Time Commitments in LNG Shipping and Natural Gas Price Convergence

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ABSTRACT

Inter-continental Liquefied Natural Gas (LNG) trade can facilitate the development of a global natural gas market. However, in addition to explicit shipping costs, such trade requires time commitments in shipping due to the long hauls of many shipping routes. We show that this time commitment adds an additional economic cost to LNG shipping, and creates a positive relationship between the economic cost of LNG trade and regional natural gas price spreads. Necessary time commitment therefore augments the other costs of LNG trade, and contributes to weaken the ties between global natural gas markets.

Keywords: LNG, Natural gas, Trade, Price convergence

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1. INTRODUCTION

Inter-continental Liquefied Natural Gas (LNG) trade can facilitate the development of a global natural gas market. LNG trade has been consistently growing (2018 was another record year, up 9.8% from 2017 according to the International Gas Union, IGU (2019)), and LNG is set to become an important part of the global energy trade. LNG may also contribute to the transition away from carbon intensive energy sources[1] by reducing the price of natural gas in locations currently dependent on higher-emission alternatives. Gilbert and Sovacool (2017) show that LNG exports from the U.S. to China can have both positive and negative effects on greenhouse gas emissions depending on future replacement scenarios of high emissions energy sources, while Song et al (2017) show that switching from diesel to LNG in heavy-duty vehicles in China reduces greenhouse gas emissions from heavy-duty vehicles by 8%. In addition, LNG can serve as a cost-efficient substitute for marine fuels derived from oil (Yoo, 2017), and reduce conventional air pollution in port cities.

Evidence that LNG trade has significantly contributed to improve global natural gas market integration, is limited although some evidence points towards improved spatial price convergence over time (Neumann, 2012; Li et al., 2014; Mu and Ye, 2018). Recently, the U.S. shale gas revolution and the Fukushima incident have highlighted the compartmentalized nature of natural gas markets. These events have revealed how economic costs of LNG trade are positively related to regional natural gas price spreads, which limit profitable trade opportunities (Dehnavi and Yegorov,

1. Halicioglu and Ketenci (2018) demonstrate the importance of natural gas energy inputs along with international trade in output in limiting CO_2 emissions in the EU-15 countries. In a case study of natural gas transportation from Norway, CO_2 emission intensity is found to be higher for LNG compared to pipeline transportation (Shaton, Hervik and Hjelle, 2019).

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2012; Oglend et al., 2016). Lumpy and time-consuming investments in regasification, liquefaction, and shipping makes supply of LNG trade infrastructure inelastic. A positive natural gas demand shock (such as resulting from the aftermath of the Fukushima incident), increases derived demand for transportation services. As idle transportation capacity declines, prices of services increase, resulting in cost escalations that limit profitable trade. This again affects trade flows and natural gas price formation. In this setting, high cross-market price spreads are necessary to ensure competitive returns on invested capital and are not a signal of market inefficiency. Nevertheless, occasionally tight transportation capacity markets provide a source for time varying LNG transportation costs that positively correlates with cross-market natural gas price spreads.

While these cost effects are known, an additional economic cost of LNG shipping that arises from time commitments in shipping has, to the best of our knowledge, not previously been highlighted in the literature. Dehnavi and Yegorov (2012) and Oglend et al (2016) investigate time varying economic cost and profitability of LNG trade. In this paper, we investigate how time commitments in shipping add to the economic cost of LNG trade and introduces an additional component to the economic shipping cost that is positively related to cross-market natural gas price spreads.

We show how owning an LNG ship is equivalent to owning a recurring American call option on the price spread between destination and home market, with a strike price equal to the direct transportation cost. An LNG ship can be valued as a recurring American call option. 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”.

We also show how the time commitment raises the economic cost of long-distance energy trade. Optimally exercising the option requires a price spread that exceeds the direct transportation cost. This is necessary to compensate the ship owner for committing to the long-distance trade. This wedge to the spread then contributes to weaken the ties between natural gas markets. The opportunity cost may make it optimal to idle a ship for a period of time, something that does not happen in models minimizing direct costs alone. The opportunity cost also implies that trade will be affected not only by the current configuration of prices, but by the anticipated prices expected to be available for the time the ship is being used.

The aim of this paper is not to present a full-fledged optimization model for LNG transportation, or a detailed technical model of the cost of LNG shipping. The data used in this paper (monthly frequency aggregates of prices and freight rates) is of too low resolution to isolate specific engineering elements of trade costs (i.e. such as impacts of loss due to boil-off). In addition, LNG trade is constantly evolving, and has changed substantially in the period we investigate, which limits what can be learned historically that is relevant today. Conditions of trade vary across regions and shipping routes (i.e. differences in LNG contracts and remunerations, the cost of using the Panama Canal), across technology (differences in ships), and across the behavior of the agents involved. This paper instead aims to highlight and investigate the additional economic cost of shipping that arises from time commitments, and its potential contribution to supporting persistent regional natural gas price spreads. Although the necessary time commitment in shipping will vary across routes and ships, a large time commitment is a general feature of the LNG shipping economy. A large part of the LNG freight is inter-continental and takes considerable time both to make the original voyage, and to re-position the vessel to make the next voyage. LNG ships are special purpose and thus make one-way voyages to deliver their cargo. By contrast general cargo ships, such as container ships, carry cargo in both directions.

