
What you will learn:

- How natural gas is cooled and liquefied
- The three basic steps in the liquefaction process
- Typical costs of liquefaction
- Where liquefaction plants exist today and where new plants have been proposed
- The key issues affecting future liquefaction development

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SECTION THREE: LIQUEFACTION

As you learned in the last Section, the LNG delivery chain (liquefaction, shipping and regasification) replaces the transportation function generally attributed to interstate pipelines. In the first step, liquefaction, natural gas is converted from its gaseous state to a liquid state so that it can be transported via tanker. In the simplest of terms, the liquefaction process takes raw feed gas, removes impurities and other components, cools the gas until it liquefies, and finally moves the liquid into storage tanks. The LNG is then loaded onto tankers for transportation to market. While this sounds reasonably simple, the actual process is quite a bit more complex. In this Section we will explore the technology and costs associated with the liquefaction process. We will also discuss both existing and planned liquefaction infrastructure around the world as well as the key issues affecting the future of liquefaction.

Liquefaction Technology

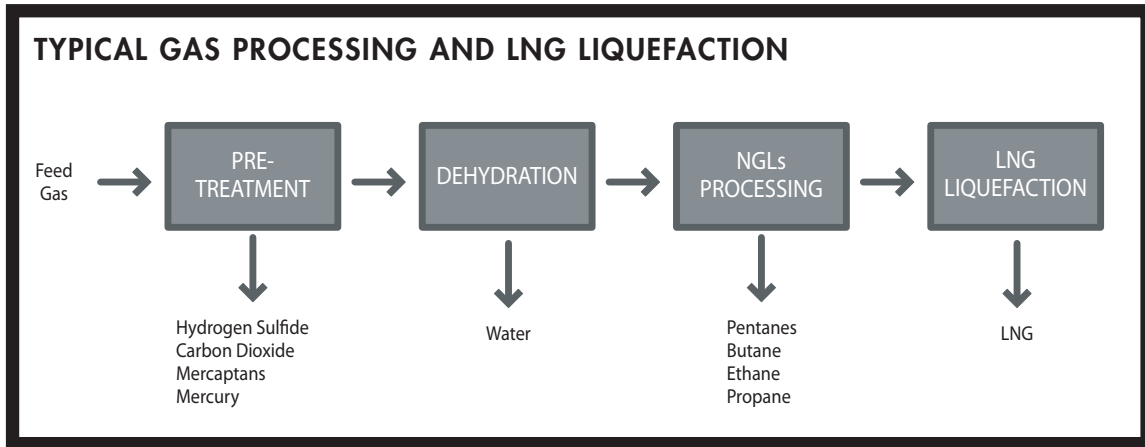
The three basic steps of the liquefaction process are as follows:

1. Removal of impurities and recovery of natural gas liquids (NGLs)
2. Refrigeration of the gas until it liquefies
3. Movement of the LNG to storage and ultimately into the tanker

