The Switching Relationship between Natural Gas and Crude Oil Prices

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This analysis more accurately captures the cointegrating relationship between natural gas and crude oil prices by controlling for nonstationarity induced by *endogenous* changes in regime.

- Note, the changes in regimes are determined solely by the underlying data generating process.

Introduction and Motivation

We allow the parameters of the cointegrating equation to switch between m states, according to a first-order Markov process.

- The process may be stationary within each regime, but nonstationary as a whole.

Introduction and Motivation

Once regime changes are controlled for, the long-term equilibrium relationship may be modeled over wider and more varied sample periods. This affords:

- a better measure of present market integration.
- a more thorough undertstanding of how technological changes affect the relative pricing relationship.
- possibly better forecasts of relative prices.

Further, our results add to the literature by:

- Explaining apparent 'decoupling' between natural gas and crude oil prices, and abrupt changes in the cointegrating relationship (Ramberg and Parsons (2012)).
- Providing a more accurate model of the error correction mechanism[1] between the two price series.

[1] for more on cointegration and the error correction mechanism, see Engle and Granger (1987).

Introduction and Motivation

Understanding the relative pricing of natural gas and oil is important for energy producers and consumers (particularly with respect to capital budgeting decisions), and well as policy makers.

However, Villar and Joutz (2006) note that structural changes in the cointegrating equation can cause forecast failure. This renders the model less useful for policy decisions.

- This analysis explicitly models the structural change in the cointegrating equation as a first-order Markov-switching process.

Why would you expect natural gas and oil prices to be related?

- Substitution of fuels.
  - There is limited substitution of oil derivatives and natural gas in industrial processes.
- Oil and natural gas production and pricing.
  - Often natural gas is produced alongside, or dissolved in, crude oil (associated gas). This led natural gas, in many contracts, to be priced as a percent of crude oil.
- This led to various rules-of-thumb for natural gas vs. oil pricing, such as by prices at the burner-tip, and by relative energy content (1 barrel of WTI contains 5.825 mmBtu).
- See Brown and Yücel (2008), Ramberg and Parsons (2012), and particularly Villar and Joutz (2006), among other papers, for more background.

Why would there be changes in regime?

The relative behavior of natural gas and oil may exhibit regime shifts due to technological changes or legislation.

- Hartley et al (2008) found evidence that the introduction of the combined-cycle combustion turbine made natural gas electricity generation more cost effective, thereby markedly increasing demand for natural gas and therefore increasing prices.
- More recently hydraulic fracturing techniques have increased the supply of natural gas from shale reserves, which has reduced prices.

The Cointegrating Equation: First-Order, M-State, Markov-Switching

$$P_{HH} = \beta_{0,S_t} + \beta_{1,S_t} P_{WTI} + e_t, \quad e_t \sim N\left(0, \sigma^2_{S_t}\right)$$

$$P(S_t = j | S_{t-1} = i) = p_{ij},\ \forall j \in 1,2,...,M,\ and \sum_{j=1}^{M} p_{ij} = 1$$

$$\beta_{0,S_t} = \beta_{0,1} S_{1t} + \beta_{0,2} S_{2t} + ... + \beta_{0,M} S_{Mt}$$

$$\beta_{1,S_t} = \beta_{1,1} S_{1t} + \beta_{1,2} S_{2t} + ... + \beta_{1,M} S_{Mt}$$

$$\sigma_{0,S_t} = \sigma_{0,1} S_{1t} + \sigma_{0,2} S_{2t} + ... + \sigma_{0,M} S_{Mt}$$

$$where\ for\ m \in 1,2,...M,\ if\ S_t = m \Rightarrow S_{mt} = 1,\ and\ S_{mt} = 0\ else$$

Estimation

- Construction of the likelihood function for the above Markov Switching cointegrating equation was done by prediction error decomposition using the Hamilton filter[2].
- Minimization of the negative log-likelihood was done using the *optim* function in the R programming language.

[2] see Hamilton (1994) or Kim and Nelson (1999) for prediction error decomposition using the Hamilton filter, and Harvey (1989) on prediction error decomposition in general

State-Weighted Residuals

- Given estimated model parameters and transition probabilities, I calculate the *filtered*[3] state probability $P\left(S_t = i|\varphi_{t-1}\right)$ where φ_{t-1} denotes the information set at time $t-1$.
- I use these filtered probabilities to calculate the model's state-weighted residuals which are, for two states:

$$e_t = e_{s_t=1} P\left(S_t = 1|\varphi_{t-1}\right) + e_{s_t=2} P\left(S_t = 2|\varphi_{t-1}\right)$$

[3] as opposed to smoothed probabilities $P\left(S_t = i|\varphi_T\right)$

Data: Cointegrating Equation

Monthly and weekly logged prices for rolling font month NYMEX full-sized natural gas (symbol: NG) and west Texas intermediate crude oil (symbol: CL) contracts.

