Shale Gas and the Relationship between the U.S. Natural Gas, Liquefied Petroleum Gases and Oil Markets[1]

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Abstract

Natural gas liquids and liquefied petroleum gases have played an important role in the current US shale gas boom. Depressed gas prices in recent years have made pure natural gas operations less profitable. The result is that liquids components in gas production have become increasingly important in ensuring the profitability of shale gas operations. In this paper we investigate whether the shale gas expansion, which has led to an increase in associated LPG production, has also affected the historically strong relationship between LPG and oil prices. Revealing the strength and stability of the LPG/oil relationship is relevant when it comes to the future profitability and development of the U.S. natural gas sector. Our results suggest that the LPG/oil relationship has weakened in recent years with a move towards cheaper liquids relative to oil. This is consistent with developments in the gas sector with increased liquids production. A consequence is that U.S. natural gas operations cannot automatically rely on high liquids prices to ensure profitability.

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1. Introduction

The US natural gas market has changed dramatically in recent years. The shale-gas boom has increased domestic natural gas production to the degree that only minimal LNG imports might be required to meet domestic demand in the future. After George P. Michell's pioneering work for one and a half decade, the use of hydraulic fracking had a commercial breakthrough in the late 1990s in the Barnet Shale. Devon Energy took this breakthrough further when they combined the use of hydraulic fracking with horizontal drilling in 2003 (Yergin, 2011). This combined development allowed the recovery of shale gas at significantly reduced costs. This has led to an influx of so called unconventional gas on the domestic market. In lack of sufficient export capacity this additional supply has depressed US natural gas prices substantially relative to pre shale-gas levels.

Prior to the shale-gas boom US oil and natural gas prices where integrated (Bachmeier and Griffin, 2006; Villar and Joutz, 2006; Neumann, 2009; Erdős, 2012), even though the relationship was weak and a significant share of natural gas prices was unaccounted for by the oil prices (Parsons and Ramberg, 2012). The integration of US oil and natural gas markets was established through intercontinental gas-to-gas competition (Neumann, 2009) and domestic inter-fuel substitution.[2] In the Manufacturing Energy Consumption Survey for 2002, the US Energy Information Administration pointed out that "many manufacturers have the ability to substitute the consumption of one fuel for that of another when the economic conditions call for making such a change" (Villar and Joutz, 2006). The heavily oil indexed European and Asian gas market (Asche et al., 2002; Asche et al., 2006; Siliverstovs et al., 2005) ensured that US natural gas was integrated with global oil price as long as intercontinental arbitrage lead to sufficient gas-to-gas competition. This arbitrage relationship is contingent on sufficient gas transport capacity between regions. Expecting increased US need for imports, LNG gasification capacity was substantially increased. However, with the shale-gas boom the global gas trade flow changed unexpectedly. In lack of gas export facilities intercontinental gas competition towards the US

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[2] Hartley et al. (2008) find evidence that the link between natural gas and crude oil prices is indirect, acting through competition at the margin between natural gas and residual fuel oil.

broke down. Consequently, US natural gas is no longer integrated with US oil prices (Erdős, 2012).[3]

Much focus in the literature has been directed towards examining the relationship between oil and natural gas markets. Less focus has been directed towards other important petroleum products and their relationship with oil and natural gas markets. Westgaard et al. (2008) and Myklebust et al. (2010) examine the price dynamics of propane, butane and naphtha traded in the north European market. They find that prices contain a random walk component making price predictions challenging. In light of discussions of the relationship between oil and natural gas markets it seems relevant to consider the role of other petroleum markets which are related to both the oil and natural gas markets. One such market segment is Liquefied Petroleum Gases (LPG). LPGs such as propane and butane are related to oil and natural gas both on the demand side (through its use for fuel and heating) and the supply side (production comes from both natural gas liquids processing and crude oil refining). It is reasonable to assume that the state of the liquids markets can affect the relative prices of oil and natural gas. High liquids prices, due to for example high oil prices, might increase gas production and hence depress gas prices (because of the associated gas in natural gas liquids processing). This implies that the relationship between oil and natural gas does not only depend on direct inter-fuel substitution or gas-to-gas competition but also the state of the liquids markets.

In this paper we investigate the relationship between LPG (as measured by propane and butane), oil and natural gas prices is the U.S. Our main research question is whether the shale gas expansion, which has affected the oil/natural gas relationship, has also affected the relationship between LPG and oil prices. Even though the oil price has historically been the main determinant for LPG prices, the new supply of LPG from shale gas operations might have been sufficient to move LPG prices away from oil prices. The shale gas boom provides a natural experiment to evaluate the effects of a significant and persistent supply shock on the historically stable LPG/oil price relationship. This question is of interest not only in terms of establishing the relationship between oil, natural gas and LPG markets, but also in terms of the future

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[3] See also Brown and Yucel (2009).

development of US energy markets. If the LPG markets have remained largely unaffected by the shale gas boom, absorbing most of the supply without affecting long run prices, it is more likely that the low natural gas prices might persist for a significant period. If however the additional supply can affect the LPG/oil relationship it is more likely that natural gas production might decline as future shale gas operations are likely to become less profitable. For gas operations the liquids markets have ensured an exposure to world energy markets in a time where lack of natural gas exports have led to a segmented and depressed U.S. natural gas market. The stability of the liquids markets is therefore important in terms of the need for natural gas exports. A liquids market largely unaffected by the domestic natural gas market will reduce the need for natural gas exports. However, if U.S. liquids markets move in the direction natural gas price has moved this will make additional export capacity more important.

In the next section we discuss the LPG markets and their relationship to natural gas and oil. Following this we investigate the relationship between natural gas and oil prices with a focus on testing for a structural change. Using the date of the oil/natural gas structural change we investigate the full markets, including oil, propane, butane and natural gas, using a generalized cointegrated vector autoregressive model allowing for structural breaks. Testing the stability of the long-run relationships is then done by imposing restrictions on the general model.

2. Liquefied Petroleum Gases

Liquefied Petroleum Gases are light hydrocarbon gases, Propane and Butane. LPG is produced from two industries: natural gas liquids (NGL) processing and crude oil refining. Historically approximately 60% of the LPG production has come from natural gas processing, and 40% from crude oil refining. With reduced LPG production from refineries, about ¾ of LPG production now comes from Natural Gas processing plants. The extracted NGLs from Natural Gas Production has increased from 2,5 bcf/day in 2007 to 3,5 bcf/day in February 2013 (EIA Data). Figure 1 shows the development in U.S. NGL extraction from 1996 to 2012. As the figure shows production has significantly increased following a low in the middle part of the last decade.

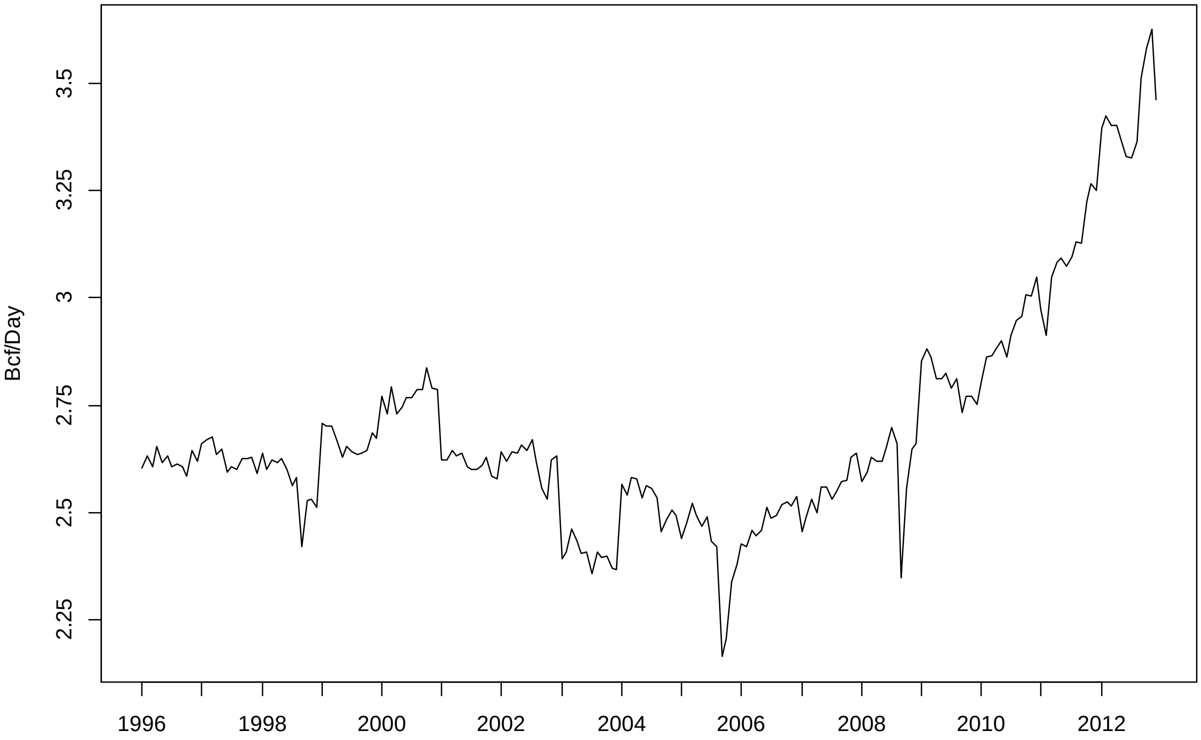

Figure 1. U.S. NGL Extraction (EIA Data)

While propane is used as petrochemical feedstock, fuel and for heating purposes, butane is also used as a blending component for motor gasoline. According to Dow Chemical (2010), 85% of butane in the US was used for gasoline blending in 2008, 5% for chemical feedstock and 5% as fuel. As such, LPG competes to some degree directly with crude oil and other crude oil derivatives (butane), in addition to natural gas for heating (propane); while also to a certain degree being mutual substitutes. While propane has a boiling point at -42 Celsius, butane has a boiling point at 0 Celsius and is less efficient in cold weather as a fuel. As butane is more energy efficient, the use of propane and butane as a fuel depends on the local temperatures.