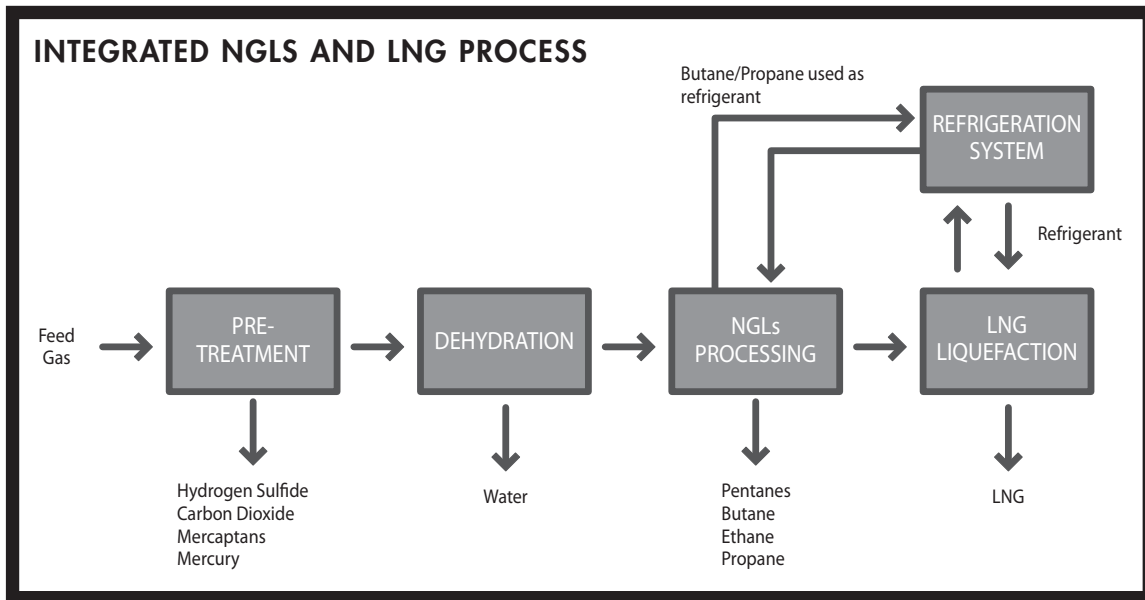
Removal of Impurities and Recovery of NGLs

The gas supply that comes from the production field is called raw feed gas. This is typically made up of methane; other hydrocarbons such as ethane, propane, butane, and/or pentane; and substances such as water, sulfur, mercury, and other impurities. The raw feed gas is delivered via pipeline to a processing plant. Here the gas is processed to remove impurities as well as valuable NGLs. The first step is pretreatment, which includes the removal of acid gas such as carbon dioxide and sulfur, as well as mercury and other substances. All of these must be removed either because their freezing points are well above the temperature of the final LNG product (and

they could freeze and damage equipment during the cooling process), or because they are impurities that must be removed to meet pipeline specifications at the delivery point. Next water is removed.



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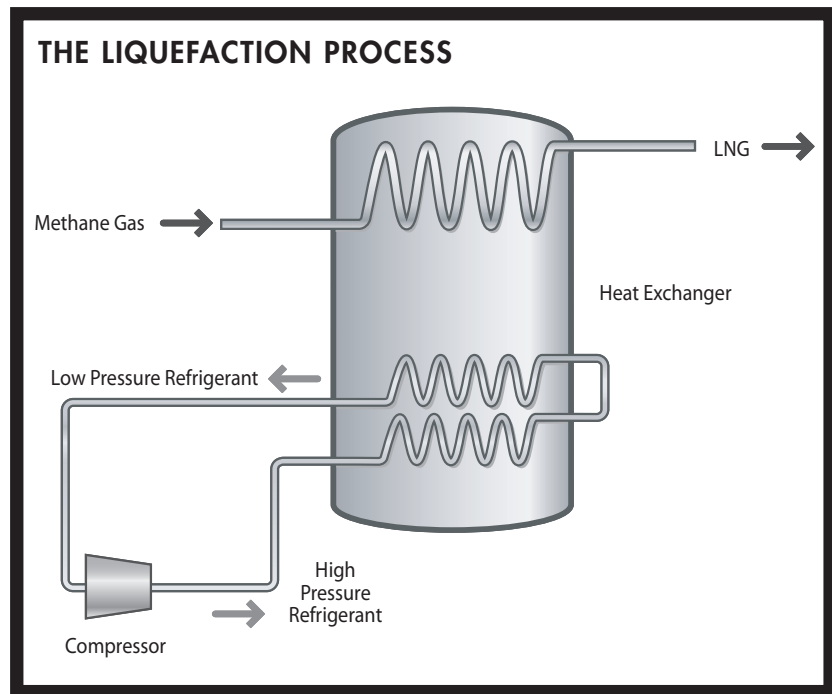
After the above steps, the NGLs such as ethane, propane, butane, and pentanes (also known as heavy hydrocarbons) are removed and collected. In many cases the gas is processed upstream of the liquefaction unit, using traditional gas processing technology (i.e., the same processing that is done to any gas entering an interstate pipeline system). In other cases, the NGLs recovery may be done as an integral step in the liquefaction process. The NGLs collected are valuable products in their own right, and may also be used as refrigerants for the liquefaction process or may be reinjected into the

LNG stream at a later point to adjust the Btu content and flammability characteristics of the LNG. Pentanes and other heavy hydrocarbons are generally exported as a gasoline product. Butane and propane are often also exported as separate products and/or used as refrigerants. Ethane is often reinjected into the LNG stream and may also be used as a refrigerant.