The question of the economic cost of LNG trade is highly relevant to the future role of natural gas as a competitive part of the global energy supply. It is relevant to the question of reducing EU's reliance on Russian pipeline gas, and the potential impact of the U.S.-China trade war on the competitiveness of U.S. LNG in Asia. The time commitment cost reduces competitiveness of long-haul LNG trade relative to natural gas pipeline supply. This is relevant to the question of how cheap U.S. natural gas needs be to compete with Russian pipeline supply, and the impact of possible tariffs on U.S. LNG imports to China. China is a growing LNG market, accounting for 16.7% of LNG imports in 2018 (IGU, 2019). The results in this paper highlight that while LNG shipping costs vary according to market conditions, time commitment cost can provide an additional impediment to LNG trade.

The paper is structured as follows. We start the next section by providing some background information on LNG trade and natural gas markets. We use LNG freight rates as a measure of the explicit cost of LNG shipping, and highlight the historic co-movement between shipping cost and cross-regional natural gas price spreads. We also provide empirical estimates of historic price convergence under different assumptions about transportation costs. This demonstrates how shipping costs historically have supported large differences in regional natural gas prices. However, we also show that the explicit shipping cost is not sufficient to account for the full spread. Motivated by this, we investigate the role of time commitments in contributing to the economic cost of LNG shipping. In section 4, we investigate whether plausible model parameters can generate economically significant time commitment costs by looking at a case of LNG trade from the U.S. to Europe. We end the paper with concluding remarks in section 5.

2. LNG TRADE AND NATURAL GAS PRICES

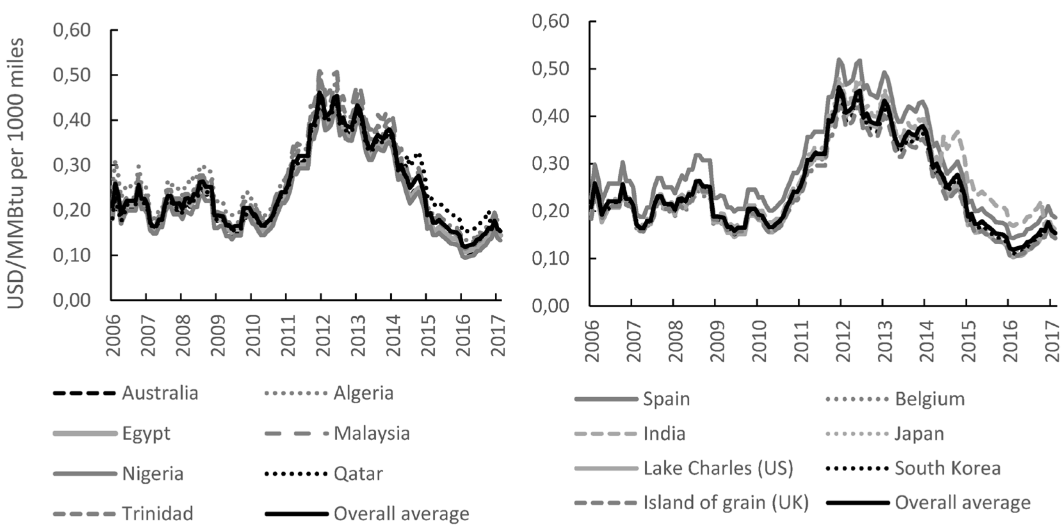
The primary role of LNG trade is to connect supply and demand regions not connected by pipeline. Consequently, much LNG trade occurs over long distances. In 2018, the top five LNG exporting countries where Qatar, Australia, Malaysia, U.S. and Nigeria (IGU, 2019). The top five importing countries in 2018 were all in Asia: Japan, China, South Korea, India and Pakistan. In Europe, Spain comes in as the 6th largest importer in the world, France as the 8th largest and Italy as the 10th largest. With growth in LNG trade, new markets for LNG are likely to emerge (Sida, 2017).

The LNG trade infrastructure can be divided into three necessary stages. First, trade requires liquefaction terminals connected to production regions, primarily by pipeline. These liquefaction terminals chill and compress the incoming natural gas. In this process, the gas is purified and compressed to 0.2% of its input volume, resulting in an LNG energy density around 60% that of diesel fuel. Second, the liquefied gas is shipped via specially built cryogenic tankers to destination markets. Finally, once at the destination, regasification terminals are required to convert the LNG back to a gaseous form that is then injected into the local pipeline infrastructure. Each of these stages are necessary for the LNG trade.

Investments in liquefaction, regasification and shipping capacity are specific, lumpy due to moderate economics of scale, and time consuming (even after accounting for the regulatory process of approving investments). Lumpy investments in otherwise competitive markets lead to cyclicality in prices of services. After new capacity investments are made, excess supply might drive prices down to reflect marginal operating costs. However, such pricing would not provide a competitive return on investments. As time progresses, invested capital decays (and/or demand expands) and prices tend to increase until they trigger new expansions in investments. However, unexpected changes in market conditions makes this process irregular. Periods of shortages in capacity can arise unexpectedly if market conditions change from initial plans. This will often drive prices of services well above marginal operating costs. In a competitive market with lumpy investments, such price outcomes are necessary to ensure competitive returns on investments. Occasional tightness in available capacity explains why LNG transportation costs, such as LNG freight rates and LNG ship rental rates, periodically rise to high levels. Furthermore, capacity investments are decentralized, leading to problems in synchronizing added capacity at different stages of the trade infrastructure, which contributes to fluctuating transportation costs. For instance, because of the necessity of each stage of the trade infrastructure, adding new shipping capacity can severely depress freight rates if matching liquefaction and/or regasification capacity is not yet available. This was highlighted in 2015 when several new LNG carriers where added to the fleet without new liquefaction capacity yet coming online.

Figure 1 shows monthly normalized LNG freight rates (cost of transporting one MMbtu natural gas as LNG 1000 miles in USD) averaged over different exporting (left) and importing regions (right). The figures show that the markets for LNG freight are highly integrated; the trend is similar across all exporting and importing areas. A decomposition of the total freight rate variance shows that 70% of the variation in freight rates is due to the common trend (as shown by the black lines in both figures).

