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Linkage among the U.S. Energy Futures Markets

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ABSTRACT

This study tests the price linkage among the U.S. major energy sources, considering structural breaks in time series. We use the Johansen cointegration method and find that only weak linkage sustains among the NYMEX WTI crude oil, Brent crude oil, gasoline, heating oil, coal, natural gas, uranium, and ethanol futures prices. Our tests reveal that the uranium and ethanol futures prices have very weak linkage with other U.S. major energy source prices. This indicates that the U.S. energy market is still at a stage where none of the probable alternative energy source markets are playing the role as a substitute or a complement market for the fossil fuel energy markets.

JEL-classification: C32; G14; Q42

Keywords: Futures market; Structural breaks; Johansen cointegration method

1. INTRODUCTION

With climate change becoming one of our major concerns, it is becoming more important for the United States to reduce its current level of CO_2 emissions. In order to achieve this mission the U.S. will have to find ways to replace carbon-intensive fuels with lower-carbon fuels that do not emit much CO_2 such as hydropower, nuclear, wind, or solar power (Jean-Baptiste and Ducroux, 2003). However, nearly 80% of the energy consumed in the U.S. came from non-renewable energy sources such as petroleum, natural gas, and coal in 2008 (EIA, 2008). The use of nuclear power and renewable energy is increasing, but those sources still account for only a small portion of the total energy use in the U.S.[1]

Understanding the major energy source markets and their relationships is helpful for constructing an effective policy to change the types of major energy sources and reduce the dependence on fossil fuels. If the prices of multiple energy sources follow similar time trends and that the energy markets in the U.S. have long-run linkage, those energy sources can be approached via the same policy because integrated markets often share price information. However, if energy source prices move independently, there will be no information flows among the energy source markets and for policies to take effect on each market they need to be treated individually. Bachmeier and Griffin (2006) showed that the major U.S. energy source markets, such as crude oil, coal, and natural gas were very weakly linked and that there was not a primary energy market in the U.S. between 1991 and 2004. As shown in this study, the U.S. energy source markets may not be integrated as one market but it is likely that price linkage does exists between some of the major energy sources, such as between crude oil and coal or between natural gas and coal. However, at present, such price linkage among the current U.S. major energy sources has not been characterized in detail.

To fill this gap this study examines and identifies the overall price linkage among the major energy source markets in the U.S. Along with testing the linkage among the U.S. energy source markets, the study considers effects of structural break in times series. To find the market linkage among the major U.S. energy sources, we test the price relationships among crude oil, gasoline, heating oil, coal, natural gas, uranium, and ethanol futures contracts traded at the New York Mercantile Exchange (NYMEX). To our knowledge, there are no previous studies testing the overall linkage among the major U.S. energy source prices in which uranium and ethanol prices are included in the

[1] Nuclear power and renewable energy accounted for about 8% and 7% of the total U.S. energy consumption in 2008 (EIA, 2008).

model. Furthermore, all of the data used in this study come from a single institution – NYMEX – whereas most previous studies use data from various local regions of the U.S. or from multiple countries. Hence, this study minimizes the effects of spatial differences, regulation differences among market institutions, and other factors that influence energy source prices.

We also tested the price relationship under the effects of structural breaks because it is known that considering the effects of structural breaks in natural resource prices is important for proper econometric estimation of the series (Lee et al., 2006). Recently, several studies have addressed structural breaks when using time-series data. For example, Maslyuk and Smyth (2009) allowed the structural break when testing the price relationships among various grades of WTI (West Texas Intermediate) and Brent crude oil spot and futures prices. They found that spot and futures prices were cointegrated during the period of 2001-2009 but they suggest that their study is limited because they included only one structural break when testing the cointegration between the spot and futures prices. This study overcomes that limitation by using the Bai-Perron (1998) test, which can test for multiple structural breaks, and applying cointegration tests to each period created from the break dates determined by the Bai-Perron test. We treat the structural breaks differently from Maslyuk and Smyth (2009). This is because in our study the breaks are identified exogenously while Maslyuk and Smyth (2009) take the breaks as endogenous in the cointegration model. This study uses data from the 2001-2010 period, a period that includes Hurricane Katrina in August 2005 and the global financial crisis in September 2008. We study whether the break dates identified by the Bai-Perron test are related to the dates on which those events occurred and to determine how the break dates affected the price linkage among the major U.S. energy sources.

The following section provides a brief literature review of studies testing the price relationships among various energy markets. In the third section, the empirical methods used in this study are explained. Details of the data are presented in the fourth section, and the results are presented in the fifth section. In the last section, conclusions and implications are discussed.

