Testing persistence of WTI and Brent long-run relationship after the shale oil supply shock☆

Massimiliano Caporin[a], Fulvio Fontini[b,*], Elham Talebbeydokhti[b]

[a]Department of Statistical Sciences, University of Padua, Italy
[b]Department of Economics and Management, University of Padua, Italy

ARTICLE INFO

ABSTRACT

In the paper, we study the long-run relationship in the WTI-Brent oil time series, taking into account the occurrence of two relevant events: the rise of shale oil production, in early 2011, and the widening and closing of the WTI-Brent price spread, from 2011 to 2014. Monthly data of WTI and Brent crude oil prices, as well as US shale oil quantities from January 2000 to December 2017 is used for the analyses. The empirical results of the cointegration tests with structural breaks show that two structural break occurs, in February 2011 and in October 2014. We then estimate a Vector Error Correction Model (VECM), considering the structural break suggested by the cointegration test results, the timing of the rise in shale oil production and the dynamics of the WTI-Brent price spread. Our analysis reveals that WTI and Brent crude oil prices have had a long-run relationship up to 2011; no cointegration existed during the period of widening of the spread; again, a new long-run relationship arises after the closing of the gap, which includes the shale oil production. In the last period, the cross price elasticity of Brent on WTI slightly reduces compared to the pre-2011 era, whilst the shale oil production increases its importance in explaining the long-run relationship between WTI and Brent fivefold. Using the Generalized Impulse Response Functions (GIRFs) we finally study the impact of exogenous shocks on the variables, showing that in the first period, with limited shale oil production, oil prices reacted to shale oil and not vice versa. After October 2014, the opposite becomes true and shale oil production follows changes in both WTI and Brent prices.

1. Introduction

There exist various types of internationally traded crude oils, each one with different qualities and characteristics, expressed by density (light to heavy) as well as acidity and sulphur content (sweet, which refers to low sulphur content, and sour, which refers to high sulphur content). The two dominant oil reference prices are the West Texas Intermediate (WTI)[1] and the Brent crude oil.[2] WTI and Brent crude are classified as sweet, light crude oil-sweet because of their low sulphur content and light because of their relatively low density-thus making them ideal for refining diesel fuel, gasoline and other high-demand products. However, Brent crude is not as sweet and light as WTI is.

The arbitrage principle applied to almost homogeneous products such as WTI and Brent needs to reduce their price differentials; however, there are factors that can limit arbitrage, such as their intrinsic quality, on the one hand, and/or external factors such as transportation constraints and costs, on the other hand.

---

[1] WTI is the main oil benchmark in the US (Fattouh, 2010). It refers to oil extracted from wells in the US and sent via pipeline to Cushing, Oklahoma. For over three decades, Cushing has been a major oil supply hub connecting oil suppliers to the Gulf Coast, and, therefore it is the price settlement point for WTI. WTI is traded on the New York Mercantile Exchange (NYMEX) for delivery at Cushing.

[2] Brent is a European benchmark related to oil extracted from the North Sea. Brent is composed of four crude blends: Brent, Forties, Oseberg, and Ekofisk (BFOE). The Brent and Forties blends are produced offshore in the waters of the UK, and the Ekofisk and Oseberg blends are mainly produced offshore in the waters of Norway (Energy Information Administration, EIA (2016)). In recent years, Brent has been used to price two third of the world's internationally traded crude oil supplies. Brent is traded on the Intercontinental Exchange (ICE) for delivery at Sullom Voe.

Several scholars have studied the crude oil price differentials (Fattouh, 2007, 2010; Kao and Wan, 2012; Borenstein et al., 2014). Historically, Brent and WTI crude oil prices have been tracked closely, with a price difference per barrel of ± 3 USD/bbl and with WTI usually priced higher than Brent, as shown in Fig. 1. This pattern of price differential probably denotes that arbitrage opportunities were kept at a minimum, with the price premium of WTI depending on its sweeter content. The rather stable behaviour of the spread also denotes that WTI and Brent were linked by a long-run equilibrium relationship. However, evidence from previous studies investigating whether WTI and Brent are integrated is mixed. Reboredo (2011) suggests that crude oil prices are linked with the same intensity during bull and bear markets, thus supporting the hypothesis that the oil market is a single pool, in contrast with the hypothesis stating that the oil market is regionalised. Gülen (1999) argues that market segmentation generates market inefficiencies and gives rise to arbitrage opportunities. Likewise, oil market co-movements have potentially important implications for portfolio allocation and hedging strategies involving spot and future oil contracts. Hammoudeh et al. (2008), Liao et al. (2014) and Wilmot (2013) support the idea of the globalisation hypothesis. On the other hand, Weiner (1991) claim that the world oil market is far from being completely united. (Kim et al., 2013) has found that the long-run relationships among WTI, Brent and Dubai crude oil prices hold from January 1997 to July 2012, even when the effects of the breaks are considered. Aruga (2015) claims that WTI no longer has a long-run relationship with the Brent and Dubai crude oil markets. Büyükşahin et al. (2013) find that a structural break in the long-term relationship between WTI and Brent occurred in 2008 and 2010. (Coronado et al., 2016) find a double causality patterns between Brent and WTI, includes also the Argus Sour Crude Index. In early 2011, the longstanding relationship between WTI and Brent prices began to change; Brent crude oil started to be priced much higher than WTI was. The discrepancy between WTI and Brent prices resulted from exogenous factors. Whilst the WTI production was rising, limited transportation facilities impeded moving the WTI stockpiles at their delivery point at Cushing, Oklahoma, to refineries located in the Gulf Coast. The spread rose to 27 USD/bbl in September 2011. Eventually, the expansion of the transportation and refining capacity, including the addition of new pipelines at Cushing, allowed pushing back the price spread: in late 2014, the Brent-WTI spread was narrowed considerably.[3]

At the same time the WTI-Brent price spread was rising, the US oil industry was facing a major change. The application of two technological innovations, horizontal drilling and hydraulic fracturing (or fracking) was enabling the US to grow dramatically the production of abundant shale oil resources (see Fig. 2).[4] Shale oil technology can be
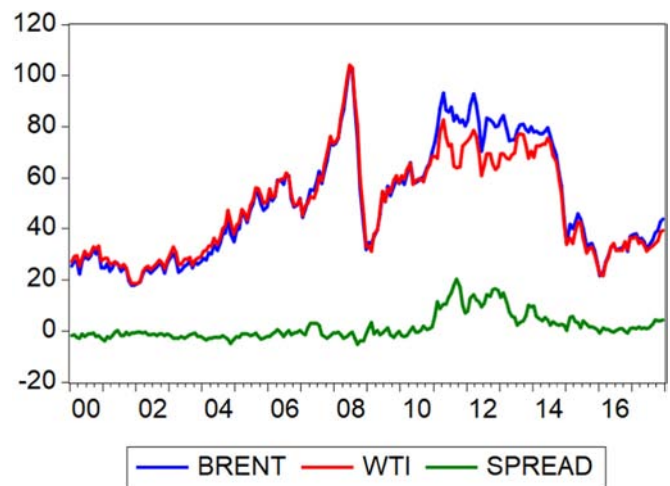

Fig. 1. WTI and Brent monthly Prices, and their spread — values in Dollars per Barrel deflated using US CPI.

regarded as a permanent innovation of the US oil production industry; shale oil production has gained a large share of the overall WTI production.

The purpose of this study is to investigate whether these two phenomena, i.e. the rise and drop of the WTI-Brent price spread and the surge of the shale oil production, have influenced the long-run relationship between WTI and Brent prices. More precisely, we investigate (1) if we can statistically confirm a long-run relationship in the WTI-Brent oil time series before the rise in shale oil production in the US market, (2) if a structural break has occurred in the long-run relationship and when this has occurred, (3) if it has coincided with the rise in shale oil production, (4) if, after the entrance in the market of abundant shale oil, on the one hand, and the closing gap between the WTI-Brent price, on the other hand, a new long-run relationship has emerged between WTI and Brent prices and (5) if so, of which kind. We also test the dynamics of the long-run relationships, namely, the relative impact of the changes of one series on the other series and on the convergence to the equilibrium, if any, as well as by how much this has been influenced by the rise in shale oil production.

