Compressed Natural Gas (CNG): An Alternative to Liquefied Natural Gas (LNG)

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Summary

Natural gas is rapidly becoming an even more important resource of energy, with its share in the world consumption expected to increase dramatically over the next two decades. Currently, natural gas is transported to the markets by pipelines as LNG. Transporting the natural gas by pipelines is convenient and economically attractive onshore. For the offshore transport of natural gas, pipelines become challenging as the water depth and transporting distance increase. LNG, an effective means of transporting gas for long distances across the seas, constitutes 25% of the world gas movement. But LNG projects require large investments, along with substantial natural-gas reserves, and are economically viable for distances of 2,500 miles and beyond.

CNG provides an effective way for shorter-distance transport. The technology is aimed at monetizing offshore reserves that cannot be produced because of the unavailability of a pipeline or because the LNG option is very costly. Technically, CNG is easy to deploy, with lower requirements for facilities and infrastructure. "Coselle" and "Votrans" are two would-be commercial, high-pressure gas-storage and -transport technologies for CNG. Technical and economic analyses of these two technologies were done in this study, and a comparison is provided. The results show that for distances up to 2,500 miles, natural gas can be transported as CNG at prices ranging from U.S. $0.93 to $2.23 per MMBtu compared to LNG, which can cost anywhere from $1.5 to $2.5 per MMBTU depending on the actual distance. At distances beyond 2,500 miles, the cost of delivering gas as CNG becomes higher than the cost for LNG because of the disparity in the volumes of gas transported with the two technologies.

Introduction

Consumption of natural gas internationally has been increasing rapidly, making it one of the most important energy resources in the world. At the time of this writing, world consumption of natural gas has touched 100 Tcf, an increase of approximately 25% in a decade (compared with a 16% increase for oil and a 5% increase for coal) (Energy Information Administration 2004). Over the next 20 years, natural gas is predicted to increase its world energy share substantially from the present 23% (Economides et al. 2000). Much of the increased consumption is seen to be in electric-power generation, but transportation will likely be the deciding factor on the actual and potential dramatic increase.

The lower carbon emissions compared to oil and coal and other reduced emissions of nitrogen oxides and particulates make gas environmentally attractive. More important is that the cost of power generation using natural gas is as much as 50% less than using coal (Oligney and Economides 2002). In the U.S. alone, there are projections of annual natural-gas consumption in power generation from 5.25 Tcf in 2004 to 9.5 Tcf in 2024, an increase of 80% (Energy Information Administration 2006). Similar trends are seen in rapidly developing parts of the world such as China and Southeast Asia.

This increased consumption of natural gas, along with the anticipated reduction of the market share of coal and oil, has raised the specter of shortages in supply in the United States and other nations. With the emerging demand and with new market opportunities expected to arise, the methods of transporting the gas from offshore reserves and overseas sources have generated considerable and renewed interest.

Existing means of transporting natural gas consist primarily of pipelines and LNG. Pipelines account for 75%, with LNG accounting for the rest (Energy Information Administration 2004). LNG provides an appropriate way of delivering natural gas from offshore. However, because of the large upfront investment, LNG requires large reserves of natural gas near the facilities to support an LNG project and to get acceptable-returns capital investment. New LNG projects need approximately 0.5 to 1 Bcf per day of gas throughput to justify the investment (Hakes 1997). One other requirement for LNG is the need for a large demand at the user site. For example, a typical LNG import would require gas-fired power-generating capacity of up to 5,000 MW (Oligney and Economides 2002). Such demand limits the potential receivers of LNG to a handful of countries and locations.

Satisfying small-demand markets and monetizing small reserves are the two things that CNG transport of natural gas is intended to target. CNG technology can be used readily for the transportation of gas from smaller and marginal fields with small throughputs of, for example, 100 MMscf/D (Oligney and Economides 2002). The technology is simple and can be brought into commercial application easily. Currently, no major CNG projects are commercially operated, but recent developments in the ability to ship economically large volumes of gas and ongoing work in engineering designs suggest that the technology is at the threshold of being applied commercially (Dunlop and White 2003).

A comparative cost study of sea-going natural-gas transportation technologies was presented recently by the authors (Subero et al. 2004). The study analyzed the available data on capital, operating, and shipping costs for proposed, conceptual, and actual gas-transport costs. Integrating these data into an economic model, the comparative attractiveness of different sea-going natural-gas transportation methods (including CNG, LNG, and subsea pipelines) was presented. The results, examining several volumes of gas and distances, supported the notion that CNG projects are better suited for shorter distances (e.g., 1000 to 2500 km), while LNG is better suited for longer-distance projects. Subsea pipelines, on the other hand, are appropriate for much-shorter-distance natural-gas transportation (e.g., less than 500 km; see **Fig. 1**).