2. PREVIOUS STUDIES

Several studies have tested the long-term relationships among prices of crude oil, natural gas, and coal (Asche et al., 2006; Bachmeier and Griffin, 2006; Mohammadi, 2009). It is known that crude oil and its refined products exhibit long-run relationships. For example, Asche et al. (2003) find cointegration relationships between crude oil and refined oil products in the U.K. market using monthly price data collected between 1995 and 1998. However, only weak price linkage seems to hold among the crude oil, coal, and natural gas markets. Bachmeier and Griffin (2006) discover that crude oil, coal, and natural gas do not belong to one economic market and that they are linked only superficially. They argue that substitution between these energy sources is limited to the number of facilities that can burn multiple fuels. Brown and Yucel (2008) show that since the year 2000, the price of natural gas has moved independently of the price of crude oil. Hartley et al. (2008) suggest that the natural gas and petroleum markets are moving together in the long run, but they find that variables such as weather, inventories, and hurricanes could affect their relationship in the short run.

The U.S. may soon increase its use of non-fossil fuels, such as nuclear or biofuel, to reduce the effect of energy consumption on climate change. However, few studies have included uranium and ethanol, which are important components of nuclear fuel and biofuel, when testing the market linkage among the major energy sources.

The study by Mjelde and Bessler (2009) is one of the few that include the price of uranium to test the market integration among the U.S. electricity wholesale price and the major fuel source prices. They test the dynamic price information flows among U.S. electricity and major fuel source prices and found that crude oil, coal, natural gas, and uranium markets in the U.S. were not fully integrated. However, they did not identify the individual long-run relationships among the price of uranium and other energy sources because their study conducted only a multivariate cointegration analysis. Amavilah (1995) tests the price relationships between uranium, crude oil, and coal between 1965 and 1989 using a structural model and finds that the price of uranium is significantly affected by the price of coal.

Among studies on renewable energy prices, Zhang et al. (2010) and Peri and Baldi (2010) analyze the price relationships between petroleum-related products and vegetable oils, but those studies focus only on the price flows among the oil and vegetable oil products. Therefore, coal, natural gas, and uranium prices were not considered in those studies.

3. METHODOLOGY

The Johansen method (Johansen and Juselius, 1990) is used for testing the price linkage among the NYMEX energy source futures prices. Many studies have used the Engle and Granger test for examining the price linkage (see Goodwin and Schroeder, 1991), but this study uses the Johansen method. Johansen method is more efficient when analyzing the variables of interest as endogenous in the model and is more useful in a multivariate framework. Darrat (1998) suggests that the Johansen test has an advantage over the Engle and Granger test even in a bivariate cointegration framework because the Johansen test does not require Gaussian errors.

All price series used in this study need to be integrated at the same order for the series to be cointegrated (Quan, 1992). Before performing the cointegration tests, all price series are tested for their stationarity by the augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) unit root tests. The ADF and PP unit root tests test for the null hypothesis of non-stationarity of the price series, while the KPSS tests for the stationarity of the series. Once it is confirmed by these tests that the variables are integrated of the same order, multivariate and bivariate Johansen tests are conducted among the energy prices.[2]

Let Y_t be the $n \times 1$ vector of the non-stationary variables and k be the order of the vector autoregressive process. Then, the vector autoregressive model used for the Johansen cointegration test is denoted as follows:

$$Y_t = \sum_{i=1}^{k} \Pi_i Y_{t-i} + \Phi D_t + \varepsilon_t \tag{1}$$

where Y_t are the endogenous variables of interest (prices of the energy sources), Π_i is a $n \times n$ matrix of parameters, Φ is a coefficient parameter, D_t is a deterministic term that includes a constant and a linear time trend, and ε_t denotes a normally distributed n-dimensional white noise process. Converting this model into the error correction model leads to:

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta Y_{t-i} + \Phi D_t + \varepsilon_t \tag{2}$$

where $\Pi = -I + \sum_{i=1}^{k} \Pi_i$ and $\Gamma_i = -\sum_{j=i+1}^{k} \Pi_i$. Because the Y_t variables are integrated of the same order by assumption, whether the variables of interest become cointegrated depends on the rank of the Π matrix. The rank of a matrix is equal to its number of significantly positive characteristic roots, which is called the eigenvalue. Using this eigenvalue, the trace and maximum eigenvalue tests are performed among the price series.

[2] As explained in the next section, the period used for the cointegration tests is different when ethanol and uranium prices are included in the model. This is due to the data availability of the NYMEX uranium and ethanol futures prices.

The Bai-Perron (1998) test is used to identify the structural breaks in the series. The Chow (1960) test has long been the major method for determining structural change in time-series data, but it is inadequate when the break date is unknown (Rapach and Wohar, 2006). Quandt (1960) and Andrews and Ploberger (1994) developed a method based on the Chow test for testing structural breaks when the break is unknown, but those methods were limited to testing one structural break and deficient in identifying the breakpoints when the series were nonstationary (Hansen, 2000). The Bai-Perron test overcomes these problems and is useful for finding breaks when the potential break date is unknown and the series tend to have more than one break.

