exports/LNG-primer/Liquefied-Natural-Gas-exports-lowres.pdf March 2014

[99] IGU 2011, 2009 – 2012 Triennium Work Report, June 2012, Programme Committee PGCD LNG SG1: Enhancing LNG Facilities Compatibility.

connections may be due to human error, faulty equipment and incorrect connection, according to a MARAD study on LNG bunkering[100].

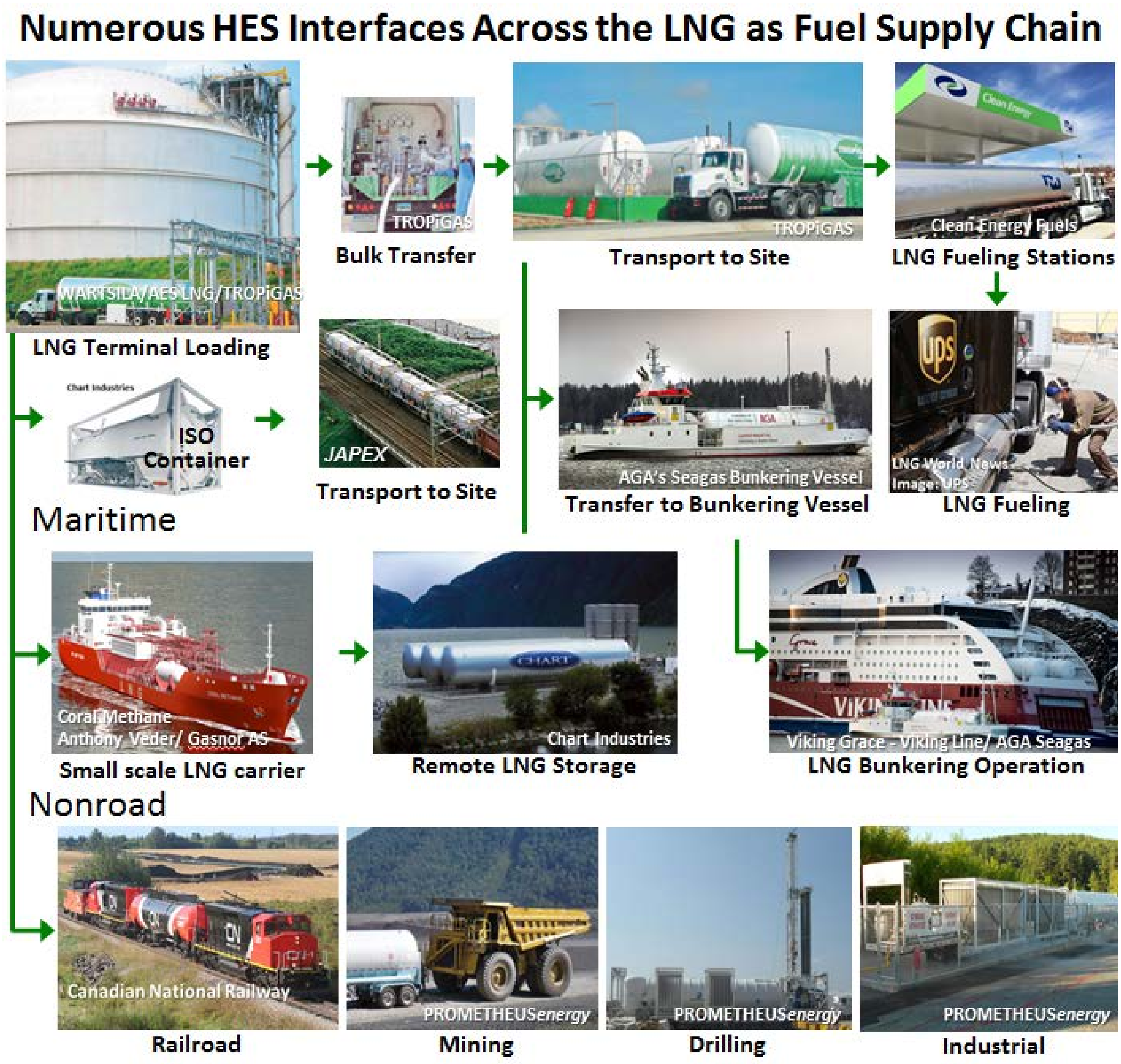

Figure 62 - Numerous HES Interfaces across the LNG as Fuel Supply Chain

Training is the principal means of minimizing the chance of human error. Regular inspection and preventive maintenance should act as sufficient safeguards for the prevention of using damaged equipment. Until there is standardization of LNG connections, the use of interconnector fittings is the existing safeguard to make leak-tight connections. In all cases, MARAD reports that best practices, adopted from the large scale LNG industry and shipping sector, include: placement of multiple gas detection systems, use of drip free Quick Connect Disconnect (QCDC) couplings and use of an Emergency Release System (ERS).

a. National Fire Protection Association

The National Fire Protection Association (NFPA) publication NFPA 59A Standard for the Production, Storage and Handling of Liquefied Natural Gas is the industry recognized

[100] Liquefied Natural Gas (LNG) Bunkering Study, MARAD. DNV-GL Report No. PP087423-4, Rev. 3, September 14, 2014.

authority for storage volumes above 70,000 gallons (approximately 265 cubic meters) [101]. The standards apply to:

- Facilities that liquefy natural gas,
- Facilities that store, vaporize, transfer, and handle liquefied natural gas,
- Training of all personnel involved with LNG, and
- Design, location, construction, maintenance, and operation of all LNG facilities.

NFPA 57 - Liquefied Natural Gas Vehicular Fuel Systems Code is applicable for LNG storage capacity below 70,000 gallons and has been incorporated into NFPA 52 - Vehicular Gaseous Fuel Systems. These codes and standards are available to the jurisdictions having authority over the design and operation of LNG facilities affecting public safety including local fire marshals and state regulators. A list of key LNG standards publications is given in Appendix 9.9.

b. LNG Bunkering

MARAD partnered with other government agencies, industry and academia to determine the feasibility and likelihood of using natural gas as a propulsion fuel in the maritime sector. MARAD identified information needs and contracted DNV-GL to complete the study with the objective of analyzing existing LNG bunkering infrastructure, safety, regulations and training, as well as identifying and recommending best practices[102].

Four bunkering options were evaluated: PTS, TTS, STS and PTT. In Northern Europe, LNG infrastructure generally begins with large users that can support TTS operations economically. This transitions into more permanent infrastructure like PTS or STS as additional vessels switch to LNG as fuel.

Key Findings of the study are summarized below:

- No single bunkering option can meet the requirements of all port stakeholders.
- Initial developments are cooperative, minimizing the risk to first movers.
- No LNG bunkering option will dominate since first movers dictate initial development based on specific project needs.
- TTS bunkering will be utilized by vessels with smaller fuel tank capacities (e.g., tugs) and for remote refueling where infrastructure is not currently established (e.g., ferries).
- PTS bunkering will be primarily developed for larger fueling needs through partnerships with vessel operators or designed to vessel needs (e.g., Harvey Gulf).
- STS bunkering may grow significantly including use of bunker barges within ports, but will also be considered where shore-based options are less attractive or infeasible.

[101] NFPA 59A: Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG). Current Edition: 2013. http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code&code=59A

[102] Liquefied Natural Gas (LNG) Bunkering Study, MARAD. DNV-GL Report No. PP087423-4, Rev. 3, September 14, 2014.

- Management of risks to the public, workers, critical infrastructure, and business interruption will be essential to prevent catastrophic events that may affect the natural gas/LNG industry.

The study reports that significant regulatory gap exists in the U.S. for LNG bunkering and associated infrastructure operation. Establishment of uniform standards and guidelines for state and local lawmakers would allow for a consistent and predictable regulatory framework. Specific gaps were identified for LNG metrology, jurisdiction over bunkering operations, and framework for the review of potential risks related to bunkering from non-self-propelled barges. The study identified the need for greater clarity in regulations addressing simultaneous operations (SIMOPS).

The study also found that proper training for crew and operators involved with LNG bunkering operations is critical for establishment and maintenance of safe practices. In general, crewmembers and local first responders are expected to follow and comply with governing regulations, operation manuals, maintenance regimes, and emergency response plans for LNG bunkering operations. Training will vary according to the type and location of the installation. Specific training content is required based on the different levels of employment and responsibilities of the crew members and local first responders.

MARAD's Liquefied Natural Gas Bunkering Study by DNV-GL is an excellent resource for detailed information and references on LNG bunkering options, bunkering and safety, U.S. regulatory gaps and training requirements.

The IAPH World Ports Climate Initiative (WPCI) LNG working group has developed three harmonized bunkering checklists for LNG operations in ports, including PTS, TTS and STS transfer[103]. These checklists are a great resource to vessel owners on bunkering LNG in different ports, as the lists reduce the potential for confusion caused by having to comply with varying rules and regulations in each port. The WPCI has launched a new and informative website focused on LNG as a maritime industry fuel[104]. The website provides a detailed overview of the use of LNG as ship fuel, and it lays out the technical requirements for ships, bunkering infrastructure and vessels under development, as well as the business case for using LNG in the maritime environment. The checklists are available on this website.

DNV-GL published a report on LNG fuel bunkering in Australia[105]. The study was a Joint Industry Project supported by ten experienced partners representing a cross-section of the LNG-fuel value chain. Two case studies examined dockside marine bunkering operations, by truck-to-ship and by tank-to-ship. Although the bunkering procedures in principle are the same there are differences in guidelines on initial precooling of terminal components, as outlined in Figure 63.

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[103] International Association of Ports and Harbors' World Ports Climate Initiative, LNG Bunkering. http://lngbunkering.org/lng/

[104] http://www.lngbunkering.org

[105] Joint Industry Project, LNG Fuel Bunkering in Australia: Infrastructure and Regulations, Public Version, Report No.: CTC_R_2012038, 20 January 2013

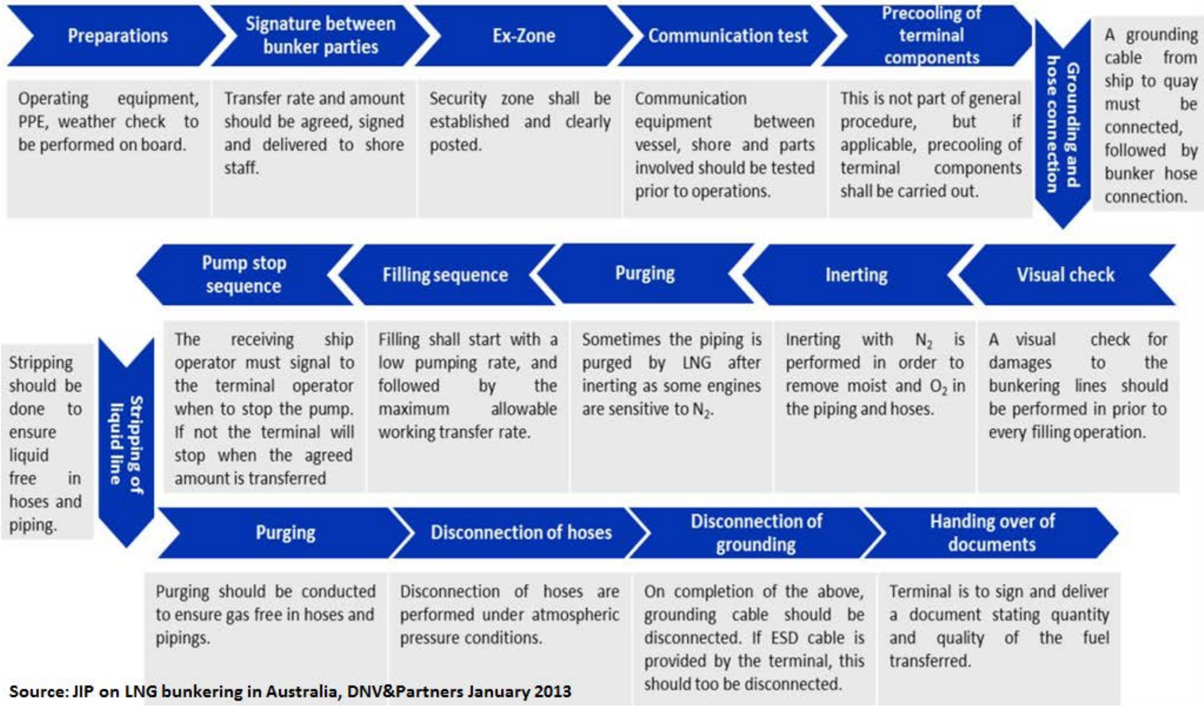

Figure 63 - Truck to ship LNG bunkering procedures; courtesy DNV-GL

The DNV-GL report points out that the main risks during bunkering operations are associated with methane slippage during connections and disconnections of transfer lines. Purging of lines is an essential step before pressuring or de-pressuring lines. The DNV-GL report is another excellent resource on maritime bunkering. The section on Relevant Laws and Standards, Chapter 6, provides a review of the Commonwealth of Australia regulatory processes for bunkering ships with LNG; the table of contents is given in Appendix 9.9.

c. LNG Terminal Bulk Transfer

The Center for Liquefied Natural Gas LNG points out that the LNG industry's highest priority has always been safety and security[106]. Import and export terminals are designed with multiple layers of protection and must meet rigorous safety regulations. They are equipped with spill containment systems, fire protection systems, multiple gas, flame, smoke and low- and high-temperature detectors and alarms, automatic and manual shut-down systems, video surveillance systems, and highly trained personnel. These systems and safety measures also apply to LNG bunkering facilities and LNG truck loading racks.

The Zeebrugge LNG Terminal in Belgium provides an example of the services available between a LNG terminal operator and a buyer: LNG Truck Approval Service, LNG Truck Cool Down Service, and LNG Loading Services[107]. The procedures, rules and regulations governing the terminal services provided to the buyer are contained in the Access Code for LNG Truck Loading, as approved by Belgium's Regulatory Commission for Electricity and Gas (CREG). These procedures define the operating rules for truck loading, beginning with

[106] CLNG website: http://www.lngfacts.org/about-lng/safetysecurity/

[107] LNG Access Code for Truck Loading for the Zeebrugge LNG Terminal, and the LNG Agreement for LNG Truck Loading at the Fluxys LNG Terminal in Zeebrugge, approved by Belgium's Regulatory Commission for Electricity and Gas (CREG), on September 19th 2013, Applicable as of January 1st 2014.

scheduling procedures, readiness notices, arrival, and truck loading station safety and operating procedures. Trained terminal personnel are responsible for performing all procedures and inspections. The driver provides assistance as directed.

The LNG Truck Approval Procedure is a prerequisite to loading service at the terminal. In addition to providing a checklist of technical details on the LNG trailer, the buyer must also provide a safety impact analysis for side and overturning impact based on the finite element method showing compliance with technical and safety standards. The purpose is to ensure the buyer's LNG transport, which is comprised of the truck, the trailer and the driver, conform in each and all respects to the International Carriage of Dangerous Goods by Road (ADR) regulations, and also to the International Maritime Dangerous Goods (IMDG) code[108, 109]. Moreover, the buyer should at all times be an ISO 9001 certified company[110].

The truck must be in cold condition (below -120˚C, -184˚F) at the start of the transfer operation. Cool down service is provided if needed. Under no circumstances are traces of oxygen, CO_2, water vapor or any other contaminants or impurities allowed inside the buyer's trailer or associated piping. The typical LNG transfer rate is 120 cubic meters per hour and loading time for a LNG trailer in optimal, cold condition is approximately 45 minutes[111]. Maximum filling pressure is 5 barg. The station weighbridge is continuously monitored during the transfer operation.

After LNG transfer is complete, the terminal operator provides the driver with the Quality and Quantity document. The driver is responsible to provide other documents required by regulation and must have all documents in hand before the truck leaves the loading station.

Each terminal will have their respective set of procedures, rules and regulations governing the terminal services. These rigorous procedures are meant to ensure that trucks loaded with LNG are in compliance before the truck leaves the terminal and LNG transport begins.

d. LNG Truck Transport

Truck transport of LNG also has an excellent safety record. LNG trailers in most countries are of a double-shell construction with an inner tank constructed of a cryogenic alloy to contain the LNG, an outer tank of carbon steel and an evacuated annular space containing perlite insulation[112]. Stiffening rings are incorporated in the outer shell to improve its structural strength and prevent its collapse. A typical 11,000-gallon tanker has a length of 42 feet, an inner tank diameter of 7 feet 4 inches, and an outer tank diameter of 8 feet. The LNG trucks have a relatively high center of gravity compared to other petroleum trucks due to the low density of LNG and the large tank diameter. This feature increases the truck's susceptibility to overturning accidents in some situations. However, the double-shell construction provides additional weight to compensate for the cargo weight and furthermore

[108] European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), a 1957 United Nations treaty

[109] The International Maritime Dangerous Goods (IMDG) Code governs the transport of dangerous goods by sea.

