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WTI and Brent Futures Pricing Structure

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Abstract

WTI and Brent crude oil futures are competing pricing benchmarks and they jockey for the number one position as the leading futures market. The price spread between WTI and Brent is also an important benchmark itself as the spread affects international trade in oil, refiner margins, and the price of refined products globally. In addition, the shapes of the WTI and Brent futures curves reflect supply and demand fundamentals in the U.S. versus the world market, respectively.

On the analysis of the relationship between the two futures prices, we identify a structural break in the WTI–Brent price spread in January 2011 and a break in the corresponding shapes of the futures curves around the same time. The structural break was a consequence of a dramatic rise in U.S. production due to fracking, a series of supply disruptions in Europe, binding storage constraints, and the U.S. crude oil export ban. These events are studied in the context of a simulation model of world oil prices. We reproduce the stylized facts of the oil market and conclude that the 2011 break in pricing structure was consistent with standard commodity storage theory.

Keywords: crude oil futures, commodity storage, WTI, Brent, competitive storage model

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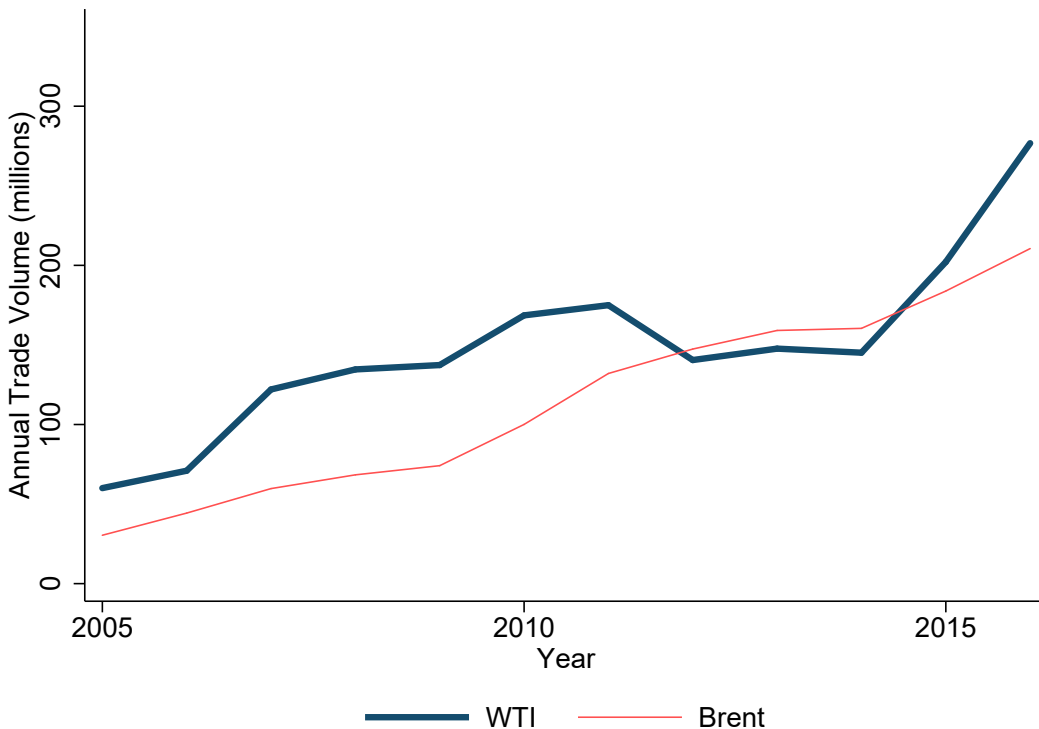
1. Introduction

The crude oil futures market is dominated by two competing benchmark grades, West Texas Intermediate (WTI) and Brent crude. As benchmarks, WTI and Brent provide a reference price against which oil around the world is traded at a premium or discount. WTI is primarily traded on the NYMEX (CME Group) while Brent is primarily traded on the Intercontinental Exchange (ICE). The CME Group and ICE both cross list WTI and Brent. However, the CME accounts for over 80% of WTI volume and the ICE accounts for about 90% of the Brent trading volume.

The pricing point for WTI is delivery into either a pipeline or storage facility in Cushing, Oklahoma. Brent crude specifies delivery onto a vessel at the Sullom Voe oil terminal on the Shetland Islands in the North Sea. The chemical characteristics of Brent and WTI are nearly identical, with Brent crude being the slightly less sulfurous of the two. Annual trading volume for each of the contracts is displayed in Figure 1 where it is shown that for three recent years (2012-2014) Brent displaced WTI as the most heavily traded oil futures market. During this time period, the U.S. government's Energy Information Administration (EIA) abandoned WTI for its reference oil price, and substituted the North Sea Brent contract, in its 2013 *Annual Energy Outlook*. The reasoning was that WTI was somewhat disconnected from the global market. At the time Brent was a superior benchmark because imported crude into the eastern and western U.S. coastal markets and refined products in the U.S. are priced off the global market. But shifting to Brent as a reference price was not ideal because oil production in the North Sea is dwindling due to aging oil fields in that region.

Crude oil sold in the U.S. is priced off the WTI contract, while oil sold internationally is typically priced off Brent. Therefore the spread between the two is a very important metric in the global oil complex. The spread reflects the competitiveness of U.S. in the world market and in addition the WTI–Brent price spread is an indicator of refiner profitability in the U.S.

Figure 1: WTI and Brent Annual Futures Contract Trading Volumes



Source: <https://www.theice.com/marketdata/reports/7> for Brent and Bloomberg for WTI.

26 versus world market. Refiner profits are impacted by the spread because their input (oil)
27 could be benchmarked off WTI (depending on the source) but their output (gasoline or other
28 refined products) could be more closely benchmarked to Brent. In this paper we study the
29 WTI–Brent price spread and the shapes the futures curves for each of the two contracts. Our
30 specific aim is to explain what happened in 2011 when the spread diverged from historical
31 levels, sending WTI to more than a \$20 discount under WTI and resulting in the WTI being
32 viewed as a broken benchmark for a time. At the same, time the shape of the WTI and Brent
33 futures curves became dissimilar from one another, with different slopes, which was unusual.

