

Evolution of the International LNG Market

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June 23, 2002

Abstract

We argue that 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 change in market structure would mimic previous changes in the world oil market, adding credence to the hypothesis that fundamental economic factors are the dominant driving force.

¹. The authors gratefully acknowledge financial support from the James A. Baker III Institute for Public Policy.

1. Introduction

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. We argue that the LNG market may become more like the oil market of today in which contracts are of shorter duration, substantial sales and purchases are made on the spot market, multilateral trades and switches in trading partners are more common, and firms invest in infrastructure without first arranging long term contracts with specific trading partners.

Jaffe and Shook (2001) observe that the LNG market in the Atlantic Basin (essentially the US and Europe) has already begun to evolve in the direction that we describe. They note that Atlantic Basin LNG suppliers and buyers increasingly are looking for a variety of durations ranging from 1-2 years and 3-5 years to complement established 20-year bilateral LNG contracts or pipeline supplies. Spot transactions also have risen in number. Finally, terminals, regasification plant expansions and LNG tankers are being built with only part of their capacity locked in to long-term, fixed-volume commitments.

The possibility that the world LNG market will change in the way that we describe may have important implications for some new LNG projects. In particular, in projects such as the proposed exploitation of Sakhalin gas deposits to supply the Japanese energy market, LNG competes with building a new pipeline. While a pipeline would tie Japan to the Sakhalin fields, additional LNG capacity could be used to import energy from many sources. LNG thus looks more favorable as the worldwide market expands and becomes more multilateral and short term in nature.

A number of fundamental changes are affecting the LNG market. Most important is the recent dramatic fall in the costs of transporting LNG. Other factors working in the same direction include recent reductions in up-front infrastructure investment costs for producing LNG and using it to generate electricity, and a rapid expansion in the demand for natural gas as a fuel source for producing electricity.

We 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 incen-

tives 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 benefit of investing without having arranged a specific trading partner 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. By contrast, 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.

There also potential costs of investing without having arranged a partner. Until a partnership is formed, a large amount of capital may need to be financed without the benefit of revenue from sales to customers.

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 spot 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.

2. 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.² Thus, if a firm in a poor match meets another firm and the result would be a poor match, no pairing 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.

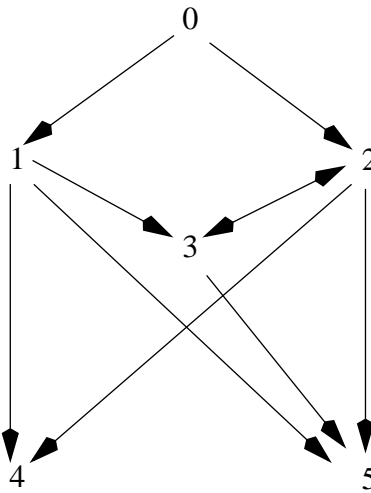


FIGURE 1. Possible flows between states

The possible flows between the various states are depicted as in Figure 1. In particular, notice that

² 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.

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 .

2.1 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, gas 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 $a(x-1)$ per unit time. The *total number* of meetings per unit time would then be $ax(x-1)$. This “quadratic search technology” 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.

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.³ Denote the expected value of

³. 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.

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.

2.2 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 .⁴

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 that 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 and must be compensated $(V_3 - V_2)$ for the breach. The joint surplus of the resulting agreement is given by the difference between the value of the new arrangement and the value of the old one

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

Since the 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 :

⁴ 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.

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

Similarly, 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 $a(x_2+x_3-1)$. 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 $pa(x_2+x_3-1)$. The expected time to form a good match, and thus to breach the existing agreement, therefore will be

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

The probability that any given meeting is with a firm in state 2 is $x_2/(x_2+x_3-1)$ and the probability that the match is with *another* firm in state 3 is $(x_3-1)/(x_2+x_3-1)$. 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 :

$$V_3 = e^{-(r+\delta)T_3} \left\{ \frac{x_2}{x_2+x_3-1} V_5 + \frac{x_3-1}{x_2+x_3-1} [V_5 - (V_3 - V_2)] \right\} + \int_0^{T_3} e^{-(r+\delta)t} (u_2 - c) dt. \quad (8)$$

Equation (8) can be simplified to

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

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

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

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

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

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:

$$T_1 = \frac{1}{a(x_1 - 1)} \quad (16)$$

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.