[110] International Organization for Standardization (ISO) 9001 identifies quality management system requirements for production, installation and services. ISO 9001:2008 is the latest version.

[111] LNG Access Code for Truck Loading for the Zeebrugge LNG Terminal.

[112] Freeport LNG Export Project and BOG/Truck Project Environmental Assessment, March 2009.

provides damage protection to minimize the potential for a major shell failure and product release.

As the demand for LNG increases, the number of LNG tank trucks on roadways, in populated areas and in harbors will increase. Similarly, as LNG bunkering demand increases, port and maritime traffic density and patterns will change. Truck and bunker vessel presence will increase public exposure to LNG operations. A single incident could impact public perception causing a ripple effect that could negatively impact the broader natural gas industry.

Incidents resulting from collision and tank rupture have been reported citing instances of both integrity of the tank and the rare failure[113]. The rupture of a tank containing a pressurized liquid above its boiling point is known as a Boiling Liquid Expanding Vapor Explosion (BLEVE). This type of accident is the most hazardous and poses the greatest risk to the public and emergency personnel. There has only been one BLEVE incident involving LNG.

A global study of BLEVE incidents from 1926 to 2004 showed that of 89 events only one incident in 2002 involved a truck carrying CNG whose tank ruptured and ignited post-accident[114]. Since 2004, two BLEVE incidents involving road transport of natural gas have occurred. In China in 2008, an LPG tanker ruptured and ignited post-accident. The Center for Liquefied Natural Gas (CLNG) noted that LPG has very different properties than LNG[115]. LPG is a mixture of propane and butane and heavier than air. LNG is mostly made up of methane and at room temperature is lighter than air. In addition, LNG is not explosive in an unconfined space. Although substantial energy is stored in LNG, it cannot be released rapidly enough to cause the overpressures associated with an explosion in an unconfined area.

In Spain in 2011, an LNG tanker collision resulted in a truck fire which subsequently engulfed and ignited the ruptured LNG tank. There are currently two types of ADR-approved LNG transport road tankers: the double-walled stainless steel tank and perlite and vacuum insulation, and the single-walled steel tanks with polyurethane insulation and aluminum outer shell. The road tanker carrying LNG involved in this accident was of the latter type.

Of the BLEVE incidents in the global study the most frequent initiating events were tank exposure to fire (36%), mechanical damage (22%) and overfilling (20%). A review of BLEVE incidents published in 2014 offered a number of recommendations to prevent basic technical causes that can lead to BLEVEs[116]. Two in particular are cited here, and recommended in this study for global adoption, as they are particularly applicable to the supply and distribution of LNG as fuel:

[113] LNG: A safe fuel for trucks, UN Economic Commission for Europe, WP15-Transport of Dangerous Goods, November 2013.

[114] The Boiling Liquid Expanding Vapor Explosion (BLEVE): Mechanism, consequence assessment, management. Journal of Hazardous Materials 141, 2007, p489–519, Tasneem Abbasi, S.A. Abbasi.

[115] CLNG: LNG Not Cause of Truck Explosion in China, LNG World News, October 12, 2012.

[116] Boiling liquid expanding vapour explosions (BLEVEs): A brief review; Rolf K. Eckhoff, University of Bergen, Dept. Physics and Technology, Bergen, Norway. Journal of Loss Prevention in the Process Industries. 2014.

- Preventing mechanical damage of PLG-containing vessels: Trucks and railroad cars carrying a gas liquefied under pressure (PLG) should be protected from accidental damage generating spills by using double-walled vessels with thermal insulation between the walls. Collisions or overturning during transportation may then damage the outer wall, without any spills occurring. It is then important to make the outer wall sufficiently strong to provide sufficient protection of the inner wall.

- Preventing overfilling of vessels and vessel overpressure: Rigid compliance with standards for filling and weighing of vessels that may become exposed to BLEVEs, as well as for standards for relief devices has reduced the frequency of BLEVEs due to overfilling. Relief-devices can get plugged, but this can be compensated for by installing rupture disks in parallel to the relief valve.

As LNG as fuel becomes more common, there will be an increasing number of LNG transport trucks on the road with the potential for increased occurrence of incidents. It is recommended that emergency responders and civil authorities be informed of LNG related transport and operational activities in their jurisdictions and the emergency personnel be trained to respond to situations involving LNG. Additionally, industry forums for sharing lessons learned and best practices on the safe uses of LNG as fuel are highly encouraged as a means for stakeholders to maintain awareness of advances, issues, experiences and continued improvement.

e. LNG Dispensing

LNG heavy trucks and buses are usually associated with fleet operations. LNG dispensing may take place at a central depot, private or public LNG fueling station along major corridors. As LNG stations increase worldwide, there will be increasing exposure to LNG fuel dispensers by fleet drivers, independent heavy vehicle drivers and the public. Hence, there is a strong HES driver to make the LNG dispensing stations as safe as possible.

It is recommended that small-scale LNG industry provide readily accessible training courses, educational materials and Personal Protective Equipment (PPE) to all assigned users of LNG dispensing stations, and provide the opportunity to purchase the same to other potential users.

LNG fleet drivers and LNG station attendants are trained on use of safety equipment, dispenser controls, remote emergency shut off switches, fueling procedures and use of Personal Protective Equipment (PPE) such as masks and cryogenic gloves, as shown in Figure 64.

Figure 64 - LNG Dispensing Using Personal Protective Equipment; courtesy UPS

In the Netherlands, guideline PGS 33-1, published in mid-2013, is a series on dangerous substances regarding LNG fueling stations[117]. This guideline describes the latest technical knowledge on the design, construction and functioning of LNG fuelling stations. PGS 33-1 clarifies for all parties concerned the specific requirements a LNG fuelling station must fulfill to be in compliance on all safety issues.

As referenced in Section 2.e, Maritime Transport, the ABS study on Bunkering of Liquefied Natural Gas-fueled Marine Vessels in North America provides a structured process for implementing an LNG fuel supply project with regard to seeking compliance with local regulations. ABS chapters 3, 4, and 5 provide details of the regulations and guidance on implementation. This study is an excellent resource intended to help operators and owners of gas-fueled vessels, LNG bunkering vessels, and waterfront facilities who need background information and guidance to address North American (U.S. and Canada) federal regulations, state/provincial and port requirements, international codes, and standards and potentially waterway requirements or restrictions as well as unique issues such as regional and local restrictions on storing LNG.

[117] National LNG Platform, Introduction of LNG as transport fuel will generate billions of euros and thousands of jobs, Rotterdam, 10 July 2013.

8. Findings and Conclusions

The objective of this study is to present a comprehensive analysis of the use of LNG as fuel, which is regasified for consumption in a natural gas engine or dual-fuel engine. The scope of study focused on road, maritime and non-road uses, as well as LNG bulk transfer, distribution, bunkering, dispensing and associated HES aspects. The study discussed considerations impacting an end user's decision-making on whether to convert or replace conventional fueled engines with natural gas or dual-fuelled equipment which use LNG as fuel.

a. Findings

Chapter 2: Outlook, Emissions, Regulations

- The IEO2014 reference case forecasts world petroleum and liquids consumption will grow by 38% between 2010 and 2040, increasing only in the transportation and industrial sectors predominately in non-OECD countries.
- The IEO2013 notes that two energy sectors combined are the source of about two-thirds of global CO_2 emissions in 2011: Electricity-and-Heat (42%) and Transport (22%). Within the transport sector, road transport accounts for 72.3% of emissions followed by maritime transport (9.0%) and aviation (6.6%).
- World CO_2 emissions are projected to increase 45% between 2010 and 2040, on a trajectory far above the internationally agreed target. As a result the global climate debate is driving the push for change to clean burning natural gas and alternative fuels.
- SOx is a major concern, particularly from shipping which accounts for only 2.7% of world CO_2 emissions but causes 14% of the world SOx pollution.
- LNG as fuel is a viable mitigant reducing emissions of CO_2 up to 20%, SOx up to 100%, NOx up to 90%, and PM up to 99% compared to HFO.
- IMO MARPOL 1973/1978, Annex VI is the main convention to minimize airborne emissions from ships. Within ECAs the 1% sulphur limit on HFO was reduced to 0.1% from January 2015. A global sulphur cap of 3.5% is scheduled to reduce to 0.5% from January 2020, pending evaluation by 2018 of LSFO availability.
- Governments worldwide have implemented CO_2 reduction initiatives based on US EPA regulations, EU directives and country specific codes to limit On-road and Non-road sources.

Chapter 3: Fuel Options and Engines

- There are two types of natural gas fueled engines: SI engines, which are typically for use in light to medium duty applications, and CI engines fueled by a variable combination of natural gas and diesel used in heavy duty, high horsepower applications. High pressure direct injection engines can displace up to 95% of the diesel with gas.

- Market pull from owners of buses, heavy trucks, ships, locomotives and drilling equipment has caused engine manufacturers to design and build a wide range of natural gas and dual fuel engines for use with LNG.

- LNG has lower energy density than gasoline or diesel which is a key factor in the distance a vehicle can travel before refueling. For the same fuel capacity, a LNG fueled heavy vehicle can travel about 60% the distance of a diesel fuel vehicle, requiring different fueling infrastructure.

- MN is a measure of resistance of fuel gases to engine knock, an occurrence induced by gas quality variations. LNG quality and gross heating value vary depending on source, gas composition and BOG while in transit and storage. Supply, engine and regulatory stakeholders are challenged to address this issue.

Chapter 4: End User Sectors

- The On-Road transportation sector, which is the largest contributor to transportation emissions, has the potential to have the greatest impact on reducing emissions by using LNG as a fuel supply in the heavy vehicle (over 33,000 lbs) segment. Heavy vehicles are characterized by high utilization on defined corridors and regular schedules, which facilitates planning refueling infrastructure.

- The Maritime transportation sector is rapidly developing LNG as fuel capability with 134 LNG fueled ships in operation or on order as of January 2015. By 2020, DNV-GL expects 1000 new buildings to be delivered with natural gas engines, equal to 10-15% of new ships. Additionally, 600 to 700 ships could be retrofitted to run on LNG. After 2020, DNV-GL estimate 30% of new builds annually (3,600 to 4,500) will be LNG fueled.

- The Non-Road transportation sector is making advances using LNG as a fuel supply for mining and drilling operations, remote small-scale power barges, remote community and industrial fuel supplies, railway locomotive test programs, and very long lead time aviation research.

Chapter 5: LNG Distribution

- A dilemma exists between level of LNG demand and availability of LNG supply and distribution, with owners on both sides of the business depending on the other to anchor new investments. As a result cooperatives and partnerships are being formed to mitigate commercial risks, align business interests and move supply and demand projects forward in parallel.

- Small parcel distribution facilities at LNG terminals via truck racks and bulk transfer loading to bunker vessels, ISO containers (holding times up to 75 days) and freight railcars are important to the development and growth of small scale LNG retail markets outside traditional large scale natural gas grids.

- In small-scale sea transport (LNG carriers) and using LNG as fuel for any type of new build vessels, the development of tank systems is a key factor. Several tank technology companies have developed or are adapting IMO A and membrane tank designs to smaller tank sizes with the aim of reducing construction cost and time, and improving insulation methods to limit BOG.

- LNG bunkering, the fueling of ships with LNG as the energy source, can be performed by four methods: PTS, TTS, STS and PTT.

- In Europe, the Blue Corridors project is underway to establish LNG fueling infrastructure and to demonstrate the economic viability for heavy trucking to encourage growth. The project includes buildup to 14 new LNG or LCNG stations along four corridors connecting Europe's South to North and West to East and a fleet of 100 LNG heavy duty vehicles.

Chapter 6: Value Proposition

- The predominant driver for use of LNG as a mobile fuel supply is compliance with tightening emissions regulations. A potential benefit may be fuel cost savings of natural gas relative to diesel fuel cost if the advantageous price differential in some regions becomes a sustainable reality.

- World diesel prices have risen at an average annual rate of 11.4% from 2002-2012, while substantial new liquefaction capacity has begun construction and US shale gas production has soared. If the forecast surplus of natural gas becomes a reality, the delivered price into Asia could come down over the next 5-10 years.

- Current oil price cycle poses a challenge for LNG as Fuel applications and is expected to delay greater acceptance and implementation due to owners' preference to use lower cost fuels and utilize abatement measures.

- If LNG is taxed on a volumetric basis, this could be detrimental for LNG because it has lower energy content per unit volume than diesel and could vary from station to station depending on source and local conditions. Levying tax on an energy basis would require more sophisticated measurement equipment and methodology, which are yet to be resolved.

- The world shipping industry will be challenged to respond to MARPOL Annex VI limitations for SOx and NOx. A ship owner has three possible compliance options: Switch to LSFO if secure supply can be assured, invest in abatement technologies to scrub sulphur from exhaust gas, or invest in LNG fueled engine systems.

Chapter 7: HES

- HES aspects of LNG as fuel are primarily concerned with operational standards and procedures of three major functions: 1) Bulk transfer and distribution (truck trailers, ISO containers, bunker vessels, rail tenders, and storage tanks); 2) Bunkering of ships (PTS, TTS, STS and PTT); and 3) Dispensing to road and non-road fuel tanks (LNG and LCNG stations, mining, drilling and remote industrial fueling).

- Methane slippage during connection poses the greatest risks. MARAD finds that human error, faulty equipment and incorrect connections are the main factors. Training is the principal means of minimizing the chance of human error. Regular inspection and preventive maintenance should prevent use of damaged equipment. Use of interconnector fittings is the existing safeguard to make leak-tight connections.

- Tanks carrying LNG should be protected from risk of accidental damage generating spills by using double-walled vessels with thermal insulation between the walls.

- A single LNG incident could impact public perception causing a ripple effect that could negatively impact the broader natural gas industry.

- LNG tanks and vessels should be protected against risk of overfilling by requiring rigid compliance with standards for filling and weighing of LNG vessels as well as standards for use and maintenance of relief devices.

- Government and industry (MARAD, ABS, DNV-GL, IAPH, and Lloyds Register among others) have published studies, guidelines and checklists to assist LNG stakeholders in understanding and implementing existing and planned regulations to protect air quality.

b. Conclusions

- Drivers: The predominant driver for use of LNG as fuel is compliance with increasingly stringent regulations worldwide to reduce carbon emissions from On-road and Non-road sources. LNG is a viable mitigant significantly reducing CO_2, SOx, NOx and PM compared to diesel and HFO.

- Response: Within the transportation sector, heavy vehicles and shipping are the low hanging fruit which yields the greatest and fastest impact on reducing GHG emissions. Market pull from fleet owners of buses, heavy trucks, ships, locomotives and drilling equipment has caused many engine manufacturers to design and build a range of natural gas and dual fuel engines for use with LNG.

- Enablers: Government and industry have published studies, guidelines and checklists to assist stakeholders to understand and implement existing and planned regulations to protect air quality. Projects are underway to demonstration operational and economic viability for land and maritime applications of LNG as fuel. Small-scale LNG facilities are a key enabler.

- Challenges: A dilemma exists between the level of LNG demand and the availability of LNG supply and distribution, with owners on both sides of the business depending on the other to anchor new investments. As a result cooperatives and partnerships are being formed to mitigate commercial risks, align business interests and move supply and demand projects forward in parallel. The value can be captured by those willing to take the risk and invest in the future of LNG as fuel.

- Value: The value proposition is primarily driven by compliance with regulatory requirements in order to continue doing business, and to varying degree may benefit from fuel cost savings depending on local availability and relative pricing of alternative fuel supplies in comparison with the cost of abatement technologies and ongoing maintenance and waste disposal requirements.

- Safety:
  - The greatest HES risk is connection leakage at all interfaces along the supply and distribution chain to the end user's equipment. The principle causes of leakage are human error, faulty equipment and incorrect connections. Standardization of LNG connections would streamline the physical operation while leading to standardized training requirements, tools, inspections and maintenance, thereby helping to reduce the chance of human error and use of faulty equipment.
  - Rigid compliance with standards for filling and weighing of LNG vessels as well as standards for use and maintenance of relief devices should be required as a means of preventing overfilling.
  - The LNG industry has a vested interest to continue to publish and widely disseminate safety studies, standards, guidelines, checklists, training materials and information on all aspects of LNG transfer, transport and dispensing to all parties interested in LNG as fuel.
  - Lists of industry recognized references and resources should be published and maintained on easily assessable websites with the cooperation and support of leading LNG stakeholders.
  - As the demand for LNG as fuel increases, the number of LNG tank trucks on roadways and bunker vessels in ports and harbors will increase affecting traffic flow and increasing public exposure to LNG operations. LNG tankage should be contained in double walled vessels and thermally insulated to protect against risk of accidental damage.
  - Industry, local government authorities and first responders must maintain a high level of awareness of LNG related activities and ensure all stakeholders are:
    - Engaged in promoting a culture for protection of health, environment and safety.
    - Providing the training, personal protective equipment, tools and resources to perform their duties.
    - Prepared to respond to any incident involving LNG in the manner appropriate for each level of responsibility.