The first stage of the Bai-Perron test considers whether the price series contains unknown breaks using the "double maximum tests" (UD max and WD max tests) (see Bai and Perron, 1998). Those tests use the maximum F-statistic that is calculated from the global minimum of the sum of squared residuals of the m-partitioned multiple regression models:

$$\mathrm{y_t} = \mathrm{z_t'}\delta_\mathrm{j} + \mathrm{u_t} \quad where\ \ j = 1, \cdots, m+1 \tag{3}$$

where $\mathrm{y_t}$ is the dependent variable at time t, $\mathrm{z_t}$ is a vector of covariates, δ_j is the corresponding vector of coefficients, m is the number of breaks, and $\mathrm{u_t}$ is the disturbance at time t. When the double maximum tests do not reject the null hypothesis of having no structural breaks in the series, there will be no significant evidence of a break in the series.

In the second stage, if the results of the double maximum tests suggest that there is at least one break in the price series, the number of appropriate potential breaks is identified by testing the null of l breaks versus the alternative of $l+1$ breaks. The null hypothesis of l breaks is rejected in favor of $l+1$ breaks if the overall minimum value of the sum of squared residuals of a model with $l+1$ breaks is sufficiently smaller than that of the l breaks model (Bai and Perron, 1998). Because this test uses the $\mathrm{supF}(l+1|l)$ test statistic, this test is called the supF test, and the critical values are provided in Bai and Perron (1998).

The natural logarithm of ratios between the energy prices is used for the Bai-Perron test because this test is specifically tested on single series. For example, the log of the price ratio between the prices of WTI crude oil and unleaded gasoline is used for testing whether breaks existed in the relationship of the two price series. The price ratios are obtained for all combinations of the eight price series used in the study, and the Bai-Perron test is conducted for all of those price ratios.[3]

After the breaks are determined by the Bai-Perron test, the two price series that will be used to test the price linkage are split into periods using the break dates. Then, the bivariate Johansen cointegration tests are performed on all combinations of energy prices for each period separated by the break dates. Unit root tests are performed on every energy price for each period that was identified as explained above. If those tests suggest that the price variables are not integrated of the same order during the test period, it would mean that those variables are not cointegrated because cointegration tests require the test variables to be integrated of the same order (Quan, 1992).

The bivariate cointegration tests conducted on each period identified by the breaks are useful for understanding if the cointegration relationships between the two energy source prices changed before and after each break date. If the results suggest that the cointegration relationship differed between the periods before and after the breaks, it would imply that the breaks found by the Bai-Perron tests influenced the relationship between the two energy price series during the test period.

4. Data

The daily futures prices traded on the NYMEX are used for each price series. The daily price data is the continuation data created by taking the highest traded volume contract for each commodity and is obtained from the EODData, LLC. For all energy price series except for the uranium and ethanol futures markets, the period of the study is from July 2001 to May 2010. That term was selected because the coal futures market on the NYMEX opened in July 2001. The NYMEX launched the uranium futures market in May 2007 and started to trade ethanol in April 2008, so the terms used for these price series are from May 2007 to May 2010 and from April 2008 to May 2010, respectively. Hence, the cointegration and the Bai-Perron tests are conducted only after May 2007 and April 2008, when uranium and ethanol prices are involved.

[3] Here, too, the period used for the Bai-Perron test is different when the prices of uranium and ethanol are included due to data availability.

