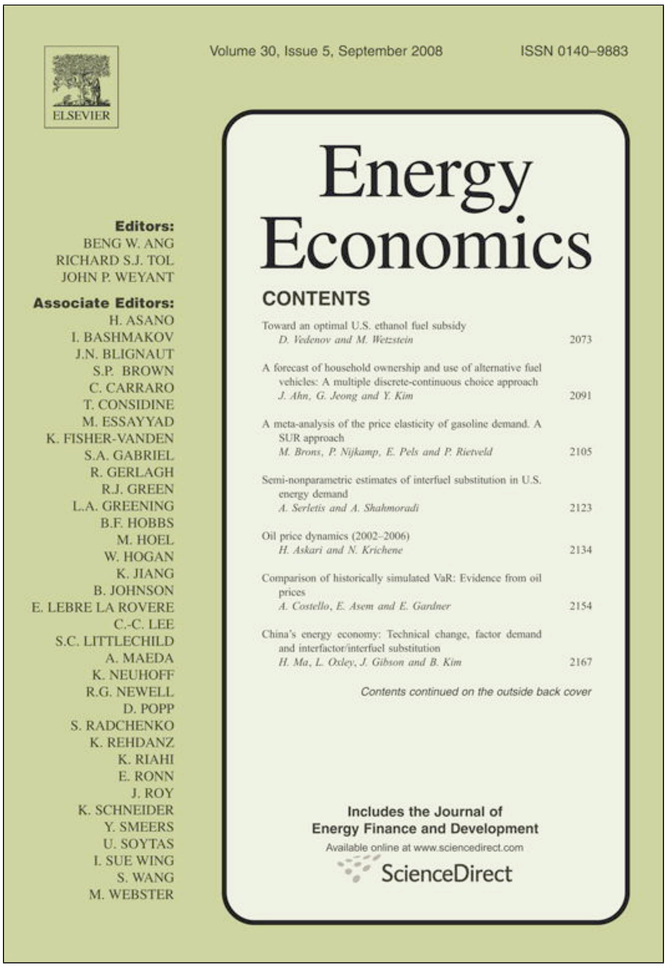
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Oil prices: The role of refinery utilization, futures markets and non-linearities ☆

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ABSTRACT

We test the hypothesis that real oil prices are determined in part by refinery capacity, non-linearities in supply conditions, and/or expectations and that observed changes in these variables can account for the rise in prices between 2004 and 2006. Results indicate that the refining sector plays an important role in the recent price increase, but not in the way described by many analysts. The relationship is negative such that higher refinery utilization rates reduce crude oil prices. This effect is associated with shifts in the production of heavy and light grades of crude oil and price spreads between them. Non-linear relationships between OPEC capacity and oil prices as well as conditions on the futures markets also account for changes in real oil prices. Together, these factors allow the model to generate a one-step ahead out-of-sample forecast that performs as well as forecasts implied by far-month contracts on the New York Mercantile Exchange and is able to account for much of the $27 rise in crude oil prices between 2004 and 2006.

1. Introduction

Causes for the rapid rise in the price of crude oil between 2004 and the summer of 2006 are the subject of debate. Some of the debate focuses on changes in the so-called downstream sector especially the refining

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sector. The number of refineries in the United States has not increased since 1981 (Annual Energy Review, 2006), and in the spring of 2007, a significant fraction of refining capacity was closed due to unscheduled maintenance (New York Times, 2007). Under these conditions, a lack of spare refining capacity is seen as one cause for the on-going rise in the price of crude oil and refined petroleum products.

Other hypotheses for the sharp rise in oil prices include the lack of spare production capacity, a non-linear relationship between oil prices and supply, and changed perceptions of the balance between supply and demand. Although a linear relationship can be a reasonable approximation under normal circumstances, extreme events may shift the market equilibrium between supply and demand towards different types of market functioning in which prices are much more sensitive to shocks than under normal conditions. On the supply side, non-linearities may be caused by lags associated with building additional extraction and refining capacity (Kaufmann and Cleveland, 2001; Kaufmann, submitted for publication). Given these constraints, oil prices would be more sensitive to supply as production approaches capacity. Finally, expectations about the supply/demand balance, as reflected by conditions in the futures market, may affect current prices.