2.3 Solving for V_2 and V_3

From equations (2) and (9) we have

$$\frac{x_3 - 1}{(x_2 + x_3 - 1)} V_2 - \left[e^{(r+\delta)T_3} + \frac{x_3 - 1}{(x_2 + x_3 - 1)} \right] V_3 + \frac{u_2 - c}{r + \delta} e^{(r+\delta)T_3} + \frac{u_1 - u_2 + c}{r + \delta} = 0 \quad (18)$$

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

$$\left[e^{rT_2} - \frac{px_3}{x_2 + x_3 - 1} \right] V_2 + \left[p - \frac{x_2 - 1}{x_2 + x_3 - 1} \right] V_3 = \frac{c}{r} (1 - e^{rT_2}) + \frac{pu_1}{r + \delta} \quad (19)$$

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,

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

2.4 The stationary distribution of firms in each state

The flow of new firms entering the market is x_0 per unit of time. For notational convenience, we will use b (equal to zero or one) to denote the number of these firms that choose to invest before

searching while $1-b$ (equal to one or zero respectively) denotes the number that choose to search before investing. Firms in state 1 will change state only by forming a match. Each match causes two firms to exit state 1. 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 $a(x_1-1)$ of meeting another type 1 firm, is $ax_1(x_1-1)$. The differential equation describing changes in the number of firms in state 1 thus is

$$\dot{x}_1 = -a2x_1(x_1-1) + (1-b)x_0 \quad (21)$$

Firms in state 2 can exit either by matching with other firms in state 2 (causing two firms exit state 2) or state 3 (in which case only one firm exits state 2). 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

$$\dot{x}_2 = -a(2x_2 + px_3)(x_2-1) + ap(x_2 + 2x_3)(x_3-1) + bx_0 \quad (22)$$

Firms in state 3 can exit by forming a good match and going to state 5 or through exogenous partnership dissolution. The good matches would be formed by meeting a different firm also in state 3 or a firm in state 2. In the former case, two poor matches will be converted to two good ones, so four 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

$$\dot{x}_3 = a\{\lambda(1-p)2[x_1(x_1-1) + x_2(x_2-1)] - p(2x_2 + 4x_3)(x_3-1)\} - 2\delta x_3 \quad (23)$$

The differential equation for firms in state 4 is given by

$$\dot{x}_4 = a(1-\lambda)(1-p)2[x_1(x_1-1) + x_2(x_2-1)] - 2\delta x_4 \quad (24)$$

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

$$\dot{x}_5 = ap\{2[x_1(x_1-1) + x_2(x_2-1) + x_3(x_3-1)] + x_2(x_3-1) + x_3(x_2-1)\} - 2\delta x_5 \quad (25)$$

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

$$x_0 = 2\delta(x_3 + x_4 + x_5) \quad (26)$$

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 deriva-

tives in the differential equations (21), (22), (23), (24) and (25) 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 1.

TABLE 1. Equations determining the number of firms in each state in a stationary equilibrium

<i>Regime 1: Search first, continue to search in a bad match (only $x_1, x_2, x_3, x_5 > 0$)</i>	
i	$x_0 = 2ax_1(x_1 - 1)$
ii	$x_0 = 2\delta(x_3 + x_5)$
iii	$2x_2^2 - (2-p)x_2 = 2px_3^2 - px_3$
iv	$a(1-p)[x_1(x_1 - 1) + x_2(x_2 - 1)] = ap(x_2 + 2x_3)(x_3 - 1) + \delta x_3$
v	$ap\{2[x_1(x_1 - 1) + x_2(x_2 - 1) + x_3(x_3 - 1)] + x_2(x_3 - 1) + x_3(x_2 - 1)\} = 2\delta x_5$
<i>Regime 2: Search first, stay in a bad match (only $x_1, x_4, x_5 > 0$)</i>	
i	$x_0 = 2ax_1(x_1 - 1)$
ii	$x_0 = 2\delta(x_4 + x_5)$
iii	$a(1-p)x_1(x_1 - 1) = \delta x_4$
iv	$apx_1(x_1 - 1) = \delta x_5$
<i>Regime 3: Invest first, continue to search in a bad match (only $x_2, x_3, x_5 > 0$)</i>	
i	$x_0 = a[2x_2^2 - 2px_3^2 + px_3 - (2-p)x_2]$
ii	$x_0 = 2\delta(x_3 + x_5)$
iii	$a(1-p)x_2(x_2 - 1) = ap(x_2 + 2x_3)(x_3 - 1) + \delta x_3$
iv	$ap\{2[x_2(x_2 - 1) + x_3(x_3 - 1)] + x_2(x_3 - 1) + x_3(x_2 - 1)\} = 2\delta x_5$
<i>Regime 4: Invest first, stay in a bad match (only $x_2, x_4, x_5 > 0$)</i>	
i	$x_0 = 2ax_2(x_2 - 1)$
ii	$x_0 = 2\delta(x_4 + x_5)$
iii	$a(1-p)x_2(x_2 - 1) = \delta x_4$
iv	$apx_2(x_2 - 1) = \delta x_5$

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

$$ax_1(x_1 - 1) = \delta(x_4 + x_5)$$

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

$$ax_1(x_1 - 1) = \delta(x_3 + x_5) \quad (27)$$

while equations (iv) and (v) yield

$$a[2x_1(x_1 - 1) + 2x_2^2 - (2 - p)x_2 - 2px_3^2 + px_3] = 2\delta(x_3 + x_5) \quad (28)$$

Then equation (iii) will imply (27) and (28) are identical. Thus, the number of independent equations in Table 1 characterizing the stationary state in each regime will equal the number of unknown x_i that need to be determined.