However, a more detailed comparative analysis based on the techniques and costs for the LNG and CNG was needed. In this paper, we try to fill that gap, and demonstrate the commercial promise for CNG in shorter distance and smaller volume (and, therefore, smaller required dedicated reserves) for sea-going natural-gas transportation vs. LNG.

LNG

Converting natural gas to LNG reduces it to one-six-hundredth of its standard-conditions volume, allowing transportation by specialized tanker ships over long distances. The production and storage of LNG are usually conducted in onshore facilities. The major components of the value chain include: (1) natural gas production,

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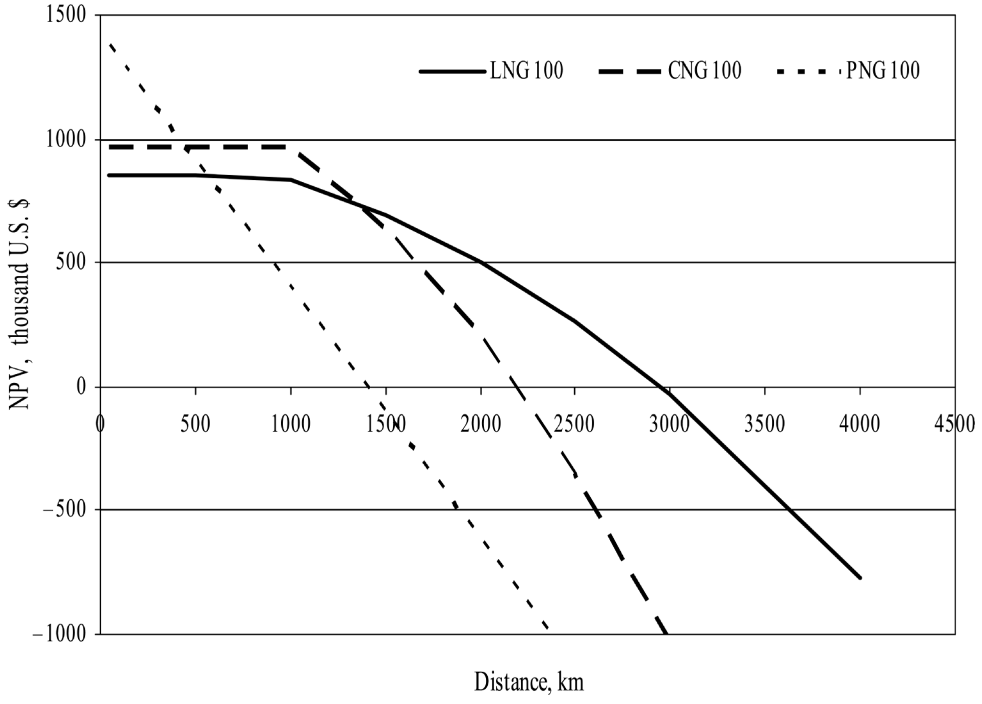

Fig.1—Sea-going transportation techniques: comparison results for 100 MMscf/D (Subero et al. 2004).

(2) the liquefaction process (the "cascade" cycle is the most common technology) in which the pretreated natural gas becomes liquefied at a temperature of approximately –256°F (–160°C), (3) transportation, (4) regasification, and (5) distribution.

Cost of the Technology

The equipment involved in the processing and transportation of LNG is very capital intensive and highly specialized. The liquefaction plant is the most expensive unit of LNG production, costing from U.S. $750 million to $1.25 billion (Hakes 1997). This is nearly 50% of the total investment. Offloading of the LNG requires special facilities, namely a regasification terminal. Regasification facilities cost $500–550 million depending upon terminal capacity (Stone 2001). LNG tankers, dedicated specifically to each project, are complex and expensive. Shipping of LNG is a function of distance of transport. Assuming the ships for transporting LNG are newly built, the unit cost of shipping ranges from U.S. $0.41 to $1.5/MMBtu for distances from 500 to 5,000 miles (Andersen 1997). Overall for LNG, the total investment can range from U.S. $1.5 to $2.5 billion depending on the market needs and number of ships required. **Fig. 2** shows the cost components for a typical LNG project; a very large part of the investment is in fixed assets.

