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The Economics of Compressed Natural Gas Sea Transport

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Abstract

Natural gas has come to the forefront of the international energy debate. The reasons include increasing demand in the United States, China and India and a changing worldwide preference in power generation because of environmental concerns. As a result, the transport of natural gas becomes important. Currently, 70 percent of gas is transported to market by pipeline and 30 percent as liquefied natural gas (LNG).

Pipelines are attractive but, offshore, their feasibility is greatly hindered by distance limits and terrain restrictions. On the other hand LNG facilities are expensive to construct and the process is complicated, costly and energy wasteful. It is applicable primarily for long distances and large volumes of gas.

Sea-going compressed natural gas (CNG) is an alternative that has been proposed in recent years but has not made substantial headway for two reasons: 1) the emphasis for investments by producers and large consumers has been primarily on LNG; 2) CNG boat designs and projects have been envisioned to eke a bite out of the LNG pie which is not necessarily a good approach.

CNG must make a niche in smaller markets and shorter distances. Here we present definitive economics by performing a specific case study for Sakhalin Island, Russia. Results delineate the landscape where this mode of transport is attractive and how it can be deployed with specific requirements of distance, market size and size distribution. Our studies show that for shorter distances (e.g., 500 km, about 300 miles) and even relatively large volumes, LNG cannot compete with CNG and at longer distances (e.g., 2,000 km, about 1,250 miles) CNG is far more attractive at small volumes, assuming that offshore pipelines are not feasible. For volumes such as 1 to 2 billion cubic meters per year (about 35 to 70 billion cubic feet per year), CNG is the only feasible solution to bring this energy source to many markets. These findings suggest that many parts of the world (such as the entire Mediterranean basin, the Scandinavian peninsula, Sakhalin Island, South-East Asia and the Caribbean) would be better served by CNG even if LNG projects have already been approved and under construction.

We also performed a sensitivity study on gas price (both at the source and at the market) impacts on the value of both CNG and LNG projects and determine the breakeven points under a given gas demand of e.g., 1.5 Bcm/yr (about 50 Bcf/yr) and a distance of 1,500 km (about 900 miles). For example if the source price is $6/MMBtu then the breakeven price for CNG is $10.05 whereas for LNG it will have to be $14.24, a 40% increase.

Introduction

Arguably, natural gas is becoming a more and more important resource of energy, with its share in global consumption expected to increase dramatically over the next two decades. According to the most recent data available (Energy Information Administration, EIA, 2008), world consumption of natural gas is more than 105 Tcf (Trillion cubic feet), about 3,000 Bcm, an increase of 28% in a decade (compared with, approximately, 16% increase for oil and a 5% for coal). In the late 1990s analysts began to predict radical increases in the world natural gas energy share. Particularly aggressive was the forecast provided by Economides and Oligney (Economides *et al*, 2001), who predicted that by 2020 natural gas will make up 45 to 50% of the world energy mix, starting from a 22% share in 2000. Such increases in demand will be excruciating and will be the result of massive restructuring of the transportation sector to use natural gas either as CNG directly or, indirectly, by electrifying vehicles.

Besides the U.S, Europe, Japan and Korea, historically the leaders in natural gas consumption and whose demand will increase significantly, fast evolving large Asian economies such as China and India will definitely become new players in this rapidly expanding market. The dominant exporter of natural gas is and will be by far Russia, with its leading position in proved reserves (1,680 Tcf, about 50,000 Bcm) and production (over 23 Tcf, about 650 Bcm, produced in 2006) (EIA, 2008). However, other major energy producing nations will increase their natural gas activities, some with already established histories such as Algeria, Indonesia and Nigeria, others emerging already such as Qatar and, yet others, still lagging for various reasons such as Libya and Iran.

Because of all the above, methods of transporting gas from offshore and remote reserves have generated considerable and renewed interest. Such methods will certainly include the existing means of transporting natural gas such as pipelines and LNG but also others.

Whenever distance, sea depth or terrain constraints make offshore pipelines unsuitable, LNG carrier vessels are today the only means of transporting natural gas by sea. Nonetheless, because of the huge upfront investment required and large operating costs, LNG transportation can be economical only when large volumes of natural gas are shipped over long distances.

There is an alternative: Compressed natural gas, CNG. Satisfying small markets and monetizing small reserves are the two main targets that CNG schemes intend to pursue. This would unlock reserves which otherwise would remain stranded, and would supply many small markets that could not be economically justified via pipeline or LNG.

The scalability of the CNG sea transport system and the opportunity to reuse its major assets (the carrier vessels) make this concept even more attractive (Wagner *et al*, 2002).

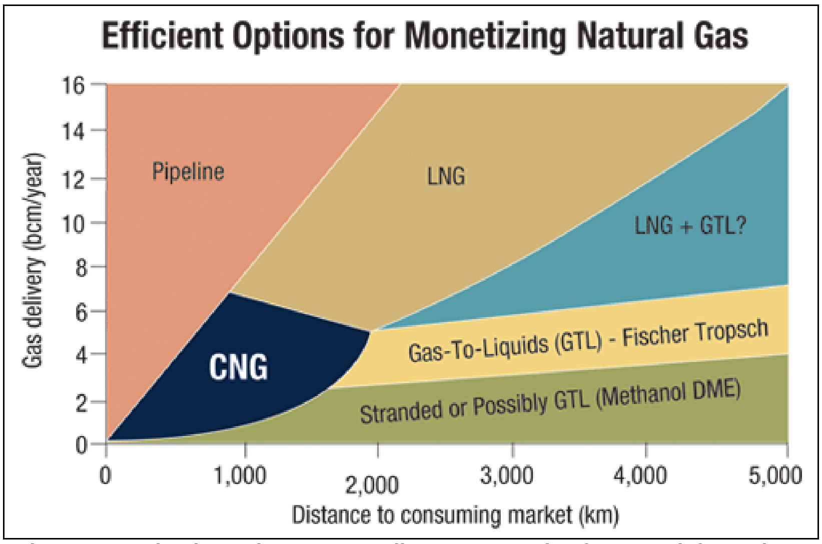

Figure 1: Production volume versus distance to market framework for various gas technologies, from Wood *et al.,* 2008.

