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The Bias in the Long Run Relation between the Prices of BRENT and West Texas Intermediate Crude Oils

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ABSTRACT

This paper is about the magnitude of association between two crude oils, the UK BRENT and the Texan West Texas intermediate. Practice presumes and theory predicts a unitary and a proportionate association, especially for the log-log specifications. A battery of cointegration tests are conducted to test whether the slopes, or the cointegrating vectors, are statistically significant and are statistically higher than +1. All cointegrating vectors are found to be statistically higher than +1 whatever the sample frequency selected, monthly, weekly, or daily, and whatever the functional forms or the econometric procedures adopted. Subsidiary results are that the samples chosen do not contain calendar structural breaks, and that regionalization of the oil market is strongly denied. These results reject the underlying intuition and theory, and set the stage for a possible financial anomaly.

Keywords: BRENT and West Texas Intermediate Crude Oil Spot Prices, Cointegration, Error-correction Models, Generalized Auto-regressive Conditional Heteroscedasticity Methods, Bias in the Association, Three Data Frequencies, Oil Market Integration

JEL Classifications: C22, C12, G15, Q41

1. INTRODUCTION

Crude oils are nonrenewable, exhaustible, natural resources with different origins and qualities. BRENT crude oil is extracted from the North Sea and is considered to be a benchmark due to its location, and the ease in its transportation. West Texas Intermediate (WTI) is extracted from the fields of Texas, Oklahoma, New Mexico, and Kansas. There are two characteristics that identify the quality of a crude oil. The first is the gravity of the American Petroleum Institute (API) and the second is the sulfur content. Crude oils with low API densities (between 35° and 40°) are light crude oils. The crude oil is said to be sweet if the sulfur content is <0.5%. Since the sulfur content should be removed before refining, the higher the percentage of sulfur, the less sweet the crude oil is. The WTI and BRENT crude oils have an API of 39.6° and 38.3° respectively, and they have a sulfur content of 0.24% and 0.37%, respectively. This makes them both light and sweet crude oils. WTI has a slightly better quality than BRENT as it is made up of a less sulfur percentage.

Adelman (1984) described the oil market as one great pool, like the world ocean. To continue with the same picturesque analogy J. F. Kennedy is quoted to have said out of context: "A rising tide lifts all boats." These comparisons intend to mean that oil markets are "integrated" or "globalized," in contrast of being "fragmented" or "regionalized." If oil markets are integrated prices of crude oils rise and fall in tandem, although the extent and the degree of association are left unspecified.

Weiner (1991) used correlation and regression analysis on monthly oil spot prices to test for this association. He concludes that the results "indicate a surprisingly high degree of regionalization, implying that the world oil market is far from completely unified." With the advent of cointegration tools for analysis, researchers became more interested in testing for a long run association, which is what cointegration intends to reveal. In brief, two variables have a cointegrating association if there exists a cointegrating coefficient between them that reduces the order of integration of a combination of these two variables. A stationary series has a zero order of integration while a random walk has a unitary order of integration.

Gülen (1997; 1999) uses the bivariate and multivariate cointegration tests introduced by Johansen (1988) and Johansen and Juselius (1990). Gülen (1997) applies the tests on monthly data, while Gülen (1999) applies them on weekly data. All variables are logged. Regionalization of oil markets is rejected for both frequencies of data. In addition, Gülen (1999) discovers that the two subsamples, one of falling prices, and the other for rising prices, have different degrees of co-movement, with the latter being stronger during the second sub-period, that of rising prices.

Hammoudeh et al. (2008) find that there is a long run equilibrium relation between BRENT and WTI, among others, allowance being made for an asymmetric adjustment process. Hammoudeh et al. (2008) carry out their tests on the bivariate spreads between the crude oil prices they study, assuming implicitly that the cointegrating vector is unitary, an assumption which should not to be taken for granted. This paper provides evidence that invalidates such an assumption. Fattouh (2010) also studies the weekly dynamics of crude oil price spreads and these are modeled to follow a two-regime threshold auto-regressive process. The spreads show strong evidence of stationarity, but the adjustment process to the long run follows a non-linear equilibrium. Liao et al. (2014) also studies spreads, and specifically monthly, weekly, and daily spreads, and applies on the data a quantile unit root approach with structural breaks. They find that the monthly and weekly BRENT/WTI spreads contain a unit root in the lower quantiles but in the upper quantiles there is a pronounced mean reversion. However the daily spreads reject the null of unit root for all quantiles, and hence these spreads are stationary and revert to the mean at all quantiles.

Bentzen (2007) studies four crude oil daily prices that include BRENT and WTI over the period 22 April 1987-31 December 2004. Bentzen runs bivariate cointegrating regressions, and is the only one in the literature to report the cointegrating vector. For example this vector is 1.046 between BRENT and WTI. Unfortunately Bentzen does not report a standard error on this coefficient. So there is no way to test for a unitary coefficient. Bentzen carries out residual-based cointegration tests, also called Engle and Granger tests (Engle and Granger, 1987). However when testing spreads between crude oil prices Bentzen rejects the null of no-cointegration by both Engle-Granger tests and by Johansen tests that are not reported. This prompts Bentzen to study oil price differentials subsequently. While testing the vector error-correction models (VECM) of spreads Bentzen adds a conditional variance equation and this variance is modeled to be integrated or order one generalized auto-regressive conditional heteroscedasticity (IGARCH). Finally Bentzen splits the sample into three subsamples chosen according to severe macroeconomic shocks. All in all Bentzen supports the initial evidence of Gülen (1997; 1999) about integration of oil markets, and rejects strongly regionalization. However Bentzen concludes that the adjustment to the long run is too slow as measured by the absolute value of the coefficient on the error-correction lagged cointegration residual. Another look at the adjustment process shows that the adjustment between BRENT and WTI has a maximum of 48 days or around 10 weeks, which cannot be considered slow at all.