The LPG markets provide a link between the natural gas and the oil market. Historically, propane and butane prices have been strongly influenced by crude oil prices due to a strong demand side connection. Although the natural gas industry is the major producer of propane and butane, natural gas prices have historically been less informative on LPG prices. Low Natural gas prices make propane less attractive for heating in the residential and commercial sectors. Abundant quatities of ethane from NGL fractionating makes propane less attractive for ethylene production. During 2012 we have also seen that ethane has been rejected and left in the Natural gas stream due to low prices and lack of demand from the petrochemical industry (ethylene cracking) (EIA, 2013). This situation creates a surplus of propane, and we have seen an increase in propane (and propylene) exports from 50.000 barrels/day in 2008 to 170.000 barrels/day in 2012 (EIA Data). At the same time the price of butane has been supported by crude oil and gasoline prices.

The LPGs are a subset of the NGLs. The typical barrel of NGLs consists of 40-45% of ethane, 25-30% propane, 5-10% normal butane, 10% iso-butane and 10-15% natural gasoline. Ethane is used by the petrochemical industry and the output of ethane will typically be dependent on the economics of rejection of the ethane (ethane is kept in gas stream, resulting in less NGLs processed out). Depending on the economics, propane will follow a similar pattern. We have chosen propane as the representative LPG product when it comes to relationship towards natural gas, and butane at the representative LPG product when it comes to crude oil via motor gasoline.

Low natural gas prices have shifted the focus of producers towards “wet” gas areas containing more liquids. The result has been an increase in the supply of liquefied petroleum gases. In their Investor presentation from March 2013, EOG Resources refers to a representative well in the Permian Basin with 1/3 crude oil, 1/3 NGLs and 1/3 natural gas production. Other areas have other ratios between the different hydrocarbons. As such the high liquids prices, connected to the high oil price, have contributed to keeping natural gas prices low. Natural gas prices might drop below marginal production costs as long as associated liquids sufficiently inflate the marginal revenue from the shale gas operations. In the next section we present our LPG prices along with natural gas and oil prices before we continue with the formal analysis of the markets.

3. Data

Our LPG prices will be propane and butane spot prices from the Mont Belvieu, TX, hub. Prices are denoted in UC/Gal. Mont Belvieu is the larger of the two main hubs for natural gas liquids processing, storing and trading in the US, the other being the Conway Hub in Texas. Mont Belvieu is accordingly considered the main NGL hub in the US. It is located close to critical Natural Gas Liquids systems, product distribution pipelines and the Gulf of Mexico petrochemical feedstock market. Our oil price is the crude oil WTI spot Cushing price, measured in dollars per barrel. Considering that the WTI price has shown some idiosyncratic behavior relative to other U.S. oil prices and the Brent price in recent periods[4], we also did the analysis using the Louisiana Light Sweet (LLS) spot price as the oil price. For now, however, the oil price refers to the WTI price. We discuss the results using the LLS oil price in the analysis section. The natural gas price is the Henry Hub spot prices in dollar per MMBTU. Prices were collected from DataStream. All prices are measured weekly from January 1996 to December 2012, totaling 891 observations for each series.

Figure 2 shows all prices on an equivalent energy basis ($/MMbtu). The figure indicates that the propane and butane prices closely track the WTI oil price, with a somewhat larger spread towards the end of the sample. The natural gas price shows an increasing spread relative to oil, with price trends moving in opposite direction after 2008. The changing relationship between oil and natural gas is analyzed in more detail in the next section.

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[4] Büyükşahin et al. (2012).

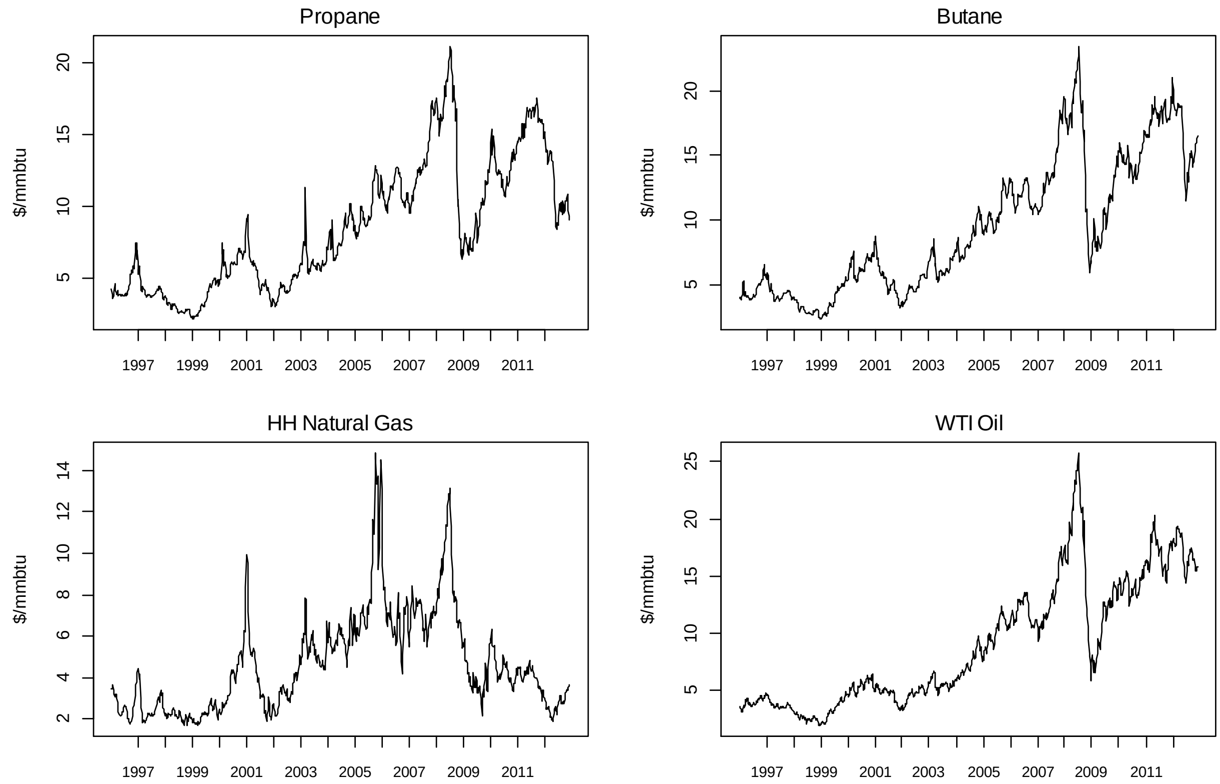

FIGURE 2. Prices of propane, butane, natural gas and oil

The figure indicates strong correlation across the petroleum prices, but with somewhat more idiosyncratic movement towards the end of the sample. Table 1 reports the correlation matrix for two relevant sub-samples, January 1996-December 2008 and January 2009-December 2012. In the first sub-sample correlations were generally high across all products, with natural gas correlation towards oil being the lowest with a correlation of 0.882. After 2008 the correlations decrease across all products, with the decrease being strongest towards the natural gas price. However, the correlation between propane/butane and oil also decreases, with a larger decrease for propane than butane relative to oil.