- Crude oil is deliverable in Cushing Oklahoma, and natural gas at the Henry Hub in Louisiana.
- Data are from the Energy Information Agency at the US Department of Energy.

The cointegrating equation was estimated allowing for the number of states to range between 1 and 3.

- AIC is in favor of two states (using both weekly and monthly prices).
- Two states exhibit stable states with distinct regime switching.[4] The expected state duration in the two state model with monthly prices is 6.94 and 4.66 years for state 1 and 2 respectively. Using weekly prices the expected duration is 3.10 and 2.13 years for state 1 and 2 respectively.

[4] The expected duration of state m, where p_{mm} denotes the transition probability from state m to state m:

$$E(D_m) = \sum_{j=1}^{\infty} j(P[D_m = j]) = \frac{1}{1-p_{mm}}$$

Results: 2 states & monthly prices

Table 1. Results of Estimating Cointegrating Equation Regressions (equations 1-5) with Monthly Prices

There are 225 monthly observations for natural gas and oil prices. The one-state model has 222 degrees-of-freedom, and the two-state model has 217. The alternative hypothesis in the augmented Dickey-Fuller and Phillips-Perron tests is to conclude the residual series is stationary. Residuals in the two-state model are weighted by the filtered state probability. p-values are below the coefficient in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively.

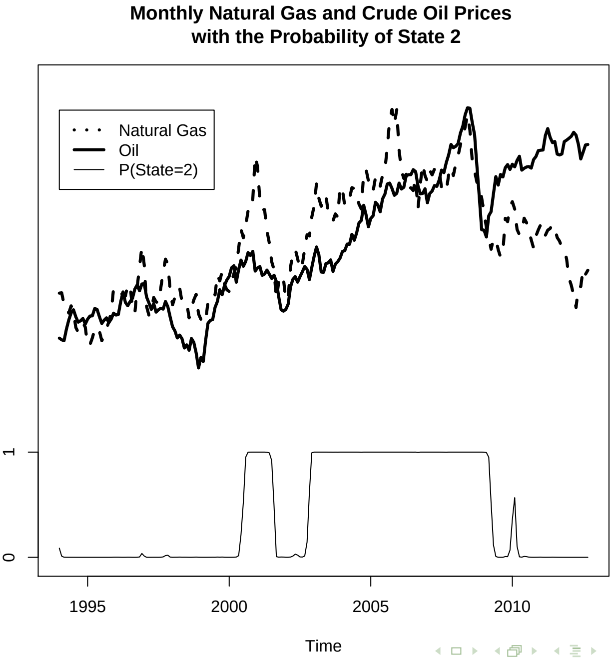
	One-State Model	**Two-State Model**	
State	1	1	2
β_0	-0.6910 (5e-6)***	-0.0287 (0.7518)	0.3351 (0.2068)
β_1	0.5608 (<1e-10)***	0.2889 (<1e-10)***	0.3949 (1.4e-8)***
σ^2	0.1537 (<1e-10)***	0.2017 (<1e-10)***	0.2634 (<1e-10)***
$P(S_t = 1 \| S_{t-1} = 1)$		0.9880	
$P(S_t = 2 \| S_{t-1} = 2)$		0.9821	
-ln(Likelihood)	108.59	-8.36	
AIC	0.9919	-0.0032	
Augmented Dickey-Fuller Test	-1.9168 (0.6109)	-4.4297 (0.01)***	
Phillips-Perron Test	-10.062 (0.5434)	-46.2419 (<0.01)***	

Results: 2 states & weekly prices

Table 2. Results of Estimating Cointegrating Equation Regressions (equations 1-5) with Weekly Prices