Hypotheses that refining capacity, non-linearities, and expectations, have an important effect on oil prices are consistent with the performance of models that exclude their effect. For instance, the model by Dees et al. (2007), which specifies crude oil prices as a function of OPEC capacity, OECD crude oil stocks, OPEC quotas and cheating by OPEC on those quotas, performs well in-sample (1986–2003), but consistently under-predicts real oil prices out-of-sample, 2004–2006 (Fig. 1). This bias indicates that the model omits variables that are largely responsible for the increase in oil prices between 2004 and 2006.

In this paper, we test the hypothesis that real oil prices are influencedby by refinery capacity, non-linearities in supply conditions, and/or expectations about supply/demand balances and that observed changes in these variables can account for the rise in prices between 2004 and 2006. To do so, we expand the equation described by Kaufmann et al. (2004) to include observations for US refining utilization rates

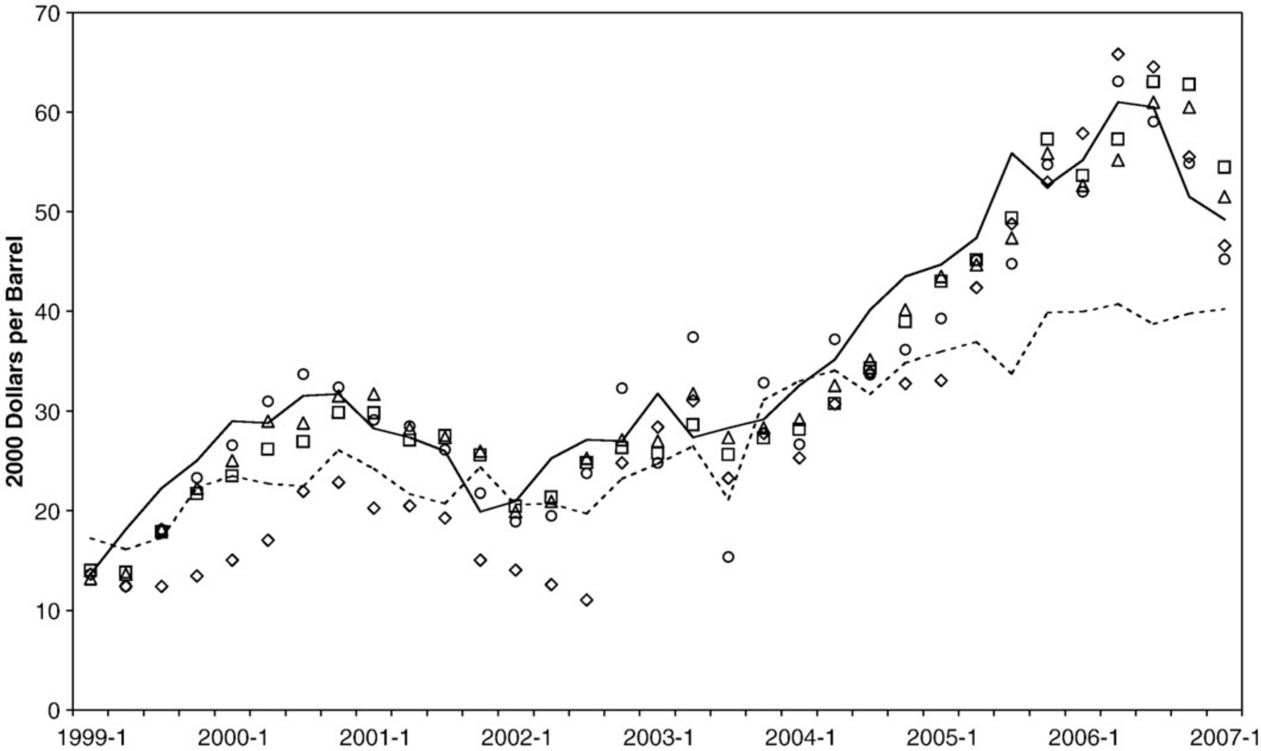

Fig. 1. The observed value of the near month contract on the NYMEX (solid line). The forecast for the average prices for US crude oil imports generated by a model that omits the effects of refinery utilization, non-linearities, and market conditions in the NYMEX (dotted line). The one-step ahead out of sample forecast generated by the econometric model (Eqs. (1) and (2)) is given by open circles (root mean square error = 4.07), the forecast implied by the near month contract on the NYMEX is given by the open squares (root mean square error = 3.54), a random walk, as given by the lagged value of the near month contract on the NYMEX (mean square error = 3.08). Open diamonds represent the price simulated by the econometric model with information about the exogenous variables only (root mean square error = 6.87).