TABLE 1. Correlations and Unit Root Tests

	Correlation Matrix Jan. 1996 – Dec. 2008			
	Oil	Propane	Butane	Nat.Gas
Oil	1			
Propane	0.978	1		
Butane	0.983	0.994	1	
Nat.Gas	0.882	0.905	0.900	1

	Correlation Matrix Jan. 2009 – Dec. 2012			
	Oil	Propane	Butane	Nat.Gas
Oil	1			
Propane	0.739	1		
Butane	0.905	0.894	1	
Nat.Gas	-0.336	0.149	-0.155	1

	Tests on Price Levels					*Tests on 1^{st} Differences*				
	ADF		KPSS			ADF		KPSS		
	Const.	Trend	Const.	Trend	RUR	Const.	Trend	Const.	Trend	RUR
Propane	-1.86	-2.79	11.64**	0.61**	2,04	-11.71**	-12.08**	0,06	0,05	0.33**
Butane	-1.43	-3.16	12.52**	0.48**	2,34	-12.36**	-12.35**	0,03	0,03	0.30**
Nat. Gas.	-2.35	-2.38	5.17**	2.10**	1,40	-14.25**	-14.25**	0,04	0,03	0.40**
Oil	-1.30	-3.37	13.21**	0.61**	3,18	-8.427**	-8.422**	0,04	0,04	0.56**

Note: ADF test is the augmented dickey fuller test with constant and trend for the null of unit-root. KPSS test has the null of stationarity. RUR is the Range unit root test for the null of a unit-root. All lags are chosen using the Akaike Information Criteria

Table 1 also reports unit-root tests for the log of price levels and log first differences of prices. The parametric tests (Augmented Dickey Fulle rand KPSS tests) include both a constant and a constant and linear trend to account for a trend stationary alternative. The unit-root null of the ADF test is not rejected for all price levels, but is rejected for first differences. The KPSS test (Kwiatkowski et al., 1992) has a null of a stationarity. Consistent with the ADF tests, stationarity is rejected for price levels but not for first differences. In addition to the parametric tests we use a non-parametric test with a null of a unit-root. This is the Range Unit Root test of (Aparicio et al., 2006). The RUR test is robust against non-linearities, error-distributions, structural breaks and outliers. The RUR test confirms the result of the ADF and KPSS tests. We conclude that all series are integrated of order one.

TABLE 2. Cointegration Tests

	Rank	Trace Test	p-value	Max Test	p-value	Trend Specification:
Propane/Butane	0	34,04	0.003**	24,48	0.006**	Restricted Trend
	1	9,56	0.152	9,56	0.151	
Propane/Nat.Gas	0	21.06	0.179	11.76	0.450	No Trend
	1	9.30	0.167	9.30	0.167	
Propane/Oil	0	36,13	0.001**	27,59	0.002**	Restricted Trend
	1	8,54	0.217	8,54	0.217	
Butane/Nat.Gas	0	10,91	0.558	8,07	0.550	No Trend
	1	2,84	0.617	2,84	0.616	
Butane/Oil	0	28,85	0.002**	26,85	0.000**	No Trend
	1	2	0.775	2	0.774	

Nat.Gas/Oil	0	22.31	0.131	16.99	0.108	Restricted Trend
	1	5.32	0.560	5.32	0.561	

Note: Bi-variate cointegration tests using the Trace and Max. eigenvalue statistics. Trend specification based on testing a trend exclusion restriction in the cointegration(Wald test) relationship. Lag length of VAR chosen by minimizing the Akaike Information Criteria.

To examine the degree of cointegration between prices we perform bivariate cointegration rank tests across the full sample (Johansen, 1988). Results are reported in table 2. The cointegration rank analysis indicates that propane/butane and oil are cointegrated, sharing a stochastic trend across the full sample. We find no evidence for cointegration towards natural gas across the full sample. In the next section we analyse the relationship between oil and natural gas in more detail, with focus on dating the suggested regime change in the relationship between the variables.

4. The Changing Relationship between Natural Gas and Oil

As was discussed by Erdős (2012) oil and natural gas in the US separated towards the end of 2008. Erdős establishes this by splitting the sample in December 2008 and performing cointegration tests on the sub samples. As is well known the over-supply of shale gas in combination with lack of export capacity has led to persistently low and declining natural gas prices. The over-supply of tight oil from the Bakken play, continued increase of crude oil imports from Canada, and increased US other inland liquids production in combination with the lack of export capacity to the US Gulf Coast, has consequently led to persistently low and declining WTI prices since 2011. Despite this development of WTI, US natural gas prices and WTI are still not cointegrated. In the same period the global oil price has followed an increasing trend, with the US Gulf crude Light Louisiana Sweet (LLS) being linked to Brent as the global reference crude. Energy substitution domestically has not been sufficient to absorb the excess gas, and export possibilities towards the European and Asian gas markets have been insufficient to establish a link towards the global oil price through the oil indexed European and Asian gas markets (Neumann, 2009).

To our knowledge no formal structural change tests has been performed in the literature to formally examine and date the break between natural gas and oil markets the U.S. In recent years several tests for cointegration with structural breaks have been developed (Arai and Kurozumi, 2007; Lutkepohl et al., 2004; Trenkler et al., 2007; Carrion-i-Silvestre and Sanso, 2006; Davidson and Monticini, 2010; Maki, 2012). What differentiates most of the tests is the null hypothesis. The residual based test of Gregory and Hansen (1996) has the null of no cointegration against the alternative of cointegration with a structural break. Fewer tests exist with the reversed null of cointegration with structural break against the alternative of no cointegration. One such test was developed by Arai and Kurozumi (2007). We consider both of these tests in examining the natural-gas/oil relationship. We consider two structural break models[5]:

$$p_{gas,t} = \mu_1 + \mu_2 \varphi_{tT_B} + \alpha t + \beta p_{oil,t} + e_t, \qquad \text{(Level shift with trend Model)}$$

$$p_{gas,t} = \mu_1 + \mu_2 \varphi_{tT_B} + \beta_1 p_{oil,t} + \beta_2 p_{oil,t} \varphi_{tT_B} + e_t, \qquad \text{(Regime Shift Model)}$$

where $\varphi_{tT_B} = 1\{t > T_B\}$ is the indicator function dating the break. In addition to having different nulls, the Gregory and Hansen (1996) and Arai and Kurozumi (2007) tests differ in the use of test statistics to date the break. The Gregory and Hansen (1996) test evaluates the ADF t-statistics and the Z_α and Z_t statistics of Phillips (1987) on the sample residuals of the above models. The specific break date is chosen by minimizing the statistics over feasible values of T_B. A trimming parameter is chose to avoid too few parameters in either regime. The Arai and Kurozumi (2007) test statistics is the cumulative sum of squared residuals from the regression weighted by a consistent estimator of the long-run residual variance. To avoid endogeneity issues (e_t being correlated with leads and lags of the oil price), leads and lags of the first difference of the oil price up to a truncation lag is added to the regression models (Saikkonen,

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[5] We consider a discrete regime shift . One might argue that the shift has been smooth, in which case our approach will be an approximation to the smooth shift.

1991). We use a truncation lag of 10 weeks. Several methods exist to consistently estimate the long-run residual variance. In accordance with Arai and Kurozumi (2007) we us a semi-parametric estimator applying the Bartlett-kernel. The kernel requires a bandwidth parameter. We consider two bandwidths, 12 and 24 (see equation 13 in Arai and Kurozumi (2007) for the specific estimator). The break date is chosen by minimizing the sum of squared residuals (SSR) over all allowable break dates.

Figure 3 shows the SSR and ADF t-statistics over all allowable break dates using the full regime shift model (we use a trimming of 0.15). As the figure show there is a strong signal in the data that a break occurs around the end of 2008/start of 2009.