34 The Brent and WTI contracts are differentiated in two important ways. The price
35 settlement points are separated by over four thousand miles and the delivery specifications
36 differ substantially. Brent crude can be readily transported anywhere in the world and thus its

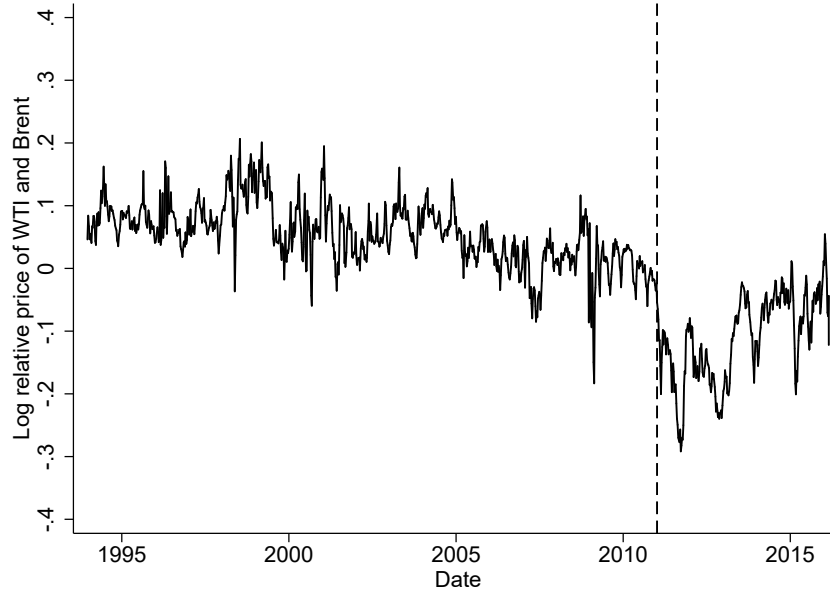
37 spot price is more correlated with port and coastal grades of crude oil (The Intercontinental
38 Exchange, 2013). Alternatively, WTI is more responsive to U.S.-specific supply and demand
39 fundamentals and infrastructure issues. Further, the WTI pricing point is co-located with
40 substantial above-ground storage, 73 million barrels of storage capacity (EIA, 2016c). The
41 Brent location is more of a just-in-time production model with only 8.4 million barrels of
42 available storage (Olsen, 2012, BP, 2016). Conceptually, the vastly different storage facilities
43 could give rise to alternative inter-temporal price spreads in one market versus the other.
44 The *law of one price* suggests that the spot prices for these nearly equivalent grades of crude
45 oil should differ by no more than the transactions costs of transporting oil from one market
46 to another. This is why the spot prices were so closely linked prior to 2011, when the U.S.
47 was a major net importer of oil (Fattouh, 2010).

48 Inter-temporal prices are linked through storage (Working, 1949, Brennan, 1958,
49 Wright and Williams, 1982) and spatial prices are linked by trade (Makki, Tweeten and
50 Miranda, 1996, Miranda and Glauber, 1995). There have been other cases in the commodities
51 space where the law of one price has broken down, but typically, these are short lived events.
52 For instance, in early 2014 natural gas prices at the Algonquin citygate hub serving Boston
53 reached about \$25 per mmBTU compared to \$5 per mmBTU in Henry Hub due to pipeline
54 capacity constraints (EIA, 2016b). However, this price differential lasted only a matter of
55 months compared to the lengthy WTI–Brent differential.

56 Figure 2 shows the log relative spot price of WTI and Brent from 1993 to 2016. The
57 relative price remained relatively stable from the beginning of the series until some time in
58 early 2011 where the relative price sharply falls, indicating a divergence in the spot prices.
59 Figure 2 also includes a dashed line at the January 6, 2011 breakpoint which is discussed in
60 Section 2.

61 Not only did the spot prices diverge in early 2011, but so did the shape of the
62 futures curves for both WTI and Brent. We observe a marked difference between inter-

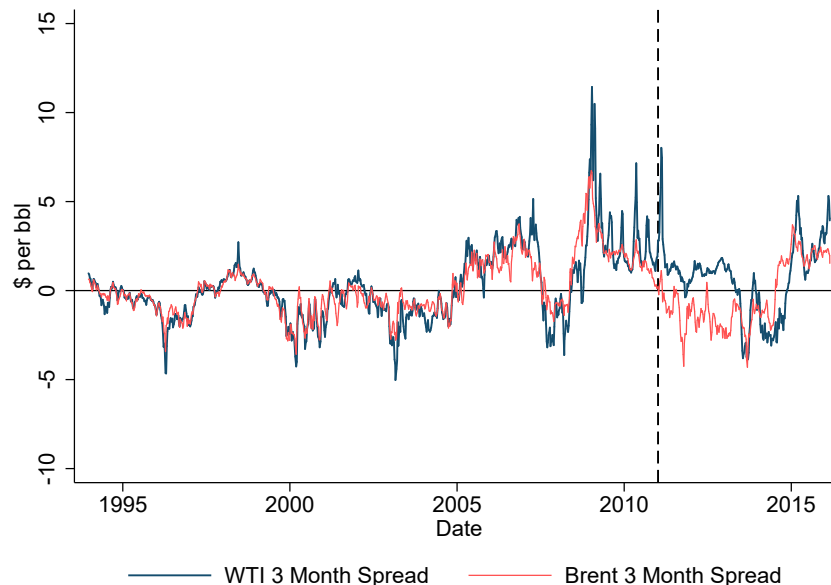
Figure 2: Log Relative Price of WTI and Brent Spot Prices



*Note: Log of the ratio of WTI and Brent weekly spot prices. Dashed line indicates January 6, 2011.
Source: Data obtained from United States Energy Information Administration.*

63 temporal futures price spreads for WTI and Brent, shown below in Figure 3. We define
64 the inter-temporal price spread for each crude oil grade as the fourth month futures price
65 minus the front month price. We choose this measure of inter-temporal price spread to
66 yield a three-month time horizon within which trade and storage decisions can be made. We
67 observe that in 2011, the price spread for WTI was positive, or in “contango,” and the spread
68 for Brent was negative, or in “backwardation.” In the early portion of the sample, these
69 contracts exhibit similar price spreads where typically they were either both in contango
70 or both in backwardation at any given time. The contango structure of the WTI futures
71 curve is indicative of an oversupplied market, that is the market is putting a premium on oil
72 delayed for sale in the future. Whereas, the Brent in backwardation indicated the market was
73 placing a premium on immediate delivery of oil. Figure 3 shows that, around the same time
74 the spot prices diverged, the shape of the futures curves for WTI and Brent also diverged.
75 WTI remained in contango and Brent went into backwardation. This divergence of WTI
76 and Brent prices led some to question the legitimacy of WTI as the global oil benchmark,

Figure 3: WTI and Brent, Weekly Three-Month Price Spreads



Note: The three-month price spread is calculated as the futures price for delivery four months in the future minus the futures price for delivery one month in the future. Dashed line indicates January 6, 2011. Source: Data obtained from Quandl.com.

77 suggesting that Brent should take its place (Kilian, 2016). However, Kilian (2016) notes that
78 Brent suffers from its own drawbacks such as declining North Sea production leading to low
79 liquidity, and the continual broadening of the definition of the Brent benchmark to include
80 lower grades of crude. Kilian (2016) wrote that it is “unclear whether there remains enough
81 oil in the North Sea to sustain a Brent benchmark in the long run” (p. 33).

