Testing for Market Integration Crude Oil, Coal, and Natural Gas

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Prompted by the contemporaneous spike in coal, oil, and natural gas prices, this paper evaluates the degree of market integration both within and between crude oil, coal, and natural gas markets. Our approach yields parameters that can be readily tested against a priori conjectures. Using daily price data for five very different crude oils, we conclude that the world oil market is a single, highly integrated economic market. On the other hand, coal prices at five trading locations across the United States are cointegrated, but the degree of market integration is much weaker, particularly between Western and Eastern coals. Finally, we show that crude oil, coal, and natural gas markets are only very weakly integrated. Our results indicate that there is not a primary energy market. Despite current price peaks, it is not useful to think of a primary energy market, except in a very long run context.

1. INTRODUCTION

The recent oil price spike coinciding with abnormally high coal and natural gas prices has prompted energy traders to ask how demand shocks for one fuel create price reverberations in other fuels. This question is also of great interest to industrial organization economists, who would like to determine whether these fuels are sufficiently integrated to constitute a primary energy market. For energy products to belong in the same integrated product and geographic market, a common, as opposed to disparate, set of supply/demand

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factors determine price formation and product flows. Up until the last decade, energy economists routinely analyzed crude oil as a world market while coal and natural gas belonged to geographically segmented markets. For example, it was widely accepted by Adelman (1984) and others that "the world oil market, like the ocean, is one great pool," but for coal even the US market appeared segmented.

A number of alternative methods for testing for market integration have been proposed (Stigler and Sherwin (1985), Weiner (1991), DeVany and Walls (1993), Sauer (1994), Gulen (1999), and Kleit (2001) among others). As pointed out by Kleit, many of these methods tend to give yes or no answers to the question of market integration. More often, the question is not whether two markets are integrated but the degree of integration. Our purpose here is to use a common technique in modern time series analysis, the error correction model popularized by Engle and Granger (1987), to examine the degree of market integration both among and between crude oil, coal, and natural gas. We argue that the error correction model provides useful insights to energy traders as well as to those interested in market delineation issues.

The error correction model approach to market delineation is both empirically straightforward and yields readily interpretable summary statistics. While our results have implications for the controversy over the extent of integration in the world oil market, they are perhaps more interesting for their implications about coal and natural gas. For coal, the evidence for an integrated US market – much less an integrated world coal market – is problematic. Accordingly, our coal analysis looks at various coal types in the US to determine the extent of regional market integration. Our analysis of coal is unique because we use previously unavailable data on spot coal transactions for various regions in the US collected by Platt's since the early 1990's. Finally, we ask whether spot sales of natural gas traded at Henry Hub, Louisiana is to any degree integrated with West Texas Intermediate crude oil traded at Cushing, Oklahoma or with Wyoming coal.

The intuition of the basic error correction model is that if two markets are integrated, price changes in one market will be linked with price changes in the second market because common supply/demand factors determine prices. Any differences that are not instantly arbitraged away will be arbitraged in subsequent periods. Underlying the error correction model is the notion that prices of close substitutes are linked together in a long run cointegrated relationship with price differences due to transportation costs, or quality differentials. As noted by DeVany and Walls (1993), "cointegration is a natural method for testing market integration."

Standard tests for cointegration, however, focus only on the existence of the long run relationship between the two prices and not on the speed of adjustment between the prices. Consequently, they are designed to provide a yes or no answer to the question of market integration. The advantage of the error correction model is that it embodies cointegration analysis by providing a test for the existence of a long run cointegrating relationship, but also provides readily interpretable summary statistics on the degree of market integration.

Section II describes the basic error correction model and how it yields readily interpretable summary statistics on the extent of market integration. Normally, error correction models are estimated from data of a uniform time dimension — either daily, weekly, or monthly data. But because coal price data are sampled at varying intervals from as short as seven days to as long as 28 days or more, we devise a technique to accommodate unevenly-spaced data sources. Section III applies the error correction model to test for market integration among five very different crude oils — West Texas Intermediate (WTI), North Sea Brent, Alaskan North Slope (ANS), Persian Gulf Dubai, and Indonesian Arun using daily price data. These crude oils differ significantly in their location and gravity and sulphur characteristics, so that market integration may differ significantly among them. Section IV focuses on coal and uses Platt's coal prices for five different US locations. These results stand in sharp contrast to the crude oil results. Section V applies the error correction model to examine market integration between WTI crude, natural gas at Henry Hub, and Wyoming coal. Section VI recapitulates the key findings and the flexibility of the error correction model to investigate market integration.

