

Energy Economics Research



at the Bureau of Economic Geology

Bureau of Economic Geology, Scott W. Tinker, Director
Jackson School of Geosciences, The University of Texas at Austin



INTRODUCTION TO LNG

An overview on liquefied natural gas (LNG),
its properties, the LNG industry,
and safety considerations



Bureau of Economic Geology, Jackson School of Geosciences
The University of Texas at Austin

Michelle Michot Foss, Ph.D.
Chief Energy Economist and CEE Head
1801 Allen Parkway
Houston, Texas 77019
Tel 713-654-5400 Fax 713-654-5405
energyecon@beg.utexas.edu
www.beg.utexas.edu/energyecon/lng

June 2012

© Center for Energy Economics

No reproduction, distribution or attribution without permission.

Table of Contents

INTRODUCTION TO LNG	1
EXECUTIVE SUMMARY	3
Introduction.....	5
Overview.....	6
What Is LNG?	6
Does the U.S. Need LNG?.....	8
Is LNG a Competitive Source of Natural Gas?	9
Brief History of LNG.....	10
Composition of Natural Gas and LNG	14
The LNG Value Chain.....	15
How Much Does LNG Cost?.....	21
Is LNG a Safe Fuel?.....	26
APPENDIX 1: CONVERSION TABLE	32
APPENDIX 2: OTHER FUEL TERMINOLOGIES.....	33
APPENDIX 3: GLOSSARY OF TERMS'	36

INTRODUCTION TO LNG¹

EXECUTIVE SUMMARY

This briefing paper is the first in a series of articles that describe the liquefied natural gas (LNG) industry and the growing role LNG may play in the U.S. energy future. This paper's first edition was published in January 2003. It introduces the reader to LNG and briefly touches on many of the topics relating to the LNG industry. The second and third papers, ***LNG Safety and Security*** and ***The Role of LNG in North American Natural Gas Supply and Demand***, followed in October 2003 and September 2004 accordingly. All of these reports, with supplemental information, were compiled in a complete online fact book, ***Guide to LNG in North America***, www.beg.utexas.edu/energyecon/lng.

LNG is the liquid form of the natural gas people use in their homes for cooking and heating. To engage in international LNG trade, energy companies must invest in the LNG value chain, which is a number of different operations that are highly linked and dependent upon one another. Natural gas can be economically produced and delivered to the U.S. as LNG within a price range of about \$2.50-3.50 to \$4.50-5.50 per million Btu (MMBtu) at Henry Hub in Louisiana, depending largely on shipping cost. (Please refer to [APPENDIX 1: CONVERSION TABLE](#) for information on units and measure used in our papers.)

LNG has been safely handled for many years. The industry is not without incidents but it has maintained an enviable safety record, especially over the last 40 years. Worldwide, there are 25 LNG export (liquefaction) terminals, 91 import (regasification) terminals, and 360 LNG ships altogether handling approximately 220 million metric tons of LNG every year. LNG is also used for domestic storage and delivery. There are currently about 260 peakshaving and LNG storage facilities worldwide, some operating since the mid-60s. The U.S. has the largest number of LNG facilities in the world. There are 121 active LNG facilities spread across the U.S. with a higher concentration of the peakshaving and storage facilities located in the northeastern region.

The need for additional natural gas supplies during the late 1990s-2000 time frame, including the reopening of existing LNG facilities at Cove Point, Maryland and Elba Island, Georgia focused public attention on the safety and security of LNG import facilities. The safe and environmentally sound operation of these facilities, both ships and terminals, and the protection of these facilities from terrorist activities or other forms of accident or injury are a concern and responsibility shared by operators as well as federal, state, and local jurisdictions across the U.S. Onshore

¹ This publication was supported by a research consortium, ***Commercial Frameworks for LNG in North America***. Sponsors of the consortium were BP Energy Company-Global LNG, BG LNG Services, ChevronTexaco Global LNG, Shell Gas & Power, ConocoPhillips Worldwide LNG, El Paso Global LNG, ExxonMobil Gas Marketing Company, Tractebel LNG North America/Distrigas of Massachusetts. The U.S. Department of Energy-Office of Fossil Energy provides critical support and the Ministry of Energy and Industry, Trinidad & Tobago participates as an observer. The report was prepared by CEE researchers Michelle Michot Foss, Fisoye Delano, Gürcan Gülen, and Dmitry Volkov. Peer reviews were provided by university faculty colleagues and outside experts.

LNG import facilities are industrial sites and, as such, are subject to all rules, regulations and environmental standards imposed by the various jurisdictions. These same or similar concerns apply to natural gas storage, pipeline transportation and distribution, and our daily use of natural gas as customers and consumers.



INTRODUCTION

This briefing paper is the first in a series of articles that describe the liquefied natural gas (LNG) industry – technology, markets, safety, security and environmental considerations and the growing role LNG may play in the nation's energy future. This paper also introduces the reader to LNG and briefly touches on many of the topics relating to the LNG industry. The second paper, ***LNG Safety and Security***, deals with the safety and security aspects of LNG operations in more detail. A third paper, ***The Role of LNG in North American Natural Gas Supply and Demand*** provides an in-depth analysis of why additional LNG will be needed to meet U.S. energy demand in the near future. All three papers, plus supplemental information, are included in a complete fact book, ***Guide to LNG in North America***.

LNG is the liquid form of the natural gas people use in their homes for cooking and heating. Natural gas is also used as fuel for generating electricity. Natural gas and its components are used as raw material to manufacture a wide variety of products, from fibers for clothing, to plastics for healthcare, computing, and furnishings. Natural gas makes up about one-fourth of all energy consumed in the United States each year. The most common use of LNG in the U.S. is for “peakshaving.” Peakshaving is a way local electric power and gas companies store gas² for peak demand that cannot be met via their typical pipeline source. This can occur during the winter heating season when cold fronts move through or when more natural gas is needed to generate electric power for air conditioning in the summer months. The utility companies liquefy pipeline gas when it is abundant and available at off-peak prices, or they purchase LNG from import terminals supplied from overseas liquefaction facilities. When gas demand increases, the stored LNG is converted from its liquefied state back to its gaseous state, to supplement the utility's pipeline supplies. LNG is also currently being used as an alternative transportation fuel in public transit and in vehicle fleets such as those operated by many local natural gas utilities companies for maintenance and emergencies.

² We use the term “gas” as shorthand for “natural gas.” In the U.S., we often refer to gasoline, the most heavily used vehicle transportation fuel, as “gas,” but gasoline is manufactured from crude oil, a different fossil fuel that is often found together with natural gas in underground reservoirs.

Natural gas comes from reservoirs beneath the earth's surface. Sometimes it occurs naturally and is produced by itself (non-associated gas), sometimes it comes to the surface with crude oil (associated gas), and sometimes it is being produced constantly such as in landfill gas. Subsurface natural gas is a fossil fuel, meaning that it is derived from organic material deposited and buried in the earth millions of years ago. Other fossil fuels are coal and crude oil. Together crude oil and gas constitute a type of fossil fuel known as "hydrocarbons" because the molecules in these fuels are combinations of hydrogen and carbon atoms.

The main component of natural gas is methane. Methane is composed of one carbon and four hydrogen atoms (CH_4). When natural gas is produced from the earth, it includes many other molecules, like ethane (used for manufacturing), propane (which we commonly use for backyard grills) and butane (used in lighters). We can find natural gas in the U.S. and around the world by exploring for it in the earth's crust and then drilling wells to produce it. Natural gas can be transported over long distances in pipelines or as LNG in ships across oceans. Natural gas can be stored until needed in underground caverns and reservoirs or as LNG in atmospheric tanks. Transportation of LNG by truck takes place in the United States on a limited basis. Such transportation is more common in countries without a national pipeline grid but truck transport could grow in the United States if LNG niche markets, such as LNG vehicular fuel, expand

OVERVIEW

What Is LNG?

Liquefied natural gas (LNG) is natural gas that has been cooled to the point that it condenses to a liquid, which occurs at a temperature of approximately -256°F (-161°C) and at atmospheric pressure. Liquefaction reduces the volume by approximately 600 times³ thus making it more economical to transport between continents in specially designed ocean vessels, whereas traditional pipeline

³ LNG production, shipping, and storage are generally reported in metric tons and cubic meters whereas natural gas is generally presented in standard cubic feet or standard cubic meters. One metric ton of LNG is equivalent to 48.7 thousand cubic feet of gas (Mcf). Note: exact conversion factor depends on gas molecular weight. A conversion table with more units is included in Appendix 1.

transportation systems would be less economically attractive and could be technically or politically infeasible. Thus, LNG technology makes natural gas available throughout the world.