Our aim is to contribute to the literature testing the existence of a long-run relationship between WTI and Brent, as well as the role of shale oil quantity.
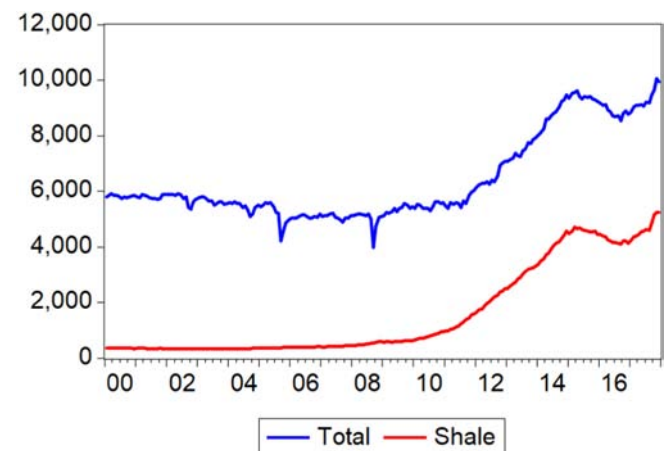
---

[3] Some scholars have studied the dynamics of the WTI-Brent price spread. (Chen and Huang, 2015) have shown that the WTI-Brent spread time series has become non-stationary after the rise of the price-spread. A similar result has been found by (Liu et al., 2018), who use IRFs showing that the spread depends on the US supply shocks.

[4] Shale oil, is sometimes also known as tight oil or light tight oil (LTO). We use here data from the US EIA. The EIA "[…] has adopted the convention of using the term tight oil to refer to all resources, reserves, and production associated with low-permeability formations that produce oil, including that associated with shale formations." However, the EIA acknowledges that "The oil and natural gas industry's colloquial use of the term tight oil is rather recent, and does not have a specific technical, scientific, or geologic definition." (Source: https://www.eia.gov/energy_in_brief/article/shale_in_the_united_states.cfm). For this reason and for consistency with the rest of the literature, we shall use the term shale oil instead of tight oil. Shale oil is petroleum that contains light crude oil with low sulphur content; it is found in some rock formations deep below the earth's surface. It is conventional oil trapped in an unconventional formation of low permeability. Multi-stage hydraulic fracturing causes cracks in the rock formation that allow the crude oil, deposited within open spaces in the rock, to flow into the wellbore. Most of this growth in the US shale oil has come from the following basins: Bakken in Montana and Dakota, Eagle Ford and Permian Basin in Texas.

Fig. 2. US crude oil and shale oil production — thousands of barrels per day.

The rest of the paper is structured as follows. Section 2 outlines the methodologies used for the cointegration analysis. Section 3 describes the data. Section 4 provides all the empirical results. Finally, Section 5 presents the conclusions, and the references follow.

2. Methodology

From a statistical viewpoint, the time series of energy commodities' prices behave like the time series of financial instruments' prices, and they are usually non-stationary. Therefore, a simple ordinary least squares regression between two commodity prices would potentially lead to a spurious regression. Such an event does not realise if the series of interest share a common trend and are linearly related by an equilibrium condition. To deal with this issue, we first assess whether the variables under consideration are non-stationary or characterised by a unit root, i.e. integrated of order one, or $I(1)$. We might use traditional unit root tests, such as the Augmented Dickey-Fuller (ADF) test, but we are aware that our time series might be contaminated by a structural break because of the shale oil supply shock. Therefore, we need to consider the possible existence of a break in each time series, either in the intercept, in the trend or in both the intercept and the trend. Consequently, we apply the Perron (1997) unit root test that allows for a break at an unknown location and enables the evaluation of the null hypothesis of integration and the identification of the break location. Notably, the identification of the break date comes from the evaluation of the minimum of the test statistic for a number of possible break dates.

If the series are integrated, despite being possibly affected by a structural break, we are allowed to test the existence of cointegration, i.e. to verify the existence of a long-run relationship between the series of interest. We follow here the Gregory and Hansen (1996) cointegration analysis because again, we need to deal with the possible presence of structural breaks. The approach of Gregory and Hansen (1996) allows verifying the existence of cointegration in the presence of a structural break of an unknown location.

Considering a simple model,

$$y_{1t} = \mu + \delta t + \alpha y_{2t} + e_t, \quad t = 1, \ldots, n \tag{1}$$

where y_{1t} and y_{2t} are the two variables of interest, both $I(1)$, t is a time trend, and e_t is a stationary innovation term; the structural breaks might be of different forms. In fact, we might have a structural break in the intercept, i.e. only μ changes after the break date, with different behaviours of the test statistic depending on the presence or absence of the deterministic trend component. Alternatively, we might have a structural break leading to changes in both the intercept and the cointegration parameters, i.e. both μ and α change after the break date.

In all cases, the test of the null hypothesis of no cointegration is residual based. In other words, we can regard y_{1t} and y_{2t} as being cointegrated by examining whether the residuals e_t do not have a unit root. Gregory and Hansen (1996) constructed three statistics for those tests: Z_a^*, Z_t^* and ADF^*. The test statistics Z_a^* and Z_t^* build upon the Philips-Perron test statistics, whilst ADF^* is based on the Augmented Dickey-Fuller (ADF) statistics. The null hypothesis is rejected if the statistic, either ADF^*, Z_a^* or Z_t^*, is smaller than the corresponding critical value. In all cases, the critical values are tabulated as the test statistics do not follow a standard density.

If the tests proposed by Gregory and Hansen (1996) show evidence in favour of cointegration, a Vector Error Correction Model (VECM) can be specified to identify both the long-run relationships between the variables of interest and, at the same time, to account for the structural break.

The VECM can lead to a better understanding of the nature of long-run and short-run relationships among the modelled variables. In our case, the model allows evaluating the existence of long-run relationships across three variables, namely, WTI and Brent prices and the shale oil quantity. To identity the number of cointegrating relations, we rely on the tests of Johansen (1988, 1995). However, to account for the presence of structural breaks, we use the Johansen et al. (2000) and Giles and Godwin (2012) critical values. In its most general representation, the VECM model takes the following form:

$$\Delta X_t = \Pi X_{t-1} + \sum_{j=1}^{p} \phi_j \Delta X_{t-j} + \delta D_t + \epsilon_t, \tag{2}$$

where X_t is the vector of the modelled variables (in logs), Δ identifies the first difference of the variables (i.e. the growth rates), the summation monitors the short-run dynamics of the series growth rates, and, finally, D_t contains a set of deterministic variables, namely a constant and a linear trend, and might include terms needed to account for the structural break (see Johansen et al., 2000).

In the presence of cointegrating relationships, the matrix Π might be decomposed as $\Pi = \alpha\beta'$, where the product $\beta' X_{t-1}$ contains disequilibrium errors, the matrix β provides the cointegration coefficient, i.e. the coefficient of the long-run relationship between variables, and the vector α contains the adjustment coefficients for the past disequilibrium.

In our setting, we expect to identify a long-run (cointegrating) relationship. In fact, with a stable relationship over time assumed, the link between Brent and WTI prices (thus excluding the shale oil quantity for the moment) would read as follows:

$$WTI_t - \mu - \beta_1 Brent_t = \epsilon_t, \tag{3}$$

where WTI_t denotes the WTI real log-price, $Brent_t$ is the Brent real log-price, and ϵ_t is the stationary error term. If the two oil prices have a stable and long-run link, we expect the coefficient β_1 to be statistically significant and close to one, suggesting that movements in the Brent (WTI) price are replicated in the WTI (Brent) price. Moreover, shocks to one of the two prices might lead to adjustments towards the equilibrium by means of the VECM specification, as governed by the adjustment coefficients and the lag structure.