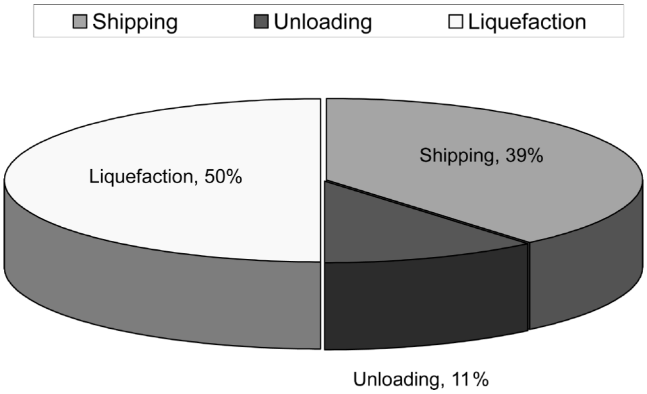

Fig. 2—Cost components for an LNG project (Economides 2005).

CNG

CNG as a mode of transport of natural gas is now pursued with renewed interest. Earlier attempts in the 1960s to commercialize the technology were met with technical difficulties, which, along with the requirement of heavy investments and the price of natural gas, made the commercial application of the technology unfeasible (Dunlop and White 2003).

The discovery and development of a new type of pressure-containment vessel, called a Coselle (coil in a carousel), promises to make CNG transportation attractive. This high-pressure gas-storage and -transportation system is a very large coil of relatively small-diameter pipe sitting in a steel-girder carousel (Coselle 2006). A typical Coselle CNG carrier is a 60,000-DWT bulk carrier with 108 Coselles and a gas capacity of 330 MMscf. **Fig. 3** shows the Coselle CNG ship arrangement. The idea seeks to reduce the manufacturing cost of the gas-containment system. Spooling small-diameter (6-in.) coiled tubing into large carousels achieves the purpose. The gas is pressured up to 3,000 psi at ambient temperatures.

Another approach to transporting CNG has been named the Votrans (Volume Optimized Transportation and Storage), in which the natural gas is compressed and cooled to lower temperatures. This reduces the volume of the compressed gas, compared to just compressing it at ambient temperatures. At the lower temperatures of 0 to –40°F, the process works at lower pressures than would be required at ambient temperatures. For the Votrans concept, the ships carry the chilled compressed gas in a boxlike structure called the "CNG module". The design of the module consists of horizontal or vertical stacking of pipes **(Fig. 4).**

CNG Technology

The basic concept for CNG is to compress the original natural gas, which is at a certain temperature and pressure, to higher pressures and, in one method, chill it to lower temperatures. Specially designed ships, which have a containment system, transport the cold compressed gas. The technology can be divided into three parts: compression, refrigeration, and transportation.

The required brake horsepower of the compressor and compression stage can be calculated on the basis of the compression ratio, volume of gas, temperatures, and pressures (Arnold and Stewart 1999). Cran's studies (personal communication 2005) give

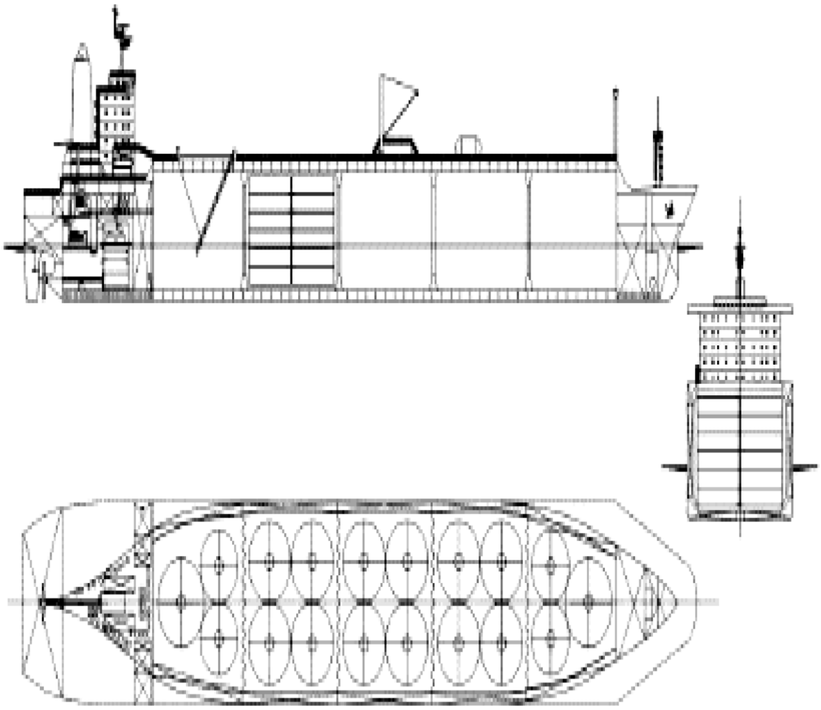

Fig. 3—Coselle CNG ship arrangement (Energy Information Administration 2006).