82 We hypothesize that a series of events, beginning in the late 2000s, led to a situation
83 where the combined effect was a break in integrated WTI and Brent markets. The shale
84 revolution greatly increased U.S. domestic oil production starting in 2008 (Brown and Yücel,
85 2013). A thorough overview of the shale revolution can be found in Kilian (2016) and Alquist
86 and Guénette (2014). As U.S. production rose, more oil began flowing to Cushing, OK than
87 could be refined and then moved via pipeline. Therefore, crude oil stocks in Cushing began to
88 climb (Wilmoth, 2012). In March 2011, storage capacity utilization reached 91% in Cushing,
89 OK (EIA, 2015).

90 At the same time, Europe was experiencing negative supply shocks. The Libyan
91 Crisis disrupted production and this incident persisted much longer than expected (Meyer,
92 2011). Nigerian pipeline sabotage also disrupted supply (Vidal, 2011). In addition, bad
93 weather in the North Sea caused production outages (Meyer, 2011). These supply disruptions
94 resulted in severe drawdowns of Brent inventories (Blas and Blair, 2011).

95 Prior literature has identified the U.S. shale revolution, non-U.S. production disrup-
96 tions, U.S. infrastructure and transportation bottlenecks, the U.S. export ban, reweighting
97 of the S&P GSCI commodity index in favor of Brent, and the Dow Jones UBS commodity
98 index including Brent for the first time, as explanations for the divergence of the WTI and
99 Brent prices (Alquist and Guénette, 2014, Büyüksahin et al., 2013, Chen, Huang and Yi,
100 2015, Kilian, 2016, Ye and Karali, 2016).

101 We develop a stylized, simulation model of world oil prices that we parameterize and
102 calibrate to represent the characteristics of the crude oil market before the structural break.
103 We impose features of the key stylized facts: positive production shocks in the U.S., negative
104 production shocks in Europe, maximum and minimum storage constraints, and a U.S. export
105 ban. We then simulate the model and compare the results with the characteristics of the
106 oil market before and after the structural break. We are able to successfully reproduce the
107 structural break in the oil market.

108 This paper is organized as follows: in Section 2, we present stylized facts of the world
109 oil market and we test for and identify a break in cointegration between WTI and Brent daily
110 spot prices as well as daily nearby futures prices. In Section 3, we present our hypotheses
111 as to why there was a structural break. Next, in Section 4 we develop a stylized model of
112 world oil prices based upon the competitive storage model employed by Gustafson (1958),
113 Wright and Williams (1982), Deaton and Laroque (1992), and the extensions by Miranda
114 and Glauber (1995) and Makki, Tweeten and Miranda (1996) which incorporate trade into
115 the model. Section 5 presents the results of our simulation of the model and compares them

116 to the key stylized facts of the oil market following the structural break. Finally, Section 6
117 concludes.

118 **2. Stylized facts of the world oil market**

119 Key stylized facts related to the WTI and Brent markets are shown in Table 1.
120 When comparing average data for the three years before the 2011 price break to the average
121 for the three years following, U.S. production increased by 43% and North Sea production
122 decreased by 29%. Storage levels at the WTI pricing terminal increased by 32% and storage
123 levels in OECD Europe declined by 4%.¹ Exports from the North Sea to the U.S. declined by
124 76% and the average spot price premium for WTI over Brent fell from \$0.92 to -\$11.18. The
125 shape of the forward curve also experienced a shift as the percent of trading days that WTI
126 was in contango fell from 90% to 69%, whereas for Brent it fell from 92% to 45%.² In the
127 years following the price break, Brent was in backwardation more often than in contango.
128 Futures trading volume in the WTI front month contract fell by 19%, whereas the Brent
129 front month (the contract for most immediate delivery) trading volume increased by 61%.

130 When linked by trade, the spot prices of WTI and Brent crude should be arbitrated.
131 Since the inception of the Brent crude benchmark in 1993 through 2011, this was largely
132 true. The 52-week rolling correlation between the weekly spot prices of WTI and Brent are
133 presented in Figure 4.³ It is apparent that the correlation between these two price series does
134 not deviate much from the mean of 0.96 up until some point in 2011 when the relationship
135 broke down. The correlation dropped and remained persistently depressed following the start

¹The ideal measure for Brent storage is storage levels at the Sullom Voe terminal, however, these data are unavailable. As a proxy, storage levels for OECD Europe as a whole declined between these two time periods.

²Percent of trading days in contango is measured as the proportion of trading days where the settlement price for the futures contract four months ahead is greater than the settlement price of the futures contract one month ahead.

³On a given week, the 52-week rolling correlation calculates the correlation between two series for the past 52 weeks.

Table 1: WTI and Brent Oil Markets, Stylized Facts

	2008 - 2010	2012 - 2014	% Δ
Production			
U.S. (thousand bbl/day)	5,277	7,546	+43%
North Sea (thousand bbl/day)	3,702	2,650	-28%
Storage			
Cushing, OK (thousand bbl)	28,065	37,362	+33%
OECD Europe (thousand bbl)	332,333	317,467	-4%
International Trade			
North Sea to U.S. (thousand bbl/day)	140	34	-76%
Prices			
WTI-Brent Average Spot Premium	\$0.92	-\$11.18	-1,315%
Percent of Trading Days in Contango			
WTI	90%	69%	-23%
Brent	92%	45%	-50%
Front Month Trading Volume			
WTI	285,591	232,665	-19%
Brent	110,570	178,326	+61%

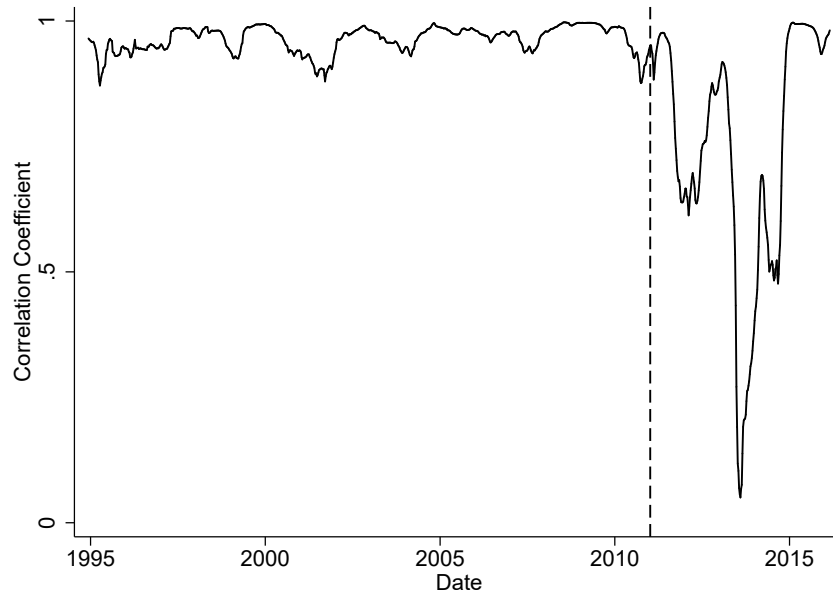
Source: U.S. production data (EIA, 2016f), North Sea production data (EIA, 2016a), Cushing, OK storage data (EIA, 2016g), and North Sea to U.S. international trade data (EIA, 2016e) are from the U.S. Energy Information Administration. North Sea production and international trade data are computed as the sum of country-specific values for Denmark, Germany, the Netherlands, Norway, and the United Kingdom. OECD Europe storage data are from the IEA Oil Market Reports for February 2012 and February 2016 (IEA, 2012, IEA, 2016). The WTI-Brent average spot premium is calculated as the difference the WTI spot price minus the Brent spot price per the Energy Information Administration (EIA, 2016d). Percent of trading days in contango is based on the portion of days where the fourth month futures price exceeds the front month futures price based on daily futures settle prices for the CME WTI contract and ICE Brent contract obtained from Quandl.com. Front month trading volume for the CME WTI contract and ICE Brent contract are based on daily trading volume obtained from Quandl.com.