9. Appendices

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Appendix A. OECD and non-OECD Nations

a. Organization for Economic Co-operation and Development (OECD)

Membership includes:

Australia	France	Korea	Slovenia
Austria	Germany	Luxembourg	Spain
Belgium	Greece	Mexico	Sweden
Canada	Hungary	Netherlands	Switzerland
Chile	Iceland	New Zealand	Turkey
Czech Republic	Ireland	Norway	United Kingdom
Denmark	Israel	Poland	United States
Estonia	Italy	Portugal	
Finland	Japan	Slovak Republic	

Within the **OECD**:

- **Australia** excludes the overseas territories
- **Denmark** excludes Greenland and the Danish Faroes
- **France** includes Monaco, and excludes Guadeloupe; Guyana; Martinique; New Caledonia; French Polynesia; Reunion; and St.-Pierre and Miquelon
- **Germany** includes the new federal states of Germany from 1970 onwards
- **Italy** includes San Marino and the Vatican
- **Japan** includes Okinawa
- The **Netherlands** excludes Suriname and the Netherlands Antilles
- **Portugal** includes the Azores and Madeira
- **Spain** includes the Canary Islands
- **Switzerland** includes Liechtenstein for oil data
- **United States** includes the 50 states and the District of Columbia. Oil statistics as well as coal trade statistics also include Puerto Rico 3; Guam; the Virgin Islands; American Samoa; Johnston Atoll; Midway Islands; Wake Island and the Northern Mariana Islands

b. Non-OECD

Membership includes: Africa; Asia (excluding China); China (P.R. of China and Hong Kong, China); Non-OECD Americas; Middle East; Non-OECD Europe and Eurasia.

- **Africa:** Includes Algeria; Angola; Benin; Botswana (from 1981); Cameroon; Congo; Democratic Republic of Congo; Côte d'Ivoire; Egypt; Eritrea; Ethiopia; Gabon; Ghana; Kenya; Libya; Mauritius; Morocco; Mozambique; Namibia (from 1991); Nigeria; Senegal; South Africa; Sudan; United Republic of Tanzania; Togo; Tunisia; Zambia; Zimbabwe and **Other Africa**.
- **Other Africa**: Includes Botswana (until 1980); Burkina Faso; Burundi; Cape Verde; Central African Republic; Chad; Comoros; Djibouti; Equatorial Guinea; Gambia; Guinea; Guinea-Bissau; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Namibia (until 1990); Niger; Reunion; Rwanda; Sao Tome and Principe; Seychelles; Sierra Leone; Somalia; Swaziland; Uganda and Western Sahara (from 1990).
- **Asia (excluding China):** includes: Bangladesh; Brunei Darussalam; Cambodia (from 1995); India; Indonesia; DPR of Korea; Malaysia; Mongolia (from 1985);

Myanmar; Nepal; Pakistan; Philippines; Singapore; Sri Lanka; Chinese Taipei; Thailand; Viet Nam and **Other Asia**.

- **Other Asia**: Includes Afghanistan; Bhutan; Cambodia (until 1994); Cook Islands; East Timor; Fiji; French Polynesia; Kiribati; Laos; Macao, China; Maldives; Mongolia (until 1984); New Caledonia; Palau (from 1994); Papua New Guinea; Samoa; Solomon Islands; Tonga and Vanuatu.
- **China (including Hong Kong):** includes: the People's Republic of China and Hong Kong.
- **Non-OECD Americas**: includes Argentina; Bolivia; Brazil; Colombia; Costa Rica; Cuba; Dominican Republic; Ecuador; El Salvador; Guatemala; Haiti; Honduras; Jamaica; Netherlands Antilles; Nicaragua; Panama; Paraguay; Peru; Trinidad and Tobago; Uruguay; Venezuela and **Other Non-OECD America**s.
- **Other Non-OECD Americas**: Includes Antigua and Barbuda; Aruba; Bahamas; Barbados; Belize; Bermuda; British Virgin Islands; Cayman Islands; Dominica; Falkland Islands (Malvinas); French Guyana; Grenada; Guadeloupe; Guyana; Martinique; Montserrat; Puerto; St. Kitts and Nevis; Saint Lucia; Saint Pierre et Miquelon; St. Vincent and the Grenadines; Suriname; and Turks and Caicos Islands.
- **Middle East**: Includes Bahrain; Islamic Republic of Iran; Iraq; Jordan; Kuwait; Lebanon; Oman; Qatar; Saudi Arabia; Syrian Arab Republic; United Arab Emirates and Yemen.
- **Non-OECD Europe and Eurasia:** includes Albania; Armenia; Azerbaijan; Belarus; Bosnia and Herzegovina; Bulgaria; Croatia; Cyprus; Former Yugoslav Republic of Macedonia (Former Yugoslav Republic Of Macedonia); Georgia; Gibraltar; Kazakhstan; Kosovo; Kyrgyzstan; Latvia; Lithuania; Malta; Republic of Moldova; Montenegro; Romania; Russian Federation; Serbia ; Tajikistan; Turkmenistan; Ukraine; Uzbekistan; Former Soviet Union and Former Yugoslavia.

Memo: European Union – 28: Includes Austria; Belgium; Bulgaria; Croatia; Cyprus; the Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; the Netherlands; Poland; Portugal; Romania; the Slovak Republic; Slovenia; Spain; Sweden and the United Kingdom.

Memo: OPEC: Includes Algeria; Angola; Ecuador; Islamic Republic of Iran; Iraq; Kuwait; Libya; Nigeria; Qatar; Saudi Arabia; the United Arab Emirates and Venezuela.

Appendix B. Organizations and Missions (Examples)

Organization	Mission
American Bureau of Shipping (ABS) [118]	ABS' mission is to serve the public interest as well as the needs of our clients by promoting the security of life and property and preserving the natural environment. The responsibility of the classification society is to verify that marine vessels and offshore structures comply with Rules that the society has established for design, construction and periodic survey.
Bureau Veritas [119]	Bureau Veritas is a global leader in Testing, Inspection and Certification (TIC), delivering high quality services to help clients meet the growing challenges of quality, safety, environmental protection and social responsibility. Bureau Veritas supports industries by assessing equipment and processes from the design stage to installation, commissioning and operation. Bureau Veritas offers a wide range of services to ensure a safety-assurance process and asset availability performance for: Oil and Gas, Power Generation, Transportation, Process, Metals & Minerals.
China Classification Society (CCS) [120]	China Classification Society (CCS) is the only specialized organization of China to provide classification services for shipping, shipbuilding, offshore exploitation and related manufacturing industries and marine insurance by furnishing reasonable and reliable classification requirements and providing independent, impartial and integral classification and statutory services to ships and offshore installations, for the promotion and safeguarding of the safety of life and property at sea and for the prevention of pollution to the marine environment. CCS is one of the thirteen full members of the International Association of Classification Societies (IACS).
China Corporation Register of Shipping [121]	China Corporation Register of Shipping, commonly known as CR, was founded on February 15, 1951 in Taiwan, Republic of China as a non-governmental and non-profit technical organization. CR functions as a classification society. The aim of this Society is to provide our clients with excellent techniques, high efficiency and services in respect of the development of design, construction and maintenance of marine equipment as well as the confirmation of their relevant standards.
Det Norske Veritas Germanischer Lloyd (DNV-GL) [122]	As of 12 September 2013, DNV and GL have merged to form DNV-GL. We now form the world's largest ship and offshore classification society, the leading technical advisor to the global oil and gas industry, and a leading expert for the energy value chain including renewables and energy efficiency. We've also taken a position as one of the top three certification bodies in the world. DNV-GL provides classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. DNV-GL also provides certification services to customers across a wide range of industries.
Equasis [123]	The Quality Shipping Campaign, launched by the European Commission and the UK Government in November 1997, aims to bring together all players involved in the various fields of marine business in an effort to improve marine safety. One of the greatest impediments to a genuine quality culture in shipping is the lack of transparency in the information relating to the quality of ships and their operators. While much relevant information is collected and available, it is scattered and often difficult to access. One of the main conclusions of the Quality Shipping Conference in Lisbon in June 1998, was an unanimous call from the participants representing the whole range of industry professionals (including ship-owners, cargo owners, insurers, brokers, classification societies, agents, ports and terminals), to make such information more accessible. In response to this call, the European Commission and the French Maritime Administration decided to co-operate in developing an information system collating existing safety-related information on ships from both public and private sources and making it available on the Internet.

[118] Website: www.eagle.org/eagleExternalPortalWEB/
[119] Website: www.bureauveritas.com
[120] Website: www.v-c-s.org/china-classification-society-certification-company
[121] Website: www.crclass.org.tw/english/eccr-1/ea1.html
[122] Website: www.dnvgl.com/
[123] Website: www.equasis.org/EquasisWeb/public/About?fs=HomePage

Organization	Mission
European Environment Agency (EEA) [124]	The EEA is an agency of the EU tasked to provide sound, independent information on the environment. We are a major information source for those involved in developing, adopting, implementing and evaluating environmental policy, and also the general public. Currently, the EEA has 33 member countries. EEA's mandate is: To help the Community and member countries make informed decisions about improving the environment, integrating environmental considerations into economic policies and moving towards sustainability, and To coordinate the European environment information and observation network (Eionet).
FleetMon [125]	FleetMon.com is an open database of ships and ports world-wide. It serves you with real-time AIS position data, technical information and photos on more than 380,000 vessels. Use the search function to explore the vast FleetMon Vessel Database resources, look up ship particulars, their schedules and port arrivals for the coming weeks, and analyse ship trading patterns.
IHS Maritime [126]	IHS Maritime brings you the largest maritime database in the world, evolved from the Lloyd's Register of Ships published since 1764, covering ship characteristics, movements, ownership, casualties, ports, news and research. World Merchant Fleet Database provided by the Lloyd’s Register Fairplay.
Indian Register of Shipping (IRS) [127]	Indian Register of Shipping is an internationally recognized independent ship classification society, which has full membership in the International Association of Classification Societies (IACS), the major international body of classification societies. Today IRS provides completely independent and highly efficient third party technical inspection and certification services for all types of ships, marine craft and structures. These services also cover a range of offshore and industrial projects. Mission: promote Quality, Occupational Health & Safety and protection of the environment by making every effort to be a Safer, Smarter and Greener Organization.
Institute for Environment and Sustainability (IES) [128]	One of the seven scientific institutes of the European Commission’s Joint Research Centre (JRC). Its mission is to provide scientific and technical support to EU policies for the protection of the European and global environment. A JRC report [Regulating Air Emissions From Ships: The State Of The Art On Methodologies, Technologies And Policy Options] issued in 2010 summarizes findings from extensive research and provides a reference framework for analytical tools to help define a policy strategy for regulating air emissions from ships. It outlines the main methodological aspects of designing policy, namely identification of the impacts, estimation of emissions, and identification and selection of technological and policy options to abate air emissions from ships. Insights are provided into how to best design and apply efficient and equitable policy instruments to support the regulation of air emissions from ships.
International Civil Aviation Organization (ICAO) [129]	The ICAO is the specialized agency of the United Nations responsible for promoting the safe and orderly development of international civil aviation throughout the world. It sets standards and regulations necessary for aviation safety, security, efficiency and regularity, as well as for aviation environmental protection. The Organization serves as the forum for cooperation in all fields of civil aviation among its 191 Member States.
International Energy Agency (IEA) [130]	The IEA is an autonomous organization which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA's four main areas of focus are: energy security, economic development, environmental awareness, and engagement worldwide. The IEA has several "Standing Committees" made up of member country officials to coordinate and be responsible for associated interests.

[124] Website: www.eea.europa.eu/about-us

[125] Website: www. FleetMon.com

[126] Website: www.ihs.com/products/maritime-information/index.aspx

[127] Website: www.irclass.org/about_us/policy-statements-and-corporate-objectives#

[128] Website: http://ies.jrc.ec.europa.eu/

[129] Website: www.icao.int/Pages/default.aspx

[130] Website: www.iea.org/aboutus/whatwedo/

Organization	Mission
International Maritime Organization (IMO) [131]	The IMO is the specialized agency of the United Nations responsible for adopting and updating international treaties for shipping. Its objectives are summed up in the IMO slogan: safe, secure and efficient shipping on clean oceans. IMO (June 2013) has 170 Member States and three Associate Members. Its governing body is the Assembly, which meets once every two years. Between sessions, the Council, comprised of 40 Member Governments elected by the Assembly, acts as IMO's governing body. IMO is a technical organization and most of its work is carried out by committees and sub-committees. The Maritime Safety Committee (MSC) deals with all matters relating to the safety of shipping, as well as maritime security issues, piracy and armed robbery against ships. The Marine Environment Protection Committee (MEPC) is responsible for coordinating the Organization's activities in the prevention and control of pollution of the environment from ships.
Korean Register of Shipping (KR) [132]	Established in 1960 as a not-for-profit ship classification society, Korean Register of Shipping has been promoting safe ships and clean oceans by continually developing technology and human resources pertaining to shipping, shipbuilding and other industrial services. KR became a member of the International Association of Classification Societies (IACS) in 1988, and in 1990, became listed in the Institute Classification Clause (ICC) of London Underwriters.
Lloyd's List Intelligence [133]	Lloyd's List Intelligence accesses a unique global network of specialist sources of business-critical maritime data. It brings together the expertise of a global staff of maritime analysts and journalists with the most extensive system of shore based and satellite intelligence gathering to create the complete information support service for the maritime industry.
Lloyd's Register of Ships [134]	The Register published for the years 1764-66, 1768-71 and then annually since 1775, records the details of merchant vessels of the world. Since the 1870's Lloyd's Register has tried to include all merchant vessels over 100 gross tonnes, which are self-propelled and sea-going, regardless of classification. Before this time only those vessels classed by Lloyd's Register were listed.
National Fire Protection Association (NFPA) [135]	NFPA is an international organisation that develops, publishes, and disseminates consensus codes and standards to reduce fire risks. The mission of the international non-profit organization founded in 1896 is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training, and education. Below are initiatives that support our mission.
Nippon Kaiji Kyokai (Class NK or NK) [136]	NK is a ship classification society actively engaged in a growing range of ship related activities and services aimed at contributing to promoting the protection of human life and property at sea as well as protection of the marine environment. The principal is to undertake surveys to ensure that the rules which it has developed are applied to new buildings and existing ships to ensure their safety. The rules cover hull structures, propulsion systems, electrics, electronic systems, safety equipment, cargo handling gear, and various other areas.
Registro Italizno Navale (RINA) [137]	RINA is a private sector non-profit organization that carries out activities to promote safety of life, property and the environment. RINA Services is active in the marine sector and in the environmental, energy, infrastructures and transport, logistics, safety, quality, food, social accountability and real estate sectors, and offers conformity assessment, control and certification services in compliance with national and international standards, related to materials, projects, technology, products, plants and personnel, including activities assigned by governmental bodies and other authorities.