To make LNG available for use in a country like the U.S., energy companies must invest in a number of different operations that are highly linked and dependent upon one another. The major stages of the **LNG value chain**, excluding pipeline operations between the stages, consist of the following.

- **Exploration** to find natural gas in the earth's crust and **production** of the gas for delivery to gas users. Most of the time natural gas is discovered during the search for oil.
- **Liquefaction** to convert natural gas into a liquid state so that it can be transported in ships.
- **Shipping** the LNG in special purpose vessels.
- **Storage and Regasification**, to convert the LNG stored in specially made storage tanks, from the liquefied phase to the gaseous phase, ready to be moved to the final destination through the natural gas pipeline system.

Liquefaction also provides the opportunity to store natural gas for use during high demand periods in areas where geologic conditions are not suitable for developing underground storage facilities. In the northeastern part of the U.S., which is a region lacking in underground storage, LNG is a critical part of the region's supply during cold snaps. In regions where pipeline capacity from supply areas can be very expensive and use is highly seasonal, liquefaction and storage of LNG occurs during off-peak periods in order to reduce expensive pipeline capacity commitments during peak periods.⁴

⁴ EIA: *U.S. LNG Markets and Uses*. June 2004.

Does the U.S. Need LNG?

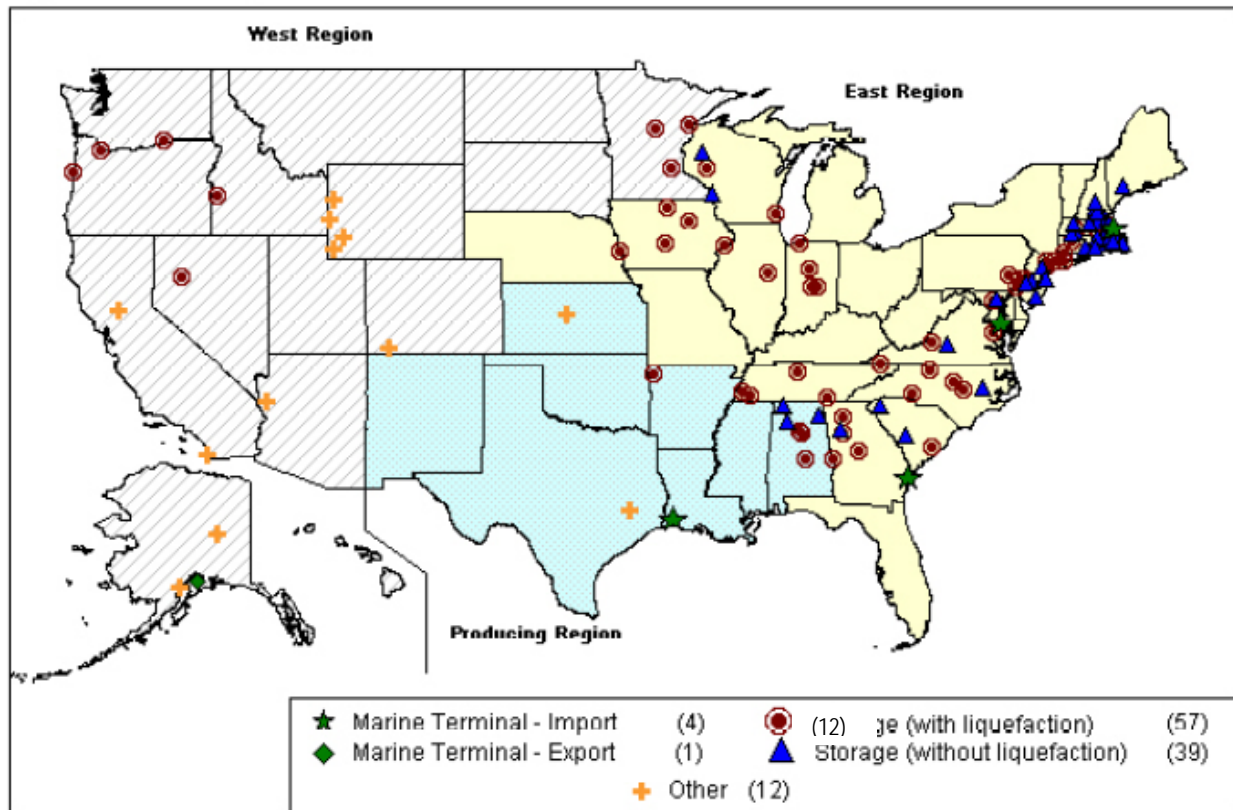
The demand for natural gas in the U.S. was boosted in the 1980s in part by the desire to diversify energy resources in the wake of global oil shocks⁵. Such demand has continued due to the clear environmental advantages of natural gas over other fossil fuels and its superior thermal efficiency when used in power generation. End use customers in the U.S. (residential, commercial, industrial, electric power, and vehicle transport) consumed about 22 trillion cubic feet or TCF of natural gas in 2011. Even with a rich domestic resource base and abundant supply, imported LNG plays a key role in helping to balance supply and demand and address seasonal swings.

Currently, LNG imports account for less than one percent of the total U.S. consumption of natural gas. There are at least 121 active LNG facilities in the United States, including marine terminals, storage facilities, and operations involved in niche markets such as vehicular fuel as shown in the figure below. Most of these facilities were constructed between 1965 and 1975 and were dedicated to meeting the storage needs of local utilities. Approximately 55 local utilities own and operate LNG plants as part of their distribution networks.⁶ Prior to 2002, four marine import terminals existed in the continental U.S. Since 2002, eight new import terminals (including three ship-based offshore systems) plus an onshore terminal in Atlantic Canada and two in Mexico have been built and put into operation, and three of the four original import terminals have been expanded. Information on the U.S. terminals is provided by the U.S. Federal Energy Regulatory Commission (FERC; <http://www.ferc.gov/industries/gas/indus-act/lng/exist-term.asp> and <http://www.ferc.gov/industries/gas/indus-act/lng/LNG-existing.pdf> for all North American terminals).

⁵ Schleede, Glenn R.: *Why Would an Electric Utility Want to Increase Dependence on Natural Gas?*, Contributed paper in *The Case for Natural Gas*: edited by Jacqueline Weaver, The Natural Gas Project, University of Houston, 1991.

⁶ EIA: *U.S. LNG Markets and Uses*. November 2002.

Figure 1. U.S. LNG Facilities⁷



Notes: Map excludes the import facility in Puerto Rico. Other includes: stranded utilities, vehicular fuel facilities, nitrogen rejection units and other special processing plants.

Sources: Energy Information Administration, Office of Oil and Gas, and industry sources.

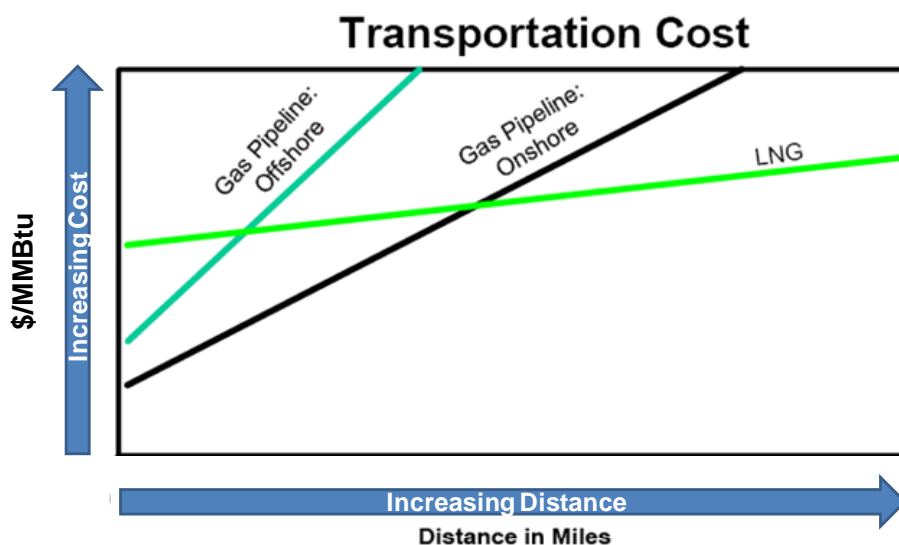
Is LNG a Competitive Source of Natural Gas?

