Irreversible Time Commitments for LNG Trade: Constraints on Spatial Market Integration

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Abstract

This paper discusses a novel barrier to trade that exists when trade involves irreversible time commitments. The direct transportation cost is augmented by an opportunity cost equal to the option value of the time commitment. Under plausible conditions, this cost is positively correlated with the exporter's terms of trade. Consequently, the presence of the timing option reduces cross-market price convergence, and biases price convergence estimates that does not account for the opportunity cost, and trade flows might appear inefficient when comparing the spread against the direct transportation cost. We discuss the timing option in the context of LNG trade. We show empirically that the dynamics of LNG transportation costs, including the implied timing opportunity cost, limits the ability of LNG in facilitating a fully integrated global market for natural gas. The paper supports a technological argument for the weak performance of LNG in integrating regional natural gas markets.

Keywords: LNG; natural gas; export; trade policy

JEL code: F13; Q27; Q48

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1. Introduction

Trade in a globalized economy often requires transportation of commodities over long distances. This involves a time commitment since the commodity has to spend some time "in transit" before reaching its destination market. It is natural that such time commitments factor into decisions on trade flows. If the time commitment is irreversible, owning an export licence is equivalent to owning a recurring American call option on the price spread between destination and home market with strike price equal to the direct transportation cost. Contrary to a conventional American call option, the recurrent option does not vanish after being exercised. It becomes operational again after the "ship has come back to port", whereby a new commitment can be made. In this paper, we investigates the implications of irreversible time commitments for spatial market integration. That is, the ability for trade to equalize prices for the same commodity across different markets. We show that the time commitment raises an additional barrier to trade through adding an opportunity cost to the direct transportation cost. Under plausible conditions, this cost is positively correlated with the terms of trade conditions for the exporter. If the opportunity cost factors into aggregate trade decisions, the consequence is that spatial market integration is weakened. This is because the opportunity cost drives a wedge between the price spread and the direct transportation cost that increases to better is the terms of trade for the exporter. In addition, estimates of market integration or price convergence that does not account for the opportunity cost will be negatively biased due to an omitted variable bias.

To the best of our knowledge, this mechanism is a new novel barrier to trade. We show that this can be empirically relevant liquefied natural gas (LNG) trade. For spot contracts, LNG vessels are flexible, i.e., they can choose their preferred destination. However, sales contracts are irreversible. Entering into contract with one destination precludes other destinations. Thus, there is a timing option for the days committed to transit. LNG allows trade of natural gas between geographically dispersed, but it is technologically demanding. In addition to liquefaction and regasification plants, it requires specially built LNG carriers to move the liquefied gas. Global trade volume has been consistently growing over the last ten years (2016 was a new record year, up 5% from 2015 according to the International Gas Unions, IGU (2017)). LNG is set to become increasingly important for the global energy trade, both in terms of increasing value of existing natural gas resources (I.e. U.S. shale gas), and as a means to limit carbon emissions in the transition away from carbon intensive energy sources.

LNG trade has the potential to generate an integrated global market for natural gas akin to the global market for crude oil. So far, this does not appear to be the case, although some evidence point towards improved spatial price convergence due to LNG (Neumann, 2012; Li et al., 2014). Recent years have seen large persistent regional natural gas price spreads due to regional specific market events (U.S. shale gas, Fukushima incident). This has significantly increased the interest in LNG trade. The large prices spreads has pushed the trade value chain to full capacity with resulting cost of transportation that has prevented large arbitrage opportunities and limited regional price convergence (Dehnavi and Yegorov, 2012; Oglend et al., 2016).

This paper makes two specific empirical contributions on LNG trade and natural gas market integration. We extend the freight cost data used in Oglend et al. (2016) to include a full adjustment cycle in the LNG freight market that started due to the US Shale and Fukushima shocks. We corroborate the finding in Oglend et al. (2016) that an important reason for the apparent weak cross-region price convergence in this period has been high prices of transportation services limiting arbitrage opportunities. Secondly, we estimate a market integration model with added opportunity cost due to time commitments, and proceed to show that the price spread dynamics fits better this model than the standard linear fixed cost model. Specifically, failing to account for the non-linear opportunity cost component in the spread dynamics biases price convergence downwards by around 35%.

The main finding of this paper is that the inefficiency of LNG in facilitating a global market for natural gas is primarily due the technologically demanding nature of the trade itself, not market externalities or other inefficiencies. When factoring in time commitments and the short run inelastic supply of capacity along the value chain, weak market integration is not surprising. Regulatory efficiency can help to reduce barriers, but important technological constraints remain. At the current technology, it is unlikely that we will see in the near future a global market for natural gas the same as the single global market for crude oil.

The rest of this paper is structured as follows. In the next section, we provide some facts about LNG trade and natural gas prices. Specifically we look at the joint development of LNG freight rates and cross-market natural gas price spreads over the last ten years. We provide estimates of cross-market price convergence under different specifications of transportation costs. In section 3, we look at time commitments in the trade decisions. We establish how committing to trade in case of irreversible time commitments introduces an additional opportunity cost that should be added to the economic cost of trade. We establish some characteristics of this opportunity cost under plausible assumptions. In section 4, we estimate a model of the price spread dynamics that includes the opportunity cost component to the transportation cost. This estimate is compared to the estimates without the opportunity cost introduced in section 2. Section 4 then offers some concluding remarks.

2. Facts About LNG Freight Rates and Natural Gas Prices

LNG trade can be divided into three stages that each constitute important bottlenecks in trade. First, trade requires available liquefaction terminals connected to production regions by pipeline. The liquefaction terminals chill and compress the natural gas. The gas is purified and compressed to 0.2% of its input volume, resulting in an LNG energy density nearly 60% that of diesel fuel. Secondly, the liquefied gas must be shipped via specially build cryogenic tankers. Lastly, at the destination market there must be available regasification capacity that converts the LNG to back to gaseous form before it can be injected into the local pipeline.

Investments into any of the three transportation services are highly specific, lumpy and time consuming (even after accounting for the regulatory process of approving investments/trade). This means that supply of capacity is inelastic in the short run, and variations in demand for services can have large and persistent effects on prices of services. The lumpiness of investments leads to cyclicality, as we will see below in the freight cost data. In addition, investments are decentralized, and so capacity at any of the three stages are not necessarily synchronized at any point in time. For instance, adding new shipping capacity can severely depress freight rates if liquefaction capacity is constrained. For instance, in 2015 several new LNG carriers where added to the fleet without the new liquefaction capacity yet coming online. The result was a substantial decline in freight rates.

Due to the geographic dispersion of production and consumption regions, trade occurs over long distances. The main LNG exporting countries are Australia, Algeria, Egypt, Malaysia, Nigeria, Qatar and Trinidad, while main destination markets are Asia (Japan, South Korea), Europe (Belgium, Spain and the UK), India, and to a less degree now the US. Figure 1 shows monthly normalized LNG freight rates (cost of transporting one MMbtu natural gas for 1000 miles in USD) averaged over the above mentioned export markets (left) and import markets (right), along with the overall average normalized freight rates (black solid line). The data is from February 2006 to March 2017.