and price differences between the far month and near month contract for crude oil on the New York Mercantile Exchange (NYMEX). To test for non-linearities, the linear specification for capacity utilization by OPEC in Kaufmann et al. (2004) is replaced with a cubic function. Results indicate that the refining sector plays an important role in the recent price increase, but not in the way described by most analysts. The relationship is negative such that higher refinery utilization rates reduce crude oil prices. This effect is associated with shifts in the production of heavy and light grades of crude oil and price spreads between them. Together with a non-linear relationship between OPEC capacity utilization and oil prices as well as conditions on the futures market, the expanded equation generates a one step ahead out-of-sample forecast that performs as well as the forecasts implied by far-month contracts on the New York Mercantile Exchange and is able to account for much of the $27 rise in the real price of crude oil between 2004 and 2006.

These results and the methods used to obtain them are described in five sections. Section 2 describes the data and econometric techniques used to estimate a cointegrating relationship for crude oil prices. Results are described in Section 3. Section 4 discusses the effect of refinery utilization rates on crude oil prices, the importance of non-linearities in marginal supply, and expectations, as measured by conditions in the futures market. It also presents the ability of this econometric equation to forecast oil prices. Section 5 concludes.

2. Methodology

To explore the effect of refinery utilization rates, non-linearities, and expectations on crude oil prices, we update the quarterly data set used to estimate the price equation described by Kaufmann et al. (2004) and expand it to include US refinery utilization rates and conditions in the New York Mercantile Exchange. Because there are a large number of I(1) explanatory variables, the cointegrating relationship for crude oil prices is estimated using dynamic ordinary least squares (DOLS) (Stock and Watson, 1993). Short run dynamics are estimated using an error correction model.

2.1. Data

The quarterly data set (1986Q1–2000Q4) used by Kaufmann et al. (2004) to evaluate the effect of OPEC on crude oil prices includes observations on the average F.O.B price for all crude oil imported by the US, OPEC capacity utilization, OPEC production quotas, OECD oil demand, and OECD stocks of crude oil. All variables are updated with observations through 2006Q4, the most recent quarter for which a complete set of observations is available.

To evaluate the effect of conditions in the refining sector on crude oil prices, we collect data on US refinery utilization rates, which vary between zero and one. Monthly observations are available from the Energy Information Administration. Ideally, we would prefer global data, but only US data are available; nonetheless, US refinery capacity utilization is a satisfactory proxy as US refinery capacity represents about 20% of world capacity in 2006. Indeed, as there is one global market, even for refined petroleum products, it is unlikely that utilization rates in one part of the world will decouple dramatically from other parts. So long as one can ship refined petroleum products, it is, for instance, unlikely that US refinery utilization rates will increase significantly while European rates will decline significantly.[2] Finally, if the greatest shortage of refining capacity does occur in the US, then US refinery utilization rates are the relevant measure because they would reflect conditions at the margin, which by definition, determine prices.

The preceding argument is based on results that indicate the price of crude oil produced in geographical disparate parts of the world cointegrate (e.g. Bachmeier and Griffin, 2006). If refinery utilization rates affect crude oil prices, cointegration among crude prices implies that refinery utilization rates in different parts of the globe share the same stochastic trend. If refinery utilization rates do not share the same stochastic trend, the different stochastic trends in refinery utilization rates would prevent cointegration among prices for different types of crudes. If refinery utilization rates do not affect crude prices, statistical results will fail

[2] For example, immediately after hurricane Katrina hit the Gulf of Mexico in September 2005, there was a very large increase in US imports of finished motor gasoline during September and October 2005 relative to the same months during 2004. Presumable, non-US refiners increased their utilization rates to generate this extra gasoline.

to reject the null hypothesis of no relationship between refinery utilization rates and crude oil prices, regardless of which time series for refinery utilization rate is used in the statistical model.