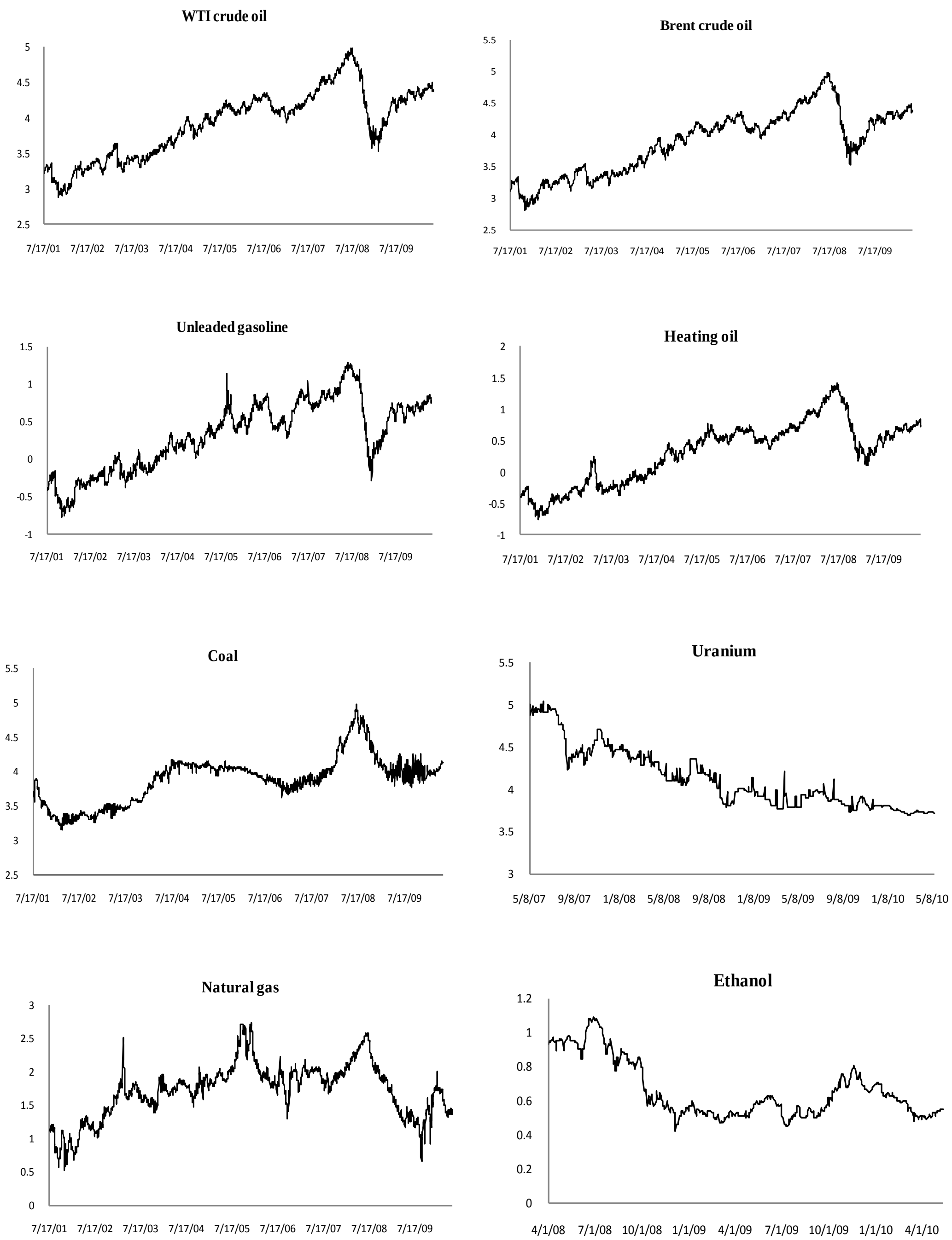

Fig. 1. Time series plots of natural log futures prices for WTI crude oil, Brent crude oil, unleaded gasoline, coal, uranium, natural gas, and ethanol traded at the NYMEX.

Two crude oil futures prices are used in the analysis. One is the futures price of WTI crude oil, which is also known as Texas Light Sweet. The other is the price of Brent crude oil. This is based on a light sweet North Sea crude oil. They are very similar in product but differ in that WTI crude oil is mostly used in the U.S., while Brent is demanded more in Europe. Unleaded gasoline and heating oil are both refined products of crude oil, and both prices are for physical delivery at the New York Harbor. The NYMEX futures price for coal is based on Central Appalachian Coal; the price for natural gas is based on physical delivery at the Henry Hub in Louisiana; the uranium price is based on the UxC index published by Ux Consulting Company; and the ethanol price is based on physical delivery at the New York Harbor.

Fig. 1 plots the natural logarithms of futures prices for all energy sources used in this study. As explained above, the time periods considered are different for uranium and ethanol prices versus the other energy sources, but it appears that after mid-2008 all of the energy source prices decreased dramatically. This price drop may have resulted from the global financial crisis that began in September 2008. It is also noticeable from the graph that the petroleum related-products (WTI crude oil, Brent crude oil, unleaded gasoline, and heating oil) all seem to show similar trends. The graph for coal seems to be smoother compared to that of petroleum products and is slower to recover after the price decline in mid-2008. Natural gas shows a different pattern from those of all other energy sources. It exhibits a spike in 2005 in addition to the spike in 2008. The spike in 2005 may be related to the effects of Hurricane Katrina, from which the Henry Hub suffered a direct hit. For the graphs of uranium and ethanol, no data are available before May 2007 and April 2008, respectively. The uranium price seems to show a downward trend, while the ethanol price spikes around mid-2008 and late 2009.

5. RESULTS

Table 1 Unit root tests

Variable	Log Level			First difference of log level		
	ADF	PP	KPSS	ADF	PP	KPSS
WTI crude oil	-1.448	-1.410	4.508*	-8.332*	-50.178*	0.065
Brent crude oil	-1.455	-1.426	4.619*	-53.017*	-53.005*	0.044
Unleaded gasoline	-1.810	-1.796	4.328*	-49.822*	-49.885*	0.028
Heating oil	-1.453	-1.454	4.518*	-51.239*	-51.232*	0.071
Coal	-1.123	-2.013	3.186*	-10.452*	-93.073*	0.054
Uranium	-2.036	-2.151	3.048*	-20.653*	-40.817*	0.107
Natural gas	-2.287	-2.671	1.542*	-11.390*	-49.227*	0.081
Ethanol	-1.759	-1.773	1.381*	-23.943*	-23.937*	0.120

Notes: * denotes significance at 1%. All the unit root tests for the level and first differences include a constant. Lag orders for the ADF tests are determined by the AIC and the bandwidth for the PP and KPSS tests are identified by Newey-West using Bartlett kernel (Siliverstovs et al., 2005). July 17, 2001 to May 11. 2010 period is used for the WTI crude oil, Brent crude oil, unleaded gasoline, heating oil, coal, and natural gas price series. May 8, 2007 to May 11, 2010, and April 1, 2008 to May 11, 2010 periods are used for the uranium and ethanol price series respectively.

