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NEW ENERGY TECHNOLOGIES IN THE NATURAL GAS SECTORS:
A POLICY FRAMEWORK FOR JAPAN

USING SAKHALIN NATURAL GAS IN JAPAN

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Abstract

Reserves of natural gas offshore from Sakhalin Island provide a new, relatively close, source of energy for Japan. Sakhalin gas could be imported by pipeline or as LNG, or it could be converted to electricity and transmitted to Japan via a high voltage line. Despite the recent drop in LNG shipping costs, none of these methods of importing energy from Sakhalin is likely to be substantially cheaper than the others. Nevertheless, LNG may be the preferred option. First, LNG is associated with less technological, geological and environmental risk than is a gas pipeline. Second, lower shipping costs together with some other recent changes in the LNG industry are likely to favor shorter term multilateral trades of LNG relative to long term bilateral and project-specific contracts. Such a radical change in the worldwide market for LNG would reduce the risk of a Sakhalin LNG project. By contrast, building a pipeline or high voltage electricity transmission line would tie the Japanese economy more closely to political and economic developments in Russia.

Introduction

The discovery of substantial reserves of natural gas offshore from Sakhalin Island has opened new possibilities for importing energy to Japan. In particular, it has now become feasible to build a major natural gas trunk pipeline connecting the different regions of Japan. Such a pipeline could deliver benefits apart from a cheaper or more reliable source of energy. For example, it could increase the competitiveness of the Japanese energy industry. Nevertheless, we shall argue that it may be preferable to import the Sakhalin gas in the form of LNG.

The nature of the worldwide market for LNG could change radically in the next few years. A dramatic expansion in LNG trade as a result of falling transport costs and increased demand for natural gas for electricity generation is likely to favor short term multilateral trading over long term bilateral project-specific contracts. Japan will be in a much better position to benefit from such a change in market structure if it continues to use LNG rather than tie a substantial amount of its energy infrastructure to the Sakhalin fields.

This strategic argument also applies to the option of importing the energy content of Sakhalin gas in the form of electricity. A new high voltage electricity transmission line may provide ancillary benefits such as increased competition in the electricity supply industry, reduced air pollution and improved stability of the transmission grid. However, it also shares a major disadvantage with a natural gas trunk pipeline. The new infrastructure would tie the Japanese economy more firmly to future economic and political developments in Russia.

The Sakhalin Gas Fields

The gas reserves in the Russian Far East are substantial. The proven and probable reserves (2-P) are on the order of 50–65 trillion cubic feet and the proven, probable and possible (3-P) may be as high as 847 trillion cubic feet.¹ Table 1 below provides a breakdown for the different Sakhalin projects.

Table 1: Sakhalin Gas Reserves^a

Project	Official Reserves (2-P)	Wood Mackenzie Estimates (3-P)
Sakhalin I	6.7	14
Sakhalin II	11.9	16.1
Sakhalin III	NA	24
Sakhalin IV	NA	NA

a. Source: Troner (2000: 12).

These reserves are relatively close to Japan. Sakhalin is about 1,000 kilometers from Hokkaido and 2,200 kilometers from Tokyo.² The gas can be transported to major markets in Japan by pipeline or as LNG. As we shall discuss in more detail later, the energy content in the gas could also be transported to markets in Japan in the form of electricity.

The costs of moving LNG are fairly well defined. There are fixed costs that involve liquefaction, re-gasification, loading and unloading. These fixed costs run from \$1.40 to \$1.90 per 1,000 cubic

¹. For a very good discussion of these fields, and the physical obstacles to exploiting them, see Troner (2000).

². A pipeline more than likely would need to be longer than the great circle distances.

feet. The variable costs are \$0.15 per 1,000 cubic feet per 1,000 miles.³

By contrast with the situation for LNG, estimates of the cost of transporting the gas by pipeline to Japan vary widely. As Troner (2000) notes, the climatic conditions are very difficult. Temperatures range between -30°C to + 30°C and there are substantial construction problems. The sea is frozen four to six months a year and the sea freezes to the bottom in shallow off-shore waters. The geological conditions are also difficult, as the area is seismologically active and earthquakes are common. In addition to nature’s obstacles, the legal structure is difficult. Japan does not have eminent domain, and for this and other reasons construction costs there are among the highest in the world.

Troner estimates that the cost of transporting the gas by pipeline are between \$1.30 to \$1.80 per 1,000 cu. ft. At the Baker Institute Energy Forum Workshop in April, 2001, Wilson Crook of ExxonMobil and Paul D’Arcy of Shell Gas and Power Japan Ltd. also presented estimates of the cost of transporting gas to Japan from Sakhalin. The ExxonMobil estimate is reproduced as Figure 1.

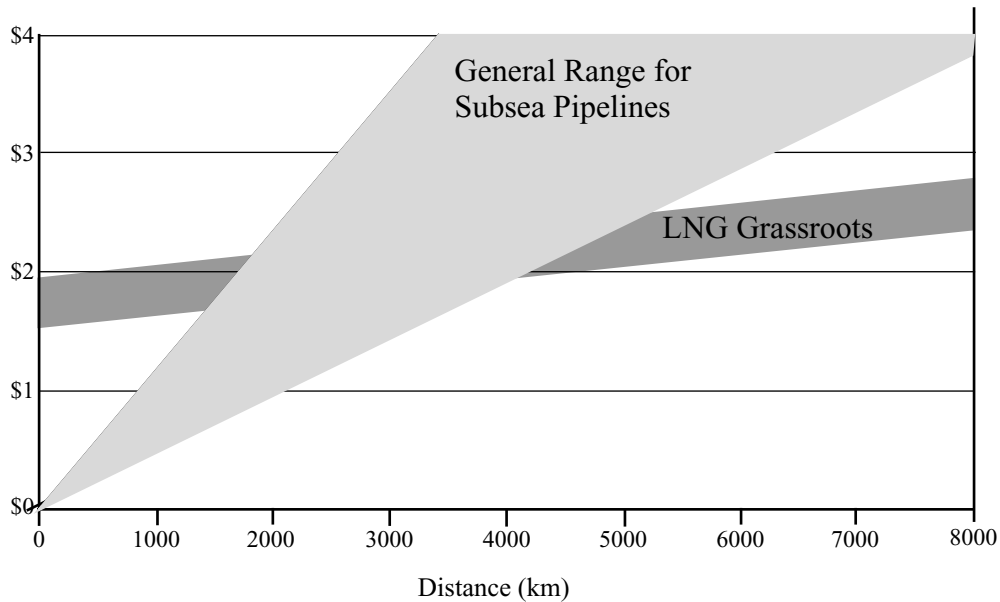


Figure 1: ExxonMobil Estimates of Relative Gas Transport Costs

³. These numbers were inferred from the calculations presented in Crook (2001), D’Arcy (2001) and Troner (2000).

The ExxonMobil numbers suggest that transporting gas by pipeline from Sakhalin to Tokyo is competitive with LNG. According to the ExxonMobil data, LNG and a pipeline could be competitive in the 2,000 to 3,000 kilometer range. As we would expect, however, pipeline cost estimates have more variance. In the best case, a pipeline is less expensive, but a pipeline could be much more expensive.

Shell Gas and Power Japan Ltd. presented estimates of the cost of transporting gas by onshore and offshore pipelines at the same Baker Institute seminar. Their estimate is reproduced as Figure 2.

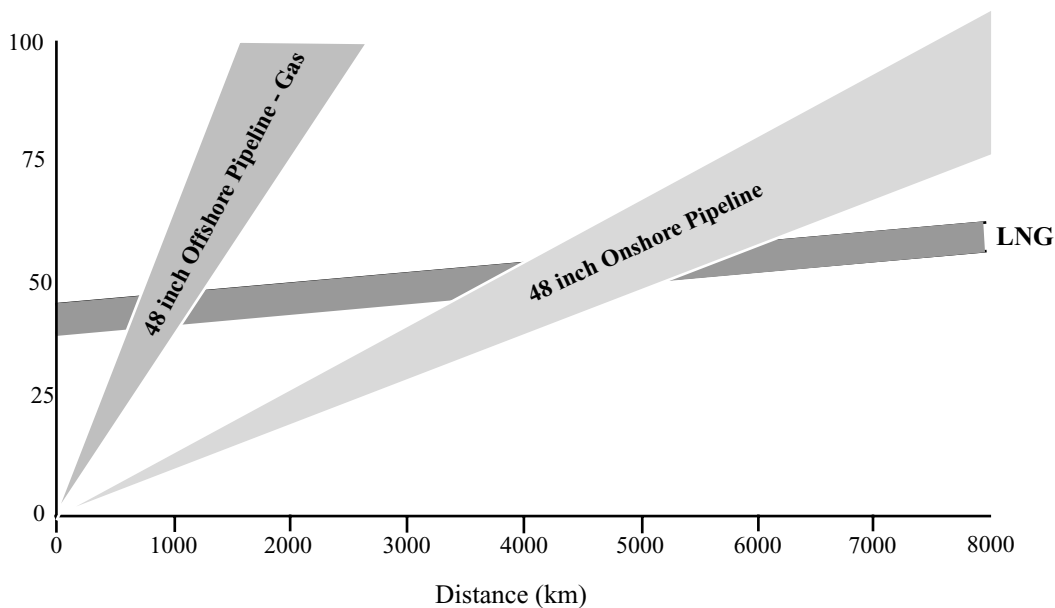


Figure 2: Shell Gas and Power Japan Ltd. Estimates of Relative Gas Transport Costs

Since the cost numbers presented by Shell are on a scale of 0 to 100, it not possible to compare them directly to the ExxonMobil numbers. If we use the cost of moving LNG as a common base, however, one point on the Shell scale would correspond to about \$0.035. Figure 2 also does not directly address the question of the cost of moving gas from Sakhalin to Japan. The Shell data imply, however, that an important element in deciding the cost is the proportion of the pipeline that has to be offshore.