This paper adds to the literature evidence that the relation between the price of the UK BRENT crude oil and the price of the WTI crude oil is statistically significantly different from +1. As a matter of fact the relation is statistically significantly higher than +1. While theoretically a unitary relation is predicted for a log-log regression and is routinely assumed in most of the literature, a non-unitary relation is predicted for a linear regression in the levels of the oil prices. Because of the theoretical implications, regressions in the levels of the prices are uniquely conducted here, and hence are not to be found elsewhere. Moreover three sample frequencies are considered: Monthly, weekly, and daily. As a background to the empirical results it is necessary to test whether there are endogenous, or otherwise, calendar breaks in the series. Since the sample includes more and very recent data, which is comprised of all types of trends, upward, downward, and steady, it should come as no surprise that the tests reject strongly the hypothesis of the existence of breaks for all of the three frequencies of prices, and for the two underlying categories of variables, in levels, and in log-levels.

The evidence on a long run coefficient of association that is greater than +1 derives from more than one cointegration test. The first is the Johansen (1988; 1991; 1995), and the Johansen and Juselius (1990) tests. The three next ones are the fully-modified ordinary least squares (FMOLS) (Phillips and Hansen, 1990; Hansen, 1992a; 1992b), the dynamic OLS (DOLS) (Saikkonen, 1992; Stock and Watson, 1993), and the canonical cointegrating regression (CCR) (Park, 1992), where OLS stands for ordinary least squares. The fifth one is the auto-regressive distributed lag model (ARDL) (Pesaran and Shin, 1999; Pesaran et al., 2001), which identifies the VECM. And the last one is by estimating the VECM from the ARDL regression routine with the addition of a conditional variance equation, whether symmetric or asymmetric, to account for conditional heteroscedasticity (Engle, 1982).

The paper is organized as follows. In the next section two theoretical models are constructed to justify the association between the two crude oils considered: BRENT and WTI. This is necessary because the literature does not explore any underlying theory, and assumes a relation without any theoretical back-up, except that these two crude oils are close substitutes. Then in section 3, which is the empirical part, the regression estimates are carried out, and are explained and interpreted. This section begins by testing for stationarity of the variables. This is necessary as a requisite for cointegration. Then we look for structural breaks in the data. We end the section by the identification of the best regression specifications. The hypothesis that the long run coefficient of association is higher than +1 is tested for all model specifications with the same common result: This coefficient is always statistically higher than +1. The final section summarizes and concludes.

2. THEORETICAL MODELS

2.1. Perfect Substitutes in Consumption

According to any microeconomics textbook, perfect substitutes have the linear indifference curve, generated by a utility function for the two goods X and Y of the form:

$U(X,Y)=\alpha X+\beta Y$ with $\alpha>0$ and $\beta>0$

This utility implies that the marginal rate of substitution (MRS) is a constant and is equal to α/β. If MU(.)=Marginal utility, and P is the price, then one has:

$$\text{MRS}=\frac{\text{MU(X)}}{\text{MU(Y)}}=\frac{P_X}{P_Y}=\frac{\alpha}{\beta}=\text{constant}$$

Which implies the regression function:

$$P_X=\gamma_0+\gamma_1 P_Y+\text{error with } \gamma_0=0, \text{ and } \gamma_1=\frac{\alpha}{\beta}>0$$

And implies the log-log regression model:

$$\text{LOG}(P_X)=\delta_0+\delta_1\text{LOG}(P_Y)+\text{error with } \delta_0=\text{LOG}(\alpha/\beta) \text{ and } \delta_1=1$$

This latter equation can be called a form of unbiasedness hypothesis between the log-prices of the WTI and BRENT oil prices, if these oils are indeed perfect substitutes. One may want to describe this equation as a test of the law of one price.

The analysis so far was for the short run. In the long run the prices of perfect substitutes must be equal, while in the short run they may diverge. The reasoning is as follows. If the price of X is lower than the price of Y, then there will be an excess demand for X, which raises the price of X and returns the market to equilibrium. So, in the long run one has:

$$P_X=\gamma_0+\gamma_1 P_Y+\text{error with } \gamma_0=0, \text{ and } \gamma_1=\frac{\alpha}{\beta}=1$$

And:

$$\text{LOG}(P_X)=\delta_0+\delta_1\text{LOG}(P_Y)+\text{error with } \delta_0=\text{LOG}(\alpha/\beta)=\text{LOG}(1)=0 \text{ and } \delta_1=1$$

These two regressions describe unbiasedness, or the law of one price. Unbiasedness requires the joint hypothesis that the intercept be zero and the slope equals +1. This applies to a linear functional form and to a log-log functional form. This unbiasedness condition can be named to be strong. A weaker unbiasedness condition is that the slope equals +1, leaving the intercept to take other values than zero, especially if there are fixed transportation costs that have an impact on γ_0 and δ_0. See Kleit (2001) for estimates of transportation costs. It must be stressed that in this model weak unbiasedness holds only in the long run for the linear model, but holds in both short and long runs for the log-log model.

2.2. Perfect Substitutes in Production: Similar Technologies

The model settings are as follows:

1. A Cobb-Douglas production function, i.e., production (Q) is a function solely of labor (L) and capital (K). There are two firms, each a monopoly in its industrial organization, producing each a different category of crude oil, and they have the same technology.
2. Constant returns to scale. Therefore $Q=L^{\alpha} K^{1-\alpha}$. Firms cannot grow or shrink forever, and are on a steady state path. This assumption can be relaxed without undue repercussions.
3. The two firms are price takers in the factor input market with a given wage rate w and with a given interest rate r.
4. The two firms act as monopolies but are faced by different demand curves, and different price elasticities of demand denoted as $\in_1^d$ and $\in_2^d$