The natural logarithms of the price series are used for all statistical tests conducted in this paper. Table 1 shows the results of the ADF, KPSS, and PP unit root tests using the data between July 2001 and May 2010 for all price series except those for uranium and ethanol. The unit root tests are conducted for the May 2007 through May 2010 period for the uranium prices and the April 2008 through May 2010 period for the ethanol prices. The results indicate that all price series are integrated of order one during those periods. Thus, multivariate and bivariate cointegration tests are appropriate tests for finding price linkage among the energy source prices.

Table 2 Multivariate cointegration tests

Test A. Model with all variables (CL, SC, UG, HO, QL, UX, NG, QB)
Tested period (April 2008 - May 2010)

H_0: rank=r	Trace test	Max test
r=0	184.88**	66.01**
r<=1	118.87	33.99
r<=2	84.88	27.66
r<=3	57.22	21.10
r<=4	36.12	18.27
r<=5	17.85	9.98
r<=6	7.87	4.77
r<=7	3.10	3.10

Test B. Model without ethanol (CL, SC, UG, HO, QL, UX, NG)
Tested period (May 2007 - May 2010)

H_0: rank=r	Trace test	Max test
r=0	160.34**	63.66**
r<=1	96.69**	36.45
r<=2	60.24	27.64
r<=3	32.60	15.95
r<=4	16.65	10.01
r<=5	6.64	3.87
r<=6	2.77	2.77

Test C. Model without uranium and ethanol (CL, SC, UG, HO, QL, NG)
Tested period (July 2001 - May 2010)

H_0: rank=r	Trace test	Max test
r=0	199.37**	93.19**
r<=1	106.18**	50.41**
r<=2	55.77**	30.02**
r<=3	25.75	13.70
r<=4	12.05	9.52
r<=5	2.53	2.53

Test D. Model with oil related products (CL, SC, UG, HO)
Tested period (July 2001 - May 2010)

H_0: rank=r	Trace test	Max test
r=0	134.01**	67.23**
r<=1	66.78**	38.12**
r<=2	28.66**	26.09**
r<=3	2.58	2.58

Note: ** represents significance at 5% level. CL, SC, UG, HO, QL, UX, NG, and QB are the WTI crude oil, Brent crude oil, unleaded gasoline, heating oil, coal, uranium, natural gas and ethanol log futures prices.

Initially, the following four multivariate cointegration tests are conducted to see the overall linkage among the energy source markets in the U.S. (tests A, B, C, and D). Test A includes all eight energy prices, test B does not include the ethanol price, test C does not include the uranium and ethanol prices, and finally in test D, only the four oil-related price series are included. The results of those tests are presented in Table 2.

Tests A and B have only one or two cointegration relationships. Their results imply that energy prices are very weakly linked during the examined period. Test C has three cointegration relationships but here too the overall linkage among these markets is not so strong since the test was performed for six energy prices. Finally, test D resulted in three cointegration relationships, suggesting that the oil-related energy markets have strong overall linkage. Because the only difference between tests C and D is the inclusion of the coal and natural gas prices along with the oil prices, the test results indicate that the coal and natural gas futures markets are not integrated with the oil markets and that they show different trends from the oil markets.