Calculating the cost of the pipeline assuming that at least 1,000 kilometers must be offshore, we see in Figure 3 that the Shell numbers imply that LNG is cheaper for distances greater than 2,000

kilometers. The exact cost difference will depend on many uncertain factors, including how much of the pipeline is likely to be offshore.

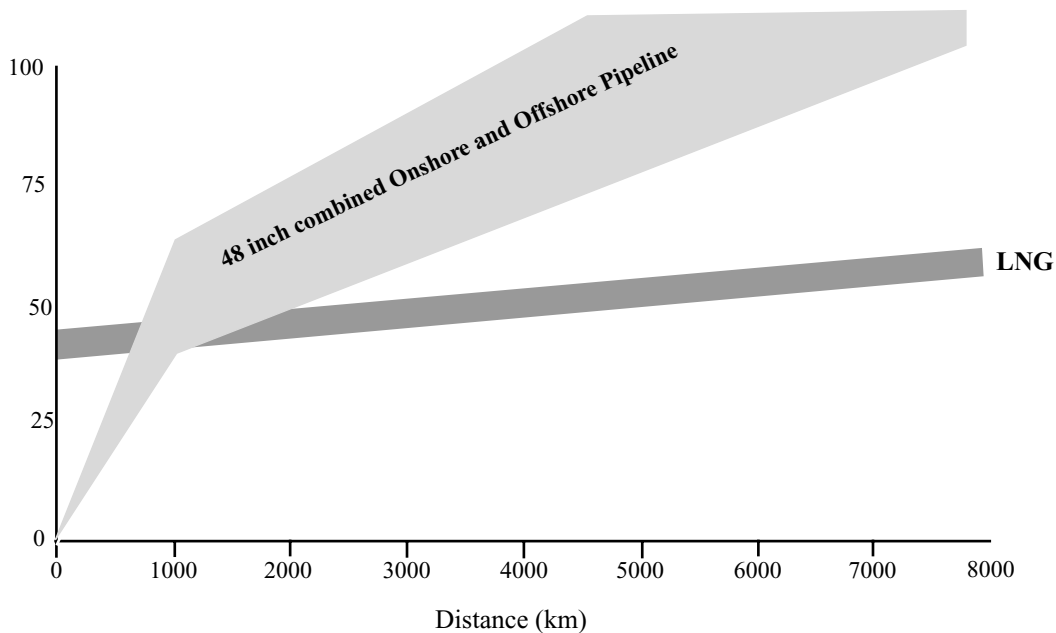


Figure 3: The Implied Cost of a Sakhalin Pipeline Using the Shell Numbers

The three studies that we have examined suggest that the costs of the two options for transporting gas are likely to be quite similar. Ultimately, if the choice is to be made on the basis of cost it will be necessary to have very detailed engineering, legal and environmental studies. Even then, it may not be possible to resolve a substantial part of the uncertainty until construction. We argue below that a major advantage of the LNG alternative is that there is less risk involved.

Given that there appears to be very little difference, a priori, in the cost of the two gas transport technologies, the question may not be one of pure economics, but rather one of political economy. We argue in section 4 below that the drop in the price of moving LNG in the past five years is likely to change the market for LNG. Currently, most LNG is produced under long term bilateral contracts. A more liquid market for LNG will turn it into a commodity more like oil, where contracts are of shorter duration, the spot market is more important, and switches in trading partners are more common. As Jaffe and Shook (2001) argue, this process has already started in the US. Before discussing the evolution of the market for LNG in more detail, however, we wish to exam-

ine another alternative to transporting gas either by pipeline or in the form of LNG.

Electricity Transport

Instead of transporting gas from Sakhalin to Honshu, the gas could be used in Hokkaido to generate electricity which could then be transported south to the main demand centers. The electricity link could be either high voltage direct current (HVDC) or alternating current (AC). We shall argue that a number of factors favor HVDC transmission from Hokkaido to a back-to-back converter station on the boundary between the Tokyo and Chubu electric utility districts.

The overall benefits of the favored electricity transport option would depend on a number of factors that could only be ascertained through detailed modeling of the Japanese electricity system. For example, one would need to examine the effect of a new transmission line on the stability of the overall electrical network in Japan. The marginal cost of 2-3,000MW of gas-fired power plants in Hokkaido and the associated transmission facilities will also depend critically on the planned path of investment in new generating capacity in Japan. Other factors, such as environmental and strategic considerations, or the likely effect of the new facility on competition between the major electric utilities, may also play a critical role in comparing the overall social costs and benefits of the favored electricity transport alternative relative to the favored gas transport alternative.

Competing Electricity Transport Options

Electricity can be transported over long distances using either high voltage AC or HVDC. In the current instance, the natural gas could be brought ashore in northern Hokkaido.⁴ Depending on the daily flow of gas from the Sakhalin fields, a number of gas-fired power plants could be built, perhaps up to 3,000 MW of capacity. To allow the existing transmission system to carry additional power from the north, the capacity of the AC lines in Hokkaido and northern Honshu would need to be upgraded, as would the existing undersea DC link between the two islands. An alternative would be to build an HVDC line from northern Hokkaido all the way to the vicinity of the pumped

⁴ As noted above, this would require the construction of perhaps 1,000 km of pipeline but would not require the fixed costs associated with constructing liquefaction and gasification plants.

storage facilities and Shin-Shinano link between the Tokyo and Chubu utility areas.⁵

A number of factors are likely to favor the HVDC option. The first is a direct cost comparison in treating the two transmission augmentations as stand-alone investments. For the same transmission capacity, a DC line has lower construction costs than an AC line. High voltage AC transmission lines are three-phase and therefore require at least three conductors. Arrillaga (1998: 260) observes, however, that a double three-phase line is needed to make the reliability of AC transmission equivalent to two-pole DC transmission. A typical DC line has two conductors (one for the return current flow), and thus requires smaller towers. Of particular relevance for Japan, where the costs of land are high, the DC line also requires a smaller right-of-way. The right of way for an AC line designed to carry 2,000MW is roughly 70% greater width than the right of way for a DC line of equivalent capacity. An offsetting factor is that the terminal stations for a DC line cost more. A longer transmission link implies that the saving in line construction costs can offset the additional cost of the stations. The so-called⁶ break-even distance occurs where the investment costs of the two types of lines are equal. Arrillaga (1998: 265) notes that the break-even distance increases with the amount of power to be transferred. In the presence case, the distance to Tokyo from the generating stations would be around 1,200 km and the amount of power involved at least 2,000 MW suggesting (depending on construction, land and other costs) that the investment costs for the HVDC line are likely to be lower.

Operating costs, in the form of transmission losses, are also lower on optimized⁷ DC lines than on optimized AC lines of the same power capacity. An offsetting factor is that the DC system has additional losses in the terminal stations where DC is converted to or from AC. The trade-offs between losses and capital costs will depend on factors specific to each project, including the cost of a right-of-way. For typical systems designed to transfer 2,000 MW of power, however, the losses in the HVDC system will be lower for distances above about 200 km.

5. Since there are no effective circuit breakers for DC lines, HVDC transmission is restricted to point-to-point flows.

6. This calculation ignores differences in operating costs discussed below.

7. The optimized lines balance out the discounted present value of transmission losses against capital costs. In general, losses can be reduced by using a more expensive transmission system. At the optimal trade-off between capital costs and losses for each type of system and the same power capacity, the DC system has lower losses.

It might be thought that the analysis of two competing systems transmitting the same power over the same distance is not relevant in the current case. After all, there already is a high voltage transmission system linking northern Japan with Tokyo and load centers further to the south and west. Thus, while a HVDC system would require an entirely new link an AC system might be able to use much of the existing transmission network.

The east coast of Honshu north of Tokyo already has 14 nuclear generating plants. One more is under construction and three are in the planning stage. In addition, one nuclear plant is under construction at the very north end of Honshu while four more are planned for the same region. Two of these planned nuclear plants will be owned by the Tokyo Electric Co. The objective obviously is to export electricity from the Tohoku area to Tokyo.⁸ In order to do so, the AC network at the northern end of Honshu island will need to be upgraded. Part of this network is at most 154kV, with the 500kV links extending no more than 300km north of Tokyo.

Adding gas-fired capacity in Hokkaido would only increase the need to upgrade the capacity of the AC links on Honshu. In addition, the existing DC link between the islands of Hokkaido and Honshu would need to be upgraded if additional power were to be transmitted between the islands.⁹ Some of the costs associated with building higher cost converter stations would thus be incurred even if most of the power were transmitted to Tokyo using the AC network on Honshu. It would make more sense, once the power from new gas-fired plant has been converted to DC, to transmit the power directly to the Tokyo region.

It is likely that a parallel HVDC north-south link would improve the stability and controllability of the existing AC system. Potential instabilities in an AC transmission system can be grouped into problems with frequency control,¹⁰ voltage levels¹¹ or unplanned outages. Since a DC link is an asynchronous connection, while the conversion stations at either end of the link include fre-

⁸. In financial year 1999, the Tokyo, Chubu and Kansai utilities had the lowest ratio of generation to sales, suggesting these centrally located and large demand areas imported power from the neighboring regions.

⁹. The current link is a bipolar 125 kV cable, 43 km in length and 600 MW capacity.