With the surge in shale oil production, shale oil quantity can also play a role in the long-run equilibrium relation. In this case, the single equilibrium relation would not only link the two prices, as above, but will also allow shale oil quantity to play a role. The latter term would act as a possible driver of the diverging behaviour among prices. In fact, if we denote with $ShaleQ_t$ the shale oil total quantity (in logs), the equilibrium relation becomes

$$WTI_t - \mu - \beta_1 Brent_t - \beta_2 ShaleQ_t = \epsilon_t. \tag{4}$$

The coefficient β_1 should be again statistically significant and close to 1; deviations from the equilibrium because of a shock on, say, the Brent price might lead to an adjustment on both the WTI price and the shale quantity, thus having a possible effect also on the spread. Similarly, shocks on the shale oil quantity might have an effect on the prices. The shale oil quantity has a significant role only if the coefficient β_2 is statistically significant. In the case of cointegration between the three variables, the coefficients β_1 in Eqs. (3) and

(4) might not be identical, even though we expect them to be very close, and the shale oil quantity might not to be predominant.

Finally, we note that, because the variables are expressed in logs, the coefficients β_1 and β_2 represent the cross-price elasticity and the elasticity of the WTI price w.r.t. shale oil quantity, respectively.

Once the VECM has been estimated, short-run dynamics and the adjustment because of disequilibrium in the long-run relationship can be examined by considering the impulse response functions (IRFs). These functions measure the time profile of the effect of a shock, or impulse, on the (endogenous) variables of interest. A crucial element is given by the chosen approach to orthogonalise the shocks. The most common one uses a Cholesky decomposition of the innovation's covariance of the VECM model. However, the resulting IRFs would depend on the variables ordering. In our case, the two prices, Brent and WTI, are highly correlated, and we expect a high correlation even among the VECM model innovations. This characteristics makes the choice of any ordering questionable. Moreover, when we introduce the shale oil quantity, choosing the proper variables ordering is even more challenging. Consequently, we opt for the more flexible Generalized IRF (GIRF) of Pesaran and Shin (1998). The GIRFs are independent from the variables ordering and correspond to the reaction of a target variable to a unit shock on one endogenous innovation. We note that in the VECM model, the effect of shocks will lead to movements in the endogenous variables both through the disequilibrium that the shocks generate (from the impact of the error correction term, as measured from the adjustment coefficients), as well as from the dynamic interaction among growth rates (i.e. through the lags of the VECM model, involving the variables' first difference). In the empirical analysis we focus on GIRFs up to 24 lags (two years) and compute bootstrap confidence intervals.

In the following sections, we proceed to the analysis of the Brent and WTI prices, together with shale oil production. To evaluate the existence of long-run relationships among these variables, we have the following steps. Firstly, we analyse the series for the presence of unit roots, a pre-requisite for cointegration. In this step, we allow the presence of breaks in the series. Secondly, given the results of the unit root test, we focus on cointegration testing, again allowing the presence of breaks. Finally, we move to the estimation of the VECM model and the derivation of the GIRF. All steps will be properly discussed from an economic viewpoint; the results obtained from the bivariate system including prices only and from the trivariate system including also the shale oil quantity will be compared.

3. Data analysis

We use the monthly real spot prices of WTI and Brent crude oil (dollars per barrel) and the monthly tight oil quantities and US crude oil production (thousand barrels per day) from the US Energy Information Administration. The observation period is from January 2000 to December 2017, which yields a sample size of 216 observations. Table 1 gives the summary statistics for the monthly growth rates of crude oil prices and quantities. We use logarithmic growth rates, which allow us to interpret the coefficients of the linear models estimated as elasticities. Considering the significant rise in shale oil production starting on February 2011, we divide the full-sample period into two sub-samples. The growth rate of the two prices is, on average, negative in the second sub-sample, whereas the US crude oil production (WTI quantity) increases from February 2011 onward, mostly caused by the increase in shale oil production. The table includes additional sub-samples; we discuss the criteria for their identification in the following section.

Note that the second sub-sample period saw the rise and fall of the WTI-Brent price spread, as shown in Fig. 1. As mentioned before, the crucial factor determining it was the bottleneck in US refinery and transport infrastructures, coupled with the rise in shale production,

that impeded the arbitrage between WTI and imports. By 2015, the expansion of transportation infrastructure eliminated the bottleneck, allowing light crude oil that was landlocked in the centre of the US to reach refineries (Borenstein et al., 2014; Kilian, 2016).[5]

We then assess the stationarity property of WTI and Brent prices and shale oil quantity before performing the analysis of cointegration. Table 2 reports the results for the Perron (1997) test for unit roots in the presence of structural breaks. Notably, in all cases we accept the null hypothesis, i.e. the presence of a unit root. With respect to the break date, we observe some heterogeneity in it. In fact, the break date oscillates from 2008 to 2014, with some prevalence of dates around the 2011 and 2014. If we look at the plots for the test statistic computed for various candidate break dates[6], we observe that the test statistic has, in many cases, a somewhat flat pattern from 2011 up to the end of 2014. This feature challenges the proper identification of the break date from purely statistical tools. Therefore, given the empirical evidence of the increase in the shale oil production at the beginning of 2011 and the contemporaneous amplification of the spread between Brent and WTI prices, we decided to fix a first break date between January and February 2011. Furthermore, given our previous comments on the pattern of the WTI-Brent price spread and the existence of the transportation bottleneck, we expect a possible break date in the last months of 2014. We then proceed to a second set of tests based on the restricted sample starting in February 2011 and ending in December 2017. Table 2 presents the results. We find a confirmation of the non-stationarity of the series; all tests provide evidence in favour of the null hypothesis, i.e. the presence of a unit root. Notably, we found for both prices a break in the last months of 2014, which is consistent with the graphical evidence of the spread. Considering the test outcomes of the full table, we do have evidence of a second break data in the last quarter of 2014, which we set between September 2014 and October 2014. Summarising, by combining the graphical evidence, the results of the test statistics, and the exogenous elements affecting the oil market, we believe that the long-run relation among our variables of interest might be affected by two possible break dates. The first was at the beginning of 2011, associated with the rise in shale oil production and the widening of the Brent-WTI spread (because of exogenous elements), and the second was at the end of 2014, associated with the narrowing of the spread (the transportation bottleneck leading to the spread was removed) and the start of the shale oil production stabilisation.

4. Long-run relationships between oil prices and shale quantity

As the unit root test of Perron (1997) suggests that the WTI and Brent prices and shale oil quantity are $I(1)$, we proceed to the evaluation of the possible presence of cointegration between WTI and Brent prices by using the methodology introduced by Gregory and Hansen (1996). Then, we replicate the analysis including also shale oil quantity. We are reminded that the most interesting case, from our viewpoint, is the presence of a structural change in the cointegrating vector, identified by Gregory and Hansen (1996) as the

---

[5] We test for the relevance of other external factors in explaining the WTI-Brent price spread. In particular, we check whether external control variables explain the price spread. We consider three possible drivers of the spread: the trade-weighted value of the US dollar against a basket of major currencies, as a proxy of the US dollar strength; the US Economic Policy Uncertainty index of Baker et al. (2016), as a measure of economic policy instability in the US market; and the Industrial Production Index, in order to track the US business cycle. The very limited R-squared of the regression and the limited significance of the controls (either contemporaneous and/or lagged) show that these external factors cannot explain the spread. The results are available from the authors upon request.

[6] Plots available upon request.

Table 1
Descriptive analyses of monthly growth rates.