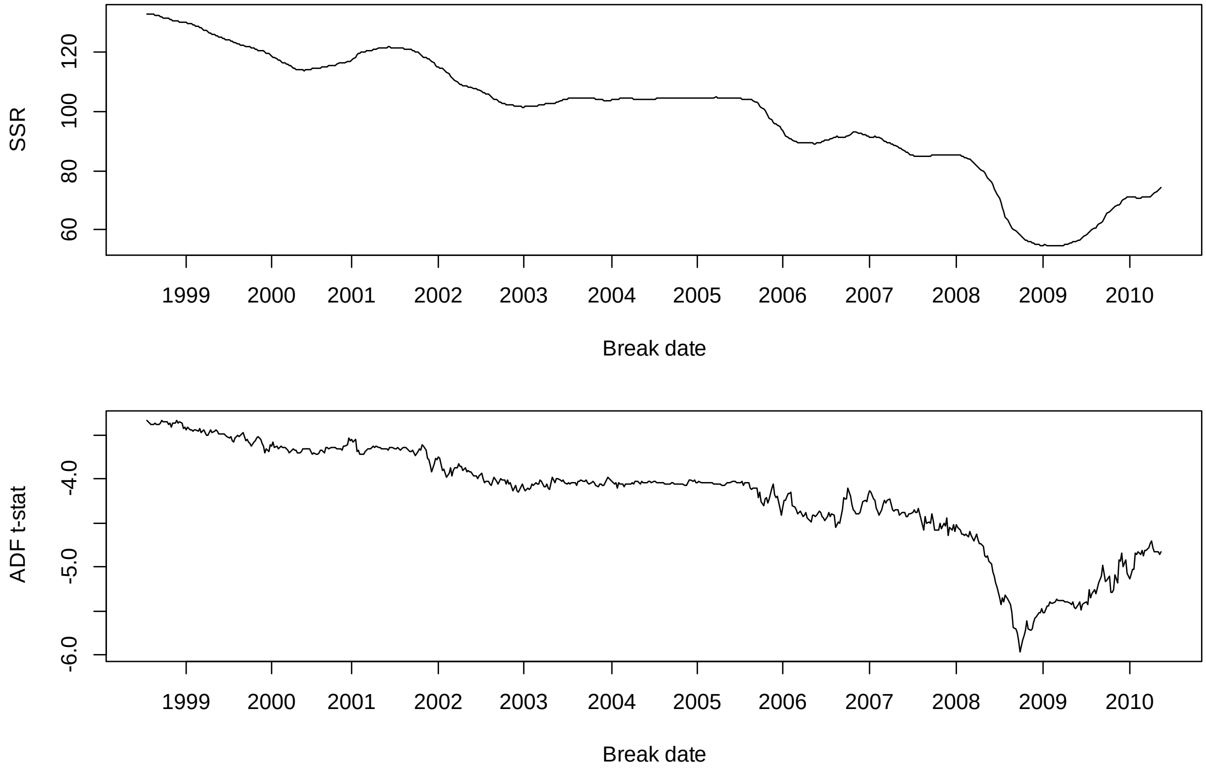


FIGURE 3. SSR and ADF t-statistic for different break dates

Table 3 reports the Gregory and Hansen (1996) and Arai and Kurozumi (2007) test statistic for the test of cointegration with a structural break. Despite the strong signal in the data for a break, the test statistics are inconclusive. The Gregory and Hansen (1996) test rejects no-cointegration in favor of cointegration with a structural break for all statistics considered. However, the Arai and Kurozumi (2007) test statistics tend to reject the null of cointegration with a structural break in favor of no cointegration (although the rejection here is weaker than for the Gregory and Hansen (1996) test). A likely reason for this inconsistency is that none of the tests has the correct null or alternative hypothesis. As indicated, the relationship between natural gas and oil seems to turn from cointegration to no-cointegration. None of the tests have established power against the alternative of structural change with a change in the cointegration rank.

TABLE 3. Structural Change tests on the oil/natural gas cointegration relationship

Gregory and Hansen (1996) *test:* H_0: No cointegration, H_A: Cointegration with structural break

Regime Shift				*Level Shift with trend: Model:*			
Break-point:	ADF stat.	Z_t stat.	Z_a stat.	Break-point:	ADF stat.	Z_t stat.	Z_a stat.
Week 41,2008	-5.962**	-5.255*	-53.580*	Week 19,2009	-5.563**	5.024*	-49.03*

Arai and Kurozumi (2007) test: H0: Cointegration with structural break, HA: No cointegration

Regime Shift:			*Level Shift with trend:*		
Break-point:	B.W.=12	B.W.=24	Break-point:	B.W.=12	B.W.=24
Week 3, 2009	0.2332*	0.174	Week 12,2009	0.1914**	0.151**

Note: ** rejection at 1%, * rejection at 5%. For the Hansen (2003)test break points found by minimizing the ADF t-statistic. For the Arai and Kurozumi (2007) test break-points found by minimizing SSR. B.W.= 12(24) refers to the test statistic with a 12(24) lag cut-off in the Bartlett kernel used for the long-run variance estimator. Trimming parameter is 0.15 for all tests.

Although these tests are inconclusive, the test statistics (figure 3) show a strong signal for a change in the relationship between natural gas and oil towards the end of 2008. Splitting the sample in December 2008 we perform cointegration tests on each sub-sample. Results are reported in table 4.

TABLE 4. Sub-sample cointegration tests of oil vs. natural gas

Sub-sample: January 1996 – December 2008

Johansen test:					*Residual based tests:*		
Rank	Trace test	p-value	Max test	p-value	ADF	Z_t	Z_a
0	19.93	0.054	17.8	0.022*	-4.865**	-5.033**	-37.015**
1	2.13	0.75	2.13	0.749			

Sub-sample: January 2009 – December 2012

Johansen test:					*Residual based tests:*		
Rank	Trace test	p-value	Max test	p-value	ADF	Z_t	Z_a
0	17.28	0.402	12.5	0.383	-2.4878	-2.7568	-2.256
1	4.78	0.633	4.78	0.635			

Note: ** rejection at 1%, * rejection at 5%.

Both the Johansen rank test and residual based tests indicate that the markets were integrated up to December 2008 and not integrated from January 2009 to December 2012. This is the same result established by Erdős (2012), however, with one more year of data (Erdős sample ended in December 2011) and is consistent with previous research.

This section formally confirms the strong signal in the data that the relationship between oil and natural gas changed towards the end of 2008. As stated, the change is due to the shale gas revolution significantly affecting the domestic natural gas supply. Given the strong signal for a change, the date provides a suitable timing to split sample in order to examine whether the relationship between liquefied petroleum gases and il has changed.

5. Testing for Changes in LPG and Oil markets

Given the change in the relationship between natural gas and oil we now turn to examine whether the LPG markets, and their relationship to oil, has also changed in this period. Our method of analysis will be a generalized cointegrated vector autoregressive model for the oil, propane, butane and natural-gas prices. The generalized model allows for structural changes in the adjustment matrix and cointegration vectors. The generalized cointegrated vector autoregressive model was first discussed and analyzed by Hansen (2003). Hansen (2003) establishes a new estimation technique which allows for likelihood ratio tests for different structural forms of the model. The benefit for our application is that we can formally test whether and how the long-run connections between markets changed following December 2008. The general model considered in our analysis can be written as

$$\Delta X_t = a_0 + \alpha(t)\beta(t)'X_{t-1}^* + \sum_{i=1}^{p} \Gamma_i \Delta X_t + \varepsilon_t, \qquad (1)$$

where $X_t = [p_{oil,t}, p_{propane,t}, p_{butane,t}, p_{gas,t}]'$ is a vector containing the log of prices at time t. Furthermore a_0 is a $[4 \times 1]$ vector of constants, Γ_i is a $[4 \times 4]$ matrix of parameters guiding the short-run dynamics and $\{\varepsilon_t\}$ is a sequence of independent Gaussian variables with mean zero and covariance Ω. X_t^* is equal to X_t augmented by a one and a linear trend term at the end to allow for a constant and trend in the cointegration relationships. The long run relationships are modeled by the piecewise constant matrix $\alpha(t)\beta(t)'$, where $\alpha(t)\beta(t)' = \alpha_1\beta_1'\varphi_{tT_B} + (1 - \varphi_{tT_B})\alpha_2\beta_2'$ and φ_{tT_B} is equal to one for $t \leq T_b$ and zero else. T_b is our break time set to the last week of December 2008. To be consistent with the above analysis, where results indicate that oil and natural gas are not cointegrated in the second regime, the rank of $\alpha_1\beta_1'$ is 3 while the rank of $\alpha_2\beta_2'$ is 2. Subsequently α_1 is a $[4 \times 3]$ matrix containing the adjustment parameters for regime 1 (prior to January 2009) and β_1 is the normalized $[6 \times 3]$ matrix containing the three cointegration relationships in this regime. Equivalently α_2 is a $[4 \times 2]$ matrix containing the adjustment parameters for regime 2 (after December 2008) and β_2 the $[6 \times 2]$ matrix containing the cointegration vectors in regime 2. We normalize the cointegration vectors relative to oil

$$\beta_1 = \begin{bmatrix} 1 & 1 & 1 \\ \beta_{1,propane} & 0 & 0 \\ 0 & \beta_{1,butane} & 0 \\ 0 & 0 & \beta_{1,nat.gas} \\ c_{1,propane} & c_{1,butane} & c_{1,nat.gas} \\ \tau_{1,propane} & \tau_{1,butane} & \tau_{1,nat.gas} \end{bmatrix} \text{ and } \beta_2 = \begin{bmatrix} 1 & 1 \\ \beta_{2,propane} & 0 \\ 0 & \beta_{2,butane} \\ 0 & 0 \\ c_{2,propane} & c_{2,butane} \\ \tau_{2,propane} & \tau_{2,butane} \end{bmatrix}. \qquad (2)$$

In equation (2) the last two rows refer to the constant and trend coefficients in each relationship. The trends and the exclusion of natural gas in regime 2 will later be tested formally. In our hypothesis testing we test different restrictions on the adjustment matrixes and cointegration vectors. To achieve this we follow (Hansen, 2003) and define the joint regime parameters $A = (\alpha_1, \alpha_2)$ and $B = (\beta_1, \beta_2)$, where A contains 24 parameters and B 15 free parameters in the unrestricted model. Restrictions on adjustments A can be imposed by defining a $[24 \times p_\psi]$ matrix G, where p_ψ is the number of free adjustment parameters collected in a vector ψ, satisfying $\mathrm{vec}(\mathrm{A}) = \mathrm{G}\psi$. Restrictions on the cointegration vectors can be imposed equivalently by defining a $[30 \times \mathrm{p}_{\phi}]$ matrix H, where p_{ϕ} is the number of free parameters collected in a vector ϕ, satisfying $\mathrm{vec}(\mathrm{B}) = \mathrm{H}\phi + \mathrm{h}$. Here h is a known $[30 \times 1]$ vector used to normalize/identify the parameters in A and B. Formulating appropriate restrictions, the model can be estimated.