¹⁰. The generators in an AC system need to be synchronized so they rotate in unison at a speed that produces a consistent frequency. If the load on a generator decreases (increases) while the mechanical power driving the turbine remains constant the generator accelerates (decelerates). Changes in consumption, the output of other generators, or line faults can thus affect the frequency of oscillation of the power input into the system from the generators.

quency control functions, a HVDC link can assist with frequency control in the parallel AC system. A DC link also allows for a redistribution of the power flow in the AC network in response to swings in loads and generation inputs. The DC link is de-coupled from the AC system, allowing power transmission on the DC link to be freely and rapidly adjusted up to the design limits of the DC converter stations. HVDC links also can be controlled to carry a specific maximum amount of power. The outage of parallel AC lines then cannot overload the DC line. This may make the overall system more fault tolerant. An HVDC line can also assist with controlling reactive power in the AC system.

A new HVDC link from Hokkaido to the Tokyo region in Japan may thus greatly enhance the stability of the overall transmission system. If so, it would also enhance the capacity of the existing AC network to safely transfer power between regions. These conjectures would need to be tested using an engineering model of the Japanese electricity network augmented with the proposed new HVDC link.

Another feature of the Japanese electricity supply system favors a new HVDC link over an augmentation of the existing transmission network. The Japanese electrical system is divided between a 50Hz region including Tokyo and regions to the north and a 60Hz region including Nagoya, Osaka and regions further west and south. The advantages of being able to transfer power between the two frequency regions led to the development of the world's first zero distance DC link. The Sakuma interconnection was built in 1965, and upgraded to use solid-state thyristor valves in 1993 (Arrillaga, 1998: 87, 93). It allows for the transfer of up to 300MW in either direction.

A second back-to-back frequency conversion scheme, the Sin-Shinano link was built in 1977. It used solid state valves, but these were replaced by more modern valves in 1992 (Arrillaga, 1998: 93). The capacity of this link is also 300MW. A third back-to-back converter, the Higashi-Shimizu link, was completed in 1999. It also has a capacity of 300MW.

¹¹. Voltage instability can occur in an AC system as a result of reactive power flows. For example, consumers experiencing a large drop in voltage draw more current from the system. Reactive power flows then increase, causing additional voltage losses in the system.

The total capacity to transfer power between the 50Hz and 60Hz regions therefore is 900MW. This compares with a total 1999 installed generating capacity in the Tokyo electric utility area of 55,600MW and in the Chubu utility area immediately to the west of 25,020MW. By contrast, the existing system also allows the Tokyo utility to transfer 4,000MW with its neighbor (Tohoku) in the 50Hz system and Chubu to exchange up to 2,500MW with its neighbor (Kansai) in the 60Hz region.¹²

A 2,000–3,000MW HVDC link from Hokkaido could be terminated somewhere near the existing Shin-Shinano frequency converter. The greatest advantage of terminating the HVDC link in the Shin-Shinano region is that the southern end of the link could be terminated with two frequency converters. This would allow the power from the north to be used in either the 50Hz or the 60Hz region depending on where the demand for electricity is greatest. In effect, the transfer capability between the two regions might be increased from 900MW to something much closer to 3,000MW.¹³ A greatly increased capacity to transfer power between the two frequency zones could bring sufficient cost savings to pay for a substantial part of the capital cost of the scheme.

A further advantage of placing the terminal near the existing Shin-Shinano frequency converter is that there is substantial pumped storage capacity in the vicinity. The pumped storage would allow power from the link to be stored at times when it is not needed by end users. The transmission link probably could be operated profitably at full capacity most of the time, allowing maximum value to be obtained from the initial capital investment.

Transporting Electricity or Gas

A catalog of existing HVDC links might suggest that transporting electricity is more costly than transporting natural gas. Most of the earliest HVDC links involved submarine cables where the

¹². In 1999, Tohoku had an installed generating capacity of 12,750MW and Kansai an installed capacity of 29,960MW (International Energy Agency, 1999: 94).

¹³. Maintaining stability of the 50Hz AC network might mean that some of the power transferred on the HVDC link might always need to be supplied to the 50Hz region. Hence, the full capacity of the HVDC link might not be available to arbitrage between the two frequency regions. A model of the whole transmission system would be required to evaluate the different options.

cost advantage of DC over AC is greatest. Others involved exploiting hydroelectric resources that are located far from the sources of demand. Unlike natural gas or coal, there is no practical alternative to long distance high voltage transmission of hydroelectric energy. There have also been some interesting variations on these themes, however, and it may be instructive to examine a couple of these.

In 1970, the Pacific DC intertie was constructed to link the northwest and southwest areas of the US.¹⁴ The most unusual feature of the scheme was that the DC link was installed in parallel with two AC (60Hz) circuits at 500kV. Arrillaga (1998: 88) claims that a major motivation for using a DC link in addition to the AC circuits was that the DC link helped stabilize the system and provide additional control features. This has an obvious parallel with the proposed HVDC link in Japan, suggesting that it, too, may provide system control services.

The Square Butte scheme was another interesting application of HVDC in the US. Installed in 1977, this was one of the earlier uses of solid state thyristor technology, which has played such a large role in reducing the cost of HVDC transmission in more recent decades. In the Square Butte scheme, the cost of siting a generating plant in North Dakota and transporting the electricity to Minnesota via a 750km, 500MW DC link at 250kV was found to be cheaper than transporting the coal to a generating station sited in Minnesota. Again, system stabilization was one of the ancillary benefits provided by the DC link.

Lignite deposits are similar to hydroelectric resources in so far as the lignite is often very expensive, if not impossible to transport. The high moisture content of lignite makes it liable to spontaneously combust. The Coal Creek/Dickinson project in the US, built in 1979, was justified as a cost effective way of using a lignite deposit to generate base load bulk power (Arrillaga, 1998:90). The HVDC link transported 1,000MW over 702km at 400kV.

Perhaps the most instructive North American example for our current purposes, however, is the

¹⁴. The 1,440MW link is bi-directional. Seasonal diversity in load and generation between the north and south make it desirable to transmit power in both directions at different times of the year. The link thus was not justified solely by the need to transmit hydroelectric power from remote regions to major load centers. The link was upgraded to 1,920MW in 1986 when solid state thyristors were also installed.

so-called Neptune Project.¹⁵ This is a proposal to use natural gas from the Canadian provinces of Nova Scotia and New Brunswick to supply electricity in Boston, Connecticut, and New York City. Natural gas from these Canadian provinces has, since late 1999, been supplied to the Canadian-US interconnected pipeline network. The gas is thus already available for electricity production in the northeast of the US without any further expansion in the geographic extent of the gas pipeline network.¹⁶ The proposed project nevertheless would involve a 1,200MW HVDC submarine cable link between New York City and Nova Scotia, a distance of approximately 1,000km. Even though cable transmission is more expensive than the type of overhead network we are suggesting for Japan, the promoters of the Neptune Project believe that the proposed HVDC cable is competitive with the transport of gas.

The proposal is to complete the New Brunswick-New York link in 2004. This would be preceded by a short 1,200MW submarine link between New York City, Long Island and New Jersey in 2003. The New York City-Canada link would be followed by two more 1,200MW submarine links from Canada to the US. Scheduled to be completed in 2005 and 2006, these would link Nova Scotia with Maine, the Boston area, Connecticut and, via the New Brunswick link, New York City.

The promoters argue that there are a number of benefits of the Neptune Project over the alternatives. The first is said to be that the project will improve the stability of the AC transmission network. Another major benefit is said to be more economical sharing of generation facilities. The southern part of the proposed link has a peak demand for electricity in the summer while the northern end has a peak demand in the winter. The link will allow power to be transmitted in either direction. The promoters have also suggested that there are environmental benefits of the proposed scheme. Power generated with oil and distillate fuels in New York City could be replaced by power imported over Neptune, significantly reducing air pollution in the New York metropolitan area. A related issue is that planning approval for new power generation plants may be more difficult to obtain in the New York City area than in remote Nova Scotia. In addition, the

¹⁵. Information about this project is available at <http://www.neptunerts.com/>.

¹⁶. Additional demand for natural gas for electricity generation in New York City, Boston or Connecticut would, however, require the capacity of some pipelines to be increased.

cost of land and other costs associated with building a power plant (for example, labor costs and the costs of complying with emissions standards) could be higher in the New York metropolitan area.

Arrillaga (1998: 275-276) briefly discusses the comparative costs of transmitting gas via pipeline and transmitting electricity via an overhead HVDC line. He argues that the variable cost of transporting gas is substantially higher than the costs of transmitting electricity via HVDC, with the cost advantage of electricity transmission increasing with the price of land. Since the gas transmission alternative does not involve stations for converting power between DC and AC, however, the cost of the plant is higher for the HVDC alternative. Arrillaga presents some rough calculations for cost of two “green fields projects” (that is, two systems designed simply to move energy from point A to point B with no other issues involved). His numbers suggest that for a transmitting 2,000MW over 1,000km, the HVDC alternative is likely to be slightly less costly.

Of course, calculating the costs of two “green fields projects” is not the relevant comparison in the present case. Either option is likely to have significant side-effects that need to be taken into account.

An potentially important difference between transporting gas and transporting electricity is that the former option may be more compatible with minimal disruption of the existing plans for development of the electricity network. If Sakhalin gas were converted to LNG and used largely in place of gas imported from Southeast Asia, Australia and elsewhere, the same terminal facilities and power stations could be used as was planned in the absence of Sakhalin gas.¹⁷ LNG currently provides about 12% of Japan’s energy used to produce electricity. Three combined cycle plants using LNG as an input and with a total capacity of close to 5,000MW are due to be completed by 2005.¹⁸

¹⁷. In practice, the availability of Sakhalin gas may change the planned addition of generation capacity by increasing the use of natural gas or the optimal siting of new plants. Our point is imply that this need not be the case if changes in such plans would otherwise be costly.