The Lagrangian is therefore as follows:

$$\text{Minimize } wL+rK+\lambda(Q\text{-}L^{\alpha}\text{-}K^{1-\alpha})$$

After many manipulations the result is that total cost is a linear function of quantity, implying that the marginal cost (MC) is constant:

$$\text{Total Cost}=Q\left(\frac{w}{\alpha}\right)^{\alpha}\left(\frac{r}{1\text{-}\alpha}\right)^{1\text{-}\alpha} \Rightarrow \text{MC}=\left(\frac{w}{\alpha}\right)^{\alpha}\left(\frac{r}{1\text{-}\alpha}\right)^{1\text{-}\alpha}=\text{constant}$$

Since each monopolist maximizes profits then marginal revenue (MR) must be equal to MC, which is equal to a constant. And since the two firms have the same production technology, producing each a different category of crude oil, then:

$$\text{MC}=\text{MR}=\text{MR}_x=\text{MR}_y=P_x\left(1\text{-}1/\in_x^d\right)=P_y\left(1\text{-}1/\in_y^d\right)$$

Hence:

$$P_x=P_y\left[\left(1\text{-}1/\in_y^d\right)/\left(1\text{-}1/\in_x^d\right)\right] \text{ and}$$

$$\text{LOG}\left(P_x\right)=\text{LOG}\left[\left(1\text{-}1/\in_y^d\right)/\left(1\text{-}1/\in_x^d\right)\right]+\text{LOG}\left(P_y\right)$$

The first equation on the LHS predicts that the slope of a regression of P_x on P_y has a slope different from +1, whereas the equation in logs on the RHS predicts a slope of a regression of LOG (P_x) on LOG (P_y) of +1. There is again weak unbiasedness.

All these equations demonstrate that if the two crude oils can be considered as perfect substitutes in consumption, or as perfect substitutes in production, the relation between the logs of their two prices is unitary, while the relation between the levels of their two prices may be different from +1.

2.3. Realistic Assumptions?

How realistic are the assumptions of the two theoretical and tentative models? The first model assumes perfect substitutes in consumption. As a matter of fact there are around 700 oil refineries in the world (Billege, 2009) that consume directly these two crude oils. Such a large number of consumers create strong competition on the demand side. The second model assumes that the price elasticities of demand for BRENT and of WTI are different. Ideally we would like to have direct estimates of these elasticities. Unfortunately only elasticities by country are available. One might argue that the US and Canadian price elasticities are closer to a WTI price elasticity, and that a European price elasticity is closer to a BRENT price elasticity. Cooper (2003) estimates the US price elasticity to be −0.061 in the short run and −0.453 in the long run, and the Canadian price elasticity to be −0.041 and −0.352 respectively. This contrasts with a short run elasticity of −0.068 for the United Kingdom, and a long run one of −0.182. Italy's short run price elasticity is −0.035, and its long run one is −0.208. More recent estimates are in Javan and Zahran (2015).

The US short run elasticity is found to be −0.05, and the long run is −0.18, while the Canadian elasticities are −0.02 and −0.08 respectively. However, Italy's price elasticity is estimated as −0.16 in the short run and −0.27 in the long run, both higher than their US counterparts. The UK, relative to the US, has a higher short run elasticity of −0.10, but a lower long run elasticity of −0.16. These data present evidence on how disparate the price elasticities are. Hence assuming that the price elasticities are not constant is indeed realistic.

A second assumption is about the MR and the MC. We assumed that the MC of producing BRENT and WTI are the same, and are equal to their MR. From the web site of EOG Resources, and Specifically from the Annual Reports (2005; 2008; 2011; 2014; 2015) the MR is estimated to be \$ 41 per barrel and the MC \$ 35 per barrel. The MR is calculated as the ratio of the yearly change in total revenue on the yearly change in total production. The MC is calculated as the ratio of the yearly change in total cost over the yearly change in total production. Since the computed MC does not include a cost for the equity of the firm it shall inevitably be lower than MR. Hence the data imply a mark-up for the cost of equity of around 17%, i.e., (1+0.17) MC≈MR, which is reasonable.

EOG resources, Inc., produces mostly a WTI blend. From the web site of Total S.A., and especially from its "fact book 2015," the MC is \$ 36.5 per barrel on average for the years 2013-2015 (page 30 of the fact book), and the average margin for the years 2010/2015 is \$ 27.65 per metric ton (page 7), which is equivalent to a margin of \$ 3.87 per barrel, making the MR equal to \$ 40.4 per barrel. Total S.A. is a French company producing mostly a BRENT blend (Total, 2016). Hence although the MR and the MC are different for each firm, and therefore for each blend, with the MR higher than the MC, the two MR and the two MC for the two firms are quasi the same. Since the model hinges on the fact that price elasticities of demand are different but that, nevertheless, the MR of the two blends are equal, the assumptions of the model are met with great realism. As a conclusion, and although the models are simple and little sophisticated they can describe the oil market with much exactitude.

3. EMPIRICAL RESULTS

3.1. Data

We conduct our study on WTI and BRENT crude oil spot prices, extracted from the US Energy Information website, accessed in 2016, for the following periods:

i. The period starting May 20, 1987 till May 9, 2016 for daily spot prices, making up 7.246 observations.
ii. The period starting May 15, 1987 till May 6, 2016 for weekly prices, making up 1.513 observations.
iii. The period starting May 1987 till April 2016 for monthly prices, making up 348 observations.

The tests will include the levels of the spot crude oil prices, with their first difference, and the natural logs of the spot prices, with their first difference. Since the theory, in the previous section, predicts different relations for level and log-level data, both level and log-levels data are considered. Considering level data is totally original within the empirical literature.

The theory predicts that the level linear associations may or may not be unitary, while it predicts that the log linear associations are always unitary. We decided to associate the spot prices of BRENT upon the spot prices of WTI. Since most estimated relations have some sort of cointegration specification, the choice of which variable is the dependent and which variable is the independent regressor does not matter, as cointegration is known to be robust to simultaneity bias.