	WTI price	Brent price	WTI prod.	Shale prod.	WTI ex-shale prod.	WTI price	Brent price	WTI prod.	Shale prod.	WTI ex-shale prod.
	Full-sample									
Mean	0.005	0.007	0.003	0.013	0.000					
Median	0.014	0.018	0.003	0.009	−0.001					
Maximum	0.236	0.217	0.193	0.084	0.211					
Minimum	−0.277	−0.257	−0.205	−0.026	−0.231					
Std.Dev.	0.084	0.088	0.030	0.021	0.034					
Skewness	−0.440	−0.552	−1.423	0.712	−1.212					
Kurtosis	3.795	3.610	27.673	3.222	25.761					
	2000M01–2011M01					2011M02–2017M12				
Mean	0.011	0.012	0.000	0.008	−0.001	−0.003	−0.003	0.007	0.021	0.001
Median	0.021	0.029	0.001	0.004	0.000	0.006	0.005	0.007	0.021	−0.002
Maximum	0.228	0.217	0.193	0.078	0.211	0.236	0.214	0.059	0.084	0.072
Minimum	−0.277	−0.257	−0.205	−0.022	−0.231	−0.215	−0.229	−0.027	−0.026	−0.052
Std.Dev.	0.086	0.092	0.036	0.018	0.039	0.081	0.080	0.017	0.024	0.023
Skewness	−0.663	−0.733	−1.269	1.036	−1.313	−0.067	−0.250	0.568	0.161	0.498
Kurtosis	4.091	3.534	22.745	4.645	23.308	3.626	4.212	3.308	2.523	3.769
	2011M02–2014M09					2014M10–2017M12				
Mean	0.001	0.000	0.012	0.034	0.002	−0.008	−0.006	0.003	0.006	−0.001
Median	0.000	0.002	0.010	0.031	−0.002	0.008	0.016	0.003	0.001	−0.003
Maximum	0.155	0.100	0.059	0.084	0.063	0.236	0.214	0.041	0.061	0.072
Minimum	−0.130	−0.137	−0.027	−0.003	−0.052	−0.215	−0.229	−0.025	−0.026	−0.041
Std.Dev.	0.058	0.049	0.018	0.018	0.025	0.101	0.105	0.015	0.020	0.020
Skewness	0.203	−0.104	0.439	0.370	0.257	−0.016	−0.161	0.534	0.887	0.903
Kurtosis	3.687	3.404	3.256	3.356	2.964	2.789	2.920	3.083	3.683	5.853

regime-shift case. Furthermore, as the authors propose three different test statistics to assess the null of no cointegration, in the case of conflicting results among the test statistics, we will draw the conclusions by focusing on the Z_t^* statistic, which is described by Gregory and Hansen (1996) as the most powerful statistic.

Table 3 contains the test results. When we consider the cointegration between WTI and Brent prices, the Gregory and Hansen (1996) test statistics are all concordant in suggesting the existence of a cointegration relationship, with a structural break occurring either in 2010M10 or 2011M02. Also in the case of WTI, Brent prices and shale oil quantity, the three statistics reject the null hypothesis of no cointegration for all possible models (i.e. with a break in intercept only or in the case of regime shift). In this case, however, the break might occur in 2011M02, 2011M03 or 2013M04. By focusing on the most powerful test statistic and the most relevant type of break, i.e. the regime shift, we find that the break date is between 2010M10 and 2011M03. This result confirms the time identification of the break

as coinciding with the rise in the shale oil production, from early 2011 onward, which agrees also with the our interpretation of the unit root test results of the previous section. The discrepancies in the time lags can be attributed to the slow impact of the shale oil on the cointegration relationships or to the anticipation effect of the expectation of the shale oil rise.

The behaviour of the WTI-Brent price spread and the results of the unit root tests with break, based on the reduced sample starting in 2011M02, call for a further cointegration analyses. Therefore, to obtain a complete picture and verify if cointegration exists in the subsample from 2011M02 to 2017M12 in the presence of a further break, we run again the Gregory and Hansen (1996) cointegration test. The results are shown in Table 3. The findings are now challenging. In fact, the cointegration test of Gregory and Hansen (1996) indicates that the series are not cointegrated, in particular, in the case of regime shift and for the most powerful test statistic. Therefore, we do have conflicting evidence because over the full sample, the series seem

Table 2
Perron unit root test.

	Break in trend & intercept				Break in intercept				Break in trend			
	Break dates	Lags	Test statistics	C.V. at 5%	Break dates	Lags	Test statistics	C.V. at 5%	Break dates	Lags	Test statistics	C.V. at 5%
Full sample: 2000M1–2017M12												
WTI Price	2014M09	1	−4.52	−5.59	2014M07	1	−4.88	−5.23	2011M10	1	−4.09	−4.83
Brent Price	2014M09	1	−4.39	−5.59	2014M06	1	−4.88	−5.23	2012M08	1	−3.93	−4.83
Shale oil Q.	2008M11	4	−4.31	−5.59	2011M02	4	−2.15	−5.23	2005M08	4	−4.12	−4.83
Restricted sample: 2011M2–2017M12												
WTI Price	2014M11	1	−4.02	−5.59	2014M10	1	−4.06	−5.23	2016M12	1	−2.44	−4.83
Brent Price	2014M11	1	−4.87	−5.59	2014M11	1	−5.07	−5.23	2016M12	1	−2.48	−4.83
Shale oil Q.	2013M12	4	−3.30	−5.59	2015M05	4	−4.49	−5.23	2013M09	4	−3.30	−4.83

[1] The table reports the critical values of the Perron (1997) unit root test in the presence of a structural break in a series intercept and/or linear trend. We consider three different cases: break in both trend and intercept; break in intercept only; break in trend only. The table also includes the optimal break date for each series and the optimal number of lags used for the computation of the test statistic. The null hypothesis of the test is the presence of a unit root.

Table 3
Gregory–Hansen cointegration test results.

	ADF*	Break dates	Z_t^*	Break dates	Z_a^*	Break dates	ADF*, Z_t^*	Z_a^*
	Test statistics		Test statistics		Test statistics		C.V. at 5%	C.V. at 5%
Full sample — from 2001M01 to 2017M12								
WTI and Brent prices								
C	−5.92	2011M02	−6.03	2010M10	−63.99	2010M10	−4.61	−40.48
C/T	−6.10	2010M10	−6.18	2010M10	−67.20	2010M10	−4.99	−47.96
C/S	−6.28	2010M10	−6.39	2011M02	−70.82	2010M10	−4.95	−47.04
WTI and Brent prices, and Shale oil production								
C	−6.70	2013M04	−6.80	2013M04	−77.47	2013M04	−4.92	−46.98
C/T	−6.87	2013M04	−7.01	2013M04	−81.82	2013M04	−5.29	−53.92
C/S	−7.09	2011M03	−7.18	2011M02	−86.24	2011M02	−5.50	−58.33
Restricted sample — from 2011M02 to 2017M12								
WTI and Brent prices								
C	−4.90	2013M03	−4.51	2013M04	−35.25	2013M04	−4.61	−40.48
C/T	−5.03	2013M03	−4.63	2013M04	−36.42	2013M04	−4.99	−47.96
C/S	−4.95	2013M03	−4.54	2013M04	−35.56	2013M04	−4.95	−47.04
WTI and Brent prices, and Shale oil production								
C	−5.12	2013M03	−4.81	2013M03	−38.80	2013M03	−4.92	−46.98
C/T	−5.12	2013M03	−4.81	2013M03	−38.80	2013M03	−5.29	−53.92
C/S	−5.39	2013M03	−4.98	2013M04	−40.70	2013M04	−5.50	−58.33

[1] Note that C.V. stands for critical value. C = Level shift, C/T = Level shift with trend, C/S = Regime shift.

cointegrated, whereas over a restricted sample, the series do not seem cointegrated. We read this as a possible consequence of the widening of the spread between prices. These results motivate us to deepen the analysis, starting from the standard unit root tests applied on the sub-samples.