¹⁸. These and other data on the characteristics of generating plant in use or under construction in Japan are available from the Japan Electric Power Information Center internet site <http://www.jepic.or.jp/english/jdata/index.html>.

Building a trunk gas pipeline to import Sakhalin gas may be somewhat more disruptive of the current plans for investment in new electricity generation capacity. The optimal locations of combined cycle plants are likely to change once new sources of gas become available.¹⁹ The cost minimizing fuel mix is likely to change for some utilities. The availability of pipeline gas may also alter the demand for electricity from some large industrial users. In some applications, natural gas could displace electricity as an energy input, wholly or in part. Co-generation of electricity by large industrial users may also become more feasible and could potentially displace some of the new capacity the utility companies had been planning to install. Under the 1995 amendments to the Japanese law regulating the electric utilities, the entry rules for independent power producers (IPPs) were liberalized (IEA, 1999: 76). An IPP no longer requires a permit from MITI to enter the generating business.

Building an HVDC link from new gas-fired generating plant in Hokkaido would also be a more disruptive way of exploiting Sakhalin gas than exploiting the resource as LNG. The increased capacity to transfer power between the Tokyo and Chubu utility areas could alter the capacity expansion plans of both utilities. The new source of electricity is also likely to displace some older, higher cost plants that otherwise might not have been replaced until a later date. By advancing the scrapping date for these older plants, the new link would impose some short term capital costs. On the other hand, the lower combined operating costs of the new combined cycle gas plants and the HVDC link would, in the interim, produce savings in present value terms that would offset the higher up-front investment expenditures. Once the plants that were due to be decommissioned in the near future have been displaced, the new capacity should have few effects on the future investment path beyond that date.

It is likely that some of the plants that would be displaced by a new HVDC link would be old oil-fired plant in Tokyo, Yokohama, Nagoya or Osaka. Some of these plants date from the 1960s.

¹⁹. A gas pipeline that encourages the use of combined cycle gas turbines may also produce a more stable transmission network. An electricity network with many small, widely dispersed generators can be easier to stabilize than a system that requires large transfers of AC power over long distances. Modern combined cycle gas turbines are also fast-acting, with drives that have low mechanical inertia. They thus can be started and stopped at short notice and this further aids controllability of the system. It is more difficult to say how the stability of such a system is likely to compare with the stability of the existing network augmented by a new HVDC link from the north.

Some of the younger oil-fired plants built in the late 1960s or 1970s have been converted to burn LNG. There are, however, quite a few small plants burning heavy oil that are likely to have high operating costs. There is an added benefit of displacing such plants with electricity imported from Hokkaido. Such plants are likely to be significant contributors to air pollution in major Japanese cities. As with the Neptune Project in Canada and the US discussed above, reduced air pollution may be a substantial benefit of generating electricity at gas fields located in a relatively unpopulated region and transporting the electricity to the major population centers via HVDC.

Competition in the Electricity Industry

The International Energy Agency (IEA, 1999: 70) notes that Japanese electricity prices are the highest in the OECD. It attributes these high prices to a number of factors.

- Generation capital costs are high. The IEA argues that this is the result of “expensive land, compensation payments made to local communities, and high safety standards” and also limited competition among suppliers to the industry.
- Fuel costs are high by international standards. The IEA attributes this mainly to taxes and to levies imposed to support the small and inefficient domestic coal industry. The IEA also notes that prices for imported LNG “are much higher than natural gas prices in OECD countries that use pipeline gas.”
- High transmission and distribution costs which in turn are the result of expensive land, mountainous terrain, and high standards partly imposed to cope with earthquakes and typhoons.
- Strict environmental and safety regulations, including a mandated frequency of maintenance that is excessive by international standards. While extensive maintenance can reduce unplanned outages, plants are unavailable while they are being maintained. As a result, additional capacity may be needed to avoid shortages while plants are off-line.
- A low load factor, or ratio of energy produced from generating plant to the potential output if all plants were used at peak capacity throughout the year. A low load factor can reflect an absence of time of day pricing, or more generally, a poor correspondence between prices and the marginal costs of production. As a result, consumers are given few incentives to alter their demand profile to avoid the peak periods when electricity is more expensive to generate. A low

load factor might also, however, reflect the small amount of trade in electricity between the utilities. If peak periods do not coincide in different parts of the country, additional trade in electricity can smooth out fluctuations in demand on the system as a whole.

The IEA (1999: 89) argues that competition in electricity generation is needed in Japan. The separation of the electricity supply system into two separate and weakly linked 50Hz and 60Hz systems is one significant barrier to such competition. This is particularly so given that Tokyo and Yokohama are in the 50Hz region while the next largest population centers are in the 60Hz region. Normally, one would have expected substantial trade in electricity between such large demand regions, yet the link capacity across the frequency barrier is only 900MW, or 1.6% of the capacity of the Tokyo Electric Power Company. A significant benefit of the possible HVDC link from Hokkaido is that it could dramatically expand the amount of power exchange between the two frequency regions. It may also enable more extensive trade of electricity within the 50Hz zone by helping to stabilize the AC transmission network. Greater competition in electricity generation might thus be an additional ancillary benefit of the HVDC alternative.

Yakutia-Sakhalin-Japan 'Energy Bridge' Proposal

Russian commentators have discussed a more ambitious electricity trading link in North-East Asia. In particular, Ivanov (1999) suggests that an electricity cable between Sakhalin and Japan could be extended back to Yakutia region of Russia.²⁰ Like Sakhalin, Yakutia has oil and gas reserves that could be exploited to generate electricity for export to Japan and Korea.²¹ Ivanov also observes, however, that there is enormous potential to develop hydroelectricity generation in Eastern Russia and Siberia:

Combined, the Russian Far East and eastern Siberia possess more than 80% of the hydropower resources of the Russian Federation, and in the long term they can produce about 450-600 billion kilowatt-hours of electricity annually, equal to 45-

^{20.} Anatoly Chubais, chairman of the EES Russia Company, operator of the biggest power grid in Russia, has also suggested a similar scheme.

^{21.} The gas in Yakutia also could be exported by a land-based pipeline to Korea.

60% of the electricity generated in Japan or China in 1995.

Ivanov lists seven hydroelectric power projects, with a total capacity of 8,115MW, that are currently under construction or planned for the Russian Far East. He suggests that these projects alone could supply 15 billion kWh of electricity annually by the year 2005, and 40-45 billion kWh after completion. In order to exploit the full potential of these hydroelectric sources, the generated power would need to be exported to Japan and Korea via HVDC links.

Ivanov argues that the hydroelectric power could be combined with power generated from the natural gas reserves of Sakhalin and Yakutia, and coal reserves in Sakhalin. A 1,800 km HVDC link, with a capacity of about 11,000MW, would enable electricity to be exported to Japan. Ivanov envisages the power being transported to Hokkaido. We suggest, however, that it would make more sense to extend the HVDC link to the Shin-Shinano region. This would increase the length of the link by about 1,200 km but would yield the additional benefits discussed above.

Ivanov suggests that once the hydroelectric projects are included in the proposed scheme, the average production cost of the electricity falls below \$US0.01 per kWh, although he does not say what discount rate or assumed project life underlies this calculation. Given the large capital costs involved, these assumptions would be critical.

While development of the hydroelectric resources of Siberia might make HVDC transmission more attractive, there are many obstacles to overcome. The electricity transmission capacity within Siberia is limited. The Russian Far East does not yet have a unified electricity transmission grid. Arrillaga (1998: 273–274) also notes that for power transfers above 5,000MW, ultra-high voltages above 1,000kV are likely to be optimal. The highest voltages currently in use are 600kV. While 800kV is likely to be achievable with current technology, further development is required to extend HVDC transmission to 1,000kV and above. Solutions probably could be found for such technical problems. The overall scheme also may appear cost effective. In practice, however, we argue in the next section that the continuing fragility of political and economic institutions in Russia is a major obstacle to developing energy resources in Siberia to be used in Japan.

Strategic Considerations

One of the main potential difficulties associated with building a gas pipeline or a HVDC link could be avoided by using LNG. Both the pipeline and the electricity transmission line would tie the Japanese electricity industry much more firmly to the Sakhalin gas fields than would the use of LNG. As we argue below, technological and economic developments are turning LNG into a widely traded commodity, with many potential sources of supply to a country such as Japan. If any one source becomes unavailable, there should be many other sources to take its place.

An investment in a gas pipeline or a HVDC link would be largely wasted if the Sakhalin gas fields were to become unavailable. An electricity link from Hokkaido to the Shin-Shinano region might be slightly less problematic in this regard in so far as the planned expansion in nuclear capacity in the north of Honshu island might also gain some benefit from lower cost access to the electricity markets further south. Furthermore, benefits associated with transmission system stabilization or the reduction of pollution in the main population centers would still be obtained.

Arrillaga (1998: 274) notes that inter-connection of electricity transmission systems requires cooperation between system operators. This is much harder to achieve across international boundaries. In particular, until the political and economic situation in Russia stabilizes, Japan is likely to find siting new gas-fired generating capacity in Hokkaido far more satisfactory than having generating plant critical for supplying electricity to the Japanese economy located in Sakhalin or Siberia. Although the schemes proposed by Russian commentators might make economic sense if Russia were Canada and Japan the United States, they most likely involve unacceptable risks for Japan under current circumstances.