To evaluate the effect of expectations, as embodied by conditions in the New York Mercantile Exchange, we compile observations on the price of the near month contract and the four-month contract for West Texas Intermediate (WTI Cushing–dollars per barrel). To generate quarterly observations, we average values for days on which contracts are traded. We use these data to calculate the spread between the near month and 4-month contract. Finally, we compile quarterly observations for the US GDP price deflator (basis 100 in 2000) to compute oil prices in real terms.

2.2. Model explanation

To test the hypothesis that refinery utilization rates, non-linearities, and conditions in the New York Mercantile Exchange affect crude oil prices, we expand the equation reported by Kaufmann et al. (2004). That equation specifies oil prices as a linear function of crude oil stocks, OPEC capacity utilization, OPEC quotas, and cheating on those quotas. In the following equation, we eliminate OPEC quotas, fold cheating on OPEC quotas into the capacity utilization variable, add non-linear terms for OPEC capacity utilization, refining capacity, and conditions in the futures market, and retain stocks and OPEC capacity utilization:

$$\begin{aligned}\text{Price}_t = {} & \alpha + \beta_1 \text{Days}_t + \beta_2 \text{Caputil}_t + \beta_3 \text{Caputil}_t^2 + \beta_4 \text{Caputil}_t^3 + \beta_5 \text{Refine}_t \\ & + \beta_6 (\text{NYMEX4}_t - \mathit{NYMEX}1)_t + \mu_t \end{aligned} \tag{1}$$

in which Price is the real average F.O.B. price for US crude oil imports (2000 US$). Days is days of forward consumption of OECD crude oil stocks, which is calculated by dividing OECD stocks of crude oil by OECD demand for crude oil. Caputil is capacity utilization by OPEC, which is calculated by dividing OPEC production by OPEC capacity, multiplying this quotient by OPEC's share of global oil production, and dividing this product by the rate at which OPEC cheats on its quota (dividing the difference between OPEC production and OPEC quota by world oil demand)[3]. Refine is the US refinery utilization rate. NYMEX4 is the price for the 4-month contract for WTI and NYMEX1 is the price for the near-month contract for WTI.

The dependent variable in Eq. (1) is the average FOB price (Free on board, which is the price charged at the producing country's port of loading) for crude oil imported by the US because it represents the price paid for physical barrels obtained from a variety of sources. As such, it is relatively unaffected by conditions unique to a single market. For example, the price of West Texas Intermediate is influenced by local conditions, such as stocks of crude oil in Cushing Oklahoma and conditions in refineries that depend heavily on WTI.

We expect the regression coefficient associated with Days to be negative—an increase in stocks reduces real oil price by reducing reliance on current production and thereby lowering the risk premium that is associated with a supply disruption. We also expect a negative relationship between refinery utilization rates and crude oil prices. As described in the next section, effect can be understood two ways. Increasing rates of refinery utilization forces refiners to buy crudes that are less well suited to their refineries. This reduces yield, which decreases the value of products they produce, which reduces the price they are willing to pay for crude oil. Similarly, as refineries reach capacity, the demand for crude oil drops, which also reduces prices.

The cubic specification for Caputil allows for two turning points (or inflection points). We expect β_2 and β_4 to be positive and β_3 to be negative. Under these conditions, prices increase exponentially up to the first turning point and increase exponentially after the second turning point. Between these turning points there is a normal operating range in which changes in capacity utilization have a small impact on prices. This non-linear relationship is based on the assumption that producers prefer to lift oil within a normal operating range. At levels well above this range, high utilization rates can interfere with field maintenance that is needed to ensure a well's long-run productivity. Similarly, operators are reluctant to pump at very low utilization rates because the fixed costs of production are very much greater than operating costs—so

[3] We modify *Caputil* by cheating because cheating could increase capacity utilization by OPEC but reduce oil prices by increasing supply relative to the quota that balances world oil demand and non-OPEC production. To account for this effect, Caputil is divided by cheat. This division allows increased rates of cheating to reduce oil prices even as cheating causes capacity utilization to rise.