2. THE ERROR CORRECTION MODEL

A. The Basic Error Correction Model

The basic error correction model proposed by Engle and Granger (1987) can be written as follows:

$$\Delta P_{1t} = \phi \Delta P_{2t} - \theta(P_{1,t-1} - \alpha_0 - \alpha_1 P_{2,t-1}) + \varepsilon_t \qquad (1)$$

Note that equation (1) involves the contemporaneous price change term as well as an error correction term so that deviations from the long run cointegrating relationship $(P_{1,t-1} - \alpha_0 - \alpha_1 P_{2,t-1})$ force the price adjustment back to the long run cointegrating relationship at a speed of adjustment θ. Note that the first term $\phi \Delta P_{2t}$ essentially measures Stigler/Sherwin's simple correlation between first differences in prices, ΔP_1 and ΔP_2. The parameter ϕ_0 approximates the correlation coefficient when the variances of ΔP_1 and ΔP_2 are equal.[1]

Several theoretical models can be used to justify the conclusion that equation (1) will produce a high correlation if the two products are in the same market. If the two products are perfect substitutes, the two prices would be equal and perfectly correlated (ϕ_0=1). Alternatively, one could envisage a spatial model with the two products differing in price only by a fixed transportation cost. Assuming P_1 and P_2 are measured in similar units, even though the level of prices

1. $r_{\Delta P_1, \Delta P_2} = \dfrac{\text{cov}(\Delta P_1, \Delta P_2)}{\sqrt{\text{var}(\Delta P_1)\,\text{var}(\Delta P_2)}} = \sqrt{\dfrac{\phi^2\,\text{var}(\Delta P_2)}{\text{var}(\Delta P_1)}}.$
Note that when the variances of ΔP_1 and ΔP_2 are equal, the correlation coefficient equals ϕ.

would not be equal, the changes in prices would be equal, again yielding a perfect correlation and an estimate of ϕ_0=1. Equation (1) also explicitly builds in the long run cointegrating relationship:

$$P_{1,t-1} = \alpha_0 - \alpha_1 P_{2,t-1} \qquad (2)$$

which is typically estimated separately with the error correction term being

$$\hat{\mu}_{t-1} = P_{1,t-1} - \hat{a}_0 - \hat{a}_1 P_{2,t-1}.$$

As noted earlier, DeVany and Walls (1993), and others now routinely perform tests of a long run cointegrating relationship on equation (2) as evidence of market integration. These tests essentially involve whether the implicit error term in equation (2) obeys stationarity. If so, the prices are said to be cointegrated and they interpret this as evidence of market integration. But cointegration tests per se do not focus on the economically interesting parameters of the error correction model — α_0, α_1, θ and ϕ_0. Even though the error correction model embodies the long run cointegrating relationship, it also explicitly characterizes the dynamic adjustment process. The coefficients in equation (2), α_0 and α_1 also provide useful plausibility tests. Assuming P_1 and P_2 are measured in similar units, we expect *a priori* a value of α_1 of approximately one. Also, we typically have strong priors for the intercept α_0. For example, if P_1 and P_2 are identical products but good two must incur shipping costs of \$0.10 per unit, then α_0 would be expected to take on a value of 0.10. Or alternatively, if good two was a lower quality substitute, thenwould be expected to equal the value of the product quality differential.

Another important parameter of the error correction model is θ, the speed of adjustment to the long term cointegrating relationship. A value of $\theta \approx 0$ would imply a very slow adjustment back to a long run equilibrium, which would imply severe market frictions. Finally, ϕ_0 measures the contemporaneous price response — an important indicator of the short-run relationship between the two prices. A value of ϕ_0 near one, implies very rapid adjustment of the error correction model.

We find it useful to compute two summary statistics that speak to our concerns with characterizing the degree of market integration. We know the long-run effect of a \$1 increase in P_2 is an increase of α_1 in the price of P_1. The fraction of that long-run increase that is realized instantaneously is simply ϕ_0 divided by α_1. We define "instant %" as follows:

$$\text{Instant } \% = \frac{\phi_0}{\alpha_1} \bullet 100. \qquad (3)$$

Likewise, any disequilibrium not captured by the instantaneous adjustment is assumed to adjust exponentially at rate θ. The half-life of the adjustment process is simply:

$$\text{half-life} = \ln(0.5)/\theta. \tag{4}$$

A high Instant % coupled with a short half-life would suggest that the two markets are highly integrated and constitute an economic market.

In principle, one can generalize the basic error correction model in equation (1) in a variety of directions. Sauer (1994) utilized a vector error correction model (VECM), which is a generalization of the simple bivariate error correction model. While the VECM model can accommodate prices in a number of markets and allows one to compute impulse response functions and thereby examine the speed of price convergence, it lacks the simple elegance and transparency of the basic error correction model focusing on pairwise price analyses. As illustrated in the subsequent empirical results, we reach similar conclusions as the VECM model of Sauer, but with a considerable gain in simplicity.[2]

Another less ambitious generalization of (1) (that retains parsimony) is to allow the effects of prices in market two to enter with lags as well as contemporaneously as follows:

$$\Delta P_{1t} = \phi_0 \Delta P_{2t} + \phi_1 \Delta P_{2,t-1} + \ldots + \phi_n \Delta P_{2,t-n} - \theta[P_{1\,t-1} - \alpha_0 - \alpha_1 P_{2,t-1}]. \tag{5}$$

In this specification lagged values of ΔP_2 are included as long as they are statistically significant and positive, as suggested by economic theory. As we see later, the addition of lagged price changes is only important in a few instances and has little impact on instant % and half-life.