A Model of the Evolution of the Worldwide Market for LNG

At current prices, the costs of transporting gas by pipeline or as LNG between Sakhalin and Japan appear to be quite similar. Furthermore, constructing a HVDC link to carry electricity from Sakhalin or Hokkaido to the major population centers in Japan is likely to cost a similar amount to the two gas transport options. Any one of these projects is likely to be commercially feasible if

undertaken alone. None of them is likely to go ahead in the absence of political decisions required, for example, to secure rights-of-way or sites for terminals, processing facilities and other infrastructure. Political and other ancillary factors therefore are likely to be critical in determining which option will be chosen.

In this section of the paper, we argue that the recent drop in LNG shipping costs, together with other recent developments, may radically alter the LNG market in a way that will reduce the attraction to Japan of firmly committing to buy gas from Sakhalin. In the current LNG market, as in the oil market prior to the 1980s, long term bilateral contracts are standard. Firms search for trading partners and sign long term contracts before investing in production or end-user infrastructure. In the future, the market may become more like the oil market of today, in which substantial sales and purchases are made on the spot market, and firms invest in infrastructure without first arranging long term contracts with specific trading partners.

We shall use ideas developed by Diamond (1985) and Diamond and Maskin (1979) to formally model a transition from a market where firms search before investing to one where they invest before searching. The model abstracts from details of the market for LNG in order to focus on the incentives to finance infrastructure investments with long term bilateral contracts and how those incentives are affected by changes in transport costs and other relevant factors.

Our argument can be summarized as follows. The disadvantage of investing before searching for a partner is that the investment cost is borne immediately while revenue is not received until a partnership is formed. The benefit of investing first is that new entrants are then able to arrange trades at short notice from any firm that has already invested. The latter includes firms that are in marginally profitable contractual arrangements and are searching for something better and firms that have suffered a previous breach of contract. New entrants to the market that have not invested in production or end-user infrastructure can search for partners only in a separate long term bilateral contract market. A firm seeking LNG for an ongoing project is unlikely to enter into a contract with a supplier that has not invested in production capacity. Similarly, a firm that has already developed LNG production facilities is unlikely to contract with an electric utility or other purchaser that has yet to invest in end-use infrastructure. The bilateral contract market thus will have

fewer firms searching for partners than will the market for trades between parties that have infrastructure in place. With fewer firms searching, the market will be less liquid and suitable trades will take longer to arrange.

A drop in the cost of transporting LNG makes it easier to find a good trading partner. As the expected time required to find a good trading partner decreases, the present value cost of delaying the receipt of revenue until a match is found declines. This tends to favor the option of investing before searching for a partner.

Other recent changes have reduced the disadvantage of investing before searching by lowering infrastructure investment costs. Improvements in liquefaction and gasification technologies have reduced the cost of bringing LNG projects to market. On the demand side of the market, combined cycle technologies have reduced the capital costs of gas-fired power plants.

The market for natural gas also is expanding quite rapidly, not least because more stringent air pollution requirements have favored natural gas as it is a relatively clean fossil fuel. The increased demand for natural gas has expanded the depth and geographical extent of the market for LNG producers. Expanded market alternatives reduce the risk to any one producer or customer of investing in infrastructure without having secured long term contracts for selling or buying LNG.

If some new firms begin to invest before searching, other entrants also find it beneficial to invest first so that they, too, can search in the more liquid market. Entrants abandon the relatively illiquid long term bilateral contract market where partnerships are arranged before firms invest.

The formal model presented below expands on this brief description by facilitating a quantitative assessment of the effects of each of the factors mentioned above. The formal analysis also reinforces the notion that the movement away from bilateral project-specific contracting that previously occurred in the market for oil was the result of fundamental economic forces. It therefore lends credibility to the claim that such a transition is likely to be repeated in the market for LNG in the coming decade as similar economic forces begin to operate. Readers who do not wish to follow the details of the model could read sections 4.1 and 4.2 to familiarize themselves with our

notation and then skip ahead to the discussion of the numerical results in section 4.6.

The Market Model

Following Diamond (1985), we do not differentiate between suppliers and buyers of gas. Firms cannot obtain any benefits without finding a trading partner, and partnerships can be a good or a poor match. In the LNG market, the quality of a match primarily reflects differences in transport costs. Thus, the recent drop in LNG transport costs has increased the probability that any given match will be good.

Firms also need to invest an amount K (in present value terms) in infrastructure before a match can generate any returns. We show that an increase in the probability of forming a good match will favor the option of investing in infrastructure before searching. The model therefore implies that a fall in transport costs could reduce long term bilateral project-specific contracts for buying or selling LNG.

Firms that have made a poor match may or may not continue to search. The decision to continue searching after making a poor match depends on the difference in the surplus associated with a better match and the cost of search.

Any firm that has invested in infrastructure and is searching may choose to make a match with another firm that is currently unmatched or with a firm that is currently in a poor match and is searching (the latter having invested by definition). In the latter case, a new match shall breach an existing partnership contract. If the searching agent also is currently in a poor match, the re-pairing will result in a double breach of contracts. We assume that a party that is breached must be compensated for the loss of surplus that results from the breach. The choice of whether to accept an offer depends on the cost associated with compensating parties for any breaches of existing contracts and the value of the state to which the firm will transition.

We assume that partnerships will not form unless they make both parties strictly better off.²² Thus, if a firm in a poor match meets another firm and the result would be a poor match, no pair-

ing will occur. We will also make the simplifying assumption that partners of parties that do not search also do not search.

Firms in the model can be in six possible situations (or *states*):

- 0: Initial situation deciding whether to search or invest first;
- 1: Searching without investing;
- 2: Searching without a partner after investing;
- 3: In a poor match and searching;
- 4: In a poor match but not searching;
- 5: In a good match.

The possible flows between the various states are depicted as in Figure 4. In particular, notice that even if firms decide to search without investing there may be some firms in state 2 that are searching after investing. Firms in a poor match will have invested, and if the poor match is subsequently breached one of the firms may move from state 3 to state 2. Let x_i denote the number of firms in state i .

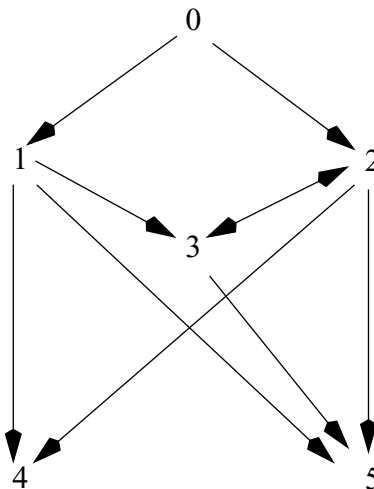


Figure 4: Possible Flows Between States

²² This is not equivalent to assuming that the equilibrium is Pareto optimal. In fact, the search process we examine exhibits an externality. A decision to search increases the number of potential partners for other firms engaged in search and reduces the time it takes them to find a suitable trading partner.

Costs and Benefits of Search

We assume that a firm incurs an explicit cost c per unit of time to search for a partner. In addition, delaying forming a partnership postpones the receipt of net revenue, the cost of which depends on the interest rate, r .

Projects can end (or partnerships dissolve) at any time for exogenous reasons (for example, reserves are exhausted). Let the rate of dissolution be δ per unit of time and assume that after a partnership dissolves for exogenous reasons the former partners exit the market. At the same time, there is a constant flow x_0 of new entrants to the market. We examine only stationary equilibria where the number of participants in the market remains constant from one period to the next.

Following Diamond and Maskin (1979), we assume that the probability per unit time (denoted a) of meeting, or potentially matching, *a specific designated partner* is independent of the number of other potential partners. If x firms are searching, the probability that a given firm would meet another firm *at all* would then be ax per unit time. The *total number* of meetings per unit time would depend on the square of the number of firms searching.²³

When any two firms meet, we assume that a good match can be formed with probability p and a bad match can be formed with probability $(1-p)$. Assume that a good match yields a gross surplus to both partners together at a flow rate of $2u_1$ per unit of time while a poor match yields a gross surplus of $2u_2$ per unit of time, with $u_1 > u_2$. Following Diamond and Maskin (1979), we assume that the net surplus in all matches is divided evenly between parties.²⁴ Denote the expected value of being in state i by V_i . Define T_i , $i = 1, 2, 3$ as the expected times a firm in state i must search before forming a partnership.

²³. Hence, the technology is called a “quadratic search technology”. It is an appropriate assumption when a small number of entities is engaged in search. It leads to an externality since a decision to search raises the probability that other firms will find a suitable partner.

²⁴. In Diamond-Maskin model, the surplus is divided when both partners stop searching, whereas we allow surplus to accrue gradually over time. This difference is necessitated by the characteristics of the LNG market where contracts are defined on a flow over time and a partner in a poor match performs until the breach. A technical difficulty created by this different assumption is defining how contracts end. We assume that both partners to a contract have a probability of ceasing to exist at any point in time and that this probability is stationary.

Firm Maximizing Behavior

New entrants need to choose whether or not to invest before searching. Their choice will depend on the relative values of V_1 and V_2 .²⁵

A firm that forms a good match transitions to state 5 and ceases to search. A firm in a poor match can continue to search and go to state 3, or cease to search and go to state 4. The firm would again choose depending on the relative values of the two states, in this case V_3 versus V_4 .