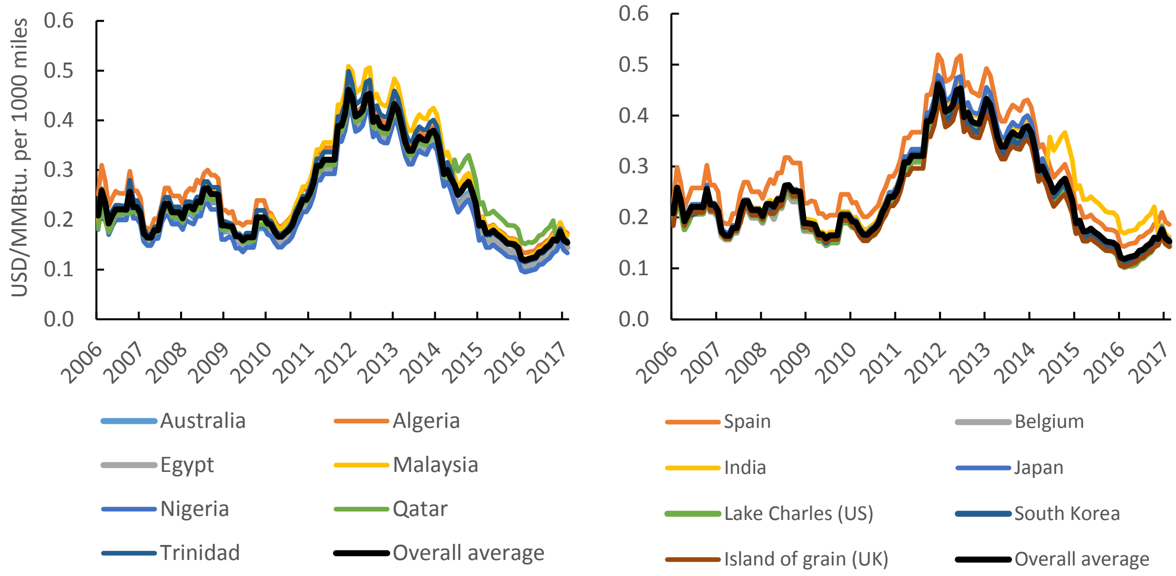

FIGURE 1. Normalized LNG Freight rates averaged over exporters (left) and importers (right) along with overall average each month (black line). Data source: *DataStream*.

Figure 1 tells a story of a competitive and well integrated market for LNG freight. The trend in the price is similar for all exporter or importer markets. As we would expect for well integrated markets, the common trend is more important than cross-section variation for the overall variation in freight rates. A decomposition of the total freight rate variance shows that 70% of the variation is due to the common trend.

The price of freight was stable up to around 2010. The period 2010 to 2016 is a cyclical pattern explainable by strong persistent demand for inelastic freight services. Strong demand led to a strong build up of rates up to 2013. The strong market signal triggered investments in freight capacity. A surge of newbuilds entered the market starting in 2014. During 2016, 31 ships where added to the fleet, compared to 29 new builds in 2015. At the end of 2016, there was 439 LNG tankers in the global LNG fleet (IGU, 2017). This has put downwards pressure on the freight rates to a level below pre-cycle levels. This "undershooting" is due substantial new ships being added to the fleet before the new liquefaction/regasification capacity came online.

The LNG freight cycle is a textbook example of price effects of persistent demand shocks with inelastic short run supply and lumpy capacity investments. The strength of demand for LNG freight is proportional to the regional natural gas price spreads. Figure 2 shows monthly natural gas prices in the US, EU and Asia along with the common trend in the freight rates (as measured by the cross-sectional mean over individual exporter/destination prices).

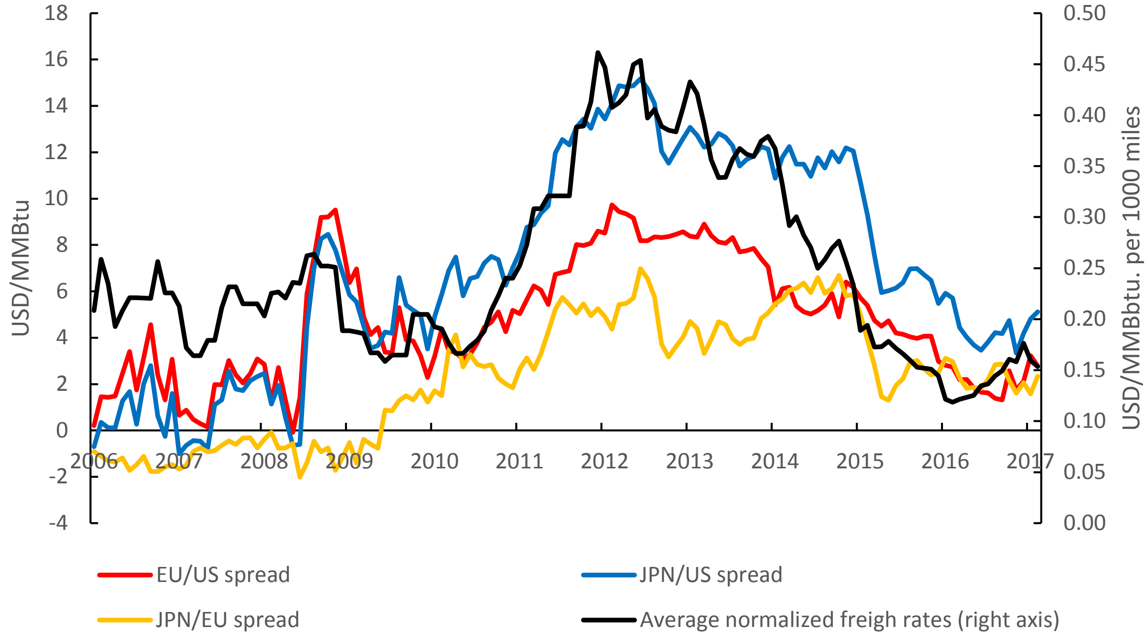

FIGURE 2. Regional natural gas price differences (left axis) and average normalized freight rates (black line, right axis). The US natural gas price is measure by the Henry Hub spot price, the EU price is average import border price with a component of spot price, including UK and the Japan price is LNG, import price, cif. All natural gas prices are from the World Bank Commodity Price data set.