136 of 2011. The absolute prices are presented in Figure 5.

137 We analyzed the long-term relationship between WTI and Brent series; as they
138 were non-stationary⁴ we tested for cointegration between them using weekly spot prices and
139 performing the two-step Engle-Granger test for cointegration (Engle and Granger, 1987). We
140 suspect that the two price series are cointegrated during the early portion of our sample, but
141 the cointegration degrades at some point. To test for a break in the cointegration between

⁴We performed the augmented DF-GLS test on the daily spot prices from 1993 to 2016 and found both series non-stationary (Dickey and Fuller, 1979, Elliott, Rothenberg and Stock, 1992). The DF-GLS test statistic for WTI was -1.577 and for Brent -1.307, therefore it was not possible to reject the hypothesis of non-stationarity in levels.

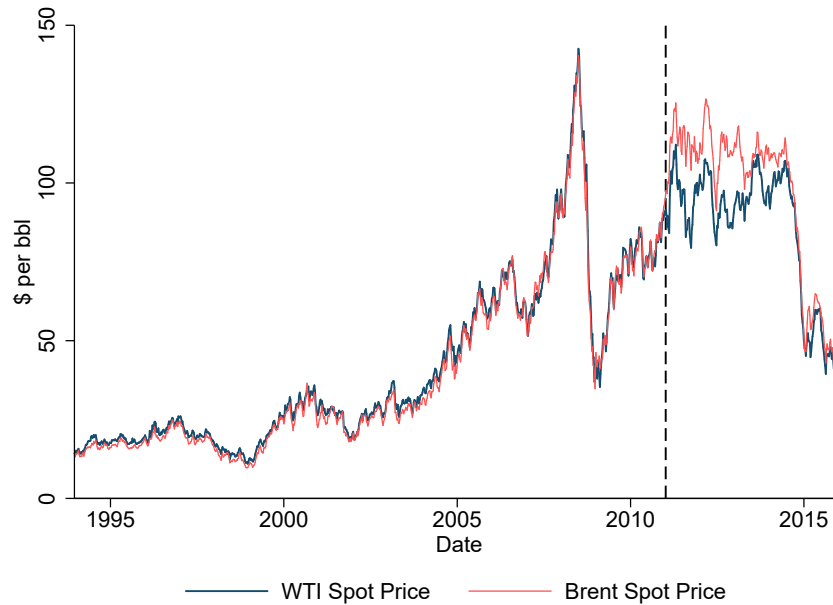
Figure 4: 52-week Rolling Correlation of WTI and Brent Weekly Spot Prices



Note: Dashed line indicates January 6, 2011.

Source: Data obtained from United States Energy Information Administration.

Figure 5: WTI and Brent Weekly Spot Prices



Note: Dashed line indicates January 6, 2011.

Source: Data obtained from United States Energy Information Administration.

142 WTI and Brent, we perform a supremum Wald test for a structural break at an unknown
143 break date using symmetric trimming of 15% in the equation

$$WTI_t = \alpha + \beta Brent_t + u_t \quad (1)$$

144 where WTI_t is the daily spot price of WTI at time t , and $Brent_t$ is the daily spot price of
145 Brent at time t . Our test finds a breakpoint on January 6, 2011 which is consistent with
146 other studies which have identified December 2010 as the date of a structural break in the
147 WTI-Brent price spread (Büyüksahin et al., 2013, Chen, Huang and Yi, 2015, Ye and Karali,
148 2016) and in WTI-Brent cointegration (Chen, Huang and Yi, 2015).

149 To more formally test for a breakdown in the cointegration between these series, we
150 repeat the Engle-Granger cointegration test for the periods before and after the breakpoint.
151 We find strong evidence of cointegration between WTI and Brent in the period before the
152 January 6, 2011 breakpoint and we fail to reject the hypothesis of no cointegration in the
153 period after the breakpoint, at the 1% significance level. Test statistics for the stationarity
154 and cointegration tests for the pre- and post-breakpoint periods are presented in Table 2.
155 As a robustness check, we test for a structural break in the cointegration of Brent and WTI
156 daily spot prices using the Gregory-Hansen test (Gregory and Hansen, 1996). We perform
157 the Gregory-Hansen test on Equation 1 allowing for structural change in the level and slope
158 of the cointegrating relationship and reject the null hypothesis of no cointegration in favor
159 of a structural break on January 10, 2011 at the 1% significance level.

160 Turning to the futures market, the 52-week rolling correlation between the front
161 month WTI and Brent future prices is reported in Figure 6 and for the fourth month in
162 Figure 7. We find statistical evidence of a structural break in the relationship between the
163 WTI and Brent front month futures prices on January 6, 2011 as well as between the fourth

Table 2: Tests for Stationarity and Cointegration

Test	Pre-Breakpoint	Post-Breakpoint
WTI Stationarity	-2.263	-0.830
Brent Stationarity	-1.967	-0.664
WTI-Brent Cointegration	-8.066**	-2.650

* $p < 0.05$, ** $p < 0.01$

Stationarity and cointegration tests are conducted on daily WTI and Brent spot prices per the Energy Information Administration (EIA, 2016d). The Pre-Breakpoint time period is December 17, 1993 to January 5, 2011 and the Post-Breakpoint time period is January 7, 2011 to February 26, 2016. Test statistics reported above are the results of DF-GLS tests allowing for a trend and including lag terms as specified by the Schwarz Criterion. The results are preserved under alternative choices of lag length and restrictions on trend.