[131] Website: http://www.imo.org/About/Documents/What%20it%20is%20Oct%202013_Web.pdf
[132] Website: www.krs.co.kr/eng/intro/about/A_about_introduction.aspx
[133] Website: www.lloydslistintelligence.com/llint/index.htm
[134] Website: www.lr.org/about_us/shipping_information/Lloyds_Register_of_Ships_online.aspx
[135] Website: www.nfpa.org/about-nfpa/our-initiatives
[136] Website: www.classnk.or.jp/hp/en/about/aboutNK/index.html
[137] Website: www.rina.org/EN/istituzionale/presentazione.aspx

Organization	Mission
Society of International Gas Tanker and Terminal Operators (SIGTTO) [138]	SIGTTO is the international body established for the exchange of technical information and experience, between members of the industry, to enhance the safety and operational reliability of gas tankers and terminals. The Society publishes studies, papers and works of reference for the guidance of industry members. It maintains working relationships with other industry bodies, governmental and intergovernmental agencies, including IMO, to better promote the safety and integrity of gas transportation and storage schemes.
Society for Gas as a Marine Fuel (SGMF)[139]	SGMF is a non-governmental organisation established to promote safety and industry best practice in the use of LNG as a marine fuel. SGMF encourages the safe and responsible operations of vessels using gas as fuel and all marine activities relating to the supply of gas used for fuel. The Society publishes studies, information papers and works of reference to promote best practice for safe and responsible operations for both LNG-fuelled vessels and LNG bunker supply logistics. The Society maintains working relationships with other industry bodies, governmental and intergovernmental agencies, including IMO, to better develop and disseminate industry best practice advice and guidance amongst its members.
United Nations Conference on Trade and Development (UNCTAD) [140]	UNCTAD, which is governed by its 194 member States, is the United Nations body responsible for dealing with development issues, particularly international trade – the main driver of development. Its work can be summed up in three words: think, debate, and deliver. Reflection on development is at the heart of UNCTAD's work. It produces often-innovative analyses that form the basis for recommendations to economic policymakers. The aim is to help them make informed decisions and promote the macroeconomic policies best suited to ending global economic inequalities and to generating people-centered sustainable development.
United Nations Economic Commission for Europe (UNECE) [141]	UNECE's major aim is to promote pan-European economic integration. To do so, it brings together 56 countries located in the European Union, non-EU Western and Eastern Europe, South-East Europe and Commonwealth of Independent States (CIS) and North America. All these countries dialogue and cooperate under the aegis of UNECE on economic and sectorial issues. However, all interested United Nations member States may participate in the work of UNECE. Over 70 international professional organizations and other non-governmental organizations take part in UNECE activities.
European Commission Joint Research Centre (JRC) [142]	JRC is the scientific and technical arm of the European Commission. It is providing the scientific advice and technical know-how to support a wide range of EU policies. Its status as a Commission service, which guarantees independence from private or national interests, is crucial for pursuing its mission: "As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle. Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

[138] Website: www.sigtto.org/sigtto/purpose
[139] Website:http://www.sgmf.info/
[140] Website: http://unctad.org/en/Pages/AboutUs.aspx
[141] Website: www.unece.org/termsofreferenceandrulesofprocedureoftheunece.html
[142] Website: http://ec.europa.eu/dgs/jrc/index.cfm?id=1370

Appendix C. Railroad LNG Test Programs (Examples)

United States
Burlington Northern (1988-1995), Air Products and Chemicals and Energy Conversions Inc. converted two diesel locomotives to run on natural gas. APC developed fueling locations and two tender cars, each with 25,000 gallon capacity, for Refrigerated Liquid Methane. The engines ran on diesel at low speed with gas injection starting at notch 3 and increasing to 95% by notch 8. The engines provided service on the Olympic Peninsula, then hauled coal from Wyoming to Minnesota and Wisconsin for 4 years[12].
Union Pacific (1992-1995) conducted separate research and development programs with Electro-Motive Diesel (EMD) and GE Transportation Systems (GE) on use of natural gas in line-haul, high-horsepower locomotive engines[143]. UP modified two new EMD SD60M locomotives (3800 hp rating) to run in a dual fuel or a diesel only mode. Similarly, UP modified two new GE Dash-8 locomotives (4100 hp rating).
UP and BN (1993-2013) equipped four switcher locomotives with Caterpillar spark ignited gas engines using LNG as fuel. The program demonstrated reduced emissions in Los Angeles Basin for 20 years[144].
BNSF (2013) is testing six natural gas-powered locomotives, three each from Caterpillar and GE. Plan is to make a decision in 2014 on whether to start switching its fleet of approximately 7000 locomotives to LNG.[145]
CSX (2013) and GE Transportation joined forces to explore LNG technology for locomotives beginning with a pilot program in 2014, using the Evolution Series locomotive equipped with the GE's NextFuel Natural Gas Retrofit Kit, which meets US EPA Tier 3 emission standards for 2012-2014[146].
Santa Fe, Union Pacific and Norfolk Southern (2013) are working with manufacturers on using natural gas as an alternative power source for freight trains[147].
Canada
Canadian National (2012-current) is testing ECI technology on two main line diesel-electric locomotives fueled by LNG, between Edmonton and Fort McMurray. The retrofitted locomotives use 90% natural gas, with 10% diesel fuel for ignition. The LNG tender was upgraded by Chart; LNG is provided by Encana.
Canadian National (2013-current), EMD, Westport Innovations and Gaz Métro Transport Solutions are developing an LNG locomotive and standardized LNG tender. CN provided two 4300-hp locomotives, EMD provided engine conversion and integration with the natural gas engine using Westport Innovations high-pressure direct injection (HPDI) and LNG fuel system technologies. The tender will utilize a standard 40 ft LNG ISO tank with 10,000 gallon capacity supplied by INOxCVA. CN ordered four tenders from Westport with the first to be delivered by end 2013. Laboratory tests are planned in 2013. The first high pressure direct injection (HPDI) locomotive will be field demonstrated in 2014 through a consortium program funded by Sustainable Technology Development Canada[148],[149].

[143] An Evaluation of Natural Gas-fueled Locomotives. Report prepared by: BNSF Railway Company, Union Pacific Railroad , Company, The Association of American Railroads, California Environmental Associates. November 2007.
[144] Natural Gas Locomotives, S. Ditmeyer, TRB Mtg, "Natural Gas as a Fuel for Freight Transport", July 18, 2013.
[145] BNSF to test LNG as fuel in freight locomotives, 8 March 2013, Railway Technology.com.
[146] U.S. EPA, Emission Standards Reference Guide,http://www.epa.gov/otaq/standards/nonroad/locomotives.htm
[147] GE Races Caterpillar on LNG Trains to Curb Buffett Cost, by Tim Catts, Mar 7, 2013, www.Bloomberg.com.

Brazil
Brazil (2010 – current) converted three locomotives to inject NG to replace up to 50% diesel. The locomotives operate on Vale's Vitoria-Minas Railroad heavy haul mining line[150].
Russia
Russian Railways (RZD) placed an order at the end of 2006 with Kuznetsov Scientific & Technical Complex in Samara to develop and build a prototype engine for a gas turbine-electric locomotive (GTEL) fueled with LNG. The locomotive with an 8300-kilowatt (more than 11,000 horsepower) gas turbine began service in July 2008, and achieved a milestone in December 2010 when it hauled a 12,000-tonne freight train on the Moscow Railway's Bekovka – Bekasovo line. A second milestone was achieved in 2011 when the GT-1 hauled a record 16,000-ton load in 170 railcars with one propulsion unit at the All Russia Railway Research Institute (VNIIZHT) test track at Shcherbinka, south of Moscow. The two-section GT1 combines a turbine and power unit with a separate section containing the 17 tonne fuel tank, which gives a range of 750 km[151,152].
RZD and the Sinara Group concluded an agreement in June 2013 to supply 40 mainline GTELs fueled using LNG by 2020. The locomotives will be produced at the Lyudinovsky Locomotive Plant. The twin-section designated GT1h-002 is rated at 8.3 MW and has a maximum speed of 100 km/h. One section contains the gas turbine supplied by Kuznecov which drives an electrical generator from YeTM Privod, while the second section contains the LNG tanks supplied by Uralkriomash and fuel systems from Kriomash BZKM. If the unit performs as expected, an order for 39 additional LNG locomotives is expected in 2015, for delivery in 2020[153].
India
Indian Railways announced an international tender in November 2012 for the supply of gas-turbine electric locomotives. Indian Railways' Research Design & Standard Organization (RDSO), a research wing of the Ministry of Railways based at Lucknow, is working on development of the prototype locomotive fueled by LNG. Once the prototype is proven in field tests, Indian Railways plan to order another 20 LNG based locomotives[154].
Australia
The Australian Rail Association proposed In November 2010, to initiate a joint research and development program into the use of natural gas in Australian locomotives[155].

[148] Westport in R&D Project for Natural Gas-Fueled Locomotives, Dec. 8, 2011 R. Brooks, American Machinist.
[149] Canadian National Railway Orders Four LNG Tenders from Westport, LNG World News Staff, June 05, 2013.
[150] Natural Gas Locomotives, S. Ditmeyer, TRB Mtg, "Natural Gas as a Fuel for Freight Transport", July 18, 2013.
[151] Russian LNG-powered trains headed to India, September 6, 2012 V. Ponomarev, Expert Magazine.
[152] More LNG Locomotives in Russia, June 30, 2012 in LNG, Rail by Rich Piellisch.
[153] Gas fuelled turbine-electric locomotive prototype, Oct 6, 2013, Railway Gazette.
[154] Indian Railways Developing LNG Locomotives, Oct 3rd, 2013, LNG World News.
[155] A Greener Future...Improving rail's environmental performance, November 2010, Australia Railway Association.

Appendix D. Maritime LNG Programs (Examples)

Country	Stakeholders	Description Maritime LNG Programs (Examples)
Argentina and Uruguay [156, 157]	**New high-speed LNG fueled ferry.** Constructed by Australian ferry builder Incat, and operated by Buquebus for service between Buenos Aires and Montevideo, Uruguay.	The high-speed LNG fueled ferry "Francisco" has been launched in Buenos Aires. The new ferry, operated by Uruguay-based transportation and tourism company Buquebus, will carry up to 1000 passengers and 150 cars at speeds of about 52 knots (60 mph). Buquebus plans to supply its own fuel by using mini-liquefaction plants from GNC Galileo SA. Australian ferry builder Incat attributed its speed to the combination of Incat wave piercing catamaran design, the use of lightweight, strong marine grade aluminum, and the power produced by the two 22MW GE LM2500 gas turbines driving Wartsila LJX 1720 SR waterjets.
Argentina and Uruguay [158]	**LNG fueling infrastructure** for ferry service on River Plate between Argentina and Uruguay operated by Buquebus.	Seven Cryobox® LNG nano stations, designed and manufactured by Galileo, will fuel the 'López Mena', the world's first high speed passenger RO-RO ship powered by gas turbines fed on LNG. Together, 7 stations will produce 84 tpd or 49,000 gpd of LNG for delivery to the Buquebus wharf. The ferry will make daily river crossings.
Canada [159]	**BC Ferries** on the Tsawwassen – Southern Gulf Islands route, British Columbia.	BC Ferries plans to commission three new vessels to operate on LNG. Two vessels will be capable of carrying 145 vehicles and up to 600 passengers and crew; the third vessel will be capable of carrying 125 vehicles and 600 passengers and crew for peak and shoulder season service, plus provide refit relief for the other two new ships. The new ships will be designed to operate on diesel or LNG.
Canada [160]	**LNG bunkering** on the West Coast of Canada is being studied by a joint industry team, including Port Metro Vancouver, BC Ferries, Seaspan, and the British Columbia Institute of Technology.	The West Coast Marine LNG Supply Chain Project is a joint industry effort focused on the use of LNG on the West Coast of Canada. The study aims to identify and address barriers for LNG as a marine fuel, and involves 17 participating organizations including Port Metro Vancouver, BC Ferries, Seaspan ULC, and the British Columbia Institute of Technology along with marine classification societies, technology and services providers, standards development groups, federal and provincial governments, and natural gas producers and suppliers. Stringent emissions regulations coming into force in 2015-2016 mean that vessel owners operating within 200 miles of the West Coast and in other regions of Canada will need to use lower sulphur distillate fuel, install exhaust after treatment technologies or switch to LNG in order to comply.
China [161]	**LNG Carriers** from Australia to China. China Shipping Group and Sinopec Kantons Holdings.	The first electrically propelled LNG carriers (174,000 cm) built in China will incorporate power and propulsion systems developed and built by GE's Power Conversion business. Six LNG carriers will be built by Hudong-Zhonghua Shipbuilding Group at its shipyard in Shanghai. GE will supply induction motors with propulsion technology driven by electricity generated from high-efficiency "dual-fuel" engines that can run on natural gas from LNG boil-off, marine diesel gas or heavy fuel oil.

[156] LNG-powered ferry rolls out in gas-rich Argentina. Blake Sobczak, October 1, 2013: Energywire.
[157] The World's Fastest Ship - Incat High Speed Ferry Excels. 06/18/2013: INCAT.
[158] Galileo Cryobox Nano Station Broadens Scope for LNG Refuelling, 10 May 2013, Argentina, Buenos Aires: Galileo.
[159] BC Ferries to Build LNG-Fuelled Vessels. July 25, 2013 | Canada, Victoria BC: NGV Global News.
[160] West Coast Project to Show Way for LNG Use in Canada's Marine Sector. May 29, 2013: CNW Newswire.
[161] GE Power Conversion to Deliver Next-Generation LNG Carriers to China. July 11, 2013: GE Press Release.

Country	Stakeholders	Description Maritime LNG Programs (Examples)
China [162]	**Harbor tug** for Gaolan Port in Zhuhai, near Hong Kong. China State Shipbuilding Corporation (CSSC), CNOOC Energy Development.	China State Shipbuilding Corporation (CSSC) launched China's first dual-fuel harbor tug, the CNOOC 521, from their Huangpu Shipyard in July 2013. The vessel is the first of two liquefied natural gas powered vessels being built for sustainable operations out of Gaolan Port. The vessels are each equipped with 6-cylinder Wärtsilä 34DF in-line dual-fuel engines with 2x25 cm LNG tanks.
China [163]	**LNG Carriers** for Asia-Pacific trade. MAN Diesel & Turbo, Sinopec Kantons, MOL and Shanghai based CSLNG	MAN Diesel & Turbo has won the contract to supply the engines for six Chinese LNG carriers (LNGCs). The order is for the 30 × MAN 51/60DF dual-fuel engines. The configuration covers 5 × 8L51/60DF engines. Fuel-sharing mode will be applied to each unit. The vessels will be constructed at Hudong-Zhonghua Shipyard.
China [164]	**Rolls-Royce, CNOOC and Zhenjiang shipyard**	Rolls-Royce announced today an order from Chinese state oil company CNOOC to power Asia's first gas powered tugs. The order includes two tugs to be built at the Zhenjiang shipyard in Jiangsu, China, with an option for two additional vessel. Each newbuild tug will feature a pair of Rolls-Royce Bergen C26:33L9PG engines fueled purely by liquefied natural gas (LNG).
Denmark [165]	**Ferry** for Domestic Danish trade. Fjordline, Danish OSK-ShipTech A/S, DMV, Samsø Municipality, and Remontowa Yard in Gdansk	The first LNG-fueled ferry for domestic trade in the EU is being built at Remontowa Yard in Gdansk, Poland. Danish OSK-ShipTech A/S designed the new ferry and conducted the EU tender process on behalf of the owner, Samsø Municipality. The vessel will be classed by DNV-GL. The ferry's first journey between the island of Samsø and Jutland on the Danish mainland is planned to take place 1 October 2014. The new ferry can carry a maximum of 600 passengers and 160 cars.
EU [166]	**Maritime LNG fueling infrastructur**e. Atlantic Member States (Ireland, France, Portugal, Spain and the United Kingdom)	The European Commission "Maritime Strategy" Action Plan to revitalize the Atlantic maritime economy includes consideration of financing to upgrade marine infrastructure, such as equipping ports with LNG refuelling capacity.
EU & US [167]	**Guidelines for LNG Fueling Infrastructure**. Int'l Asso. of Oil and Gas Producers (OGP) and Int'l Org. for Standardisation (ISO).	OGP and ISO have agreed an interim solution for standardization (OGP 118683, 2013) providing guidelines for systems and installations for supply of LNG as fuel to ships, covering equipment, systems, procedures and training. The guidance is for the planning and design of the bunkering facility, the interface with the ship, procedures for connection and disconnection, emergency shutdown interface, and the LNG bunkering process control.

[162] China Shipbuilding (CSSC) Launches Dual-Fuel Harbour Tug. July 10, 2013 | China, Zhuhai: NGV Global News.
[163] Chinese Ship Owners Order MAN Dual-Fuel Engines for 6 LNG Carriers. July 19, 2013 | China and Denmark: NGV Global News.
[164] Maritime Propulsion, LNG Powered Tugs Ordered in China, Eric Haun at March 19, 2014.
[165] LNG-fueled Ferry a First for Denmark. July 21, 2013 | Denmark, Copenhagen: NGV Global News.
[166] EU Marine Strategy Includes LNG Refuelling Infrastructure, May 13, 2013 | Belgium, Brussels. Source: Europa.
[167] OGP and ISO Agree an Interim Specification for Supply of LNG as Marine Fuel. June 15, 2013 | United Kingdom, London: NGV Global News.