3.2. Stationarity Tests

In conformity to parts of the literature, for example Bentzen (2007), three unit root tests are usually used and these will be used to test the variables for stationarity. The first is the Augmented Dickey-Fuller (ADF) test (Dickey and Fuller, 1979; 1981, Said and Dickey, 1984). The second is the Phillips and Perron (1988) P&P test. The third is the Kwiatkowski et al. (1992) KPSS test. The first two tests have the null hypothesis of non-stationarity, while the KPSS test has the null of a stationary series. All tests include a constant and a time trend.

Table 1a applies the ADF test on BRENT, LOG(BRENT), and their first differences, while Table 1b applies the same test on WTI, LOG(WTI), and their first differences. The null hypothesis of a unit root fails to be rejected on BRENT and LOG(BRENT), with a minimal ADF P = 0.199900. The null hypothesis is rejected for Δ(BRENT) and Δ(LOG[BRENT]) with a maximal P = 0.0001. The null hypothesis of a unit root fails to be rejected on WTI and LOG(WTI), with a minimal P = 0.093900. The null hypothesis is rejected for Δ(WTI) and Δ(LOG[WTI]) with a maximal P = 0.00001. The maximum allowable lag for the ADF test is 16 for monthly data, 23 for weekly data, and 35 for daily data. The optimal lag length is selected auto-matically by minimizing the Schwarz information criterion (SIC).

The null hypothesis of a unit root fails to be rejected on BRENT and LOG(BRENT), with a minimal P&P P value of 0.362400 (Table 2a). The null hypothesis is rejected for Δ(BRENT) and

Table 1a: ADF unit root tests

H_0: BRENT (LOG[BRENT]) has a unit root (is non-stationary) H_a: BRENT (LOG[BRENT]) has no unit root (is stationary)				
Sample	BRENT		LOG(BRENT)	
	Level	1st difference	Level	1st difference
Monthly	0.199900	0.000000	0.226800	0.000000
Weekly	0.634400	0.000000	0.414700	0.000000
Daily	0.718600	0.000100	0.409000	0.000100

Actual P values are reported, ADF: Augmented Dickey-Fuller

Table 1b: ADF unit root tests

H_0: WTI (LOG[WTI]) has a unit root (is non-stationary) H_a: WTI (LOG[WTI]) has no unit root (is stationary)				
Sample	WTI		LOG(WTI)	
	Level	1st difference	Level	1st difference
Monthly	0.093900	0.000000	0.176300	0.000000
Weekly	0.502700	0.000000	0.336600	0.000000
Daily	0.504900	0.000100	0.227300	0.000000

Actual P values are reported, WTI: West Texas intermediate, ADF: Augmented Dickey-Fuller

Δ(LOG[BRENT]) with a maximal P&P P value of 0.0001. The null hypothesis of a unit root fails to be rejected on WTI and LOG(WTI), with a minimal P&P P value of 0.209600 (Table 2b). The null hypothesis is rejected for Δ(WTI) and Δ(LOG[WTI]) with a maximal P&P P value of 0.00001. The bandwidth of the P&P tests is selected auto-matically by the Newey-West method.

According to the KPSS test, reported in Tables 3a and 3b, all level and log-level variables reject the null hypothesis of stationarity and contain one unit root with a marginal significance level less than 1%, while all first-differences of the level and log level variables fail to reject the null hypothesis of stationarity, with a P > 10%. The only weak exception is the monthly Δ(BRENT) which has a P-value between 5% and 10%. The bandwidth of the KPSS tests is selected auto-matically by the Newey-West method.

Table 2a: Phillips and Perron unit root tests

H_0: BRENT (LOG[BRENT]) has a unit root (is non-stationary) H_a: BRENT (LOG[BRENT]) has no unit root (is stationary)				
Sample	BRENT		LOG (BRENT)	
	Level	1st difference	Level	1st difference
Monthly	0.515100	0.000000	0.412600	0.000000
Weekly	0.376700	0.000000	0.362400	0.000000
Daily	0.670800	0.000100	0.448000	0.000100

Actual P values are reported

Table 2b: Phillips and Perron unit root tests

H_0: WTI (LOG[WTI]) has a unit root (is non-stationary) H_a: WTI (LOG[WTI]) has no unit root (is stationary)				
Sample	WTI		LOG(WTI)	
	Level	1st difference	Level	1st difference
Monthly	0.351900	0.000000	0.385400	0.000000
Weekly	0.209600	0.000000	0.315500	0.000000
Daily	0.521300	0.000100	0.332600	0.000100

Actual P values are reported, WTI: West Texas intermediate

3.3. Calendar Breaks

Having ascertained the presence of one unit root, the differenced data is examined for structural breaks. A majority of the research papers found the need to divide the sample into two or more breaking points. However the inclusion of very recent data on the spot prices may reverse such a proposition, because the analysis will cover periods of rising prices, periods of falling prices, and periods when the spot prices are steady.

Two tests for breaks are carried out, both with a 15% trimming. The first is the Quandt-Andrews unknown breakpoint test (Andrews, 1993; Andrews and Ploberger, 1994) with probabilities computed using Hansen's (1997) method. This test has the following statistics: The maximum of the individual Chow F-statistics (Chow, 1960), denoted as maximum statistic, the log of the average exponential Chow test, denoted Exp statistic and the average of the Chow F-statistics, denoted as Ave statistic. These three statistics have each one a couple of separate tests: One using a likelihood ratio F-statistic, and the other using a Wald F-statistic. Note that in linear equations these couples are identical. In the daily sample 5.072 breakpoints are compared. In the weekly sample 1.059 breakpoints are compared. In the monthly sample 242 breakpoints are compared.

The second generalized Quandt-Andrews test, known as Bai-Perron, is a test that allows for multiple breakpoints (Bai, 1997; Bai and Perron 1998; 2003a). The critical values are taken from Bai and Perron (2003b).