Figure 1 shows the range of application for the currently known or contemplated technologies suitable to monetize natural gas (Wood *et al*, 2008).

In this paper we will present definitive economics, providing a quantitative support to the schematic presented in Figure 1. We will show the range where CNG transport is attractive and how it can be deployed within specific distances, market sizes and size distribution. We will show that for short distances (such as 500 km) and relatively small demand (such as 1 to 2 Bcm per year) CNG is the only feasible solution to deliver natural gas to the final destination markets, and even at longer distances (e.g., 2,000 km) CNG is still the most attractive option, assuming that offshore pipelines are not feasible.

We will apply the concept to case studies focusing on Sakhalin Island targeting markets in Korea, Japan and China.

Facilitating Technologies for CNG Sea Transport

The basic concept for CNG is to compress the natural gas at pressures ranging between 1,500 and 3,000 psi (about 100-200 atmosphere), and sometimes chill it to lower temperatures (up to -40°F, -40°C). The CNG technology is quite simple and can be easily brought into commercial applications. Nonetheless, no CNG sea transport projects are currently operated, even if the technology is already proven in several applications, including fueling taxis, private vehicles and buses worldwide. In 1969 the first attempt to build up a CNG carrier vessel brought to commissioning a rudimentary cargo bottles with CNG capacity of 1,300 Mcf, but the overwhelming required investment (compared to the scarce profit achievable in those years with extremely low natural gas prices) made the application and diffusion of the technology impracticable.

The development in the last decade of several innovative containment concepts is finally promising to make CNG sea transportation attractive.

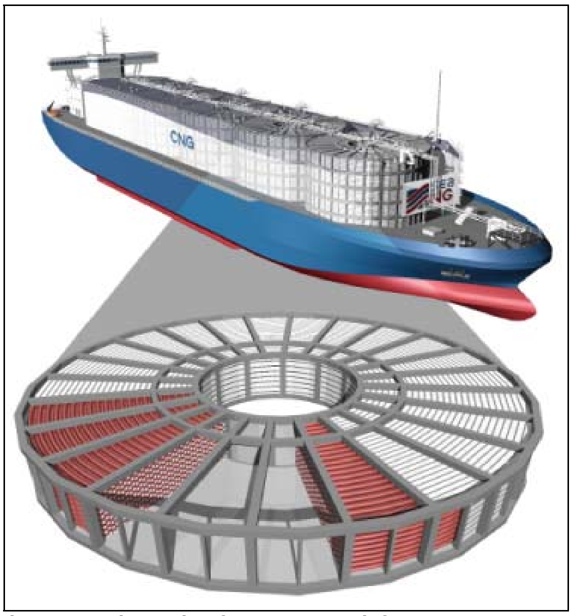

Figure 2: Schematic of a CNG vessel, from Sea NG Corp., 2008.

One of these concepts, employs a high-pressure gas storage and transportation system based on a coil of relatively small-diameter pipe (6 to 8 inches, about 15 to 20 cm) sitting in a steel-girder carousel. Considering natural gas compressed at 3,000 psi and at ambient temperature, a typical CNG carrier assembled with 108 carousels can offer up to 330 MMscf (about 10 MMscm) of capacity. Figure 2 shows such a CNG vessel arrangement.

Another concept requires that the compressed gas is also cooled to temperatures generally below 0°F, in order to achieve a further reduction of the gas specific volume. This high-pressure gas storage and transportation system is based on horizontal or vertical arrays of 36 meter (about 118 ft) long large diameters pipes (40 inches, about 1 m), segregated and manifolded into common pressure and flow system in groups of 24, called modules.

These modules are then arranged in holds, whose count determines the CNG carrier capacity; the largest model of such a vessel can offer up to 800 MMscf (about 22 MMscm) of capacity. Figure 3 shows this CNG vessel arrangement.

The on-shore facilities required to load and off-load the gas for CNG transport are minimal, if compared to LNG. Essentially, a compression station is required at the loading site, unless the gas transported via pipeline from the processing plant is already available at pressures compatible with the one required by the vessel containment technology. Simple jetties (or buoys, if the vessel is moored at a certain distance from the coast) are used to connect to the vessels and guarantee a continuous loading/offloading flow. According to the distance of the gas final destination from the offloading site, another compression station may be necessary to send the CNG at the required pressure.

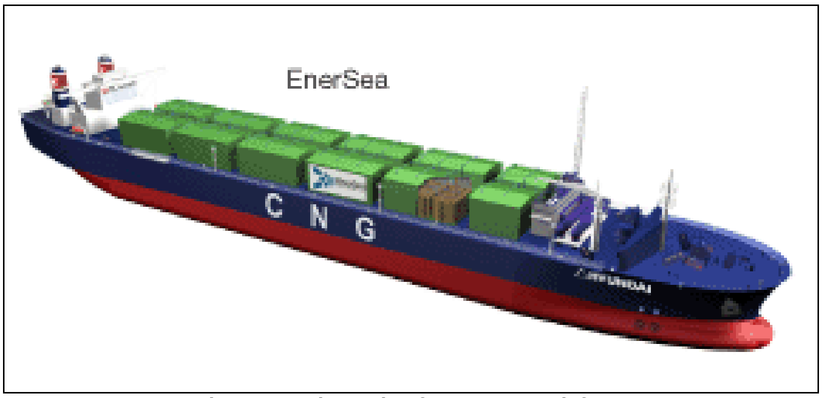

Figure 3: Schematic of a CNG vessel, from Enersea Transport LLC, 2008.

Both CNG loading and offloading sites have virtually no environmental impact, especially if compared with the massive installations required to process, liquefy and load the gas into LNG vessels, and to offload, re-gasify and store the gas at the receiving terminals. These relevant differences are illustrated in Figure 4.