Large reserves of natural gas have been found in areas for which there is no significant market. Such hydrocarbon reserves are stranded in North and West Africa (with significant new discoveries in Mozambique); South America and the Caribbean (Trinidad & Tobago has been one of the most important exporting countries to the United States); the Middle East (Qatar has become the largest exporter worldwide); and Indonesia, Malaysia, Northwestern Australia and Alaska. Natural gas is liquefied at these locations for shipping to countries where no indigenous supply exists or where pipeline shipments are prohibitive (such as Japan, Taiwan, Korea, and parts of Europe) and where seasonal or other needs are

⁷ Source: US LNG Markets and Users: June 2004 update. EIA, 2004. Available at http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2004/lng/lng2004.pdf

such that imported LNG is needed for market balancing (such as the U.S.). In many instances, LNG offers greater trade flexibility than pipeline transport, allowing cargoes of natural gas to be delivered where the need is greatest and the commercial terms are most competitive. The figure below shows that as the distance over which natural gas must be transported increases, usage of LNG has economic advantages over usage of pipelines. In general, liquefying natural gas and shipping it becomes cheaper than transporting natural gas in offshore pipelines for distances of more than 700 miles or in onshore pipelines for distances greater than 2,200 miles.⁸

Figure 2. Example of Natural Gas Transportation Costs



Source: Institute of Gas Technology.

LNG development is especially important for countries like Nigeria and Angola. In these countries, most of the natural gas that is produced with crude oil is flared because there are few alternatives for usage or disposal of the excess gas.

Brief History of LNG

Natural gas liquefaction dates back to the 19th century when British chemist and physicist Michael Faraday experimented with liquefying different types of gases,

⁸ In this chart, the cost term "\$/MMBtu" or dollars per million British thermal unit, is a standard measure of heat content in energy fuels. See appendix 3. The chart reflects the competition between natural gas transported in pipelines and natural gas transported as LNG.

including natural gas. German engineer Karl Von Linde built the first practical compressor refrigeration machine in Munich in 1873. The first commercial liquefaction plant was built in Cleveland, Ohio, in 1941.⁹ The LNG was stored in tanks at atmospheric pressure. The liquefaction of natural gas raised the possibility of its transportation to distant destinations. In January 1959, the world's first LNG tanker, *The Methane Pioneer*, a converted World War II liberty freighter containing five, 7000 Bbl aluminum prismatic tanks with balsa wood supports and insulation of plywood and urethane, carried an LNG cargo from Lake Charles, Louisiana to Canvey Island, United Kingdom. This event demonstrated that large quantities of liquefied natural gas could be transported safely across the ocean.



British Gas Canvey Island LNG Terminal,
A World First (Source: BG)

Over the next 14 months, seven additional cargoes were delivered with only minor problems. Following the successful performance of *The Methane Pioneer*, the British Gas Council proceeded with plans to implement a commercial project to import LNG from Venezuela to Canvey Island. However, before the commercial agreements could be finalized large quantities of

natural gas were discovered in Libya and the gigantic Hassi R' Mel field in Algeria which are only half the distance to England as Venezuela. With the start-up of the 260 million cubic feet per day (MMCFD) Arzew GL4Z or Camel plant in 1964, the United Kingdom became the world's first LNG importer and Algeria the first LNG exporter. Algeria has since become a major world supplier of natural gas as LNG.

After the concept was shown to work in the United Kingdom, additional liquefaction plants and import terminals were constructed in both the Atlantic and Pacific regions. Four marine terminals were built in the United States between 1971 and 1980. They are in Lake Charles, Louisiana; Everett, Massachusetts; Elba Island,

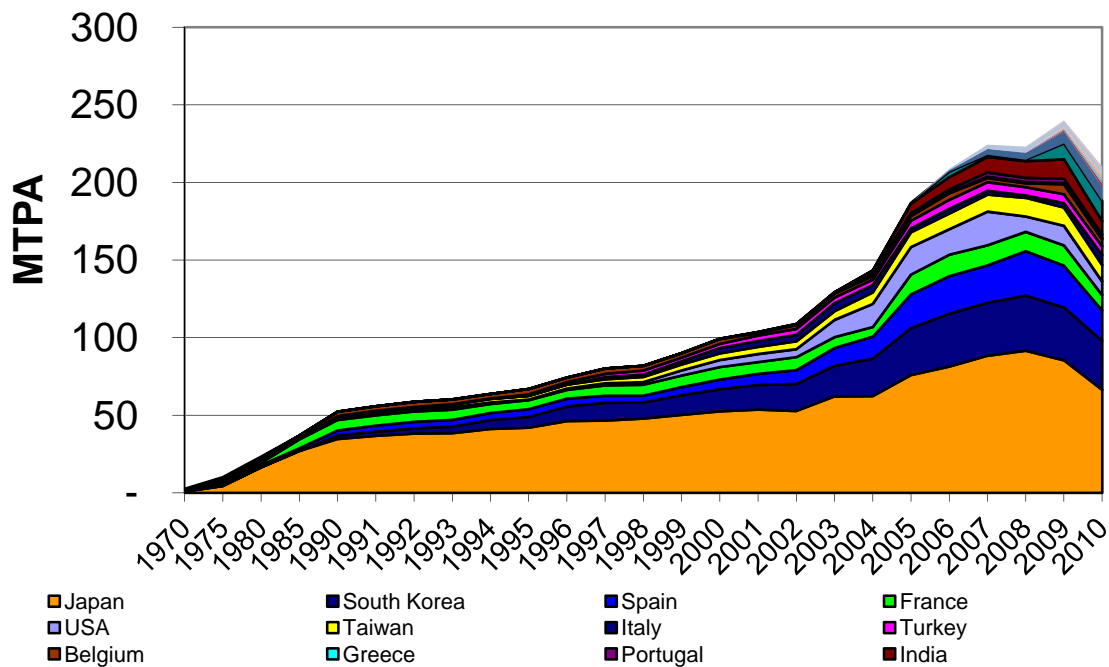
⁹ Based on information from Platts (no longer publicly available).

Georgia; and Cove Point, Maryland. After reaching a peak receipt volume of 253 BCF (billion cubic feet) in 1979, which represented 1.3 percent of U.S. gas demand, LNG imports declined because a gas surplus developed in North America and price disputes occurred with Algeria, the sole LNG provider to the U.S. at that time. The Elba Island and Cove Point receiving terminals were subsequently mothballed in 1980 and the Lake Charles and the Everett terminals suffered from very low utilization.

The first exports of LNG from the U.S. to Asia occurred in 1969 when Alaskan LNG was sent to Japan. Indeed, shipment of Alaskan natural gas in the form of LNG to Tokyo Harbor established one of the premier LNG trade routes. Alaskan LNG is derived from natural gas produced from fields in the southern portions of the state of Alaska, liquefied at the Kenai Peninsula LNG plant (one of the oldest, continuously operated LNG plants in the world), and shipped to Japan. In 1999, the first Atlantic Basin LNG liquefaction plant in the western hemisphere came on production in Trinidad. This event, coupled with an increase in demand for natural gas in the U.S., particularly for power generation, and an increase in U.S. natural gas prices resulted in a renewed interest in the U.S. market for LNG. As a result, the two mothballed LNG receiving terminals were reactivated. Elba Island was reactivated in 2001. In October 2002, the FERC gave approval to Dominion Resources for its plans to re-open Cove Point LNG facility in 2003.

The figure below shows worldwide growth in LNG since 1970 (including the impact of soft economic conditions worldwide since 2009).

Figure 3. Growth in LNG Global Demand



Source: Cedigaz, BP Statistical Review of World Energy June 2011

Strong U.S. natural gas price signals supported a wave of import terminal projects through the late 2000s. These price signals also supported drilling activity and success as new supplies were proved up. Proposals for exporting U.S. and Canadian domestic production emerged in 2011 as supply, including new production from shale basins, exceeded domestic demand. As of this 2012 update, one LNG export facility in the U.S. has been approved (Sabine Pass, commissioned in 2008 as a new import terminal), five additional U.S. sights have been proposed, two projects have been proposed in western Canada (British Columbia), and several potential projects are under consideration.¹⁰ Natural gas development and use, and

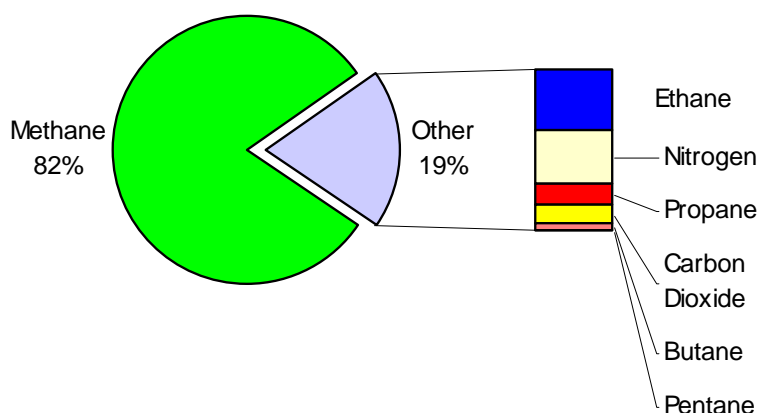
¹⁰ All LNG project information from the U.S. Federal Energy Regulatory Commission (FERC). See <http://www.ferc.gov/industries/gas/indus-act/lng.asp> for information. The FERC certifies export facilities, just as it does import facilities. The U.S. Department of Energy (DOE) approves imports and exports of natural gas via pipeline and LNG.