Table 3 Bivariate Cointegration tests without breaks

Variables	H_0: rank=r	Trace test	Max test	Variables	H_0: rank=r	Trace test	Max test
CL and SC	r=0	61.89**	59.87**	UG and QL	r=0	13.72	11.17
	r<=1	2.02	2.02		r<=1	2.55	2.55
CL and UG	r=0	38.61**	36.51**	UG and UX	r=0	6.76	4.41
	r<=1	2.10	2.10		r<=1	2.35	2.35
CL and HO	r=0	33.03**	31.03**	UG and NG	r=0	12.14	8.66
	r<=1	1.99	1.99		r<=1	3.48	3.48
CL and QL	r=0	11.95	9.85	UG and QB	r=0	6.24	4.56
	r<=1	2.10	2.10		r<=1	1.68	1.68
CL and UX	r=0	7.28	5.90	HO and QL	r=0	12.07	10.18
	r<=1	1.39	1.39		r<=1	1.89	1.89
CL and NG	r=0	10.12	8.26	HO and UX	r=0	7.08	5.80
	r<=1	1.86	1.86		r<=1	1.28	1.28
CL and QB	r=0	7.64	5.45	HO and NG	r=0	10.73	8.53
	r<=1	2.19	2.19		r<=1	2.20	2.20
SC and UG	r=0	32.26**	30.35**	HO and QB	r=0	10.99	8.39
	r<=1	1.91	1.91		r<=1	2.60	2.60
SC and HO	r=0	31.62**	29.37**	QL and UX	r=0	7.99	5.29
	r<=1	2.25	2.25		r<=1	2.69	2.69
SC and QL	r=0	11.35	9.18	QL and NG	r=0	15.08	11.87
	r<=1	2.18	2.18		r<=1	3.21	3.21
SC and UX	r=0	7.07	5.55	QL and QB	r=0	15.72**	12.52
	r<=1	1.52	1.52		r<=1	3.20	3.20
SC and NG	r=0	9.82	7.84	UX and NG	r=0	7.67	6.04
	r<=1	1.98	1.98		r<=1	1.63	1.63
SC ad QB	r=0	6.80	4.76	UX and QB	r=0	15.62**	11.88
	r<=1	2.05	2.05		r<=1	3.74	3.74
UG and HO	r=0	25.30**	22.72**	NG and QB	r=0	13.28	10.13
	r<=1	2.58	2.58		r<=1	3.15	3.15

Note: ** represents significance at 5% level. CL, SC, UG, HO, QL, UX, NG, and QB are the WTI crude oil, Brent crude oil, unleaded gasoline, heating oil, coal, uranium, natural gas and ethanol log futures prices.

Bivariate cointegration tests are also conducted on all possible combinations of energy prices. As seen in Table 3, the pairs among the four oil-related prices, WTI crude oil, Brent crude oil, unleaded gasoline, and heating oil prices are all cointegrated of order one, which is consistent with the result of the multiple cointegration test (see test D of table 2). However, the bivariate tests among the prices of oil products, coal, uranium, natural gas, and ethanol indicate that no price relationships exist among these prices, except between coal and ethanol and between uranium and ethanol. Although cointegration relationships are found among coal, uranium, and ethanol, these relationships are very weak. The maximum eigenvalue statistics reject the cointegration relationships among those products, and the results of the trace tests became statistically insignificant when tested at the 10% significance level. From Table 3, we see that price linkage persists only among the oil-related energy sources and that inter-fuel price linkage is weak among the major U.S. fuel sources.

Table 4 Bai-Perron tests

	ln(CL/SC)	**ln(CL/UG)**	**ln(CL/HO)**	**ln(CL/QL)**	**ln(CL/UX)**	**ln(CL/NG)**	**ln(CL/QB)**
Test	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic
UDmax	117.66**	23.53**	6.39	25.10**	11.74**	17.32**	12.41**
WDmax	117.66**	27.12**	7.81	28.06**	14.58**	17.32**	12.41**
sup-F(2|1)	24.90**	21.16**		9.48	4.99	8.43	13.16**
sup-F(3|2)	6.51	4.95					5.71
	ln(SC/UG)	**ln(SC/HO)**	**ln(SC/QL)**	**ln(SC/UX)**	**ln(SC/NG)**	**ln(SC/QB)**	**ln(UG/HO)**
Test	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic
UDmax	47.39**	18.22**	27.62**	15.26**	17.38**	8.27	11.66**
WDmax	47.39**	25.53**	30.35**	15.26**	17.52**	12.62**	11.66***
sup-F(2|1)	15.35**	27.76**	6.32	6.76	9.31		4.66
sup-F(3|2)	4.49	5.39					
	ln(UG/QL)	**ln(UG/UX)**	**ln(UG/NG)**	**ln(UG/QB)**	**ln(HO/QL)**	**ln(HO/UX)**	**ln(HO/NG)**
Test	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic
UDmax	18.66**	19.01**	17.90**	17.08**	28.28**	16.30**	21.21**
WDmax	23.95**	19.01**	18.03**	17.08**	34.58**	21.34**	21.21**
sup-F(2|1)	7.77	3.59	7.88	4.80	31.18**	19.69**	8.62
sup-F(3|2)					3.92	8.43	
	ln(HO/QB)	**ln(QL/UX)**	**ln(QL/NG)**	**ln(QL/QB)**	**ln(UX/NG)**	**ln(UX/QB)**	**ln(NG/QB)**
Test	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic
UDmax	9.83***	87.68**	28.49**	61.26**	13.77**	20.32**	21.00**
WDmax	15.09**	87.68**	28.49**	63.76**	17.51**	20.32**	21.00**
sup-F(2|1)	9.08	31.97**	7.95	49.55**	5.65	12.58**	7.72
sup-F(3|2)		7.10		3.03		3.27	

Note: **, and *** denote significance at 5%, and 10% respectively. CL, SC, UG, HO, QL, UX, NG, and QB are the WTI crude oil, Brent crude oil, unleaded gasoline, heating oil, coal, uranium, natural gas and ethanol futures prices.