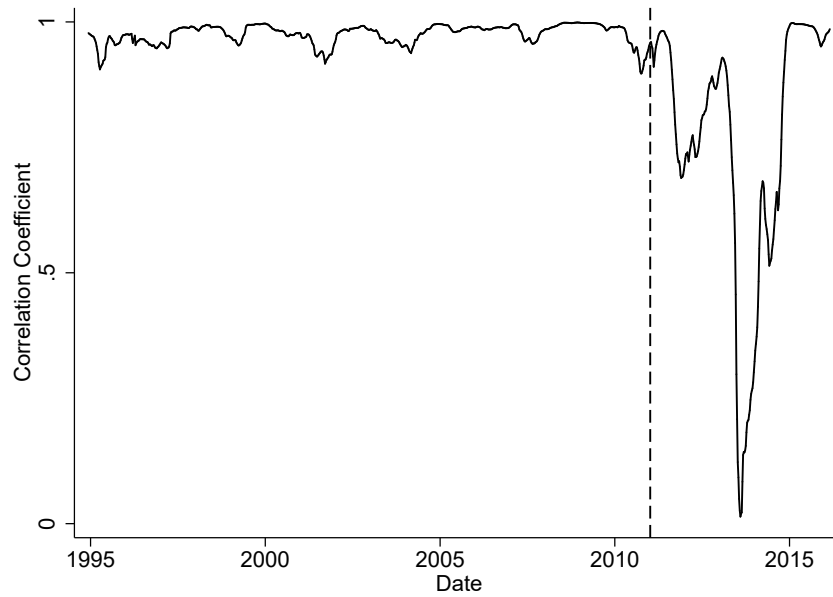
164 month futures prices on January 25, 2011.⁵

165 3. What drives the new price structure?

166 We hypothesize that the reason behind the breakdown of the correlation between
 167 the spot prices, the futures prices, and the inter-temporal spreads was a result of both supply
 168 shocks and barriers to arbitrage. The U.S. had been a significant importer of crude oil, but
 169 reliance on imports (particularly imports from the North Sea region) was greatly diminished
 170 post-2010. The U.S. experienced a strong positive supply shock and inventory buildup at
 171 the same time that Europe was experiencing negative supply shocks and inventory depletion.
 172 Additionally, as indicated in Büyüksahin et al. (2013) and Ye and Karali (2016), the U.S.
 173 and EU also experienced shocks to demand at this time. The reweighting of the commodity
 174 indices S&P GSCI and the Dow Jones UBS served to increase demand for Brent at the
 175 expense of reduced demand for WTI. Further, increased Japanese oil demand following the
 176 Fukushima disaster served to increase demand for Brent to replace lost nuclear electricity
 177 generation. The shocks in demand experienced by the U.S. and the EU impact the spot

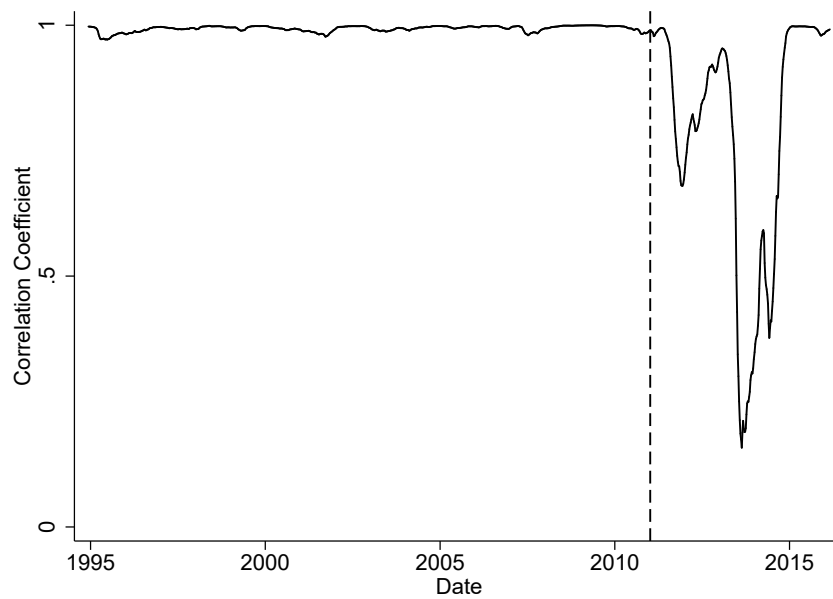
⁵We estimate structural breaks for the front and fourth month contracts using the supremum Wald test for a structural break at an unknown break date using symmetric trimming of 15%. The front month structural break and fourth month structural break are also statistically significant at the <0.0001% level.

Figure 6: 52-week Rolling Correlation of WTI and Brent Weekly Front Month Futures Prices



*Note: Dashed line indicates January 6, 2011.
Source: Data obtained from Quandl.com.*

Figure 7: 52-week Rolling Correlation of WTI and Brent Weekly Fourth Month Futures Prices



*Note: Dashed line indicates January 25, 2011.
Source: Data obtained from Quandl.com.*

178 price, futures price, and inter-temporal spread relationships in the same direction as the
179 supply shocks. That is, the negative demand shock experienced by the U.S. exacerbates the
180 impact of the positive supply shock on the futures pricing relationship. For the EU, the
181 positive demand shock exacerbates the impact of the negative supply shock. In Section 5.1,
182 we describe an alternative specification of our competitive storage model where we implement
183 structural change in the form of demand shifts rather than supply shifts and our results are
184 robust to this change in specification.

185 The supply shocks in the U.S. and EU oil markets resulted in the price of WTI
186 falling below the price of Brent by an amount that far exceeded shipping costs of about \$2
187 per barrel (Scheid, 2014). The average price difference between 2000 and 2010 had WTI at a
188 premium of \$1.40 per bbl. The price difference between WTI and Brent reached the extreme
189 of WTI at a discount of \$29.59 per bbl on September 23, 2011. However, due to the U.S.
190 crude oil export ban, this price difference was not arbitraged away. Traders were unable to
191 move oil from the United States to Europe or elsewhere to correct the price differential which
192 lasted until 2015. As a consequence of the unexpected positive oil supply shocks in the U.S.,
193 storage capacity in Cushing, OK reached its maximum. One curious element of the steep
194 contango in the United States is that with the relatively new production boom in historically
195 non-producing regions (e.g. North Dakota) why would these producers not simply "store"
196 their oil in place rather than extract and deliver into a market that indicate higher prices
197 would await in a few months time. Nevertheless, these producers in these regions did extract
198 their oil during despite facing a steep contango. When there is no opportunity to put oil into
199 storage, it creates pressure to sell immediately thus driving down the spot price relative to
200 the futures price. The contrary is true of the Brent market; as unexpected supply disruptions
201 persisted and continued to draw down inventories, this put upward pressure on the spot price
202 of oil relative to the futures prices. We theorize that had there been no export ban, or if the
203 U.S. had plenty of excess storage capacity and Europe had plenty of crude oil in storage, the
204 integration of the two markets would have persisted.

