Energy Economics 56 (2016) 229–238

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Research Article

Integration of physical and futures prices in the US natural gas market

Hamed Ghoddusi

School of Business, Stevens Institute of Technology, 1 Castle Point on Hudson, Hoboken, NJ07030, USA

ARTICLE INFO

Article history:
Received 30 March 2015
Received in revised form 12 March 2016
Accepted 13 March 2016
Available online 23 March 2016

JEL classification:
Q40
Q43
N72

Keywords:
Natural gas
Spot–futures cointegration
VECM
Causality

ABSTRACT

This paper examines the integration between the prices of different types of physical (upstream/end-use) and futures contracts of natural gas in the US for the period of June 1990–Dec 2014. To examine the equilibrium relationship between physical and futures prices, several cointegration tests are applied. The study finds that (a) futures prices are cointegrated with wellhead, power, industrial, and citygate prices; (b) NG1 futures prices Granger cause all physical prices; (c) upstream physical prices Granger cause futures prices; (d) shocks to wellhead prices are the only ones among physical prices with persistent long-term effects; (e) shocks to futures prices have persistent effects on all physical prices; (f) futures contracts with a longer time-to-maturity explain a larger portion of commercial gas price variations; and (g) commercial and residential prices show different behavior compared to other physical prices in multiple tests.

1. Introduction

The US natural gas market consists of a set of production, import/export, transmission, storage, and consumption nodes, with market prices associated with different nodes. The price of gas at different end-use nodes (e.g., industrial, commercial, or residential points) follows a long-run equilibrium relationship with wholesale prices (Mohammadi, 2011). The connection between spot and futures prices have been investigated extensively in the literature (e.g. Garbade and Silber, 1983; Chinn et al., 2005; Joseph et al., 2014). Because of the forces connecting prices an integration between physical and futures markets is also expected to hold. However, the physical/futures markets integration has not been tested empirically. The goal of this paper is to address this question using 25 years of monthly data.

The U.S. natural gas market went through a series of regulatory reforms in the 80s and 90s. As a consequence of these changes implemented by the Federal Energy Regulatory Commission (FERC), the production and trading of natural gas are decoupled from gas transportation[1] . The production and trading sides of the natural gas market are competitive. However, due to a typical natural monopoly effect, transportation (mainly through pipelines) tends to be concentrated and requires supervision by a regulatory body (Cuddington and Wang, 2006; De Vany and Walls, 1993).

In the years following the physical market reforms, a liquid and well-functioning futures market has also developed and evolved. An active futures market provides opportunities for market participants (producers and consumers) to hedge their price risk. Hedging would be more effective and cost efficient if for every type/location of physical price there existed a corresponding futures contract. This is not the case in reality. For the majority of commodities (including natural gas), futures contracts are offered only for one or a very limited number of underlying spot prices. For example, in the case of refined products, futures contracts are mainly available for gasoline and heating oil. Consumers of other types of products (e.g., jet fuel) should use existing contracts as an imperfect cross-hedging[2] solution.

E-mail address: hghoddus@stevens.edu.
URL: http://www.ghoddusi.com (H. Ghoddusi).

[1] The 1985 FERC decision allowed interstate natural gas pipelines to transport the gas owned by their customers instead of the prior practice, which forced them to own the transported gas. The new regulation set the stage for the emergence of spot prices in different locations (Walls, 1995).

[2] Cross-hedging refers to using an available futures contract as a proxy for another (usually non-existent) contract . To provide an effective hedge, the two contracts should have a reasonably high correlation and move in the same direction.

http://dx.doi.org/10.1016/j.eneco.2016.03.011

Table 1
Description of natural gas prices

Price variable	Description
Wellhead	The price of unprocessed gas at the head of a gas well.
Industrial	The price of gas used for manufacturing purposes, such as production feedstock or to produce heat.
Power (electricity)	The price of gas purchased by power companies for the purpose of converting gas to electricity.
Citygate	The price paid by a natural gas retail company receiving gas from the end of a main transmission pipeline.
Commercial	The price paid by service companies such as restaurants and hotels.
Residential	The price paid by households. The gas is mainly used for heating purposes.

The mismatch between futures and physical prices also exists in the U.S. natural gas market. While natural gas is traded in many locations in the country and for different purposes (e.g., residential, industrial, and electricity generation [power]), futures contracts exist only for spot prices of the Henry Hub, Louisiana delivery node. In the absence of futures contracts written specifically on all other natural gas prices, users should rely on Henry Hub (HH) futures contracts as a cross-hedging solution. The stronger the integration of physical and Henry Hub futures prices, the more effective the hedging practice will be. Thus, understanding the degree of cointegration between different types of wholesale and end-use prices (“physical prices”) and marketed futures contracts is an important question for understanding hedging effectiveness in this market.

Moreover, the speed of response to news in the physical and futures market is different. If futures contracts are an unbiased predictor of future events, using futures contracts for hedging will be efficient. However, if they are biased in a certain direction, hedgers may end up paying an additional “error premium” . An efficient futures market will quickly reflect expectations regarding future supply and demand. Retail prices are usually less responsive but will eventually follow the path behavior of more responsive ones (Mohammadi, 2011). Knowing the direction and speed of shock transmissions between physical and futures markets will improve our understanding of the natural gas market efficiency.

The prior literature has recognized the importance of incorporating cointegration relationship in the estimation of optimal hedging ratio, tests of market efficiency, and pricing of spread options (Alexander, 1999). da Hsiang (1996) shows that failing to consider the cointegration between spot and futures prices results in underhedging.

Motivated by the above discussions, the goal of this paper is to study the relationship between futures contracts and various types of physical prices. To the best of my knowledge, there has been very little work on testing the connection between the two markets, with disaggregated physical prices, for the U.S. natural gas industry. The only exception is Walls (1995) who examines market efficiency of the U.S. futures market by testing the cointegration between futures prices and spot prices in major delivery locations. However, Walls (1995) uses only 44 observations and does not allow for structural breaks in the cointegration relationship. Moreover, the paper is not concerned with the integration between various types of natural gas end-use prices and futures prices.

The paper's research question can be perceived as testing a triangle relationship between cointegrated prices. Futures prices are usually cointegrated with their underlying spot prices. Moreover, as Mohammadi (2011) reports, different physical price pairs are cointegrated with each other. However, we also need to test the cointegration of other physical prices with futures prices to gauge their effectiveness for hedging.

Following the open access reform, a set of papers tested the impact of changes in market regulation on the efficiency and integration of markets. De Vany and Walls (1993) was one of the first papers that applied cointegration tests to market price pairs between 20 locations, and concluded that reforms have significantly increased the level of spatial integration. King and Cuc (1996) and Serletis (1997) examine market integration for the North American (U.S. and Canada) market. King and Cuc (1996) use a Kalman Filter approach to account for time-varying parameters, and concludes that while the North American market has become more integrated following FERC reforms, there is a split between West–East markets. In contrast, Serletis (1997) uses Engle and Granger (1987) and Johansen (1988) cointegration tests and rejects the so-called West–East split. In a more recent study, Park et al. (2008) finds that two decades after the reforms, the U.S. and Canadian markets are highly integrated.