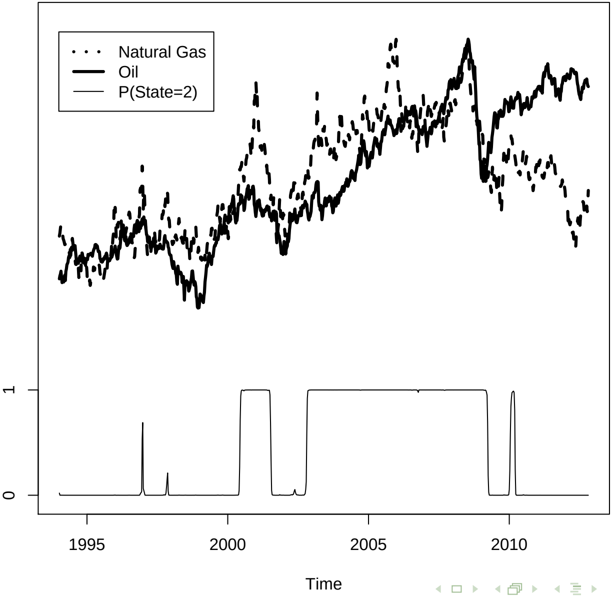
There are 978 weekly observations for natural gas and oil prices. The one-state model has 975 degrees-of-freedom, and the two-state model has 970. The alternative hypothesis in the augmented Dickey-Fuller and Phillips-Perron tests is to conclude the residual series is stationary. Residuals in the two-state model are weighted by the filtered state probability. p-values are below the coefficient in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively.

	One-State Model	**Two-State Model**	
State	1	1	2
β_0	-0.6867 (<1e-10)***	-0.1350 (0.0050)***	0.2806 (0.0043)***
β_1	0.5591 (<1e-10)***	0.3214 (<1e-10)***	0.4074 (<1e-10)***
σ^2	0.1566 (<1e-10)***	0.2116 (<1e-10)***	0.2025 (<1e-10)***
$P(S_t = 1 \mid S_{t-1} = 1)$		0.9938	
$P(S_t = 2 \mid S_{t-1} = 2)$		0.9910	
-ln(Likelihood)	481.2024	-110.1142	
AIC	0.9902	-0.2086	
Augmented Dickey-Fuller Test	-2.3475 (0.4312)	-5.2500 (0.0100)***	
Phillips-Perron Test	-14.7862 (0.2849)	-75.7543 (<0.01)***	

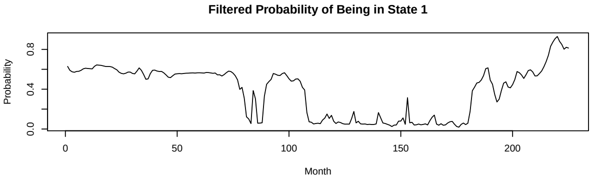


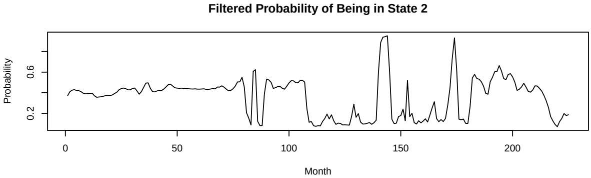
Monthly Natural Gas and Crude Oil Prices
with the Probability of State 2
Natural Gas
Oil
P(State=2)
1
0
1995
2000
2005
2010
Time

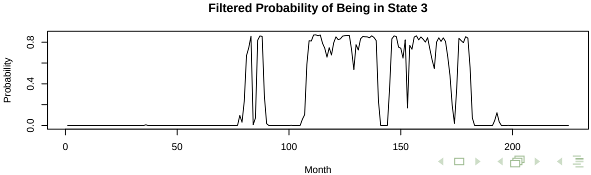
Weekly Natural Gas and Crude Oil Prices
with the Probability of State 2



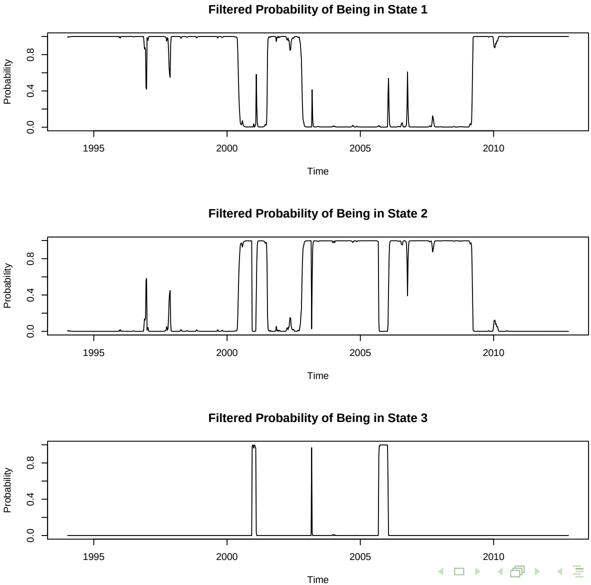
State Probabilities: Allowing 3 States, monthly prices