205 4. A stylized model of world oil prices

206 As Deaton and Laroque (1992, 1996) employed the competitive storage model to
207 reproduce the stylized facts of autocorrelation and price spikes in commodity prices, we
208 employ the competitive storage model to reproduce the Brent-WTI oil market pricing struc-
209 ture linked by trade. As in Miranda and Glauber (1995), we conceptualize a two-region
210 oil market allowing competitive interregional trade, competitive storage, lagged production
211 decisions and uncertain output and prices. While a two-region model is a simplification of
212 the complex geography of the world oil market, this representation is useful in isolating the
213 impacts of barriers to spatial and inter-temporal arbitrage. Since models of trade and storage
214 under uncertainty do not have analytical solutions (Gustafson, 1958, Deaton and Laroque,
215 1992, Miranda and Glauber, 1995, Gardner, 1979), we solve and simulate the competitive
216 storage model numerically using the Rational Expectations Complementarity Solver created
217 by Christophe Gouel (2012). In order to capture the nature of the oil market at the time of
218 the market pricing anomaly, we impose the restriction on trade that United States may not
219 export oil and we impose constraints on storage such that storage levels may not fall below
220 zero or exceed some maximum capacity specific to each region. For each region $i = 1, 2$ and
221 period t , market price is denoted by $P_{i,t}$, planned production by $H_{i,t}$, ending stocks by $S_{i,t}$,
222 consumption by $C_{i,t}$, exports from region i by $X_{i,t}$ and the discount rate is denoted by r . The
223 quantity of oil available in each region at the beginning of each period, $A_{i,t}$, is equal to the
224 ending stocks of last period plus current production which is determined by a multiplicative,
225 exogenous shock, $e_{i,t}$, on a production decision last period:

$$A_{i,t} = S_{i,t-1} + H_{i,t}e_{i,t}. \quad (2)$$

226 Available oil at the beginning of the period plus current period imports must equal
227 current period consumption plus ending stocks plus current period exports:

$$A_{i,t} + X_{\sim i,t} = C_{i,t} + S_{i,t} + X_{i,t}. \quad (3)$$

228 In the above market clearing condition, $X_{\sim i,t}$ denotes imports into region i . We
 229 assume isoelastic demand functions in each region:

$$C_{i,t} = D_i \times (P_{i,t})^{\varepsilon_i} \quad (4)$$

230 with demand parameterized by the constants D_i and ε_i . We also assume isoelastic supply
 231 functions in each region:

$$H_{i,t} = g_i \times \left(\frac{E_t [P_{i,t+1} e_{i,t+1}]}{(1+r)} \right)^{\eta_i} \quad (5)$$

232 with the supply functions parameterized by the constants g_i and μ_i for each region. The
 233 price of oil in the United States can only exceed the price of oil in Europe by, at most, the
 234 amount of shipping costs. Therefore, either the WTI minus Brent price spread is less than
 235 shipping costs or exports from Europe to the U.S. are greater than zero. The spatial arbitrage
 236 complementary slackness condition is then:

$$X_{2,t} \geq 0 \quad \perp \quad P_{1,t} - P_{2,t} \leq \tau, \quad (6)$$

237 where τ is the per-barrel shipping cost.⁶ There is no spatial arbitrage condition allowing for
 238 trade from the United States to Europe while the crude oil export ban is in place. When the
 239 ban is lifted, the spatial arbitrage condition for trade from the United States to Europe is

⁶The symbol \perp indicates that both weak inequalities hold and at least one holds with equality.

$$X_{1,t} \geq 0 \quad \perp \quad P_{2,t} - P_{1,t} \leq \tau. \quad (7)$$

240 In this model, we have considered linear shipping costs and no transport constraints beyond
 241 the U.S. export ban, though nonlinear shipping costs and transportation constraints could
 242 be included.

243 Similar to the trade arbitrage condition above, merchants in both markets can store
 244 crude oil and will do so if the discounted expected price of oil in that market exceeds the
 245 current price by storage costs within the bounds of minimum, 0, and maximum, \bar{S}_i , storage
 246 levels. The inter-temporal arbitrage complementary slackness conditions are then:

$$0 \leq S_{i,t} \quad \perp \quad \frac{E[P_{i,t+1}]}{1+r} - P_{i,t} \leq k, \quad (8)$$

$$S_{i,t} \leq \bar{S}_i \quad \perp \quad k \leq \frac{E[P_{i,t+1}]}{1+r} - P_{i,t}, \quad (9)$$

248 where k is the per-barrel cost of storage.

249 The multiplicative, exogenous shocks, $e_{i,t}$, are assumed to be independent over time
 250 and across regions and distributed as:

$$\begin{bmatrix} e_{1,t} \\ e_{2,t} \end{bmatrix} \sim \mathcal{N}(\mu, \Sigma). \quad (10)$$

251 We calibrate the model to pre-2011 market conditions characterized by: (1) low variance in
 252 WTI-Brent spot price spread, (2) WTI price slightly higher than Brent, (3) inter-temporal
 253 price spreads highly correlated, (4) oil trade in only one direction, and (5) minimum and

254 maximum storage constraints.⁷ The parameters are chosen such that the steady-state equi-
 255 librium values of production, storage, trade, and prices match the mean values for 2008-2011
 256 time period for each of these regions which are presented in Table 1. We then solve the
 257 competitive storage model for the decision rules in both the United States and Europe under
 258 both the presence of the export ban and the absence of the export ban. Choices for parameter
 259 values are presented in Table 3.

Table 3: Competitive Storage Model Simulation Parameter Values

Parameter	Symbol	Value
Per Barrel Storage Cost	k	0.06
Per Barrel Shipping Cost	τ	5
Supply Elasticity 1	η_1	0.2
Supply Coefficient 1	g_1	2,201
Supply Elasticity 2	η_2	0.2
Supply Coefficient 2	g_2	1,550
Demand Elasticity 1	ε_1	-0.2
Demand Coefficient 1	D_1	12,997
Demand Elasticity 2	ε_2	-0.2
Demand Coefficient 2	D_2	8,649
Maximum Storage 1	\bar{S}_1	73
Maximum Storage 2	\bar{S}_2	8.4
Discount Rate	r	2%
Mean Shock	μ	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$
Shock Covariance Matrix	Σ	$\begin{pmatrix} 0.025 & 0 \\ 0 & 0.025 \end{pmatrix}$

260 5. Simulation Results

261 We simulate the model by setting initial values for the beginning-of-period avail-
 262 ability, $A_{i,t}$, in each region and providing a sequence of random shocks. We generate two
 263 sequences of random shocks, first selecting 100 random shocks from the distribution $\mathcal{N}(\mu, \Sigma)$.⁸
 264 Then, to represent the coincident supply shocks of higher than expected production in the

⁷Minimum storage constraint is zero in both markets. The maximum level of storage in the United States, $\bar{S}_1 = 2$, is set to be ten times larger than the maximum level of storage in Europe, $\bar{S}_2 = 0.2$, to reflect actual market conditions.