To test whether the price series contain structural breaks and how such breaks affect the relationships among the energy source prices, Bai-Perron tests are conducted on the series.[4] The results of this test are enumerated in Table 4. The tests are conducted for every price ratio among the energy source prices. If the double maximum tests are both rejected, the tests continue to determine the appropriate number of potential breaks using the supF tests. As seen in the table, most of the price ratios contained structural breaks, except for the price ratios between WTI crude oil and heating oil (ln(CL/HO)) and between Brent crude oil and ethanol (ln(SC/QB)). The appropriate number of breaks is either one or two, and none of the price ratios were identified to have three breaks.

Table 5 Bivariate Cointegration tests with breaks

Period	CL and SC	R	CL and UG	R	CL and QL	R	CL and UX	R
1	Jul. 17, 01 - Feb. 21, 05	y	Jul. 17, 01 - Jul. 31, 03	y	Jul. 17, 01 - May 19, 05	n	May 8, 07 - Mar. 27, 09	n
2	Feb. 22, 05 - Feb. 21. 07	n	Aug. 1, 03 - Jul. 10, 07	y	May 20, 05 - May 11, 10	n	Mar. 30, 09 - May 11, 10	n
3	Feb. 22, 07 - May. 11, 10	y	Jul. 11, 07 - May 11, 10	y				

Period	CL and NG	R	CL and QB	R	SC and UG	R	SC and HO	R
1	Jul. 17, 01 - Dec. 19, 05	n	Apr. 1, 08 - Sept. 4, 08	n	Jul. 17, 01 - Aug. 1, 03	y	Jul. 17, 01 - Aug.22, 06	y
2	Dec. 20, 05 - May 11, 10	n	Sept. 5, 08 - Feb. 11, 09	n	Aug. 4, 03 - Jul. 10, 07	y	Aug. 23, 06 - Aug. 5, 08	y
3			Feb. 12, 09 - May 11, 10	n	Jul. 11, 07 - May 11, 10	y	Aug. 6, 08 - May 11, 10	n

Period	SC and QL	R	SC and UX	R	SC and NG	R	UG and HO	R
1	Jul. 17, 01 - May 12, 05	n	May 8, 07 - Jul. 15, 09	n	Jul. 17, 01 - Dec. 20, 05	n	Jul. 17, 01 - Dec. 19, 05	y
2	May 13, 05- May 11,10	n	Jul. 16, 09 - May 11, 10	n	Dec. 21, 05 - May 11, 10	n	Dec. 20, 05 - May 11, 10	n

Period	UG and QL	R	UG and UX	R	UG and NG	R	UG and QB	R
1	Jul. 17, 01 - May 19, 05	n	May 8, 07 - Mar. 27, 09	n	Jul. 17, 01 - Feb. 09, 06	y	Apr. 1, 08 - Dec. 25, 08	n
2	May 20, 05 - May 11, 10	n	Mar. 30, 09 - May 11, 10	n	Feb. 10, 06 - May 11, 10	n	Dec. 26, 08 - May 11,10	n

Period	HO and QL	R	HO and UX	R	HO and NG	R	HO and QB	R
1	Jul. 17, 01 - Feb. 21, 06	n	May 8, 07 - Nov. 13, 08	n	Jul. 17, 01 - Dec. 19, 05	n	Apr. 1, 08 - Oct. 1, 08	n
2	Feb. 22, 06 - Jul. 23, 08	y	Nov. 14, 08 - Jul. 15, 09	n	Dec. 20, 05 - May 11, 10	n	Oct. 2, 08 - May 11, 10	n
3	Jul. 24, 08 - May 11,10	n	Jul. 16, 09 - May 11, 10	n				

Period	QL and NG	R	QL and QB	R	QL and UX	R	UX and NG	R
1	Jul. 17, 01 -Jul. 22, 08	n	Apr. 1, 08 - Feb. 18, 09	n	May 8, 07 - Nov. 13, 08	n	May 8, 07 - Sep. 4, 09	n
2	Jul. 23, 08 - May 11, 10	n	Feb. 19, 09 - Oct. 9, 09	y	Nov. 14, 08 - Oct. 1, 09	n	Sep. 7, 09 - May 11, 10	n
3			Oct. 12, 09 - May 11, 10	n	Oct. 2, 09 - May 11, 10	n		

Period	UX and QB	R	NG and QB	R
1	Apr. 1, 08 - Jan. 2, 09	n	Apr. 1, 08 - Nov. 12, 09	n
2	Jan. 5, 09 - Sep.11, 09	n	Nov. 13, 09 - May 11, 10	n
3	Sep. 14, 09 - May 11, 10	n		

Note: CL, SC, UG, HO, QL, UX, NG, and QB are the WTI crude oil, Brent crude oil, unleaded gasoline, heating oil, coal, uranium, natural gas, and ethanol log futures prices. The column labeled R gives the cointegration test results based on the 5% significance level using the trace statistic: y represents the existence of a cointegration between the two price series and n means that there is no cointegration. n is also applied when unit root tests conducted for different periods for each variable suggest that they are not integrated of the same order.