State Probabilities: Allowing 3 States, weekly prices



Summary: Results of the Cointegrating Equation

- The cointegrating equations residuals are stationary when using the switching model (the series are cointegrated), and nonstationary when the relationship is constrained to one state (the series are not cointegrated). This is evidence in favor of the regime-switching model.
- The filtered probabilities in the two-state model exhibit stable states with distinct regime-switching.
- The coefficients in the two-state model are all significantly different depending on the state (i.e. β_{01} is significantly different from β_{02}, etc.)
- We will therefore use the residuals from the two-sate cointegrating equation in the ECMs which follow.

Matching Conditional[5] Error-Correction Model (ECM): An Application

The ECM is:

$$\Delta P_{HHt} = \beta_0 + \beta_1 e_{t-1} + \beta_2 \Delta P_{WTIt} + \beta_3 \Delta P_{RFOt} + \\ \sum_{i=1}^{p} \rho_i \Delta P_{HHt-i} + \sum_{n=1}^{N} \mu_n X_{nt} + \xi_t$$

where X is a txn matrix of stationary exogenous control variables. The variables are:

- Cooling & Heating Degree Days
- Deviations from the average number of Cooling & Heating Degree Days
- Natural Gas Storage Differential from the 5-year Average
- First-differenced Baker-Hughes' Rig Count

[5] following Ramberg and Parsons (2012).

ECM Analysis: A note on present form

This specification treats crude oil prices as exogenous; that is, we do not have to account for the effect of natural gas on oil prices in an additional equation.

- This standard specification is motivated by crude oil being priced in a global market, and natural gas pricing being to a greater extent affected by local (north American) conditions.

Sample Periods

Full sample: June 1997 to September 2012.

- We report results for ECMs using two-state switching residuals only.
- Since the residuals from the non-switching cointegrating equations are nonstationary, we cannot use these in an ECM.

We chose the largest and most recent subsample period over which the residuals from the non-switching cointegrating equations were stationary at 5%. This period was October 2004 to September 2012.

- Over this subsample we estimate ECMs with both switching and nonswitching residuals.
- This allows us to directly compare the two models over the same sample period.

Full-sample ECM Results: Switching cointegrating equation

- The coefficient of the cointegrating term is about -0.15, which implies a 90% adjustment to equilibrium takes 14 months[6].
    - The term is negative and significant.
    - It is robust to both the number of lags of natural gas prices included, and the addition of fuel oil.
- Consistent with theory, the crude oil coefficient is positive, and significant when fuel oil is not included.
    - An increase in crude oil prices tends to increase natural gas prices in subsequent periods.

[6] $(1 - .15)^t = 0.1 \Rightarrow t = 14$

Full-sample ECM Results: Switching cointegrating equation

- The exogenous variables are of the appropriate sign and most are significant.
- The full-sample ECMs explain about 27% to 38% of the variation in the logged differences in natural gas prices.

Full-sample ECM Results: Switching cointegrating equation

We conclude that the residuals from the two-state equation appropriately model the long-term relationship between natural gas and crude oil prices in the ECM framework.

- Over the full sample, an ECM with one-state residuals cannot be used due to nonstationarity in the residuals due to regime switching.
- However, the two-state Markov-switching cointegrating equation successfully controls for this nonstationarity and affords a properly specified ECM.

This result broadens the applicability of the ECM to longer, and more varied, sample periods.

Results: Full Sample, Two-state, ECM

Table 3. Full-Sample, Two-State (Switching), Error-Correction Model Results: Below are estimates of the error correction model on monthly data from June 1997 to September 2012. There are 184 observations. The response variable is the change in the log Henry Hub natural gas price from time *t-1* to time *t*. *, **, *** denote significance at the 10%, 5%, and 1% levels respectively.