Cuddington and Wang (2006) uses daily spot prices at 76 locations to assess the market integration impact of FERC's open access reforms. The paper concludes that the low connectivity between the U.S. West and the rest of the country causes a poor price integration between that region and prices in other locations. Mohammadi (2011) examines the integration of upstream and downstream markets. However, his analysis is limited to the physical market. Arano and Velikova (2009) concludes that the residential (end-user) and citygate prices are cointegrated in 90% of U.S. states. The literature on the market efficiency of natural gas outside of the U.S. is also abundant. For example, Asche et al. (2000) studies France's natural gas market and finds a long-run integration between the prices of imported gas from Norway, the Netherlands, and Russia. Brown and Yücel (2009) tests the integration between the U.S. and European markets and finally, Asche et al. (2006) examine the decoupling of natural gas, oil, and electricity prices in the UK market.

A few papers have studied the integration between spot and futures prices of crude oil, such as Maslyuk and Smyth (2009), who examine the cointegration relationship between spot and futures prices of different types of crude oil (WTI and Brent). Similarly, Chen et al. (2014) considers the effect of structural breaks on the relation between spot and futures prices, and finds that the presence of structural breaks affects conclusions regarding the efficiency of the crude oil market. Compared to the crude oil market, the existence of several types of physical prices in the natural gas market makes the problem

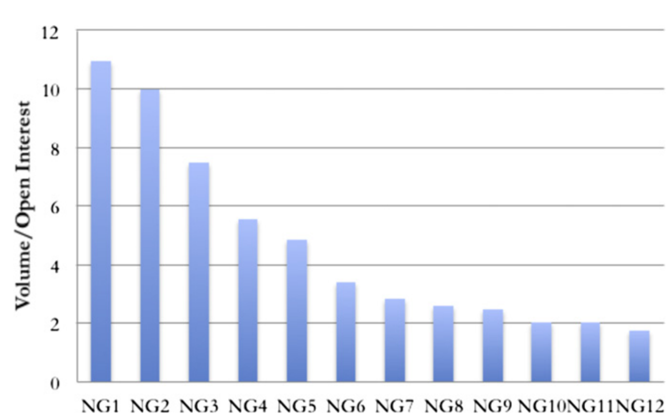

Fig. 1. Ratio of volume to open interests for NG1 to NG12, for Year 2014. The trend suggests that contracts with shorter maturity have a higher liquidity (volume) in the market.

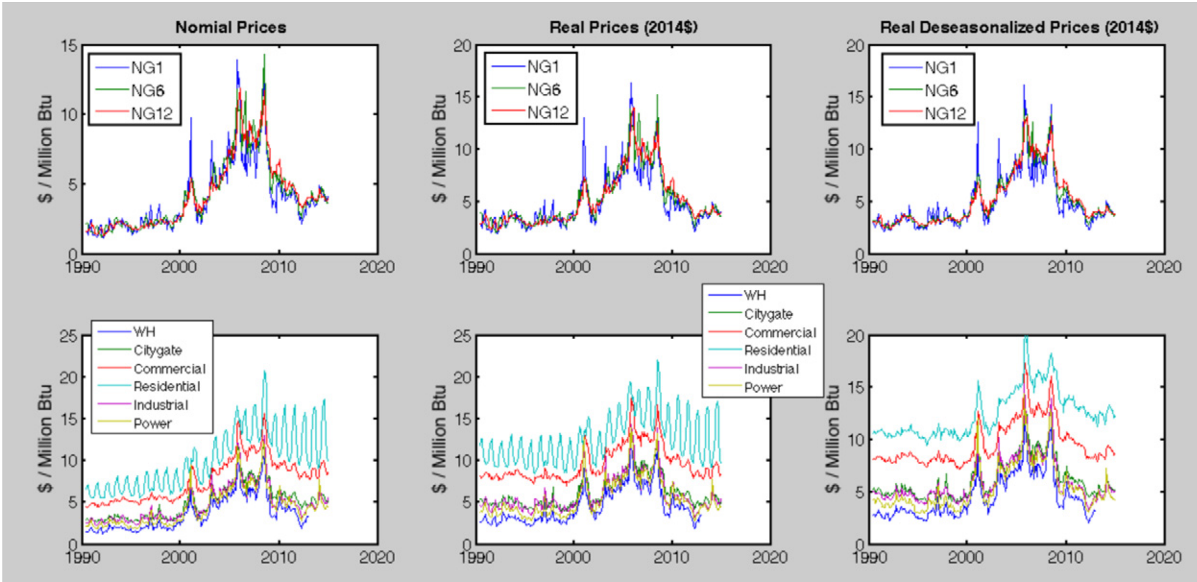

Fig. 2. Time-series of natural gas prices. Prices in the left panel are nominal and prices of the middle panel are real prices (2014$). The right panel shows the real prices after removing the seasonal component of the price using the X-12 procedure.

even more interesting from a policy perspective. Wei and Zhu (2006) study the empirical determinants of the convenience yield and risk premium in the US natural gas market.

The rest of the paper has the following sections: Section 2 briefly describes the definitions of different prices and the overall behavior of raw data. Section 3 discusses econometrics techniques used in the paper. Section 4 presents numerical results of the study. We conclude in Section 5 by summarizing the results and proposing possible topics for future research.

2. Data

This section introduces the data used for the study and the overall behavior of the original time-series.

2.1. Data

The monthly prices of natural gas futures, for maturities between 1 and 12 months, are obtained from Bloomberg. The series starts at 1990/06 and ends at 2014/12, producing 295 observations. Monthly prices of different types of natural gas are collected from the Energy Information Administration (EIA) website[3] . This price series starts in 1984; however, since a balanced panel of data is required for this study, I limit the starting date of physical prices to the starting date of futures prices.

2.1.1. Natural gas prices

The Energy Information Administration provides price series for several types of natural gas supply and end-use points. The prices considered in this paper are wellhead, industrial, power (electricity), citygate, commercial, and residential. Table 1 provides a short description of each type of price.

2.1.2. Futures contracts

The futures contracts for natural gas were introduced at the New York Mercantile Exchange (NYMES) in June 1990. The underlying asset of one futures contract is 10,000 million British thermal units (MMBtu) of natural gas. The delivery location of this underlying physical asset is Henry Hub, Louisiana. Thus, the futures contract is closely connected to the spot prices of Henry Hub and not necessarily to other locations. The natural gas futures market is a liquid market.

As explained by Budzik (2002), the wellhead price reported by the EIA is an average of wellhead prices from different locations, published with a delay. Henry Hub prices are used as a proxy for the real-time price of natural gas in the U.S. Budzik (2002) tests for a cointegration relationship between two prices, and finds that they are strongly integrated with each other.