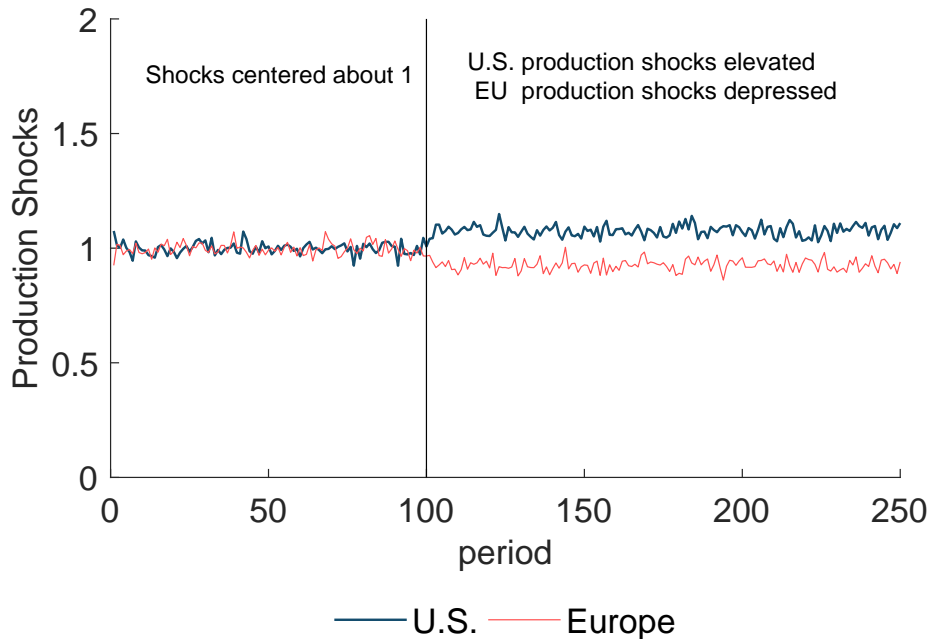
⁸We have also considered specifications for the covariance matrix which are not symmetric nor independent and find that these alternate specifications do not affect our results.

265 United States and lower than expected production in Europe, we select 150 random shocks
 266 from the distribution $\mathcal{N}(\mu', \Sigma)$ where $\mu' = \mu + \begin{pmatrix} 0.075 \\ -0.075 \end{pmatrix}$. That is, starting in period 100 and
 267 running to the end of the simulation, the mean production shock in the United States is
 268 increased by 1.5 standard deviations and the mean production shock in Europe is decreased
 269 by 1.5 standard deviations. Lastly, to illustrate the consequence of the U.S. crude oil export
 270 ban, beginning at period 150 and running to the end of the simulation, we remove the export
 271 ban and allow trade to flow from the U.S to the EU. The storage constraints are imposed by
 272 limiting S_i to $[0, \bar{S}_i]$ where $\bar{S}_i < \infty$. The export ban is imposed by restricting $X_{1,t} = 0$ for
 273 the periods where the export ban is in place, where $X_{1,t}$ is the quantity of exports from the
 274 U.S. to Europe in time t . The imposition of the shifts in production and lifting the export
 275 ban partition the sample into three regimes. Regime 1, from period 1 to 100, is considered to
 276 be the reference case where the production remains unaltered and the export ban is in place.
 277 Regime 2, from period 101 to 150, has U.S. production elevated and EU production depressed
 278 along with the export ban in place. Regime 3, from period 151 to 250, has U.S. production
 279 elevated and EU production depressed along with no restrictions on trade between U.S. and
 280 the EU.

281 Given the initial values for beginning oil availability, decision rules computed in the
 282 rational expectations model and the production shock series, we simulate the model to solve
 283 for optimal choice of storage levels and export flows in each region and the model yields spot
 284 prices and price expectations in each region. We present the simulated storage levels, spot
 285 prices, export flows, and inter-temporal price spreads in Figure 9.

286 From the simulation results, it is apparent that in the first regime, WTI and Brent
 287 spot prices are highly correlated, as are inter-temporal price spreads. In the second regime,
 288 however, the elevated production in the United States causes U.S. storage to increase and
 289 often binds at the maximum storage level. In Europe, the decreased production results in
 290 decreased storage levels which often bottom out at zero. As these storage markets bind at the