Figure 4: Loading and offloading facilities for LNG and CNG, from XGAS, 2008.

Economic Analysis of CNG and LNG Sea Transport Projects

The criterion selected for the assessment of the economic desirability of CNG and LNG sea transport projects is the Net Present Value (NPV). We have developed a comprehensive calculation model that, starting from a hypothetical market demand of natural gas located at a certain distance from a source, determines the optimal configuration for the transportation scheme (optimal number of vessels with a given size) and then determines the discounted cash flow as the difference between the generated annual revenue stream and the tailored outlay of capital and operating costs. By comparing full project life conclusions from expected NPVs can be drawn about the profitability of the transporting option (CNG versus LNG) as well as the specific configuration for the transportation schemes. One example of potential CNG application presented in this paper is to transport stranded gas from Sakhalin Island to Northeast Asia.

Sakhalin Case Study

Background Information

Sakhalin Island is located off Russia's eastern shore with recoverable oil reserves around 7 billion barrels, and natural gas reserves at approximately 2,200 Bcm (80 Tcf) (Energy Information Administration, IHS Energy, 2008). Up to May 2008, Sakhalin has been housing six oil and gas projects. Five of the six projects have been in different stages of development, and two of the projects, Sakhalin I and Sakhalin II projects are already in advanced stages of development with Asian markets as the ultimate target (see Figure 5).

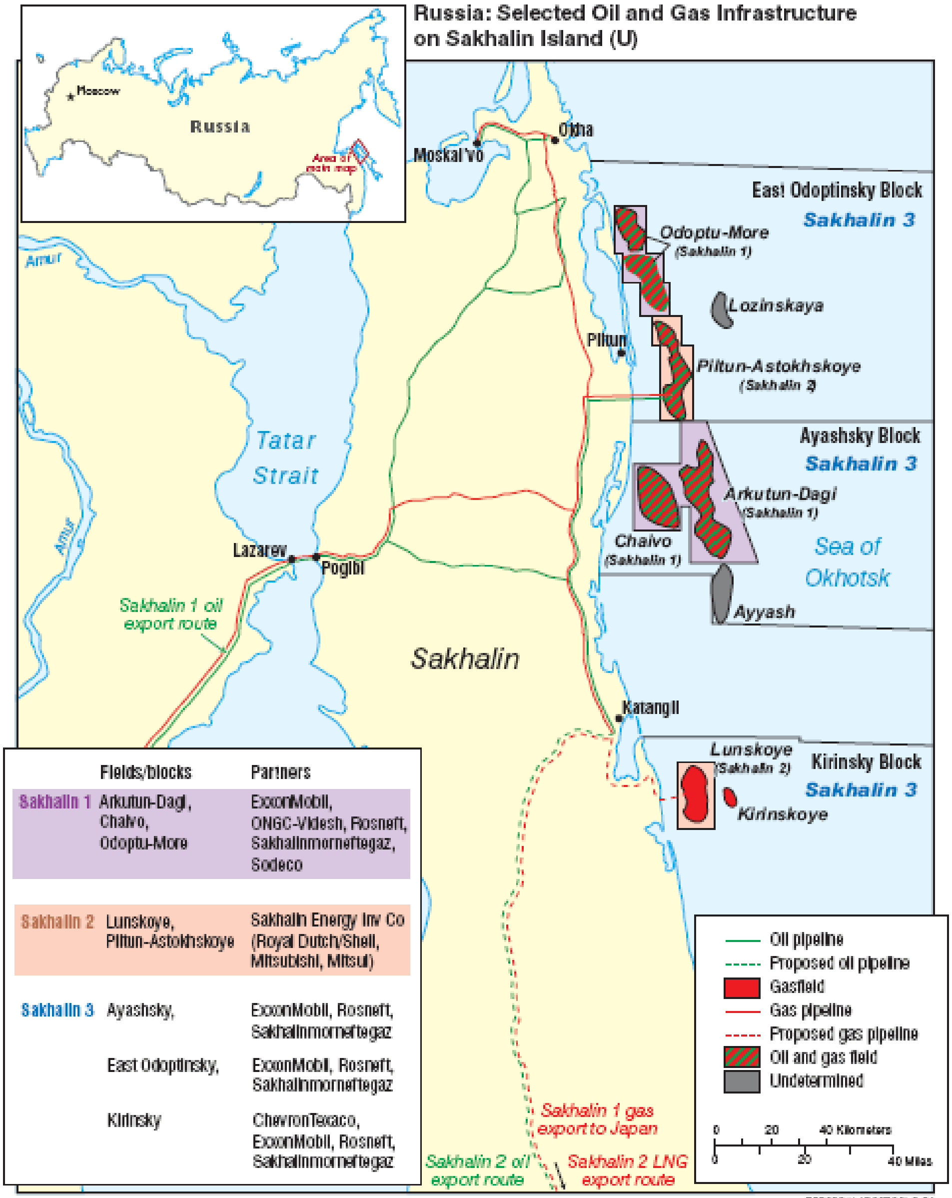

Figure 5: Sakhalin I, II and III projects, from EIA, 2008.

- Sakhalin I includes three fields: Chayvo, Odoptu, and Arkutun Dagi. These three fields with natural gas resources estimated at 17 trillion cubic feet (485 billion cubic meters, Sakhalin I website, 2008), can provide a large, long-term commercial supply of gas for export and also supplement regional domestic supplies in Russia. As of January 2008, domestic gas sales totaled 76 Bcf (2.2 Bcm), with an average supply rate of 115 MMscf/day (3.27 MMscm/day) in 2007 (Sakhalin I website, 2008). ExxonMobil is proposing to send the natural gas to the south via pipeline to China, yet other shareholders and Gazprom prefer marketing natural gas as LNG via Sakhalin II (Energy Information Administration, 2008), which would require an expansion of the facilities there.
- Sakhalin II comprises two fields in the sea of Okhotsk offshore Sakhalin Island: the Piltun-Astokhskoye field which is primarily an oil field with some associated gas and the Lunskoye field which has large reserves of gas and some oil. The two fields together contain in place reserves of approximately 140 million tons (1 billion barrels) oil and 550 Bcm (20 Tcf) natural gas. (Sakhalin Energy Investment Company website, 2008). The gas reserves represent nearly five years of Russian gas exports to Europe, or enough to supply current global LNG demand for four years. The oil and gas will be transported via a 800 km onshore pipeline to the site of a planned LNG plant and oil and LNG export terminals in Prigorodnoye, in the south of Sakhalin Island. From there, natural gas will be transported to the United States, Japan and South Korea via LNG tankers. Due to logistical, environmental, technical, and geo-political issues, LNG production has been delayed (Energy Information Administration, 2008).