a correlation to predict the compression horsepower per unit MMcf/D as a function of the compression ratio **(Fig. 5).**

The discharge temperature of the compressed gas depends on the type of aftercoolers used. With air-cooled aftercoolers, the discharge temperatures are approximately 100°F (Toromont Process Systems 2006). Usage of seawater in the aftercoolers can reduce the discharge temperatures to 60°F (Toromont Process Systems 2006). To estimate the chilling requirement to cool the compressed gas to 0°F, –20°F, or –40°F, heat duty needs to be estimated on the basis of gas mass-flow rate, gas specific heat, and temperature difference (Paragon Engineering Services 2005). **Fig. 6,** also provided by Cran, predicts the refrigeration horsepower per unit MMcf/D based on the final discharged temperature.

The technology part of transportation includes the loading, the voyage using the CNG carriers, and the unloading. The transportation of CNG is capital intensive, requiring 85 to 90% of the total capital requirements for the process (Enersea Transport 2006). The onshore infrastructure for loading the compressed gas into the ship requires mainly the compressor and accessories. The chillers are on board the transporting ships, which reduced the need for special loading infrastructure to handle chilled fluids. Unloading of the gas is accomplished with a fluid-displacement mechanism. The displacing fluid is a mixture of ethylene glycol and water.

Cost of CNG Technology

This transport of natural gas requires less capital to deploy than LNG and is well suited to exploit isolated supply sources and limited consuming markets (Arnold and Stewart 1999). A CNG plant with loading facilities including compressors, pipelines, and buoys costs U.S. $30 to $40 million (Enersea Transport 2006). CNG ships, with chiller and fluid displacement on board, cost from $150 million to $300 million for ship capacities of 400 to 1,000 MMBtu (Enersea Transport 2006) for Votrans. The number of ships required for a certain transport distance depends upon the loading rate, voyage distance, and time required for a ship to make a complete cycle of loading, transporting, unloading, and returning. Therefore, the required CNG ship numbers will increase with the transportation-distance increase. **Table 1** shows the estimated number of ships required for transporting distances of 500 to 5,000 miles (Enersea Transport 2006).

For the Coselle technology, **Fig. 7** depicts the relation between the ship capacity and ship capital cost, where SSY represents a widely quoted London shipbroker, Simpson, Spence & Young (Cran 2005). CNG offloading facilities consisting of separators, scrubbers, and heaters cost from U.S. $16 to $20 million (Enersea Transport 2006). Overall, for CNG the total investment can range from $1 to $2 billion, depending upon the number of ships required. **Fig. 8** shows the cost components for a typical CNG project. One of the main attractions of CNG is that the bulk of the

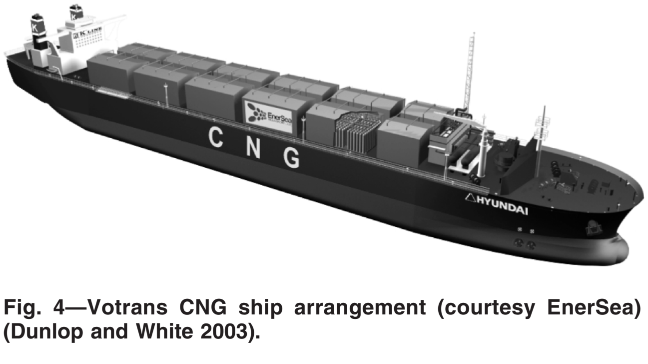

Fig. 4—Votrans CNG ship arrangement (courtesy EnerSea) (Dunlop and White 2003).