long as prices remain above operating costs owners prefer to operate their wells at capacity to pay their fixed costs. Preferences to operate within this range coupled with inelastic price elasticities of demand imply that oil prices must change significantly to move OPEC capacity utilization rates back towards the normal operating range. As capacity utilization rises beyond normal operating conditions and supplies become tight, inelastic demand implies that large prices increases are needed to reduce demand and thereby bring utilization rates back to the normal range. On the downside, inelastic price elasticities of demand imply very large price reductions are needed to increase consumption (or make it economical to decommission capacity) to move capacity utilization back towards the normal operating range. Similar arguments can be made for a non-linear relationship between refinery utilization rates and prices, but preliminary estimates of this specification indicate that the squared and cubic terms of refinery utilization are not statistically different from zero.

Finally, we expect β_6 to be positive. The difference between the far- and near-month contracts indicates whether the market is in backwardation (the price for the near-month contract is higher than the far-month) or in contango (the price for the near-month contract is lower than the far-month contract). Contango provides an incentive to build and hold stocks, which bolsters demand, and ultimately price.

2.3. Econometric methodology

As indicated by previous analyses, time series for the real price of crude oil and its determinants probably contain a stochastic trend. We evaluate the time series properties of variables in Eq. (1) using the Augmented Dickey Fuller statistic (Dickey and Fuller, 1979) and a test statistic for quarterly data (Hylleberg et al., 1990). Results in Table 1 indicate that these variables contain an annual root. The ADF statistic fails to reject the null hypothesis of a unit root for all variables (Table 1). This result is generally confirmed by the π_1 statistic, which fails to reject the null hypothesis of an annual unit root for variables other than Caputil and Days. None of the variables contain seasonal unit roots, as indicated by results that reject $\pi_2 = 0$ and a joint test $F\pi_3 \cap \pi_4 = 0$.

The presence of I(1) trends invalidates the blind application of ordinary least squares (OLS) because the diagnostic statistics generated by OLS will indicate a meaningful relationship among unrelated I(1) variables more often than implied by random chance (Granger and Newbold, 1974). Such relations are termed spurious regressions. To avoid confusion that is associated with spurious regressions, the relationship among variables in Eq. (1) is evaluated by determining whether they cointegrate. Following a well established method to determine whether two (or more) variables cointegrate (Engle and Granger, 1987), Eq. (1) is estimated by OLS. The regression error (μ) is analyzed for a stochastic trend using the ADF and HEGY statistics. If these test statistics fail to reject the null hypothesis, the non-stationary residual indicates that the regression is spurious. Test statistics that reject the null hypothesis indicate that the regression error is stationary, therefore the variables cointegrate. In this case, Eq. (1) can be interpreted as a cointegrating relationship.

Table 1
HEGY statistics for annual and seasonal unit roots

	ADF	π_1	π_2	π_3	π_4	$F\pi_3 \cap \pi_4$
Univariate tests						
Price	−0.93	− 0.57	− 3.23**	− 4.97**	− 1.26	14.85**
Days	− 2.31	− 3.49+	− 4.29**	− 6.94**	0.01	21.07**
Caputil	− 2.07	− 1.36	− 2.58	− 5.45**	− 4.21**	35.93**
Refine	− 1.53	− 5.51**	− 4.63**	− 5.10**	− 1.70+	15.52**
NYMEX4–NYMEX1	− 2.44	− 2.40	− 2.69	− 5.25**	− 3.07**	18.61**
OLS regression residuals						
Eq. (1)	− 4.81+	− 3.89**	− 4.89**	− 6.32**	− 1.82*	23.85**

** Value exceeds $p<.01$, *$p<.05$, and + $p<.10$.
Univariate HEGY tests include an intercept, time trend, and seasonal dummies. HEGY statistic calculated from the OLS regression errors does not include an intercept, time trend, or seasonal dummies. Significance levels from Hylleberg et al. (1990).
Univariate ADF test includes an intercept time trend, and seasonal dummies. ADF tests of cointegrating relation do not include a constant or intercept. Number of augmenting lags chosen using the Akaike information criterion (Akaike, 1973). Significance levels from MacKinnon (1996) using the number of observations. Asymptotic values have a higher significance level.