5.1. Estimation and Testing procedure

The unrestricted model can be estimated by reduced rank regression techniques. Reduced rank regression was applied to the cointegration framework by Johansen (1988). The reduced rank regression however is not applicable when linear restrictions are imposed on $vec(A)$ and $vec(B)$. To estimate the model with linear restrictions, Hansen (2003) develops a Generalized Reduced Rank regression procedure. The Generalized Reduced Rank regression is related to the switching algorithm of Boswijk (1995) and the minimum distance estimator of Elliott (2000).

Collecting all parameters except the ones related to the adjustments (ψ) and cointegration relationships (ϕ) in the vector θ, the estimation procedure consists of switching between estimating ψ, ϕ and θ in an iterative procedure. Conditional on the other parameter vectors, estimating the individual vectors reduces to a Generalized Least Squares problem. For the specific analytical form of the individual vector estimators, see Hansen (2003). Convergence of the procedure is evaluated by the likelihood function. Each iteration will increase the value of the likelihood and since the likelihood is bounded by its global maximum, the procedure converges to the maximum likelihood given by $\left(\hat{\psi}, \hat{\phi}, \hat{\theta}\ \right) = (2\pi e)^{-\frac{Tp}{2}} \left|\hat{\Omega}\right|^{-\frac{T}{2}}$. Under conventional assumptions on H, G and the parameter vectors, the maximum likelihood estimators are consistent for the true parameters. In addition, $\hat{\psi}$ is asymptotically Guassian and $\hat{\phi}$ asymptotically mixed Gaussian.

Even though the Generalized Reduced Rank estimator in theory converges to a global maximum, in practice there is a concern that the procedure will settle at a local maximum. This implies that special care should be taken in defining the initial values for the iterative procedure. To address this we anchor our initial values to the standard linear cointegration model. The idea here is that the standard linear cointegration estimator is presumably less likely to end up at a local maximum, and given the structural change maximum likelihood is not too far from the standard linear approximation, this should provide good starting values for the Generalized Reduced Rank regression.

We want to test different structures of the cointegration model to examine if and how the relationship between markets have changed since 2008. Testing is done using conventional likelihood ratio statistics. Relevant to this Hansen (2003) establishes that for two models M_1 and M_0, where M_1 is nested in M_0 with q fewer parameters, the asymptotic distribution of the likelihood ratio test of M_1 against M_0 is χ^2 with q degrees of freedom.

5.2. Testing for General Structural Change

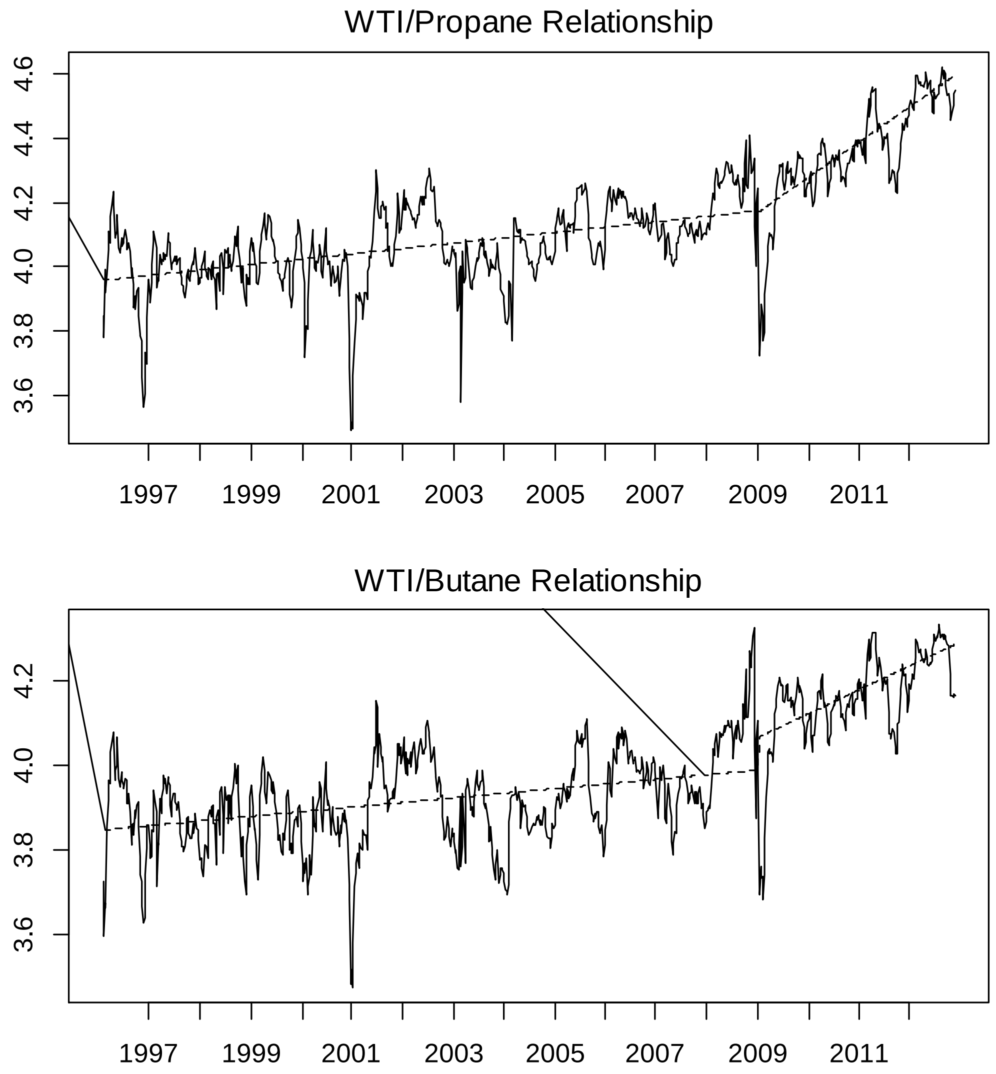
We start the testing procedure by considering four nested models. Our benchmark model is the most general structural change model, equation (1), where both the adjustment matrix and cointegration relationships are allowed to change across regimes. Next we consider one model where only the adjustments to the long-run equilibriums are allowed to change, and one model where only the cointegration relationships are allowed to change. Finally we consider the model without any structural change. Lag length for the short-run dynamics is chosen according to the Akaike Information Criteria. Table 5 reports the Likelihood ratios for each model against the full structural change model.

TABLE 5. Testing against General Structural Change Cointegration Model

	Log-Likelihood	Distribution	Likelihood-Ratio[1]	p-value[2]
M_1: Full Structural Change Model	6270,0		-	
M_2: Only Adjustment Matrix Change	6261.2	$\chi^2(6)$	17,6	0.007
M_3: Only Cointegration Vectors Change	6259.2	$\chi^2(8)$	21,6	0.000
M_4: No Structural Change	6227.6	$\chi^2(14)$	63,2	0.000

Note: [1,2] Tested against the general model M_1.

As the tests show, we cannot reject the full structural change model relative to any of the alternative models, including the model with no structural change. This provides evidence against a hypothesis of constant adjustments or cointegration relationships across the two periods. As such the result is consistent with the change in the relationship between oil and natural gas in the same period.



Note: Dotted lines show equilibrium for each relationship across regimes. Calculated using general model M_1.

Figure 3. Cointegration Errors across regimes

To illustrate the the long-run relationships we plot the cointegration errors (solid lines) along with the long-run equilibrium relationships (dotted lines) for WTI relative to propane and butane in figure 3. The cointegration relationships are derived using the full structural change model. We observe that following the break, the oil price starts increasing significantly relative to both the propane and butane price. This is consistent with the influx of natural gas liquids from gas operations depressing the relative value of liquids relative to oil. Like for natural gas, energy substitution between oil and propane/butane does not appear to have been sufficient to absorb the excess supply. We now turn to examining the nature of this break in more detail, starting with the cointegration vectors.