The unit root tests are first performed on each period before conducting the

[4] The maximum number of breaks (m) and the trimming value (ε) are set to 3 and 0.20 (see Bai and Perron (1998) for more technical details).

bivariate cointegration tests for every period identified by the breaks. If this test result indicates that the price series are integrated at different orders, these variables are not cointegrated. If the result suggests that they were integrated of the same order, the bivariate Johansen test is performed. The results of this cointegration test with breaks are presented in Table 5. The dates in the table represent the time period used for the cointegration tests. Because the Bai-Perron test identified different numbers of breaks for different price ratios, the number of periods and the time period used for the cointegration tests depend on the type of price relationships tested.

Here, too, it is noticeable that a cointegration relationship existed between the oil-related products for most of the periods identified by the Bai-Perron test. However, as seen in the test results between WTI and Brent crude oil (CL and SC) and between unleaded gasoline and heating oil (UG and HO), the break that occurred in 2005 changed the cointegration relationships for those price series. Both of the price relationships had cointegration relationships before the break in 2005, but they ceased to be cointegrated after the breaks identified in 2005 (February 22, 2005, and December 20, 2005). Another break that appeared in the price ratio between Brent crude oil and heating oil (SC and HO) in August 2008 also changed the cointegration relationship between those price series. Brent crude oil and heating oil were cointegrated before August 6, 2008, but that price relationship disappeared after the break occurred. As explained before, the four oil prices had strong linkage over the whole test period. Thus, these changes in the cointegration relationships during the break periods imply that the breaks that occurred during 2005 and 2008 had large impacts on the price relationships among the U.S. major energy sources.

For the non-oil-related energy sources, no significant linkage exists between the pairs of energy prices based on the results in Table 5. Coal (QL) was cointegrated with heating oil (HO) and ethanol (QB) in one of the periods identified by the breaks, but these cointegration relationships were not present during other periods. It is likely that these energy sources are not cointegrated in general, as indicated in the test result without breaks in Table 3 and that the cointegration observed in one period reflects the effects of structural breaks in the series.

No cointegration with uranium prices were observed in any of the periods identified by the breaks, and none of the breaks affected the price relationships between uranium and other energy sources. Uranium also showed no cointegration relationship when tested without breaks (see Table 3). Hence, the test results with breaks in Table 5 suggest that the uranium market is very independent from other energy markets and that its price relationship with other energy markets is not affected even by structural breaks.

The results in Table 5 suggest that natural gas prices did cointegrate with unleaded gasoline (UG) prices between July 2001 and February 2006. As seen in Fig. 1, natural gas prices experienced a spike during 2005, which is likely to be related to the effects of Hurricane Katrina. Thus, the break found for the price ratio between natural gas and unleaded gasoline in February 2006 may be associated with this spike. Because that break changed the cointegration relationship between natural gas and unleaded gasoline, the results indicate that the natural gas market was strongly influenced after the break in February 2006. It is likely that this break caused the independent movement of the natural gas market throughout the study period.

Finally, the ethanol market did not have strong linkage with any of the energy source markets. As seen in Table 5, ethanol prices were only cointegrated with coal prices during the period from February 2009 to October 2009 and did not exhibit a cointegration relationship in other periods. The result of the bivariate cointegration test without the consideration of structural breaks also indicated that ethanol prices are very weakly linked with other energy source markets. Therefore, the cointegration with coal prices that occurred for a short period in 2009 is likely to be an effect of the structural break in the series.

6. CONCLUSIONS

This study investigated whether market linkage exists among the major energy source markets in the U.S. when structural breaks are considered in price series. We showed that strong price linkage exists among the NYMEX WTI crude oil, Brent crude oil, gasoline, and heating oil futures markets but only weak linkage holds among these four oil-related markets, coal, natural gas, uranium, and ethanol futures markets. The price linkage among the four oil-related markets is not surprising because it is known from a previous study that price linkage exists among oil-related products (Asche et al., 2003) and it is common to find price relationships between input and output prices (Mjelde and Bessler, 2009) such as between crude oil and gasoline and heating oil prices. However, our finding that only weak linkage exists among the four oil-related products, coal, natural gas, uranium, and ethanol markets provides important empirical evidence that at the moment no primary energy source market exist in the U.S. and the major U.S. energy markets move independently. This implies that when applying market intervention policies for the U.S. energy market every U.S. major energy source market will have to be treated individually.

The test on price linkage when structural breaks are considered also suggested that the price linkage only exists among the oil-related energy markets and only weak linkage exists among the U.S. major energy source markets. Especially we found from this test that the uranium and ethanol futures prices have very weak linkage with other U.S. major energy source prices. This indicates that the U.S. energy market is still at a stage where none of the probable alternative energy source market plays the role as a substitute or a complement market for the fossil fuel energy market.

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