I use futures contracts with three maturity lengths of 1, 6, and 12 months. The front month (1-month) contract is the closest one to a spot price reflecting the most current set of information. On the other end of the maturity horizon NG12 is a reasonable choice because the liquidity of contracts beyond 12 months is limited. To have a reliable price series, a liquid market is required. Although futures contracts for natural gas are traded beyond 12 months (especially in recent years), I limit the time-to-maturity to 12 months to ensure sufficient liquidity and price discovery. Fig. 1 shows the ratio of trade volume of each futures contract to the number of open interests for that contract. As expected, the NG1 contract (i.e., the front month contract) has the highest ratio of volume to open interest and thus is the most liquid contract.

Futures prices, in particular at maturities less than one year, usually form a continuous line and don't show a sudden change of behavior. To economize the representation of results and in order to focus on key findings, I choose to report results for three representative futures contracts. NG1 is a natural choice to represent the short horizon. NG12 is a reasonable candidate for long-term contracts with a large number of historical observations and liquidity. Finally, NG6 (the mid point between NG1 and NG12) is chosen to represent a medium-range futures contract[4].

[3] Currently, the EIA website doesn't provide a full history for all price series. Hassan Mohammadi was kind to share with me the data he previously downloaded from the website for his paper, Mohammadi (2011).

[4] A robustness check using NG2, NG7, and NG11 show that results are not very sensitive to the choice of adjacent contracts.

Table 2
Descriptive statistics of original prices. Since all prices are non-stationary the descriptive statistics should be interpreted with enough caution. Since prices don't show a strong trend the descriptive statistics can provide some intuitive measures of price level and volatility within the sample period. The results shouldn't be interpreted as steady-state values.

Price	Mean	Median	Standard deviation	Skewness	Kurtosis
Wellhead	3.63	2.96	2.04	1.10	3.78
Industrial	4.80	4.33	2.13	1.21	4.36
Power	4.43	4.18	2.19	1.05	3.84
Citygate	5.05	4.76	2.11	0.98	3.58
Commercial	7.75	7.79	2.54	0.57	2.52
Residential	10.09	9.77	3.49	0.58	2.41
NG1	4.02	3.48	2.41	1.41	5.16
NG6	4.23	3.76	2.54	1.20	4.05
NG12	4.27	3.82	2.49	1.01	3.24

Table 3
Unit root tests. The results of the three major tests are mostly consistent with each other. Except for NG1 all other price levels are detected as having a unit-root. All first-differenced values are stationary. The unit-root hypothesis for the NG1 series is rejected at the 95% confidence interval (5% significance); however, not rejected at 99% confidence interval (1% significance). The numbers in parentheses under the Perron (1997) column show the time of a single structural break. The null hypothesis if the KPSS test is the processing being stationary. Thus, a value larger than the critical value indicates the rejection of stationarity with 5% significance level.

	ADF level		ADF diff		Perron (1997)		KPSS (C/T)	
Variable	C	C/T	C	C/T	Level	Diff	Level	Diff
WH	−2.18	−2.40	−14.89	−14.88	−4.63 (2005/06)	−7.44 (2008/07)	0.23	0.03
Industrial	−2.52	−2.91	−14.97	−14.95	−4.25 (2005/06)	−9.24 (2008/07)	0.25	0.02
Power	−2.80	−3.29	−8.68	−8.68	−4.17 (2005/02)	−8.21 (2008/06)	0.26	0.03
Citygate	−2.18	−2.52	−16.11	−16.09	−4.30 (2005/02)	−7.83 (2005/10)	0.25	0.04
Commercial	−2.02	−2.69	−7.40	−7.40	−3.89 (2005/02)	−8.70 (2005/10)	0.25	0.05
Residential	−1.43	−2.20	−14.57	−14.55	−3.89 (2005/06)	−8.29 (2005/10)	0.23	0.05
NG1	−2.98	−3.32	−18.02	−18.00	−4.76 (2005/06)	−8.35 (2008/07)	0.27	0.03
NG6	−1.89	−1.92	−16.93	−16.92	−4.42 (2005/06)	−7.90 (2008/07)	0.27	0.05
NG12	−1.47	−1.23	−17.94	−17.96	−4.42 (2005/02)	−8.95 (2008/07)	0.27	0.08
Critical values	−2.88	−3.42	−2.88	−3.42	−4.83	−4.83	0.14	0.14

2.2. Preliminary look at the data

To provide a visual representation of possible structural breaks, all price series are plotted in Fig. 2. The following observations are noteworthy in this figure: First, a structural break around 2008 is likely to be found in econometrics tests. This coincides with the take-off in the production of shale gas. Prices prior to 2005 seem to follow a Geometric Brownian Motion (GBM) process, whereas after 2005, the price series looks more stationary (mean-reverting). Second, physical and futures prices follow similar long-run dynamics. However, they are not perfectly tied to each other. This observation highlights the importance of running rigorous econometric tests to identify possible cointegration relationships between various markets. Finally, as expected natural gas prices (in particular with commercial and residential prices) exhibit some seasonal behavior. The seasonal component of the price creates additional noise for econometrics tests; thus, this component of the prices is removed using the X-12 procedure and all tests are performed using seasonally-adjusted data.

Table 2 shows the descriptive statistics of original data. We observe that the mean and the median price increase by moving from the upstream to downstream sectors. However, the skewness of downstream prices (commercial and residential) are substantially smaller than upstream. A smaller skewness is a sign of more symmetric distribution around the mean. Except for residential and commercial prices, all other prices show excess kurtosis, which is a sign of fat tails and the possibility of extreme price realizations.

3. Methodology

The paper deals with 9 prices, which are most likely non-stationary. The econometrics methods used in each step are briefly explained in this section.

3.1. Test for stationary behavior

The first step is to test for the existence of a unit-root in the univariate time-series of physical and futures prices, using Augmented Dickey–Fuller (ADF), KPSS, and Perron (1997) tests. The latter test is applied to data because the graphical representation of data (Fig. 2) suggests the possibility of a major structural break. Perron (1997) offers a unit-root test in the presence of an endogenous structural break.

If series are detected to be non-stationary, the next step is to run cointegration tests for pairs of futures and physical prices. For two non-stationary price series, P^F and P^S, a cointegration relationship requires the existence of a linear combination of them that is stationary. It immediately follows that the residual, θ, in the following linear regression must be a stationary process.

$$P_t^S = \alpha + \beta P_t^F + \theta_t \tag{1}$$

Where P^F and P^S are usually I(1) and θ is an I(0) process. The cointegration relationship holds when the residual term θ is a stationary process.

The classic tests of cointegration, including Engle and Granger as well as Johansen procedure, do not consider the possibility of structural breaks and their potential impact on biasing results. Similar to Mohammadi (2011) I also use the Gregory and Hansen (1996) test, which allows for endogenous breaks[5].