The cycle in the freight rates coincides with the period of large regional natural gas price spreads, consistent with demand being proportional to spreads. When interpreting these kind of figures it is also important to keep in mind the variation in how LNG and natural gas is traded in different markets. Historically, most LNG has been traded on long-term, fixed destination contracts (LTCs), and this is still important for trade. In Japan in 2013, 73% of LNG trade took place under LTCs (Agerton, 2017). LTCs are considered desirable since they provide security of trade for buyers and sellers in a thin market, leading to lower financing costs for large and irreversible capital investments (Brito and Hartley, 2007; Hartley, 2015). Asian LTC pricing normally have a three to six month lag with an oil price index (Japan Crude Cocktail), while European natural gas contracts typically have a six to nine months lag with crude (Brent) and fuel oil. Oil indexation explains, in part, why natural gas prices in Europe and Asia are integrated with oil prices (Asche et al., 2002; Asche et al., 2006; Asche et al., 2017; Siliverstovs et al., 2005; Panagiotidis and Rutledge, 2007). The 2014 drop in the oil price led to a drop in Asian and European LNG import prices. However, they remain at a substantial premium to the non-indexed US natural gas price. In the US, gas-to-gas competition is stronger than in Asia and Europe, and the relationship between oil and natural gas price weaker (Villar and Joutz, 2006; Parsons and Ramberg, 2012). The US shale gas expansion has reinforced this (Kerr, 2010; Joskow, 2013). Excess supply from shale gas production has led to fully decoupled gas and oil prices in the US (Erdős, 2012; Oglend et al., 2015). Differences in pricing of natural gas thus contributes to some of the variation in regional natural gas spreads.

Strong persistent natural gas price deviations do not support the claim of LNG as creating a more integrated global market for natural gas. However, as illustrated by the freight rates in figure 1, the weak price convergence has to be seen in the context of the developments in transportation costs, which themselves reflect the technological constraints in the trade(as was also pointed out in (Oglend et al., 2016). The regional natural gas shocks (then primarily the shale supply shock in the US and the Fukushima demand shock in Japan) allow us to evaluate more precisely the role of the transportation service sector in influencing the degree of cross-regional price convergence. Let $S_t = P_{1t} - P_{2t}$ be the price spread between any two natural gas markets, and let C_t be the marginal cost of transportation. If we assume as a first order approximation that the price spreads S_t adjusts proportionally to the net spread $S_t - C_t$. This suggests the following simple empirical model for the dynamics of the spread,

$$\Delta S_{t+1} = \alpha(S_t - C_t) + \varepsilon_t, \quad (1)$$

where ε_t is an appended mean zero weakly stationary stochastic error. By hypothesis $-1 < \alpha < 0$, which ensures that in the long-run $S_t = C_t$; a reasonable economic restriction. It also implies market integration in the sense that regional price spreads converge to the marginal cost of transportation.

The price spreads and the freight rate in figure 2 all contain a stochastic trend over our sample period[1], but they are weakly stationary in first differences. The implication in terms of (1) is that if $-1 < \alpha < 0$ then S_t is be perfectly cointegrated with C_t (that is $S_t - C_t$ does not contain a stochastic trend). This however assumes we are correctly able to measure the relevant cost C_t. We now turn to estimating the degree of price convergence α for our three prices spreads in figure 2. To do this we consider three measures of the transportation cost, these are

$$C_t = \beta_0, \quad (2a)$$

$$C_t = \beta_0 + distance \times \widetilde{freight\_rate}, \quad (2b)$$

$$C_t = \beta_0 + \beta_1 \times \widetilde{freight\_rate}, \quad (2c)$$

where $\widetilde{freight\_rate}$ is the normalized freight rate standardized to have sample mean zero.

The first measure (2a) assume a fixed transportation cost β_0, where β_0 is estimated. In (2b) the transportation cost is constructed assuming the actual freight cost is the normalized freight rate multiplied by the distance travelled. We again estimate β_0, the mean transportation cost. In (2c) we

[1] The data are I(1). The ADF unit root test fails to reject the null of a unit root. ADF t-statistic of -1.17 for the EU/US spread, -1.77 for the Japan/EU spread, -1.58 for the Japan/US spread and -1.57 for the freight rate, 5% critical value is -2.89, and lags in the ADF specification chosen by minimizing the Akaike Information Criteria from zero to 10 lags. In first differences a unit root is rejected (ADF t-statistic of -5.1 for the EU/US spread, -4.97 for the Japan/EU spread, -3.21 for the Japan/US spread and -6.76 for the freight rate).

allow more flexibility by estimating both the mean transportation cost β_0 and the proportionality factor β_1 on the freight rate. This will allow a richer magnitude of variation in the freight rate to explain the price spread. In light of the above discussion, we would expect α to be greater in magnitude for the measures that include a varying transportation cost (2b and 2c). Table 1 shows the results of the estimation over the three spreads for the three costs.

TABLE 1. Estimation results, price convergence of regional natural gas prices

	Cost model (2a)		Cost model (2b)		Cost model (2c)	
EU/US spread equation	Est.	t-stat.	Est.	t-stat.	Est.	t-stat.
α	-0.072	-2.83	-0.094	-3.23	-0.195	-5.04
β_0	5.039	2.33	4.973	3.14	4.854	4.90
β_1	-	-	4.6	fixed	23.47	5.03
R^2	0.0414		0.055		0.121	
JPN/US spread equation						
α	-0.034	-1.77	-0.046	-1.95	-0.087	-2.43
β_0	8.302	1.75	7.953	1.93	7.474	2.40
β_1	-	-	9.2	fixed	41.78	2.43
R^2	0.0238		0.0335		0.0715	
JPN/EU spread equation						
α	-0.034	-1.77	-0.0492	0.0228	-0.052	-2.29
β_0	2.945	1.70	2.720	2.03	2.686	2.14
β_1	-	-	10.8	fixed	17.72	2.28
R^2	0.0204		0.0306		0.0334	

Note: t-statistics based on HACSE standard errors, Newey and West (1987).

Table 1 confirms the importance of including transportation cost when evaluating the degree of price convergence. All estimates show that when the freight rate is included (models 2b and 2c), the measured degree of price convergence (the magnitude of α) increases. In other words, part of the reason for the weak observed price convergence between regional natural gas markets is the inelastic supply of transportation services, which reflects the technologically demanding nature of LNG transportation. This effect is strongest between the EU/US spread. Limiting LNG freight is not the complete story. As stated, differences in how LNG is traded also contributes to divergence in observed regional prices. In Japan, the majority of LNG is traded on contracts indexed to the Japan Crude Cocktail index. A substantial change in the oil price will affect the spreads mechanically through differences in contract pricing. As such, for the Japan/US and Japan/EU spreads the varying freight rate appear less important in explaining the price spread. This is also confirmed if we test the degree of co-integration between the spread and freight rate. Consistent with table 1 we find by using the Johansen (1988) trace test that the freight rate is cointegrated with the EU/US spread, but not with the JPN/US or the JPN/EU spread[2]. For the latter two spreads there is substantial stochastic trending even after controlling for the freight rate trend. We can pursue this further by looking at the difference between cost estimates (2b) and (2c). Both assume an affine cost structure, however model (2b) assumes freight cost proportional to the actual transportation distance, while model (2c) allows the proportional factor to fit the data. In other words, measure (2b) is the actual freight cost while measure (2c) is the freight cost that best fits the spread. This suggests that the difference between implied costs (2c) and (2b) can be regarded as an excess profitability measure on LNG freight. For instance, when this differences is positive the best fit cost is higher than the actual cost, suggesting excess profit correlated with the spread by not priced in observed freight rate. Figure 3 plots the difference between the estimated implied cost (2c) and (2b) for the three spreads.