	Does not include fuel oil		Includes fuel oil	
Intercept	0.1117 (0.0028)***	0.0850 (0.0103)**	0.1018 (0.0033)***	0.1084 (0.0012)***
e_{t-1}	-0.1295 (0.0182)**	-0.1527 (0.0054)***	-0.1568 (0.0049)***	-0.1405 (0.0046)***
ΔP_{WTIt}	0.3457 (0.0004)***	0.3603 (0.0003)***	0.2241 (0.1063)	0.2660 (0.0517)*
ΔP_{RFOt}			0.3059 (0.0863)*	0.2900 (0.1034)
ΔP_{RFOt-1}			-0.2636 (0.0595)*	-0.2483 (0.0639)*
ΔP_{HHt-1}	0.1135 (0.0820)*	0.1883 (0.0119)**	0.1877 (0.0163)**	0.1712 (0.0205)**
ΔP_{HHt-2}	-0.0550 (0.4773)	-0.0007 (0.9925)	0.0390 (0.6217)	
ΔP_{HHt-3}	-0.0832 (0.2845)	-0.0134 (0.8562)	-0.0061 (0.9340)	
ΔP_{HHt-4}	0.0540 (0.4498)	0.0908 (0.2070)	0.1184 (0.1088)	
ΔP_{HHt-5}	-0.1064 (0.1330)			
ΔP_{HHt-6}	0.0064 (0.9274)			
ΔP_{HHt-7}	-0.0201 (0.7677)			
ΔP_{HHt-8}	-0.1159 (0.0851)*			
ΔP_{HHt-9}	-0.2603 (0.0002)***			
ΔP_{HHt-10}	-0.0113 (0.8746)			
ΔP_{HHt-11}	-0.0578 (0.4070)			
ΔP_{HHt-12}	-0.1261 (0.0721)*			
CDD_t	-0.0006 (0.0001)***	-0.0005 (0.0002)***	-0.0006 (0.0000)***	-0.0006 (0.0001)***
$CDDDEV_t$	0.0025 (0.0000)***	0.0022 (0.0000)***	0.0022 (0.0000)***	0.0019 (0.0001)***
HDD_t	-0.0001 (0.0998)*	-6.9e-05 (0.1621)	-9.7e-5 (0.0612)*	-0.0001 (0.0397)**
$HDDDEV_t$	0.0008 (0.0000)***	0.0008 (0.0000)***	0.0008 (0.0000)***	0.0008 (0.0000)***
STORAGE $DIFF_t$	-0.0001 (0.0233)**	-2.2e-05 (0.5597)	-1.4e-5 (0.7012)	-4e-5 (0.2239)
RIG COUNT $DIFF_t$	0.0002 (0.0446)**	6.2e-05 (0.4234)	6.9e-5 (0.3742)	7e-5 (0.3119)
F-statistic	6.316 (0.0000)***	6.622 (0.0000)***	6.095 (0.0000)***	7.438 (0.0000)***
adj. R^2	0.3848	0.2748	0.2872	0.2824

Subsample ECM Results (10/2004-9/2012), Switching vs. Nonswitching

Both one and two state residual series are significant at 5% by both augmented Dickey-Fuller and Phillips-Perron tests.

- The error correction term is negative and significant in the ECMs with two-state switching residuals.
- The error correction term is insignificant (and in one case positive) in the ECMs with one-state residuals.
    - The two-state residuals are consistent with the ECM form, while the one-state residuals are not.

Subsample ECM Results (10/2004-9/2012), Switching vs. Nonswitching

- The coefficient of crude oil is positive and significant in all ECMs.
- The exogenous variables are all of the appropriate sign.
- The ECM with two-state (one-state) residuals explain 43.7% (42.39%) of the variation in logged natural gas prices.

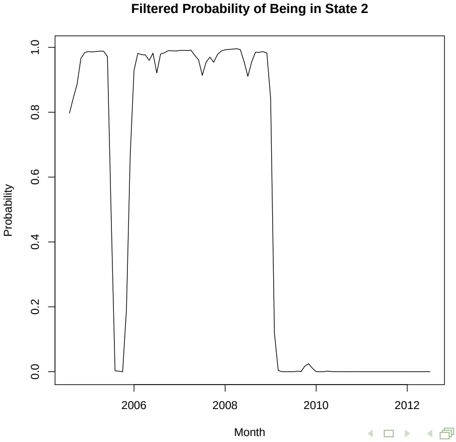
Results: Subsample ECM, Switching vs. Nonswitching

Table 4. Subsample Error-Correction Model Results: Switching versus Nonswitching Below are estimates of the error correction model on monthly data from October 2004 to September 2012. There are 96 observations. Over this subinterval both the one and two state cointegrating equations have stationary residuals, and so each ECM is internally consistent. The response variable is the change in the log Henry Hub natural gas price from time *t-1* to time *t*. *, **, *** denote significance at the 10%, 5%, and 1% levels respectively.