B. Dealing with Data with Uneven Time Intervals

A problem with estimating an error correction model with coal price data is that the data are sampled irregularly.[3] More recent coal price data comes at seven day intervals while earlier data can be 14 or 28 day intervals. Our technique is only applicable to the basic error correction model in equation (1), but can be applied for a variety of data frequencies. For illustrative purposes, consider data of only a seven day and 14 day frequency. The basic error correction model for seven day data frequency is

$$P_{1t} - P_{1,t-7} = \phi(P_{2t} - P_{2,t-7}) - \theta[\hat{\mu}_{t-7}] + \varepsilon_t. \tag{6}$$

2. We are not claiming that the simplicity of our approach makes it better than a VECM model. The same information could be found by estimating a system of equations (the error correction models we estimate are one equation from a VECM model). The main advantage of our approach is the interpretation we give to the parameter estimates, as discussed in Section II. The interpretation of our results differs from the usual practice of calculating impulse response functions, which except for a few special cases requires estimating a VECM model.

3. Irregularly spaced data have been studied in other contexts (Engle and Russell (1998)).

Lagging equation (6) an additional 7 days gives:

$$P_{1,t-7} - P_{1,t-14} = \phi(P_{2,t-7} - P_{2,t-14}) - \theta[\hat{\mu}_{t-14}] + \varepsilon_{t-7}. \tag{7}$$

Combining equations (6) and (7) yields

$$P_{1t} - P_{1,t-14} = \phi(P_{2t} - P_{2,t-14}) - \theta[\hat{\mu}_{t-7} + \hat{\mu}_{t-14}] + \varepsilon^{*}_{t}. \tag{8}$$

Estimation of equation (8) for 14 day data frequency requires only an estimate of $\hat{\mu}_{t-7}$ (the error correction term for the period t-7). We propose estimating it as an autoregressive process for the data spanning the seven day frequency:

$$\hat{\mu}_{t-7} = \hat{\delta}\hat{\mu}_{t-14}. \tag{9}$$

Given $\hat{\delta}$ obtained from the seven day frequency data, we apply $\hat{\delta}$ to the 14 day frequency data to get an estimate $\hat{\mu}_{t-7}$ of $\hat{\mu}_{t-7}$:

$$\hat{\mu}_{t-7} = \hat{\delta}\hat{\mu}_{t-14}. \tag{10}$$

Thus given an estimate of $\hat{\mu}_{t-7}$, equations (6) and (8) can be estimated jointly.

3. US OIL MARKET INTEGRATION

Unlike previous tests for crude oil market integration, we will use daily, as opposed to monthly spot prices for five geographically separated crude oils of varying quality characteristics. Previous researchers were constrained to data sets that were not entirely well-suited to test for market integration. For example, the early studies by Weiner (1991) and Sauer (1994) used the average monthly cargo prices for particular crude oil types landed at various worldwide ports. For example, Weiner (1991) analyzed for various crude oils whether price changes in a given month were correlated across various locations and based on low correlations concluded that crude oil markets were not integrated. However, monthly average delivered cargo prices suffer from a number of problems.[4] Gulen (1997) overcomes these problems by relying on monthly spot prices for specific crude oils over time. But monthly average spot prices are not nearly as rich a data source as daily spot prices, particularly if one wants to measure instant % and the half-life of subsequent adjustments following the single day response.

To test Adelman's hypothesis of a world oil market, we have selected the following five geographically dispersed crude oils with daily price observations

4. First, since prices vary daily, a much more natural unit of investigation is daily data. Second, crude oil deliveries, particularly for a given crude oil type, do not occur uniformly within a month. Consequently, because of the large intra-month price volatility, the price changes in one market may not be correlated with those in another just because of the different dates at which their contract prices were negotiated. Third, some cargo prices are based on long term contracts while others are pegged to some spot prices.

available since 1989: West Texas Intermediate (WTI) traded at Cushing, Oklahoma, Brent crude from the U.K. sector of the North Sea, Dubai crude from the Middle East, Arun crude from Indonesia, and Alaskan North Slope (ANS) crude traded near Los Angeles (the refining center for most ANS crude).

Table 1 shows the results of pairwise price comparisons between WTI crude and the other four geographically dispersed crude oils. We use equation (1) to compute pairwise error correction models. Since a maintained assumption of the error correction model is that the two prices are determined simultaneously, it is arbitrary which crude is treated as the dependent variable. Generally, it makes little difference which variable is used as a regressor.