Country	Stakeholders	Description Maritime LNG Programs (Examples)
EU	**MV Eiger, push-tow barge.** Cryonorm Systems, Koedood Dieselservice	Barge retrofit consists of LNG bunker stations on portside and starboard, the Vacuum Insulated Type C LNG Fuel Gas tank, the LNG Tank Connection Space, the Class approvals, HAZIDS, Control system, glycol-water system, vaporizers, valves, instruments and gas processing equipment.
Finland [168]	**LNG Icebreaker.** Russia's United Shipbuilding Corporation, the Finnish branch of shipbuilding group STX Arctech Helsinki Shipyard, and Finnish Transport Agency.	United Shipbuilding and Arctech won a tender for the construction of an icebreaker for the Finnish Transport Agency. The icebreaker will use both diesel and LNG. The vessel has been designed especially for the demanding ice-breaking operations in the Baltic Sea. The vessel will be able to break a 25 meter wide channel in 1.2 meter thick ice at speed of 6 knots, as well as to reach 9 –11 knots of average speed.
Germany [169]	**Engines for LNG-Hybrid Barge** Caterpillar, Becker Marine's subsidiary, Hybrid Port Energy	Five Cat G3516 marine engines were selected to power Hybrid Port Energy's LNG-Hybrid Barge which will operate in the Port of Hamburg. It is a V16 configuration, providing 1550 ekW @ 1,500 rpm. The fuel system is an inlet fumigated low pressure gas system. Also, recently-introduced MaK dual fuel engines in the 34 and 46 cm bore class.
Germany [170]	**Engine manufacture for Merchant trade**. Caterpillar Marine Power Systems.	Caterpillar Marine Power Systems has developed a new marine dual-fuel engine platform for the commercial marine market, the MaK™ M 34 DF. The engine boasts a power rating of 500 kW per cylinder at 720 and 750 rpm in diesel and gas modes, and will share the same footprint as the M32C engine series. Although designed for unlimited operation on LNG, MDO and HFO, the M 34 DF will reach industry- leading efficiency in gas mode.
Germany [171]	**Engine manufacture for ferry conversion.** Service between Emden and Borkum Island on the Lower Saxon Wadden Sea National Park. Wärtsilä, Brenn – und Verf ormungstechnik Bremen GmbH (BVT), Aktien-Gesellschaft "EMS" (AG EMS)	Wärtsilä has been awarded a retrofitting contract by the German shipyard BVT to convert the MV Ostfriesland, a car and passenger ferry owned by AG EMS, to operate using LNG as fuel. The vessel will be fitted with two 6-cylinder Wärtsilä 20DF dual fuel generating sets and a Wärtsilä LNGPac. The dual-fuel engines will run primarily on LNG as the main fuel, but have the capacity to switch to conventional liquid fuels if necessary. The LNGPac, innovated and developed by Wärtsilä, comprises on-board liquid natural gas bunkering, storage tanks, and handling equipment with related safety and automation systems.
Global [172]	**Engine manufacture for Fast ferry.** General Electric.	GE has developed the LM2500 Fast Ferry using LNG versus MDO. The high power output, low weight and size of aeroderivative gas turbines make them ideal for the fast ferry application.
Japan [173]	**LNG-Fueled Tug.** NYK Line	Japan's NYK Line will build a tugboat featuring a dual-fuel engine that can be powered by either liquefied natural gas (LNG) or heavy oil. Other than LNG carriers, this tugboat will be the first building in Japan of an LNG-fueled vessel. Tokyo Gas Co. Ltd. will supply the LNG, and with the support of Tokyo Gas, NYK will make arrangements for a safe LNG supply system.

[168] Arctech to Build LNG Icebreaker for Finland. January 25, 2014 | Finland, Helsinki: NGV Global News.
[169] Caterpillar Sends Engines for LNG-Hybrid Barge in Germany, 2 April 2014, LNG World News.
[170] Caterpillar Develops 2nd High Performance Dual-fuel Marine Engine. May 31, 2013 | Germany: NGV Global News.
[171] LNG Selected to Limit Environmental Impact of Wadden Sea Ferry. July 18, 2013 | Germany: NGV Global News.
[172] LM2500 Fast Ferry LNG. Ecomagination: GE website.
[173] NYK to Build Japan's First LNG-Fueled Tug. December 24, 2013 | Japan, Tokyo: NGV Global News.

Country	Stakeholders	Description Maritime LNG Programs (Examples)
London [174]	**LNG safety and best practices.** SIGTTO, SGMF.	SIGTTO established the Society for Gas as a Marine Fuel (SGMF) – a non-governmental organization (NGO) to help enhance the safety and best practices in the use of LNG as a marine fuel. SIGTTO says that while the use of LNG as a ship fuel lies outside the Society's terms of reference, its knowledge and experience of liquefied gas handling, including in the use of cargo boiloff gas in LNG carrier propulsion systems, will be invaluable to the LNG bunkering sector.
Netherlands [175]	**Inland LNG tanker** for service upstream on the Rhine and Danube rivers. VEKA Group and Deen Shipping B.V.	VEKA DEEN LNG is developing an LNG tanker with capacity of 2250 cm to serve inland waterways. The vessel length will be 86m, width 10.5m and is proposed to have a 3285 kW generator for LNG propulsion and a 1,500 kW emergency diesel generator. The cargo tanks will be insulated to reduce 'boil off ' to less than about 0.2%, which will be used for both propulsion and electrical power.
Netherlands [176]	**LNG fueled chemical tanker** for Inland waterways. Deen Shipping subsidiary, Argonon Shipping B.V., Lloyd's Register.	The MT Argonon, said to be the world's first new LNG fueled chemical tanker, has been delivered in Rotterdam to Lloyd's Register. LR helped the owners and regulators to identify the risks, meet regulatory requirements and overcome the technical challenges for the precedent-setting 6,100-dwt dual fueled chemical tanker. The LNG is stored in a transport tank located on deck.
Netherlands [177]	**Subsidy for LNG bunkering** at the Port of Antwerp. Antwerp Port Authority, European Commission.	Antwerp Port Authority has received positive news from the European Commission concerning its application for a subsidy for LNG to develop and build a LNG bunkering station for barges in the port of Antwerp. The preparatory study work for the LNG bunkering station has already started, and the objective is to have the station in operation by the end of 2015.
Netherlands [178]	**LNG bunkering** at the Port of Antwerp. Antwerp Port Authority, EXMAR.	The Port of Antwerp Port Authority has appointed (September 2013) ship owning company EXMAR as its strategic partner in a plan to provide LNG bunkering in the port. Through their strategic alliance, the Port Authority and EXMAR want to facilitate the use of LNG as ship fuel, and to that end both partners plan to start with the actual construction of a LNG bunker ship early 2014.
Netherlands [179]	**LNG bunkering** at the Port of Rotterdam. Rotterdam Port Authority.	The municipality of Rotterdam has amended the Port Management Regulations to allow bunkering LNG for inland shipping from 1 July 2013, in the Seinehaven, a port east of the Europort area of Rotterdam.
Norway [180]	**Engine manufacture for merchant ship conversion** for Bergen Tankers AS by Rolls-Royce Plc.	Rolls-Royce Plc has won a contract with Norwegian ship owner Bergen Tankers AS to convert the merchant ship Bergen Viking to run on engines powered by LNG, replacing the current diesel engines.

[174] SIGTTO launches latest initiative to promote efficient LNG bunkering. 29 May 2013: Port Technology International.
[175] Netherlands Collaboration Produces Inland LNG Carrier. May 29, 2013 | Netherlands, Werkendam: NGV Global News.
[176] LNG-Fuelled Chemical Tanker a First for Europe's Inland Waterways. January 7, 2012 | Netherlands: NGV Global News.
[177] Port of Antwerp gets EU Subsidy for LNG Project. July 24, 2013 | Belgium, Antwerp: NGV Global News.
[178] Port of Antwerp Gets Practical About LNG Bunkering. September 18, 2013: MarineLink.com
[179] Rotterdam Regulates Bunker LNG. July 2, 2013 | The Netherlands, Rotterdam: NGV Global News.
[180] Bergen Tankers Selects Rolls-Royce Engines for LNG Conversion Project. June 6, 2013 | Norway: NGV Global News.

Country	Stakeholders	Description Maritime LNG Programs (Examples)
Norway [181]	**Research on North American Emission Control Area (ECA)** for IMO by DNV-GL.	The IMO has chosen DNV-GL to gather knowledge about the potential of LNG powered international shipping in the North American Emission Control Area (ECA) and identify the necessary conditions for the successful implementation of LNG as a fuel source in the region. The report will be delivered to the IMO in October, 2013.
Norway [182]	**LNG Bunker Barge Concept**. NLI Solutions, DNV-GL, Wilhelmsen Technical Solutions	Offshore oil and gas engineering specialist NLI Solutions has developed a concept for a LNG Bunker Barge based on the NLI LNG tank design. The concept has been further developed in a design study together with the Marine division of Rolls-Royce and Wilhelmsen Technical Solutions.
Norway [183]	**LNG platform supply vessels (PSVs).** Siem Offshore, Wärtsilä	Siem Offshore contracted with Wärtsilä (Jan 2014) to supply the design and integrated solutions for four PSVs to be built at the Remontowa yard in Poland, utilizing the Wärtsilä VS 4411 DF ship design and dual-fuel propulsion system. The vessels will operate in the North Sea.
Norway[184]	**Boreal Transport Nord AS, Fiskerstrand Verft AS, Rolls Royce**	Boreal Transport Nord AS and Fiskerstrand Verft AS have signed an agreement of building two new ferries with LNG propulsion. BOREAL will install 1 x Rolls Royce Bergen SI gas engine in each ferry.
Singapore [185]	**Alternative fuel infrastructure**. Shell Trading.	At the 2012 Singapore Int'l Bunkering Conference, Shell Trading encouraged the industry to decide quickly which form of alternative fuels it will use in place of fuel oil as more stringent regulation deadlines loom. Should the IMO introduce the 0.5% global sulfur cap revision in 2020, the industry would not be able to make the fuel switch if they do not pick one alternative now and invest in it collectively.
Singapore [186]	**LNG bunkering guidelines.** Port of Singapore. Lloyd's Register, Port of Singapore.	Lloyd's Register has won a Maritime and Port Authority of Singapore (MPA) contract to develop technical specifications, LNG bunkering procedures, and development of crew competency for LNG bunkering in the Port of Singapore, to support supply of LNG as a fuel for ships by 2015.
Spain [187]	**Gas Natural Fenosa, Rolls Royce**	Gas Natural Fenosa has signed a collaboration agreement with Rolls Royce Marine to develop and install a pure-gas Bergen engine aboard the Baleària-operated ferry Abel Matutes.
Sweden [188, 189]	**LNG bunkering** at the Port of Gothenburg, Swedegas AB, Vopak.	Open access LNG bunkering at the Port of Gothenburg will be available by 2015, when tougher limits on marine fuel sulfur content go into effect in the European ECA. Vessels in the port will not need to enter a special terminal for bunkering but will be able to get fuel directly from a bunker tanker while the vessel is loading or unloading, which the port said would open up potential for large-scale LNG bunkering.
Sweden [190]	**LNG powered cargo vessel.** Erik Thun A.B., Ferus Smit, Wartsila.	Ferus Smit to build 2 LNG powered ships for Erik Thun, with 2 more units on option, using Wartsila Dual fuel main engine and pressurized LNG tank. The first vessel will be delivered in 3Q2015 from the Westerbroek yard, Groningen. The ships will be bulk cargo 5800DWT, ice class 1A. Classification will be done by Lloyds Register.

[181] IMO Selects DNV to Assess LNG Marine Fuel Implementation in North America. June 18, 2013: NGV Global News.
[182] Large Volume LNG Bunker Barge Concept Unveiled. June 10, 2013 | Norway: NGV Global News.
[183] Wartsila Secures Contract for Four More LNG PSVs, Feb. 17, 2014, LNG World News.
[184] Press Release by Boreal Transport Nord AS and Fiskarstrand Verft AS.
[185] Shipping industry needs to choose bunker fuel alternatives fast: executive. Singapore (Platts)--18Oct2012.
[186] LLoyd's Register to Guide Port of Singapore Toward LNG Bunkering Capabilities. July 9, 2013 | Singapore: NGV Global News.
[187] MarineLink.com, Spain's First Pure-Gas Marine Engine, Michelle Howard, 20 February 2015.
[188] LNG Bunkering Will Be Available in Time for 2015 Emissions Rules. Thursday October 4, 2012: Ship & Bunker.
[189] LNG Bunker Ship to Ship. LNG/GOT, June 15, 2012: Port of Gothenburg.
[190] Ferus Smit to Build LNG Powered Ships for Erik Thun, Feb. 17, 2014, LNG World News.

Country	Stakeholders	Description Maritime LNG Programs (Examples)
USA [191]	**LNG Carriers.** Teekay LNG Partners L.P. (Teekay LNG) and Cheniere Marketing, LLC (Cheniere)	Teekay will provide Cheniere with transportation services using two ships powered by MAN MEGI gas injection engines. The 173,400 cm LNG carrier newbuildings under construction by Daewoo will have M-type, Electronically Controlled, Gas Injection (MEGI) twin engines. The system offers the advantage of being almost independent of gas/oil fuel mixture as long as a small amount of pilot oil fuel is injected for ignition.
USA [192]	**Gulf Coast LNG fueling Infrastructure.** Harvey Gulf International Marine	Harvey Gulf will operate the first US LNG marine fueling facility to be located in Port Fourchon, Louisiana. Harvey Gulf operates LNG-fueled Offshore Supply Vessels (OSV); a sixth OSV has been ordered. The LNG refueling facility, consisting of two sites each with 270,000 gallons of LNG storage capacity, will be able to refuel at a rate of 500 gal/min. Completion of the first site is planned for early 2014, and the second site shortly after. The facility will also have capacity to refuel on-road vehicles supporting heavy duty trucking.
USA [193]	**LNG Conversion, RoRo Cargo.** Totem Ocean Trailer Express, Wartsila	Totem Ocean will convert two roll-on/roll-off cargo ships, each with four 12-cylinder Wärtsilä 50 DF dual fuel engines and generator sets, two 1100m^3 LNG fuel storage tanks, and integrated LNG storage and fuel gas handling systems (LNGPac™) for the largest LNG conversions ever undertaken in North America. The contract was signed in the fourth quarter of 2013.

[191] Teekay Charter Two MEGI Propelled Newbuilds to Cheniere. June 9, 2013 | Bermuda, Hamilton: NGV Global News.
[192] Harvey Gulf Builds LNG Bunkering Facility for Expanding Fleet of OSVs. June 15, 2013 | USA, New Orleans LA: NGV Global News.
[193] Wartsila Wins LNG Conversion Gig from Totem Ocean, Feb 19, 2014 |LNG World News.

Appendix E. Non-Road LNG Programs (Examples)

Country	Stakeholders	Description Non-Road LNG Programs
Canada [194]	**Mine Haul Trucks.** Westport Innovations Inc., Caterpillar.	Westport and Caterpillar are co-developing Westport high pressure direct injection (Westport™ HPDI) technologies for off-road engines, including large mine trucks, with 95% substitution of diesel with natural gas. The top ten mining companies consume over two billion gallons of diesel fuel annually. With more than 28,000 large mine trucks (>100 ton capacity) operating around the world, typically burning 150,000 to 450,000 gallons of diesel per year.
Canada [195]	**Mine Haul Trucks.** Shell Canada and Caterpillar. Fort McMurray, Alberta	Shell Canada and Caterpillar have signed an agreement to test a new engine and fuel mix using LNG that could reduce operating costs and emissions from oil sands mining in northern Alberta. In addition to the new truck Caterpillar is developing, Shell will retrofit existing trucks with the new engine for the trial, as well as provide fuelling infrastructure. Caterpillar's product line-up currently includes gas turbines and spark-ignited engines for the electric power and gas compression markets, as well as a dual-fuel engine option for the petroleum market.
Canada [196,197]	**LNG Fueled Power Plant.** Northwest Territories Power Corp. (NTPC)	Construction of the Inuvik plant began in August. Two cargoes of LNG have already arrived at the facility, allowing NTPC to offset half of the diesel needed to supply Inuvik's electricity. In less than two years, two LNG production plants are expected to open in northern B.C. and Alberta, which will decrease fuel transportation distance and costs.
France [198]	**Aviation Research.** Airbus, Royal Melbourne Institute of Technology (RMIT).	RMIT's Cryogenic Liquid Methane Aircraft (CLiMA) team is one of five finalists selected by Airbus engineers in the 2013 *Fly Your Ideas* global university challenge. The UNESCO-backed competition encourages students to develop ideas for a more sustainable aviation industry. The team of aerospace engineering students delivered a proposal for the development of aircraft fuelled by a blend of liquefied biomethane and liquefied natural gas. The Bio-LNG will be stored in wing-mounted tanks insulated to preserve the cryogenic-induced liquid state.
India [199]	**LNG Fueled Power Plant.** Kochi. Petronet LNG	Petronet LNG will set up a Rs3500 (US$626.7 million) natural-gas fired power plant adjacent to its Kochi import facility, The Hindu Business Line reported July 30. The plant will generate up to 1200 MW using LNG imported from Australia's Gorgon project.

[194] Westport's New VP Will Focus on Natural Gas for Mining and Rail. Sept. 18, 2013. Canada, Vancouver BC: NGV Global News.
[195] Shell Canada and Caterpillar to Explore LNG for Mining Trucks. December 16, 2013 | Canada, Calgary AB: NGV Global News.
[196] LNG deliveries start to fuel Inuvik power plant in Canada's far north. January 16, 2014: Arcticgas.gov
[197] Inuvik's LNG facility 'breaks trail' in the North, Maria Church, January 13, 2014: Northern Journal.
[198] European Commission, Climate Action, Reducing emissions from aviation. RMIT Student Project on Cryogenic Liquid Methane Aircraft Reaches Airbus Finals. May 21, 2013 | Australia, Melbourne: NGV Global News.
[199] Petronet to set up LNG-fueled power plant. August 03, 2012: Zeus Intelligence.