Figure 1: Normalized LNG freight rates averaged over exporters (left) and importers (right) along with overall average each month (black line).

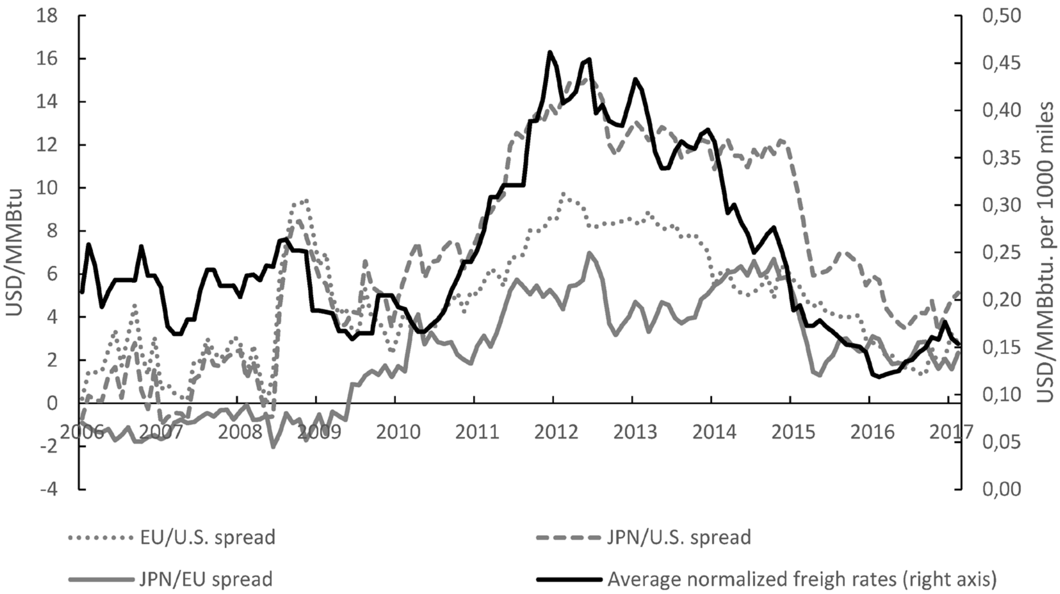


Source: DataStream.

The price of freight was fairly stable until around 2011. The period from 2011 to 2016 shows a cyclical expansion/contraction phase in rates. The aftermath of the Fukushima incident led to strong demand for freight services, and tightness in capacity raised rates, while also triggering new investments in capacity. A surge of new builds entered the market, starting in 2014. In 2015, 29 ships were added to the fleet, in 2016, 31 new builds entered the market. Towards the end of 2016, there were 439 LNG tankers in the global fleet (IGU, 2017). The influx of capacity put downwards pressure on freight rates to a level below the pre-2010 levels. This undershooting was primarily due to new ships being added to the fleet before matching liquefaction/regasification capacity came online.

Figure 2 shows some monthly regional natural gas spreads along with the freight rate trend (as measured by the cross-sectional mean over individual exporter/destination prices). While freight

Figure 2: Regional natural gas price differences (left axis) and average normalized freight rates (black line, right axis).



Notes: The U.S. natural gas price is measured 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.

rates from Figure 1 display greater common pricing than regional natural gas prices, the freight rate (black) coincides with a cycle in the price spreads. Higher spreads in the aftermath of the Fukushima incident (and impacts of U.S. shale gas), increased derived demand for freight, leading to a tightness in capacity and higher freight rates.

Historically, most LNG has been traded using long-term fixed destination contracts (LTCs). In Japan in 2013, 73% of LNG trade took place under LTCs (Agerton, 2017). LTCs are desirable because they provide security for buyers and sellers in a thin market, leading to lower financing costs for large, ireversible investments (Brito and Hartley, 2007; Hartley, 2015). Asian LTC pricing has a three to six months 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 co-vary strongly with oil prices (Asche et al., 2002; Asche et al., 2006; Asche et al., 2017; Siliverstovs et al., 2005; Panagiotidis and Rutledge, 2007). In the U.S. market, gas-to-gas competition is stronger and the relationship between oil and natural gas prices is weaker (Villar and Joutz, 2006; Parsons and Ramberg, 2012). The U.S. shale gas expansion reinforced the difference between U.S., European and Asian prices (Kerr, 2010; Joskow, 2013). Excess supply from shale gas production led to fully decoupled gas and oil prices in the U.S. (Erdős, 2012; Oglend et al., 2015). A well-integrated and liquid freight market together with volatile natural gas spreads provide incentives for more flexible spot trading contracts, which indeed have become more prevalent (IGU, 2019). There has also emerged a new group of "portfolio traders". These traders contract to deliver LNG to customers without specifying where they will obtain each cargo. Instead, the seller decides on the purchase location, or origin port for the resulting shipment, depending on the prices and the availabilities of LNG and ships.

2.1. An Empirical Analysis of Price Convergence

The large and persistent natural gas price spreads revealed recently do not appear consistent with LNG trade facilitating a more global natural gas market. However, as highlighted above, price spreads need to be analysed in concert with developments in transportation costs.

Let $S_t = P_{1t} - P_{2t}$ be the price spread between a natural gas importing and exporting region, and let C_t be the marginal cost of transportation, representing the direct marginal cost of sourcing the natural gas, excluding the purchase price P_{2t}, and delivering the natural gas in the import market. Note that the exact components of such a marginal cost will depend on where in the supply chain the natural gas is sourced and delivered (i.e. at the regasification or liquefaction terminals, or pipeline gas). We assume at a minimum that it contains freight rates associated with shipping the LNG.