Gregory and Hansen (1996) allow for regime shift in the intercept or coefficients of the cointegraton relationship. The procedure contains four cases: a conventional cointegration test (no structural

[5] Codes to implement the Gregory and Hansen procedure can be downloaded from http://www.ssc.wisc.edu/~bhansen/progs/joe_96.html.

Table 4
Johansen cointegration test results. Results indicate the existence of 1 cointegration equation for all pairs at the 5% significance level. For pairs including wellhead, power, industrial, and citygate prices the model is specified with unrestricted intercept and no trend in the VAR and for pairs including commercial and residential prices the specification is with an intercept and trend in the cointegration relationship.

		Wellhead		Industrial		Power		Citygate		Commercial		Residential	
		0 CE	1 CE	0 CE	1 CE	0 CE	1 CE	0 CE	1 CE	0 CE	1 CE	0 CE	1 CE
NG1	Trace	31.70	4.63	35.23	7.57	24.27	6.37	37.83	3.71	49.04	6.49	34.80	6.00
	Max Eigen	20.07	4.63	27.66	7.57	17.89	6.37	34.13	3.71	42.54	6.49	28.79	6.00
NG6	Trace	26.43	2.30	33.16	2.35	26.54	2.49	24.68	3.62	37.84	3.54	32.37	3.74
	Max Eigen	24.14	2.30	30.80	2.35	24.05	2.49	22.86	3.62	34.29	3.54	28.62	3.74
NG12	Trace	19.87	1.94	28.04	1.97	24.14	2.10	24.69	2.61	33.85	3.38	27.44	3.55
	Max Eigen	17.93	1.94	26.06	1.97	22.04	2.10	22.06	2.61	30.44	3.38	23.89	3.55
Critical Values	Trace	20.26	9.16	20.26	9.16	20.26	9.16	20.26	9.16	25.87	12.51	25.87	12.51
	Max Eigen	15.89	9.16	15.89	9.16	15.89	9.16	15.89	9.16	19.38	12.51	19.38	12.51

breaks), a shift of the intercept (C model), a shift in the common trend term (C/T model), and a shift in the intercept and coefficients (C/S model). The results of this additional test are reported in the Appendix.

3.2. Vector error correction (VECM)

To test the transmission of shocks from one price series to another, the VECM formulation is used to study short-term and long-term relations between pairs of prices. The compact form of a VECM representation of the time-series has the following structure:

$$\Delta P_t = \sum_{i=1}^{n-1} \Phi_i^* \Delta P_{t-i} + \Pi P_{t-1} + \mu_0 + \phi D + u_t \tag{2}$$

where P is the vector of prices, Δ is the first-difference operator, Π and Φ^* are matrices of parameters, μ_0 is the vector of unrestricted constant term, u_t is the vector of error terms, and D is the vector of seasonal dummies.

With two variables P^F and P^S the system of VECM can be written in a more extensive form as:

$$\Delta P_t^S = \gamma_S \theta_{t-1} + \sum_{i=1}^{r} a_i \Delta P_{t-i}^F + \sum_{i=1}^{s} b_i \Delta P_{t-i}^S + \mu_1 + \phi_1 D + \epsilon_{1,t}$$
$$\Delta P_t^F = \gamma_F \theta_{t-1} + \sum_{i=1}^{m} c_i \Delta P_{t-i}^F + \sum_{i=1}^{n} d_i \Delta P_{t-i}^S + \mu_2 + \phi_2 D + \epsilon_{2,t}$$

where θ_{t-1} is the error-correction term introduced in Eq. (1). γ_S and γ_F measure the speed-of-adjustment of a variable to previous period's disequilibrium between physical and futures prices.

4. Results

4.1. Unit root tests

It is a well-known fact that the spot prices of many storable commodities are likely to exhibit a behavior close to a unit-root. As the first step, I test the existence of unit-roots in physical and futures prices using ADF, Perron (1997), and KPSS tests. Results reported in Table 3 support that almost all prices are non-stationary at the 5% significance level with residential price being the only border-line case. Structural breaks identified by the Perron test are mainly clustered around 2005, the year when the production from unconventional resource has taken off.

4.2. Johansen's tests of cointegration

As reported in the previous subsection, natural gas prices are non-stationary. However, equilibrating forces in energy systems (e.g., transportation and storage) may bring two non-stationary series together, causing a linear combination of them to be stationary. In addition to the equilibrium itself, it is important to note the speed at which a deviation from the equilibrium will return in the long-run.

The results of the Johansen procedure (Table 4) indicate one cointegration relation between all physical and futures prices. I notice that under the specification of an unrestricted intercept and no trend in the VAR, no cointegration is found between futures prices and commercial/residential prices. However, after allowing for an intercept and trend in the cointegration relationship the existence of 1 cointegration equation is accepted at the 5% significance level. This is an important result to be noted. Despite the fact that we find a cointegration relationship between futures and commercial/residential prices a cointegration relation with a trend doesn't mean that price pairs will stay close to each other. They will get a predictable distance from each other over time governed by the trend line.

4.3. Cointegration relationships

Following the results showing that almost all pairs are cointegrated, I estimate the cointegration relationship between pairs of physical/futures prices using the fully modified OLS (FMOLS) procedure. The regression equation is:

$$P_t^S = \alpha + \beta P_t^F + \epsilon_t \tag{3}$$

Table 5 shows the estimation result for the cointegration coefficients along with the t-test for $\beta = 1$. We observe that for almost all pairs, the intercept is positive. Moreover, the β coefficient is smaller than or equal to 1 for all physical prices[6] . As we move from the wellhead to residential prices the slope parameter β increases, until it reaches one for commercial and residential prices.

4.4. Causality

A causal relationship between futures and physical prices provides important information about the drivers of price formation in each of physical/future markets. The notion of causality can be discussed over short-term and long-term horizons. I report the results for both types of causalities using the Granger causality (for the short-term causality) and the speed of the adjustment of the error-correction model (for the long-run causality).

[6] The statistical tests didn't support the rejection of $\beta = 1$ for residential and commercial prices.

Table 5
Cointegration relationships.

	Wellhead		Industrial		Power		Citygate		Commercial		Residential	
	α	β	α	β	α	β	α	β	α	β	α	β
NG1	0.32	0.82	1.23	0.89	0.77	0.91	1.50	0.89	3.61	1.03	5.38	1.17
	(3.41)	(52.93)	(17.28)	(68.88)	(6.54)	(48.21)	(11.42)	(40.85)	(15.96)	(31.69)	(12.53)	(20.72)
	−13.45		−9.03		−4.69		−4.87		0.64		1.89	
NG6	0.43	0.75	1.39	0.81	0.93	0.83	1.60	0.82	3.64	0.97	5.35	1.12
	(3.31)	(29.32)	(8.40)	(29.38)	(4.89)	(26.70)	(10.82)	(33.73)	(17.39)	(31.96)	(14.06)	(21.86)
	−12.47		−8.33		−6.63		−8.50		−0.66		1.58	
NG12	0.45	0.74	1.40	0.80	0.94	0.82	1.58	0.82	3.57	0.98	5.21	1.14
	(2.59)	(21.48)	(6.46)	(22.41)	(3.57)	(20.63)	(9.34)	(28.55)	(17.34)	(31.41)	(15.50)	(23.74)
	−10.37		−6.94		−6.03		−7.97		−0.50		2.02	

t-stats are in parenthesis. The third row shows the $t(\beta = 1)$.