Our assertion of an absence of breaks is in general supported (Table 4). All tests fail to reject the null hypothesis of no breakpoint at the 2.5% marginal significance level. Only six statistics are significant at the 5% marginal significance level. The total number of test statistics is 84. The statistics that reject the null hypothesis of no breakpoint are both weekly and correspond to the first difference of BRENT, i.e., Δ(BRENT), and the first difference of WTI, i.e., Δ(WTI). These first-differences do not have any economic

Table 3a: KPSS unit root tests

H_0: BRENT (LOG[BRENT]) has no unit root (is stationary) H_a: BRENT (LOG[BRENT]) has a unit root (is non-stationary)				
Sample	BRENT		LOG(BRENT)	
	Value of statistic at level	Value of statistic at 1st difference	Value of statistic at Level	Value of statistic at 1st difference
Monthly	0.248320	0.139091	0.254729	0.094411
Weekly	0.450641	0.072063	0.472248	0.073519
Daily	0.937438	0.103015	0.986588	0.082659

Critical values are 0.216 (1%), 0.146 (5%), and 0.119 (10%)

Table 3b: KPSS unit root tests

H_0: WTI (LOG[WTI]) has no unit root (is stationary) H_a: WTI (LOG[WTI]) has a unit root (is non-stationary)				
Sample	WTI		LOG(WTI)	
	Value of statistic at Level	Value of statistic at 1st difference	Value of statistic at level	Value of statistic at 1st difference
Monthly	0.2477460	0.1152550	0.2405200	0.0866740
Weekly	0.4164270	0.0566840	0.4404800	0.0667570
Daily	0.8504570	0.0836140	0.9156860	0.0686559

Critical values are 0.216 (1%), 0.146 (5%), and 0.119 (10%). WTI: West Texas intermediate significance, in contrast to the first differences of LOG(BRENT), i.e., Δ(LOG[BRENT]), and of LOG(WTI), i.e., Δ(LOG[WTI]), which measure proportional returns, i.e., what the literature calls log returns. As a matter of fact they measure the continuously compounded rate of return.

3.4. Johansen Tests

Tables 5a and 5b apply respectively the trace test and the maximum Eigen value test on the relation between BRENT and WTI, and LOG(BRENT) and LOG(WTI). Since from the previous section all series were found to be integrated of order one, a Johansen cointegration test can be carried out. A zero cointegrating vector is rejected for all relations at a marginal significance level <0.01. The existence of at most one cointegrating vector fails to be rejected for all relations with a minimal marginal significance level of 0.0576. As a conclusion BRENT and WTI are cointegrated for all three data frequencies, monthly, weekly and daily, and LOG(BRENT) and LOG(WTI) are also cointegrated for these same three data frequencies. This is true according to the trace tests and the maximum Eigen value tests. Therefore one can say that the crude oil market, as exemplified by the BRENT and the WTI markets, are integrated and form a common pool.

In Table 6 the null hypotheses of statistically insignificant slope coefficients are tested with a t-statistic. The cointegrating vectors, i.e., the slope coefficients, are all highly significant statistically with a minimum t-statistic of 32.6377. This applies to the linear level regressions and the log-log specifications, and is true for all data frequencies. In Table 7 the null hypotheses of unitary slope coefficients are tested with a Chi-square test. The cointegrating vectors, i.e., the slope coefficients, are all statistically significantly different from +1 with a maximum actual P = 0.004652. This applies to the linear level regressions and the log-log specifications, and is true for all data frequencies.

Table 4: Quandt-Andrews unknown breakpoint tests, and Bai-Perron multiple breakpoint tests

Monthly	Δ(WTI)	ΔLOG(WTI)	Δ(BRENT)	ΔLOG(BRENT)
Maximum LR F-statistic	0.0821	0.3723	0.0871	0.4146
Maximum Wald F-statistic	0.0821	0.3723	0.0871	0.4146
Exp LR F-statistic	0.3072	0.5010	0.2350	0.5178
Exp Wald F-statistic	0.3072	0.5010	0.2350	0.5178
Ave LR F-statistic	0.5626	0.5600	0.5260	0.5807
Ave Wald F-statistic	0.5626	0.5600	0.5620	0.5807
Bai-Perron test	>0.05	>0.05	>0.05	>0.05
Weekly				
Maximum LR F-statistic	0.0415	0.4359	0.0421	0.4310
Maximum Wald F-statistic	0.0415	0.4359	0.0421	0.4310
Exp LR F-statistic	0.2897	0.6065	0.1739	0.5336
Exp Wald F-statistic	0.2897	0.6065	0.1739	0.5336
Ave LR F-statistic	0.5604	0.6414	0.4779	0.5874
Ave Wald F-statistic	0.5604	0.6414	0.4779	0.5874
Bai-Perron test	>0.025 and<0.05	>0.05	>0.025 and<0.05	>0.05
Daily				
Maximum LR F-statistic	0.1696	0.7180	0.0987	0.6046
Maximum Wald F-statistic	0.1696	0.7180	0.0987	0.6046
Exp LR F-statistic	0.6161	0.8246	0.3447	0.6823
Exp Wald F-statistic	0.6161	0.8246	0.3447	0.6823
Ave LR F-statistic	0.7478	0.8194	0.5920	0.7102
Ave Wald F-statistical	0.7478	0.8914	0.5920	0.7102
Bai-Perron test	>0.05	>0.05	>0.05	>0.05

The null hypothesis for all tests is no breakpoint. Trimming is 15% for both tests. Number of breaks compared for the Quandt-Andrews test are 242 (monthly data), 1059 (weekly data), and 5072 (daily data). Maximum number of breaks is 5 for the Bai-Perron test, WTI: West Texas intermediate

Table 5a: Actual P values of the Johansen test (trace test)

Sample	Zero cointegrating vector		At most one cointegrating vector	
	BRENT/WTI	LOG(BRENT)/LOG (WTI)	BRENT/WTI	LOG(BRENT)/LOG(WTI)
Monthly	0.001800	0.00010	0.057600	0.10100
Weekly	0.006000	0.00000	0.112700	0.14320
Daily	0.000000	0.00010	0.136100	0.13610