Figure 8: Competitive Storage Model - Production Shocks

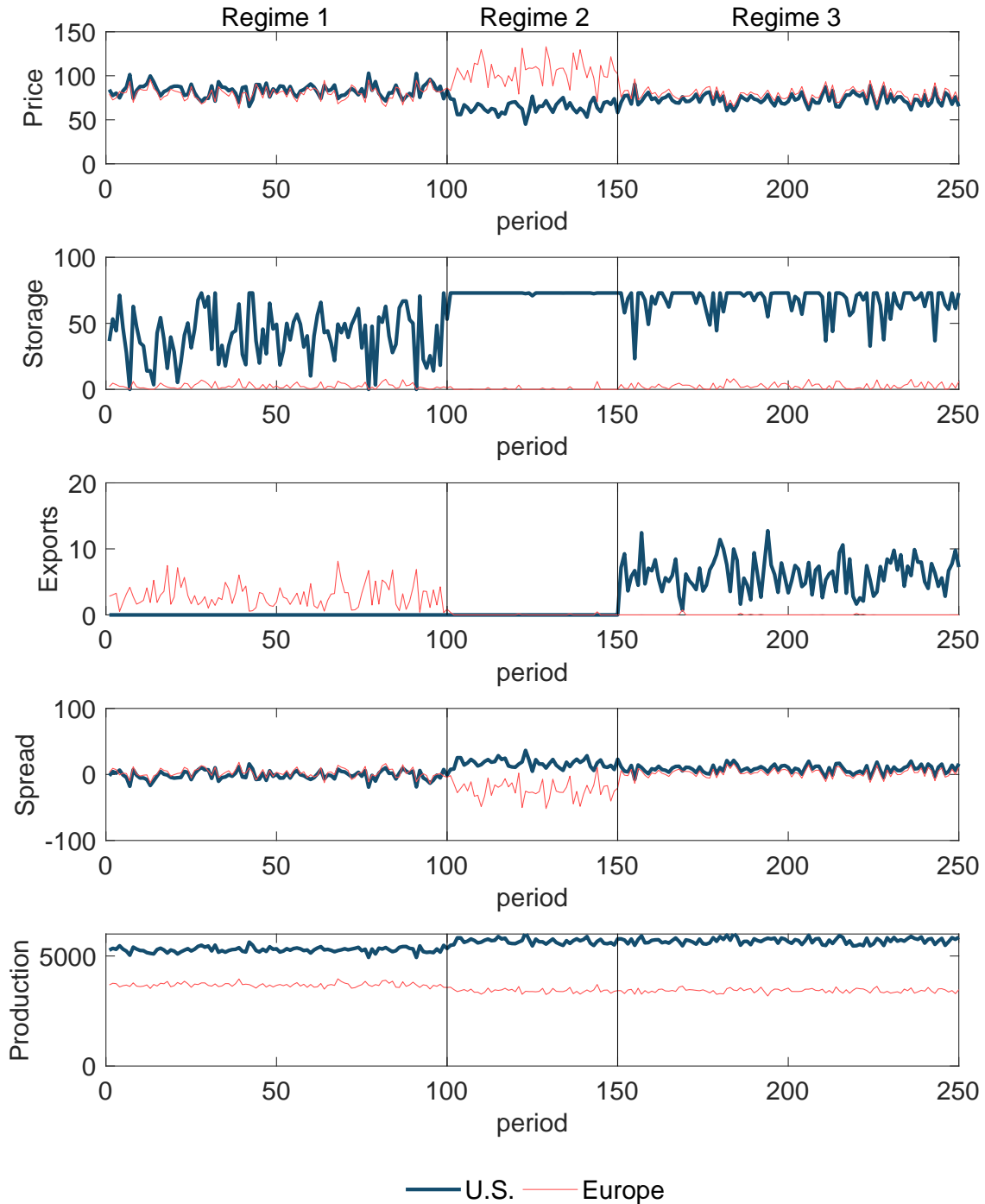


291 maximum and minimum possible storage levels, the opportunity for inter-temporal arbitrage
 292 vanishes. Further, exports from Europe to the United States go to zero in period two as
 293 Europe is experiencing a supply disruption and the spatial arbitrage opportunity in this case
 294 would be to export oil out of the United States and deliver to Europe.⁹ Due to the crude oil
 295 export ban, this was impossible. While U.S. exports of petroleum products (*e.g.* gasoline,
 296 diesel, etc.) are permitted, this mode of spatial arbitrage was insufficient to correct the price
 297 disparity, possibly due to the fact that refinery utilization rates at the WTI delivery point
 298 were already at 90% and above in 2011.

299 In this scenario in which all inter-temporal and spatial methods of arbitrage are

⁹Storage and export levels reaching zero is a limitation of the modeling framework. In practice, storage levels do not typically reach zero as there are physical requirements on minimum storage levels for floating roof style storage facilities as well as storage amounts held for operational reasons. In terms of exports, there are several possible reasons why EU producers would continue to ship oil to the U.S. even if the arbitrage conditions suggest they would be doing so at a loss. One possibility is that EU producers might have long-term contracts with U.S. buyers. Nevertheless, the general result of EU storage levels and exports decreasing substantially is consistent with the observed stylized facts.

Figure 9: Simulation Results - Price, Storage, Exports, Spread, & Production



Note: Regime 1 is the reference case where production is unaltered and the export ban is in place. Regime 2 has U.S. production elevated, EU production depressed, and the export ban in place. Regime 3 has U.S. production elevated, EU production depressed, and no export ban. Price is in USD per barrel, storage is in millions of barrels, exports are in thousands of barrels per day, spread is in USD per barrel, and production is in thousands of barrels per day.

300 unavailable, the spot prices of these near identical grades of crude separate. The price in the
301 United States falls, the price in Europe rises and the inter-temporal spreads in these regions
302 take on opposite shapes. The simulation results replicate the situation where the WTI price
303 is lower than Brent, WTI is in contango, Brent is in backwardation, U.S stocks reach the
304 maximum, European stocks are drawn down to the minimum, and trade from Europe to the
305 U.S goes to zero.

306 In the third regime where U.S. production is elevated, EU production depressed,
307 and no export ban, the U.S. is able to take advantage of the spatial arbitrage opportunity.
308 Following the repeal of the export ban, the simulation indicates oil flowing from the U.S. to
309 the EU, storage levels falling in the U.S., storage levels climbing in the EU, and prices and
310 price spreads converging back together.

311 *5.1. Robustness Check*

312 We consider the scenario where instead of a structural change in supply, we im-
313 plement a structural shift in demand. Our original specification implements the structural
314 change in supply by shifting the means of the multiplicative supply shocks in Equation 10
315 from μ to μ' . In this specification, we leave the mean of the shock distribution constant
316 at μ and shift out the EU demand and shift in the U.S. demand, reflecting the change in
317 demand due to the reweighting of commodity indices and the increase in Japanese demand.
318 Simulating the model under this alternate specification yields equivalent results in terms
319 of separation of spot prices, cessation of international trade, hitting storage maximum and
320 minimum levels, and yielding opposite price spreads during the period where the structural
321 change is implemented and the export ban is in place.

322 6. Conclusion

323 The WTI and Brent contracts compete for the role as the world benchmark price
324 of oil. Traders, including hedgers, typically choose one or the other contract. This means
325 there is great interest in the WTI-Brent pricing structure, including the shape of the two
326 futures curves, the absolute price difference between the two benchmarks, and the dynamics
327 of the degree of integration of the markets. These markets are heavily traded (directly
328 and indirectly) by hedgers and financial investors. Prices of jet fuel, heating oil, diesel, and
329 gasoline follow these markets closely. And there are also a large number of derivative financial
330 products such as swaps and options based on either WTI or Brent, or based on the price
331 spread between them.

332 From early 2011, the price of WTI went to a significant discount to Brent, but
333 U.S. crude could not be exported to the world market to arbitrage away the spread. This
334 break in the pricing relationship arose largely because of expanded U.S. production, reduced
335 production of Brent, and storage capacity factors. For similar reasons, the shape of the two
336 futures curves diverged around the same time. WTI was in contango and Brent displayed
337 backwardation. We develop a simulation model that explains the change in the pricing
338 structure in 2011. The key stylized facts of the WTI and Brent pricing structure are replicated
339 with our model. This means the break in the WTI-Brent futures pricing structure can be
340 explained by standard commodity storage theory.

341 Since the break in the WTI-Brent relationship, a number of fundamental changes
342 have occurred in the U.S. crude oil infrastructure. In May 2012, a major pipeline connecting
343 the WTI terminal in Cushing, OK to the Gulf Coast reversed its flow direction allowing crude
344 to be sent from the WTI terminal to the coast. In December 2015, U.S. Congress lifted
345 the crude oil export ban. Given that the barriers to spatial arbitrage in the WTI-Brent
346 market have been lifted, the 2011 market segmentation in the crude oil market is unlikely to

347 reoccur. As a result, the arguments for abandoning WTI as the main crude benchmark have
348 been corrected, and the arguments against using Brent as the main global crude benchmark
349 remain.

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