Liquefaction of the Methane

Next, the methane along with any reinjected components, is further cooled to -260 degrees Fahrenheit using LNG liquefaction technology. In this step, the methane mixture liquefies into the final cryogenic liquid state. Although slightly different processes are used in various liquefaction facilities, the basic cooling and liquefaction principles of each process are the same. The key technology is multiple heat exchangers.

Here, a cold liquid refrigerant is passed through cooling coils and the natural gas stream is allowed to flow over them, resulting in cooling of the gas stream. As the temperature drops to about -260 degrees Fahrenheit, the gas becomes liquid and can then be pumped into a storage tank.

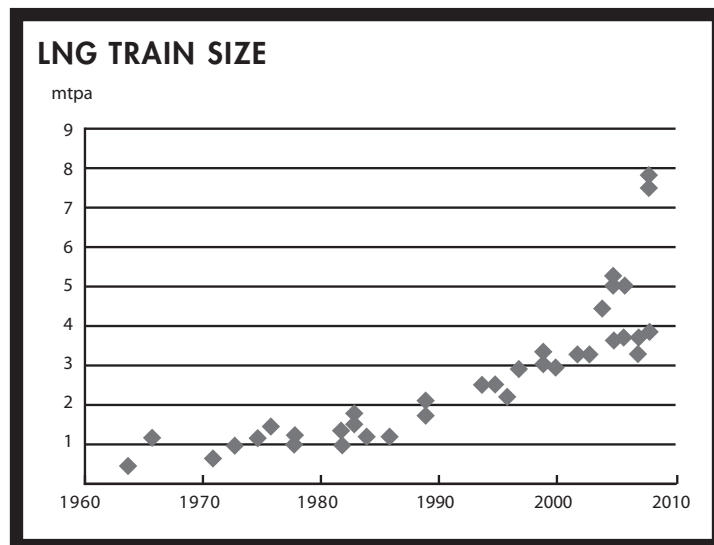


An additional key technology is the drive train for the compressor that pressurizes the refrigerant. Most earlier liquefaction plants were built using steam turbines. But beginning in the late 1980s, gas turbine drive became the norm and most facilities constructed since then have utilized gas turbines. The recently constructed Snohovit plant in Norway used a third alternative – electric drive – so as to minimize greenhouse gas emissions. Compressor sizing and layout is a facility-specific design decision.

Different liquefaction processes include the APCI MCR (Air Products and Chemicals, Inc. Multi-Component Refrigerant) Process, the Phillips Optimized Cascade Process, and various mixed refrigerant processes. The processes differ by type of refrigerant used and by design of the cooling stages. Since each process is proprietary and owned by a specific company, the choice of what process to use is critical since it will tie the plant owner to a specific technology licensee for the life of the plant. Over 80% of the liquefaction plants use the APCI MCR technology. This process uses pre-cooling with propane followed by final cooling with the proprietary refrigerant. A variation called the APCI AP-X process, currently under construction in Qatar, will allow train sizes to increase to 8 mtpa. The Phillips Optimized Cascade Process is in use in four existing plants. This process uses three refrigerants to progressively cool the gas. Mixed refrigerant processes use different refrigerants mixed together in various stages. Current mixed refrigerant processes in use or under construction include the Shell dual mixed-refrigerant (DMR) process and the Statoil-Linde mixed-fluid (MCF) process.

3 The process ultimately chosen is a design decision and depends on various factors including the composition of the feed gas, the availability of refrigerants, whether the NGLs are being removed upstream, the size of the facility, requirements for operational flexibility, and the cost/availability of power for compressors.