In late 2004, Sakhalin Energy signed a contract with Coral Energy to supply 1,800 Bcf of LNG over 20 years to a power plant on the border of California and Mexico, using a re-gasification terminal being constructed in Baja California, Mexico. In March 2004, Sakhalin II announced the sale of 300,000 TPA of LNG to Japan's Tokyo Gas and Tokyo Electric Power (TEPCO), initially planned to start in summer 2008. In July 2005, the project operators announced a 20-year sales agreement for 1.6 million TPA of LNG to Korea Natural Gas (KOGAS).

Although LNG transportation is already in the picture, (see Figure 6 for the planned LNG transportation routes), it may not be the best option from an economic point of view. Based on our modeling, it is far more attractive to transport CNG from Sakhalin island to Northeast Asia such as Japan, South Korea, and possible to Shanghai in China. Here is why.

The distances from the source (Sakhalin Island) to the markets (Japan, South Korea, and China) are in the range of 1,500 to 3,000 km (about 900 to 1,800 miles) (See Figure 7). For comparison purpose, we use the proposed LNG routes as the routes for CNG transportation plus an additional route to transport gas from Sakhalin to Sapporo (500 km, about 300 miles), Japan.

The parameters used for this study are:

- Gas demands: 1 and 2 Bcm/yr, respectively;
- Distances: 500 (Sakhalin to Sapporo), 1,500 (to Tokyo), 2,600 (to Shanghai, China or Seoul in South Korea), and 3,000 km (to Taipei), respectively.

Figure 6: Sakhalin LNG proposed exportation routes, from Sakhalin Energy Investment Company LTD, 2008.

The capital cost allocation for CNG and LNG are illustrated in Figures 8 and 9, respectively. Detailed cost comparison of CNG and LNG transportation is summarized in Appendix 1. Constant gas consumption (delivery) rate is assumed.

Another important assumption for this study is that the receiving terminal is not equipped with any temporary storage facility (neither land nor offshore). This means that once the vessels are moored and connected to the offloading system, gas will be fed directly to the final destination point, at an offloading rate equal to the required consumption rate. The optimal number of vessels needed is determined as a direct function of the following parameters:

- vessel capacity;
- vessel sailing speed;
- transit distance between source and final destination;
- gas loading rate (the offloading rate is assumed to be the same as the required consumption rate);
- connecting and disconnecting times to the loading/offloading systems.

Each vessel is required to continuously iterate the cycle of loading and offloading at the source and market, in a perfectly synchronized schedule with the other vessels employed. The minimum required number of vessels is set to be three.
Gas thermal content ratio is set at 1,040 Btu/scf, gas price at source is set at $8/MMBtu, gas selling price is set at $16/MMBtu and discount rate is set at 15%.

Based on these assumptions, NPV is calculated for 15 years, capital expenditures are invested at time zero.

Figure 7: Five potential transport routes for CNG and LNG projects, from South Sakhalin Island.

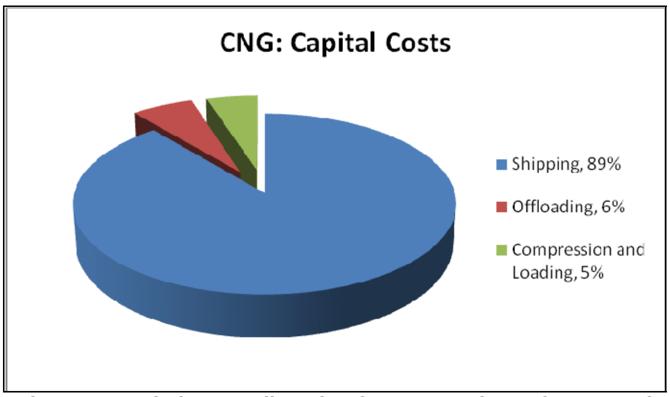

Figure 8: Capital costs allocation for CNG projects, from Wood *et al*, 2008 and Economides *et al*, 2005.

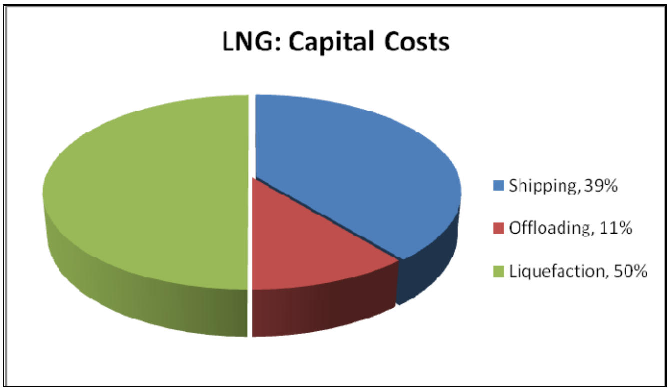

Figure 9: Capital costs allocation for LNG projects, from Wood *et al*, 2008 and Economides *et al*, 2005.