Solving the problem requires that the values of the states V_i be defined. First, note that since no further search occurs in states 4 and 5,

$$V_4 = \int_0^{\infty} e^{-(r+\delta)t} u_2 dt = \frac{u_2}{r+\delta} \quad (1)$$

and

$$V_5 = \int_0^{\infty} e^{-(r+\delta)t} u_1 dt = \frac{u_1}{r+\delta}. \quad (2)$$

A firm in state 3 would stay in that state unless a good match is found. A poor match would be no better than the existing relationship the firm is in and thus no breach will occur. A firm in state 3 therefore will search until it meets an x_2 or x_3 that is a good match.

If a firm in state 3 meets a firm in state 2 that is a good match, the firm in state 3 will breach the existing contract. The former partner will move to state 2. The joint surplus of the resulting agreement is given by

$$2V_5 - (V_3 - V_2) - (V_2 + V_3) = 2V_5 - 2V_3 \quad (3)$$

where the term $(V_3 - V_2)$ represents the damages that must be paid to the party breached. Since the

²⁵ In the following, we do not consider the knife-edge case where $V_1 = V_2$. In such a case, new entrants would randomly choose whether or not to invest before searching.

surplus is divided equally, the benefit to the party in state 3 of making a good match with a party in state 2 is the surplus share plus the initial value V_3 :

$$\frac{2V_5 - 2V_3}{2} + V_3 = V_5 \quad (4)$$

If a firm in state 3 meets another firm in state 3 and the match is good, the joint surplus is given by

$$2V_5 - 2(V_3 - V_2) - 2V_3 = 2V_5 + 2V_2 - 4V_3 \quad (5)$$

where the term $2(V_3 - V_2)$ represents the damages to the other two parties breached. Since the surplus (5) is divided equally, the benefit to the party in state 3 is

$$\frac{2V_5 + 2V_2 - 4V_3}{2} + V_3 = V_5 - (V_3 - V_2) \quad (6)$$

With a total of $(x_2 + x_3)$ firms searching for partners, the probability that a given firm would meet another firm is $a(x_2 + x_3)$. Since the probability that any given meeting results in a good match is p , the probability of making a good match per unit of time is $pa(x_2 + x_3)$. The expected time to form a good match, and thus to breach the existing agreement, therefore will be

$$T_3 = \frac{1}{pa(x_2 + x_3)} \quad (7)$$

The probability that any given meeting is with a firm in state 2 is $x_2/(x_2 + x_3)$ and the probability that the match is with a firm in state 3 is $x_3/(x_2 + x_3)$. Noting that a firm will receive the benefits of the good partnership only from T_3 on, and that both types of partnerships can dissolve for exogenous reasons at the rate δ , using (4) and (6) we can write V_3 as a function of V_2 and V_5 :

$$V_3 = e^{-(r+\delta)T_3} \left\{ \frac{x_2}{x_2 + x_3} V_5 + \frac{x_3}{x_2 + x_3} [V_5 - (V_3 - V_2)] \right\} + \int_0^{T_3} e^{-(r+\delta)t} (u_2 - c) dt \quad (8)$$

Equation (8) can be simplified to

$$V_3 = e^{-(r+\delta)T_3} \left\{ V_5 - \frac{x_3}{x_2 + x_3} (V_3 - V_2) \right\} + \frac{u_2 - c}{r + \delta} [1 - e^{-(r+\delta)T_3}] \quad (9)$$

where T_3 is given by (7).

Now consider a firm that is in state 2, and thus is searching after investing. If such a firm meets another firm that is in state 3, the surplus is again given by (3) above. Since the surplus is divided equally, the benefit to the party in state 2 is

$$\frac{2V_5 - 2V_3}{2} + V_2 = V_5 - (V_3 - V_2) \quad (10)$$

If a party in state 2 meets a party in state 2 and a good match is formed, the surplus is given by $2V_5 - 2V_2$. Since the surplus is divided equally the benefit to the party in state 2 is

$$\frac{2V_5 - 2V_2}{2} + V_2 = V_5 \quad (11)$$

If a party in state 2 meets a party in state 2 and a poor match is formed, the surplus is given by $2V_3 - 2V_2$. Since the surplus is divided equally the benefit to the party in state 2 is

$$\frac{2V_3 - 2V_2}{2} + V_2 = V_3 \quad (12)$$

A firm in state 2 will continue to search until a match is made. Again, the probability that the firm would meet another firm is $a(x_2 + x_3)$ per unit time. The probability that the match is with a party in state 2 is $x_2/(x_2 + x_3)$. The probability that a firm in state 2 will make a good match with another firm in state 2 is $px_2/(x_2 + x_3)$ and the probability that it will be a poor match is $(1-p)x_2/(x_2 + x_3)$. The probability that the match is with a party in state 3 is $px_3/(x_2 + x_3)$, since the only possible match with such a party is a good match. Thus, the expected time to form a match is given by

$$T_2 = \frac{1}{a(x_2 + px_3)} \quad (13)$$

Using (10), (11) and (12) we can now write V_2 as a function of V_3 and V_5 :

$$V_2 = e^{-rT_2} \left\{ p \left[V_5 - \frac{x_3}{x_2 + x_3} (V_3 - V_2) \right] + (1-p) \frac{x_2}{x_2 + x_3} V_3 \right\} - \frac{c}{r} [1 - e^{-rT_2}] \quad (14)$$

If search is not optimal after making a poor match, then we would have

$$V_2 = e^{-rT_2}[pV_5 + (1-p)V_4] - \frac{c}{r}[1 - e^{-rT_2}] \quad (15)$$

where T_2 is given by (13). A firm in state 2 also makes an up-front investment cost of K if entering state 2 from state 0 but not from state 3. We subtract K from V_2 when considering whether to move from state 0 to state 2.

Now consider a firm in state 1. A firm that has not invested can search in a market only with other firms that have not invested. Hence, the expected time to make a match will be:

$$T_1 = \frac{1}{ax_1} \quad (16)$$

Surpluses from matches are measured as of the time the match occurs. Since a firm in state 1 has not yet invested in capacity to produce or consume the LNG, the investment of K will need to be paid at T_1 . Hence, the joint surplus from a good match is $2V_5 - 2K$, while the joint surplus from a bad match is either $2V_3 - 2K$ or $2V_4 - 2K$ depending on whether or not it is optimal to continue searching after a bad match has been made. The value of being in state 1 therefore is given by:

$$V_1 = e^{-rT_1}[pV_5 + (1-p)\max(V_3, V_4) - K] - \frac{c}{r}[1 - e^{-rT_1}] \quad (17)$$

where T_1 is given by (16). A firm in state 0 would compare V_1 to $V_2 - K$ and choose the largest.

Solving for V_2 and V_3

From equation (9) we have

$$e^{(r+\delta)T_3} \left[V_3 - \frac{u_2 - c}{r + \delta} \right] = \frac{u_1 - u_2 + c}{r + \delta} - \frac{x_3}{(x_2 + x_3)} (V_3 - V_2) \quad (18)$$

and from equations (14) and (2) we have

$$V_2 = e^{-rT_2} \left\{ p \left[\frac{u_1}{r+\delta} - \frac{x_3}{x_2+x_3} (V_3 - V_2) \right] + (1-p) \frac{x_2}{x_2+x_3} V_3 \right\} - \frac{c}{r} [1 - e^{-rT_2}] \quad (19)$$

Clearly, V_3 and V_2 need to be determined simultaneously as functions of the fundamental parameters of the model. Similarly, (9) and (17) need to be solved simultaneously in the case where search remains optimal after a bad match is formed. By contrast, in the case where search is not optimal after a firm in state 2, for example, makes a poor match,

$$V_2 = e^{-rT_2} \left[\frac{pu_1}{r+\delta} + \frac{(1-p)u_2}{r+\delta} \right] - \frac{c}{r} [1 - e^{-rT_2}] \quad (20)$$

The Stationary Distribution of Firms in Each State

The flow of new firms entering the market is x_0 per unit of time. We will assume that b (equal to zero or one) of these firms choose to invest before searching while $1-b$ (equal to one or zero respectively) choose to search before investing. Firms in state 1 will change state only by forming a match. The total number of meetings per unit of time between x_1 firms of type 1, each of which is searching using a quadratic search technology with probability ax_1 of meeting another type 1 firm, is ax_1^2 . The differential equation describing changes in the number of firms in state 1 thus is

$$\dot{x}_1 = -a2x_1^2 + (1-b)x_0 \quad (21)$$

Firms in state 2 can exit either by matching with firms in state 2 or state 3. Firms can enter state 2 by investing in state 0 or from being in state 3 and suffering a breach as a result of the formation of a good match. The differential equation for state A_2 therefore is given by

$$\dot{x}_2 = -a(2x_2^2 + px_2x_3) + a(px_2x_3 + 2px_3^2) + bx_0 \quad (22)$$

Since a match between a firm in state 2 and a firm in state 3 creates a new firm in state 2, there is no net change and the px_2x_3 terms cancel. Thus, (22) simplifies to

$$\dot{x}_2 = 2a(px_3^2 - x_2^2) + bx_0 \quad (23)$$

Firms in state 3 can exit by forming a good match and going to state 5 or through exogenous part-

nership dissolution. The good matches would be formed by meeting a firm in state 2 or state 3. In the latter case, two poor matches will be converted to 2 good ones, so 4 state 3 firms will move to state 5 as a result of each match. Entry to state 3 will occur if firms in state 1 or 2 make a poor match and decide to continue to search. The latter will occur if $V_3 > V_4$. We let $\lambda = 1$ represent the case $V_3 > V_4$ (and $\lambda = 0$ the opposite case). The differential equation for firms in state 3 is then

$$\dot{x}_3 = a[\lambda(1-p)2(x_1^2+x_2^2)-p(2x_2+4x_3)x_3]-2\delta x_3 \quad (24)$$

The differential equation for firms in state 4 is given by

$$\dot{x}_4 = a(1-\lambda)(1-p)2(x_1^2+x_2^2)-2\delta x_4 \quad (25)$$

Finally, the differential equation for firms in state 5 is given by

$$\dot{x}_5 = 2ap[x_1^2+x_2^2+x_3^2+x_2 \cdot x_3]-2\delta x_5 \quad (26)$$

To keep the number of market participants constant, we also need the inflow to match the outflow:

$$x_0 = 2\delta(x_3+x_4+x_5) \quad (27)$$

We solve the model in a stationary environment where the proportions of firms in each state is constant over time. The inflow of firms into each state matches the outflow, and the time derivatives in the differential equations (21), (23), (24), (25) and (26) are all zero.