LNG in the U.S., North America, and worldwide all look to be dynamic and changing.¹¹

Composition of Natural Gas and LNG

Natural gas is composed primarily of methane, but may also contain ethane, propane, and heavier hydrocarbons. Small quantities of nitrogen, oxygen, carbon dioxide, sulfur compounds, and water may also be found in natural gas. The figure below provides a typical natural gas composition.¹²

Figure 4. Typical Natural Gas Composition

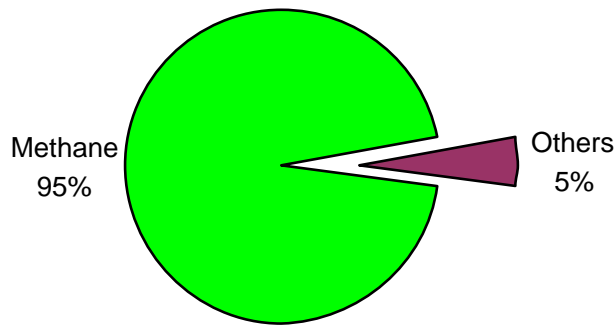


The liquefaction process requires the removal of some of the non-methane components such as water and carbon dioxide from the produced natural gas to prevent them from forming solids when the gas is cooled to about LNG temperature (-256°F). As a result, LNG is typically made up mostly of methane as shown in the figure below.

¹¹ CEE researchers are producing new papers and analysis of natural gas market conditions. See Foss, Michelle Michot, The Outlook for U.S. Gas Prices in 2020: Henry Hub at \$3 or \$10?, 2011, <http://www.oxfordenergy.org/2011/12/the-outlook-for-u-s-gas-prices-in-2020-henry-hub-at-3-or-10/> and Foss, United States Natural Gas Prices to 2015, 2007, <http://www.oxfordenergy.org/2007/02/united-states-natural-gas-prices-to-2015/>. For more information on other CEE research on natural gas and LNG contact us at energyecon@beg.utexas.edu.

¹² Danesh, Ali: *PVT and Phase Behavior of Petroleum Reservoir Fluids*, Elsevier, 1998.

Figure 5. Typical LNG Composition



Examples of LNG composition are shown below.

Figure 6. LNG Composition (Mole Percent)

LNG COMPOSITION (Mole Percent)					
Source	Methane	Ethane	Propane	Butane	Nitrogen
Alaska	99.72	0.06	0.0005	0.0005	0.20
Algeria	86.98	9.35	2.33	0.63	0.71
Baltimore Gas & Electric	93.32	4.65	0.84	0.18	1.01
New York City	98.00	1.40	0.40	0.10	0.10
San Diego Gas & Electric	92.00	6.00	1.00	-	1.00

Source: *Liquid Methane Fuel Characterization and Safety Assessment Report*. Cryogenic Fuels. Inc. Report No. CFI-1600, Dec. 1991

LNG is odorless, colorless, non-corrosive, and non-toxic. However, as with any gaseous material besides air and oxygen, the natural gas vaporized from LNG can cause asphyxiation in an unventilated confinement.

[APPENDIX 2: OTHER FUEL TERMINOLOGIES](#) explains the differences between LNG and other products used in the industry such as Natural Gas Liquids (NGLs), Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG) and Gas-to-Liquids (GTL).

The LNG Value Chain

As noted previously, the LNG value chain is composed of large scale, complex segments. A *logistics supply chain* is constituted by the discreet functions of finding

and producing natural gas; liquefying that gas for shipment; shipping to the final destination; and receiving, storage, and regasification at import terminals. The *value chain* captures the impact of costs at each step that determine the final price of imported LNG.

Figure 7. LNG Value Chain



Sources: BG, ALNG, CMS

Exploration and Production



According to the Statistical Review of World Energy 2011 by BP, for the year 2010 worldwide proved reserves of natural gas were 6,609 trillion cubic feet (TCF) and more reserves of natural gas continue to be discovered.¹³ Much of this natural gas is located a long way from current markets. In 2010, the leading countries producing natural gas and selling it to world markets in the form of LNG were Qatar, Indonesia, Malaysia, Australia, Nigeria, Trinidad &

Tobago, Algeria, and the Russian Federation. Many other countries play smaller but significant and growing roles as natural gas producers and LNG exporters. Countries like Angola and Venezuela are striving to reach their full potential in the

¹³ BP: *Statistical Review of World Energy 2011*, July 2011.
<http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481>.

global LNG marketplace, and countries like Saudi Arabia and Iran, that have vast reserves of natural gas, could also participate as LNG exporters. As mentioned above, new export projects in the U.S. and Canada are planned. Some of these may enter operation as early as 2015.

LNG Liquefaction



Feed gas to the liquefaction plant comes from the production field. The contaminants found in produced natural gas are removed to avoid freezing up and damaging equipment when the gas is cooled to LNG temperature (-256°F) and to meet pipeline specifications at the delivery point. The liquefaction process can be

designed to purify the LNG to almost 100 percent methane.

The liquefaction process entails cooling the clean feed gas by using refrigerants. The liquefaction plant may consist of several parallel units ("trains"). The natural gas is liquefied for shipping at a temperature of approximately -256°F . By liquefying the gas, its volume is reduced by a factor of 600, which means that LNG at -256°F uses $1/600^{\text{th}}$ of the space required for a comparable amount of gas at room temperature and atmospheric pressure.

LNG is a cryogenic liquid. The term "cryogenic" means low temperature, generally below -100°F . LNG is clear liquid, with a density of about 45 percent the density of water.

The LNG is stored in double-walled tanks at atmospheric pressure. The storage tank is really a tank within a tank. The annular space between the two tank walls is filled with insulation. The inner tank, in contact with the LNG, is made of materials suitable for cryogenic service and structural loading of LNG. These materials include 9 percent nickel steel, aluminum, and pre-stressed concrete. The outer tank is generally made of carbon steel or pre-stressed concrete.

LNG Shipping



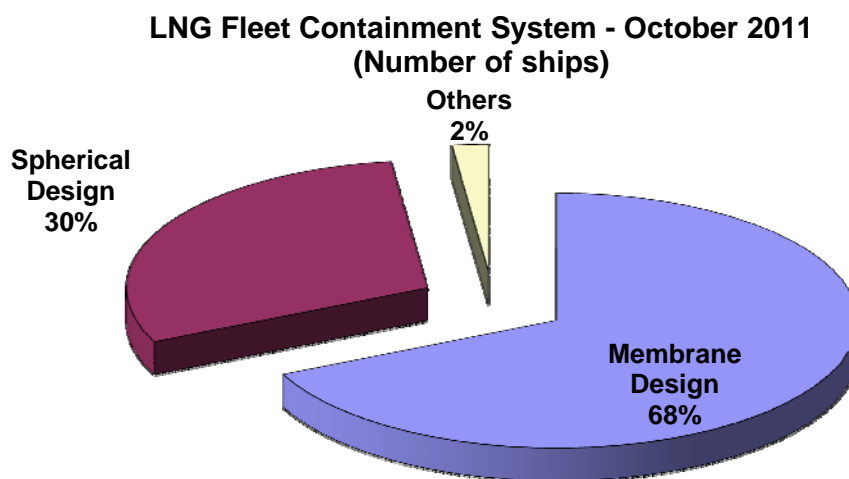
LNG tankers are double-hulled ships specially designed and insulated to prevent leakage or rupture in an accident. The LNG is stored in a special containment system within the inner hull where it is kept at atmospheric pressure and -256°F .

Three types of cargo containment systems have evolved as modern standards. These are:

- The spherical (Moss) design (like the photo above)
- The membrane design
- The structural prismatic design

Historically most of the LNG ships used spherical (Moss) tanks (52 percent in 2002). They are easily identifiable as LNG ships because the top halves of the tanks are visible above the deck. The figure below shows that the trend has changed; currently the market is dominated by carriers with membrane tanks.