Results Discussion

The results are presented in Figure 10. As expected, at low gas demand and a relative short distance, LNG simply cannot compete with CNG even at distance of 3,000 km. Results show that, at gas demand of 1 Bcm/yr, the NVP of CNG is $1,723 million at 500 km and $473 million at 3,000 km. At 2 Bcm/yr, the NPV is $767 million at 500 km and $85 million at 3,000 km. LNG, on the other hand significantly underperforms. The NPV is negative $627 at 1 Bcm/yr and $168 million/yr at 2 Bcm/yr within 3,000 km.

The reason the NPV for LNG is constant at given distances is because the calculated number of LNG vessels needed within 3,000 km is less than three, so three vessels are used for practical purposes as stated earlier. As a result, the three vessels need to spend a certain amount of time moored, doing nothing but waiting on the preceding vessel to complete its offloading phase. This “dead-time” would gradually decrease for longer and longer distances, until it reaches a specific distance at which the three vessels would be finally used at their full potential. For instance, for a gas supply rate of 2 Bcm/yr this critical distance is 6,000 km (about 3,700 miles).

The number of vessels needed for CNG is bigger than three and it is calculated based on the assumption given above. The correlation between the number of vessels needed for CNG transportation and distance is plotted in Figure 11.

The conclusion from this part of the study is that CNG is a much better solution than LNG to transport natural gas from Sakhalin to Sapporo, Tokyo, Shanghai and Taipei if the gas demand is within 2 Bcm/yr.

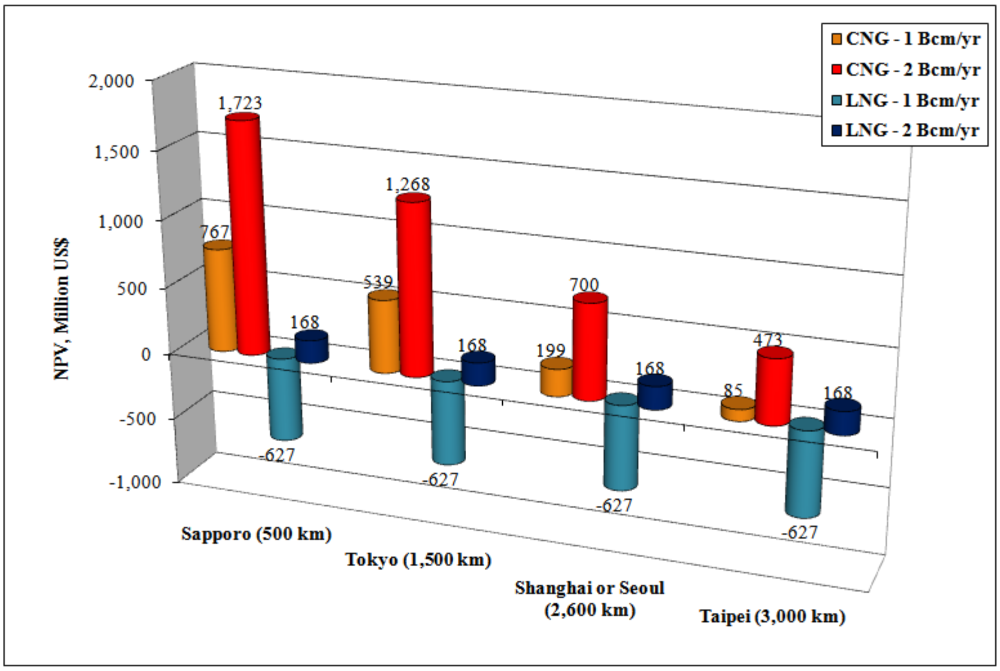

Figure 10: NPV’s calculated for CNG and LNG transportation schemes from South Sakhalin to Sapporo, Tokyo, Shanghai and Taipei.

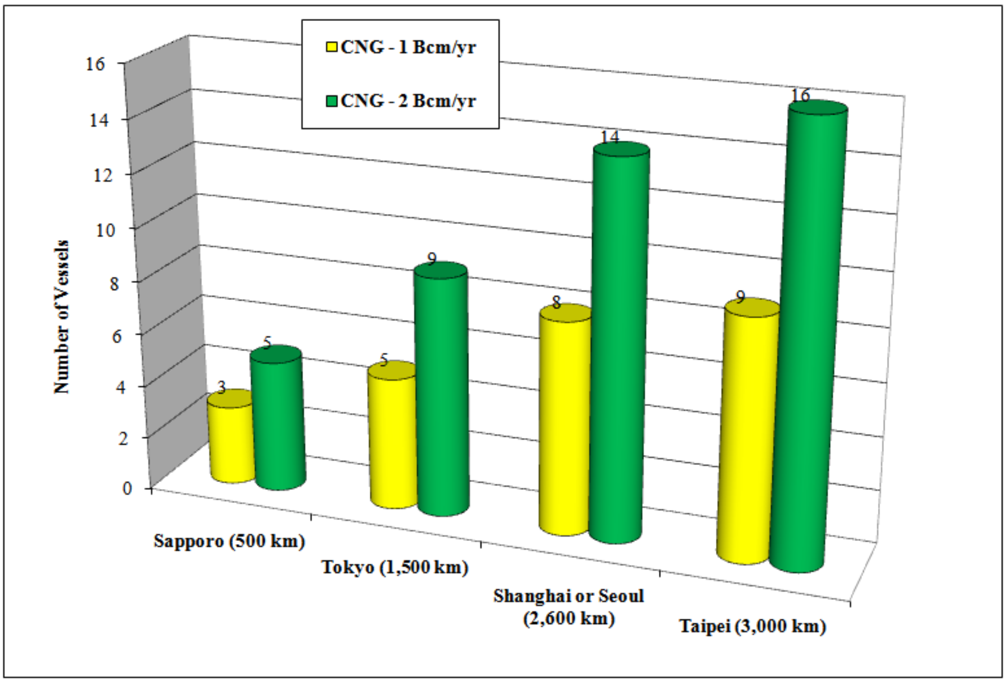

Figure 11: Required number of CNG vessels for transportation schemes from South Sakhalin to Sapporo, Tokyo, Shanghai, Seoul and Taipei.