4.4.1. Short-term: Granger causality

I use the procedure proposed by Toda and Yamamoto (1995) to test for the existence of the Granger causality in non-stationary time-series. This approach proposes setting up an augmented VAR model in level with additional exogenous lags equal to the maximum order of integration in the variables, d. In the case of our data the maximum order of integration is one. The number of optimal lags, k, (for the original model) is selected using the AIC criteria and then extra exogenous lags are added to the system. The augmented VAR(k+d) model is estimated and a joint Wald test on the original k lags of each variable (i.e. excluding the extra d exogenous lags) is run to test for causality. The corresponding VAR(k+d) model is:

$$P_t^F = \sum_{i=1}^{k+d} a_i P_{t-i}^F + \sum_{i=1}^{k+d} b_i P_{t-i}^S + \mu_1 + \phi_1 D + \epsilon_{1,t}$$
$$P_t^S = \sum_{i=1}^{k+d} c_i P_{t-i}^F + \sum_{i=1}^{k+d} d_i P_{t-i}^S + \mu_2 + \phi_2 D + \epsilon_{2,t}.$$

Table 6 shows a summary of Granger causality tests between physical and futures prices. The results suggest that NG1, NG6, and NG12 futures contracts Granger cause almost all physical prices (except two cases). This is consistent with a hypothesis of using futures prices, which tend to be more liquid and informative, to adjust physical prices especially those set by negotiations and administrative decisions. Moreover, as expected, upstream prices also Granger cause all three futures prices because they reflect demand/supply forces in the physical market.

4.4.2. Long-run: error-correction

A long-run causality between physical and futures prices means that deviations from the equilibrium relationship between the two prices should predict subsequent movements in one or both prices. The null hypothesis of no long-run prediction would be equivalent to the statement that the speed of adjustment (i.e. the coefficient of the error-correction term in the VECM equation) is zero (Zhong et al. (2004)). For the VECM setup of this paper, a long-run causality from physical prices to futures prices requires a significantly positive estimate of γ_F; and a long-run causality from futures prices to physical prices requires a significantly negative estimate of γ_S.

The speed of adjustments are reported in Table 7. A greater value of the speed of adjustment parameter suggests a faster reaction to disequilibrium deviation of the previous period. This is usually interpreted as being a follower in the price discovery mechanism, or being caused by the other variable.

Estimated values of speed of adjustment suggest a difference between the dynamic behavior of short-maturity and long-maturity futures. None of the coefficients for physical prices are significant for the NG1 row. NG1 futures contracts adjust to restore the equilibrium relationship. However, the adjustment mechanism is reversed for pairs of physical prices and NG6 or NG12. In the case of those medium and long maturity futures contracts the coefficients of all physical prices are negative and statistically significant . Physical prices adjust themselves to return to the long-run equilibrium with NG6 and with NG12. Positive and significant values of γ_S are only observed in the NG1 row. This means that all physical prices have a long-run causality on NG1; however, no long-run causality from any of the physical prices on either NG6 or NG12 is established.

Because 1-month futures contracts (NG1) are closer to maturity and also traded in a more liquid market compared to the 6-month and 12-month contracts (NG6 and NG12) it can be expected that the

Table 6
Granger causality tests between price pairs. The results of the joint Wald test are reported in the table (p-values inside parentheses). A statistically significant result means the rejection of the null hypothesis of no Granger causality. P^F refers to the futures price (rows) and P^S refers to the physical price (columns). $P^F \to P^S$ means testing for a Granger cause from the futures price to the physical price. $P^S \to P^F$ means testing for a Granger cause from the physical price to the futures price.

	Wellhead		Industrial		Power		Citygate		Commercial		Residential	
	$P^F \to P^S$	$P^S \to P^F$	$P^F \to P^S$	$P^S \to P^F$	$P^F \to P^S$	$P^S \to P^F$	$P^F \to P^S$	$P^S \to P^F$	$P^F \to P^S$	$P^S \to P^F$	$P^F \to P^S$	$P^S \to P^F$
NG1	16.21**	53.18***	11.91**	23.16***	22.41***	195.01***	18.22***	10.21	64.95***	25.74***	100.25***	7.10
	(0.02)	(0.00)	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)	(0.11)	(0.00)	(0.00)	(0.00)	(0.21)
NG6	11.14*	13.67**	35.81***	21.52***	8.24	65.84***	40.32***	10.27	51.82***	20.15***	66.26***	8.04
	(0.05)	(0.02)	(0.00)	(0.00)	(0.14)	(0.00)	(0.00)	(0.17)	(0.00)	(0.00)	(0.00)	(0.42)
NG12	10.45	29.03***	20.48***	29.17***	29.34***	135.22***	21.71***	27.40***	19.30**	23.57***	43.85***	8.42
	(0.10)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.02)	(0.00)	(0.00)	(0.20)

The results of the joint Wald test are reported in the table (p-values inside parentheses). A statistically significant result means the rejection of the null hypothesis of no Granger causality. P^F refers to the futures price (rows) and P^S refers to the physical price (columns). $P^F \to P^S$ means testing for a Granger cause from the futures price to the physical price. $P^S \to P^F$ means testing for a Granger cause from the physical price to the futures price.

* 10% significance.
** 5% significance.
*** 1% significance.

Table 7
Speed of adjustment of error correction term in the VECM model (t-stat inside parenthesis).

	Wellhead		Industrial		Power		Citygate		Commercial		Residential	
	γ_S	γ_F	γ_S	γ_F	γ_S	γ_F	γ_S	γ_F	γ_S	γ_F	γ_S	γ_F
NG1	0.14	0.69***	0.04	0.36**	0.09	0.37***	0.03	0.29***	−0.01	0.14***	−0.01	0.06***
	(0.93)	(2.93)	(0.33)	(1.97)	(1.50)	(3.57)	(0.52)	(3.03)	(−0.87)	(2.83)	(−1.32)	(2.74)
NG6	−0.30***	0.03	−0.36***	−0.17**	−0.27***	0.01	−0.31***	−0.09	−0.26***	−0.20**	−0.23***	−0.14**
	(−4.07)	(0.41)	(−5.62)	(−2.55)	(−4.60)	(0.25)	(−4.63)	(−1.24)	(−5.69)	(−2.49)	(−5.88)	(−2.34)
NG12	−0.21***	0.05	−0.27***	−0.06*	−0.23***	0.03	−0.33***	−0.08*	−0.28***	−0.21***	−0.25***	−0.17***
	(−3.62)	(1.24)	(−5.31)	(−1.70)	(−4.57)	(1.08)	(−5.19)	(−1.66)	(−6.81)	(−3.81)	(−5.86)	(−3.86)

γ_S and γ_F refer to the speed of adjustment of physical and futures prices, respectively.
* 10% significance.
** 5% significance.
*** 1% significance.

information efficiency of NG1 is higher and NG1 has a faster response to disequilibrium.