Country	Stakeholders	Description Non-Road LNG Programs
Indonesia [200, 201]	**Mine Haul Trucks.** Pertamina, PT Pertamina Gas, PT Badak NGL and PT Mandiri Indominco.	Pertamina has begun working on the LNG potential in mining sector in Kalimantan with PT Mandiri Indominco, one of major coal mining companies. A total of 4 inpit dump trucks are planned to use LNG as their fuel at an estimated LNG demand of about 60 MM btu/d. When fully implemented, there are about 84 LNG-fueled high dump trucks, consuming around 3.97 Bn btu/d. PT Pertamina will supply 160,000 cm of LNG per annum as a fuel for heavy mining vehicles. The mining vehicles will be converted to use LNG-diesel fuel with composition of 60-40. The project will be implemented in 2014; a full scale project is planned in 2015.
Philippines [202]	**LNG Fueled Power Plant.** Santa Rita, Batangas City. First Gen Corp., First NatGas Power Corp (FNPC).	First Gen Corp broke ground for its new natural gas power plant in Batangas. The 414-megawatt San Gabriel power plant project is the first of three such facilities that will allow the company to use LNG. The plant, which is expected begin operation in 2016, will sell electricity to the Luzon grid. The first unit will initially use Malampaya gas. It is planned in the future that the project, along with the other two additional plants, will operate on re-gasified LNG.
USA [203]	**LNG-Fueled Drilling Rigs.** Seneca Resources Corp. and Ensign Drilling	Seneca Resources Corp. and Ensign Drilling have installed two of GE's Jenbacher LNG engines to power drilling rigs operating in the Marcellus Shale region of Pennsylvania, replacing diesel engines. Each 1-megawatt Jenbacher J320 turbocharged natural gas engine produces 500 to 1,100 kW power, enough to supply all operations on the rig. The turbocharger keeps the machine operating at peak performance with low gas pressure. The two latest upgrades join Ensign's fleet of 15 LNG-powered rigs operating in the United States; 11 of those are operating exclusively on GE's Jenbachers.
USA [204]	**Mine Haul Trucks.** GFS Corp., Alpha Natural Resource's Belle Ayr mine in Gillette, WY.	GFS Corp added two dual-fuel LNG conversion systems for mine haul trucks. The new models are the EVO-MT 8300 for the Komatsu 830 model haul truck and the EVO-MT 9300 for the Komatsu 930 model haul truck, the company's first offering for electrical drive trucks. GFS also has LNG conversion systems are for the Caterpillar 777 and 793 mechanical drive trucks, operating on Cat 793B model haul trucks for over a year at Alpha Natural Resource's Belle Ayr mine in Gillette, Wyoming.
USA [205]	**Mine Haul Trucks.** GFS Corp., Alpha Coal West, Eagle Butte Mine, Gillette, WY	After an 18 month 3-truck pilot program of LNG-powered mine haul trucks and conversion of a fourth truck, Alpha Coal West, Inc., has placed an order with GFS Corp to convert its remaining fleet of 12 Caterpillar 793′s at the Eagle Butte Mine, near Gillette, Wyoming, to the EVO-MT™ 7930 dual-fuel System.

[200] Indonesia: Pertamina Pioneers Utilization of LNG for Transportation. Aug 7, 2012: LNG News World.

[201] Pertamina To Supply LNG To Indominco. Lili Sunardi, Arsyad Paripurna, December 9 2013: Bisnis Indonesia.

[202] First Gen building 2 more LNG power plants in Batangas. Euan Paulo C. Añonuevo, January 14, 2014: InterAksyon.com.

[203] Unconventional Gas, Innovative Power: GE Jenbacher Engines Powering LNG-Fueled Drilling Rigs. Matthew Van Dusen,Nov 27, 2012: GE ecomagination.

[204] GFS Corp Adds Two Dual-Fuel LNG Conversion Systems for Mine Haul Trucks. September 21, 2013 | USA, Chicago IL: NGV Global News.

Country	Stakeholders	Description Non-Road LNG Programs
USA [206]	**Shale Gas Drilling Rig** Chevron's Appalachian MI Business Unit, Nabors Industries.	AMBU and Nabors Industries, a drilling, well-servicing and work over contractor, developed built-for-purpose rigs for shale gas drilling. The first rig, X07, deployed in June 2013, has dual fuel engines; Rigs X08 and X09 run solely on natural gas.
USA [207]	**LNG Aviation Research.** NASA and Boeing, Lockheed Martin and Northrop Grumman.	NASA awarded Boeing a year-long extension to its concept studies for "N+3"-generation (three generations on from today's 737 and 777) airliners flying around 2030-35, to look another generation into the future targeting 2040-2050. What would another 15 years of technology development make possible? One answer: liquefied natural gas (LNG) propulsion in a hyper-efficient airliner already stacked with fuel-saving, emissions-minimizing advances.
Russia[208]	**Aviation Industry**	The Soviet Union built the first world's liquid hydrogen and liquid natural gas aircraft engine NK88as far back as in the late 1980s. The Tupolev155 aircraft made first test flights on April 15th 1988 with NK88 LH2 engine and on January 18th 1989 with the first NK88 LNG engine. A liquid hydrogen Tupolev155 made 5 test flights and the LNG version made 100 flights. It is important to note that LNG Tupolev155 flew to and was serviced and refueled with LNG in Moscow, Minsk, Bratislava, Nice and Hanover.

[205] Alpha Coal West to Convert Caterpillar 793 Fleet to Natural Gas. January 18, 2014 | USA, Bristol VA: NGV Global News.

[206] Chevron Upstream: North America Customized Natural Gas-Powered Drilling Rigs Deployed. 31 Oct 2013: Press Release.

[207] Boeing Delivers LNG-Fuelled Aircraft Concept to NASA. March 22, 2012 | USA | Source: NGV Global News/ Aviation Week.

[208] International Gas Union Report on Study Group 5.3 “Natural Gas for Vehicles (NGV)” Global Opportunities for Natural Gas as a Transportation Fuel for Today and Tomorrow.

Appendix F. Equipment Manufacturers – Engines (Partial List)

OEM[209]	Gas Focus	Road	Non-Road	Remote Power	Rail	Marine
Caterpillar	• Dual fuel engines for rail, marine, mining • Future LNG fueled locomotives, mining trucks and machinery • Acquired Mak, Progress Rail Services and Electro-Motive Diesel (EMD)		• SW Energy installed two Cat 3512C Gen. Sets with EPA-approved Cat DGB kits on a rig operating in the Fayetteville Shale. • Drilling of eight wells over the course of 45 days, saved US$100,000 in fuel costs	• Supplied the Rubart Station with 12 NG-fueled Cat gen sets, each with 20-cylinders, for total output of ~110MW • Plan to market dual-fuel power gen sets in 2014	• Retrofitted 2 BN locomotives with EMD NG engines for coal haul between Wyoming-Wisconsin from 1991-1996	• G3516 marine engine for Hybrid Port Energy's barge, Port of Hamburg • M46 DF flexibility to use LNG, MDO or HFO; in LNG mode complies with IMO III and EPA Tier 4 regulations
GE	• Jenbacher gas engines • Waukesha gas engines		• Ensign Drilling operates 15 drilling rigs on NG in the US, with 11 using GE's Jenbacher gas engines. • Provides for oilfield power generation	• GE aviation engines modified to burn NG / biofuels, 18-100 MW. • 2 Jenbacher NG engines provide power for China Huadian Eng.	• Evolution Series locomotive equipped with the NextFuel NG Retrofit Kit meets US EPA Tier 3 stds; GE and CSX tests begin in 2014	
MAN	• Commercial vehicle engines • Power • Agriculture • Marine dual-fuel	• MAN Truck & Bus supply a wide range of diesel and NG engines for varied use in many industries. • Gas engines for buses in Euro 6 are E0836 and E2876	• Agricultural machinery use the E3268 engine	• E2676 LE202 gas engine is designed for decentralized, continuous power supply in combined heat/power generation • Five series with a total of 19 NG engines are available		• MAN dual-fuel engines ordered for six LNG tankers for China and one LNG tanker for Japan (5 for each vessel)

209 Brief descriptions based on literature taken from the listed manufacturer's websites.

OEM[209]	Gas Focus	Road	Non-Road	Remote Power	Rail	Marine
Rolls Royce	• Bergen/MTU-brand high-speed engines and propulsion systems for ships, heavy road, defence vehicles and energy industry		• Planning future mining trucks • 630 Bergen SI gas engines for heat and power distribution	• MTU cogeneration plants for combined heat and power based on NG engines and/or gas turbines	• Planning future locomotives.	• 61 Bergen SI gas engines for marine; 53 now in service, 8 on order • RR NG engines meet IMO Tier III regulations; used for Gas-Mechanical and Gas-Electric applications
Volvo	• In 2014 Volvo Penta will release its full line of five Tier 4 Final-compliant industrial engines • Volvo is one of Europe's largest suppliers of NG buses	• VNL daycab has a 12L Cummins-Westport ISX12 NG engine • VNM daycab has a 8.9L Cummins ISL G engine • Volvo's 13L LNG engine delivers 30% improvement vs. SI engines	• TWG1663 GE bi-fuel 16-litre Tier 4 Interim engine is targeted for US drilling and other prime power and mobile applications. • The engine operates on ratios of up to 70% NG and 30% diesel	see Off Road		
Wartsila	• Gas power plants • Gas-fuelled engines and related systems for marine • Medium-scale LNG infrastructure development		• Future Goal is to establish a similarly strong foothold in the oil & gas business	• Multi-fuel power plants, including baseload generation, peaking and load following operation, as well as dynamic system balancing and ultra-fast grid reserve.		• Leader,150+ dual fuel ships • Supplies Totem Ocean with engines, generators, LNG storage/ fuel systems for conversion of two Orca Class cargo ships • MV Eiger barge using Wartsila 6L20DF engines for first EU inland waterway barge retrofit
Cummins	• NG engines, from 150 to 400 hp, certified with a three-way catalyst, meet or	•ISX12 G is a NG engine for heavy duty regional-haul trucks /	•Cummins Emission Solutions is a leader in after treatment			

OEM[209]	Gas Focus	Road	Non-Road	Remote Power	Rail	Marine
	exceed U.S. EPA, California Air Resources Board, and EURO emissions standards • Over 34,000 Cummins-manufactured natural gas engines are in service worldwide today	tractors • B Gas Plus 5.9L engine is ideal for shuttles, buses and medium-duty uses • C Gas Plus engine is for non-N. Amer. markets • The ISL G meets Euro 6 and 2014 EPA/DOT emissions standards	technologies for off-highway equipment ranging from 45 hp to 4000 hp			
Westport	• NG engine and LNG Fuel System for HD trucking • NG/LPG engines and fuel systems for light-duty market • WiNG™ Power System for Ford F-250/550 Super-Duty trucks in the U.S. and Canada	• 15L engine and iCE PACK LNG Tank System for HD trucks • HPDI technology for HD vehicles, and spark-ignition engine systems for automotive • NG / LPG engines / fuel systems for other OEM light-duty vehicles			• 2013 new LNG Tender for locomotives • R&D on an LNG locomotive program	

Appendix G. Engine Considerations

Different engines types for different combustion processes.

a. Premixed vs. diffusion flames

Flames are usually classified according to the following factors[210, 211]:

- The composition of the reactants as they enter the reaction zone. If the fuel and oxidizer (air or oxygen) are uniformly mixed together, the flame is designated as premixed (example: Bunsen burner). If the reactants are not premixed and must mix together in the same region where the reaction takes place, the flame is called diffusion flame (example: candle flame).

- The character of the gas flow through the reaction zone: laminar or turbulent. In laminar (or streamlined) flow, mixing and transport are done by molecular processes. In turbulent flows, mixing and transport are enhanced by the macroscopic relative motion of eddied fluids.

- The flame is steady or unsteady: The distinguishing feature here is the flame structure and motion change with time.

- The initial phase of the reactants: gas, liquid or solid.

Flames in engines are unsteady and turbulent. The different modes of burning in engines will be introduced in the following paragraphs, but the engines flames could already be classified into:

- **The conventional spark-ignition flame**: premixed, unsteady and turbulent flame. The fuel-air mixture through which the flame propagates is in the gaseous state.

- **The diesel engine combustion process**: predominantly an unsteady turbulent diffusion flame. The fuel is initially in the liquid phase.

Both these flames are extremely complicated because they involve the coupling of the complex chemical mechanism, by which fuel and oxidizer react to form products, with the turbulent convective transport process. The Diesel combustion process is even more complicated than the spark-ignition combustion process, because vaporization of liquid fuel and fuel-air mixing processes are involved too.

b. Different types of engine

i. 4-stroke engines vs. 2-stroke engines

4-Stroke Engine

A four-stroke engine, shown in Figure 65, also known as four-cycle, is an internal combustion engine in which the piston completes four separate strokes (intake, compression, power, and exhaust) during two separate revolutions of the engine's crankshaft, and one single thermodynamic cycle.

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[210] J.A. Barnard, J.N. Bradley, Flame and Combustion, 2nd. Edition, Chapman and Hall, 1985

[211] John B. Heywood, “Internal Combustion Engine Fundamentals”, Mc Graw-Hill Book Co, 1988

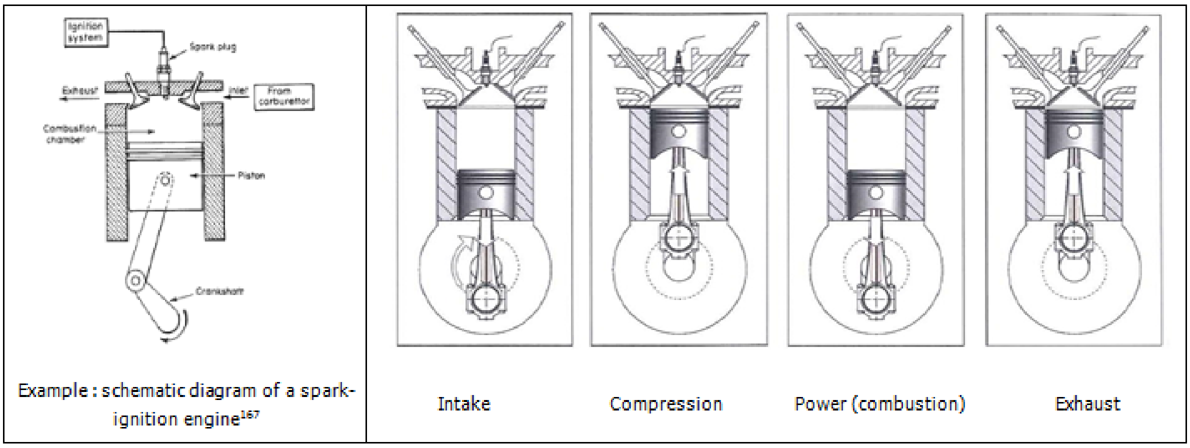


Figure 65 - 4-stroke engine cycle

The cycle begins at Top Dead Centre (TDC), when the piston is at its upper position. A cycle refers to the full travel of the piston from TDC to Bottom Dead Centre (BDC – lower position of the piston) [212]:

- **Intake stroke (or induction stroke):** the piston descends from the top of the cylinder to the bottom of the cylinder, reducing the pressure inside the cylinder. A mixture of fuel and air, or just air in a diesel engine, is forced by atmospheric (or greater) pressure into the cylinder through the intake port. The intake valve(s) then close.

- **Compression stroke:** with both intake and exhaust valves closed, the piston returns to the top of the cylinder compressing the air, or fuel-air mixture into the combustion chamber of the cylinder head.

- **Power stroke (combustion):** this is the start of the second revolution of the engine. While the piston is close to TDC, the compressed air/fuel mixture in a gasoline engine is ignited, usually by a spark plug, or fuel is injected into the Diesel engine, which ignites due to the heat generated in the air during the compression stroke. The resulting massive pressure from the combustion of the compressed fuel/air mixture forces the piston back down toward bottom dead center.

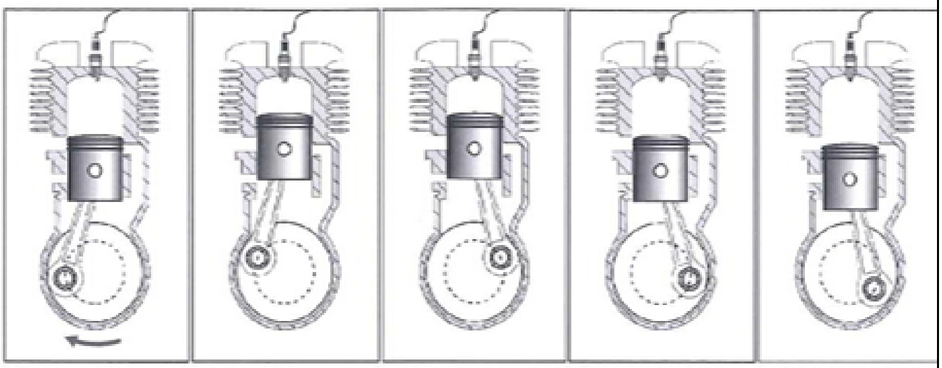
- **Exhaust stroke:** the piston returns to TDB while the exhaust valve is open. This action evacuates the burnt products of combustion from the cylinder by expelling the spent fuel-air mixture out through the exhaust valve(s).