If we assume that the price spread S_t adjusts proportionally to the net spread $S_t - C_t$, this leads to a simple empirical first order difference equation for the spread,

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

where ε_t is a mean zero weakly stationary stochastic error that accounts for changes in the spread not due to the net spread. The restriction that $-2 < \alpha < 0$ is necessary to ensure that regional price spreads converge to the marginal cost of transportation, $S_t = C_t$. The price spreads and freight rates in Figure 2 all display stochastic trends over the sample period[2], but are weakly stationary in first differences. The empirical implication of $-2 < \alpha < 0$ in such a setting is that S_t and C_t are cointegrated and share the same stochastic trend.

How the economic cost C_t is measured will influence any conclusion on price convergence. We propose three measures of transportation cost C_t when estimating price convergence. These specifications are not complete accounts of economic costs but are useful for comparison. To this end, we consider the following three measures of the transportation cost,

$$C_t = \beta_0, \tag{2a}$$

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

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

where $\widetilde{freight\_rate}$ is the normalized freight rate standardized to mean zero. Cost measure (2a) assumes a fixed transportation cost β_0. In (2b), the transportation cost includes a constant plus an estimate of actual freight cost (total distance travelled multiplied by freight rate). In (2c), we allow for a more flexible cost specification by also estimating the factor of proportionality, β_1, on the freight rate.

Our aim with these specifications is not to arrive at an exact cost model of LNG transportation. Several elements of shipping costs are not directly specified, such as losses due to boil-off, or the cost of using the Panama Canal if relevant. In addition, rental rates of LNG ships function

2. The data are I(1) (the first difference of the price series' do not contain unit roots). The Augmented Dickey Full, 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).

as an opportunity cost of shipping that also adds to economic cost from the point of view of a ship owner. Market rental rates will increase when shipping capacity is binding, and so will be positively correlated with freight rates. The purpose of the cost formulations is to provide comparative measures of the role of time-varying transportation costs. Comparing the constant cost case (2a) with the time-varying freight cost case (2b) allows us to infer the relative importance of time-varying rates on observed spreads. And, comparing the freight cost case (2b) to a more flexible specification (2c), allows us to infer how much the direct freight cost measure over or underestimates implied costs from the spreads.

Table 1 shows estimates of α, the rate of price convergence, and the cost functions in 2a–c for the EU/U.S., JPN/U.S. and JPN/EU price spreads in Figure 2.

Table 1: Estimation results, price convergence of regional natural gas prices

	Cost model (2a)		Cost model (2b), $\beta_1 = distance$		Cost model (2c)	
EU/U.S. 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	—	23.47	5.03
JPN/U.S. 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	—	41.78	2.43
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	—	17.72	2.28

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

For all cross-market spreads, the implied rate of price convergence increases when including a measure of time-varying transportation costs. This suggests that parts of the weak price convergence between regions can be explained by binding capacity constraints raising prices of transportation services when derived demand is high (spreads are high). This makes economic sense, as the spread in such cases partly compensates the owners of the scarce transportation services, rather than the pure spread traders.

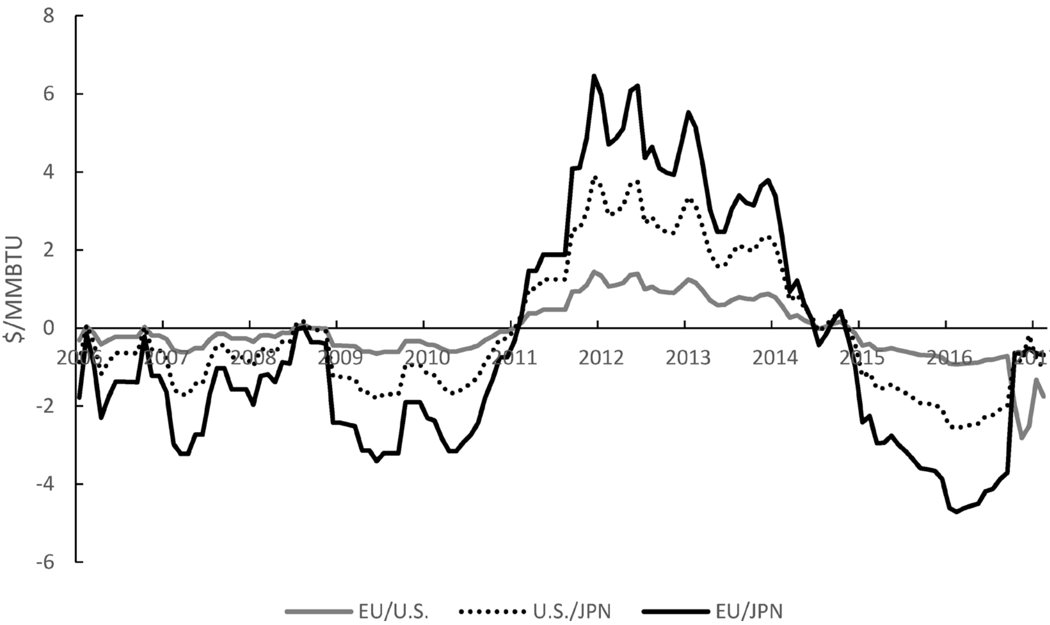
Differences in how LNG is traded is likely also to contribute to divergence in observed regional prices. As mentioned above, in Japan most LNG has been traded using contracts indexed to the Japan Crude Cocktail index. A substantial change in the oil price will therefore mechanically affect the measured price without reflecting immediate underlying supply/demand conditions for natural gas. For the Japan/US and Japan/EU spreads, the freight rate appears less important (lower t-statistics and lower magnitude of price convergence) in explaining the price spread. This is confirmed by cointegration tests between spreads and the freight rate. Consistent with Table 1, the Johansen (1988) trace cointegration test suggests that the freight rate is cointegrated with the EU/U.S. spread, but not with the JPN/U.S. or the JPN/EU spread[3].