4.5. Impulse response functions (IRF)

To study the long-run response of physical and futures prices to innovations residuals, price series are seasonally adjusted using the X-12 procedure (Findley et al. (1998)) to remove the impact of seasonal components on IRFs. To provide a comparison, the IRFs of the original series are also provided in Appendix 1.

Figs. 3 and 4 show the IRF of physical prices and futures contracts. To save space, I only plot the IRFs for 1-month and 12-month futures contracts in combination with all types of physical prices. Impulse responses are plotted for 50 periods to ensure that the system has arrived at its steady-state.

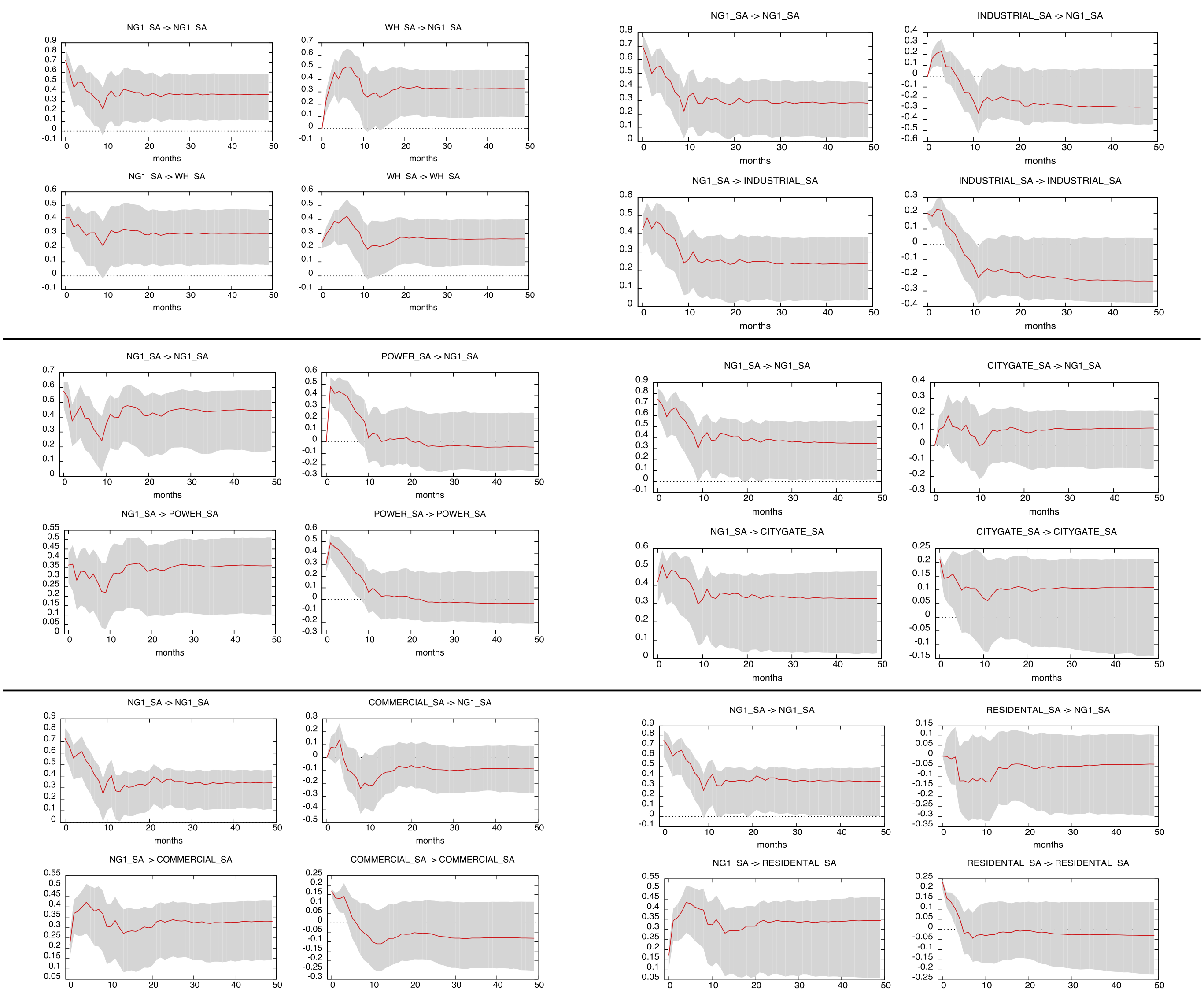

Fig. 3. General impulse response of NG1 and physical prices. The only physical price, whose shocks have a permanent effect is the wellhead prices. Shocks to NG1 have persistent effects on almost all prices.