[2]

TABLE 2. Johansen trace test for cointegration between spreads and freight rate pairs.

	EU/US		JPN/US		JPN/EU	
H0: coint. rank <=	Stat.	p-value	Stat.	p-value	Stat.	p-value
0	16.12	0.039	11.99	0.458	6.76	0.613
1	1.74	0.187	1.42	0.876	1.377	0.241

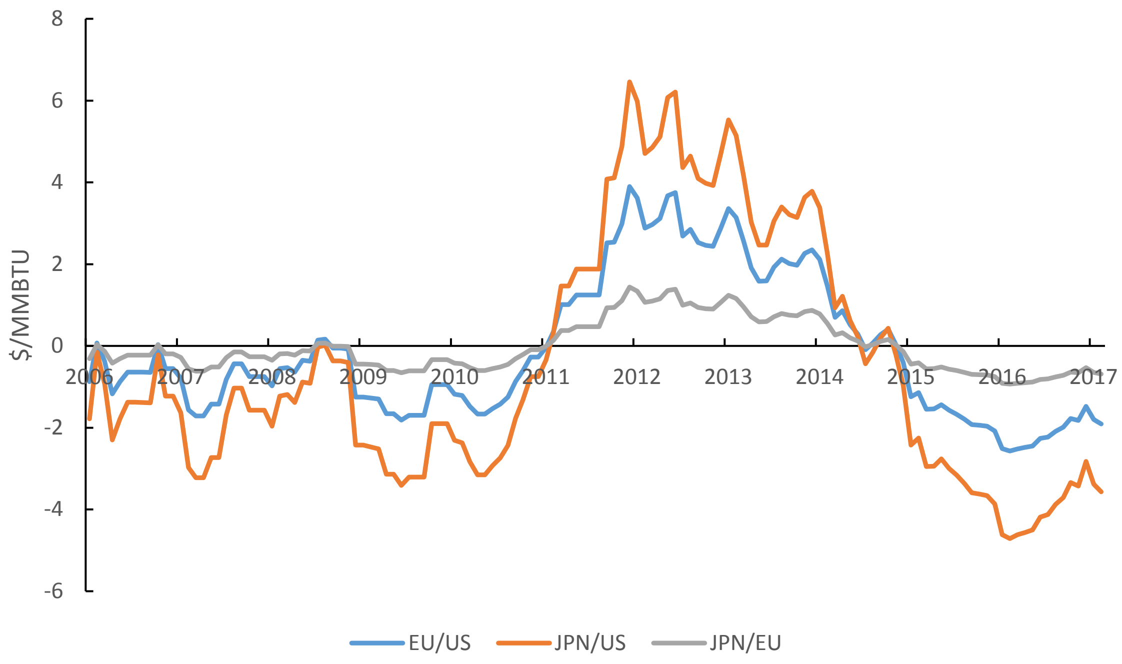

FIGURE 3. Profitability index LNG exports from EU to US (blue), US to JPN (Orange) and EU to JPN (grey)

Figure 3 is interesting in terms of what it says about the relationship between the observed freight cost and the price spreads. It is clear that our measure of the transportation cost, although better than a constant cost assumption, is not complete. There are likely other time-varying cost elements positively correlated the spread, such as variation in liquefaction and regasification costs under varying demand (these are also supplied at fixed capacity in the short run). We do not have measures on time variation in these costs. Besides these direct costs, there might be important opportunity costs associated with the technologically demanding trade. In the next section, we will see that irreversible time commitments gives rise to one such opportunity cost that like the direct transportation costs imposes a barrier to market integration.

3. The Opportunity Cost of Time Commitments in Trade

In the above section, we saw that transportation costs are positively correlated with LNG price spreads and so works as an obstruction to a global market for natural gas. We also saw that the observed freight cost is not sufficient to fully explain the weak price convergence in regional natural gas prices. Further cost factors correlated with the freight cost and the spread is needed to explain the spread. We now consider the role of irreversible time commitments to trade as a source of such a trade cost.

As above, let S_t refer to the price difference between destination and export markets for a commodity. Transportation of the commodity requires an irreversible time commitment, a "shipping time", of n periods. If an exporter makes an export commitment at time t, we assume the price is negotiated at current price levels and price risk vanishes for that shipment for the exporter. Alternative payoff structures are possible. The payoff could be based on some formula that includes the price of a close substitute, such as for oil indexed natural gas contracts. Alternatively, the exporter could sell at spot prices when the shipment arrives, facing price risk during the transportation period. These alternative payoff structures would not eliminate any opportunity cost of committing to trade as discussed in this section. This is because the time commitment is a hard technological constraint that requires the asset to lay dormant during transportation independent of the pay-off structure itself. Because of this, we choose to focus on the simplest payoff structure for exporter (this does allow us to abstract away from risk aversion) to better highlight the mechanism of interest.

Let $V(S_t)$ be the value, standardized to a unit shipping quantity, of a perpetual export licence when current terms of trade conditions are S_t. The value of the licence is assumed to only depend on the spread. We set the direct transportation cost to a fixed size C; in this section we are not interested in the variation in direct transportation costs, but in the opportunity cost of transportation associated with the irreversible time commitment.

Owning the export licence is equivalent to owning a contingent claim similar to an American call option. The licence owner has the right, at any time, to commit to exports, earning a unit revenue of S_t at exercise price C, the direct transportation cost. After exercising the option, it will becomes operational again in n periods. This takes the structure of a recurring American call option.

Definition (n-period Recurring American Call Option). Let $\mathrm{S_t}$ be the price of an asset at time t. The owner of the option has the right to buy one unit of this asset at price C. After exercising the option, it becomes operational again in n periods with the same exercise price.

The licence value $V(S_t)$ is the price of this option. We do not assume the licence is tradable, or that a continuously traded portfolio of the underlying asset and a riskless bond can replicate the value of the licence. In other words, we make no assumptions on either complete markets or lack of arbitrage, as is standard when pricing options on financial assets. Export licences are in positive net supply and can be “scarce”, commanding a substantial positive economic rent. As a note to this, if futures, or forward markets exist for the commodities, a strategy to replicate the financial exposure to S_t, at least approximately, would be to form a an equally weighted rolling portfolio of long positions in the nearest destination market futures and short positions in the nearest home market futures.