Figure 3 plots the difference between estimated costs from models (2c) and (2b) for the three spreads. Note that model (2b) assumes that the freight cost is proportional to total transportation distance, while model (2c) allows the proportionality factor to fit the data. Cost (2b) approx-

3. See Appendix 2 for table of the cointegration results.

imates actual freight cost, while (2c) approximates the freight cost that best fits the spread. The difference can be regarded as unexplained freight cost.

Figure 3: Difference in estimated LNG transportation cost between model (2c) and (2b) for LNG exports from EU to U.S., U.S. to JPN, and EU to JPN.



If the freight cost in (2b) was a complete cost measure, the lines in Figure 3 would be straight lines. This is clearly not the case. The simple freight model is not the full story, and there are probably other cost elements that positively vary with the spread. Examples are possible costs from boil-off during transportation, or varying liquefaction and regasification costs. In the next section, we investigate the potential economic cost from time commitments in shipping of LNG.

3. THE ECONOMIC COST OF TIME COMMITMENTS IN SHIPPING

We assume shipping of LNG requires a time commitment, a shipping time, of *n* periods. If a ship owner commits to a shipment at time *t*, we assume the price received is negotiated at current time *t* price levels, so that any price risk from in-transit price variations vanishes for the exporter. Alternative payoff structures are of course possible. Payoff could be based on some formula including the price of a close substitute, such as for oil indexed trading contracts. Alternatively, the ship owner could sell at destination market spot prices when the shipment arrives, or contract sales terms during transit. These alternative payoffs would not eliminate the economic opportunity cost of time commitments. The time commitment is a hard constraint that physically removes the natural gas cargo from markets during transit.

Let $V(S_t)$ be the value, standardized to one unit of the shipped commodity, of a ship when the current price spread is S_t. We set the direct transportation cost to a fixed quantity, C. We treat C as constant in order to focus on the time commitment opportunity cost. There is a robust market for renting LNG ships. By using the ship, the owner forfeits potential rental rates. This introduces an additional opportunity cost element to shipping. Furthermore, the market rental rate will vary with the tightness of the market for LNG shipping capacity. In addition, LNG shipping is subject to losses in transportation due to boil-off, which introduces a direct cost element that is proportional to natural gas prices. While we focus in this section on the economic trade-off between committing to a shipment now, or waiting, it is important to be aware that other important economic transportation cost elements exist.

Owning an LNG ship is equivalent to owning a contingent claim similar to an American call option. The ship owner has the right to commit to exports, earning a unit revenue of S_t at an exercise price of C (which might contain forfeited rental receipts). After exercising the option, the option becomes operational again in n periods. This claim takes the structure of a recurring American call option.

Definition (n-period Recurring American Call Option). Let 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.

The ship value $V(S_t)$ is the price of the option. We do not assume that a continuously traded portfolio of the underlying asset (natural gas spreads), and a riskless bond can replicate the value of the ship. Ships are in positive net supply and can be periodically scarce due to tightness in freight capacity, commanding periodically positive economic profits.

Let r be the required rate of return of the ship owner. With no time commitment, the value of the ship is $V\left(S_t\right) = E_t \sum_{i=0}^{\infty} \frac{1}{\left(1+r\right)^i} max\left\{S_{t+i} - C, 0\right\}$. Expectations are taken with regards to current period information. Exports are committed as long as the spread covers direct transportation costs. If $n = \infty$, the recurring option becomes a perpetual American call option as in Merton (1973). In this case, only one trade is made, after which the ship is no longer operational for the export venture.

Assume the economic cost of transportation is $\hat{C}\left(S_t\right) = C + \omega\left(S_t\right)$, where C is the explicit cost, and $\omega\left(S_t\right)$ is an opportunity cost of shipping. We now show how $\omega\left(S_t\right)$ stems from the time commitment. To proceed, assume the spread adjusts proportionally to the net spread, $S_t - \hat{C}\left(S_t\right)$, as in equation (1). Using the full economic cost ensures that the long-run price spread is $S_t = \hat{C}\left(S_t\right)$. This assume that the full economic cost of shipping is priced into the spread through aggregate trade decisions. In the long run, $S_t = \hat{C}\left(S_t\right)$, and ships earn zero economic profits.

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 (*exercise the option*) or delay the decision. Delaying and idling the ship provides no immediate payoff. If exports are committed, the immediate payoff is $S_t - C$. After committing the ship, the option becomes operational again in n periods. The present value of an uncommitted ship n periods from now is $\left(1+r\right)^{-n} E_t\left(V\left(S_{t+n}\right)\right)$. If no trade is committed, the option to do so remains open in the next period, valued today at $\left(1+r\right)^{-1} E_t\left(V\left(S_{t+1}\right)\right)$. This leads to the following recursive expression for the value of the ship,

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

The first term is the value of shipping today, the second term is the value of idling for one period. A shipment occurs today when the first is greater than the second,

$$S_t - C > \frac{1}{\left(1+r\right)} E_t\left(V\left(S_{t+1}\right)\right) - \frac{1}{\left(1+r\right)^n} E_t\left(V\left(S_{t+n}\right)\right). \tag{4}$$