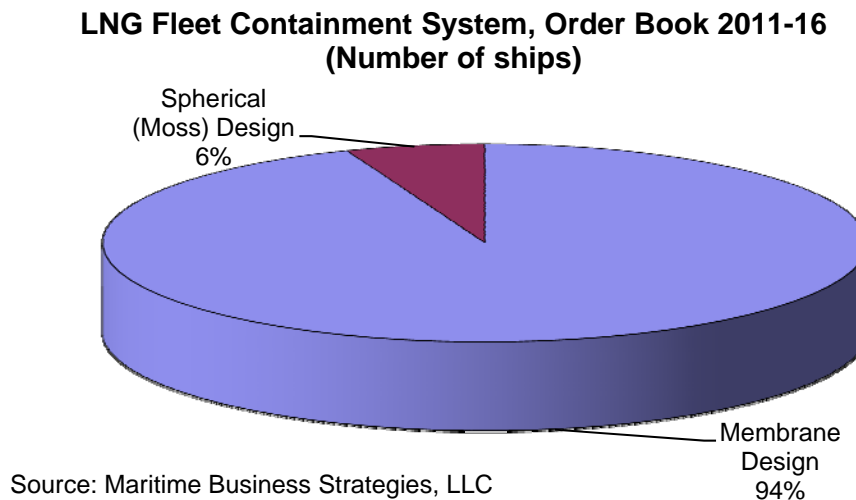
Figure 8. LNG Fleet Containment System (2011)



Source: Maritime Business Strategies, LLC

This tendency to deploy membrane design LNG ships is becoming even more obvious based on the structure of orders for LNG carriers (see Figure 9 below).

Figure 9. LNG Fleet Containment System - Order Book 2011 - 2016



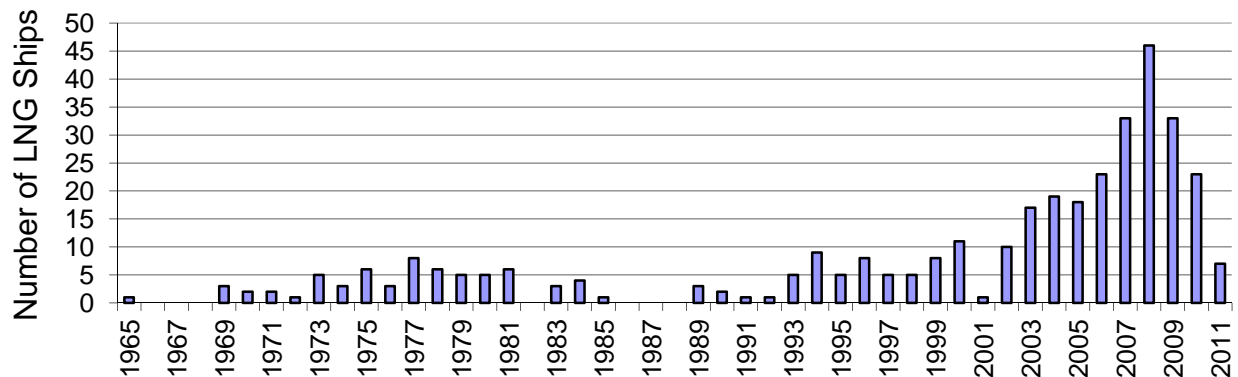
The typical LNG carrier can transport 125,000-138,000 cubic meters (CM) of LNG,¹⁴ which provides about 2.6-2.8 billion standard cubic feet (BCF) of natural gas. The typical carrier measures some 900 feet in length, about 140 feet in width and 36 feet in water draft and costs about \$160 million. This ship size is similar to that of an aircraft carrier but significantly smaller than that of Very Large Crude *oil* Carriers (VLCCs). LNG tankers are generally less polluting than other shipping vessels because they burn natural gas in addition to fuel oil as a fuel source for propulsion.

With the launch of Qatar's huge natural gas and LNG export capacity, new classes of LNG ships were developed. The giant Q-Max (266,000 CM) and Q-Flex (210,000-216,000 CM) LNG ships that are linked to Qatar Petroleum's QatarGas and RasGas subsidiaries have helped to improved the "scale economies" of LNG value chains by enabling larger cargos to be shipped over long distances. Many older import terminals are renovating harbors, berths and offloading facilities to accommodate these larger vessels.

¹⁴ Typically, LNG ship size is designated by cubic meters of liquid capacity.

The LNG shipping market is expanding. According to Maritime Business Strategies,¹⁵ as of October 2011, there were 360 existing tankers, with 51 on order. Seven new LNG tankers were ordered in 2010, all using the membrane containment system.¹⁶ About 48 percent of the fleet is less than five years old.

Figure 10. LNG Ships Built 1965-2011



Source: Maritime Business Strategies, LLC

Storage and Regasification



Source: CMS

To return LNG to a gaseous state, it is fed into a regasification plant. On arrival at the receiving terminal in its liquid state, LNG is pumped first to a double-walled storage tank, similar to those used in the liquefaction plant, at atmospheric pressure, then pumped at high pressure through various terminal components where it is warmed in a controlled environment. The LNG is warmed by passing it through pipes heated by direct-fired heaters, or seawater, or through pipes that are in heated

¹⁵Maritime Business Strategies, LLC: <http://www.coltoncompany.com/>.

¹⁶ International Group of Liquefied Natural Gas Importers: LNG Industry in 2010.

water. The vaporized gas is then regulated for pressure and enters the U.S. pipeline system as natural gas. Finally, residential and commercial consumers receive natural gas for daily use from local gas utilities or in the form of electricity.

How Much Does LNG Cost?

One major reason for the resurgence of interest in LNG in the U.S. during the late 1990s was significant reductions in unit costs during the past several years. Natural gas can be economically produced and delivered to the U.S. as LNG in a price range of about \$2.50-3.50 to \$4.50-5.50 per million Btu (MMBtu) depending largely on shipping cost. A major reason for cost reductions was development of larger liquefaction trains—capable of producing much larger tonnages of LNG along with larger ships like the Q-Max and Q-Flex tankers mentioned previously. Larger ships enable larger cargos over long distances, improving the overall economics of LNG supply and value chains.

Figure 11. Typical LNG Value Chain Costs



Total Cost = \$2.40-4.90/MMBtu

Source: CEE based on industry and government reports. Excludes certain expenses such as production taxes and fees; does not include an assumed rate of return.

Since 2000, the overall cost structure to produce or make and deliver energy of any form has been pushed upward by global demand. To manage costs, energy producers look to new technologies that can reduce risk and uncertainty and increase productivity and the human resource skills to deploy these technologies most optimally. Exploration and production costs and results are affected by improved technologies such as 3-D (three-dimensional) seismic; drilling and completion of complex well architectures; and improved subsea facilities. 3-D

seismic allows detailed complex imaging of rocks below the earth's surface, enabling exploration earth scientists to predict better where accumulations of natural gas might exist. Drilling and completion of complex well architectures allow petroleum engineers to target more precisely these accumulations and to maximize oil and gas reservoir recovery using multi-branched well architecture and intelligent completion systems. Improved sub-sea facilities allow companies to produce natural gas from deep below the surface of the ocean.

Further along the LNG value chain, technical innovations in liquefaction and shipping have allowed more LNG projects to achieve commercial viability. Design efficiencies and technology improvements contribute to improved project economics. BP's Trinidad LNG Train 1, completed in June 1999, set a new benchmark for LNG unit capital cost at less than \$200/ton¹⁷ of annual plant capacity, as shown in the figure below. Trinidad Atlantic Train 2 was completed in August 2002, two months ahead of schedule and Train 3, currently under construction is scheduled to come on stream second quarter of 2003. The capital cost of Trains 2 and 3 broke the record with capital cost of about \$165/ton of capacity. Technology that enabled larger scale LNG liquefaction trains to be built resulted in unit cost reductions (\$/Ton of LNG) of about 35 percent from the mid-1990s to the early 2000s.