There could be four different types of market structure in a stationary equilibrium depending on the values of V_3 relative to V_4 and V_1 relative to $V_2 - c_0$. The resulting equations to be solved in the four different regimes are set out in Table 2.

Observe that in regime 2 equations (i) and (ii) together imply

$$ax_1^2 = \delta(x_4+x_5)$$

which is also obtained by adding equations (iii) and (iv). Hence, there are only four independent equations.

Table 2: Equations determining the Number of Firms in Each State in a Stationary Equilibrium

Regime 1: Search first, continue to search in a bad match (only $x_1, x_2, x_3, x_5 > 0$)

- i $x_0 = 2ax_1^2$
- ii $x_0 = 2\delta(x_3 + x_5)$
- iii $x_2^2 = px_3^2$
- iv $a(1-p)(x_1^2 + x_2^2) = ap(x_2 + 2x_3)x_3 + \delta x_3$
- v $ap(x_1^2 + x_2^2 + x_3^2 + x_2x_3) = \delta x_5$

Regime 2: Search first, stay in a bad match (only $x_1, x_4, x_5 > 0$)

- i $x_0 = 2ax_1^2$
- ii $x_0 = 2\delta(x_4 + x_5)$
- iii $a(1-p)x_1^2 = \delta x_4$
- iv $apx_1^2 = \delta x_5$

Regime 3: Invest first, continue to search in a bad match (only $x_2, x_3, x_5 > 0$)

- i $x_0 = 2a(x_2^2 - px_3^2)$
- ii $x_0 = 2\delta(x_3 + x_5)$
- iii $a(1-p)x_2^2 = ap(x_2 + 2x_3)x_3 + \delta x_3$
- iv $ap(x_2^2 + x_3^2 + x_2x_3) = \delta x_5$

Regime 4: Invest first, stay in a bad match (only $x_2, x_4, x_5 > 0$)

- i $x_0 = 2ax_2^2$
- ii $x_0 = 2\delta(x_4 + x_5)$
- iii $a(1-p)x_2^2 = \delta x_4$
- iv $apx_2^2 = \delta x_5$

Similarly, equations (i) and (ii) in regimes 3 and 4 yield the same result as equations (iii) and (iv).

In regime 1, equations (i) and (ii) together imply

$$ax_1^2 = \delta(x_3 + x_5) \quad (28)$$

while equations (iv) and (v) yield

$$a(x_1^2 + x_2^2 - px_3^2) = \delta(x_3 + x_5) \quad (29)$$

Then equation (iii) will imply (28) and (29) are identical. Thus, the number of independent equations in Table 2 characterizing the stationary state in each regime will equal the number of unknown x_i that need to be determined.

Solving the Model

To solve the model, we need to specify values for the various parameters. The discount rate r should be set at the *real risk-adjusted* rate that is appropriate for mining operations, liquefaction plants or power stations. For our base case, we will take this rate to be 7% annually, leading to a value of r (under continuous compounding of interest) of about 0.068.

We normalize costs and returns by defining units so that a good match yields a flow return to each partner of $u_1 = 1$ per period. The other financial variables u_2 , K and the costs of search c , then are to be interpreted as fractions or multiples of u_1 . In our base case, we will take $u_2 = 0.4$ (so a bad match yields only 40% of the surplus of a good match). We will also assume that the up-front infrastructure investment costs of each partner, K , are initially 1.6 when measured in the same units.²⁶ Later we shall examine the effect of reducing K by 30%, which approximates the magnitude of recent declines in the cost of LNG liquefaction and gasification plant (Ellsworth, 2001). We shall also set the explicit cost of search to be $c = 0.05$ (5% of the flow returns from a good match).

The exogenous rate, δ , of dissolution of partnerships will imply an expected project lifetime for a good match of $1/\delta$. In our base case, we will take $\delta = 0.05$, which implies an average duration of a good partnership of 20 years. We later examine the effect of an increase in δ , which may be a consequence of recent technological changes. For example, 3D seismic techniques have increased the rate of depletion of reserves, while lower transport and infrastructure investment costs for LNG have reduced the size of a reserve required for it to be commercially viable. On the demand side, increased technological change in electricity generating technologies might also cause a more

²⁶ A firm in a bad match, and facing a real discount rate of 7%, would thus require more than four and a half years of surplus, once a match has been made, to recoup the up-front investment cost. In addition, as we shall see, the firm could expect to take up to 7 years to arrange a trading partner.

rapid turnover of partnerships. All of these factors are likely to reduce the optimal length of gas supply contracts even when suppliers and customers are well-matched. We shall examine the effect of reducing $1/\delta$ by 20% of its initial value.

The parameter a represents the probability per unit time of meeting any *given* possible partner. It depends on the search technology required to form partnerships in the LNG market. Diamond and Maskin (1979: 285) note that this probability needs to be small enough that we can ignore the possibility that two firms that are searching simultaneously find new potential partners. We take $a = 0.002$ throughout the analysis. We also assume initially that a good match will arise from one fourth of the meetings between two firms, so that $p = 0.25$. We later consider the implication for p of recent reductions in LNG shipping costs.

Finally, the inflow of new firms (both producers and consumers) to the market x_0 will, with δ , determine the number of matched firms in equilibrium and influence the length of time firms search for partners. For the base case, we set $x_0 = 20$ firms per year. We later consider the effect of doubling x_0 .²⁷ The complete set of initial parameter values is presented as Table 3.

Table 3: Parameter Values in the Base Case

Parameter	K	u_1	u_2	c	e^r	$1/\delta$	p	a	x_0
Value	1.6	1.0	0.4	0.05	1.07	20	0.25	0.002	20

Table 4 presents the solution for the base case parameter values. It shows that V_1 in regime 2 exceeds V_1 in regime 1 or $V_2 - K$ in either regimes 3 or 4. The optimal market structure therefore is one where firms search before investing, and then stay in whatever match they make after investigating the available alternatives. Furthermore, since V_4 exceeds V_3 in regime 1, firms would choose to remain in a bad match rather than search. Hence, the optimal market structure is also the equilibrium outcome.²⁸

²⁷ Ellsworth (2001) forecasts that LNG demand in the Atlantic and Pacific Basins will grow by 80% from 55Tcf in 1999 to 98Tcf in 2015. He also claims that “global export capacity will grow from 6.1Tcf to 8.4Tcf in the next 4-5 years.” This would be in addition to rapid growth in demand in the last decade. Ellsworth further notes that the industry has the reserves to expand: “Five of the top ten countries with the world’s largest natural gas reserves—Russian Federation, Iran, Saudi Arabia, Venezuela, and Iraq—do not yet have the capability to export LNG.”

Table 4: Base Case Solution

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	70.7	70.7	—	—
x_2	34.2	—	76.7	70.7
x_3	68.3	—	59.7	—
x_4	—	150.0	—	150.0
x_5	131.7	50.0	140.3	50.0
T_1	7.07	7.07	—	—
T_2	9.76	—	5.45	7.07
T_3	19.52	—	14.66	—
V_1	1.6105	1.6245	—	—
V_2	0.9694	—	2.2390	2.6161
V_3	3.3696	—	3.8348	—
V_4	3.3997	3.3997	3.3997	3.3997
V_5	8.4992	8.4992	8.4992	8.4992
V_0	1.1735	1.2202	0.6390	1.0161

The solution in Table 4 also reveals that, for the base case parameter values, the stationary state would be characterized by having, at any one time, about 18% of the firms in a good match, about 55% in a bad match and about 26% of firms unmatched and searching for a partner. The value for T_1 indicates that firms could expect to search about seven years before making a match. The values for T_2 and T_3 in regime 1 explain why continuing to search and breaching contracts is not optimal in equilibrium. If firms in a bad match searched for a new partner, there would be so few potential partners available that it would take a very long time to find one.

The LNG market has traditionally operated as in regime 2. There are indications, however, that the situation may be changing. Ellsworth (2001) notes that new LNG terminals are being constructed, and existing terminals expanded, with only part of their capacity committed long term. Furthermore, only half of the 27 ships on order for delivery between 2001 and 2005 have firm LNG contracts. Volumes of LNG traded in spot markets have also been rising. The question we

²⁸ Contrast this with the outcome for regimes 3 and 4. Although regime 4 yields a higher value than regime 3, a firm in a bad match would decide to continue to search if all firms were to invest before searching. In this model, the equilibrium outcome need not be optimal because the search process is characterized by externalities.

wish to examine is whether recent changes in the LNG industry could produce a radical change in regime whereby new market entrants invest before searching finding trading partners.

As noted above, we consider four developments in the LNG market. These are:

- reduced up-front capital investment costs of about 30%;
- a fall in the expected life of partnerships in the absence of breach from 20 years to 16 years;
- a doubling in the annual number of entrants on either the supply or demand side; and
- a reduction in LNG transport costs, which we represent as an increase in the probability of a good match p .