The WTI/Brent price comparison reveals an almost ideal picture of market integration. Indeed, we would expect such given that Brent crude is routinely imported into the U.S. Gulf Coast, where it competes with WTI crude. Both crudes have almost identical sulphur and gravity characteristics. The contemporaneous price adjustment, ϕ_0 is 0.96. Since ϕ_0 is the critical parameter in Stigler/Sherwin,[5] it is clear that they would interpret this as evidence of a single market. In addition, the coefficients on the long run cointegrating relationships conform to *a priori*

Table 1. Error Corrrection Models for Four Pairs of Crude Oils

$$\Delta P_{it} = \phi_0 \Delta P_{jt} = \phi_1 \Delta P_{j,t-1} - \theta[P_{i,t-1} - \alpha_0 - \alpha_1 P_{j,t-1}]$$

Equation	**1**	**2**	**3**	**4**
Dependent Variable	WTI	WTI	WTI	WTI
Independent Variable	Brent	ANS	Dubai	Arun
Sample Start	January 1990	July 1989	July 1989	July 1990
Sample End	June 1999	June 1999	June 1999	June 1999
Frequency	Daily	Daily	Daily	Daily
ϕ_0	0.959	0.860	0.981	0.746
	(0.010)	(0.008)	(0.011)	(0.022)
ϕ_1		0.044		0.262
		(0.008)		(0.022)
θ	0.102	0.025	0.032	0.104
	(0.009)	(0.004)	(0.005)	(0.009)
α_0	1.39	2.715	1.988	1.703
	(0.057)	(0.102)	(0.107)	(0.100)
α_0	1.000	0.982	1.073	0.963
	(0.003)	(0.006)	(0.006)	(0.005)
Adj. R^2	0.786	0.821	0.754	0.392
s.e.	0.258	0.232	0.271	0.442
D.W.	2.07	2.31	2.03	2.40
Instant %	95.9%	87.6%	91.4%	77.5%
Half-life (days)	6.8	27.7	21.7	6.7

5. As noted earlier ϕ and the correlation coefficient have a monotonic relationship. Indeed, assuming equal variance of P_1 and P_2, ϕ measures the simple correlation coefficient.

expectations. The estimate of α_1 is one, indicating a plausible long run relationship. Interestingly, Instant % explains 96% of the long run adjustment — indicative of a highly integrated economic market.

Another interesting anecdote is confirmed by α_0, the intercept term. The intercept coefficient indicates Brent tends to trade for about \$1.39 per barrel less than WTI. This difference can be attributable to transportation costs, which from the U.K. to the U.S. Gulf Coast ranges around \$1.00 per barrel. Finally, the coefficient θ (0.10) indicates that disequilibria are rapidly adjusted to the long run cointegrating relationship. Indeed, the half-life is only 6.8 days. This means that combined with around 96% adjustment occurring immediately, any remaining adjustment to long-run equilibrium occurs quite rapidly.

The WTI/ANS comparison in equation (2) of Table 1 reveals a surprising amount of market integration despite locational and quality differences that might argue to the contrary. Over much of the sample, ANS crude did not flow into the area East of the Rockies, nor did East of Rockies crudes (like WTI crude) flow to California. The one pipeline that allows West Coast crudes to move into the Midwest has limited capacity, much of which was idle over the period. Also, U.S. restrictions that ANS crude be transported in high cost U.S. built tankers discouraged the movement of ANS crude through the Panama Canal to the Gulf Coast.[6] In addition, ANS crude is typically an inferior quality crude oil compared to WTI. With sulphur of 1.1% and gravity of 29.6 degrees (as contrasted to WTI with 0.5% sulphur and 37 degree gravity), ANS crude cannot be processed in the "sweet" (low sulphur) refineries designed to process WTI. Despite these transportation bottlenecks and quality differences, the value of Instant % is 87.6% indicating the same type of large contemporaneous (same day) response observed between Brent and WTI crude. Note that ϕ_2 is statistically significant and has a lagged price effect of 4.4%. The estimates of the half-life of the remaining disequilibria is slower, but nonetheless relatively quick — 28 days. The values for α_0 and α_1 seem sensible as the positive coefficient of 2.715 in equation (2) probably reflects the superior quality of WTI crude. Likewise, α_1 approximates one as one would expect.

Intuitively, by any type of Elzinga-Hogarty test, these crude oil markets would appear separate,[7] yet the results of equation (2) suggest market integration. The explanation for this seeming anomaly is that Canadian crudes move both to the West Coast and the Midwest. To assure that Canadian crude moves to both markets, ANS and WTI must trade within certain bounds.

Even though relatively small volumes of Dubai crude are refined on the U.S. Gulf Coast, substantial volumes of other Middle East crudes do enter refineries in the Gulf Coast areas. Like ANS, Dubai crude tends to be relatively high sulphur

6. Actually, during the early 1990s, West Coast refineries were unable to process all the available ANS crude and residual supplies moved to the Gulf Coast via the Panama Canal. This ended, however, in 1996.

7. These tests would involve calculating the fraction of West-of-the-Rockies crude demand supplied by California and ANS crudes (the LIFO test). Likewise, the fraction of ANS and California crude sold locally would signal a distinct geographic market (the LOFI test).

(2%) compared to WTI at 0.5%.[8] The quality differential is also reflected in the intercept value in equation (3) of Table 1 of $1.99 per barrel. Interestingly, even though the price of Dubai crude is quoted halfway around the world from Cushing, Oklahoma, it gives every indication of being highly integrated with the price of WTI with an Instant % of 91.4% and a 21.7 day half-life.