The right-hand side defines the opportunity cost of the commitment for the ship owner,

$$\omega(S_t) = \frac{1}{(1+r)} E_t\left(V\left(S_{t+1}\right)\right) - \frac{1}{(1+r)^n} E_t\left(V\left(S_{t+n}\right)\right). \quad (5)$$

This summarizes how much the spread must exceed the direct cost before exports are optimally committed. By committing today, the exporter forfeits the possibility of doing so in the following period, valued at $\frac{1}{(1+r)} E_t\left(V\left(S_{t+1}\right)\right)$, but receives the opportunity of committing again in *n* periods, valued at $\frac{1}{(1+r)^n} E_t\left(V\left(S_{t+n}\right)\right)$. The opportunity cost is zero if $n = 1$, i.e. no time commitment is necessary. If $n = \infty$ then $\omega(S_t) = \frac{1}{(1+r)} E_t\left(V\left(S_{t+1}\right)\right)$, meaning that trade would be committed today given the payoff today exceeds the discounted expected value of having the opportunity tomorrow, i.e. as a conventional American option.

Using the definition of the opportunity cost, the expression for the value of the ship can be rewritten as

$$V(S_t) = E_t \sum_{i=0}^{\infty} \frac{1}{(1+r)^i} max\left\{S_{t+i} - C - \omega(S_{t+i}), 0\right\}. \quad (6)$$

We see that the ship value is the expected sum of the discounted *net* economic spread. Under free utilization of the ship, the value is bounded from below at zero. The time commitment implies that the spread must be higher than the explicit transportation cost to commit to a trade.

The appendix provides some additional technical properties of the opportunity cost and ship value, establishing that the ship value and opportunity cost are increasing and convex in *S* under reasonable conditions. From these properties, it follows by Jensen's inequality that higher spread volatility increases the ship value and the opportunity cost of committing to a trade; the benefit of waiting. More volatile price spreads provide greater opportunities for profitable trades to emerge. Weaker price convergence (lower magnitude of α) increases spread volatility, and so will increase ship value and the economic transportation cost through the opportunity cost. This is interesting as it implies that if price convergence improves, the benefit of waiting is reduced, which further contributes to reducing transportation costs and improving price convergence. As such, policies to reduce trade barriers will have an indirect benefit of reducing the speculative element of waiting for improved trade conditions, potentially providing more stable trade.

4. THE ECONOMIC SIGNIFICANCE OF TIME COMMITMENT COSTS

We have established that when shipping is subject to a time commitment, an opportunity cost of trade arises that contributes to support higher regional price differences. To see this more precisely, consider the effect of a shock today on the next period spread change, $\frac{\Delta S_{t+1}}{\Delta \varepsilon_t}$. In the absence of a time commitment, $\frac{\Delta S_{t+1}}{\Delta \varepsilon_t} = 1 + \alpha$. With a time commitment, $\frac{\Delta S_{t+1}}{\Delta \varepsilon_t} = 1 + \alpha\left(1 - \frac{\Delta \omega(S_t)}{\Delta S_t}\right)$. The time commitment reduces the effective price convergence by $\frac{\Delta \omega(S)}{\Delta S} \times 100$ percent. In the limit, market integration vanishes completely as $\frac{\Delta \omega(S)}{\Delta S}$ tends to unity. In this special case, any increase in the spread will be completely absorbed by the opportunity cost, and markets would be completely decoupled. It follows that price convergence estimates based on the (explicit or not) assumption of a constant transportation cost will suffer an omitted variable bias. For instance, the simple error correction model $\Delta S_t = \beta_0 + \beta_1 S_{t-1} + u_t$ estimated by OLS will lead to a biased estimate of price convergence equal to $E(\beta_1) = E\left(\alpha\left(1 - \frac{\Delta\omega(S)}{\Delta S}\right)\right)$.

We now re-examine the EU/U.S. natural gas price spread considering a time commitment opportunity cost. As shown above, direct transportation costs (as measured by the freight rate) are also positively correlated with price spreads. Any empirical study using historical data on LNG trade is subject to the difficulties due to the large changes in LNG trade over the period. Little U.S. to EU LNG trade occurred over our sample period, and so it is not reasonable to conclude that the opportunity costs derived from our model explain historic spread dynamics. Still, we find the case study useful as a means to investigate whether plausible parameters and market assumptions can produce economic costs from time commitments that are economically significant, and in line with the historically observed spreads.

The ship valuation implied by this case study will be the value of a ship committed to LNG exports from the U.S. to EU. The opportunity cost will be the time cost of committing to exports from the U.S. to EU. Another issue with the analysis is that we assume a ship dedicated to a specific route. In reality, LNG ships have some flexibility in choosing routes based on economic conditions, which adds to their value.

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 problem, equation (3) above[4]. Given $\omega(S;\theta)$ and using equation (5), we can calculate model predicted spread changes at any time *t*. 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 estimation with a nested optimization procedure for each parameter vector evaluation.

Before estimation, we reduce the parameter dimension. We assume *iid* errors in the empirical spread dynamics equation, equation (1). Weak dependence in errors would not bias the estimate of price convergence, but will increase standard errors of the parameter estimates. This can be corrected to some degree by applying a non-parametric autocorrelation consistent standard error estimator, i.e. Newey and West (1987). We assume a 15% annual, nominal required rate of return on export operations, which is within a reasonable range according to industry sources. A higher required rate of return will reduce ship value, but will tend to increase the opportunity cost relative to ship value by reducing the value of the post-shipment ship by more than the value of the idled next period ship through the high discount rate. The standard deviation of the residual spread 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 dataset. We are then left with two free parameters to estimate from the data, $\theta = \{\alpha, C\}$, which is the same as in the constant cost error correction model from section 2, equation 2b.