Four-stroke engines can perform either on Diesel cycle or Otto cycle combustion mode and are usually used in passenger cars, HD trucks, light ships and other vessels.

2-Stroke Engine

A two-stroke engine, shown in Figure 66, is an internal combustion engine that completes the process cycle in one revolution of the crankshaft. This is accomplished by using the beginning of the compression stroke and the end of the combustion stroke to perform simultaneously the intake and exhaust functions.

[212] IFP training, 2010



Cylinder	End of transfer / Exhaust	Compression	Power	Start of Exhaust	Exhaust / Transfer
Crankcase	Transfer	Start of intake	End of intake	Compression	Start of Transfer

Figure 66 - 2-stroke engine cycle

The two stroke engine employs both the crankcase and the cylinder to achieve all the elements of the Otto cycle in only two strokes of the piston[213]:

- **Intake stroke:** The fuel/air mixture is first drawn into the crankcase by the vacuum that is created during the upward stroke of the piston.
- **Crankcase compression**: During the downward stroke, the poppet valve is forced closed by the increased crankcase pressure. The fuel mixture is then compressed in the crankcase during the remainder of the stroke.
- **Transfer/Exhaust:** Toward the end of the stroke, the piston exposes the intake port, allowing the compressed fuel/air mixture in the crankcase to escape around the piston into the main cylinder. This expels the exhaust gasses out the exhaust port, usually located on the opposite side of the cylinder. Unfortunately, some of the fresh fuel mixture is usually expelled as well.
- **Compression:** The piston then rises, driven by flywheel momentum, and compresses the fuel mixture. At the same time, another intake stroke is happening beneath the piston.
- **Power:** At the top of the stroke, the spark plug ignites the fuel mixture. The burning fuel expands, driving the piston downward, to complete the cycle. At the same time, another crankcase compression stroke is happening beneath the piston.

Since the two stroke engine fires on every revolution of the crankshaft, a two stroke engine is usually more powerful than a four stroke engine of equivalent size. This, coupled with their lighter, simpler construction, makes the two stroke engine popular in chainsaws, line trimmers, outboard motors, snowmobiles, jet-skis, light motorcycles, and model airplanes. Unfortunately, most two stroke engines are inefficient and are terrible polluters due to the amount of unspent fuel that escapes through the exhaust port.

Two-stroke engines can also be used for specific ship applications (example: cargo or tankers). Usually 2-stroke engines are spark-ignited engines, but for this specific application, the Diesel mode is used.

[213] IFP training 2010

ii. The spark-ignition (SI) vs. Diesel 4-stroke engine

Combustion in engines is based on the different type of flames:

- The conventional spark-ignition flame: premixed, unsteady and turbulent flame. The fuel-air mixture is in the gaseous state and is ignited with a spark-plug. The flame front propagates through the mixture.

- The Diesel engine combustion process: predominantly an unsteady turbulent diffusion flame. The fuel is initially in the liquid phase. Aerodynamic motion allows the liquid to evaporate and mix with air. The ignition is allowed by the temperature and pressure conditions in the combustion chamber.

Figure 67 presents a comparison of SI and Diesel engines, and their characteristics.

	Spark-ignition engine	Diesel engine
Indirect injection	In the admission pipe (~ 3 bars)	In a pre-combustion chamber (~ 400 bars)
Direct injection	In the combustion chamber (~ 100 to 200 bars)	In the piston bowl (~ 1600 bars)
Characteristics of combustion	Homogeneous combustion Ignition with a spark-plug Auto-ignition avoided at the end of the combustion (knock risks)	Heterogeneous combustion Ignition by compression Look for auto-ignition at the beginning of the combustion
Typical equivalence ratio	$\Phi=1$ (stoichiometry), $\Phi<1$ (lean) excess of air	$\Phi<1$ lean (excess of air)
Octane (methane) / cetane numbers	High octane number to maximize the auto-ignition time (analogy with methane number for gaseous fuels)	High cetane number to minimize the auto-ignition time
Typical fuels	Gasoline, ethanol, natural gas…	Diesel, fuel oil, …

Figure 67 - Comparison of SI and Diesel engine

c. Knock

Different abnormal combustion exists, but two of the major phenomena are knock and surface ignition. These phenomena are of concern because when severe, they can cause major engine damage, and even if not severe, they are regarded as an objectionable source of noise by the engine or vehicle operator[214] .

- **Knock** is the name given to the noise which is transmitted through the engine structure when essentially spontaneous ignition of a portion of end-gas (the fuel, air, residual gas, mixture ahead of the propagating flame…) occurs. When this abnormal combustion takes place, there is an extremely rapid release of much of the chemical energy in the end-gas, causing very high local pressures and the propagation of pressure waves of substantial amplitude across the combustion chamber.

- **Surface ignition** is ignition of the fuel-air mixture by a hot spot on the combustion chamber walls such as an overheated valve or spark-plug, or glowing combustion chamber deposit. It can occur before the occurrence of the spark (pre-ignition) or

[214] John B. Haywood, "Internal Combustion Engine Fundamentals"' Mc Graw-Hill Book Co, 1988

after (post-ignition). Following surface ignition, a turbulent flame develops at each surface-ignition location and starts to propagate across the chamber in an analogous manner to what occurs with normal spark ignition.

Because the spontaneous ignition phenomenon that causes knock is governed by the temperature and pressure history of the end gas, and therefore by the phasing and rate of development of the flame, various combinations of these two phenomena (knock and surface ignition) can occur. Figure 68 shows a photograph of a badly damaged piston showing the effects of long term engine knock and charts of crank angle traces with normal, light and heavy knock [215],[216].

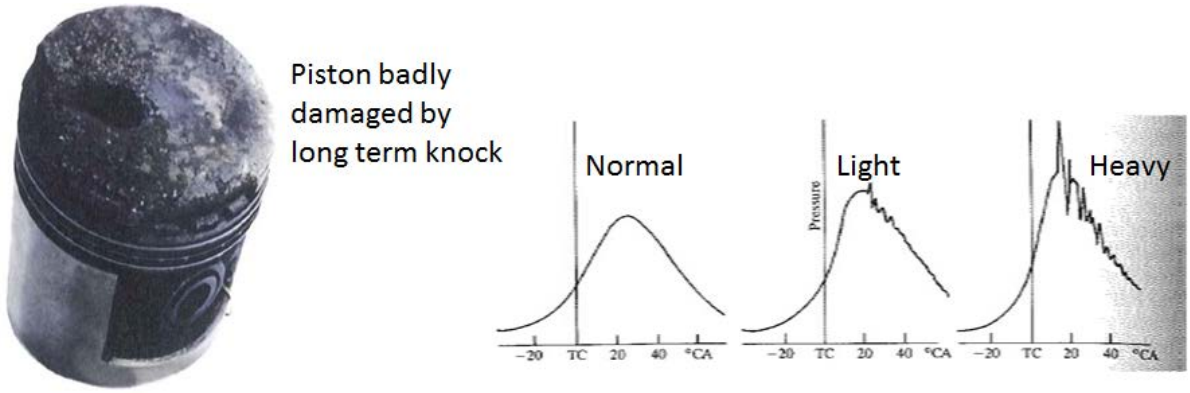


Figure 68 - Piston damage long term knock /cylinder pressure vs. crank angle traces

d. Exhaust Gas Recirculation

In internal combustion engines, exhaust gas recirculation (EGR) is a nitrogen oxide (NOx) emissions reduction technique. EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders and lead to lower combustion chamber temperatures. Because NOx forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature, EGR enables reduction of the amount of NOx the combustion generates[217].

e. Turbo charged engines

The engine performance parameters are proportional to the mass of air inducted per cycle. This depends primarily on inlet air density. Thus the performance of an engine of given displacement can be increased by compressing the inlet air prior to entry to the cylinder. Methods for achieving higher inlet air density in the gas exchange are mechanical supercharging, turbocharging and pressure-wave supercharging.

f. Impact of altitude

As altitude increases, air density and atmospheric pressure decrease. **At roughly 1500 m altitude, for example, air density in a standard atmosphere is 14% less than at sea level**. The main consequence on engine will be the decrease of horsepower, as less air will be drawn into the cylinders per cycle. Since power is directly related to the actual mass of charge burnt into the cylinder at every power stroke, then engine power is reduced.

[215] IFP training, 2010
[216] John B. Haywood, "Internal Combustion Engine Fundamentals"' Mc Graw-Hill Book Co, 1988
[217] R. Broman, P. Stallhammer, L. Erlandsson, "Enhanced emission performance and fuel efficiency for HD methane engines", International Energy Agency, AVL, 2010

Few solutions exist to maintain the engine power output while the altitude increases:

- **Turbo- or Supercharging:** enables the engine rated power above sea-level to be maintained. With a turbocharged engine there will still be some power loss with the engine operating at high altitudes, but the loss will be far less than if the engine breathing depends only on natural aspiration[218]. As can be seen on the Figure 69 at 1000 m the power loss is only 8% compared with the naturally aspirated engine where the power decrease is roughly 13%.
    - The power output and mechanical efficiencies of a supercharged engine are higher than its naturally aspirated counterpart;
    - A mechanically supercharged engine almost always has specific fuel consumption higher than its naturally aspirated counterpart.
- **The use of a specific fuel:** altitude decreases the engine octane requirements because of the change in air pressure. The higher elevations have a lower level of air pressure, which means that an engine needs **less octane to properly fire due to the lower ambient pressure.** In certain states, such as Colorado where the altitude is generally above 1,500m in the mountain areas, 85 octane gasoline is sold, while in lower elevations 87 octane is the lowest sold.
- Technical tune : high altitude carburettor jets, reduce the load on the engine by reducing pressure (larger nozzle size) or volume (change pulleys)

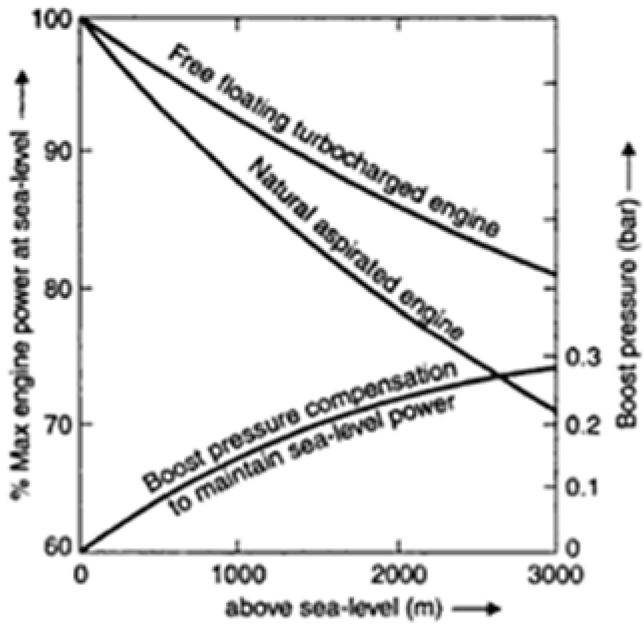


Figure 69 - Effect of altitude on engine power for aspirated and turbocharged engines

[218] A text book of automobile engineering, R.K. Rajput, 2007 – Technology & Engineering – 944 pages

Appendix H. LNG Quality and Methane Number

A number of processes are currently on-going looking into gas quality specifications (CEN, ISO, etc.). It is very important to note that the Wobbe index is not the only gas quality parameter that affects equipment performance. For gas engines, the combustion behavior of natural gases is of particular importance. A key parameter in this context is the Methane Number (MN). It characterizes the tendency to knock of fuel gases. The Wobbe index is by no means a proper measure for the knock resistance of gaseous fuels. As soon as inert gases such as N_2 and CO_2 are present in a fuel, large deviations from fuel gas without inert gases occur. Even gases without inert gases and a constant Wobbe index can produce deviations in knock resistance.

a. Methane Number (MN) as a Parameter for Gas Quality Specifications

Methane Number describes the behavior of fuel gases in internal combustion engines and it is the measure of resistance of a gas fuel to knock. Detonation is known as engine knock and can led to a serious loss in power and damage to the engine.

Knock is due to auto-ignition of the end-gas ahead of the propagating flame. When this auto-ignition takes place in the cylinder, the chemical energy contained in the end gas is released very rapidly. Beyond a certain burn rate, it causes the propagation of shock waves across the combustion chamber that is then forced to resonate at its natural frequencies. This can lead to high frequency shock waves hitting the cylinder walls and causing irreversible damages.

Thermal efficiency of an internal explosion standard engine increases with compression ratio. If the compression ratio is too high, it is possible that the phenomenon of detonation could occur. This is produced due to the auto-ignition of the mixture.

The methane number means the mole fraction expressed as a percentage of methane in a methane/hydrogen mixture which, in a test engine under standard conditions, has the same tendency to knock as the fuel gas to be examined.

Pure methane is used as the knock resistance reference fuel, i.e. the methane number of pure methane is assigned the value of 100. Pure hydrogen is used as the knock sensitive reference fuel, methane number of pure hydrogen is assigned the value of zero.

When natural gas is used to run an internal combustion engine, quality variations can induce knock occurrence and lead to increasing emissions and decreasing engine efficiency.

b. Methane Number Calculation Methods

The Methane Number is not a thermodynamic property of gas so no Equation of State (EoS) can be used to calculate it. There are different calculation methods, which do not produce the same MN result:

- GRI Method (Gas Research Institute): This method determines the MN from Motor Octane Number (MON). Two mathematical relations were developed to estimate the MON rating of natural gas:

i. Linear coefficient relation:

$$MON = (137{,}78 \cdot x_{methane}) + (29{,}948 \cdot x_{ethane}) + (-18{,}193 \cdot x_{propane}) + (-167{,}062 \cdot x_{butane}) + (181{,}233 \cdot x_{CO_2}) + (26{,}994 \cdot x_{N_2})$$

where x is the mole fraction of the corresponding components methane, ethane, propane, butane, CO_2 and N_2.

ii. Hydrogen/carbon ratio relation:

MON = -406,14 + (508,04•fH/C) + [173,55•(fH/C)2] + [20,17•(fH/C)3]

where fH/C is the ratio of hydrogen atoms to carbon atoms.

Finally, the MN is calculated from the MON. The correlation between MON and MN is not quite linear, and as a result, the equations are not exact inverses of each other:

MON = 0,679•MN + 72,3 and MN = 1,445•MON – 103,42

According to ISO/DTR 22302 since there are two equations for MON, two MNs of the gas can be calculated. The two results should both be reported in the calculation report. For the same gas, if the difference between the two MNs is more than 10, than this is extraordinary. It means the composition of the gas is unusual, for example, the gas may be diluted by LPG gas, or the gas may contain more nitrogen or CO_2. If the difference between the two MN results is more than 6, the user should consider that the two MNs are in doubt, than a test method should be utilized to determine MN for the gas.

- AVL Method (Anstalt für Verbrennungskraftmaschinen List): This method, developed in 1970s, is based on experimental measures of different gas mixtures. The procedure consists on dividing the original composition into three partial ternary mixtures. The MN is obtained by a combination of the MN of each sub-mixture. A limit in this calculation is that all hydrocarbons longer than butane have to be represented by butane.

- Different AVL implementations: Several companies have developed their own methods based on AVL data and have included corrections to take into account some components not included in the original procedure (DGC, E-ON Ruhrgas, GL Noble Denton,…).

- Engine manufacturer methods: Moreover, several engine manufacturers have developed their own MN method to be used in their engines (MWM, Wärtsilä, Cartepillar, …).

Normative references

The above-mentioned methods are described in the following standards:

- The GRI method is published in ISO standard 15403-1 Natural gas - Natural gas for use as a compressed fuel for vehicles - Part 1: Designation of the quality, and is included in draft ISO standard under development ISO/DTR 22302 Natural gas – Calculation of methane number.

- The AVL method is described in a normative Annex in the standard DIN 51624 Automotive Fuels -Compressed Natural Gas - Requirements And Test Methods, and it is mentioned in ISO 15403 and ISO/DTR 22302 as an alternative procedure to the GRI method.

Furthermore, there is an interest to include limits for the methane number in the regulations. For this reason, several works on international level (CEN, ISO, etc.) are underway with the aim of specifying one unique standard method.

The calculated methane number of typical natural gas/LNG mixtures

Figure 70 and Figure 71 show the methane number for several LNG's and NG's calculated according to the different methods explained above.