WTI: West Texas intermediate

Table 5b: Actual P values of the Johansen test (Maximum Eigen value test)

Sample	Zero cointegrating vectors		At most one cointegrating vector	
	BRENT/WTI	LOG(BRENT)/LOG (WTI)	BRENT/WTI	LOG(BRENT)/LOG(WTI)
Monthly	0.0041000	0.00010	0.0576000	0.10100
Weekly	0.0091000	0.00000	0.1127000	0.14320
Daily	0.0000000	0.00010	0.1361000	0.13610

WTI: West Texas intermediate

3.5. ARDL Models

Next ARDL models are estimated. The lag length is selected according to the SIC, and the maximum number of lags is 6 months for the monthly models, 5 weeks for the weekly models, and 10 days for the daily models. The number of models evaluated is 42 for the monthly data, 30 for the weekly data, and 110 for the daily data. The advantage of the ARDL econometric specification is that it does not impose a common lag length for the independent variables. In Table 8a t-tests on the ARDL econometric specification are conducted. For all three frequencies and for both linear level regressions and log-log regressions the null hypotheses of statistically insignificant slope coefficients, or insignificant cointegrating vectors, are rejected with a minimal t-statistic of 25.407. The minimum estimate of the cointegrating vector is 1.08216, and the maximum is 1.11747.

In Table 8b t-tests on the ARDL cointegration regressions are conducted. The null hypotheses tested are whether the slope coefficients, or the cointegrating vectors, are insignificantly different from +1. These nulls are all rejected with a minimal t-statistic of 2.409, and a maximal one of 7.588.

The evidence in this subsection corroborates the evidence in the previous subsection and this is that there is a bias in the relation between BRENT and WTI crude oil prices whatever the specification and whatever the data frequency. Furthermore one can conclude solidly that the stipulation of cointegrating vectors bigger than +1 is strongly supported.

3.6. Other Cointegration Regressions: OLS, CCR, DOLS, and FMOLS

There are other econometric specifications to test for the cointegration regressions. We begin by the residual-based Engle and Granger (1987) tests and the Phillips and Ouliaris (1990) tests which both rely on an OLS form of analysis. Table 9 provides for the results. The Engle and Granger tests reject the null hypotheses of no cointegration at a marginal significance level of <0.002. The maximum actual P = 0.01240 for one case of the Phillips-Ouliaris test: The monthly BRENT/WTI. The following next case has a P < 0.004. Therefore all OLS regressions can be described as being cointegration regressions.

Three alternative tests for cointegration are applied to the data: FMOLS (Phillips and Hansen, 1990), CCR (Park, 1992), and DOLS (Saikkonen, 1992; Stock and Watson, 1993). For details on all these tests the reader is referred to the user guides of Eviews 9.5 (2016). The FMOLS and the CCR cointegration regressions include a constant only, and the long run covariance estimate is carried out by minimizing the SIC for the lags, and using a Bartlett kernel, and a Newey-West auto-matic bandwidth. The DOLS cointegration regression selects the leads and the lags according

Table 6: Johansen cointegration test (t-statistic)

H_0: There is no long term cointegration (coefficient (WTI) =0; or coefficient of LOG (WTI)=0) H_a: There is long term cointegration (coefficient (WTI) ≠0; or coefficient of LOG (WTI)≠0)		
	Original data	**Logarithmic data**
Monthly		
Coefficient	1.142942	1.096010
t-statistic	35.2287	76.4154
P-value	0.00000	0.00000
Weekly		
Coefficient	1.129529	1.090853
t-statistic	32.6377	83.7646
P-value	0.00000	0.00000
Daily		
Coefficient	1.124958	1.092539
t-statistic	42.6217	130.3320
P-value	0.00000	0.00000

WTI: West Texas intermediate

Table 7: Johansen cointegration test (Chi-squared distribution)

H_0: There is no long run bias (coefficient of WTI=1; or coefficient of LOG (WTI)=1) H_a: There is long run bias (coefficient of WTI≠1; or coefficient of LOG (WTI)≠1)		
	Original data	**Logarithmic data**
Monthly		
Coefficient	1.142942	1.096010
Chi-squared	10.25406	17.75720
P-value	0.001364	0.000025
Weekly		
Coefficient	1.129529	1.090853
Chi-squared	8.0,10,147	21.79,999
P-value	0.004652	0.000003
Daily		
Coefficient	1.124958	1.092539
Chi-squared	14.080600	59.869440
P-value	0.000175	0.000000

WTI: West Texas intermediate

Table 8a: ARDL long run cointegration

H_0: There is no long run cointegration (coefficient=0) H_a: There is long run cointegration (coefficient≠0)			
	Dependent	**BRENT**	**LOG(BRENT)**
Monthly	Coefficient	1.117466	1.092325
	t-statistic	25.407236	73.037232
	P-value	0.000000	0.000000
Weekly	Coefficient	1.095630	1.082160
	t-statistic	27.594396	75.750400
	P-value	0.000000	0.000000
Daily	Coefficient	1.098026	1.083921
	t-statistic	34.434650	98.006827
	P-value	0.000000	0.000000

ARDL: Auto-regressive distributed lag

Table 8b: ARDL long run cointegration

H_0: There is no long run bias (coefficient=1) H_a: There is long run bias (coefficient≠1)			
Sample	**Dependent**	**BRENT**	**LOG(BRENT)**
Monthly	Coefficient	1.117466	1.092325
	t-statistic	2.670774	6.173108
Weekly	Coefficient	1.095630	1.082160
	t-statistic	2.408513	5.751085
Daily	Coefficient	1.098026	1.083921
	t-statistic	3.074168	7.587794

ARDL: Auto-regressive distributed lag

to the SIC, and the long run variance estimate is carried out by using a Bartlett kernel, and a Newey-West fixed bandwidth. The choice of the SIC in the cointegration regressions is dictated by a preoccupation for consistency within this whole paper.