4. The functional equation problem is solved by value function iterations on a grid of S. Values of the function outside grid-points are evaluated by linear interpolation. Spread shocks ε_t are approximated by Gaussian quadrature's, which together with the first order difference equation for the spread dynamics determines the forward distributions of the spread used to calculate expectations of the value function.

Section 2 established the importance of time varying explicit shipping costs. When discussing our model in section 4 we assumed a fixed cost, *C*. Time varying explicit costs would enter the model as an additional state variable for the ship value. We deal with time varying costs indirectly by assuming that exporters that observe a current explicit cost C_t, believe this cost will persist into the future (or up to any relevant planning horizon). By this assumption, we can deal with the time varying cost by estimating the fixed cost model in section 4 on freight cost adjusted spreads, $\widehat{S_t} = S_t - distance * freight\_rate$, instead of S_t. We estimate the model on both the unadjusted spread and the freight cost adjusted spread. Table 2 shows the estimation results for the opportunity cost model and the linear model (same model but excluding the time commitment effect).

Table 2: Estimation Results, Time Commitment model and Linear Model

	Unadjusted spread, S_t				Adjusted spread, $\hat{S}_t$			
	Time commitment model		Linear model		Time commitment 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		—	
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 specifications, assuming a time commitment adds a cost element that improves the fit (lower residual variance, same number of parameters), and implies greater price convergence than what is inferred from the linear model with only direct transportation costs. Note that both models have the same degrees of freedom, so the improved fit is due to the model specification.

From the OLS estimate of the linear model we have $E(\alpha_{OLS}) = E(\alpha_{NLS}\left(1 - \frac{\Delta\omega(S)}{\Delta S}\right)$, where α_{OLS} is the price convergence estimate from linear model and α_{NLS} from the time commitment model. If we substitute in our estimates and assume independence between opportunity cost slope and the α_{NLS} estimate, we have an estimate of the mean slope $\frac{\Delta\omega(S)}{\Delta S}$. For the unadjusted spread $E\left(\frac{\Delta\omega(S)}{\Delta S}\right) = 1 - \frac{\hat{\alpha}_{OLS}}{\hat{\alpha}_{NLS}} = 0.36$ and for the adjusted spread 0.33, meaning that implied time commitment to trade can reduce price convergence by 33% to 36% in this empirical example

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

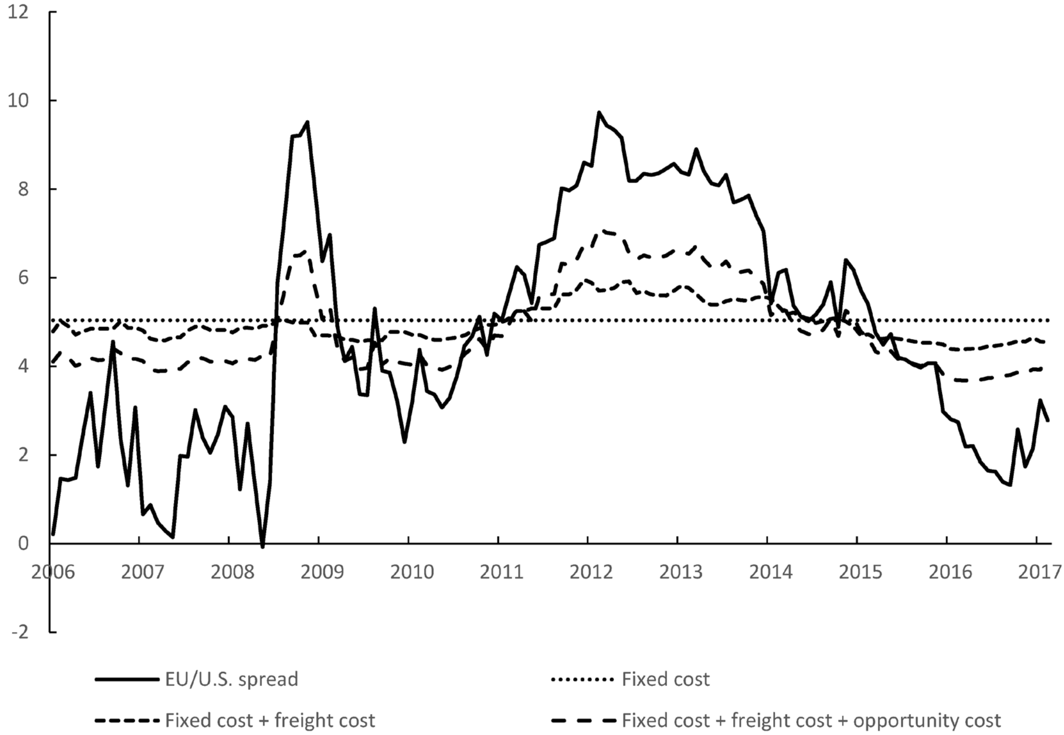
$$S = C = 5.04 \quad \text{(fixed cost)}$$

$$S = C = 4.97 + distance \times freight\_rate_t \quad \text{(fixed cost + freight cost)}$$

$$S = C = 3.5 + distance \times freight\_rate_t + \omega(S) \quad \text{(fixed cost + freight cost + time commitment cost)}$$

The first specification assumes fixed transportation cost. In the second case, we add freight costs. These two cases were dealt with in section 2, and the fixed costs estimates are from Table 1.

Figure 4: EU/U.S. spread and implied equilibrium spreads.



The last specification is from the adjusted spread estimation in Table 2 and includes time commitment cost.