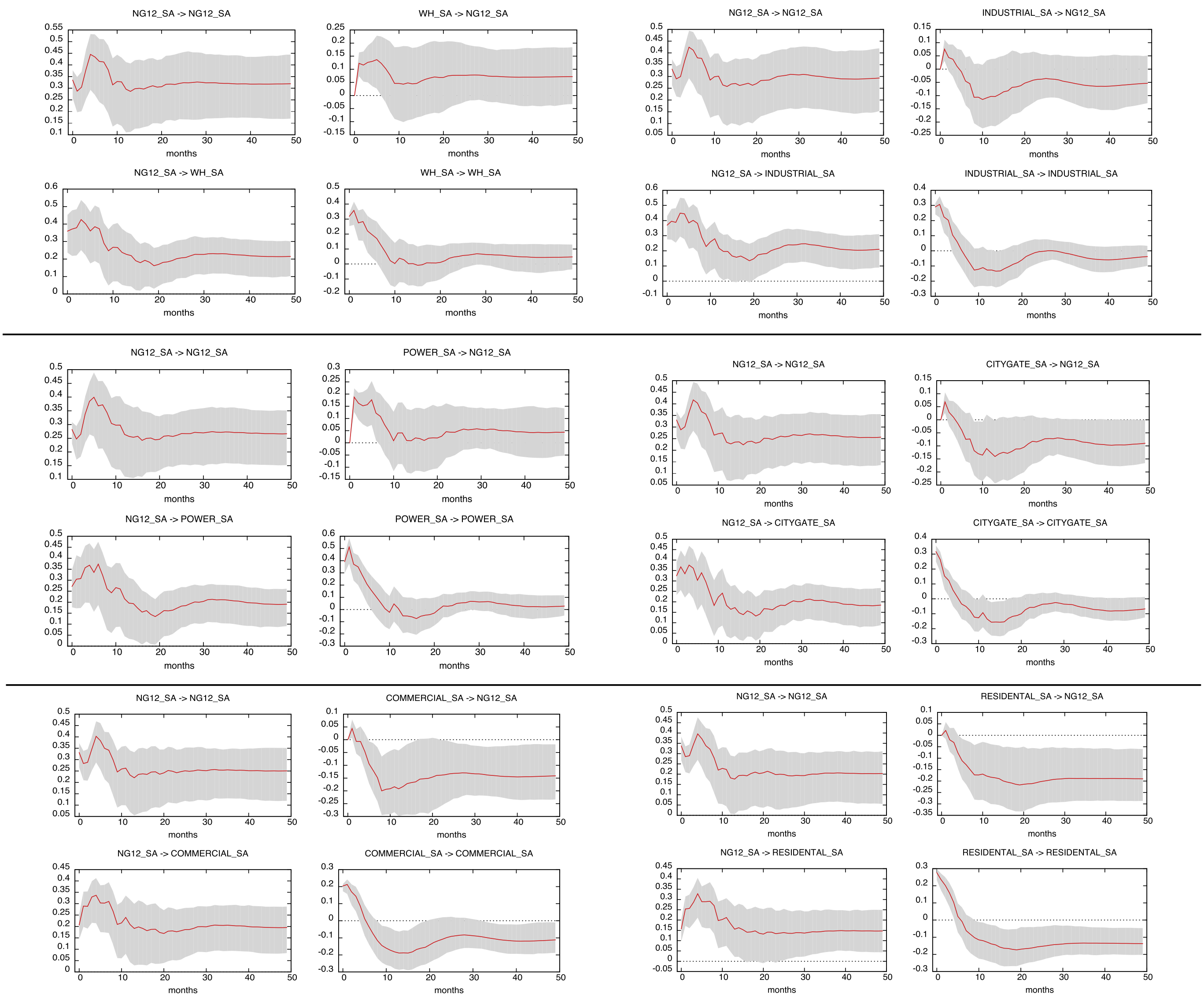

Fig. 4. General impulse response of NG12 and physical prices. Residential and commercial prices are the only physical prices having a long-lasting negative effect on long-maturity futures contracts.

We observe that in the majority of cases, the dynamic response of physical prices to their own innovation is not significantly different than zero. The only exception is the wellhead price, whose shocks are persistent. The response of futures prices to their own innovations are highly persistent. Finally, the response of physical prices to shocks of futures prices are persistent in the majority of cases.

4.6. Variance decomposition

A variance decomposition exercise reveals the power of each variable to explain the long-run variance of its own and its paired price in the VECM relationship. The Cholesky decomposition is used to generate innovations in endogenous variables and observe the error of n-period ahead forecasts.

Table 8 reports the variance decomposition of pairs of physical/futures prices over the long-run. I report the percentage of variance explained 50 months after the initial shock as the long-run effect of shocks. Table 8 doesn't include the term structure of explained variances and just shows the explained value at the final month. Based on the saturating behavior we observe at IRF graphs, the choice of 50-month horizon is a reasonable representation of the long-run steady-state.

Values reported in Table 8 suggest that wellhead and power prices explain a significant proportion of variation in NG1 prices. Other prices have a much weaker effect on NG1 variance. We also note that longer maturity contracts (especially NG12) are driven almost entirely by their own shocks. On the contrary, NG12 explains a big proportion of variation in all physical prices. This observation suggests that market expectations are first reflected in long-maturity futures contracts, and are then transmitted to physical prices.

The percentage of "commercial" gas price variations explained by different futures contracts are shown in Fig. 5. The graph suggests that futures contracts with a longer time-to-maturity explain a larger share of long-run price variations for commercial gas. This relationship holds only for commercial gas. The same analysis for "residential" prices produces a flat curve.

5. Conclusion

In this paper, I examine the integration between different types of physical (upstream/end-use) and futures prices of natural gas in the U.S. I apply cointegration tests and study the causality relationships

Table 8
Variance decompositions of physical and futures prices after 60 periods. The table reports results for seasonality-adjusted series, using the X-12 procedure.

P^F	P^S	Variation of P^F explained by		Variation of P^S explained by	
		P^F(%)	P^S(%)	P^F(%)	P^S(%)
NG1	Wellhead	25.67	74.32	25.85	74.14
	Industrial	1.03	98.96	0.34	99.65
	Power	5.06	94.93	5.57	94.42
	Citygate	3.37	96.62	0.80	99.19
	Commercial	13.26	86.73	3.64	96.35
	Residential	52.74	47.52	18.54	81.45
NG6	Wellhead	48.01	51.98	40.23	59.76
	Industrial	89.33	10.66	77.19	22.80
	Power	61.38	38.61	50.32	49.67
	Citygate	85.57	14.42	78.35	21.64
	Commercial	59.15	40.81	45.21	54.78
	Residential	66.62	33.37	25.25	74.75
NG12	Wellhead	95.83	4.16	85.87	14.12
	Industrial	44.86	55.13	32.50	67.49
	Power	80.20	19.58	58.82	41.11
	Citygate	66.17	33.82	50.31	49.68
	Commercial	86.48	13.51	65.58	34.41
	Residential	76.67	23.32	19.66	80.33

between physical and futures prices. To the best of my knowledge, this is the first attempt to provide a comprehensive account of the connection between physical and futures market prices in the US natural gas market. I find several interesting results including the following observations: (a) futures prices are cointegrated with wellhead, power, industrial, and citygate prices; (b) futures prices Granger cause all physical prices; (c) in the set of physical prices, shocks to wellhead price are the only ones with persistent long-term effects; (d) shocks to futures prices have persistent effects on all physical prices; and (e) futures contracts with a longer time-to-maturity explain a larger portion of commercial gas price variations. I also find that commercial and residential prices behave differently than other prices in several statistical tests. In particular, they only show cointegration with futures price when a trend is added. Thus, the conventional understanding of integrated price pairs (that don't diverge from each other over long-term) will not apply to those prices.

These results have potential implications for firms hedging production risks using futures contracts as well as for entities involved in natural gas trading. It has been argued that the existence of a cointegration relationship can be interpreted as a sign of deviation from strong form of a market efficiency. Cointegration implies that market participants are able to better bet on price convergence by observing the deviation from the long-run relationships.

The results of the long-run causality tests (speed of adjustment) suggest that the future values of NG1 can be predicted using the information inherent in the error-correction term. However, a similar effect for NG6 and NG12 was not observed. In the case of medium and long-term futures contracts (NG6 and NG12), it is the physical price that adjusts to the disequilibrium shocks. None of the physical prices show a sign of long-run causality on NG6 or NG12. Because NG6 and NG12 show a lack of predictability, the error-correction information cannot be used for speculative purposes for longer maturity futures contracts.