Liquefaction facilities are generally constructed in modular units called trains. A train is a complete stand-alone processing unit, but often multiple trains are built side-by-side. Train sizes currently range from less than 1 to 8 mtpa. The larger train sizes are becoming common in new plants as engineers attempt to take advantage of economies of scale.



Storage and Pumping the LNG into Tankers

After the liquefaction process, the LNG is pumped into a cryogenic storage tank. These tanks are typically double-walled, with an outer wall of reinforced concrete lined with carbon steel and an inner wall of nickel steel. Between the two walls is insulation to prevent ambient air from warming the LNG. The LNG is stored in these

tanks until a tanker is available to take the LNG to market. Storage tanks are sized based on the size of the tankers that will transport the LNG plus additional capacity to allow for scheduling flexibility and handling of plant outages. Many facilities include multiple tanks with the total capacity typically sized for twice the size of the expected tanker capacity so that up to two tankers worth of LNG can be stored at one time. Current tank sizes range from 36,000 m³ to 188,000 m³ with typical tanks sized in the 136,000 to 148,000 m³ range.

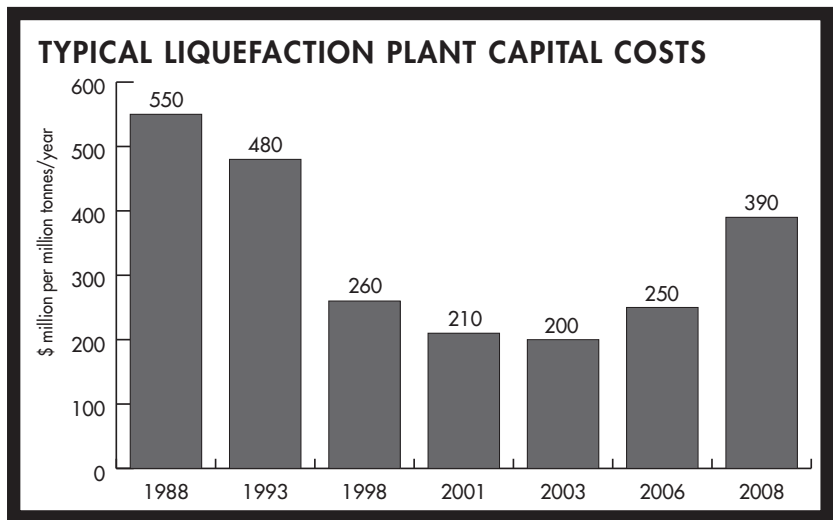
Ship Loading Facilities

Ship loading facilities include the berth where the LNG tanker docks, a jetty which is a wall built out into the water, an insulated pipeline from the tanks to the berth, and rigid loading arms. After an empty tanker docks in the berth, the LNG is loaded onto the tanker through insulated pipes that are attached to the tanker by rigid loading arms. Once the tanker is filled, the pipes are disconnected, the loading arms are swung away from the ship, and the tanker is ready to sail.

Liquefaction Plant Costs

Capital Costs

The capital cost of a liquefaction plant is a critical component of the overall cost of an LNG delivery chain. In fact, total costs of a facility can run as high as \$4 billion. The initial liquefaction plants were small in size compared to those being built today, with no trains over 2 mtpa built until the 1990s. As the LNG trade became more than a small



niche market, plant owners began looking for ways to lower costs. One key was to take advantage of economies of scale by building larger facilities. As you can see from the chart on the left, the cost of liquefaction plants has fluctuated over time. Construction costs came down in the 1990s and early 2000s due to a number of influences

including economies of scale; supplier competition; advancements in organizational learning, research and development; and project management techniques. But by 2005, costs began to escalate rapidly as worldwide demand for materials such as steel, nickel and concrete rose rapidly. Also climbing were costs for engineering contractors, engineers and skilled laborers due to a boom in building driven by rapidly growing Asian economies. As of early 2010, it was uncertain whether the economic slowdown would again bring down costs or whether they would remain high.