Figure 4 shows the model spreads along with the actual spread. We observe how the opportunity cost implied from time commitments can add non-negligible variation to the implied equilibrium spread. For instance, in late 2008 the U.S. natural gas price dropped considerably relative to the EU price. The direct freight rate did not adjust, but the implied opportunity cost of committing to trade in this high spread period did increase. This jump in economic costs is consistent with pricing in the opportunity of even greater spreads in the near future. Adding a time commitment cost generates and implied cost more in line with the flexible proportional cost specification (2c) in section 2.

As stated above, this analysis cannot say that observed spread dynamics are caused by time commitment costs. The cost specifications are likely miss-specified due to omitted costs that also correlate with price spreads, such as for instance LNG ship rental rates and possible effects of capacity constraints in liquefaction and regasification costs. In addition, differences in how natural gas is priced across regions will mechanically produce differences in observed spreads. The main take away from this case study is that time commitments can, under plausible parameters, produce economically significant costs that can weaken ties between global natural gas prices.

5. CONCLUSION

LNG trade allows natural gas to be traded between geographically markets that are not connected by pipeline. However, the trade infrastructure is logistically demanding. Investments in transportation capacity are specific, lumpy and time consuming. In addition, shipping often occurs over long distances that require substantial time commitments. Even so, LNG is set to become increasingly important for the global energy trade. It is one of few energy carriers with relatively low CO_2 emissions (compared to crude oil and coal) that can be transported over long distances.

This paper argues that an important reason for the weak impact of LNG trade on mediating regional natural gas price differences is the logistically demanding nature of the trade. We have shown that the economic cost of LNG trade is positively related to regional natural gas price spreads between the exporting and importing regions. Tightness in capacity when demand for trade is high results in cost escalations that prevent profitable trade opportunities for traders (Dehnavi and Yegorov, 2012; Oglend et al., 2016). This can explain the cyclical co-movements of the LNG freight rate and cross-market natural gas price spreads in the aftermath of the Fukushima incident in 2011. A part of the spread is transferred to owners of scarce transportation services, such as ship owners.

The main contribution of this paper has been to highlight the additional economic cost of LNG shipping that arises from the necessary time commitments in LNG shipping. The shipping time commitment implies that owning an uncommitted ship is equivalent to owning a recurring American call option on the price spread between destination and home market, with a strike price equal to the direct transportation cost. Under plausible conditions, the added cost due to the time commitment is positively correlated with the price spread. The cost drives a wedge between the price spread and the direct transportation cost. We show in an empirical case study that this economic cost element under plausible specifications can be economically significant.

Failing to properly account for the economic costs of trade can lead to the conclusion that markets are inefficient. Observed price spreads will appear to signal large and persistent profit opportunities. It is a difficult task to properly account for and measure all relevant economic costs of LNG trade. This is especially true when acknowledging that important opportunity costs might factor into trade decisions. The main finding in this paper is that for LNG trade, logistical constraints lead to shipping costs that vary according to market conditions and time commitment cost can plausibly add to the economic shipping cost. Consequently, trade evaluations that focus purely on minimizing direct costs will likely underestimate the economic costs of LNG shipping. The time commitment cost reduces competitiveness of long-haul LNG trade relative to natural gas pipeline supply. This is relevant to the questions of how cheap U.S. natural gas need be to compete with Russian pipeline supply, and the impact of possible tariffs on U.S. LNG imports to China.

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APPENDIX 1

In this appendix we state some properties of the opportunity cost and ship value. To reiterate, we assume the spread follows the error-correction process,

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

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

where ε_t is a mean zero weakly stationary error process. To allow more precise results, the following assumptions are made:

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

Assumption A1 states that the interest rate is strictly positive, a standard sufficiency assumption for the existence of a unique maximized value. Assumption A2 is an equilibrium restriction by hypothesis that ensures arbitrage opportunities are not present in the long run. Assumption A3 ensures that the error process is weakly stationary and that its support is bounded, ensuring that the license value is bounded and that a maximum exists. The parameter restriction $0 < \kappa < 1$ is not necessary for stationarity, but allows for easy ranking of outcomes in the sense that if $\varepsilon_t' > \varepsilon_t$ then $\varepsilon_{t+j}' > \varepsilon_{t+j}$ for $j > 0$, for a given realization of the shock sequence $\{u_t\}$. Specifically, A3 assumes profit opportunities decay monotonically over time. This allows us to establish that the license value is increasing in the spread.

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

Proof of Preposition 1.

Consider the following iterative procedure:

$$\Delta S_{i,t+1} = \alpha\left(S_t - C - \omega_i\left(S_t\right)\right) + \varepsilon_{t+1} \quad \text{(A1)}$$

$$\varepsilon_{t+1} = \kappa\varepsilon_t + u_{t+1} \quad \text{(A2)}$$

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

$$\omega_{i+1}\left(S_t\right) = \beta E_t V_{i+1}\left(S_{i,t+1}\right) - \beta^n E_t V_{i+1}\left(S_{i,t+n}\right), \quad \text{(A4)}$$

where $\beta = \dfrac{1}{1+r} < 1$ is the discount factor. The fixed point to this recursion is the maximized value function, equation (3), and the spread dynamics, equation (5) in the main text.

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

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 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 continuous in S_t since $S_{0,t+\mathrm{j}}$ and $V_0(S)$ are continuous. Furthermore, since $\beta < 1$ and $V_0(S)$ and $S_{0,t+\mathrm{j}}$ for any j > 0 are 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*. This establishes 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 a bound on the slope of the value function as

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

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 is zero or negative, which we have shown is not the case (we have shown that it is strictly positive). This then preserves the slope bound $-1 < \frac{\Delta\omega(S)}{\Delta S} < 1$ for $\omega_1(S)$. We remark here 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 slope 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 ship 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.

APPENDIX 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