However, even if the variables cointegrate, the OLS estimate of the cointegrating vector will contain a small sample bias and the limiting distribution will be non-normal with a non-zero mean (Stock, 1987). To avoid confusion associated with this bias, the cointegrating relationship among non-stationary variables in Eq. (1) is estimated using dynamic ordinary least squares (DOLS) (Stock and Watson, 1993). DOLS generates asymptotically efficient estimates of the regression coefficients for variables that cointegrate, it is computationally simple, and it performs well relative to other asymptotically efficient estimators (Stock and Watson, 1993). Coefficients estimated by DOLS represent the long-run relationship among variables. DOLS does not estimate the short-run dynamics—it is not necessary for asymptotically efficient estimation of the cointegrating vector. Lags and leads used to estimate the DOLS version of Eq. (1) are chosen using the Schwarz Information criterion (Schwarz, 1978). The large number of variables in Eq. (1) would make it difficult to identify cointegrating relationships using the full information maximum likelihood (FIML) estimator of a vector error correction model developed by Johansen (1988) and Johansen and Juselius (1990).

If there is a cointegrating relationship between oil prices and the right-hand side variables in Eq. (1), then we need to examine the short-run relationship among variables. To do so, OLS is used to estimate an error correction model (ECM), which is given by Eq. (2):

$$\begin{aligned}\Delta\text{Price}_t = k + \rho\eta_{t-1} + \sum_{i=1}^{s}\lambda_{1i}\Delta\text{Days}_{t-i} + \sum_{i=1}^{s}\lambda_{2i}\Delta\text{Caputil}_{t-i} + \sum_{i=1}^{s}\lambda_{3i}\Delta\text{Caputil}^2_{t-i} + \sum_{i=1}^{s}\lambda_{4i}\Delta\text{Caputil}^3_{t-i} \\ + \sum_{i=1}^{s}\lambda_{5i}\Delta\text{Refine}_{t-i} + \sum_{i=1}^{s}\lambda_{6i}\Delta(\text{NYMEX4}_{t-i}-NYMEX1_{t-i}) + \sum_{i-1}^{s}\lambda_{7i}\Delta\text{Price}_{t-i} + \delta_1 Q_1 \\ + \delta_2 Q_2 + \delta_3 Q_3 + \delta_4\text{War} + \varepsilon_t \end{aligned} \quad (2)$$

in which Δ is the first difference operator, *Q1*, *Q2*, and *Q3*, are dummy variables for the first, second, and third quarters respectively, War is a dummy variable for the first Persian Gulf War (1990Q3–1990Q4), and η is the difference between the observed value for real oil price and the value generated by the cointegrating relationship (Eq. (1)). The number of lags (s) for the right-hand side variables in Eq. (2) is chosen using the Akaike information criterion (Akaike, 1973).

The statistical significance of ρ in Eq. (2) is used to test the null hypothesis that prices are not affected by disequilibrium η between observed real oil prices and the equilibrium that is implied by the right-hand side variables in Eq. (1). A negative value for ρ indicates that disequilibrium between observed values for crude oil prices and its equilibrium moves observed prices toward the equilibrium value implied by the

Table 2
Estimates for price equation (Eq. (2))

	US FOB price	NYMEX price
Cointegrating relation (Eq. (1))		
Constant	382.80**	435.07**
	{23.27}	{19.94}
Days	−2.06**	−2.39**
	{0.14}	{0.12}
Caputil	2.46**	2.37**
	{0.58}	{0.54}
Caputil^2	−1.01E-01**	−9.31E-02**
	{3.30E-02}	{3.00E-02}
Caputil^3	7.84E-04**	7.17E-04**
	{2.96E-04}	{1.25E-04}
Refine	−2.09**	−2.29**
	{0.15}	{0.13}
NYMEX4–NYMEX1	3.25**	4.08**
	{0.40}	{0.36}
R^2	0.91	0.94
Short run dynamics (Eq. (2))		
Adjustment rate (ρ)	−0.68**	−0.70**
	(0.18)	(0.19)
R^2	0.61	0.60

{} standard error calculated using the Newey–West (1987) estimator.
** Value exceeds p<.01, *p<.05, and + p<.10.

cointegrating relationship. Under these conditions, the right-hand side variables in Eq. (1) are said to 'Granger cause' real oil prices.