In principal, Arun crude from Indonesia seems the least likely to exhibit a cointegrating relationship with WTI. Indonesian crude does not enter the Gulf Coast and only small volumes of it are imported to the West Coast. The bulk of Indonesian crudes are destined for Japanese or other Far East destinations. Again, by an Elzinga-Hogarty test, these two crudes would seem to be geographically distinct. While the results are not as compelling as for the other three pairs, the evidence still suggests that both crudes are part of the same world market. In equation (4), Instant % is 77.5%. These differences are explained by the substantial international time differences in which these markets close,[9] because the addition of a one-day lagged price change indicates an additional 26.2% response. The coefficients characterizing the long run cointegrating relationship are reasonable and θ indicates a rapid adjustment process (6.7 days). Thus even Indonesian crude appears to satisfy Adelman's hypothesis.

For the crude oil trader, the values for instant % and half-life for all the crudes are very informative. It suggests that there is little scope for arbitrage. But would this range of values indicate the existence of a world crude oil market for purposes of antitrust analysis? According to the Department of Justice procedure, could a hypothetical monopolist of one particular type of crude (say ANS) find it profitable to increase its price by a small, non-transitory amount for one year or longer? Our results suggest that in that event a monopolist for ANS crude would find its crude out of its long run cointegrating relationship with other crudes and be forced to return to the original price. Given the magnitude of instant % and half-life shown in Table 1, there seems little doubt that Adelman's conjecture is correct about the world oil market being one great pool.

Opponents of price tests might argue that it is still possible to observe results like those in Table 1 from spurious correlations. For example, correlated demand shocks across geographically separated markets could produce large values for instant %. Or, correlated cost increases across markets could produce the same phenomenon. Our response is two-fold. First, the error correction model has much greater economic content than the simple price correlation test proposed by Stigler and Sherwin (1985) because it incorporates not only a short run relationship but also a long run cointegrating relationship. Second, the skeptics would have difficulty in explaining why oil supply

8. Dubai crude has a lower gravity of 31° compared to 37° for WTI.

9. Arun and WTI are never traded at the same time. Arun closes before WTI opens, and then WTI closes before Arun opens the next morning. Therefore the coefficients don't necessarily represent responses to the same information.

disruptions in the Gulf of Mexico from hurricanes Katrina and Rita resulted in contemporaneous price spikes in North Sea Brent and other world crude oils.

4. U.S. COAL MARKET INTEGRATION

Because of the high transportation cost relative to mine-mouth price of coal,[10] we typically think of the U.S. coal market as highly fragmented. Indeed, in the Appalachian coals case of 1933, the cartel arrangement was restricted to coal mines in Appalachia.[11] But the U.S. coal industry has changed dramatically since then, driven in part by environmental factors but also by technological advances in strip mining and transportation. Consequently, western coals from Wyoming, Colorado and Utah are now increasingly shipped into markets once dominated by eastern coals. For example, in 1979, eastern coals, which are defined as coals from east of the Mississippi River, accounted for 88% of the coals consumed in the South. This left only 12% to be filled by western coal. But by 1997, western coals accounted for 37% of the coal consumed in the South. A similar phenomena occurred in the Mid-West which purchased 36% of its coal from the western states in 1979. By 1997, 67% of the coal consumed came from western states.[12] Using Elzinga-Hogerty tests for market integration using coal shipments data, western coals would surely belong in the same market with eastern coals in these areas.

Curiously, because western coal is typically low btu coal (8700 BTU/ton in Wyoming) as contrasted with eastern coals (11,800 BTU/ton in Ohio), transport costs differ dramatically in addition to the locational advantages eastern coals enjoy. Surprisingly, western coals have been able to overcome these disadvantages due to a combination of environmental regulations and technological advances in transportation and mining. As environmental regulations on sulphur oxides have become more stringent, power plants have looked to low-sulphur western coals which frequently enjoy less than 1% sulphur as opposed to eastern coals with 2% or higher sulphur. Unit trains have enabled rail rates to fall precipitously in real terms. Over the same period 1979-97, the average transportation cost per ton-mile of coal fell by 50% in real terms.[13] As a consequence, the average distance a ton of coal is transported has increased from about 470 miles in 1979 to almost 800 miles in 1997. Mining costs have fallen as well. Rapid technological change in strip mining technology is evident from the three-fold increase in labor productivity over the same period.[14] The end result is that today, Wyoming is the leading coal-producing state and accounts for 34.1% of U.S. coal production while the second leading producer, West Virginia, stands at a distant 12.8%.

10. For example, it is estimated that on average transportation costs account for about 35% of the delivered price of coal in the U.S. see www.eia.doe.gov/cneaf/coal.ctrdb/tab36.html.

11. See Scherer (1980, p. 501).

12. See www.eia.doe.gov/cneaf/coal/ctrdb/tab52.html.

13. See www.eia.doe.gov/cneaf/coal/ctrdb/tab37.html. For added detail, see EIA, "Energy Policy Act Transportation Rate Study: Final Report on Coal Transportation," October 2000.