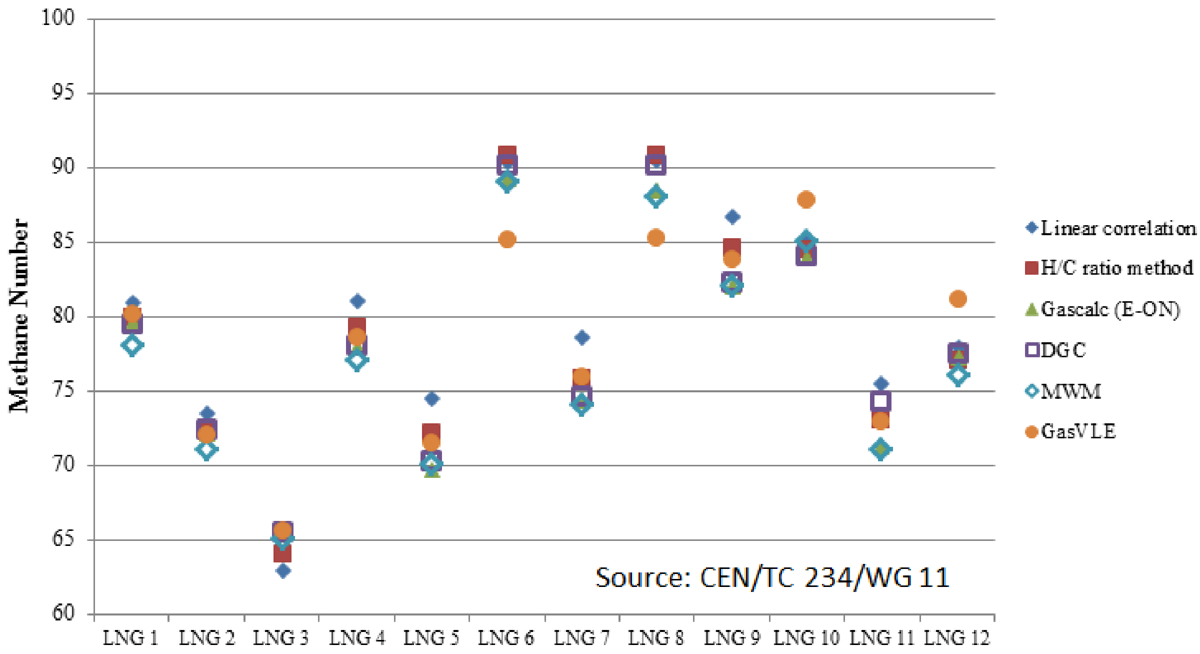


Figure 70 - Methane Number of different LNGs

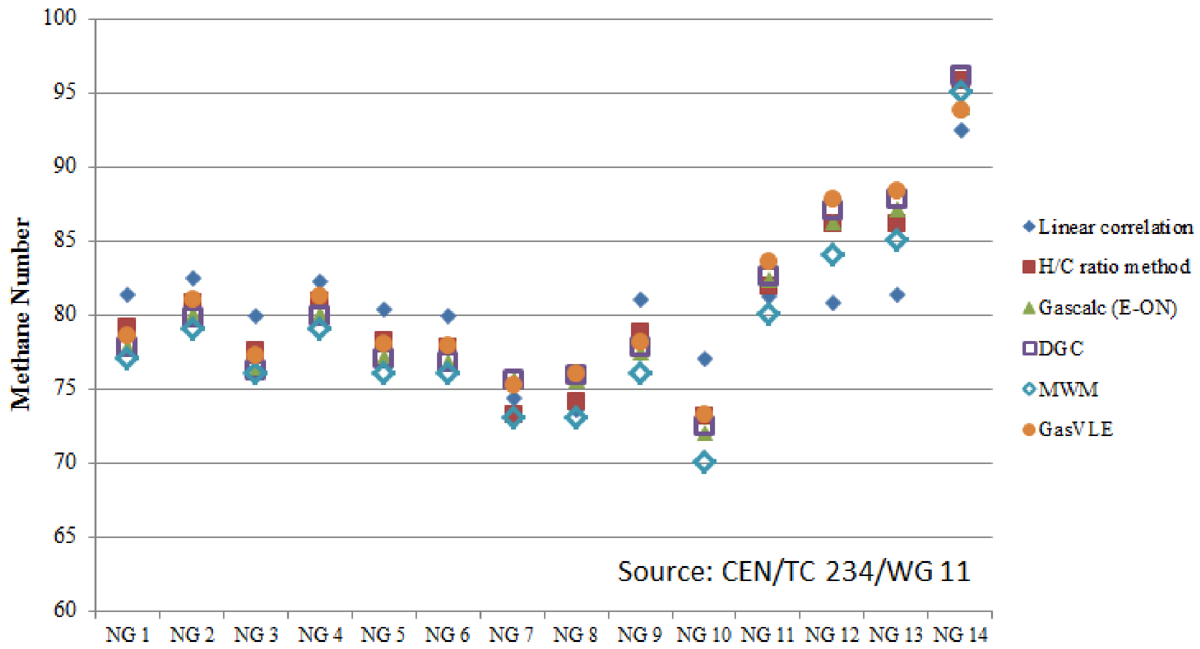


Figure 71 - Methane Number of different NGs

Methane number range and impact on LNG Supplies

Liquefied natural gas is imported from diverse sources all over the world. LNG compositions vary substantially and consequently their methane number. Therefore not all LNG is equally suitable for all engines.

c. Technical implications

Engines are characterized by the type of combustion: spark-ignited or compression-ignited, also known as diesel.

The spark-ignited engine is based on the Otto cycle, and uses a spark plug to ignite an air-fuel mixture injected at the top of a cylinder. In the Otto cycle, the fuel mixture does not get hot enough to burn without a spark, which differentiates it from the Diesel cycle. In diesel engines, air is compressed until the temperature rises to the auto-ignition temperature of the fuel. As the fuel is injected into the cylinder, it immediately combusts with the hot compressed air and expanding combustion gases push the piston to the bottom of the cylinder.

In spark-ignited engines, premixing of air with the fuel to produce “lean” conditions (more air than is needed for combustion) has the effect of lowering the combustion temperature and impeding NOx formation.

New engine designs have been developed to take advantage of the diesel process while maintaining the benefits of “lean” burning. Dual-fuel (DF) engines are designed with the ability to burn both liquid and gaseous fuels. When operating in gas mode, the gaseous fuel is premixed with air, injected just after the compression stroke and ignited by a pilot fuel flame. In this process, the pilot fuel flame acts a “spark plug” to ignite the lean gas-air mixture. DF engines retain the ability to use a backup liquid fuel when gas supply is interrupted.

Both engines spark-ignited or Dual-fuel are influenced by gas quality because the gas is injected before the combustion, Figure 72.

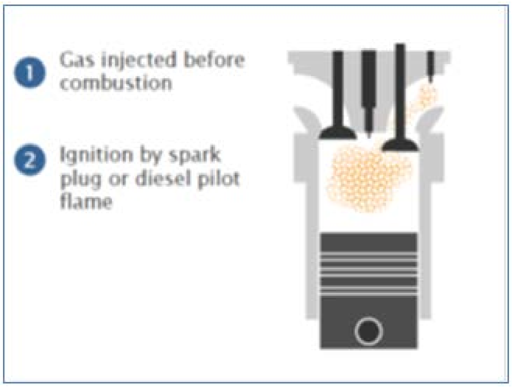


Figure 72 - LNG Engine concepts: Premixed combustion

Source: LNG Fuel Forum, Stockholm 21. September 2011

On the other hand, new LNG engine concepts as Gas-Diesel engines (GD) utilize highly compressed gas which is injected after a liquid pilot fuel is ignited. This engine allows the use of lower quality gas because the engine process is little influenced by gas quality variations, Figure 73.

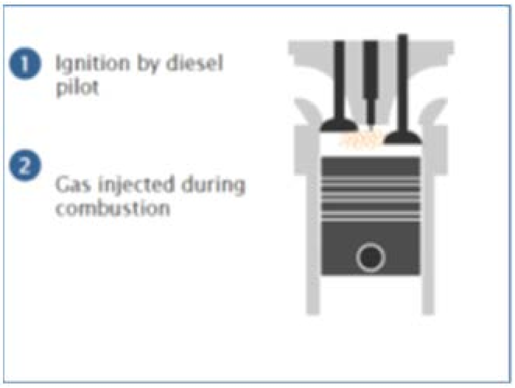


Figure 73 - LNG Engine concepts: high pressure injection

Source: LNG Fuel Forum, Stockholm 21. September 2011

Because of environmental and economic concerns, engines are set with high compression ratios. Consequently, optimal operating conditions are generally very close to those of knock occurrence.

The business sector evaluating engine performance encourages use of the Methane Number in gas quality specifications. The gas specifications proposed in the EASEE-gas Common Business Practice (EASEE-gas CBP) recommends a Methane Number higher than 65, and National Gas Rules in the U.S recommends a value higher than 75. A Methane Number of approximately 80 or higher is recommended by several dual-fuel engine manufacturers (EUROMOT: association of engine manufacturers in Europe). However, the quality of most LNG supplies in the world has a methane number lower than 80, Figure 74.

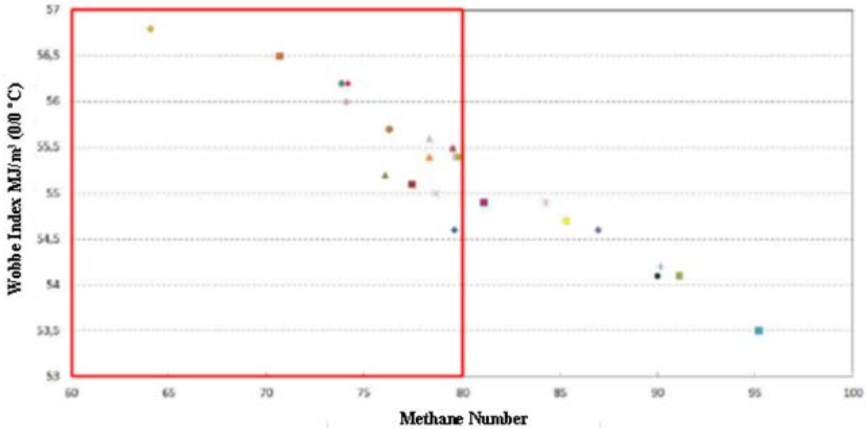


Figure 74 - Methane Number (AVL Method) vs. Wobbe Index for LNG Sources, 2011

Source: GIIGNL 2011, The LNG Industry

Manufacturers can only optimize engines if they know which minimum methane number the engine will have to handle. The knock problem for engines could appear when the MN of the gas fuel is below to the one used in the engine design or adjustment.

If MN is high means high knock resistance and good combustion, high efficiencies and thus low CO_2 emissions. If MN are too low, knock may cause engine damage, lead to loss of efficiency and performance, higher fuel consumption, higher emissions and potentially dangerous situations.

For engine manufacturers and operators the higher the MN the better. On the other hand, one must be realistic and may not exclude significant amounts of natural gases and LNG's with low MN.

d. Treatment for increasing methane number

As a method for creating an adequate gas quality, the engine sector prefers removal of part of the higher hydrocarbons to other proposals such as ballasting with CO_2 or N2. Nitrogen does not help to improve the knock resistance while CO_2 and N2 affect the flame speed and the ignitability in a negative way. In addition, CO_2 tends to decrease fuel efficiency. Ballasting with air is excluded because of the limit for oxygen in the gas.

Therefore, to increase the Methane Number excessive amounts of hydrocarbons higher than methane should be stripped off the gas. This valuable by-product can subsequently be delivered to refineries as a feedstock for liquid fuels.

Appendix I. LNG Codes and Standards

Included among published standards are:

- NFPA 52 Vehicular Gaseous Fuel Systems Code, 2010
- NFPA 59A Standard for the Production, Storage and Handling of LNG, 2009 edition
- SAE J2343 Recommended Practices for LNG Powered Heavy-Duty Trucks, 2008 Edition
- SAE J2645 LNG Vehicle Metering and Dispensing Systems, 2009 Edition
- SAE J1740 LNG Vehicular Fueling Connectors - *Status: On hold waiting for consensus building between manufacturers*
- SAE J2699 LNG Fuel Quality - *Status: Out for final vote, to be published in 2011*
- SAE J2700 LNG Fuel Tank - *Status: Task group to be reformed in 2011*
- ASME Section VIII Division 1 Boiler and Pressure Vessel Code
- ASME B31.3 Process Piping
- 33CFR Part 127 Waterfront Facilities Handling LNG and Liquefied Hazardous Gas
- 49CFR 178.57 4L Welded Cylinders Insulated
- 49CFR Part 193 Liquefied Natural Gas Facilities: Federal Safety Standards
- 49CFR 178.338 (MC338) Insulated Cargo Tank Motor Vehicle
- California Title 8, Division 1, Chapter 4.1 LNG Storage Tanks
- California Title 13, Division 2, Chapter 4.2 LNG Fuel Systems
- API 620 Design and Construction of Large, Welded Low Pressure Storage Tanks
- NFPA30A – Code for Motor Fuel Vehicle Dispensing Facilities and Repair Garages 2010 Edition.
- ISO PC252 (ISO16924, ISO 12617, ISO 12614, and ISO 12991), Natural Gas Fuelling Stations for Vehicles

LNG Stations for fuelling Vehicles, Scope: Standardization in the field of design, construction and operation of natural gas fuelling stations for vehicles; including equipment, safety devices and maintenance. The following international standards are directly related to bunkering LNG or the transfer of LNG and can give guidance for the further development of rules and standards for bunkering LNG fuelled vessels:

- ISO 28460 LNG Ship-shore Interface and Port Operations;
- IMO IGF Code draft;
- SIGTTO LNG STS Transfer Guide;
- SIGTTO ESD Systems;
- BS EN 1160 Properties and Materials for LNG;

Further standards and guidelines define the requirements for components of LNG terminals and could be used as reference for a LNG bunker guideline to be developed:

- IMO IGC Code
- EN 1474 part 1 LNG Transfer Arms;
- EN 1474 part 2 LNG Hoses;
- EN 1474 part 3 Offshore Transfer Systems;
- EN 1473 Design of Onshore LNG Terminals;
- NFPA 302 Fire protection standard for pleasure and commercial motor craft;

- NFPA 59A Storage and Production of LNG;
- BS EN 13645 Installations and equipment for LNG – Design of onshore installations with a storage capacity between 5 & 200 tonnes;
- BS 4089: 1999 Metallic Hose Assemblies for Liquefied Petroleum Gases and Liquefied Natural Gases;
- EU Directive 96/82/EC (Seveso II);
- SIGTTO/OCIMF Gas Carrier Manifold Guidelines;
- OCIMF/IAPH/ICS International Oil Tanker Terminal Safety Guide (ISGOTT);
- OCIMF Mooring Equipment Guidelines;
- IEC 60092 - 502 – Electrical Installations in Tankers –Special Features;
- ATEX Directive 94/9/EC (ATEX 95);
- ATEX Directive 99/92/EC (ATEX 137);
- European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).

In 2010, NFPA released an updated version of NFPA 52: Vehicular Gaseous Fuel Systems Code. The document provides a detailed set of codes and standards for all vehicular gaseous fuel systems, including detailed sections on LNG vehicles, fueling stations and fire protection. This document provides clear standards for:

- The performance, installation, inspection, and testing of LNG fuel supply systems for vehicle engines.
- The performance, sitting, construction, installation, spill containment, and operation of containers, pressure vessels, pumps, vaporization equipment, buildings, structures and associated equipment used for the storage and dispensing of LNG and L/CNG as engine fuel for vehicles of all types.
- LNG fire protection, personnel safety, security, LNG fueling facilities and training for LNG vehicles, and warning signs.

The Environmental, Health, and Safety (EHS) Guidelines are technical reference documents with general and industry specific examples of Good International Industry Practice[219]. When one or more members of the World Bank Group are involved in a project, these EHS Guidelines are applied as required by their respective policies and standards. These industry sector EHS guidelines are designed to be used together with the General EHS Guidelines document, which provides guidance to users on common EHS issues potentially Applicable to all industry sectors.

The EHS Guidelines for Liquefied Natural Gas (LNG) Facilities include information relevant to LNG base load liquefaction plants, transport by sea, and regasification and peak shaving terminals. For coastal LNG facilities including harbors, jetties and in general coastal facilities (e.g. coastal terminals marine supply bases, loading / offloading terminals), additional guidance is provided in the EHS Guidelines for Ports, Harbors, Terminals and LNG trucks. For EHS issues related to vessels, guidance is provided in the EHS Guidelines for Shipping. Issues related to LPG/Condensate production and storage in Liquefaction plant is not covered in this report.

[219] http://www.ifc.org/wps/wcm/connect/87e7a48048855295ac04fe6a6515bb18/Final+-+LNG.pdf?MOD=AJPERES

Appendix J. DNV-GL Report on Bunkering in Australia, Table of Contents excerpt

LNG FUEL BUNKERING IN AUSTRALIA INFRASTRUCTURE AND REGULATIONS

(Public version of Partners' internal report)

Joint Industry Project team focusing on the Australian OSV and Tugs' market

Table of Contents, Chapter 6:

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