Let r be the required rate of return on export operations. The value of the licence when no time commitments are present is $V(S_t) = E_t \sum_{i=0}^{\infty} \frac{1}{(1+r)^i} max\{S_{t+i} - C, 0\}$. Expectations are taken with regards to current period information. This is the conventional trade outcome whereby exports are committed as long as the spread covers the direct transportation cost. If $n = \infty$, the recurring American call option reduces to a perpetual American call option Merton (1973). In this case, only one trade commitment is made, after which the right to exports are forfeited.

Assume the economic cost of transportation is $\hat{C}(S_t) = C + \omega(S_t)$, where C is the direct accounting cost of transportation and $\omega(S_t)$ is some opportunity cost. Assume further that the spread adjusts proportionally to the net spread, $S_t - \hat{C}(S_t)$, as in equation (1). Using the full economic cost ensures that the long-run price spread is $S_t = \hat{C}(S_t)$, where the economic profit of the marginal exporter is zero. We therefore assume that the full economic cost is priced into the spread through aggregate trade decisions. In other words, in equilibrium the export licence has zero economic value. Its value derives from the possibility of arbitrage conditions in the short run.

Suppose there is a continuum of identical traders forming forecasts of future trade conditions based on the spread dynamics in equation (1). Any trader faces a binary decision problem: commit to exports now or delay. This is the decision of exercising the option or not. Delaying gives an immediate payoff of zero. If exports are committed, the immediate payoff is $S_t - C$. After exercising the option, it becomes operational again in n periods. The present value of the licence n periods from now is $(1+r)^{-n}E_t\big(V(S_{t+n})\big)$. If no trade is committed, the option to do so remains in the following period, valued today at $(1+r)^{-1}E_t\big(V(S_{t+1})\big)$.. This leads to the following recursive expression for the maximized value of the licence,

$$V(S_t) = max\left\{S_t - C + \frac{1}{(1+r)^n}E_t\big(V(S_{t+n})\big), \frac{1}{(1+r)}E_t\big(V(S_{t+1})\big)\right\}. \qquad (3)$$

We see from equation (3) that trade will be committed today as long as

$$S_t - C > \frac{1}{(1+r)}E_t\big(V(S_{t+1})\big) - \frac{1}{(1+r)^n}E_t\big(V(S_{t+n})\big).$$

Referring back to the assumed equilibrium condition $S_t = C + \omega(S_t)$ it follows that for our model, the opportunity cost of committing to trade today is given by

$$\omega(S_t) = \frac{1}{(1+r)} E_t\big(V(S_{t+1})\big) - \frac{1}{(1+r)^n} E_t\big(V(S_{t+n})\big). \tag{4}$$

The term $\omega(S_t)$ summarizes how much the spread must exceed the direct marginal transportation cost before exports are committed. By committing today, the exporter forfeits the possibility of doing so the following period, valued at $\frac{1}{(1+r)} E_t\big(V(S_{t+1})\big)$, but receives the possibility of committing again in n periods, $\frac{1}{(1+r)^n} E_t\big(V(S_{t+n})\big)$. If the current payoff exceeds this net cost, it is worth committing to today. The opportunity cost is zero if $n = 1$, i.e. no time commitments. If $n = \infty$ (only one commitment in the licence) $\omega(S_t) = \frac{1}{(1+r)} E_t\big(V(S_{t+1})\big)$, meaning that trade would be committed today given the payoff today exceeds the discounted expected value of having the licence tomorrow (this assume positive interest rate). This is just the conventional American call option pricing. The role of the recurrence term in the option is to reduce the cost of committing today, since the option will become active again in the future.

Using the definition of the opportunity cost, the expression for the value function can be written as

$$V(S_t) = E_t \sum_{i=0}^{\infty} \frac{1}{(1+r)^i} max\{S_{t+i} - C - \omega(S_{t+i}), 0\}.$$

This expression makes it clear that exports are committed when the current spread covers the full transportation cost, which includes both the direct transportation cost and the opportunity cost. The export value is the expected sum of the discounted net economic spread, which is bounded from below at zero under free utilization of the licence.

We have shown that the presence of irreversible time commitments in trade leads to an opportunity cost such that the direct payoff of committing today must exceed this opportunity cost for a commitment to be optimal. The important point for market integration is that such an opportunity cost will impose an additional barrier to price convergence as it increases the payoff threshold where export is committed.

We will finish this section by stating some specific properties of the opportunity cost. To reiterate, we assume the spread itself follows the error-correction process

$$\Delta S_{t+1} = \alpha \left(S_t - \hat{C}(S_t) \right) + \varepsilon_{t+1}, \qquad (5)$$

$$\hat{C}(S_t) = C + \omega(S_t),$$

where ε_t is a mean zero weakly stationary error process. To allows some more precise statements, the following assumptions are made.

Assumption A. (1) $r > 0$*, (2)* $-1 < \alpha < 0$, (3) $\varepsilon_t = \kappa\varepsilon_{t-1} + u_t$, where u_t is iid with bounded support and $0 < \kappa < 1$.

Assumption (1) states that the interest rate is strictly positive, a standard assumption sufficient for contraction mapping and the existence of the maximized value function, equation (3). Assumption (2) is an equilibrium restriction by hypothesis that ensures that arbitrage opportunities are not present in the long run. Assumption (3) ensures the error process is weakly stationary and that its support is bounded, this again ensures that the licence value is bounded and that a maximum exists. The parameter restriction $0 < \kappa < 1$ is not necessary for stationarity, but it allows easy ranking of outcomes in the sense that if $\varepsilon'_t > \varepsilon_t$ then $\varepsilon'_{t+j} > \varepsilon_{t+j}$ for $j > 0$ and a given realization of the shock sequence $\{u_t\}$. This allows us to establish that the licence value is increasing in the spread. We then have the following properties.

Proposition 1. Given Assumption A, the export licence value $V(S)$ is a continuous, increasing, bounded and strictly convex functions of the price spread S. The opportunity cost $\omega(S)$ is a continuous, bounded and strictly convex functions of S. Furthermore, the slope of the opportunity cost is bounded as $-1 < \frac{\Delta\omega(S)}{\Delta S} < 1$.

Assumption A is sufficient but not necessary for the properties in proposition 1. Since the licence value and opportunity costs are convex in S, it follows that higher volatility of the spread increases the licence value and the opportunity cost of committing to trade. Lower price convergence (magnitude of α) increases volatility, and so weaker market integration will increases the licence value and the opportunity cost, this establish a link between option theory and research on market integration. This observation is somewhat interesting as it suggests a type of feedback effect of improving market integration conditions. If market integration improves, there is an added benefit of reducing the opportunity cost of committing to trade, which further contributes to improving market integration conditions. Policies to reduce trade barriers can then have a secondary benefit of reducing the opportunity cost of trade.