14. See U.S. Annual Energy Review, Table 7.6.

It remains an empirical issue as to how integrated coal markets are and whether there is a US market for coal. An important advantage of the error correction model in contrast with simple cointegration tests is that it reveals the degree of market integration. Our analysis is based on coal price data provided by Platt's for various mining areas, which has certain peculiarities. The Platt's coal data are mine-mouth quotes expressed in dollars per ton for spot contracts on a particular day for a particular mine in a region. According to Platt's, spot coal sales account for approximately 15% of total sales. Over time, the identity of the mines may change within a region. The BTU content of the coal is specified, but it varies both over time within a region and between regions. To eliminate the problem of price variation due to changing BTU content, all data are expressed in dollars per million BTU. Unlike our daily crude oil price data, coal price data are available on roughly a monthly basis for the early 1990's and not always on the same day each month, whereas for recent years observations are typically taken at one week intervals. For some price pairs, we do not observe prices on the exact same day. In the small percentage of cases where the price observations are not observed on the same day, we must synchronize the data to a common date. We do this by adjusting the dependent variable to a date corresponding to the actual observed price date for the independent price variable. Specifically, the dependent variable is interpolated linearly between observation dates and the estimated value corresponding to the date the independent variable is chosen. The advantage of relegating any measurement error to the dependent variable is that as long as the measurement error is random, the underlying parameter estimates will retain the property of consistency.

Another peculiarity of the Platt's data is that the data frequency improves from 28 days to 14 days to seven days over the sample period from January 1990 to April 2004. Since the seven day frequency data is typically available only for the last two years of the sample, we devised an estimation strategy as outlined earlier to enable use of data back to 1990. While it allows us to use data spanning the full period, the error correction term is subject to measurement error.

Table 2 shows a comparison of the error correction model for various eastern and western coals using data for various periods since the early 1990s. Equations (1)-(3) of Table 2 compare various western coals from Colorado, Utah, and Wyoming. Equation (4) compares two eastern coals — Kentucky and Ohio — and equations (5) and (6) compare Wyoming prices against the two eastern coals.[15] In all six comparisons in Table 2, the price pairs obey a long run cointegrating relationship, but in our opinion this is not a sufficient condition to conclude these coals belong to the same economic market. Indeed, the generally low values for instant % and long half lifes suggest that these markets are only loosely tied.

Among western coals, we observe the strongest linkages between Colorado and Utah coals. Note that the coefficient α_1 equals 1.07 indicating

15. Platt's actually reports prices for a wider set of eastern coals, but because of numerous gaps in reporting, we do not attempt to analyze them.

Table 2. Tests for Coal Market Integration in the US
$\Delta P_{it} = \phi_0 \Delta P_{jt} - \theta[P_{i,t-1} - \alpha_0 - \alpha_1 P_{j,t-1}]$

	UT/CO	WY/CO	WY/UT	KY/OH	WY/KY	WY/OH
Sample Start	Jan 1990	Jan 1990	Jan 1990	Apr 1997	Jan 1990	Apr 1997
Sample End	Apr 2004	Apr 2004	Apr 2004	Jan 2002	Jan 2002	Apr 2004
Frequency (days)	7, 14, 28	7, 14, 28	7, 14, 28	14, 28	14, 28	7, 14, 28
ϕ	0.699	0.269	0.197	-0.015	0.195	0.122
	(0.042)	(0.075)	(0.080)	(0.041)	(0.088)	(0.033)
θ	0.020	0.015	0.016	0.022	0.007	0.069
	(0.008)	(0.007)	(0.007)	(0.009)	(0.010)	(0.012)
α_0	0.035	-0.126	-0.077	0.472	-0.315	0.014
	(0.020)	(0.032)	(0.033)	(0.033)	(0.037)	(0.018)
α_1	1.069	0.578	0.455	0.414	0.630	0.226
	(0.028)	(0.045)	(0.040)	(0.027)	(0.039)	(0.013)
δ	0.898	0.954	0.948	1.053	1.012	0.979
	(0.038)	(0.030)	(0.033)	(0.037)	(0.030)	(0.023)
Adj. R^2	0.539	0.059	0.039	0.026	0.023	0.195
s.e.	0.011	0.020	0.020	0.021	0.026	0.022
Instant %	65.4%	46.6%	43.3%	-3.6%	31.0%	54.1%
Half-life (days)	241.5	332.9	301.6	444.3	1411.1	70.8