3. Results

Regression results for Eqs. (1) and (2) indicate that the variables constitute a cointegrating relationship that can be interpreted as an equation for the long-run determinants of real oil prices. The ADF statistic for the OLS regression error for Eq. (1) rejects the null hypothesis of a unit root, which indicates that there are no unit roots at an annual frequency (Table 1). This conclusion is reinforced by the value of π_1, which also rejects the null hypothesis of a unit root at an annual frequency. Nor does the residual contain unit roots at sub-annual frequencies, as indicated by results that reject $\pi_2 = 0$ and a joint test $F\pi_3 \cap \pi_4 = 0$. The elements of the cointegrating vector have signs that are consistent with the effects described previously (Table 2).

Regression results for the error correction model (Eq. (2)) indicate that the cointegrating relationship given by Eq. (1) can be interpreted as an equation for the long-term determinants of price. The error correction term (ρ) in Eq. (2) is negative. This value indicates that OECD stocks, OPEC capacity utilization rates, refinery utilization rates, and conditions in the New York Mercantile Exchange "Granger cause" real oil prices. Furthermore, this effect is very rapid. The point estimate for ρ indicates that 68% of the difference between the equilibrium and observed price for crude oil is eliminated within one quarter (Table 2). Furthermore, the standard error around the point estimate implies that we cannot reject the null hypothesis $\rho = -1$ ($t = 1.77$, $p > 0.083$), which would indicate that prices adjust completely.

4. Discussion

4.1. The effect of refinery utilization on crude oil prices

The sign associated with refinery utilization (β_5) in Eq. (1) is negative—higher refinery utilization rates depress crude oil prices. This negative effect could be seen as counterintuitive because the lack of new refining capacity is mostly seen as partially responsible for higher prices. Nonetheless, the negative relationship is consistent with those generated with a reduced-form model of oil prices (Kilian, 2008).

The effect of refinery utilization rates on the price of crude oil is associated with changes in the quality of crude oils produced and the ability of refineries to convert these crudes into refined petroleum products. The quality of a crude oil is determined in large part by its density and sulfur content. The density of crude oil is measured by an API gravity index, which measures the density of crude oil relative to water. An API value of greater than 10 indicates that crude floats on water, with larger values indicating a reduction in density (i.e. lighter crude). In general, light grades of crude oil are of higher quality because they generate greater yields of more valuable light products (e.g. motor gasoline). Crude oils with a high sulfur content (so-called sour crudes) are of lower quality because they increase refinery maintenance costs due to enhanced corrosion associated with the sulfur. Based of these differences, the price for a barrel of light sweet crude generally is greater than the price for heavy and sour grades of crude oil. For example, the price of Arabian medium during the fourth quarter of 2006 was $54.38 per barrel—a barrel of Arabian Heavy cost $52.26. The $2.11 difference is termed the price spread.

At any point in time, producers from around the globe lift an array of crude oils. Because of their higher price, light, sweet crudes tend to be produced first. For producers, these crudes generate greater revenues. For refiners, light sweet crudes increase revenues and reduce costs. Because much of the world's refining capacity is set up to use light sweet crudes, increasing refinery utilization rates generally stimulate the production of heavy and sour crudes. For example, Saudi Arabia increased its production of crude oil from 7.52million barrels per day (MBD) in 1999 to 9.15MBD in 2005. Of this 1.63MBD increase, 1.58MBD came from medium grades of crude oil—the production of light grades of crude oil increased only 0.053MBD (Eni Spa, 2006). Because of the price spread among crude oils, the change in the composition of crude oil reduced the average price of crude oil produced by Saudi Arabia. Note that the dependent variable in Eq. (1) is an average of crude oil purchased by the US. So, an increase in refinery utilization rates reduces the average price of crude oil by changing the composition of crude oil imports in favor of heavy and sour grades of crude oil.

Refinery utilization rates also may affect prices by changing the spread between the price of heavy and light grades of crude oil. As refinery utilization moves towards capacity, increased demand is satisfied by expanding runs of heavy and sour crudes. But prices may drop as the quality declines and demand weakens. As utilization rates reach 100%, demand for additional barrels drops to zero. These effects suggest that increases in refinery utilization rates may lower prices of medium and heavy crude oils more than they raise the price of light crude oils. This too would lower the price of crude oil as refinery utilization rates rise.