4. Model Estimation and Comparison

We have established that when trade is subject to an irreversible time commitment, an opportunity cost of committing to trade is present that increases the barrier to spatial market integration. This effect can be seen more precisely if we consider the effect of a shock today on the spread the following period, $\frac{\Delta S_{t+1}}{\Delta\varepsilon_t}$. In the absence of the opportunity cost, the effect is $\frac{\Delta S_{t+1}}{\Delta\varepsilon_t} = 1 + \alpha$, i.e. a unit increase in the spread at time t persists as a $1 + \alpha$ increase in the spread at time $t + 1$ (and in general $(1 + \alpha)^j$ for j periods ahead). With the opportunity cost present we have $\frac{\Delta S_{t+1}}{\Delta\varepsilon_t} = 1 + \alpha\left(1 - \frac{\Delta\omega(S)}{\Delta S}\right)$. The presence of the opportunity cost reduces the effective price convergence by $\frac{\Delta\omega(S)}{\Delta S} \times 100$ percent. In addition, since $\frac{\Delta\omega(S)}{\Delta S}$ is increasing in S under reasonable conditions (the opportunity cost is convex), the implication in our model is that high spreads S will tend to persist longer than they would in the absence of the time commitment effect. Effective price convergence tends to zero when $\frac{\Delta\omega(S)}{\Delta S}$ tends to unity. This is intuitive since any increase in the spread will be completely absorbed by the trade cost, and so arbitrage is never present to incentivize trade commitments. The empirical consequence of this model is that price convergence estimates based on the (explicit or not) assumption of constant transportation cost will suffer an omitted variable bias. For instance, the error correction model $\Delta S_t = \beta_0 + \beta_1 S_{t-1} + u_t$ estimated by OLS will lead to biased estimate of price convergence given by $E(\beta_1) = E(\alpha\left(1 - \frac{\Delta\omega(S)}{\Delta S}\right))$. This suggests an alternative specification for estimating the true degree of price convergence.

We now estimate the opportunity cost model for spread dynamics (equation 5 above). We will consider the EU/US natural gas price spread as this was the spread with strongest evidence of the spread being cointegrated with the freight rate. The export licence implied by this model will be the value of an export licence from the US to EU, and so the opportunity cost will be the opportunity cost of committing to exports from the US to EU.

The model depends on five parameters, $\theta = \{\alpha, \kappa, \sigma_u, C, r, n\}$. For any given parameter vector θ we can determine the opportunity cost function $\omega(S;\theta)$ by solving the value function maximization problem determining the maximized trade licence value, equation (3). Given $\omega(S;\theta)$ we find the predicted spread $\Delta\tilde{S}_t(\theta)$ using equation (5) for the spread dynamics. We then choose the parameter vector θ that minimizes the squared loss function, $L(\theta) = \sum_{t=1}^{T}\left(\Delta S_t - \Delta\tilde{S}_t(\theta)\right)^2$. This is non-linear least squared with a nested optimization procedure for each parameter vector evaluation. This fit will then be compared to the linear model fit found in section 2 to judge how much the implied opportunity cost component influences the price convergence.

Before estimation, we reduce the parameter vector dimension. We assume iid errors ($\kappa = 0$), consistent with the implied estimates in section 2. Note that $1 > \kappa > 0$ would not bias the estimate of price convergence when $\kappa = 0$ is assumed, but it will increase the standard errors over the parameter estimates. This can be corrected to some degree by applying an autocorrelation consistent standard error estimator, i.e. Newey and West (1987). We further assume a 15% annual required rate of return on export operations. In addition, like for the OLS, the standard deviation σ_u can be estimated as $\sqrt{L(\theta)/(T-1)}$ and so is implied by the other parameters. Finally, we set the time commitment n to two months. Since we only have monthly data this is the lowest time commitment possible for our data-set. We then have only two free parameters to estimate, $\theta = \{\alpha, C\}$, the same as the simple linear error correction model.

Section 2 established the importance of time varying freight rates. Up to now we have assumed a fixed direct cost C. Time varying direct cost would have to enter as an additional state variable in the license avlue. This would significantly complicate the procedure and so take a simpler approach. If we assume that exporters and any current cost C_t believes this cost will persist at that level into the future (up to the relevant planning horizon), we can deal with the varying cost by estimating the model on the freight cost adjusted spread, $\widehat{S_t} = S_t - distance * freight\_rate$. We estimate the model on both the unadjusted spread and the freight cost adjusted spread.

TABLE 2. Estimation Results, Time Commitment model and Linear Model

	Unadjusted spread, S_t				Adjusted spread, $\widehat{S_t}$			
	Opp. cost model		Linear model		Opp. cost model		Linear model	
Parameters	Est.	S.E.	Est.	S.E.	Est.	S.E.	Est.	S.E.
α	-0.113	0.042	-0.072	0.030	-0.135	0.045	-0.091	0.033
σ_u	0.905	-	0.914	-	0.891	-	0.900	-
C	4.56	1.74	5.04	2.17	3.50	1.25	3.86	1.49
r	15% annual		-		15% annual		NA	
SSR	108.17		109.51		104.88		106.17	

Note: t-statistics based on HACSE standard errors, Newey and West (1987).

For both the unadjusted and adjusted spread the opportunity cost model provides an improved fit to the dynamics of the spread (lower residual variance), and suggests greater price convergence than inferred from the linear model. This is consistent with the linear model having an omitted variable bias as discussed above. Note that both models have degrees of freedom 2 so the improved fit is due to model specification.

From the OLS estimate, we have the bias relation $E(\alpha_{OLS}) = E(\alpha_{NLS}\left(1 - \frac{\Delta\omega(S)}{\Delta S}\right)$, where α_{OLS} is the price convergence estimate from linear model and α_{NLS} from the opportunity cost non-linear model. If we substitute our estimates for the expected values, and assume independence between opportunity cost slope and α_{NLS} estimate, we have an estimate of the mean slope $\frac{\Delta\omega(S)}{\Delta S}$. For the unadjusted spread $E\left(\frac{\Delta\omega(S)}{\Delta S}\right) = 1 - \frac{\widehat{\alpha}_{OLS}}{\widehat{\alpha}_{NLS}} = 0.36$ and for the adjusted spread 0.33, meaning that the implied opportunity cost of committing to trade reduces price convergence by around 33% to 36%.

Finally, we plot the implied spread equilibrium values under three assumptions on the transportation cost:

$S = C = 5.04$	(fixed cost)
$S = C = 4.97 + distance \times freight\_rate_t$	(fixed cost + freight cost)
$S = C = 3.5 + distance \times freight\_rate_t + \omega(S)$	(fixed cost + freight cost + opportunity cost)

The first specification simply assumes fixed transportation cost. In the second case we consider also varying freight costs. These two cases where dealt with in section 2 and the fixed costs estimates are from table 1. The last specification is from the adjusted spread estimation in table 2 and includes the opportunity cost.