Table 4 contains the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root test outcomes for the selected sub-samples. We define the latter by building on the previous evidence of the break dates. We use two possible break dates, February 2011 and October 2014, and consider two larger sub-samples, corresponding to the data split at the first break date, and two shorter sub-samples, from the first break date to the second break date, and from October 2014 to the end of the sample. The results are somewhat surprising, even though they are consistent with our previous evidence. In fact, whilst for the oil prices, we always observe the presence of a unit root, the shale oil production appears as stationary in the sub-sample, starting in February 2011 and ending in September 2014. Notably, this range corresponds roughly to the period when the oil prices spread was wider, and it represents a time range of fast increase in shale oil production (along a clear upward linear trend).

Given the evidence of non-stationarity of the series and cointegration, either in the presence of breaks or over specific restricted samples, we decided to proceed to the estimation of the VECM model under different time ranges. At first, we estimate a VECM model over the full sample but accounting, at the same time, for the presence of a structural break in the deterministic part of the model. This choice is consistent with the preliminary evidence in Table 3; to further confirm this, we will complement the estimation with a test for the presence of cointegration, following the approach of Johansen et al. (2000), i.e. allowing for a break also in the deterministic trend. We introduce a break in the form of a step dummy assuming a value of 1 from February 2011, and interacting the dummy with the intercept and the trend. We stress that the specification of the deterministic terms for both the WTI and Brent relationship and the WTI, Brent and shale oil quantity one, when using the full data sample, is intercept (no trend) in the cointegrating equation and intercepts in VAR. Such a specification is common for trending series, such as the ones we used here. Furthermore, in specifying the VECM model, we choose the appropriate maximum lag length by using the Schwarz Information Criterion (SIC).

The results are reported in Table 5. The upper part of the table presents the Johansen (1988, 1995) trace and the maximum eigenvalue tests whose critical values come, however, from Johansen et al. (2000) because of the presence of a break in deterministic components. The first column in the table shows the WTI-Brent relationship, and the second one shows WTI, Brent and shale oil. For both cases, the tests indicate the presence of cointegration when accounting for a break in the linear trend between the two series at the 5% significant level. The lower part of the table reports the results of the VECM model. Evidence indicates the existence of a strong long-run relationship between WTI and Brent prices, in both cases with and without shale oil. The Brent price coefficient is very large, above 0.9, and highly significant. Thus, a given percentage change in Brent price is coupled with an almost equivalent percentage change in WTI price. When we look at the first column, the equation adjustment coefficient for the WTI price is negative, −0.54, and significant, whereas the Brent price equation adjustment coefficient is not statistically significant. This result indicates that when some external force drives the two series away, it is the WTI price that reacts, closing the gap and bringing down the price time series to converge to the long-run equilibrium with the Brent price, whereas the Brent price does not react to the disequilibrium. This result is expected, because the Brent market is much more liquid than the WTI one, and Brent is priced worldwide, whereas WTI is priced in the US only. In the second column, empirical evidence again suggests the presence of a single cointegration relationship among the series, i.e., the presence of a long-run equilibrium. We observe that the Brent price coefficient remains almost unchanged and is highly significant compared with the previous one. The shale oil quantity coefficient is positive, close to 0.08, and statistically significant. The sign of the coefficient is consistent with the economic rationale of the WTI market: a rise in shale oil quantity implies an increase in WTI supply and, therefore, a reduction in its price. The equation adjustment coefficient for the WTI price is negative and significant, and that for the Brent one is not significant, as before, thus confirming the same behaviour observed in the bivariate VECM. The adjustment coefficient of shale oil quantity is not significant, showing that the production of shale oil in the full-sample period did not respond to changes in the long-run relationship between WTI and Brent prices.

Table 4
Unit root tests on sub-samples.

Sample/Variables	WTI price	Brent price	Shale quantity	WTI price	Brent price	Shale quantity
Test	ADF			PP		
2000/1–2017/12	0.316	0.231	0.532	0.332	0.273	0.521
2000/1–2011/1	0.174	0.065	0.999	0.204	0.209	0.999
2011/2–2017/12	0.533	0.412	0.004	0.691	0.642	0.001
2011/2–2014/9	0.598	0.639	0.013	0.559	0.625	0.002
2014/10–2017/12	0.419	0.154	0.805	0.422	0.251	0.946

[1] The table reports the ADF and PP unit root tests p-values. We use automatic selection criteria for the specification of the test equation (in terms of deterministic components and lags structure.

We then consider the existence of a break in the structural relation, as suggested by the Gregory-Hansen test results and the abrupt increase in shale oil production in 2011, in order to assess the role played by the rise in shale oil production before and after the structural break. Therefore, we replicate the analysis for the two sub-samples. We test the existence of cointegration relationships in the first sub-sample from January 2000 to January 2011, and then for the second sub-sample from February 2011 to December 2017, between WTI and Brent prices. Through this process, we can ascertain whether the long-run relationship between WTI and Brent prices has changed after a structural break. We also consider the possible presence of cointegration between the two prices over the split of the second sub-sample in October 2014, thus separating the time range associated with a widening of the spread from the most recent years when the spread reverted back to more usual levels.

Finally, we discuss the cointegration between WTI and Brent prices and shale oil quantity. However, in this case, we must consider the evidence shown in Table 4, suggesting that shale oil quantity is stationary from February 2011 to December 2017, as well as in the reduced sample starting in February 2011 and ending in September 2014. Therefore, for the three-variate VECM, we consider only two samples.

In all cases, we tested several choices of the deterministic parameters and selected the most appropriated by combining identification criteria with graphical evidence of the series behaviour. Table 6 reports the results indicating also the chosen model specification.

When looking at the first sub-sample between WTI and Brent prices and between WTI and Brent prices and shale oil quantity, the first and fifth columns in Table 6, we can observe that the Johansen (1995) tests for cointegration indicate the existence of a long-run relation among variables. In both cases, the Brent price coefficient is close to the coefficient of the full-sample analyses and is highly significant. In the trivariate VECM, the shale oil quantity coefficient is positive, slightly higher than that in the full-sample case, roughly 0.1, and statistically significant. The fact that the β_1 coefficients for the two models, with and without shale oil, are almost equivalent, is expected because of the limited quantity of shale oil production before 2011. The adjustment coefficients for WTI price, being significant also, remain negative in both the bivariate and trivariate models. Differently, the Brent price adjustment coefficient is now statistically significant, suggesting that the Brent price also reacts to the disequilibrium. In addition, in the trivariate VECM, we note that the shale oil adjustment coefficient is positive and significant, thus suggesting that shale oil quantity also reacts to the disequilibrium. Even if the shale oil quantity for the first subperiod was very limited, and, therefore, its impact on the long-run relationship is modest, the empirical evidence implies that shale oil production had enough strength to push away the time series of WTI and Brent from their long-run equilibrium.

The results for the sub-samples starting from February 2011 are even more interesting. We start from the bivariate VECM. In this case, the cointegration tests based on the trace and maximum eigenvalue suggest that the two oil prices are no longer cointegrated if we consider samples starting from February 2011 and ending either in September 2014 or in December 2017. This result is consistent with the previous evidence of cointegration tests with a structural break (see Table 3) and highlights that the increase in the shale oil production, coupled with the transportation and refining difficulties that have widened the WTI-Brent spread, had a clear impact on the long-run relationship. Differently, if we focus on the most recent sample, from October 2014 to December 2017, both in the bivariate and trivariate VECM, we do have evidence in favour of cointegration. Therefore, in the most recent years, oil prices and shale oil production seem to again be linked by a long-run equilibrium relationship. However, the strength of the relation is sensibly different. First, the coefficient β_1, i.e. the cross-price elasticity of WTI to Brent, for the trivariate VECM, is reduced to 0.881,

Table 5
Full-sample cointegration estimation.