Table 10 presents the empirical results. Two general tests are carried out. The first is whether the slopes, or cointegrating vectors, are statistically significantly different from zero. The second is whether the slopes, or cointegrating vectors, are different from +1. For the first tests the minimum t-statistic is 33.322, and for the second test the minimum t-statistic is 4.284. Whatever the marginal significance level that is usually selectable, the two null hypotheses of zero slopes and of slopes equal to +1, are rejected. Moreover, upper-tailed tests for the second set of tests can be applied. The result is that all slopes, or cointegrating vectors, are higher than +1. This is additional evidence, to be associated with the above results, that there is a bias in the long run relation between BRENT and WTI, and specifically that the bias is on the upper side.

3.7. ECM Models with Conditional Variances

The ARDL estimation process produces as a subsidiary output the error-correction model. However this model does not allow for conditional heteroscedasticity (Engle, 1982; Bollerslev, 1986). That is why we decided to estimate the following joint regression estimates with a GARCH(1,1) conditional variance, where the dependent variable of the mean equation is the first-difference of the log of BRENT, $\Delta LOGY_t$, and the independent variables, i.e., the sequence of logs of WTI, are $\Delta LOGZ_{t-i}$, and the lags of the dependent variable:

$$\Delta LOGY_t = \sum_{i=0}\alpha_i \Delta LOGZ_{t-i} + \sum_{j=1}\beta_j \Delta LOGY_{t-j} + \gamma\varepsilon_{t-1} + \vartheta_t$$

$$\varepsilon_{t-1} = LOGY_{t-1} - \text{constant} - \sum_{i=0}\delta_i LOGZ_{(t-i)}$$

$$\sigma_t^2 = \theta_0 + \theta_1\vartheta_{t-1}^2 + \theta_2\sigma_{t-1}^2$$

For the linear level joint regression Y_t is the dependent variable and the sequence of lags of $Z_{(t-i)}$ are the independent variables together with the lagged dependent variables. The GARCH(1,1) model can be easily replaced by an EGARCH model (Nelson, 1991), and/or by a TARCH model (Glosten et al., 1993; Zakoian, 1994). Both the EGARCH and the TARCH models assume asymmetry of the impact of news on the conditional variance.

The results are presented in Table 11. Blank spaces means either that the joint regression did not converge, or that the statistical software used was unable to produce results. Again two tests as in the previous section are carried out. The two null hypotheses are that the slopes, or the cointegrating vectors, are no different from zero, and that they are also no different from +1. For the first test the minimum t-statistic in the table is 68.278. And for the second test the minimum t-statistic is 3.184. A right upper-tailed test for the second set of hypotheses can be undertaken, and the conclusion is that the bias of the relation between BRENT and WTI, and in all its specifications, is upward.

In Table 12 econometric diagnostics are applied on the GARCH(1,1) specifications of the ECM models. Two sets of tests

Table 9: Residual-based cointegration tests

Sample	H_0: There is no cointegration H_a: There is cointegration Engle-Granger test		Phillips-Ouliaris test	
	BRENT/WTI	LOG(BRENT)/LOG (WTI)	BRENT/WTI	LOG(BRENT)/LOG(WTI)
P-value in monthly data	0.00060	0.00000	0.01240	0.00000
P-value in weekly data	0.00140	0.00000	0.00040	0.00000
P-value in daily data	0.00000	0.00000	0.00000	0.00000

WTI: West Texas intermediate

Table 10: Cointegrating regressions

Sample	Method	CCR		DOLS		FMOLS	
	Variable	WTI	LOG(WTI)	WTI	LOG(WTI)	WTI	LOG(WTI)
Monthly	P-value	0.00000	0.000000	0.000000	0.000000	0.000000	0.000000
	t-statistic	34.78521	79.88764	62.21868	117.71030	33.32202	79.20061
	Coefficient	1.148136	1.098352	1.107337	1.087913	1.152021	1.098767
	t-test	4.488184	7.153512	6.031028	9.512014	4.397175	7.119267
	P-value	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Weekly	P-value	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	t-statistic	37.08082	84.10703	104.8642	188.98690	36.47084	83.984310
	Coefficient	1.132159	1.090754	1.106028	1.087600	1.133094	1.090765
	t-test	4.328500	6.997931	10.05265	15.221810	4.283902	6.988501
	P-value	0.000000	0.000000	0.000000	0.000000	0.00000	0.000000
Daily	P-value	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	t-statistic	45.51130	80.171100	190.4118	331.82380	45.29607	142.59860
	Coefficient	1.121822	1.090450	1.105610	1.087537	1.121990	1.091851
	t-test	4.942222	6.649957	18.18851	26.70890	4.924868	11.99594
	P-value	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

The t-statistic is for the null hypothesis that the slope is zero. The t-test is for the null hypothesis that the slope is equal to+1. DOLS: Dynamic ordinary least squares, CCR: Canonical cointegrating regression, FMOLS: Fully-modified ordinary least squares, WTI: West Texas intermediate

Table 11: GARCH/TGARCH/EGARCH estimations

A. H_0: There is no long run cointegration (cointegrating vector=0)
H_a: There is long run cointegration (cointegrating vector≠0)
B. H_0: There is no bias in the long run (cointegrating vector=1)
H_a: There is bias in the long run (cointegrating vector≠1)

Model	Original data			Logarithmic data		
	Coefficient	z-statistic (A)	t-test (B)	Coefficient	z-statistic (A)	t-test (B)
Monthly						
GARCH(1,1)				1.06638	81.80225	5.090365
TGARCH(1,1)				1.05694	71.41045	3.847308
EGARCH(1,1)				1.06340	75.16257	4.475204
Weekly						
GARCH(1,1)	1.053741	72.20030	3.682151	1.06949	90.68073	5.889351
TGARCH(1,1)	1.052547	68.27849	3.408823	1.06948	89.86162	5.838347
EGARCH(1,1)	1.045314	73.44843	3.183952			
Daily						
GARCH(1, 4)	1.076801	80.35780	5.731418	1.08846	109.0575	8.861323
TGARCH(1, 4)	1.075275	78.06666	5.465007	1.08814	111.1410	9.007660
EGARCH(1, 4)	1.074341	81.60378	5.646867			