Variable Costs

Ongoing costs to operate a liquefaction unit are also an important factor in the overall cost of liquefaction. Important factors include use of natural gas as fuel in the liquefaction plant, taxes paid to the local government and general operating and maintenance (O&M) costs. A typical liquefaction unit might use 11% of the plant's input gas as fuel. If we assume a fuel cost of \$0.75/Mcf (current supply costs range from \$0.55 to about \$1/Mcf) then the operating cost associated with use of fuel is approximately \$0.08/Mcf. Taxes will vary depending on where the facility is located but might be on the order of \$0.15/Mcf and O&M costs are typically about \$0.10/Mcf. The resulting overall variable cost of liquefaction is then about \$0.33/Mcf.

EXAMPLE OF LIQUEFACTION COSTS

Total plant capital cost	\$2.4 billion
Plant capacity	5 mtpa (238 Bcf/year)
Utilization rate	90%
Annual cost of capital	\$310 million
Per Mcf cost of capital	\$1.44/Mcf
Fuel	\$0.08/Mcf
Taxes	\$0.15/Mcf
Operating costs	\$0.10/Mcf
Total cost of liquefaction	\$1.77/Mcf

Plant capital cost includes interest during construction.

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Liquefaction Infrastructure

Existing Plants

As of early 2010, liquefaction plants were operating in 16 countries at 26 different sites. Total production capacity was approximately 230 mtpa worldwide. Actual production was at about 80% of full capacity. The table on page 31 lists the exporting countries along with the amount of LNG they exported in 2008. A complete list of worldwide liquefaction terminals is included in Appendix D.

LIQUEFACTION MARKET SHARE (2008)

<u>Country</u>	<u>Volume (million tonnes)</u>	<u>Market Share</u>
Qatar	28.77	17.5%
Malaysia	21.32	13.0%
Indonesia	19.47	11.9%
Algeria	15.86	9.7%
Nigeria	14.89	9.1%
Australia	14.68	8.9%
Trinidad and Tobago	12.59	7.7%
Egypt	10.20	6.2%
Oman	7.90	4.8%
Brunei	6.67	4.1%
United Arab Emirates	5.47	3.3%
Equatorial Guinea	3.76	2.3%
Norway	1.59	1.0%
United States	0.70	0.4%
Libya	0.38	0.2%

Based on annual exports listed in *BP Statistical Review of World Energy 2009*.

Historically, a typical LNG liquefaction plant has consisted of between one and three process trains, though some plants have used as many as six. In simple terms, a train can be viewed as a standalone liquefaction unit (i.e., it is possible to shut down one train without impacting the operation of other trains). Multiple trains add flexibility to plant design by allowing the operator to match the number of trains online to the amount of available gas. Today some facilities are being designed for greater flexibility within a single train, allowing for a reduction in the number of trains commonly required for new or expanded facilities.

The initial liquefaction plants built in the 1960s and 1970s consisted of multiple trains with lower capacities. For example, the first commercial LNG plant was constructed with three trains, each with a capacity of .37 mtpa. Five years later, the Kenai, Alaska plant¹ came online with two trains, each with a capacity of .70 mtpa.

The initial liquefaction design, which featured smaller and multiple trains per plant, was probably necessitated by a market whose primary focus was supply security – even at

additional capital cost. The older projects were built with generous capacity margins and redundant design features to assure security of supply with the ability to meet contractual supply obligations. But beginning in the late 1990s, train size began to increase dramatically, and the common number of trains dropped to one or two per plant. Experience has allowed plant owners to decrease the design redundancy of their facilities which in turn has reduced the capital costs per train.

¹The Kenai plant is sometimes referred to as a single train facility. Its design is actually a "two-in-one" configuration, making both a single train and a two train label correct.

Although demand for new liquefaction slowed from the mid-1980s through the first half of the 1990s, a new boom in demand began in the late 1990s and continues today. In the period from 2000 to 2010, over 115 mtpa of new liquefaction capacity was commissioned, representing a doubling in world capacity over the decade. The associated capital cost for these new plants was some \$25 billion. An additional 68 mtpa of liquefaction was under construction as of early 2010.