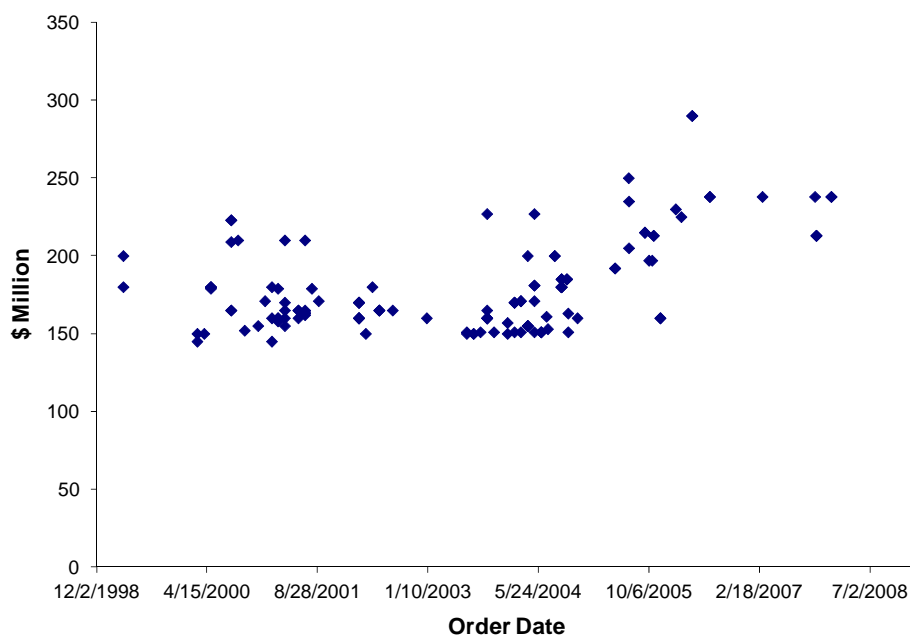
¹⁷ Williams, Bob; *Trinidad and Tobago LNG follows initial success with aggressive expansion plans*, Oil & Gas Journal, March 11, 2002. A "train" is typical terminology for LNG liquefaction plants, which are often added as separate units as a facility grows.

Figure 12. Industry Learning, LNG Liquefaction Plant Costs



In ship design, new technologies include new propulsion systems to replace the traditional steam turbine engines with smaller units that are more efficient, not only reducing fuel costs but also increasing cargo carrying capacity. Enhanced tanker efficiencies – longer operating lives, improved safety technology, and improved fuel efficiency – have lowered shipping costs substantially. Shipyard expansions in the Far East and increased competition among shipbuilders lowered LNG tanker costs by 40 percent from their peak over roughly the same period of mid-1990s to early 2000s.

Figure 13. Price Dynamics of Mid-Sized LNG Carriers (1999-2008)



Source: Maritime Business Strategies, LLC; CEE assessments and calculations

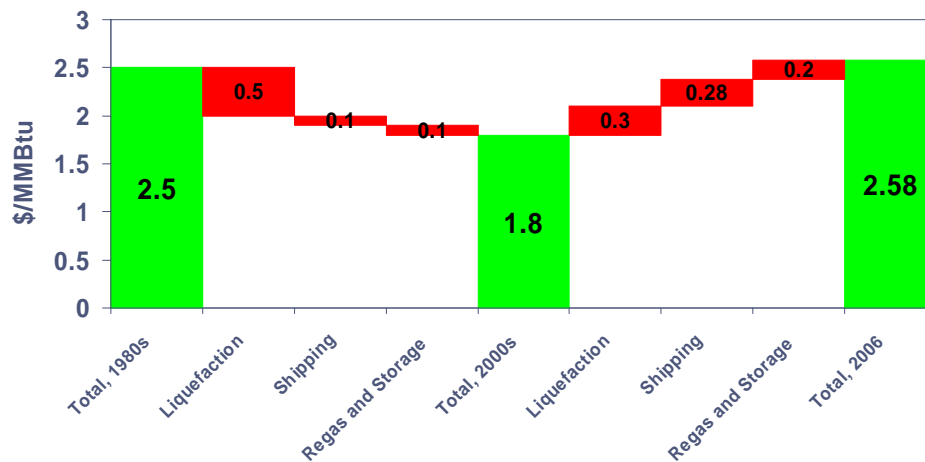
Competition among builders also drove down costs for new regasification plants. Regasification costs fell about 18 percent.¹⁸ The result of all these improvements is that the overall cost of LNG delivery has been reduced by almost 30 percent during the last 20 years.

Taken all together, technology and productivity improvements resulted in a 28 percent decline in LNG value chain cost structure between the 1980s and 2000 (see Figure 14 below). Cost pressures that accompanied strong global economic growth and persistently high commodity prices through 2007 resulted in a reversal of gains, but large scale projects continue to have cost and efficiency advantages. The learning experience accumulated as the industry experienced rapid growth over the past 20 to 30 years has yielded distinct benefits in improved operations, best practices, technology adaptation, and human resource skills. This accumulated experience allows LNG from large scale, low unit cost producing/exporting countries

¹⁸ Harmon, Harvey, Vice President, El Paso Global LNG, *The Dawn of New Golden Age for LNG*, IAEE Houston Meeting, February 2002.

to continue to be delivered to the U.S. and other locations even with very low domestic natural gas prices. Going forward, new attention is being paid to: smaller scale technologies that can serve smaller markets; floating LNG projects that can foster development of natural gas resources from offshore and other remote locations as well as provide creative solutions for receiving; and continued development and expansion of the LNG industry work force.

Figure 14. LNG Value Chain Cost Trends



Sources: CEE estimates and industry information

In sum, the decline in costs and the general growth in LNG trade fostered expansion of U.S. import terminal expansion. Technology induced gains in efficiency and productivity have enhanced global LNG trade, to the benefit of all customers, and may well support development of U.S. and Canadian LNG export projects. LNG continues to compete with pipeline gas in the North American and European markets, creating the benefits of competitive pricing for consumers, and it competes against other forms of energy like oil in Asia and other countries and regions that need diverse and affordable energy supplies.

Is LNG a Safe Fuel?¹⁹

LNG has been safely handled for many years. The industry is not without incidents, but it has maintained an enviable safety record, especially over the last 40 years. There are currently about 200 peakshaving and LNG storage facilities worldwide,²⁰ some operating since the mid-60s. The U.S. has the largest number of LNG facilities in the world with 121 active LNG facilities spread across the country (see map in previous Figure 1).

The reopening of existing LNG facilities at Cove Point, MD and Elba Island, GA, expansions of existing terminals and growth in new LNG import capacity focused public attention on the safety and security of LNG facilities. The safe and environmentally sound operation of these facilities, both ships and terminals, and the protection of these facilities from terrorist activities or other forms of accident or injury are concerns and responsibilities shared by operators as well as federal, state, and local jurisdictions across the U.S. Onshore LNG facilities are industrial sites and, as such, are subject to all rules, regulations and environmental standards imposed by the various jurisdictions. These same or similar concerns apply to natural gas storage and pipeline transportation and distribution and our daily use of natural gas.

A brief overview of the issues is presented here. The CEE briefing paper *LNG Safety and the Environment* provides details on the LNG industry safety record and incidents (see <http://www.beg.utexas.edu/energyecon/lng/>).

What is the safety record of the LNG industry?

Overall, the LNG industry has an excellent safety record compared to refineries and other petrochemical plants. Worldwide, there are 25 LNG export (liquefaction) terminals, 91 import (regasification) terminals, and 360 LNG ships, altogether handling approximately 220 million metric tons of LNG every year. LNG has been safely delivered across the ocean for over 40 years. In that time there have been

¹⁹ A second briefing paper, *LNG Safety and the Environment*, will address comprehensively the worldwide safety and security record of the industry as well as the U.S. policy and regulatory safeguards.

²⁰ CH-IV International: *Safety History of International LNG Operations*, June 2002.

over 59,000 LNG carrier voyages without major accidents or safety problems either in port or on the high seas. LNG carriers frequently transit high traffic density areas. For example in 2000, one cargo entered Tokyo Bay every 20 hours, on average, and one cargo a week entered Boston harbor.²¹ The LNG industry has had to meet stringent standards set by countries such as the U.S., Japan, Australia, and European nations.



According to the U.S. Department of Energy,²² over the life of the industry, eight marine incidents worldwide have resulted in spillage of LNG, with some hulls damaged due to cold fracture, but no cargo fires have occurred. Seven incidents not involving spillage were recorded, two from groundings, but with no significant cargo loss; that is, repairs were quickly made and leaks were

avoided. There have been no LNG shipboard fatalities.

Isolated accidents with fatalities occurred at several onshore facilities in the early years of the industry. More stringent operational and safety regulations have since been implemented.

- **Cleveland, Ohio, 1944**

In 1941, the East Ohio Gas Company built a facility in Cleveland. The peakshaving plant operated without incident until 1944, when the facility was expanded to include a larger tank. A shortage of stainless steel alloys during World War II led to compromises in the design of the new tank. The tank failed shortly after it was placed in service allowing LNG to escape, forming a vapor cloud that filled the surrounding streets and storm sewer system. The natural gas in the vaporizing LNG pool ignited resulting in the deaths of 128 people in the adjoining residential

²¹ Phil Bainbridge, VP BP Global LNG, *LNG in North America and the Global Context*, CEE/AIPN Meeting University of Houston, October 2002.