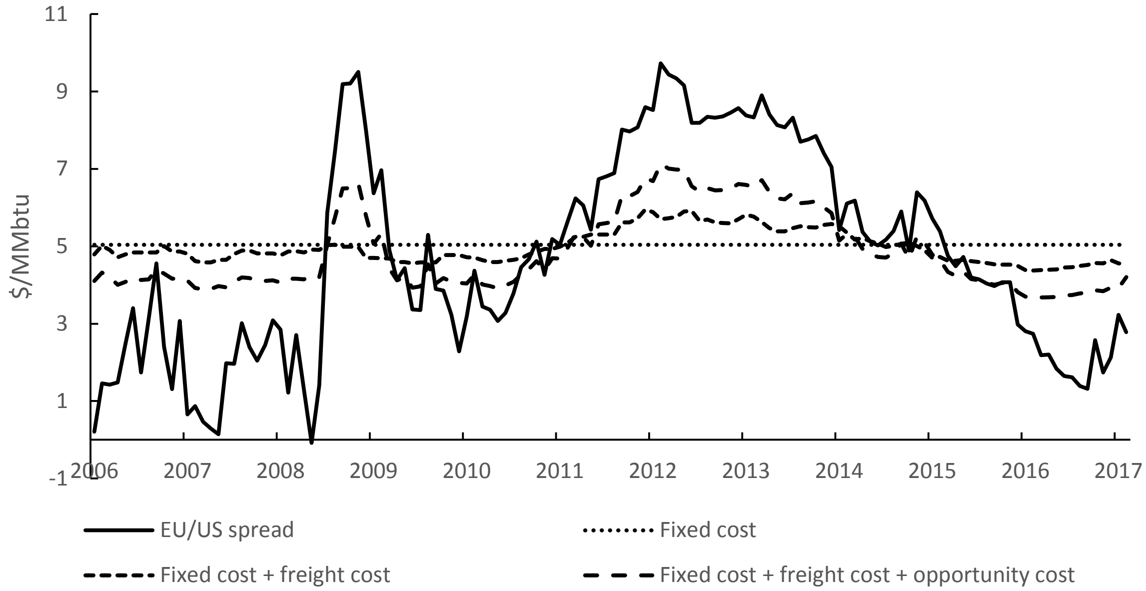

FIGURE 4. EU/US spread and implied equilibrium spreads

Figure 4 shows the spread along with the three specifications for the equilibrium. We observe how the opportunity cost adds non-negligible variation to the implied equilibrium spread. For instance, in late 2008 the US natural gas price dropped considerably relative to the EU price. The freight rate did not adjust, but the implied opportunity cost of committing to trade in this high spread period did increase. This jump up can in economic transportation cost here can then be seen as pricing in the opportunity of even greater spreads in the near future. Such waiting benefits detracts from commitments and increases barriers to market integration.

5. Conclusion

We have evaluated the option value related to timing of irreversible trade commitments. The option value has implications for the value of export licences. It also provides new insight in the field of market integration analysis, as the option value represents an opportunity cost that imposes a wedge between the natural gas price in the export and the import country, in addition to the transportation cost. Thus, the spread reflects both the transportation cost and this opportunity cost. Accordingly, the flexibility in destination port implies a reduction in price convergence. Under plausible conditions, this opportunity cost is positively correlated with the terms of trade conditions for the exporter. This has two important implications. Firstly, the degree of market integration or cross market price convergence is reduced. Actual arbitrage conditions are weaker than what they appear without considering the full opportunity cost. Secondly, empirical estimates of the degree of price convergence between markets will be negatively biased if the opportunity cost is not included. This is because the positive correlation between the opportunity cost and the price spread introduces an omitted variable bias.

We investigate the timing option value in the context of LNG trade. LNG as a technology allows trade of natural gas between geographically dispersed markets that are not connected by pipeline. However, the trade is technologically demanding. Investments in transportation capacity are specific, lumpy and time consuming. In addition, transportation is over long distances from production to consumption regions that require substantial time commitments. Even so, LNG is set to become increasingly important for the global energy trade. It is one of the few energy carriers that is fairly green and able to be transported over long distances. The paper made two specific empirical contributions for LNG trade and market integration. We extended the freight cost data used in Oglend et al. (2016) to include a full adjustment cycle in the LNG freight market that started due to the US Shale and Fukushima shocks. We us this data to shows that an important reason for the apparent weak cross region natural gas price convergence in this period has been high prices of transportation services. Secondly, we estimate a market integration model with added opportunity cost due to time commitments, and proceed to show that the price spread dynamics fits better this model than the standard linear fixed cost model. Specifically, failing to account for the non-linear opportunity cost component in the spread dynamics biases price convergence downwards by around 35%.

The main conclusion of the paper is that the apparent inefficiency of LNG in facilitating a global market for natural gas is the technologically demanding nature of LNG trade. When including both time commitments in the trade and the short run inelastic supply of capacity along the decentralized value chain, weak market integration is not surprising. Regulatory efficiency can help reduce barriers, but the important technological constraints remain. At the current technology, it is unlikely that we will see in the near future a global market for natural gas the same as the single global market for crude oil.

References:

Agerton, M. 2017. "Global LNG Pricing Terms and Revisions: An Empirical Analysis." *The Energy Journal* no. 38(1):133-65.

Asche, F., P. Osmundsen, and M. Sandsmark. 2006. "The UK market for natural gas, oil and electricity: are the prices decoupled?" *The Energy Journal*:27-40.

Asche, F., P. Osmundsen, and s.R. Tveteras. 2002. "European market integration for gas? Volume flexibility and political risk." *Energy Economics* no. 24 (3):249-265.

Asche, F., A. Oglend, and P. Osmundsen. 2017. "Modeling UK Natural Gas Prices when Gas Prices Periodically Decouple from the Oil Price." *The Energy Journal* no. 38(2).

Brito, D.L., and P.R. Hartley. 2007. "Expectations and the evolving world gas market." *The Energy Journal* no. 28(1):1-24.

Dehnavi, J., and Y. Yegorov. 2012. "Is LNG Arbitrage Possible in Natural Gas Market?." *USAEE-IAEE WP* 2110234, no. 16: 15.

Erdős, P. 2012. "Have oil and gas prices got separated?" *Energy Policy* no(49):707-18.

Hartley, P.R. 2015. “The Future of Long-Term LNG Contracts.” *Energy Journal* no. 36 (3):209:33.

IGU, 2015. “World LNG Report - 2015 Edition”. Internation Gas Union, World Gas Conference Edition.

IGU, 2017. “World LNG Report - 2015 Edition”. Internation Gas Union, World Gas Conference Edition.

Johansen, S. 1988. "Statistical analysis of cointegration vectors." *Journal of economic dynamics and control* no. 12 (2):231-254.

Joskow, P.L. 2013. "Natural gas: from shortages to abundance in the United States." *The American Economic Review* no. 103 (3):338-343.

Kerr, R.A. 2010. "Natural gas from shale bursts onto the scene." *Science* no. 328 (5986):1624-1626.

Li, R., R. Joyeux, and R.D. Ripple. 2014. "International Natural Gas Market Integration." *The Energy Journal* no. 35(4):159-79.