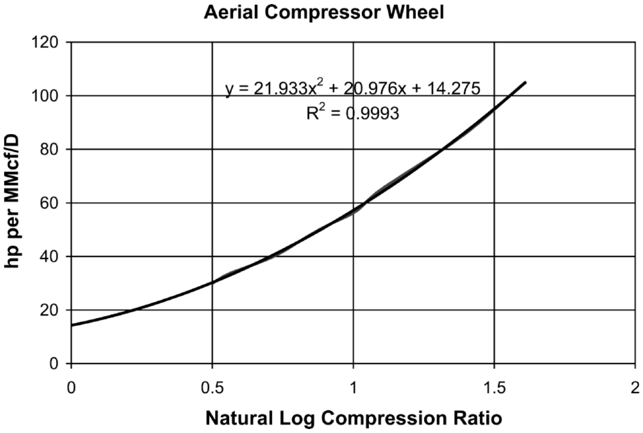

Fig. 5—Compression-horsepower prediction (Cran 2005).

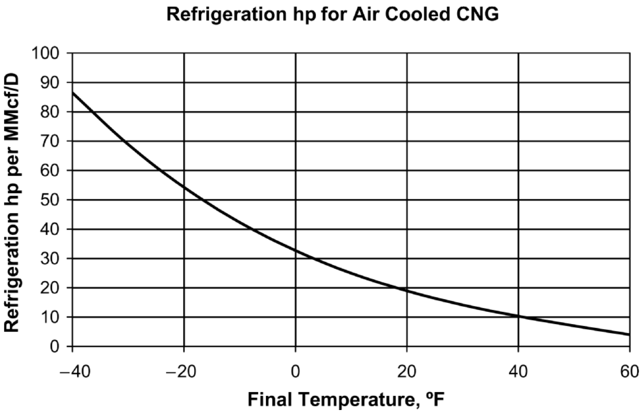

Fig. 6—Refrigeration-horsepower prediction (Cran 2005).

investment is in movable assets. To illustrate how the number of ships impacts the transport tariff price, an analysis of an actual project is presented in **Fig. 9** (Cran 2005). It shows that for a relatively short distance (less than 2000 km) and low ship capacity (650 MMscf), the number of ships affects the transport tariff considerably. This is because the total daily handled gas volume increases through the increase of ship number.

An optimized cost analysis was done for the range of containment pressures, temperatures, and distances based on an assumed 1,000-MMscf/D unloading rate. The criterion to optimize is the lowest cost sustained to transport the considered capacity of CNG. **Table 2** shows the optimum cost, in U.S. dollars per Mscf, with the optimum containment pressure and standard volume transported at those conditions at a given temperature. The results in Table 2 are for air-cooled compressors. Using water-cooled compressors and with the containment conditions remaining the same, the unit cost of delivered gas is raised by U.S. $0.01/Mscf. This translates into an increase of $8,000 to $12,000 for each cargo of CNG unloaded on the supplier side.

CNG vs. LNG

In comparing CNG with LNG, the same transporting-ship real-volumetric capacity is used. However, in making the comparison, it is worth remembering the disparity in the actual standard volume of the gas transported. For the same ship capacity, LNG transports 2.1 Bcf of natural gas compared to a maximum volume of 1.2 Bcf transported as CNG.

Keeping aside the difference in standard volumes, a proper comparison between the two technologies warrants a review of the requirements and the respective costs involved for both.

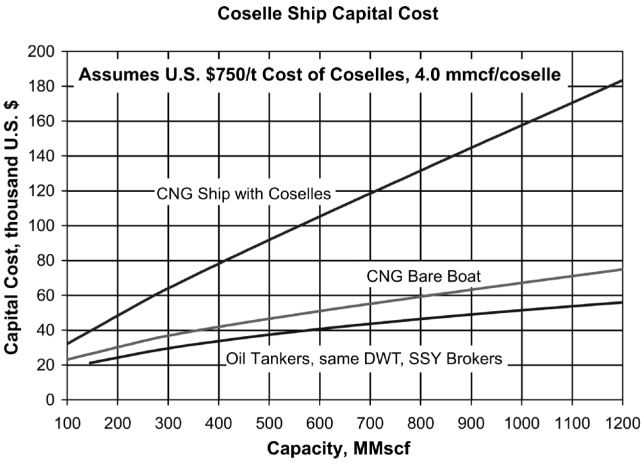

Fig. 7—Coselle ship capital cost (Energy Information Admin. 2006).