matching price changes for coals of roughly similar btu content. Instant % is 65.4% indicating that sizeable initial price responses are observed. The half-life of 241 days indicates that the bulk of the adjustment process occurs within the one year window proposed by the DOJ. Thus it seems reasonable to infer that Colorado and Utah coals compete in the same market. Between Wyoming and Colorado or Utah coals, the linkage is somewhat weaker. The implied coefficient on the long run cointegrating relationship, α_1, is between 0.46 and 0.58, suggesting that a dollar increase in a million BTU of Colorado or Utah coal will only raise Wyoming coal by about \$0.50 per million BTU. This response is not unreasonable. Wyoming coal is lower BTU coal than say Colorado or Utah coal (8700 vs 11,200 BTU/ton). It is competition at the point of delivery that should dictate α_1, because transportation costs are a major component of the delivered price. To the extent that Wyoming coal implies higher transport cost per million BTU, so the price in Wyoming should not be expected to rise proportionally. Thus we do not categorically discard estimates of the long run cointegrating relationship of 0.46 to 0.58 as unreasonable. Instant % of 47% and 43% and half-lifes of 302 to 333 days imply weaker market integration than between Utah and Colorado coals. There is a lot of random variation in prices that cannot be explained. The error correction model explains only a small fraction of the variation — between 4% and 6% of the variation as compared to 54% between Utah and Colorado. In sum, all three western coal prices follow the same long term trends both upward and downward.

Turning to a comparison between eastern coals, in equation (4) we compare Kentucky and Ohio coal prices. We would expect to observe stronger evidence of market integration than we observe. Instant % is implausible — a negative 3.6% — and the half-life of 444 days is longer than among the previous examples, suggesting that there is considerable month-to-month price variation that cannot be explained by price variation in an adjoining state. Again we observe a stable long run cointegrating relationship between the two prices but the estimate for α_0 and α_1 seem implausible. Much of the short run variation appears due to other factors — perhaps data problems.[16]

Finally, in equations (5) and (6) of Table 2 we compare Wyoming coal prices with the two eastern coals — Kentucky and Ohio. Turning first to the α_1 coefficient driving the long run cointegration relationship, we observe a value of 0.63 between Wyoming and Kentucky, which is not out of line with other comparisons, but the value of 0.23 between Wyoming and Ohio seems unreasonably low. This means that in long run equilibrium a \$1 per million BTU price increase in Ohio coal leads to a \$0.23 per million BTU price increase in Wyoming coal. This estimate seems unreasonably low and leads to a misleading estimate of instant % of 60.8%. Superficially, an instant % of 54.1% and a half-life of 70.8 days would suggest that Wyoming and Ohio coals are as closely linked as Colorado and Utah coals, but we reject such a conclusion. With a more plausible larger estimate of α_1 the result for instant % would not look appreciably different than between Wyoming and Kentucky coal. Our overall conclusion from these comparisons is that while Wyoming and Kentucky coals enjoy a long run cointegrating relationship, these offer little comfort in explaining short term price variation.

Combining these results, what inferences should we draw? It is clear from the shipments data that western coal now competes with eastern coals in many areas of the South and Mid-West. The existence of long run cointegrating relationships among the various prices confirm this observation. The fact that the error correction models explain such a low fraction of the variation and the relatively long half-lives suggest a number of things about these coals. First, there is a lot of random price variation that cannot be explained. We attribute these to short-run factors which may be idiosyncratic to the particular mines sampled by Platts. Second, rail access from specified mines to various locations introduces further frictions between markets. Thus, we should not be surprised by the apparent low degree of market integration implied by variation in these spot prices. For these reasons, we are reticent to conclude that these coals all compete in one national economic market.

16. We tested whether these results would change if the sample was restricted to observations for the last 5 years with a constant frequency of 14 days. Again we found implausible estimates for instant %.

5. EVIDENCE OF MARKET INTEGRATION AMONG PRIMARY ENERGY FUELS

What price linkages exist between coal, oil, and natural gas? Is the recent oil price spike merely a coincidental event with abnormally high natural gas and coal prices or is it evidence of market integration? While the general press often refers to the energy market, energy economists tend to be skeptical of such notions. Clearly, in the short run coal, oil, and natural gas are not fungible and direct fuel competition is limited. In the long run, these fuels become much closer economic substitutes depending on their respective costs of conversion technologies (Griffin (1979)). But certainly, based on a Department of Justice criterion for a market, the notion of a primary energy market seems destined to fail. The bulk of oil and natural gas is consumed in different uses, where little possibilities of interfuel substitution exist. For example, the transportation sector, which is dominated by oil, makes little use of natural gas. Only in isolated pockets, such as residential and commercial heating, is there direct competition between oil and natural gas. Likewise, direct competition in specific energy end uses seems even more rare for oil versus coal competition. A priori, one would expect the strongest linkages between natural gas and coal since both are used extensively in electric power generation. But here again, short-term interfuel substitution possibilities are limited to facilities that can either burn both fuels or to inter-plant substitution between plants burning different fuels.[17]

In Table 3, we perform pairwise price analyses for coal, natural gas, and crude oil. Simple tests for statistical significance on the long run cointegrating coefficients implies all three fuels are cointegrated, but this is misleading. The parameter estimates for α_1 indicate only very weak long run relationships. For example, a one dollar per barrel price increase raises the price of a million BTU of coal by three-tenths of a cent. Likewise, a dollar per million BTU increase in natural gas prices raises coal prices by 1.8 cents per million BTU. More plausibly, a \$1 per million BTU increase in natural gas prices raises crude oil prices by \$3.12 per barrel (or about \$0.60 per million BTU). Clearly, a BTU theory of fuel price parity does not hold even between oil and natural gas. Furthermore, instant % indicates very small contemporaneous price shocks. Between coal and natural gas, the instant % is negative. Between coal and oil and between oil and natural gas, the estimates are only 0.6% and 2.2%, respectively.