5.3. Testing Restrictions on the Cointegration Vectors

Several hypotheses are of interest regarding the change in the long-run relationships. Before imposing restriction we show the unrestricted long-run relationships implied by the full structural change model (M_1):

Cointegration Relationships First Regime:

$$p_{oil,t} = 3.958 + 0.993 p_{propane,t} + 0.00032t$$

$$p_{oil,t} = 3.846 + 1.025 p_{butane,t} + 0.00021t$$

$$p_{oil,t} = 1.674 + 1.495 p_{nat.gas,t} - 0.00093t$$

Cointegration Relationships Last Regime:

$$p_{oil,t} = 4.170 + 0.404 p_{propane,t} + 0.0021t$$

$$p_{oil,t} = 4.065 + 0.6025 p_{butane,t} + 0.0011t$$

A first glance suggests that the relationship between butane/propane and oil has weakened, and that oil has become more expensive relative to liquids. Notice that natural gas does not appear at all in the last regime. It could be that natural gas has had a relationship with oil through the oil/liquids relationships. The test of excluding natural gas in the last regime gives a p-value of 0.467. Although not present in the long-run relationships, natural gas is still allowed to respond to equilibrium errors.

We test whether the Law of One Price (LOP) holds in either regime. The LOP in our setup implies that the coefficient of a price relative to oil is equal to one, which means that the price moves proportional to oil. In economic terms this suggests that the commodities are strong substitutes. The models where the LOP restrictions are imposed are referred to as models $M_{1,\beta}$ to $M_{5,\beta}$.

Another hypothesis of interest is whether propane and butane have become cheaper relative to oil over time. Certainly this seems to be the case in later years, but might have started earlier as suggested by figure 3. We investigate this by testing whether we can exclude the trend term from the cointegration relationships. These models are referred to model $M_{6,\beta}$ to $M_{10,\beta}$ in table 6. In table 6, First Regime refers to the period January 1996 to December 2008, and Last Regime refers to January 2009 to December 2012.

TABLE 6. Testing Restrictions on Cointegration Vectors

	Log-Likelihood	Distribution	Likelihood-Ratio[1]	p-value[2]
$M_{1,\beta}$: LOP. Propane with Oil (First Regime)	6270.0	$\chi^2(1)$	0.0	0.999
$M_{2,\beta}$: LOP. Propane with Oil (Last Regime)	6265.1	$\chi^2(1)$	9.8	0.002
$M_{3,\beta}$: LOP. Butane with Oil (First Regime)	6269.9	$\chi^2(1)$	0.2	0.655
$M_{4\,\beta}$: LOP. Butane with Oil (Last Regime)	6268.2	$\chi^2(1)$	3.6	0.058
$M_{5,\beta}$: LOP. Nat.Gas. with Oil (First Regime)	6269.1	$\chi^2(1)$	1.8	0.180
$M_{6,\beta}$: Exclude Trend Prop./Oil (First Regime)	6268.5	$\chi^2(1)$	3.0	0.083
$M_{7,\beta}$: Exclude Trend Prop./Oil (Last Regime)	6268.1	$\chi^2(1)$	3.7	0.054
$M_{8,\beta}$: Exclude Trend But./Oil (First Regime)	6269.1	$\chi^2(1)$	1.8	0.180
$M_{9\,\beta}$: Exclude Trend But./Oil (Last Regime)	6269.1	$\chi^2(1)$	1.8	0.182
$M_{10,\beta}$: Exclude Trend Nat. Gas./Oil (First Regime)	6269.5	$\chi^2(1)$	0.9	0.332

Note: [1,2] Tested against the general model M_1.

Looking at the first regime there is strong support for the LOP holding for both propane and butane relative to oil. This suggests proportional price movements prior to 2009. Interestingly the p-value for imposing the LOP on natural gas relative to oil is 0.18, meaning that even natural gas and oil can be modeled as having proportional movements in the first regime. In the last regime (after 2009) we reject the LOP for both propane and butane prices, with strongest rejection for propane.

In terms of the trend we find strongest support for a trend in the relationship between propane and oil. This is especially true for the last regime where propane has become significantly cheaper relative to oil. For butane we find less support for a trend component, the same is true for natural gas. In relation to WTI is seems that propane has changed more than butane. This is reasonable considering the stronger demand side substitution relationship between butane and oil. Propane has a stronger link to natural gas and does appear to have adjusted more to the changes in the natural gas market.

5.4. Testing Restrictions on the Adjustment Matrix

Restrictions on the adjustment matrixes are of interest to investigate changes in how prices respond to equilibrium errors. As the tests above suggest, there is little evidence for constant cointegration relationships or adjustments across the two sample periods considered. We consider long-run weak exogeneity tests for each product across regimes. Long-run weak exogeneity here implies that the price does not adjust to deviations from a cointegration relationship. In addition we consider the adjustment of single prices to single cointegration errors. The weak exogeneity tests are reported in table 7.

TABLE 7. Tests on Long-run Weak Exogeneity

	Log-Likelihood	Distribution	Likelihood-Ratio[1]	p-value[2]
$M_{1,a}$: Oil Exogenous (First Regime)	6264.0	$\chi^2(3)$	12.0	0.007
$M_{2,a}$: Oil Exogenous (Last Regime)	6266.3	$\chi^2(2)$	7.4	0.025
$M_{3,a}$: Propane Exogenous (First Regime)	6254.2	$\chi^2(3)$	31.6	0.000
$M_{4,a}$: Propane Exogenous (Last Regime)	6267.7	$\chi^2(2)$	4.6	0.100
$M_{5,a}$: Butane Exogenous (First Regime)	6263.7	$\chi^2(3)$	12.6	0.006
$M_{6,a}$: Butane Exogenous (Last Regime)	6263.8	$\chi^2(2)$	12.4	0.002
$M_{7,a}$: Natural Gas Exogenous (First Regime)	6269.4	$\chi^2(3)$	14.8	0.002
$M_{8,a}$: Natural Gas Exogenous (Last Regime)	6261.9	$\chi^2(2)$	1.2	0.549

Note: [1,2] Tested against the general model M_1.

None of the prices satisfy the long-run weak exogeneity restricions across both regimes. Natural gas is weakly exogenous in the last regime, as is reasonable considering the idiosyncratic movements in gas prices. Propane adjusts strongly in the first regime, but much less so in the last regime. Both oil and butane prices adjust to cointegration errors in both regimes.

Table 7 shows the full adjustments for each price to the cointegration errors. The table also reports the p-values (in brackets) from imposing the restriction that the adjustment is zero.

TABLE 8. Tests on Single Equations Response to Equilibrium Errors

	Oil Price Adjusts	Propane Price Adjusts	Butane Price Adjusts	Nat. Gas Price Adjusts
Oil/Propane Eq. Error (First Regime)	0.016 [0.655]	0.225 [0.000]	-0.019 [0.527]	0.021 [0.655]
Oil/Butane Eq. Error (First Regime)	-0.083 [0.032]	-0.155 [0.000]	0.089 [0.020]	-0.070 [0.237]
Oil/Nat.Gas Eq. Error (First Regime)	0.002 [0.655]	-0.008 [0.273]	-0.006 [0.317]	0.036 [0.000]
Oil/Propane Eq. Error (Last Regime)	-0.223 [0.028]	-0.219 [0.058]	-0.350 [0.001]	0.031 [1.000]
Oil/Butane Eq. Error (Last Regime)	0.179 [0.107]	0.297 [0.032]	0.408 [0.001]	0.026 [1.000]

The single responses give some insight into how individual price adjustments have changed. For the oil/propane relationship in the first regime it is only propane that adjusts to equilibrium errors. Positive deviations from the equilibrium relationship lead to increasing propane prices. For the oil/butane relationship in the first regime all prices except natural gas adjust. Positive deviations between oil and butane means declining oil and propane prices and increasing butane prices. In the natural gas/oil relationship it is only natural gas prices that adjust. In the last regime adjustments change drastically. For the oil/propane relationship all prices but natural gas adjusts. In addition all prices adjust in the same direction. This highlights the deviating prices in this period. A positive deviation in the oil/propane relationship leads to falling propane/butane prices (thus increasing the spread) but with oil prices falling to close the gap. This might suggest that the WTI price has also adjusted to recent market changes. Declining liquids prices are associated with a declining WTI oil price. In the oil/butane relationship in the last regime, oil price does not adjust significantly. In this case a positive deviation between the oil and butane prices are associated with increasing butane and propane prices. This could be related to the substitution relationship between butane/propane and oil putting upward pressure on liquids prices in light of higher WTI prices.

To summarize our main findings in this section, we find that following the change in the relationship between natural gas and oil, dated to the end of 2008, we fail to reject the hypothesis that the relationship between propane/butane and oil prices has remained unaffected by the recent changes in the US energy markets. Barring other factors affecting the liquids and oil relationship, this suggests that the shale gas expansion and its associated increasing liquids production have affected the relationship between liquids and oil. We find that propane and butane have become cheaper relative to oil and that the historically strong link between propane/butane and oil has weakened. This is especially true for propane which has a closer connection with natural gas. It would seem that the oil/liquids substitution relationship is not sufficient to fully absorb the increased liquids supply without significantly affecting price relationships. We also find indications that that the changes in liquids markets have affected the WTI oil price with the oil price being pulled down by the declining liquids prices.