Included Variables	WTI price	WTI price
	Brent price	Brent price
		Shale oil quantity
Lags	2	2
No. of cointegration	1	1
Trace	41.06***	87.19***
Critical value at 1%	41.98	64.57
Critical value at 5%	36.06	57.43
Max. Eig.	37.37***	47.15**
Critical value at 1%	31.26	49.57
Critical value at 5%	26.10	43.22
Deterministic	IC, IV	IC, IV
Exogenous	D11, D11*T	D11, D11*T

Cointegration equation:
$$WTI_t - \mu - \beta_1 Brent_t - \beta_2 ShaleQ_t = \epsilon_t$$

WTI price	1	1
Shale oil quantity		0.078***
		(0.032)
Brent price	−0.937***	−0.938***
	(0.016)	(0.019)
Adjustment coefficients:		
WTI price	−0.543***	−0.456***
	(0.161)	(0.159)
Shale oil quantity		0.057
		(0.032)
Brent price	−0.234	−0.117
	(0.176)	(0.172)

[1] The first panel includes the cointegration test on the full-sample, and indicates the structure of the VECM model in terms of lags and deterministic and exogenous components, including intercept in the cointegration equation (IC) and test VAR (IV), step dummy from February 2011 (D11) and interaction between the step dummy and a linear trend. Star denotes rejections of the null hypotheses under the appropriate critical values reported below the test statistic (see Johansen et al., 2000; Giles and Godwin, 2012 for details). The table also reports estimated coefficients, the standard errors (in parentheses).
*** Denotes the significant level at 1%.
** Denotes significant level at 5%.

Table 6
Selected sub-samples cointegration estimation.

Included Variables	WTI price	WTI price	WTI price	WTI price	WTI price	WTI price
	Brent price	Brent price	Brent price	Brent price	Brent price	Brent price
					Shale oil quantity	Shale oil quantity
Sample	2000M01–2011M01	2011M02–2017M12	2011M02–2014M09	2014M10–2017M12	2000M01–2011M01	2014M10–2017M12
Lags	2	2	1	2	2	2
No. of cointegration	1	0	0	1	1	1
Trace	25.59***	13.89	6.08	15.49**	43.73***	44.97***
Critical value at 1%	19.94	19.94	19.94	19.94	41.08	41.08
Critical value at 5%	15.49	15.49	15.49	15.49	35.01	35.01
Max. Eig.	24.27***	12.74	6.03	14.26*	30.70***	33.19***
Critical value at 1%	18.52	18.52	18.52	18.52	29.26	29.26
Critical value at 5%	14.26	14.26	14.26	14.26	24.25	24.25
Deterministic	IC, IV	IC, IV, TC	IC	IC	IC, IV, TC	IC, IV

Cointegration equation:

$$WTI_t - \mu - \beta_1 Brent_t - \beta_2 ShaleQ_t = \epsilon_t$$

WTI price	1			1	1	1
Shale oil quantity					0.103***	0.547***
					(0.038)	(0.061)
Brent price	−0.937***			−0.721***	−0.941***	−0.881***
	(0.013)			(0.067)	(0.021)	(0.014)

Adjustment coefficients:

WTI price	−0.817***			−0.861***	−0.718***	−3.003***
	(0.262)			(0.242)	(0.259)	(0.712)
Shale oil quantity					0.109**	0.326*
					(0.049)	(0.173)
Brent price	−0.527*			−0.792***	-0.375	−2.242***
	(0.293)			(0.277)	(0.311)	(0.896)

[1] The panel includes the cointegration test on the selected sub-samples, and indicates the structure of the VECM model in terms of lags and deterministic components, including linear trend in the cointegration equation (TC), intercept in the cointegration equation (IC) and test VAR (IV). The table then reports estimated coefficients, the standard errors (in parentheses).
*** Denotes the significant level at 1%.
** Denotes significant level at 5%.
* Denotes significant level at 10%.

compared with the value in the first sub-sample, 0.941 (or to the value in the full-sample, 0.937). The same occurs for the bivariate VECM. This is an interesting results. The increase in shale oil production has somehow lowered the WTI price response to the world oil price, as proxied by Brent. We conjecture that this might be because of the higher resilience of the shale oil industry (WTI-based) to price change. It could be attributed to the shorter time-to-market and smaller scale of the shale-oil production compared to traditional oil extraction. However, this point requires further investigation. Nevertheless, the higher importance played by the shale industry in WTI price is confirmed by the coefficient β_2, linking the shale oil production to the WTI price. In the period from October 2014 onward, it remains positive and statistically significant, rising more than five times from the value observed in the first sub-sample, i.e. going up to 0.547 from the previous value of 0.103. Thus, in the new long-run relationship between WTI and Brent, from October 2014 onward, the shale oil production has become crucial: a 10% change in shale oil quantity has a 5% impact on the WTI price (if the Brent price does not move).

The adjustment coefficients in all cases have now become larger (in absolute terms) than those of the first sub-sample. Notably, in both models (bivariate and trivariate), all adjustment coefficients appear statistically significant (for the shale quantity, only at the 10% level). The adjustment coefficients for the prices are larger than 1 in modulus. This aspect might signal instability in the VECM model. However, the roots of the characteristic polynomial are all smaller than 1 in modulus, with the exception of the two roots that must be equal to 1; this confirms that the VECM model is stationary. The large value of two adjustment coefficients likely depends on the normalisation used to recover their point value, and might also be affected by the reduced sample size. In addition, the observed

point values do not lead to instability and divergence patterns of the model; the impulse response functions confirm this aspect. Finally, the large value of the adjustment coefficients implies a fast speed of convergence to the equilibrium.[7]

Figs. 3 and 4 display the impulse responses in the trivariate case for the two relevant samples, from January 2001 to January 2011 and from October 2014 to December 2017. All variables in first sub-sample were used in the VECM.[8] In the first sample, a positive shale oil supply shock leads to a negative response for the crude oil prices (panels Shale → WTI and Shale → Brent); however, the impact is rather small. We can interpret it by noting that the shale oil production was very limited in the first period, and, thus, we do not expect a large impact on the crude oil prices. The impulse response functions among prices (panels WTI → WTI, WTI → Brent, Brent → WTI, and Brent → Brent) confirm their strong relation, as shocks to WTI produce on WTI and Brent prices reactions whose patterns are almost identical to those caused by shocks on Brent prices. We note, however, that the reactions of WTI and Brent to a Brent shock are larger than those observed after a WTI shock. This occurrence is expected, as the Brent market is much larger than the WTI one, and, thus, it is less sensitive to cross-price impacts. Finally, the IRFs of the WTI on shale and Brent on shale are non-statistically significant (the confidence intervals in the graphs include the null value). Therefore, the shale oil quantity does not react