TABLE 1—NUMBER OF SHIPS ESTIMATED FOR A RANGE OF VOYAGE DISTANCES

Distance (miles)	No. of Ships
500	3
1,000	4
1,500	5
2,000	6
2,500	7
3,500	8 to 9
5,000	11 to 12

For any LNG project to be economically viable, a throughput of 0.5 to 1 Bcf/D of natural gas is required. An LNG plant of 3 MMtpa needs a gas rate of 400 to 450 MMscf/D (Hakes 1997). This translates into gas reserves of 5 to 8 Tcf for a project life of 20 years, depending on the amount of condensates in the gas (Hakes 1997). CNG projects, on the other hand, do not require such an amount of reserves for the same throughput (Paragon Engineering Services 2006). Fields with modest reserves and gas rates can support CNG projects (Arnold and Stewart 1999).

To compare CNG with LNG, a review of the costs involved with both is indicated. These do not include the transportation costs of ships and other facilities required for loading or unloading. For CNG, the ships cost approximately U.S. $230 million (Enersea Transport 2006), while for LNG, the ships cost approximately $160 million (Inst. of Energy 2003). The simplicity of the CNG operations provides an added advantage over LNG. The equipment required is easily available, with little or no detail to be customized (Inst. of Energy 2003). Both technologies share the common need for specially built ships carrying the respective cargoes of LNG or CNG. For LNG, the main consideration during its transportation is maintaining the state of the liquid, which in the case of CNG is simply maintaining the pressure and temperature without concern for changes of phase.

For LNG the typical value chain per MMBTU of gas is as follows: exploration and production, U.S. $0.5 to $1.0/MMBtu; liquefaction, $0.8 to $1.2/MMBtu; and regasification and storage, $0.3 to $0.5/MMBtu (Inst. of Energy 2003). Thus, the total cost of producing and transporting LNG can range from $2 to $4.2 per MMBTU for distances from 500 to 5,000 miles.

For CNG, keeping the same unit cost for exploration and production, the value chain per MMBTU is as follows: exploration and production, U.S. $0.5 to $1.0/MMBtu, and processing and transportation, $0.88 to $3.82/MMBtu for distances from 500 to 5,000 miles. This translates into a unit cost of $1.38 to $4.82 per MMBtu.

Taking a stranded-gas price of U.S. $0.75/MMBtu for both CNG and LNG and liquefaction cost of $1.0/MMBtu with regasification cost of $0.4/MMBtu, the unit price of LNG delivered is

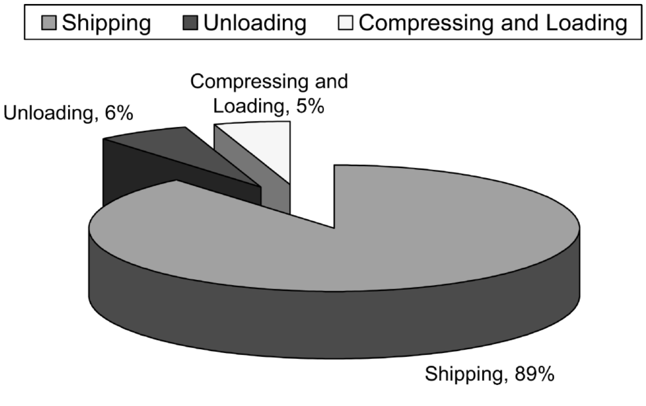

Fig. 8—Cost components for a CNG project (Subero et al. 2004).

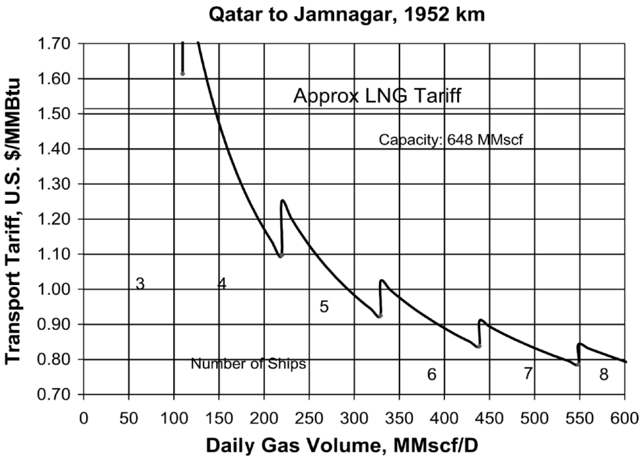

Fig. 9—Cost analysis for different ship numbers of Qatar-to-Jamnagar CNG project (Cran 2005).

shown in **Table 3. Table 4** shows the comparison of the unit price of the delivered CNG with that of LNG.