This result has important implications regarding future profitability of shale-gas operations. At the current regime shale gas operators cannot rely on consistently high liquids prices to compensate for low natural-gas prices. The liquids and oil markets have not been able to fully absorb the excess liquids from shale gas. As the market moves towards a new equilibrium we would expect a reduction in natural gas production due to lower liquids prices. Unless liquids prices pick up as substitution is allowed to take effect this suggests a normalization of the US natural gas market in the future. If export of natural gas picks up, the Atlantic and Pacific arbitrage relationship will be reestablished, pushing domestic natural gas prices up. In this case liquids production will become less profitable relatively to gas again and liquids prices might increase back to its historical relationship with oil.

5.5. Robustness and Sensitivity to the WTI Oil Price

The findings in this section might be sensitive to different modeling choices. As is well known in time-series analysis, finite sample test-statistics can be sensitive to lag-orders. Ideally lag-orders should be “integrated” out of the likelihood-ratios. One way to approximate this is to run the analysis using different lags. In our testing procedure the lags of the cointegration model was selected using the Akaike Information Criteria. With this criterion we used four lags for the lagged first differences in the error correction model. We also ran the entire tests in this section using nine lags, as was suggested by a general-to-specific likelihood-ratio selection procedure. This procedure makes no punishment for possible over-specification. The results did not change significantly when changing the lag-order.

Our results might also be sensitive to the choice of oil price. It is well known that the WTI price has changed relative to the Light Louisiana Sweet (LLS) and Brent price.[6] We re-ran the entire analysis using the LLS price instead of WTI. In terms of the structural change between LLS and natural gas, the results do not change significantly when using the LLS price. There is still a strong signal for a structural change towards the end of 2008/beginning of 2009. Overall the results are robust to the choice of oil price benchmark. The general structural change model for example is still preferred over the restricted models with less or no structural change in the long-run relationships. Some changes are however worth to mention. Using the WTI price butane did not change as much as propane relative to the oil price. Butane has changed more relative to LLS than it did to WTI. For example we could not exclude the trend component in the relationship between butane and LLS, which we could do for WTI. In addition there is stronger evidence for LLS being weakly exogenous. LLS does not adjust to deviations between butane and LLS in the first regime. Converstly, WTI did adjust to butane/WTI deviations in the first regime. For the last regime the results are similar to the WTI analysis, implying that LLS does respond to differences between propane/LLS, albeit weaker than WTI. Overall the difference between WTI and LLS is that the WTI is appear to have been more responsive to liquids prices.

As described in Section 2, abundant quantities of ethane over the last years has put a pressure on prices so that on average the price of ethane has become lower than Henry Hub gas prices. Lack of take-off of increased ethane production has been the main explanation of this situation, illustrated by the increased rejection of ethane. Lack of markets for ethane in different regions (i.e. the Marcellus) has made it necessary to keep the ethane in the gas flow. Despite increased LPG production, the prices on propane and butane have on the other hand stayed above the price of Henry Hub, although especially butane has been weaker than the WTI crude price. With more liquid and broader markets for LPGs than for ethane, we will expect these prices to be more robust towards increases in production. Also, the market for propane in the North East is to a large extent separated from the natural gas market. On the more rich part of the NGLs, the different naphtha qualities (petrochemical and motor gasoline qualities) have in general experienced higher prices than WTI. With different regional crude prices with different qualities

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[6] Büyükşahin et al. (2012).

and different regional natural gas prices, these differences will vary depending on the regional bottle-necks especially in the transportation system. We have only looked at representative market prices. Differences in the configuration of refineries and their ability to fractionate the lighter products might also explain regional differences, although we have not looked at such potential effects.

6. Conclusion

Low natural US gas prices, due to the shale gas boom, have shifted the focus of producers towards “wet” gas areas containing more liquids. The result has been an increase in the supply of associated liquefied petroleum gases. Thus, the high liquids prices, connected to the high oil price, have contributed to keeping natural gas prices low. A crucial question is whether this trend is sustainable, as an increase in LPG production is likely to put a strain on LPG prices. The shale gas boom provides a natural experiment to evaluate the effect of a significant and persistent supply shock on the historically stable US LPG/oil relationship.

Our basis for examining whether the LPG markets have been affected by the shale gas revolution is a generalized cointegrated vector autoregressive model for oil, propane, butane and natural-gas prices. The generalized model allows for structural changes in the adjustment matrix and cointegration vectors.

We find a structural break in 2009, after which both the propane and butane prices settle at a lower value relative to oil. We find that the relatively strong cointegration relationship between propane/butane and oil prior to January 2009 is significantly weakened in recent years. Whereas the oil price previously has been closely associated with LPG prices, the new supply of LPG from associated shale gas operations appear sufficient to move LPG prices away from the historical long run relationship with oil. Reduced income from liquids may further reduce profitability from shale gas wells, thus pushing upwards pressure on domestic natural gas prices again. A further expansion of greenfield petrochemical plants with increased ethane and propane demand might ease this conversion.

References:

Aparicio, F., A. Escribano, and A.E. Sipols. 2006. "Range Unit-Root (RUR) Tests: Robust against Nonlinearities, Error Distributions, Structural Breaks and Outliers." *Journal of Time Series Analysis* no. 27 (4):545-576.

Arai, Y., and E. Kurozumi. 2007. "Testing for the null hypothesis of cointegration with a structural break." *Econometric Reviews* no. 26 (6):705-739.

Asche, F., P. Osmundsen, and M. Sandsmark. 2006. "The UK market for natural gas, oil and electricity: are the prices decoupled?" *The Energy Journal* no. 27 (2):27-40.

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

Bachmeier, L.J., and J.M. Griffin. 2006. "Testing for market integration: crude oil, coal, and natural gas." *The Energy Journal* no. 27 (2):55-72.

Boswijk, H.P. 1995. "Efficient inference on cointegration parameters in structural error correction models." *Journal of Econometrics* no. 69 (1):133-158.

Brown, S.P.A. and M.K. Yucel. 2009. *Energy Journal* no. 30:167-186.

Büyükşahin, B, Lee, T.K., Moser, J.T. and M.A. Robe. 2012. "Physical Market Conditions, Paper Market Activity, and the WTI-Brent Spread". Working paper, EIA/IEA.

Carrion-i-Silvestre, J., and A. Sanso. 2006. "Testing the Null of Cointegration with Structural Breaks*." *Oxford Bulletin of Economics and Statistics* no. 68 (5):623-646.

Davidson, J., and A. Monticini. 2010. "Tests for cointegration with structural breaks based on subsamples." *Computational statistics \& data analysis* no. 54 (11):2498-2511.

Dow Chemical (2010), Product Safety Assessment: DOW™ Butane.

EIA (2013); http://www.eia.gov/todayinenergy/detail.cfm?id=9590

Elliott, G. 2000. "Estimating restricted cointegrating vectors." *Journal of Business \& Economic Statistics* no. 18 (1):91-99.

Erdős, P. 2012. "Have oil and gas prices got separated?" *Energy Policy*.

Gregory, A.W., and B.E. Hansen. 1996. "Residual-based tests for cointegration in models with regime shifts." *Journal of econometrics* no. 70 (1):99-126.

Hansen, P.R. 2003. "Structural changes in the cointegrated vector autoregressive model." *Journal of Econometrics* no. 114 (2):261-295.

Hartley, P.R., Medlock III, K.B., and J.E. Rosthai. 2008. *Energy Journal* no. 3: 47-66.

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

Kwiatkowski, D., P.C.B. Phillips, P. Schmidt, and Y. Shin. 1992. "Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root?" *Journal of econometrics* no. 54 (1):159-178.

Lutkepohl, H., P. Saikkonen, and C. Trenkler. 2004. "Testing for the cointegrating rank of a VAR process with level shift at unknown time." *Econometrica* no. 72 (2):647-662.

Maki, D. 2012. "Tests for cointegration allowing for an unknown number of breaks." *Economic Modelling*.

Myklebust, J., A. Tomasgard, and Sjur Westgaard. 2010. "Forecasting gas component prices with multivariate structural time series models." *OPEC Energy Review June 2010*:82-106.

Neumann, A. 2009. "Linking Natural Gas Markets-Is LNG Doing its Job?" *The Energy Journal* no. 30 (Special Issue):187-200.

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

Phillips, P.C.B. 1987. "Time series regression with a unit root." *Econometrica: Journal of the Econometric Society*:277-301.