Merton, R.C. 1973. "Theory of rational option pricing." *The Bell Journal of economics and management science* 4(1):41-183.

Neumann, A. 2012. "Linking Natural Gas Markets-Is LNG Doing its Job?" *The Energy Journal* no. 30 (Special Issue):187-200.

Newey, W.K., and K.D. West. 1987. "A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix." *Econometrica* 55(3):703-708.

Oglend, A., T.S. Kleppe, and P. Osmundsen. 2016. "Trade with endogenous transportation costs: The case of liquefied natural gas." *Energy Economics* no. 59:138-148.

Oglend, A., M. Lindback, and P. Osmundsen. 2015. "Shale Gas Boom Affecting the Relationship Between LPG and Oil Prices." *Energy Journal* no. 36(4):265-86.

Panagiotidis, T., and E. Rutledge. 2007. "Oil and gas markets in the UK: Evidence from a cointegrating approach." *Energy Economics* no. 29 (2):329-347.

Parsons, D.J., and J.E. Ramberg. 2012. "The Weak Tie Between Natural Gas and Oil Prices." *The Energy Journal* no. 33 (2).

Siliverstovs, B., G. L'Hégaret, A. Neumann, and C. von Hirschhausen. 2005. "International market integration for natural gas? A cointegration analysis of prices in Europe, North America and Japan." *Energy Economics* no. 27 (4):603-615.

Villar, J.A., and F.L. Joutz. 2006. "The relationship between crude oil and natural gas prices." *EIA manuscript, October*.

Appendix

Proof of Preposition 1.

We reiterate the assumption behind proposition 1 in the text, assumed to hold throughout the proof.

Assumption A. (1) $r > 0$*, (2)* $-1 < \alpha < 0$*, (3)* $\varepsilon_t = \kappa\varepsilon_{t-1} + u_t$*, where* u_t *is iid with bounded support and* $0 < \kappa < 1$*.*

Consider the following iterative procedure:

$$\Delta S_{i,t+1} = \alpha\big(S_t - C - \omega_i(S_t)\big) + \varepsilon_{t+1} \tag{A1}$$

$$\varepsilon_{t+1} = \kappa\varepsilon_t + u_{t+1} \tag{A2}$$

$$V_{i+1}(S_t) = max\{S_t - C + \beta^n E_t V_i\big(S_{i,t+n}\big), \beta E_t V_i\big(S_{i,t+1}\big)\}, \tag{A3}$$

$$\omega_{i+1}(S_t) = \beta E_t V_{i+1}\big(S_{i,t+1}\big) - \beta^n E_t V_{i+1}\big(S_{i,t+n}\big). \tag{A4}$$

The fixed point to this recursion is the maximized value function, equation (3), and the spread dynamics, equation (5).

Under assumption A, the domain of the state variable is bounded, $S \in \Sigma_S$, a compact set. Fix $V_0(S)$ to be a continuous, increasing, convex and bounded function of S. Furthermore, fix $\omega_0(S)$ as a continuous, convex and bounded function of S with slope restriction $-1 < \frac{\Delta\omega(S)}{\Delta S} < 1$.

Now, given $\omega_0(\mathrm{S})$ is continuous and convex with the given slope restriction, $S_{0,t}$ will be a stationary and bounded process, and $S_{0,t+\mathrm{j}}$ for any $\mathrm{j} > 0$ will be continuous in S_t and strictly bounded. As such, the expectation operator is well defined.

From (A3), $V_1(\mathrm{S_t})$ will be continues in S_t since $S_{0,t+\mathrm{j}}$ and $V_0(S)$ is continuous. Furthermore, since $\beta < 1$ and $V_0(S)$ and $S_{0,t+\mathrm{j}}$ for any $\mathrm{j} > 0$ is bounded, $V_1(\mathrm{S_t})$ will be bounded as well. For an increase in the spread $S_t' > S_t$, it follows that $S_{0,t+j}' > S_{0,t+j}$ for $j > 0$ for any shock sequence. Since $V_0(S)$ is increasing in S, both terms in the max expression in (A3) will increase with an increase in S, and so $V_1(\mathrm{S_t})$ will be increasing in $\mathrm{S_t}$. Finally, both terms in the max expression are convex in S since $V_0(S)$ is convex in S and the expectation operator is linear and preserves convexity. Since the max of two convex functions is convex, $V_1(S)$ is convex in S. We have now established that in the recursion, $V_1(S)$ preserves continuity, convexity, boundedness and monotonicity.

Since $V_1(S)$ is continuous and bounded, $\omega_1(S)$ will be continuous and bounded as well. The greatest impact of an increase in the spread on the licence value occurs when S is high (it is convex). For sufficiently high S any commitment will be made as soon as it is available (technically, the left hand side of the max will, for sufficiently high S, increase beyond the right hand side by boundedness of the value function). This allows us to construct and bound on the slope of the value function as

$$\frac{\Delta V_1(S)}{\Delta S_t} < 1 + \beta^n(1+\alpha)^n + \beta^{2n}(1+\alpha)^{2n} + \cdots = \frac{1}{1-\beta^n(1+\alpha)^n}.$$

The resulting opportunity cost slope is $\frac{\Delta\omega_1(S)}{\Delta S} < \frac{\beta(1+\alpha)-\beta^n(1+\alpha)^n}{1-\beta^n(1+\alpha)^n}$. This slope is below unity if $\beta(1+\alpha) < 1$, which holds by assumption A. Furthermore, for the lower bound on the slope to be below or equal to -1, we would have to have that the slope of the value function zero or negative, which we have shown is not the case (we have shown that is strictly positive). This then preserves the slope bound $-1 < \frac{\Delta\omega(S)}{\Delta S} < 1$ for $\omega_1(S)$. We remark here also that the stationarity of $S_{0,t}$ along with the continuity of $V_1(S)$ ensures the existence of the slopes of $\beta E_t V_1(S_{0,t+1})$ and $\beta^n E_t V_1(S_{0,t+n})$ at any point.

Finally, since $S_{1,t}$ is a stationary process, $\beta E_t V_1(S_{0,t+1})$ will be a more convex function of S_t than $\beta^n E_t V_1(S_{0,t+n})$ for $n > 1$. This is because of regression to the mean as n increases. It follows that $\omega_1(S)$ will be a convex function of S. We can also see this by noting that as S_t increases, the slop of $\beta E_t V_1(S_{0,t+1})$ increases by its convexity, however the slope of $\beta^n E_t V_1(S_{0,t+n})$ increases less, both because of the mean reversion in $S_{i,t+1}$, but also because $\beta^n < \beta$. This establishes that $\omega_1(S)$ inherits boundedness, continuity, convexity and the slope restriction from $\omega_0(S)$.

The iterative procedure preserves the initially conjectured properties of the licence value and opportunity cost functions. It follows that the fixed point solution also inherits these properties. This fixed point exists by the boundedness of the value function and is given by equation (3) in the main text. This completes the proof.