Fig. 10 shows a plot of the comparison of the unit price of gas delivered as CNG and as LNG. It is clear that for distances up to 2,500 miles, CNG can deliver the gas in a more cost-effective manner than LNG; for distances greater than 4,000 miles, LNG becomes more cost-effective than CNG. The main reason for the CNG cost escalation is the substantial investment required in the larger number of ships that are needed. **Fig. 11** is one case study of CNG vs. LNG cost comparison based on 400-MMscf transportation capacity (Cran 2005). These results fairly support our conclusions.

One factor in the choice between CNG and LNG is the pace of the project deployment. Typically, LNG projects require at least 4 to 5 years from the planning stage to the delivery of first cargo. CNG projects can be commissioned in a period from 30 to 36 months, beginning with the project design, planning, and construction of the required infrastructure and delivery of the first cargo (Enersea Transport 2006). Clearly, technology such as CNG would be inherent for faster application and monetization of reserves with smaller volumes and unattractive options for LNG or pipeline.

What is apparent is that CNG is eminently competitive with LNG for the considered conditions in this study. Whereas LNG has a strong point in its capability to transport larger volumes of gas in each trip, its inability to market stranded reserves makes CNG very attractive for smaller reserves and smaller users. LNG is more suitable for the long-distance transports of gas.

Opportunities of Application

What are the worldwide potential applications of CNG? The question is especially relevant in light of many recent announcements for LNG projects, all expected to remedy the otherwise looming natural-gas shortages.

TABLE 2—OPTIMUM UNIT COST OF TRANSPORTING THE GAS AS CNG PRESENTED IN U.S. $/Mscf

Distance (miles)	Cost ($/Mscf)	Pressure (psig)	Volume (MMscf)
At *T* = 0°F			
500	0.96	1,800	880
1,000	1.23	1,800	880
1,500	1.51	1,800	880
2,000	1.79	1,800	880
2,500	2.34	1,800	880
3,500	2.90	1,800	880
5,000	4.01	1,800	880
At *T* = –20°F			
Distance (miles)			
500	0.95	1,600	950
1,000	1.2	1,600	950
1,500	1.47	1,600	950
2,000	1.75	1,600	950
2,500	2.02	1,600	950
3,500	2.56	1,600	950
5,000	3.57	2,000	1,120
At *T* = –40°F			
Distance (miles)			
500	0.93	1,400	1,030
1,000	1.13	1,400	1,030
1,500	1.46	1,600	1,160
2,000	1.72	1,600	1,160
2,500	1.86	1,600	1,160
3,500	2.53	1,600	1,160
5,000	3.33	1,600	1,160

As determined in this work, for distances up to 2,500 miles (or even longer), CNG is potentially a very successful means to transport natural gas. **Fig. 12** is a map of the world showing regions with large commercial possibilities for CNG (Dunlop and White 2003). These include the major markets of North America, Asia, and Europe. Considering the present market prices of natural gas and LNG's advantage to transport more gas, LNG stands a better chance for distances between Australia, Indonesia, and Nigeria and the U.S., or the same countries and Japan or the emerging huge market of China. However, CNG would be an obvious option for transporting gas from the Pacific coast of Russia to Japan and China, Algeria and Libya to Europe, Atlantic Canada, and the northeastern U.S., and the Cook Inlet and the northwestern coast of the U.S. Even announced and developed projects such as Trinidad

TABLE 3—ESTIMATED UNIT COST OF TRANSPORTING THE GAS AS LNG

Distance (miles)	Transport Cost (U.S. $/MMBtu)	Unit Cost (U.S. $/MMBtu)
500	0.4	2.55
1,000	0.5	2.65
1,500	0.6	2.75
2,000	0.7	2.85
2,500	0.8	2.95
3,500	1.1	3.25
5,000	1.5	3.65

TABLE 4—COMPARISON OF UNIT PRICE OF DELIVERED GAS AS CNG WITH LNG FOR THE CONSIDERED DISTANCE

Distance (miles)	Transport Cost (U.S. $/MMBtu)	Unit Cost (U.S. $/MMBtu)
500	2.55	1.63–1.66
1,000	2.65	1.83–1.92
1,500	2.75	2.14–2.19
2,000	2.85	2.39–2.45
2,500	2.95	2.52–2.98
3,500	3.25	3.16–3.51
5,000	3.65	3.92–4.57