Saikkonen, P. 1991. "Asymptotically efficient estimation of cointegration regressions." *Econometric Theory* no. 7 (1):1-21.

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

Trenkler, C., P. Saikkonen, and L. Helmut. 2007. "Testing for the cointegrating rank of a VAR process with level shift and trend break." *Journal of Time Series Analysis* no. 29 (2):331-358.

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

Westgaard, S., E. Faria, and S.-E. Fleten. 2008. "Price dynamics of natural gas components: empirical evidence." *Journal of Energy Markets* no. 1 (3):37-68.

Yergin, D. 2011. "Stepping on the gas." *The Wall Street Journal, April 2, the Saturday essay*.

APPENDIX. Tables when LLS is used as the Oil price

TABLE 2. Cointegration Tests

	Rank	Trace Test	p-value	Max Test	p-value	Trend Specification:
Propane/Butane	0	34,04**	0.003	24,48**	0.006	Restricted Trend
	1	9,56	0.152	9,56	0.151	
Propane/Nat.Gas	0	21.06	0.179	11.76	0.450	No Trend
	1	9.30	0.167	9.30	0.167	
Propane/Oil	0	28.01*	0.025	19.36*	0.048	Restricted Trend
	1	8.64	0.209	8.64	0.209	
Butane/Nat.Gas	0	10,91	0.558	8,07	0.550	No Trend
	1	2,84	0.617	2,84	0.616	
Butane/Oil	0	33.04**	0.000	31.09**	0.000	No Trend
	1	1.96	0.782	1.96	0.781	
Nat.Gas/Oil	0	20.80	0.191	13.27	0.182	Restricted Trend
	1	7.53	0.301	7.53	0.301	

Note: Bi-variate cointegration tests using the Trace and Max. eigenvalue statistics. Trend specification based on testing a trend exclusion restriction in the cointegration(Wald test) relationship. Lag length of VAR chosen by minimizing the Akaike Information Criteria.

TABLE 3. Structural Change tests on the oil/natural gas cointegration relationship

Gregory and Hansen (1996) *test:* H_0: No cointegration, H_A: Cointegration with structural break

Regime Shift				*Level Shift with trend:* *Model:*			
Break-point:	ADF stat.	Z_t stat.	Z_a stat.	Break-point:	ADF stat.	Z_t stat.	Z_a stat.
Week 38,2008	-5.915**	-5.184*	-52.188*	Week 19,2009	-5.426*	-4.854*	-45.768

Arai and Kurozumi (2007) *test:* H_0: Cointegration with structural break, H_A: No cointegration

Regime Shift:			*Level Shift with trend:*		
Break-point:	B.W.=12	B.W.=24	Break-point:	B.W.=12	B.W.=24
Week 47,2008	0.3308*	0.2164*	Week 1,2009	0.2657**	0.1778**

Note: ** rejection at 1%, * rejection at 5%. For the Hansen (2003)test break points found by minimizing the ADF t-statistic. For the Arai and Kurozumi (2007) test break-points found by minimizing SSR. B.W.= 12(24) refers to the test statistic with a 12(24) lag cut-off in the Bartlett kernel used for the long-run variance estimator. Trimming parameter is 0.15 for all tests.

TABLE 4. Sub-sample cointegration tests of oil vs. natural gas

Sub-sample: January 1996 – December 2008

Johansen test:					*Residual based tests:*		
Rank	Trace test	p-value	Max test	p-value	ADF	Z_t	Z_a
0	30.70**	0.010	22.85*	0.013	-4.752**	-4.433**	-36.42**
1	7.86	0.272	7.86	0.272			

Sub-sample: January 2009 – December 2012

Johansen test:					*Residual based tests:*		
Rank	Trace test	p-value	Max test	p-value	ADF	Z_t	Z_a
0	15.08	0.575	11.25	0.500	-2.850	-3.416*	-20.209
1	3.83	0.764	3.83	0.766			

Note: ** rejection at 1%, * rejection at 5%.

TABLE 5. Testing against General Structural Change Cointegration Model

	Log-Likelihood	Distribution	Likelihood-Ratio[1]	p-value[2]
M_1: Full Structural Change Model	6314.1		-	
M_2: Only Adjustment Matrix Change	6308.0	$\chi^2(6)$	12.2	0.007
M_3: Only Cointegration Vectors Change	6305.3	$\chi^2(8)$	17.6	0.000
M_4: No Structural Change	6275.6	$\chi^2(14)$	59.4	0.000

Note: [1,2] Tested against the general model M_1.

TABLE 6. Testing Restrictions on Cointegration Vectors

	Log-Likelihood	Distribution	Likelihood-Ratio[1]	p-value[2]
$M_{1,\beta}$: LOP. Propane with Oil (First Regime)	6314.1	$\chi^2(1)$	0	1.000
$M_{2,\beta}$: LOP. Propane with Oil (Last Regime)	6310.7	$\chi^2(1)$	6.8	0.009
$M_{3,\beta}$: LOP. Butane with Oil (First Regime)	6313.9	$\chi^2(1)$	0.4	0.527
$M_{4\ \beta}$: LOP. Butane with Oil (Last Regime)	6312.9	$\chi^2(1)$	2.4	0.121
$M_{5,\beta}$: LOP. Nat.Gas. with Oil (First Regime)	6313.2	$\chi^2(1)$	1.8	0.180
$M_{6,\beta}$: Exclude Trend Prop./Oil (First Regime)	6312.4	$\chi^2(1)$	3.4	0.065
$M_{7,\beta}$: Exclude Trend Prop./Oil (Last Regime)	6308.6	$\chi^2(1)$	11	0.001
$M_{8,\beta}$: Exclude Trend But./Oil (First Regime)	6313.2	$\chi^2(1)$	1.8	0.180
$M_{9\ \beta}$: Exclude Trend But./Oil (Last Regime)	6311.5	$\chi^2(1)$	5.2	0.023
$M_{10,\beta}$: Exclude Trend Nat. Gas./Oil (First Regime)	6313.8	$\chi^2(1)$	0.6	0.439

Note: [1,2] Tested against the general model M_1.

Cointegration Relationships First Regime (Model M_1, LLS as oil price):

$$p_{oil,t} = 3.962 + 1.009 p_{propane,t} + 0.00035t$$

$$p_{oil,t} = 3.851 + 1.043 p_{butane,t} + 0.00024t$$

$$p_{oil,t} = 1.641 + 1.521 p_{nat.gas,t} - 0.00092t$$

Cointegration Relationships Last Sample (Model M_1, LLS as oil price):

$$p_{oil,t} = 4.123 + 0.420 p_{propane,t} + 0.00349t$$

$$p_{oil,t} = 4.018 + 0.619 p_{butane,t} + 0.00245t$$

TABLE 7. Tests on Long-run Weak Exogeneity

	Log-Likelihood	Distribution	Likelihood-Ratio[1]	p-value[2]
$M_{1,a}$: Oil Exogenous (First Regime)	6311.0	$\chi^2(3)$	6.2	0.102
$M_{2,a}$: Oil Exogenous (Last Regime)	6311.4	$\chi^2(2)$	5.4	0.067
$M_{3,a}$: Propane Exogenous (First Regime)	6296.6	$\chi^2(3)$	35	0.000
$M_{4,a}$: Propane Exogenous (Last Regime)	6312.2	$\chi^2(2)$	3.8	0.150
$M_{5,a}$: Butane Exogenous (First Regime)	6307.0	$\chi^2(3)$	14.2	0.003
$M_{6,a}$: Butane Exogenous (Last Regime)	6308.4	$\chi^2(2)$	11.4	0.003
$M_{7,a}$: Natural Gas Exogenous (First Regime)	6306.7	$\chi^2(3)$	14.8	0.002
$M_{8,a}$: Natural Gas Exogenous (Last Regime)	6314.0	$\chi^2(2)$	0.2	0.905

Note: [1,2] Tested against the general model M_1.

TABLE 8. Tests on Single Equations Response to Equilibrium Errors

	Oil Price Adjusts	Propane Price Adjusts	Butane Price Adjusts	Nat. Gas Price Adjusts
Oil/Propane Eq. Error (Regime 1)	0.000 [1.000]	0.233 [0.000]	-0.006 [1.000]	0.024 [1.000]
Oil/Butane Eq. Error (Regime 1)	-0.047 [0.237]	-0.153 [0.000]	0.084 [0.025]	-0.070 [0.237]
Oil/Nat.Gas Eq. Error (Regime 1)	0.001 [1.000]	-0.009 [0.206]	-0.007 [0.273]	0.035 [0.001]
Oil/Propane Eq. Error (Regime 2)	-0.201 [0.036]	-0.152 [0.180]	-0.302 [0.003]	0.071 [0.655]
Oil/Butane Eq. Error (Regime 2)	0.152 [0.157]	0.233 [0.051]	0.329 [0.002]	-0.073 [0.655]