Table 12: Serial correlation and ARCH tests on the GARCH(1, 1) standardized residuals

A. H_0: There is no further serial correlation in standardized residuals
H_a: There is further serial correlation in standardized residuals
B. H_0: There is no further conditional heteroscedasticity in standardized residuals
H_a: There is further conditional heteroscedasticity in standardized residuals

Lag number	Δ(BRENT)		Δ(LOG[BRENT])	
	(A) P value	(B) P value	(A) P value	(B) P value
Monthly				
3			0.410	0.234
6			0.196	0.229
12			0.244	0.144
24			0.411	0.430
Weekly				
1	0.773	0.454	0.717	0.835
2	0.937	0.755	0.857	0.912
3	0.903	0.770	0.951	0.966
4	0.912	0.710	0.903	0.971
5	0.957	0.796	0.879	0.975
Daily				
1	0.966	0.355	0.879	0.444
5	0.026	0.536	0.518	0.411
10	0.032	0.328	0.287	0.458
20	0.010	0.504	0.053	0.588

GARCH: Generalized auto-regressive conditional heteroscedasticity, ARCH: auto-regressive conditional heteroscedasticity

are selected. The first is for serial correlation and the second is for additional conditional heteroscedasticity. The first is a Ljung-Box Q-statistic on the standardized residuals, and the second is a Ljung-Box Q-statistic on the squares of the standardized residuals. For monthly data the lag lengths are 3, 6, 12, and 24 months. For weekly data the lag lengths are 1, 2, 3, 4, and 5 weeks. For the daily data the lag lengths are 1, 5, 10, and 20 days. Further conditional heteroscedasticity is rejected. Further serial correlation is a problem for daily data, but only for the linear model.

Finally, from the GARCH(1,1) ECM models one can retrieve the speed of adjustment to the long run. This speed is 5.92 months for the log-log monthly model. It is between 21.31 and 18.71 weeks for the weekly models. And it is between 51.82 and 47.76 days for the daily models. Adjustment to the long run is somewhat faster for the log-log specifications relative to the linear level specifications. All in all adjustment to the long run is relatively fast.

4. CONCLUSION

The empirical results we discuss in the previous section show that there exists strong evidence for a long term bias in the long term relation or cointegration regression. We use Johansen, ARDL, Engle and Granger, and Phillips-Ouliaris to test for cointegration and show that there is long term cointegration between all the bivariate studied series. Therefore, the prices of WTI and BRENT converge in the long run and the market is integrated and not regionalized.

We test for the null hypothesis of no long run bias and reject the null hypothesis in all the cases. Hence, we provide strong evidence that there exists a long run bias in all cases. Therefore, as there is a joint hypothesis, we conclude that either the theory is unrealistic and wrong, or the data does not behave according to an adequate theory, or both.

Besides that, we use ECM models with conditional variance equations to find the length of the period required by the series to achieve long run cointegration. In the monthly data, adjustment requires around 6 months. In weekly data, it requires around 20 weeks. And finally in daily data, it requires around 50 days. This is relatively fast.

We use GARCH methods added to the ECM models to estimate the best specification. The monthly and weekly data show that the estimated GARCH (1,1) model eliminates further serial correlation and conditional heteroscedasticity. This indicates that the estimates of the chosen GARCH model are efficient. We chose GARCH (1,4) models for daily data as it shows a better fit than GARCH (1,1). We fail to reject the null hypothesis of no conditional heteroscedasticity in all GARCH cases, but we reject the null hypothesis of no serial correlation in few cases in the original data. Hence, using GARCH is more efficient in monthly and weekly data. Also, we test the null hypothesis of no long run bias and reject the null hypothesis. This affirms the presence of bias even after GARCH estimation. Moreover, we test the null hypothesis of no long run cointegration. We reject the null hypothesis of no cointegration and confirm previous results of long run cointegration.

Finally, we test the null hypothesis of no asymmetric effect. We reject the null hypothesis of no asymmetric effect using EGARCH in all data frequencies and forms and using TARCH in the logarithmic form in monthly data. Therefore, in monthly logarithmic data good and bad news affect the spot prices of WTI and BRENT differently. For this reason, the investor must beware periods of high volatility and bad news, and show more risk aversion in such cases.

Some recommendations are worthwhile. New information about one crude oil price spills over to the other. Hence observance of one oil price carries much information about the price of the other. Since the two long run oil prices move in tandem in the long run, one may recommend substituting one crude oil for the other. This is highly risky because short selling is risky and because the time to full adjustment, or to the long run, is stochastic. The relation between the two crude oils is non-linear due to GARCH effects. A linear forecast is therefore biased and inefficient. For the best model fit, it is recommended to use GARCH on weekly data.

The investor should beware of excess volatility of financial markets, because it has big impacts on the market of crude oils. In the long run a one dollar increase in WTI increases BRENT by more than one dollar. This should trigger a buy recommendation on WTI. In the long run a 1% increase in WTI increases BRENT by more than 1%. Again this should trigger a buy recommendation on WTI. It is unclear whether these long run irregularities can lead to the creation of arbitrage, or riskless and abnormal trading profits, once transaction costs and all other uncertainties involved in statistical analysis are accounted for.

Some limitations to the study are notable. The theoretical model may be unrealistic although it has been described as tentative. Same macroeconomic events or microeconomic shocks may impact the two oil prices differently. The two crude oils may not be perfect substitutes. Price demand elasticities may change over time. Other fundamental factors, omitted in this research, may impact the two crude oils differently.

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