We examine each of these developments one at a time to see how the equilibrium outcome changes in response to each.

The simplest change to evaluate is a 30% reduction in the cost of investing in infrastructure. The differential equations governing the x_i , and hence the expected search times, are unaffected. The values of being in different states nevertheless change. In regimes 1 and 2, the values of V_1 change by the same amount (to 1.9080 and 1.9220), so the comparison between these regimes is unaffected. Similarly, a change in K does not affect the difference between V_2-K in regime 3 and V_2-K in regime 4. On the other hand, the difference between V_1 in either regime 1 or 2 and V_2-K in either regime 3 or 4 declines by about 18%.

Table 5 shows the effects of an increase in δ , or exogenous decline in the longevity of partnerships, along with the reduction in K . Such a change raises the search times T_2 and T_3 and thus increases the advantage of regime 2 relative to regimes 1 and 3.

Table 5 also shows that a larger value of δ leads to a smaller stock of matched firms in a steady state. For the same inflow x_0 of new firms and a higher rate of partnership dissolution, stationarity requires the number of matched partners at any one time to be smaller. The increasing popularity of natural gas as a fuel for electricity generation is, however, likely to increase the number of new entrants to the industry. In addition, if the higher value of δ is the result of smaller gas fields being exploited, or the same sized fields being depleted more rapidly, utilities that had been buying LNG

could be expected to re-enter the market when their existing supplier runs out of gas.

Table 5: K Reduced 30% and $1/\delta$ Reduced 20%

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	70.7	70.7	—	—
x_2	31.8	—	76.0	70.7
x_3	63.5	—	55.5	—
x_4	—	120.0	—	120.0
x_5	96.5	40.0	104.5	40.0
T_1	7.07	7.07	—	—
T_2	10.50	—	5.57	7.07
T_3	20.99	—	15.22	—
V_1	1.5725	1.6437	—	—
V_2	0.7495	—	1.9715	2.3379
V_3	2.9198	—	3.3008	—
V_4	3.0732	3.0732	3.0732	3.0732
V_5	7.6829	7.6829	7.6829	7.6829
V_0	1.5725	1.6437	0.8515	1.2179

Table 6 presents the steady state solutions of the model when x_0 is doubled from 20 to 40 along with the previously examined changes in K and δ . The major consequence of increasing x_0 is that, with more firms searching, the expected time needed to find a partner declines. The optimal and equilibrium market structure shifts from regime 2 to regime 1. With reduced search times, firms in a bad match now find it maximizing to continue to search for a partner. Breaches of contracts also occur in regime 1, but the result of firms continuing to search is that a larger proportion of partnerships end up being good matches. In a steady state, about 47% of firms end up in a good match in regime 1 compared with only 19% in regime 2.

An even higher proportion of firms would end in a good match if regime 3 prevailed, yet the value of V_0 in regimes 3 and 4 remain substantially below V_0 in regimes 1 or 2. The main disadvantage of regimes 3 and 4 relative to regimes 1 and 2 is that the infrastructure investment cost is borne up-front in regimes 3 and 4, while the revenue is delayed until a match is made. An increase in the probability p of a good match reduces this disadvantage by further reducing the time taken to

make a match.

Table 6: K Reduced 30%, $1/\delta$ Reduced 20% and x_0 Doubled

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	100.0	100.0	—	—
x_2	50.0	—	109.1	100.0
x_3	100.0	—	87.4	—
x_4	—	240.0	—	240.0
x_5	220.0	80.0	232.6	80.0
T_1	5.00	5.00	—	—
T_2	6.67	—	3.82	5.00
T_3	13.33	—	10.18	—
V_1	2.1380	2.0022	—	—
V_2	1.2662	—	2.4319	2.8007
V_3	3.3273	—	3.8492	—
V_4	3.0732	3.0732	3.0732	3.0732
V_5	7.6829	7.6829	7.6829	7.6829
V_0	2.1380	2.0022	1.3119	1.6807

A reduction in LNG shipping costs could be expected to raise the surplus from existing LNG trades while increasing the number of suppliers for each consumer and the number of customers for each supplier. We can estimate the effect on p by imagining consumers and producers are uniformly distributed across the face of the globe. The radius of the potential area about a particular supplier or demander where a match would be low cost would be inversely proportional to the transport costs.²⁹ Thus, the *probability* of a low cost match (which will be the ratio of two *areas*) will tend to rise with the inverse square of the reduction in transport cost. The current costs of transporting LNG are about \$0.15 per 1,000 cubic feet per 1,000 miles. This compares with about \$0.25 per 1,000 cubic feet per 1,000 miles about five years ago. An initial value for p of 0.25 would thus be raised to about 0.7 by the recent improvement in transport technology.

Table 7 presents the results when p is increased along with the other changes previously exam-

²⁹ Let the cost of moving LNG between two locations that are a distance d apart be $c = \alpha d$ and suppose that the rents are given by $u = u_0 - \alpha d$. If we define a good match to be one that yields rent greater than or equal to \bar{u} , the maximum distance that yields a good match is $(u_0 - \bar{u})/\alpha$. Thus the *probability* of a good match is given by the ratio of the area that would yield a good match to the total area yielding positive surplus (which is the only place a firm would look for a potential partner). For a constant $(u_0 - \bar{u})$, this ratio of areas would vary with $(1/\alpha)^2$.

ined. In this case, regime 3 becomes the optimal and equilibrium market structure. In regime 3, new entrants invest before searching and firms in a bad match continue to search for a better partner. If a firm in a bad match finds a better partner, a breach of contract results. Unless it is a double breach, where two pairs of former partners simultaneously find better matches, the breached party will return to state 2 to search for another partner.

Table 7: K Reduced 30%, $1/\delta$ Reduced 20%, x_0 Doubled and $p = 0.7$

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	100.0	100.0	—	—
x_2	27.8	—	101.8	100.0
x_3	33.2	—	23.1	—
x_4	—	96.0	—	96.0
x_5	286.8	224.0	296.9	224.0
T_1	5.00	5.00	—	—
T_2	9.79	—	4.24	5.00
T_3	11.70	—	5.72	—
V_1	3.6014	3.4812	—	—
V_2	2.4354	—	4.7504	4.2797
V_3	3.6355	—	5.0365	—
V_4	3.0732	3.0732	3.0732	3.0732
V_5	7.6829	7.6829	7.6829	7.6829
V_0	3.6014	3.4812	3.6304	3.1597

We interpret the shift from regime 2 (the current situation) to regime 3 as a move away from long term project-specific contracting (where partners need to be arranged before investments are made) toward a situation where firms invest without having a contract with a specific trading partner. The advantage to new entrants of investing before they search is that they can search in the same market as firms in states 2 and 3. By contrast, if firms attempt to form partnerships before investing in infrastructure they would have to search in a separate market for long term contractual relationships. The greater liquidity of the unified market in regime 3 results in much lower expected times to form a partnership ($T_2 = 4.2$ in regime 3 versus 9.8 in regime 1, while T_3 is 5.7 years in regime 3 versus 11.7 years in regime 1).

Another advantage of regime 3 is that a larger proportion of firms ultimately end up in a good match. In regime 3, 70% of firms are in a good partnership versus 64% in regime 1 and only 53%

in regime 2 where firms in a bad match do not continue to search. Conversely, while only 5% of firms are in a bad match at any one time in regime 3, the corresponding proportion is 7% in regime 1 and 23% in regime 2.

Despite these benefits of regime 3, the overall expected value of regime 3 to an entering firm is not much higher than the expected value of regime 1 ($V_2 - K = 3.6304$ versus $V_1 = 3.6014$). The cost of investing in infrastructure up-front while delaying the receipt of revenue until partnerships are formed is a substantial disadvantage of regimes 3 and 4.

The relatively small size of the differential between regime 3 and regime 1 in Table 7 suggests that it may be difficult to transform the LNG market from the current situation, which is analogous to regime 2, to the new regime where firms invest before arranging partnerships. The results in Table 7 represent the outcomes achieved after each regime has evolved to a stationary state. The incentive for any one firm to invest first will depend, however, on what other firms are doing. Although V_3 exceeds V_4 in Table 7, this calculation presumes that other new entrants have already decided to invest before searching. When this is not the case, any single new entrant would not reap substantial benefits by deciding to invest first.

A possible solution to this problem is that the United States may be emerging as a residual market able to absorb substantial amounts of LNG on short notice and without much of a change in price (see Jaffe and Shook, 2001 and Ellsworth, 2001). Ellsworth also argues that increasing competition between LNG and pipeline gas in Europe will allow Europe to serve as a residual market for LNG in the near future. He observes that LNG already is traded as a commodity in the United States and United Kingdom. Ellsworth suggests, in addition, that deregulation of electricity and gas markets in many countries is creating uncertainty and making buyers reluctant to commit to new long-term contracts. These developments would greatly reduce the risk of undertaking LNG projects before trading partners have been arranged.

Conclusion

The formal model of the worldwide LNG market examined in section 4 of the paper suggests that the structure of that market may change over the next few years. We could see a decrease in the number of firms seeking project-specific finance and signing long term contracts with trading

partners before investing in production or end-use infrastructure. Greater market liquidity would result, which in turn would encourage firms to invest in infrastructure before they have tied down sources of gas or customers for their LNG output. According to Jaffe and Shook (2001), changes of this sort already are occurring.

The possibility of radical change in the LNG market favors exploiting the Sakhalin gas deposits by importing LNG. The alternative of building new infrastructure that is closely tied to the Sakhalin project is more risky and may leave Japan with less flexibility to take advantage of new market opportunities that are likely to eventuate in the near future.

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