Interestingly, even though a priori we conjectured that the strongest linkage would be between coal and natural gas, that is clearly not the case. Oil and natural gas enjoy the strongest extent of market integration. Nevertheless, they still fall short of what one would expect if the two fuels belonged in the same

17. Plourde and Watkins (2000) have analyzed the relationship between crude oil and natural gas in Canada. From 1975 to 1985, natural gas prices were explicitly linked on a BTU-content basis to the price of crude oil. Plourde and Watkins find a much weaker relationship between the two price series after these regulations were removed, especially for the time period after 1993.

Table 3. Error Correction Model Between Crude Oil, Wyoming Coal, and Natural Gas
$\Delta P_{it} = \phi_0 \Delta P_{jt} - \theta[P_{i,t-1} - \alpha_0 - \alpha_1 P_{j,t-1}]$

Equation	1	2	3
Dependent Variable	Coal	Coal	Oil
Independent Variable	Oil	Natural Gas	Natural Gas
Sample Start	Jan 1990	Jan 1991	Jan 1991
Sample End	Apr 2004	Apr 2004	Aug 2004
Frequency (days)	7, 14, 28	7, 14, 28	Daily
ϕ	0.000	-0.001	0.070
	(0.000)	(0.002)	(0.097)
θ	0.026	0.028	0.073
	(0.009)	(0.007)	(0.007)
α_0	0.231	0.233	13.60
	(0.014)	(0.011)	(0.147)
α_1	0.003	0.018	3.12
	(0.001)	(0.003)	(0.045)
Adj. R^2	0.027	0.046	0.035
s.e.	0.021	0.021	1.53
Instant %	0.6%	-7.7%	2.2%
Half-life (days)	189.4	173.8	9.5

economic market. The long run cointegrating parameter of 3.12 is well below the value of 5 which one might expect.[18] Instant % is only 2.2% implying little day-to-day co-movement in prices. Even with a half-life of only 9.5 days, it would take a considerable period for prices to return to the long-run cointegrating relationship.

6. SUMMARY AND CONCLUSIONS

Researchers wishing to use time series variation in price data as a means of delineating markets face a variety of choices, varying greatly in terms of complexity and transparency. The two simplest procedures are (1) simple correlations of price changes and (2) estimation of a long run cointegrating relationship based on price levels. At the other extreme is vector error correction models (Sauer (1994)) which can involve more than two price series with potentially long lags on the independent and lagged dependent variables. The adjustment paths of prices as calculated by the impulse response functions are data driven because the underlying specification places no restrictions from economic theory. Our approach is to embrace the simple error correction model, which can be thought of as combining (1) simple correlations of price changes (the ϕ term) and (2) estimation of a long run cointegrating relationship through the error correction term. This model yields parameter estimates that can be tested against

18. Based on a BTU theory of value, we would expect α_1 to equal 5.5.

a priori market information. Moreover, the instant % and half-life estimates are easily interpretable by practitioners.

Our tests for market integration among crude oils basically corroborates Adelman's intuition and the findings of other researchers that crude oils from around the world trade in a highly integrated world market. Our use of daily data shows that price disparities are rapidly arbitraged away. The results show that price shocks reverberate around the world as the instant % is on the order of 90% and the half-life of the remaining price disparities among crude oils ranges from six to 28 days.

Our tests for market integration among various U.S. coal regions are novel and provide interesting insights. Nevertheless, we caution the reader that these results must be viewed as tentative because of the data quality. We do observe long run cointegrating relationships among and between various western and eastern coals. But we also show that while these coals may obey long run relationships, the extent of unexplained short run variation is huge, instant % is often only 50% or less, and the half-life of adjustment is often 200+ days. This is hardly evidence of the type of highly integrated market we observe for crude oil. It is interesting that we observe certain patterns among these coals. Western coals — Utah, Colorado, and Wyoming — indicate substantial market integration. The comparison with Eastern coals becomes much more tenuous. We conjecture that these results are largely driven by short term rigidities in transportation facilities and costs to particular destinations. As broader spot markets evolve in the future, the error correction model is likely to adjust much quicker and have greater instantaneous responses.

Finally, while lay persons may refer to energy as if it were one economic market, this is clearly not the case. Wyoming coal and natural gas prices as well as coal and crude oil are only very superficially linked. Oil and natural gas are cointegrated in the long run and exhibit stronger evidence of market integration. Nevertheless, this relationship is weak compared to the market integration we observe among crude oils or Western coals. These examples serve to underscore the flexibility of the error correction model in categorizing the degree of market integration.

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