So where is the boundary of CNG application in terms of gas volume? To answer this question, a specific scenario with 2,600 km (about 1,600 miles, such as Sakhalin-Seoul and Sakhalin-Shanghai) and different gas demands are selected.

Results are shown in Figure 12. Results show the intersection point between the CNG and LNG lines is about 4 Bcm/yr (about 140 Bcf/yr). That means if the distance between the source and the market is 2,600 km and the gas demand is within 4 Bcm/yr, CNG will be a better option than LNG.

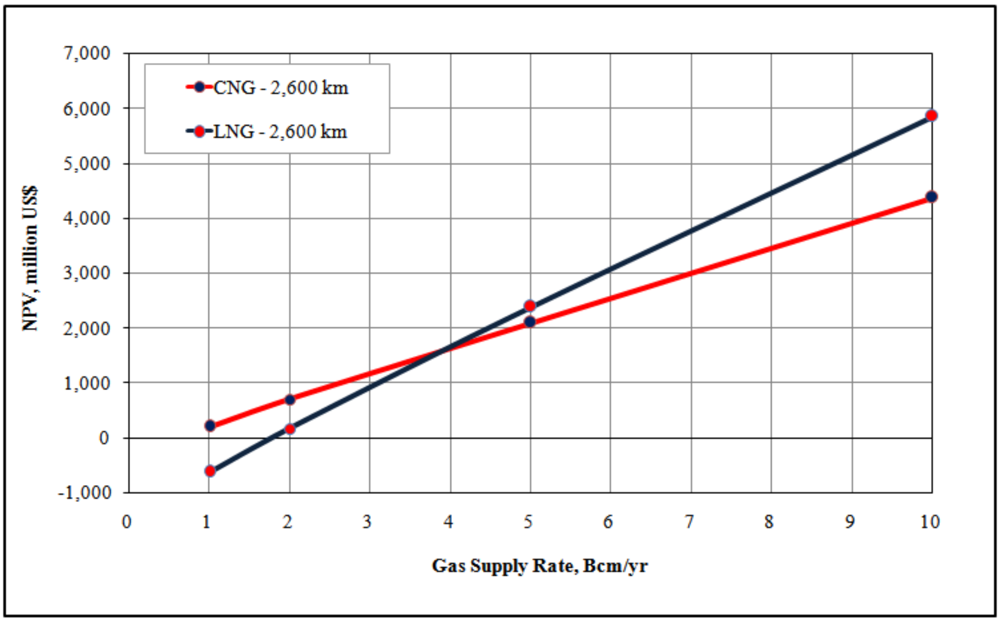

Figure 12: NPV's calculated at different gas supply rate for CNG and LNG transportation at distance of 2,600 km.

As second exercise, we have considered a specific project gas supply rate (2 Bcm/yr), and calculated additional NPV at longer distances. Results are illustrated in Figure 13. The intersection point between the CNG and the LNG lines represents the distance boundary for this gas supply rate for CNG to be preferable to LNG. This is 3,600 km (about 2,200 miles). Beyond this point, LNG should be used. Thus for the Sakhalin case, it is more economic to export 2 Bcm/yr of natural gas by CNG anywhere that is within 3,600 km. Although at 2 Bcm/yr and beyond 3,600 km LNG should be considered, it is not optimal for this LNG project as the NPV is still a constant through 6,000 km. This means that within 6,000 km, the number of needed LNG vessels is less than three and three is selected for practical purpose. That is why “small scaled LNG” has become part of the debate recently.

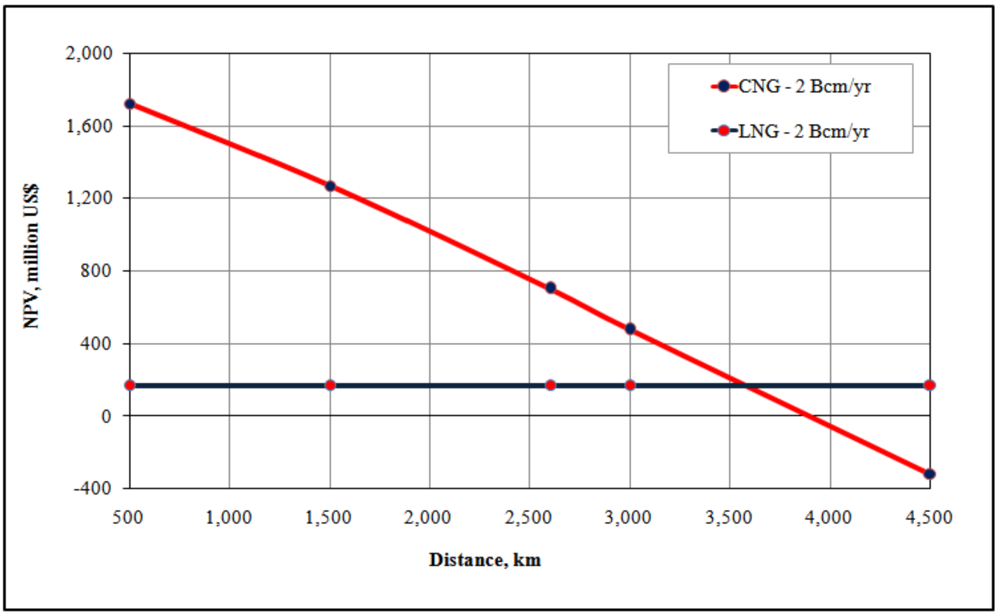

Figure 13: NPV’s calculated for CNG and LNG transportation schemes at 2 Bcm/yr, for greater distances.

So far the study has been based on different gas demands and distances. Beside these two parameters, there are many other parameters that are keys to the project. Below are sensitivity studies on the impact of gas prices on the NPV for both CNG and LNG projects.