On the hedging side, cointegration improves the ability of physical market participants to hedge their exposure to market prices using futures prices. The results of this paper suggest that the hedge ratio (the ratio of futures to physical positions) will be higher compared to a case with only pure correlation and no cointegration. A higher hedge ratio provides a better hedging effectiveness.

Future research can apply this framework to natural gas markets in other countries. An interesting case could include testing the connection between physical prices in different European countries and contracts traded in EU futures markets.

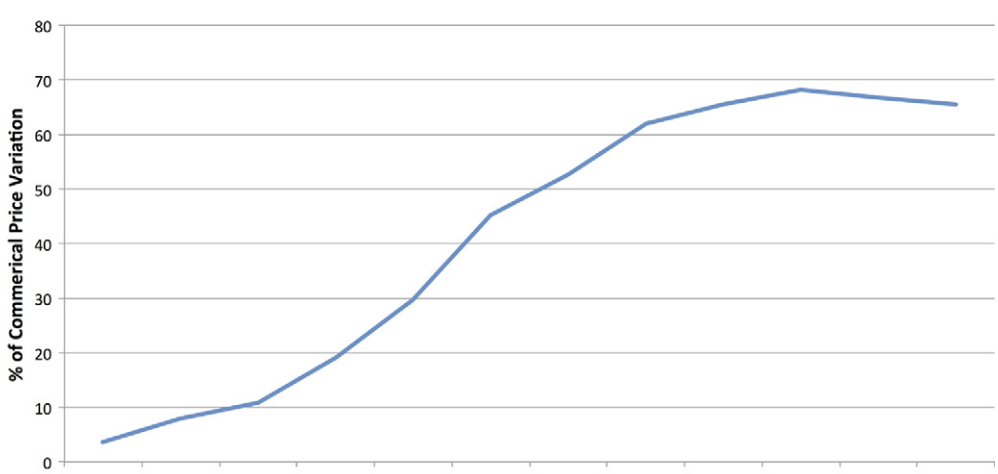

Fig. 5. Percentage of commercial gas price variance explained by different futures contracts. We observe that the explained variance of commercial gas price increases with the time-to-maturity of the futures contract.

6. Acknowledgment

I am indebted to the editor and three anonymous reviewers for providing valuable comments on the earlier version of this paper. I also thank Mohamad Afkhami and Daniela Cardona for excellent research assistantship and Hassan Mohammadi for sharing natural gas price data with me.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.10.1016/j.eneco.2016.03.011.

References

Alexander, C., 1999. Optimal hedging using cointegration. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 357 (1758), 2039–2058.
Arano, K., Velikova, M., 2009. Price convergence in natural gas markets: city-gate and residential prices. Energy J. 129–154.
Asche, F., Osmundsen, P., Sandsmark, M., 2006. The UK market for natural gas, oil and electricity: are the prices decoupled?. Energy J. 27–40.
Asche, F., Osmundsen, P., Tveterås, R., 2000. Market integration for natural gas in Europe.
Brown, S.P.A., Yücel, M.K., 2009. Market arbitrage: European and North American natural gas prices. Energy J. 167–185.
Budzik, P., 2002. US natural gas markets: relationship between Henry Hub spot prices and US wellhead prices. Energy information administration report. pp. 1–5.
Chen, P.F., Lee, C.C., Zeng, J.H., 2014. The relationship between spot and futures oil prices: do structural breaks matter?. Energy Econ. 43 (0), 206–217. http://www.sciencedirect.com/science/article/pii/S014098831400053X. http://dx.doi.org/10.1016/j.eneco.2014.03.006.
Chinn, M.D., LeBlanc, M., Coibion, O., 2005. The predictive content of energy futures: an update on petroleum, natural gas, heating oil and gasoline. Technical report. National Bureau of Economic Research,
Cuddington, J.T., Wang, Z., 2006. Assessing the degree of spot market integration for US natural gas: evidence from daily price data. J. Regul. Econ. 29 (2), 195–210.
da Hsiang, D.L., 1996. The effect of the cointegration relationship on futures hedging: a note. J. Futur. Mark. (1986-1998) 16 (7), 773.
De Vany, A., Walls, W.D., 1993. Pipeline access and market integration in the natural gas industry: evidence from cointegration tests. Energy J. 1–19.
Engle, R.F., Granger, C.W.J., 1987. Co-integration and error correction: representation, estimation, and testing. Econometrica 251–276.
Findley, D.F., Monsell, B.C., Bell, W.R., Otto, M.C., Chen, B.C., 1998. New capabilities and methods of the x-12-arima seasonal-adjustment program. J. Bus. Econ. Stat. 16 (2), 127–152.
Garbade, K.D., Silber, W.L., 1983. Price movements and price discovery in futures and cash markets. Rev. Econ. Stat. 289–297.
Gregory, A.W., Hansen, B.E., 1996. Residual-based tests for cointegration in models with regime shifts. J. Econ. 70 (1), 99–126.
Johansen, S., 1988. Statistical analysis of cointegration vectors. J. Econ. Dyn. Control. 12 (2), 231–254.
Joseph, A., Sisodia, G., Tiwari, A.K., 2014. A frequency domain causality investigation between futures and spot prices of indian commodity markets. Econ. Model. 40, 250–258.
King, M., Cuc, M., 1996. Price convergence in North American natural gas spot markets. Energy J. 17–42.
Maslyuk, S., Smyth, R., 2009. Cointegration between oil spot and future prices of the same and different grades in the presence of structural change. Energy Policy 37 (5), 1687–1693.
Mohammadi, H., 2011. Market integration and price transmission in the US natural gas market: from the wellhead to end use markets. Energy Econ. 33 (2), 227–235.
Park, H., Mjelde, J.W., Bessler, D.A., 2008. Price interactions and discovery among natural gas spot markets in North America. Energy Policy 36 (1), 290–302. http://www.sciencedirect.com/science/article/pii/S0301421507004119. http://dx.doi.org/10.1016/j.enpol.2007.09.012.
Perron, P., 1997. Further evidence on breaking trend functions in macroeconomic variables. J. Econ. 80 (2), 355–385.
Serletis, A., 1997. Is there an east-west split in North American natural gas markets?. Energy J. 47–62.
Toda, H.Y., Yamamoto, T., 1995. Statistical inference in vector autoregressions with possibly integrated processes. J. Econ. 66 (1), 225–250.
Walls, W.D., 1995. An econometric analysis of the market for natural gas futures. Energy J. 71–83.
Wei, S.Z.C., Zhu, Z., 2006. Commodity convenience yield and risk premium determination: The case of the us natural gas market. Energy Econ. 28 (4), 523–534.
Zhong, M., Darrat, A.F., Otero, R., 2004. Price discovery and volatility spillovers in index futures markets: some evidence from mexico. J. Bank. Financ. 28 (12), 3037–3054.