Proposed and Future Plants

It appears that growth in liquefaction will continue to be strong. Countries with excess gas supply exist in many regions around the globe and most are looking at whether LNG development could allow them to monetize these assets.

Much of the current construction of liquefaction capacity is in the Middle East, driven by Qatar's push to increase its position as the world leader in LNG production. Qatar commissioned a new 7.8 mtpa plant in 2009 and as of early 2010 had an additional 39 mtpa of capacity under construction, consisting of five more 7.8 mtpa "mega-trains." Also under construction in the Middle East was a 10.8 mtpa facility in Iran.

3 8.8 mtpa of capacity was under construction in the Pacific Basin as of early 2010. This includes the Pluto LNG facility in Australia and Peru LNG in South America. Meanwhile in the Atlantic Basin, 10 mtpa of capacity was under construction including the rebuild of Skikda GI 1K in Algeria, Angola LNG, and Skangass in Norway. The Atlantic projects will add an additional 3 trains.

When current construction is complete, Angola, Iran, Peru, Russia, and Yemen will have joined the list of countries exporting LNG within a three-year time span. In addition to the projects under construction, there are liquefaction plants in the advanced planning stages in Nigeria and Australia, and additional potential projects in Algeria, Angola, Canada, Egypt, Equatorial Guinea, Indonesia, Libya, Papua New Guinea, Russia, Trinidad and Tobago, and Venezuela.

Key Issues

Key issues to watch are the development of new technology needed to accommodate offshore liquefaction terminals, sizing of liquefaction trains, market changes impacting the design of liquefaction, and environmental concerns. Throughout the world, much of the stranded gas under development exists offshore. Yet to date, all liquefaction facilities have been built onshore with close proximity to a safe harbor. Because large gas reserves exist offshore, liquefaction technology is currently being developed for offshore

application. While offshore plants will have costs associated with building a platform that holds the liquefaction plant, they eliminate the need for land purchase, jetty facilities and compression, and pipeline to move gas to shore. They may also be easier to build than onshore facilities. Proponents of offshore projects currently in planning stages claim costs may be comparable or even lower than costs for onshore plants.

Similar to the debate between onshore and offshore facilities, there are differing approaches to train sizes. Some project developers believe that bigger trains will result in economies of scale driving down costs. Qatar recently completed one large 7.8 mtpa train and has five more under construction. The success of these projects will be watched closely by many. An alternative viewpoint is represented by the small 0.3 mtpa Skangass project in Norway. This project is designed to take advantage of smaller gas fields, rapid construction (which ties up less capital) and fewer environmental impacts. Its size will allow smaller tankers to be used which opens the possibility of direct LNG sales to industrial customers. The developers of this project hope to take their concept elsewhere in the world if it proves successful.

The LNG marketplace is beginning to demand more flexibility in timing and amount of gas taken from liquefaction facilities. To accommodate these contractual terms, LNG liquefaction plants have to be able to reduce their output to match market demand, or find a ship and market available to purchase the spot load. This production flexibility is dependent upon plant design as discussed previously in this Section. While growth in this market is unquestionably favorable for the asset owner, the flexibility now required makes the business significantly more complicated.

In addition to volume flexibility, the evolving marketplace for spot sales impacts the quality requirements of gas produced from liquefaction. If a liquefaction facility has the ability to adjust the Btu content of the LNG as needed, more markets are available to that product. Thus facilities with quality adjustment capability will be more profitable in today's buyer's market.

While volume and product flexibility have significant impacts on profitability in today's LNG market, environmental concerns are also important. The Norwegian Snohvit plant completed in 2007 is the first example of a facility using electric motors instead of gas compression in order to reduce NO_x emissions. This facility will also remove CO_2 from the gas stream for reinjection into the producing field to further curtail greenhouse gas emissions. Such emphasis on environmental concerns is likely to be a trend for future plants.