Sensitivity Study: The Impact of Gas Prices on the NPV Model for CNG and LNG

Customers at the final destination want to pay as little as possible for the delivered loads of either CNG or LNG, while the initial gas providers want to sell gas at the highest possible price. Therefore the potential CNG/LNG project operators have to establish long term agreements (generally linked to the project timeframe) with both gas providers and customers at the final destination and try to achieve their maximum profit. They need to identify the breakeven point at the given difference between the two gas prices (source and destination).

In simpler words, they need to be able to answer the two following questions:

- what is the maximum gas price at source that will give the project a breakeven point for a fixed gas selling price?
- what is the minimum gas selling price at the market that will give the project a breakeven point for a fixed gas price at source?

To answer these two questions, we performed a set of sensitivity studies for both CNG and LNG projects. The set of input parameters for the base case are given in Tables 1 and 2 for CNG and LNG, respectively. We assume the gas demand is 1.5 Bcm/yr and the distance from the source to market is 1,500 km, the optimal number of vessels is calculated for the CNG case (here is seven), while for the LNG case three vessels are considered, as the calculated number of the actual needed vessels are less than three (for the reason discussed above, three LNG vessels are used whenever the calculated number of vessels is less than three).

At the discount rate of 15%, the resulting break even selling gas price at the market for CNG and LNG are calculated and presented in Figure 14 for a range of buying prices at the source. Results show that gas transported as CNG can be sold at considerably lower prices than gas transported as LNG. For example, if the source price is $6 the prices for CNG would be $10.05 whereas for LNG would be $14.24, 40% higher. Similarly, the same figure shows the allowable gas price at the source for a given sale price at the destination. For $15 sale price, gas for LNG should be purchased at no more than $7 whereas gas intended for CNG can be purchased almost at $11 and still be economically attractive.

Table 1: Input values for CNG study.

Gas Supply Needed, Bcm/yr	1.5
Transit Distance, km	1,500
Sailing Speed, knots	14
Vessel Capacity, MMscf	150
Number of Vessels	7
Fuel Usage	5%
CapEx per vessel	$ 115,000,000
CapEx Loading Facility	$ 50,000,000
CapEx Offloading Facility	$ 25,000,000
Crew Daily Cost	$ 5,000
Annual Maintenance	2%
OpEx Contingency	10%
Insurance	0.8%
Project Life, yr	15
CPI	2.5%
Discount Rate	15%
Taxes	35%

Table 2: Input values for LNG study.

Gas Supply Needed, Bcm/yr	1.5
Transit Distance, km	1,500
Sailing Speed, knots	14
Vessel Capacity, MMscf	3,000
Number of Vessels	3
Fuel Usage	7%
LNG Thermal Efficiency	78%
CapEx per vessel	$ 150,000,000
CapEx Liquefaction Facility	$ 500,000,000
CapEx Regasific. Facility	$ 400,000,000
Utilities & Offsite	$ 80,000,000
Crew Daily Cost	$ 15,000
Annual Maintenance	5%
OpEx Contingency	12%
Insurance	1%
Project Life, yr	15
CPI	2.5%
Discount Rate	15%
Taxes	35%

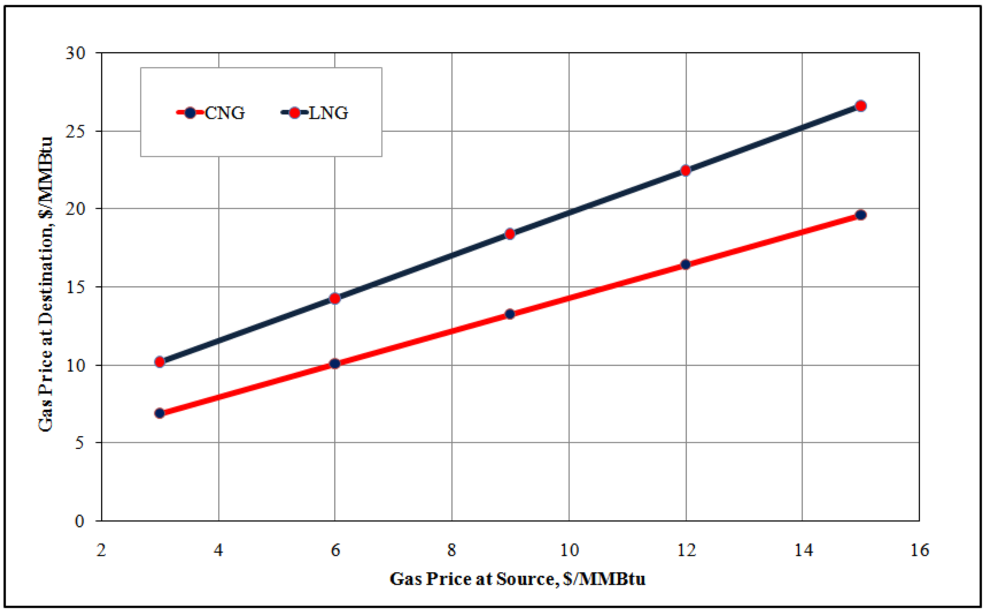

Figure 14: Project breakeven points at given gas prices.

Conclusions

In this work we have shown how a comprehensive economic model can be used to evaluate the relative attractiveness of natural gas projects transported over seas as CNG and LNG. We have confirmed that CNG offers superior economic performances within distances of 500 to 3,000 km (about 300 to 1,800 miles) and up to 4 Bcm/yr (about 140 Bcf/yr). Thus CNG allows the monetization of smaller reserves that would otherwise remain stranded and can serve smaller markets that would otherwise not be receiving gas.

We have identified the specific boundary of economical optimum between CNG and LNG transportation schemes. For a given transit distance there is a specific gas supply volume below which CNG is the best solution; likewise, for a given gas volume there is a specific transit distance below which CNG is best.

In addition to the distance and volume to be transported, the key parameters for the economic analysis of CNG and LNG transportation schemes are the gas price at source and the gas selling price at final destination. For the constraints imposed on this study, for a given buying price at the source, gas transported as CNG can sell at about 40% lower price at the destination than gas transported as LNG.