Variable	Switching		No switching	
Intercept	0.0941 (0.0746)*	0.1123 (0.0235)**	0.0869 (0.1098)	0.1270 (0.0163)**
e_{t-1}	-0.0669 (0.0943)*	-0.0929 (0.0187)**	0.0501 (0.2391)	-0.0375 (0.3060)
ΔP_{WTIt}	0.2620 (0.0359)**	0.3085 (0.0184)**	0.2223 (0.0728)*	0.2738 (0.0408)**
ΔP_{HHt-1}	-0.0468 (0.6622)	0.0954 (0.3329)	-0.0929 (0.4051)	0.0964 (0.3433)
ΔP_{HHt-2}	-0.0025 (0.9809)	0.1034 (0.2919)	-0.0532 (0.6201)	0.0893 (0.3761)
ΔP_{HHt-3}	-0.0443 (0.6826)	0.0251 (0.8056)	-0.1015 (0.3563)	-0.0007 (0.9949)
ΔP_{HHt-4}	-0.0077 (0.9348)	0.0415 (0.6721)	-0.0533 (0.5765)	0.0147 (0.8841)
ΔP_{HHt-5}	-0.1154 (0.2397)		-0.1855 (0.0661)*	
ΔP_{HHt-6}	0.0512 (0.5801)		0.0004 (0.9962)	
ΔP_{HHt-7}	-0.0987 (0.2966)		-0.1679 (0.0962)*	
ΔP_{HHt-8}	0.0043 (0.9628)		-0.0599 (0.5371)	
ΔP_{HHt-9}	-0.2440 (0.0093)***		-0.2801 (0.0039)***	
ΔP_{HHt-10}	-0.2544 (0.0128)**		-0.2962 (0.0059)***	
ΔP_{HHt-11}	-0.0434 (0.6577)		-0.0558 (0.5769)	
ΔP_{HHt-12}	-0.1075 (0.2629)		-0.1400 (0.1577)	
CDD_t	-0.0008 (0.0006)***	-0.0009 (0.0000)***	-0.0009 (0.0002)***	-0.0009 (0.0000)***
$CDDDEV_t$	0.0034 (0.0000)***	0.0031 (0.0000)***	0.0040 (0.0000)***	0.0031 (0.0001)***
HDD_t	-0.0001 (0.1324)	-0.0001 (0.0560)*	-0.0001 (0.0776)*	-0.0002 (0.0257)**
$HDDDEV_t$	0.0007 (0.0073)***	0.0010 (0.0002)***	0.0008 (0.0023)***	0.0011 (0.0004)***
STORAGE $DIFF_t$	-0.0001 (0.2887)	-6.5e-6 (0.9245)	-2.7e-05 (0.7247)	-9.7e-7 (0.9908)
RIG COUNT $DIFF_t$	0.0001 (0.2167)	0.0001 (0.2232)	0.0001 (0.2975)	0.0001 (0.3134)
F-statistic	4.1830 (0.0000)***	4.6880 (0.0000)***	4.0170 (0.0000)***	4.0310 (0.0000)
adj. R^2	0.4370	0.3505	0.4239	0.3073

Subsample results: Explanation for the better performance of the ECM with two state residuals

- The two-state cointegrating equation compensated for nonstationarity missed by standard tests (augmented Dickey-Fuller & Phillips-Perron).



Conclusions

- We have found evidence for two-state Markov regime-switching in the natural gas and crude oil cointegrating equation.
  - The two-state cointegrating equation's residuals are stationary and the one-state's are not (full sample).
  - The filtered probabilities of the two-state equation exhibit stable states with distinct regime switching.
- These results also imply, tests for regime switching should accompany any analysis of the long-term relationship between natural gas and crude oil prices.
  - The two-state equation can control for nonstationarity in the residuals which was missed by stationarity tests, i.e., a regime-switching cointegrating equation may be preferable even if the one state's residuals are stationary.

Conclusions

- We have found evidence that natural gas and oil did not 'decouple' in the early 2000s, but rather exhibited a temporary shift in August 2000 to a regime wherein natural gas performed relatively better than crude oil. In May 2009 the relationship reverted back to one marked by relatively better performance by crude oil.
- We have found evidence that the long-term relationship between natural gas and oil is stronger than a one-state model would predict. Moreover, the relationship spans broader and more varied sample periods.

Conclusion: Practitioner Takeaway

Models of the relative pricing of natural gas and crude oil should be conditioned on state probability.

Further Work/Improvements

- The determinants of regime switching, i.e. allowing time-varying transition probabilities.
- Suggestions?

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