---

[7] The size of the adjustment coefficients does not imply instability as the most common reference values are appropriate only in a bivariate system and in a VECM model with a single lag.
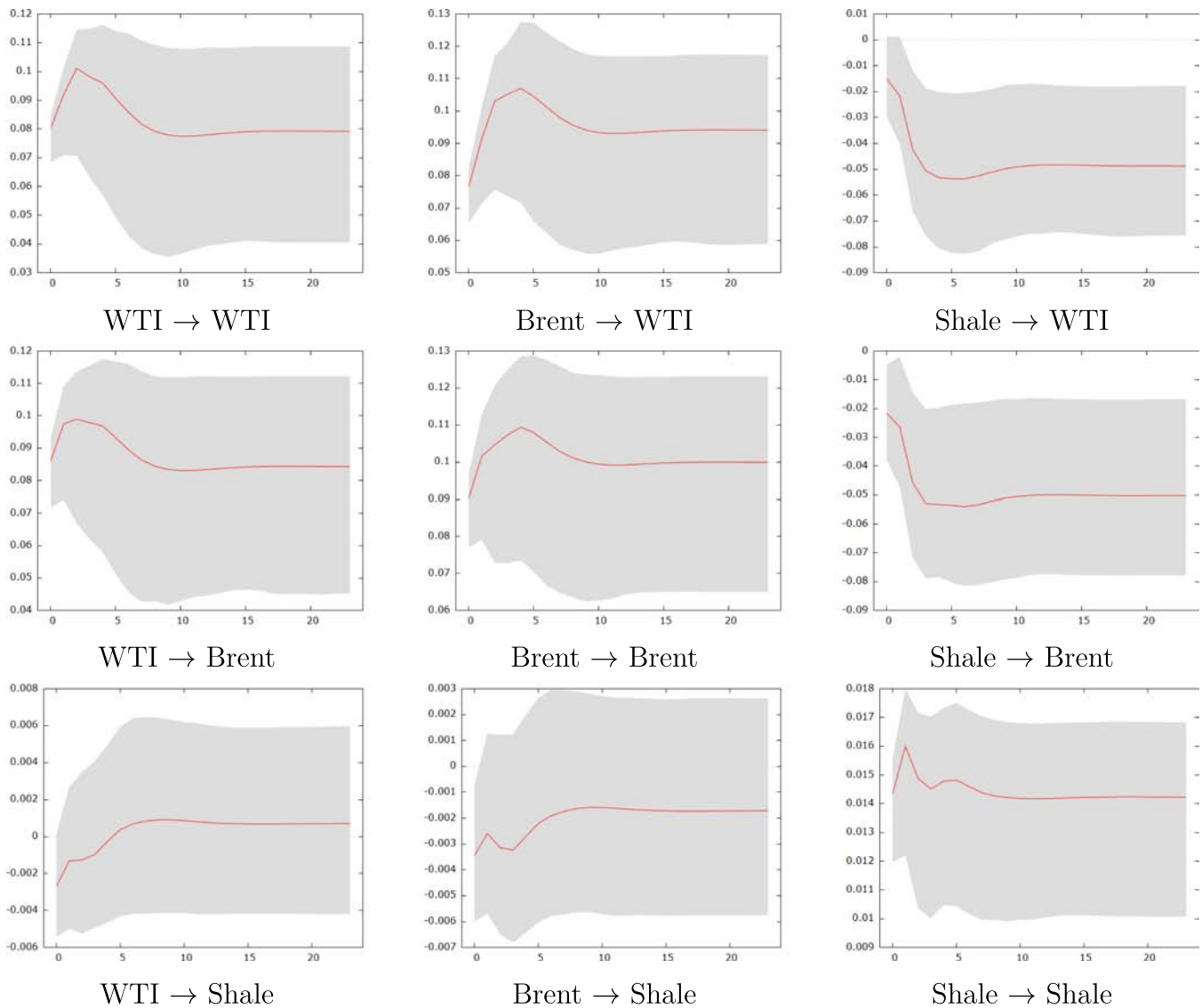[8] The impulse response plots for the bivariate case are available from the authors upon request.

Fig. 3. Generalized Impulse Response Functions — 2001/01–2011/01. The figure reports the Generalized Impulse Response Functions following Pesaran and Shin (1998) obtained from the model in Table 6, fifth column (VECM model including Brent, WTI and Shale quantity for the period 2000/01–2011/01); WTI → Brent is the response of Brent to a unit shock on WTI (the interpretation is equivalent for all plots); the shaded area represents the 90% confidence interval.

to shocks to prices. We relate this to the limited shale oil production in this sample. In the second sample, the most recent one, the impulse responses among prices are similar to those of the previous sample. The most relevant difference between the IRFs in the first and the second subsamples is the reaction of the shale oil production after a price shock (panels WTI → Shale and Brent → Shale). In particular, the IRFs in the second period are statistically significant and positive, indicating that in the recent years the shale oil quantity positively reacts after a positive oil price shock. Interestingly enough, whilst the shale production reacts positively to price increases, the opposite is not true: the IRFs of shale on prices are no more significant, meaning that prices do not react to shale production shocks. Therefore, we observe a reversion of the causality order in the two samples: up to January 2011, prices reacted to changes in shale oil production, and shale oil production did not react to a change in prices. From October 2014, the opposite is true. We conjecture that this might be caused by the different price regimes in the two subsamples: in the first period, the shale production was limited, and oil prices were rather high. Thus, an increase in shale was interpreted as an increase in oil supply. The expectations of an increase in shale supply rise might

have reinforced this effect. In the last period, oil prices are, on average, smaller (and the average growth rate is negative). Shale production is already present, so it is probably perceived as a permanent element of US oil production technology. Our data show that the shale technology becomes a market follower, not a market leader: shale oil quantity follows oil price changes (that might be caused by, for instance, to demand-side factors) rather than determines them.

5. Conclusions

This study analyses the long-run relationship between WTI and Brent before and after the rise in shale oil production. We analyse the monthly spot prices of WTI and Brent, which are benchmarks for North America, Europe and Eurasia, respectively, from January 2000 to December 2017. We apply the Perron unit root test in the presence of a structural break; we show that all the considered time series are non-stationary at their level and that an increase in shale oil production has determined a structural break in 2011. A second structural break is shown to have occurred in October 2014, when
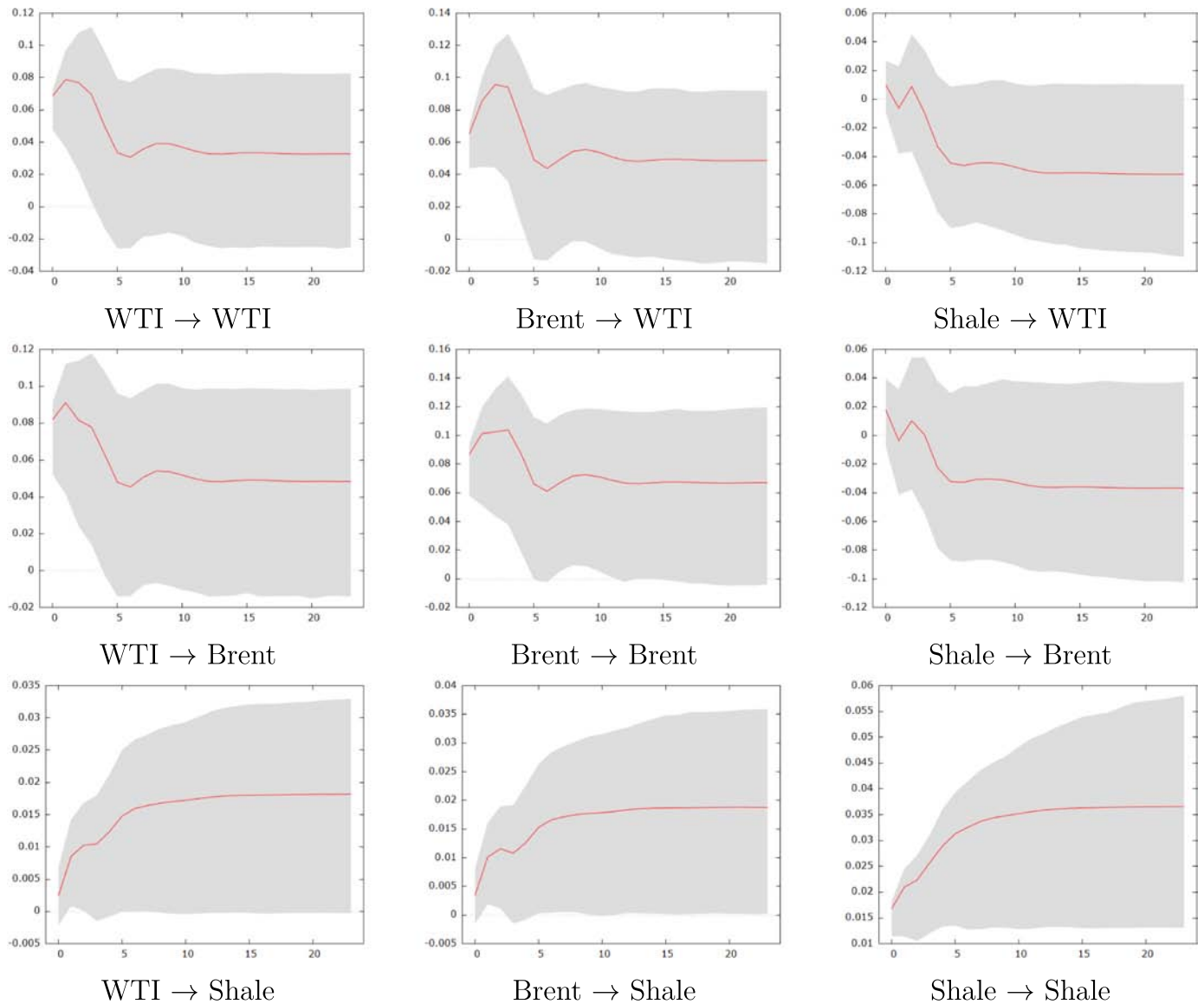
Fig. 4. Generalized Impulse Response Functions — 2014/10–2017/12. The figure reports the Generalized Impulse Response Functions following Pesaran and Shin (1998) obtained from the model in Table 6, sixth column (VECM model including Brent, WTI and Shale quantity for the period 2014/10-2017/12); WTI → Brent is the response of Brent to a unit shock on WTI (the interpretation is equivalent for all plots); the shaded area represents the 90% confidence interval.