We have then performed specific case studies for natural gas originating at Sakhalin Island and destined for East Asia and we have shown that CNG can be very attractive and superior to LNG for any location within 3,000 km. This includes a number of destinations in Japan, Korea and China.

Appendix 1: Cost Comparison of CNG and LNG Transportation

While the equipment required for processing and transportation of LNG is highly capital intensive, the simplicity of the CNG technology involves much less hardware and infrastructures, thus, much less capital to deploy than LNG.

Radically different is also the relative contribution of cost components. As illustrated in Figures 8 and 9 in the main text body, CNG projects are essentially dominated by shipping costs, while the liquefaction and re-gasification (offloading) facilities require the most of the total capital investment in LNG projects. This represents by itself an advantage for CNG because the bulk of required assets is movable and convertible to other analogous projects, while a very large part of the investment in LNG projects is in fixed assets.

The cost of a fully equipped CNG plant with compression station, pipelines, loading infrastructure and buoys ranges between $30 and $60 million (Wood *et al*, 2008, Economides *et al*, 2005, Wagner *et al*, 2002, Chang 2001 and Enersea Transport, 2006).

CNG offloading facilities, essentially consisting of separators, scrubbers and heaters cost between $16 and $20 million (Economides *et al*, 2005 and Enersea Transport, 2006).

The definition of construction costs for CNG vessels appears more uncertain: Wagner *et al*, 2002 assume that a capacity of 330 MMscf (about 10 MMscm) for a steel-girder carousel-based CNG carrier would cost about $110 million. In turn, both Wood *et al*, 2008 and Economides *et al*, 2005, mention the vertical arrays-based technology and assert that such a CNG vessel, with chiller and fluid displacement on board, would cost up to $250 million for ship capacities of 400 to 1,000 MMscf (about 11 to 28 MMscm).

However, it is a firm opinion of the authors that construction costs for CNG vessels would decrease below any current prediction, once the technology proves itself and several vessels are commissioned for various projects in different geographic areas. Furthermore, the capital cost could be cheaper if barges and tugs can be used instead of ships in CNG transportation. Current estimations for overall values of CNG investments are in the range of $1 and $2 billion or $0.5 to $1 billion if barges and tugs are used.

The liquefaction plant is the most expensive unit in the full chain LNG process. The costs of the facility show wide variation and are very site-specific (Coyle *et al*, 2003, Yost and Di-Napoli, 2003, Subero *et al*, 2004, EIA, 2008), between $750 million to $1.5 billion (Economides *et al* 2005, Hakes, 1997 and Wagner *et al*, 2002).

The EIA has published information regarding new LNG re-gasification terminals in the United States, estimated to cost $200 to $300 million for a capacity from 183 to 365 Bcf per year of natural gas. Stone (2001) and Economides *et al* (2005) mention higher costs for LNG re-gasification terminals, ranging between $500 and $550 million depending upon terminal capacity.

Construction costs for LNG vessels are defined more precisely than costs for CNG vessels. Information released by the Gas Technology Institute showed the average price of a 138,000 cubic-meter-vessel (about 3 Bcf), around $155 million. This value is essentially confirmed by Coyle *et al* (2003) and the University of Houston Law Center (2003).

Overall for LNG projects, the total investment can range from $1.5 to $2.5 billion, depending on the market demand and number of vessels required.

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References

Broeker, R.J.: “CNG & MLG-New Natural Gas Transportation Processes,” American Gas Journal (July, 1969).

Chang, S.: “Comparing Exploitation and Transportation Technologies for Monetization of Offshore Stranded Gas,” SPE 68680, presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, 17-19 April 2001.

Coyle, D., Durr, C., and Shah, P.,: “LNG: A Proven Stranded Gas Monetization Option,” SPE 84251, presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, 5-8 October 2003.

Economides, M.J., Kai, S., and Subero, G.,: "Compressed Natural Gas (CNG): An Alternative to Liquefied Natural Gas (LNG)," SPE 92047, presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, 5-7 April 2005.

Economides, M.J., Oligney, R.E., and Demarchos, A.S.:"Natural Gas: The Revolution is Coming," JPT, May 2001, pp. 64-71.

Energy Information Administration, Department of Energy (www.eia.doe.gov)

Enersea Transport LLC (www.enerseatransport.com)

Gas Technology Institute (www.gastechnology.org)

Hakes, J.: "Worldwide Natural Gas Supply and Demand and the Outlook for Global LNG Trade", Energy Information Administration/ Natural Gas Monthly, August 1997.

IHS Energy (http://energy.ihs.com)

Institute for Energy, Law and Enterprise, University of Houston Law Center: "Introduction to LNG," Technical Paper. January 2003.

Sakhalin Energy Investment Company LTD 2008 (http://www.winne.com/sakhalin/eng/shakalin%20energy.html)

Sakhalin-I Project (www.sakhalin1.com/en/project/marketing.asp)

Sea NG Corp. (www.coselle.com)

Stone, J.B.: "Applying New Technology to Lower LNG Cost", 4th Doha Conference on Natural Gas, March 2001.

Subero, G., Kai, S., Deshpande, A., McLaughlin, J., and Economides, M.J.: "A Comparative Study of Sea-Going Natural Gas Transport," SPE 90243, presented at SPE Annual Technical Conference and Exhibition, Houston, Texas, 26-29 September 2004.

Wagner, V. J., and Wagensveld, V. S.: "Marine Transportation of Compressed Natural Gas A Viable Alternative to Pipeline or LNG," SPE 77925, presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Melbourne, Australia, 8-10 October 2002.

Wood, D., Mokhatab, S. and Economides, M.J: "Technology Options for Securing Markets for Remote Gas," Proc. 87th Annual Convention, GPA, 2008.

XGAS LLC (www.xgas.us)

Yost, C., and DiNapoli, R.,: "Benchmarking Study Compares LNG Plant Costs," Oil and Gas Journal, Volume 101, Issue 15, April4, 2003.