3. A model of the traditional LNG market

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.⁵ 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 and IEA, 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

⁵ 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.

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 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 x_0 of new firms (both producers and consumers) to the market 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 .⁶ The complete set of initial parameter values is presented as Table 2.

TABLE 2. 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 3 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.⁷

⁶ 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.”

The solution in Table 3 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.

TABLE 3. Base case solution

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	71.2	71.2	—	—
x_2	34.6	—	77.2	71.2
x_3	68.6	—	60.0	—
x_4	—	150.0	—	150.0
x_5	131.4	50.0	140.0	50.0
T_1	7.12	7.12	—	—
T_2	9.84	—	5.48	7.12
T_3	19.55	—	14.68	—
V_1	1.6018	1.6165	—	—
V_2	0.9509	—	2.2249	2.6161
V_3	3.3681	—	3.8330	—
V_4	3.3997	3.3997	3.3997	3.3997
V_5	8.4992	8.4992	8.4992	8.4992
V_0	1.6018	1.6165	0.6249	1.0047

4. The consequences of changes in costs and other factors

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 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 for, and finding, trading partners.

⁷ 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.

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 1.8983 and 1.9130), 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 almost 19%.

TABLE 4. K reduced 30% and $1/\delta$ reduced 20%

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	71.2	71.2	—	—
x_2	32.2	—	76.4	71.2
x_3	63.8	—	55.8	—
x_4	—	120.0	—	120.0
x_5	96.2	40.0	104.2	40.0
T_1	7.12	7.12	—	—
T_2	10.60	—	5.59	7.12
T_3	21.04	—	15.24	—
V_1	1.5640	1.6357	—	—
V_2	0.7312	—	1.9587	2.3275
V_3	2.9184	—	3.2990	—
V_4	3.0732	3.0732	3.0732	3.0732
V_5	7.6829	7.6829	7.6829	7.6829
V_0	1.5640	1.6357	0.8515	1.2075

Table 4 shows the *combined* effects of the reduction in K and an increase in δ , or exogenous decline in the longevity of partnerships. 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 4 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 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.

TABLE 5. K reduced 30%, $1/\delta$ reduced 20% and x_0 doubled

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	100.5	100.5	—	—
x_2	50.5	—	109.6	100.5
x_3	100.3	—	87.8	—
x_4	—	240.0	—	240.0
x_5	219.7	80.0	232.2	80.0
T_1	5.03	5.03	—	—
T_2	6.71	—	3.83	5.03
T_3	13.35	—	10.19	—
V_1	2.1325	1.9975	—	—
V_2	1.2537	—	2.4223	2.7947
V_3	3.3260	—	3.8480	—
V_4	3.0732	3.0732	3.0732	3.0732
V_5	7.6829	7.6829	7.6829	7.6829
V_0	2.1325	2.0022	1.3023	1.6747

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.

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.⁸ 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 costs of transporting LNG in the near future 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 6 presents the results when p is increased along with the other changes previously examined. 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.

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

⁸ 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 $(1/\alpha)^2$.

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 ($T_2 = 4.3$ in regime 3 versus 9.9 in regime 1, while T_3 is 5.7 years in regime 3 versus 11.7 years in regime 1).

TABLE 6. K reduced 30%, $1/\delta$ reduced 20%, x_0 doubled and $p = 0.7$

	Regime 1	Regime 2	Regime 3	Regime 4
x_1	100.5	100.5	—	—
x_2	28.2	—	102.2	100.5
x_3	33.6	—	23.6	—
x_4	—	96.0	—	96.0
x_5	286.4	224.0	296.4	224.0
T_1	5.03	5.03	—	—
T_2	9.85	—	4.25	5.03
T_3	11.74	—	5.72	—
V_1	3.5932	3.4740	—	—
V_2	2.4112	—	4.7402	4.2712
V_3	3.6312	—	5.0350	—
V_4	3.0732	3.0732	3.0732	3.0732
V_5	7.6829	7.6829	7.6829	7.6829
V_0	3.5932	3.4740	3.6202	3.1512

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 6% of firms are in a bad match at any one time in regime 3, the corresponding proportion is 7% in regime 1 and 24% 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 ($V_2 - K = 3.6202$ versus $V_1 = 3.5932$). 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 6 has another implication. 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 6 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 6, 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). In a recent presentation, Ashcroft (2002) argues that the ability to sell LNG into the US gas pipeline network from either the Asia-Pacific or the Atlantic basins allows for substantial price arbitrage between the two markets and may effectively allow a single world gas market to develop.

Ellsworth (2001) argues that increasing competition between LNG and pipeline gas in Europe also 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.

5. Conclusion

The formal model of the worldwide LNG market examined in this paper suggests that the structure of that market may change over the next few years. We could see a further decline 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.

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