the WTI-Brent price spread that rose in October 2011 returned to its average 3$ value. Therefore, three periods are identified: before the shale oil production rise, during the widening of the WTI-Brent price spread and after the closing of the latter. We first investigate the existence of cointegration relationships between WTI and Brent, as well as between WTI, Brent and shale oil for the whole period, with a structural break which occurs in February 2011, when the shale oil quantity rose. Then, we test for the long-run behaviour of the WTI and Brent prices and shale oil quantity in each of three sub periods, i.e. before the rise in shale oil quantity, during the widening of the WTI-Brent price spread and after the closing of the price spread gap. The empirical results demonstrate that in the period from January 2000 to January 2011, the long-run relationship between WTI and Brent exists, and there is a unit elasticity, meaning that a given percentage change in Brent price corresponds to the same percentage change in WTI price. Moreover, the analysis of the adjustment coefficients indicates that it is the WTI price, not the Brent price, that reacts after an external shock, bringing back the two series to their long-run relationship. In the second sub-sample, during the widening of

the WTI-Brent price spread, no long-run relationship exists because the series become non-stationary. The lack of cointegration confirms the instability induced by the rise in the shale oil, on the one hand, and the transportation and refining difficulties of WTI, on the other hand. In the third period, from October 2014 onward, the long-run relationship is again confirmed, as it was in the first period. However, the analysis shows now that, whilst the long-run relationship between Brent and WTI is slightly weakened, as the cross-price elasticity is reduced, the impact of shale oil quantity on the WTI price increases fivefold, reaching a half unit elasticity. Therefore, we can conclude that after the rise in shale oil production and the widening and closing of the WTI-Brent price spread, from October 2014 onward, a new long-run relationship between WTI and Brent has emerged. The shale oil quantity has increased its importance in explaining WTI price dynamics, reaching almost half the relevance of the Brent price one. Looking at the impulse response functions and comparing the period up to February 2011 with the one that started after October 2014, we see a relevant change in the impact that shale has on oil prices and vice versa. In the former period, the shale oil quantity did not react

to the change in price, whilst the price was negatively affected by the positive supply shocks of shale. In the second period, the shale oil quantity reacts to price increases, whilst the opposite does not occur anymore. We interpret this as a signal of a change in the shale-oil price relationships: in the first period, prices were high and the shale quantity was low, so an increase in the shale oil quantity was perceived as a positive supply shock. In the last period, the oil prices were low and the shale quantity was high, so the shale quantity followed the change in prices, which were not determined anymore by supply shocks.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2018.08.022.

References

Aruga, K., 2015. Testing the international crude oil market integration with structural breaks. Econ. Bull. 35, 641–649.

Baker, S., Bloom, N., Davis, S., 2016. Measuring economic policy uncertainty. Q. J. Econ. 131, 1593–1636.

Borenstein, S., Kellogg, R., et al. 2014. The incidence of an oil glut: who benefits from cheap crude oil in the Midwest? Energy J. 35 (1), 15–33.

Büyükşahin, B., Lee, T., Moser, J., Robe, M., 2013. Physical market conditions, paper market activity, and the WTI-Brent spread. Energy J. 34 (3).

Chen, W., Huang, Z., 2015. Is there a structural change in the persistence of WTI-Brent oil price spreads in the post-2010 period? Econ. Model. 50, 64–71.

Coronado, S., Fullerton, T., Rojas, O., 2016. Causality patterns for brent, WTI, and argus oil prices. Appl. Econ. Lett. 24, 982–986.

EIA, 2016. Short-term Energy Outlook: Market Prices and Uncertainty Report. US Energy Information Administration.

Fattouh, B., 2007. WTI benchmark temporarily breaks down: is it really a big deal. Middle East Econ. Surv. 50 (20), 7.

Fattouh, B., 2010. The dynamics of crude oil price differentials. Energy Econ. 32 (2), 334–342.

Giles, D.E., Godwin, R.T., 2012. Testing for multivariate cointegration in the presence of structural breaks: p-values and critical values. Appl. Econ. Lett. 19 (16), 1561–1565.

Gregory, A.W., Hansen, B.E., 1996. Residual-based tests for cointegration in models with regime shifts. J. Econ. 70 (1), 99–126.

Gülen, S.G., 1999. Regionalization in the world crude oil market: further evidence. Energy J. 125–139.

Hammoudeh, S.M., Ewing, B.T., Thompson, M.A., 2008. Threshold cointegration analysis of crude oil benchmarks. Energy J. 79–95.

Johansen, S., 1988. Statistical analysis of cointegration vectors. J. Econ. Dyn. Control. 12 (2-3), 231–254.

Johansen, S., 1995. Likelihood-based Inference in Cointegrated Vector Autoregressive Models. Oxford University Press. https://doi.org/10.1093/0198774508.001.0001.

Johansen, S., Mosconi, R., Nielsen, B., 2000. Cointegration analysis in the presence of structural breaks in the deterministic trend. Econ. J. 3 (2), 216–249.

Kao, C.-W., Wan, J.-Y., 2012. Price discount, inventories and the distortion of WTI benchmark. Energy Econ. 34 (1), 117–124.

Kilian, L., 2016. The impact of the shale oil revolution on us oil and gasoline prices. Rev. Environ. Econ. Policy 10 (2), 185–205.

Kim, J., Kim, J., Heo, E., 2013. Evolution of the international crude oil market mechanism. Geosyst. Eng. 16, 265–274.

Liao, H., Lin, S., Huang, H., 2014. Are crude oil markets globalized or regionalized? Evidence from WTI and Brent. Appl. Econ. Lett. 21, 235–241.

Liu, P., Stevens, R., Vedenov, D., 2018. The physical market and the WTI/Brent price spread. OPEC Energy Rev. 42, 55–73.

Perron, P., 1997. Further evidence on breaking trend functions in macroeconomic variables. J. Econ. 80 (2), 355–385.

Pesaran, H.H., Shin, Y., 1998. Generalized impulse response analysis in linear multi-variate models. Econ. Lett. 58 (1), 17–29.

Reboredo, J.C., 2011. How do crude oil prices co-move?: A copula approach. Energy Econ. 33 (5), 948–955.

Weiner, R., 1991. Is the world oil market 'one great pool'? Energy J. 12, 95–107.

Wilmot, N.A., 2013. Cointegration in the oil market among regional blends. Int. J. Energy Econ. Policy 3 (4), 424.