²² Juckett, Don, U.S. Department of Energy, *Properties of LNG*. LNG Workshop, MD, 2002.

area. The conclusion of the investigating body, the U.S. Bureau of Mines, was that the concept of liquefying and storing LNG was valid if "proper precautions were observed."²³ A recent report by the engineering consulting firm, PTL,²⁴ concluded that, had the Cleveland tank been built to current codes, this accident would not have happened. In fact, LNG tanks properly constructed of 9 percent nickel steel have never had a crack failure in their 35-year history.

- **Staten Island, New York, February 1973**

In February 1973, an industrial accident unrelated to the presence of LNG occurred at the Texas Eastern Transmission Company peakshaving plant on Staten Island. In February 1972, the operators, suspecting a possible leak in the tank, took the facility out of service. Once the LNG tank was emptied, tears were found in the Mylar lining. During the repairs, vapors associated with the cleaning process apparently ignited the Mylar liner. The resultant fire caused the temperature in the tank to rise, generating enough pressure to dislodge a 6-inch thick concrete roof, which then fell on the workers in the tank killing 40 people.

The Fire Department of the City of New York report of July 1973²⁵ determined the accident was clearly a construction accident and not an "LNG accident".

In 1998, the New York Planning Board, while re-evaluating a moratorium on LNG facilities, concluded the following with respect to the Staten Island accident: "The government regulations and industry operating practices now in place would prevent a replication of this accident. The fire involved combustible construction materials and a tank design that are now prohibited. Although the exact causes may never be known, it is certain that LNG was not involved in the accident and the surrounding areas outside the facility were not exposed to risk."²⁶

²³ U.S. Bureau of Mines, *Report on the Investigation of the Fire at the Liquefaction, Storage, and Regasification Plant of the East Ohio Gas Co., Cleveland, Ohio, October 20, 1944*, February 1946.

²⁴ Lewis, James P, Outtrim, Patricia A., Lewis, William W., and Perry, Lui Xin, PTL: *LNG, The Basics*, Report prepared for BP, May 2001.

²⁵ Fire Department of the City of New York, *Report of Texas Eastern LNG Tank Fatal Fire and Roof Collapse, February 10, 1973*, July 1973.

²⁶ New York Energy Planning Board, *Report on Issues Regarding the Existing New York Liquefied Natural Gas Moratorium*, November 1998.

- **Cove Point, Maryland, October 1979²⁷**

Finally, in October 1979, an explosion occurred within an electrical substation at the Cove Point, MD receiving terminal. LNG leaked through an inadequately tightened LNG pump electrical penetration seal, vaporized, passed through 200 feet of underground electrical conduit, and entered the substation. Since natural gas was never expected in this building, there were no gas detectors installed in the building. The natural gas-air mixture was ignited by the normal arcing contacts of a circuit breaker resulting in an explosion. The explosion killed one operator in the building, seriously injured a second and caused about \$3 million in damages.

This was an isolated accident caused by a very specific set of circumstances. The National Transportation Safety Board²⁸ found that the Cove Point Terminal was designed and constructed in conformance with all appropriate regulations and codes. However, as a result of this accident, three major design code changes were made at the Cove Point facility prior to reopening. Those changes are applicable industry-wide.

How will industry ensure safety and security of critical facilities and shipping activities?

The experience of the LNG industry demonstrates that normal operating hazards are manageable. No death or serious accident involving an LNG facility has occurred in the United States since the Cove Point accident. West and Mannan of Texas A&M University concluded in their paper *LNG Safety Practice & Regulation: From 1944 East Ohio Tragedy to Today's Safety Record*²⁹ that "The worldwide LNG industry has compiled an enviable safety record based on the diligent industry safety analysis and the development of appropriate industrial safety regulations and standards."

²⁷ The content in this section is taken from CH-IV International Report *Safety History of International LNG Operations*, June 2002.

²⁸ National Transportation Safety Board Report, *Columbia LNG Corporation Explosion and Fire; Cove Point, MD; October 6, 1979*, NTSB-PAR-80-2, April 16, 1980.

²⁹ West, H.H. and Mannan, M.S. Texas A&M University: *LNG Safety Practice & Regulation: From 1944 East Ohio Tragedy to Today's Safety Record*, AIChE meeting, April 2001.

The over 40 years of experience without significant incidents caused by LNG, liquefaction plants, LNG carriers, cargoes, and regasification facilities reflects the industry's commitment to safety and safe engineering and operations.

The terrorist attacks on September 11, 2001 raised critical new security risks and exposure for consideration, not just for the LNG industry but for all major industrial activities in the U.S. and worldwide. The LNG industry employs robust containment systems, proven operational procedures and many other safeguards. During the last several decades, technologies have advanced rapidly to ensure safer containment of LNG both during shipping and at onshore facilities.

The CEE safety and security briefing paper details and evaluates safety and security measures that are currently in use and under consideration, actions by industry and government to ensure safety and security, and technologies under development by industry that will reduce the effect LNG facilities may have on local communities.

What are the roles of federal, state and local government agencies and what are their jurisdictions?

The United States Coast Guard (USCG)³⁰ is responsible for assuring the safety of all marine operations at the LNG terminals and on tankers in U.S. coastal waters. The Department of Transportation (DOT)³¹ regulates LNG tanker operations. The U.S. Federal Energy Regulatory Commission (FERC)³² is responsible for permitting new LNG regasification terminals in the U.S. and ensuring safety at these facilities through inspections and other forms of oversight. In order to maintain a competitive environment for supply and pricing, the FERC is considering its role concerning the commercial arrangements by which producers of LNG have access to U.S. terminals. The FERC's jurisdiction includes authority for permitting new long distance natural gas pipelines to be developed in the U.S., as well as for safe and environmentally sound operation of the overall "interstate" natural gas pipeline system (pipelines that cross state boundaries). The U.S. Environmental Protection

³⁰ United States Coast Guard (USCG): <http://www.uscg.mil/>.

³¹ U.S. Department of Transportation (DOT): <http://www.dot.gov/>.

³² U.S. Federal Energy Regulatory Commission (FERC): <http://www.ferc.gov/>.

Agency³³ and state environmental agencies establish air and water standards with which the LNG industry must comply. Other federal agencies involved in environmental protection and safety protection include the U.S. Fish and Wildlife Service,³⁴ U.S. Army Corps of Engineers³⁵ (for coastal facilities and wetlands), U.S. Minerals Management Service³⁶ (for offshore activities) and National Oceanic and Atmospheric Administration³⁷ (for any activities near marine sanctuaries). The U.S. Department of Energy – Office of Fossil Energy³⁸ helps to coordinate across federal agencies that have regulatory and policy authority for LNG.

State, county, and local (municipal) agencies play roles to ensure safe and environmentally sound construction and operation of LNG industry facilities. The LNG industry is responsible for safe operations and facility security in cooperation with local police and fire departments.

How can citizens interact with industry and government to learn more?

The briefing papers produced by the CEE mentioned above and the online Guide to LNG in North America provides extensive information to public audiences interested in U.S. energy trends and security; LNG industry and market developments; LNG safety, security and environmental considerations; and related regulatory and policy issues. The CEE web site provides links to industry, government and public information sources. Companies with LNG operations maintain active public information offices, as do the federal agencies charged with regulatory and policy oversight.

³³ U.S. Environmental Protection Agency (EPA): <http://www.epa.gov/>.

³⁴ U.S. Fish and Wildlife Service: <http://www.fws.gov/>.

³⁵ U.S. Army Corps of Engineers: <http://www.usace.army.mil/>.

³⁶ U.S. Minerals Management Service: <http://www.boemre.gov/>.

³⁷ U.S. National Oceanic and Atmospheric Administration: <http://www.noaa.gov/>.

³⁸ U.S. Department of Energy – Office of Fossil Energy: <http://www.fe.doe.gov/>.