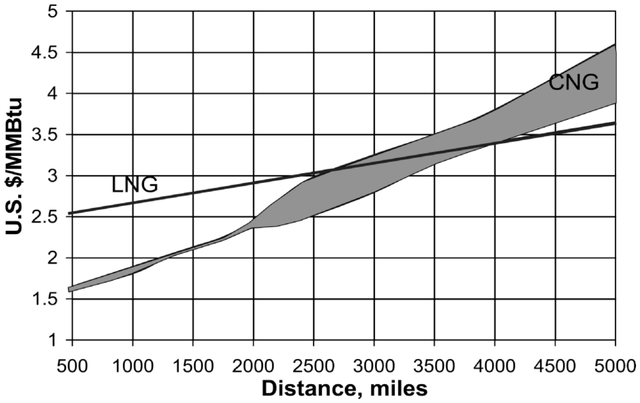

Fig. 10—Plot of unit price delivered gas as CNG and LNG against considered distance.

to the U.S., (potential) Venezuela to the U.S., and, especially, North Africa to Europe should seriously consider CNG instead of LNG.

One way of applying the CNG technology is in conjunction with LNG (Dunlop and White 2003). It can work as a complement for an LNG project because CNG can serve as a temporary solution for reserves that can eventually support an LNG project. Such an application monetizes the reserves earlier, thus accelerating "cash flow and economic return for the exploration costs." Meanwhile, the production behavior can prove CNG viability to support a long-term LNG project. Also, CNG provides the option of a fallback in the case of failure of the LNG and is far more flexible to unforeseen market fluctuations.

Conclusions

From this study, it can be ascertained that the offshore CNG transport of natural gas is economically viable. The required hardware and processes such as compression and refrigeration are easily available using standard industrial equipment. Ships for transporting the chilled compressed gas are unique in design and provide an efficient way for containment and transport of gas. Simple loading and unloading requirements provide an advantage in using the technology for offshore purposes.

For both the Coselle and Votrans technologies, 90% of the investment is in transportation, making CNG projects less risky. This gives the flexibility to move assets around as needed in case a project fails to live up to its expectations.

One drawback is the smaller volume of gas transported. LNG transports two to three times the amount of gas that CNG can transport based on present concepts. The main advantage of CNG is the low cost at which it can be transported over distances up to 2,500 miles, in which CNG is more cost-effective than LNG. CNG's ability to market small reserves is an additional benefit. The technology has a wide scope of commercial application, linking major markets such as North America, Japan, China, and Europe.

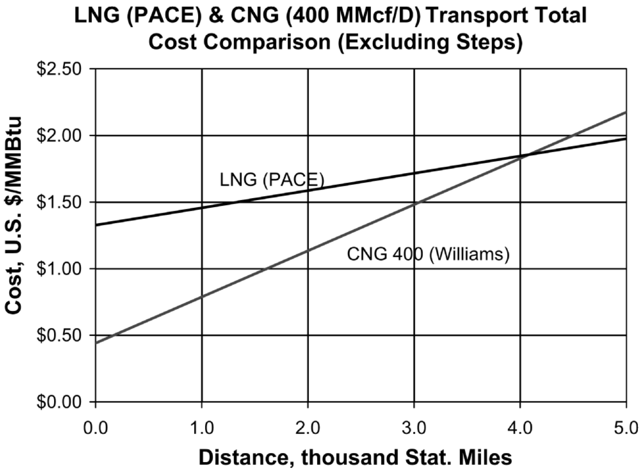

Fig. 11—LNG and CNG (400 MMscf/D) transport total-cost comparison (Cran 2005).

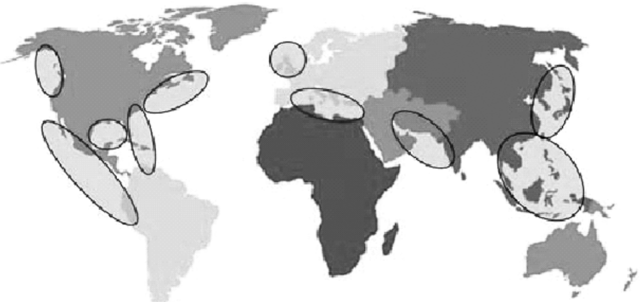

Fig. 12—Scope of applying the CNG technology worldwide (Dunlop and White 2003).

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SI Metric Conversion Factors

Btu ×	1.055 056	E+00	= kJ
ft^3 ×	2.831 685	E–02	= m^3
°F	(°F – 32)/1.8		= °C
in. ×	2.54*	E+00	= cm
mile ×	1.609 344*	E+00	= km
psi ×	6.894 757	E+00	= kPa

*Conversion factor is exact.

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