APPENDIX 1: CONVERSION TABLE

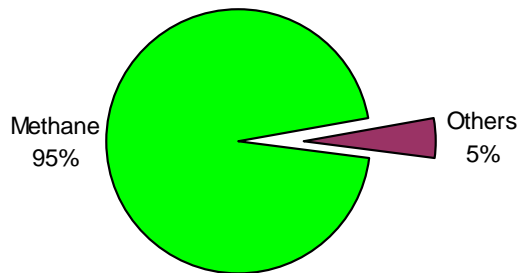
Conversion Units	Source: BP Statistical Review of U.S. Energy June 2002					
Natural gas (NG) and LNG	To: 1 billion cubic meters NG	1 billion cubic feet NG	1 million tons oil equivalent	1 million tons LNG	1 trillion British thermal units (Btus)	1 million barrels oil equivalent (Boe)
From:	Multiply by:					
1 billion cubic meters NG	1	35.3	0.90	0.73	36	6.29
1 billion cubic feet NG	0.028	1	0.026	0.021	1.03	0.18
1 million tons oil equivalent	1.111	39.2	1	0.81	40.4	7.33
1 million tons LNG	1.38	48.7	1.23	1	52.0	8.68
1 trillion British thermal units (Btus)	0.028	0.98	0.025	0.02	1	0.17
1 million barrels oil equivalent (Boe)	0.16	5.61	0.14	0.12	5.8	1

Example: To convert **FROM** 1 million tons of LNG **TO** billion cubic feet of natural gas multiply by 48.7 (100 million tons of **LNG** equals roughly 5000 billion cubic feet of **natural gas**).

APPENDIX 2: OTHER FUEL TERMINOLOGIES

LNG is often confused with other terminologies such as Natural Gas Liquids (NGLs), Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG), Gas-to-Liquids (GTL).

LNG Composition

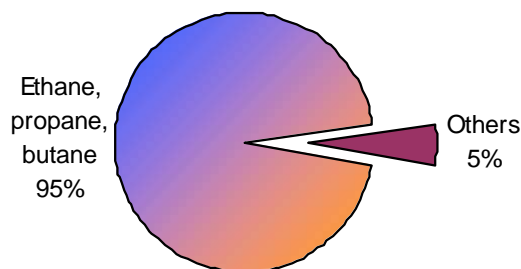


LNG is made up of mostly methane as shown in the figure below. The liquefaction process requires the removal of the non-methane components like carbon dioxide, water, butane, pentane and heavier components from the produced natural gas. LNG is odorless, colorless, non-corrosive, and non-toxic. When vaporized it burns only in concentrations of 5% to 15% when

mixed with air.

Natural gas liquids (NGLs) are made up mostly of molecules that are heavier than methane. These molecules liquefy more readily than methane. NGLs are the hydrocarbon molecules that begin with ethane and increase in size as additional

NGL Composition



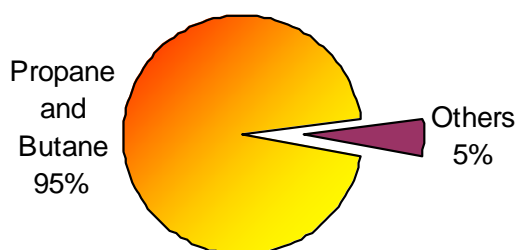
carbon atoms are added. In the U.S. NGLs are typically extracted during the processing of natural gas for industrial uses and in order for the gas to meet the pipeline specification. LNG shipped to the U.S. generally must meet pipeline heating value specifications, that is, it must contain only moderate quantities of NGLs. If LNG is shipped with NGLs, the NGLs must be removed upon receipt or blended

with lean gas or nitrogen before the natural gas can enter the U.S. pipeline system.

Few locations (only the Lake Charles, Louisiana receiving terminal in the U.S., for instance) are near processing facilities that can take LNG cargos that are “rich” with NGLs.

However, the LNG heat content specification in Japan, Korea and other Asian countries is higher than in the U.S. or Europe. For these countries, NGLs are left in the LNG and, in some circumstances LPG is added to the vaporized LNG at the receiving terminal to increase the heat content.

LPG Composition



LNG is not the same as **Liquefied Petroleum Gas (LPG)**. LPG is often incorrectly called propane. In fact, LPG is predominantly a mixture of propane and butane in a liquid state at room temperatures when under moderate pressures of less than 200 psig (pounds per square inch gauge (psig) is a common measure of pressure). The common interchanging of the terms LPG and

propane is explained by the fact that in the U.S. and Canada LPG consists primarily of propane. In many European countries, however, the propane content in LPG can be lower than 50 per cent.

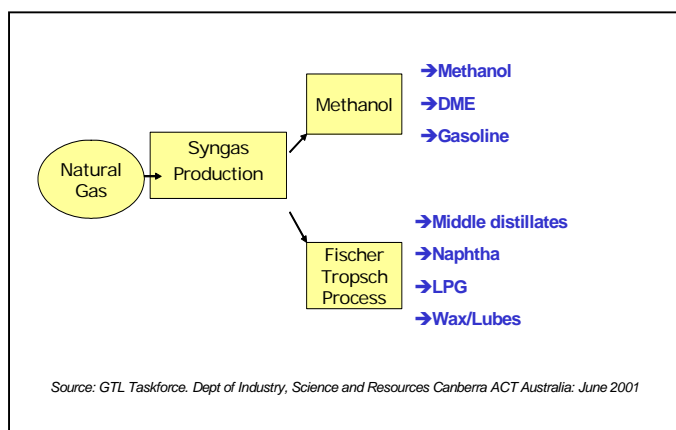
In Europe, LPG has been used as fuel in light duty vehicles for many years. Many petrol or gasoline stations have LPG pumps as well as pumps to distribute gasoline.

LPG is highly flammable and must therefore be stored away from sources of ignition and in a well-ventilated area, so that any leak can disperse safely. A special chemical, mercaptan, is added to give LPG its distinctive, unpleasant smell so that a leak can be detected. The concentration of the chemical is such that an LPG leak can be smelled when the concentration is well below the lower limit of flammability. Worldwide, LPG is used heavily for domestic purposes such as cooking and heating water.



LNG is not the same as **compressed natural gas (CNG)**. CNG is natural gas that is pressurized and stored in welding bottle-like tanks at pressures up to 3,600 psig. Typically, CNG is the same composition as pipeline quality natural gas, i.e., the gas has been dehydrated (water removed) and all other elements

reduced to traces so that corrosion is prevented. CNG is often used as a vehicle transportation fuel and is delivered to an engine as low-pressure vapor (up to 300 psig). CNG is often misrepresented as the only form of natural gas that can be used as vehicle fuel. However, LPG and LNG are also common transport fuels.



LNG also is not synonymous with **Gas-to-Liquids (GTL)**. GTL refers to the conversion of natural gas to products like methanol, dimethyl ether (DME), middle distillates (diesel and jet fuel), specialty chemicals and waxes. While the technology for producing each of these distinct products was

developed years ago, only methanol is currently in widespread commercial production. DME and specialty lubricants and waxes from natural gas are in limited commercial production. Middle distillate can be directly substituted for diesel fuel in existing compression ignition engines. The advantage of GTL diesel is that it contains almost no sulfur or aromatics and is well suited to meet current and proposed cleaner fuel requirements of developed economies.

APPENDIX 3: GLOSSARY OF TERMS^{39,40}

TERM	DEFINITION
British Thermal Unit (BTU)	A Btu is the amount of heat required to change the temperature of one pound of water one degree Fahrenheit.
Cryogenic	Refers to low temperature and low temperature technology. There is no precise temperature for an upper boundary but -100°F is often used.
Density	A description of oil by some measurement of its volume to weight ratio. The industry usually relies on two expressions of oil's volume-weight relationship-specific gravity and API degrees. The larger a specific gravity number and the smaller an API number, the denser the oil.
Fahrenheit degrees (F)	A temperature scale according to which water boils at 212 and freezes at 32 Fahrenheit degrees. Convert to Centigrade degrees (C) by the following formula: $(F-32)/1.8 = C$.
Impoundment	Spill control for tank content designed to limit the liquid travel in case of release. May also refer to spill control for LNG piping or transfer operations.
Middle distillates	Products heavier than motor gasoline/naphtha and lighter than residual fuel oil. This range includes heating oil, diesel, kerosene, and jet kero.
Mole Percent	Mole is a short form of molecular weight. Mole fraction or mole percent is the number of moles of a component of a mixture divided by the total number of moles in the mixture.
MTPA	Million Tonnes per Annum. Tonnes or Metric Ton is approximately 2.47 cubic meter of LNG.
MW	Molecular Weight
Peakshaving LNG Facility	A facility for both storing and vaporizing LNG intended to operate on an intermittent basis to meet relatively short term peak gas demands. A peakshaving plant may also have liquefaction capacity, which is usually quite small compared to vaporization capacity at such facility.
Stranded Gas	Gas is considered stranded when it is not near its customer and a pipeline is not economically justified.
Sweetening	Processing to remove sulfur. Hydrodesulfurization, for instance, can produce sweet catfeed. Caustic washing can sweeten sour natural gasolines to make them suitable for motor gasoline blending.

³⁹ Phillips Petroleum Company.

⁴⁰ Poten & Partners, http://www.poten.com/?URL=ut_glossary.asp.