To test the hypothesis that increased refinery utilization rates reduce the price of heavy grades of crude oil relative to lighter grades, we investigate the effect of refinery utilization rates on the price spread between crude oils by estimating Eqs. (3)–(6):

$$\text{Heavy} = \alpha_1 + \gamma_1 \text{Medium} + \lambda_1 \text{Util} + \varepsilon_{1t} \tag{3}$$

$$\text{Medium} = \alpha_2 + \gamma_2 \text{Heavy} + \lambda_2 \text{Util} + \varepsilon_{2t} \tag{4}$$

$$\Delta\text{Heavy} = \kappa_1 + \rho_1 \eta_{1t-1} + \sum_{i=1}^{s} \theta_{1i} \Delta\text{Heavy}_{t-i} + \sum_{i=1}^{s} \tau_{1i} \Delta\text{Medium}_{t-i} + \sum_{i=1}^{s} \upsilon_{1i} \Delta\text{Util}_{t-i} + \zeta_{1t} \tag{5}$$

$$\Delta\text{Medium} = \kappa_2 + \rho_2 \eta_{2t-1} + \sum_{i=1}^{s} \theta_{2i} \Delta\text{Heavy}_{t-i} + \sum_{i=1}^{s} \tau_{2i} \Delta\text{Heavy}_{t-i} + \sum_{i=1}^{s} \upsilon_{2i} \Delta\text{Util}_{t-i} + \zeta_{2t} \tag{6}$$

in which Heavy is the nominal price of Arabian Heavy (API index = 27°), Medium is the nominal price of Arabian Medium (31°), and Util is the US refinery utilization rate. The estimation sample includes weekly observations between January 3, 1997 and May 18, 2007 that are obtained from the Energy Information Administration. The sample period represents the longest period of nearly continuous data. Because the time series for price and utilization rates contain stochastic trends, Eqs. (3)–(6) are estimated using the same general procedure used to estimate Eqs. (1) and (2).

Eqs. (3) and (4) test the hypothesis that US refinery utilization rates do not affect the long-run spread between heavy and medium grades of crude oil produced by Saudi Arabia. This null hypothesis is tested by evaluating $\lambda_i = 0$ in Eqs. (3) and (4). Rejecting the null hypothesis $\lambda_1 = 0$ and/or $\lambda_2 = 0$ would indicate that refinery utilization rates affect the price spread. To ensure that DOLS can estimate these coefficients reliably, ADF statistics calculated from the OLS regression errors suggest that Eq. (3) can be viewed as cointegrating relationships (Table 3). The DOLS estimate of λ_1 in Eq. (3) indicates that increases in refinery utilization rates depress the price of Arabian Heavy relative to Arabian Medium—the DOLS estimate for λ_2 in Eq. (4) indicates that increases in refinery utilization rates increase the price of Arabian Medium relative to Arabian Heavy, but this effect is measurable only at the 10% level (Table 3). These results are consistent with the hypothesis that refinery utilization rates affect the price spread between crude oils.

The estimate for ρ_1 in Eq. (5) suggests ($p < .06$) that disequilibrium in the cointegrating relationship estimated from Eq. (3) moves the price of Arabian Medium towards its equilibrium value. Conversely, the estimate for ρ_2 in Eq. (6) indicates that disequilibrium in Eq. (4) has no effect on the price of Arabian Medium. This suggests that the effect of refinery utilization rates on price spreads is manifest largely by reductions in the price of medium and/or heavy grades of crude oil—this simple model does not provide

Table 3
Regression results for spreads between the price of Arabian Heavy and Arabian Medium (Eqs. (3)–(6))

	Eqs. (3) and (5)	Eqs. (4) and (6)
Medium (γ_1)	9.46E-01**	
Heavy (γ_2)		1.06**
Util (λ)	−3.26E-02*	3.25E-02+
ρ	−2.33E-01+	3.00E-02
ADF#	−3.21+	−3.24+

Length for lags and leads for the ADF test, the DOLS estimators, or the OLS estimator is chosen based on the statistical significance of lags and leads—missing values prevent the use of standard statistical criteria such as the Akaike or Schwarz criteria.
** Value exceeds $p < .01$, *$p < .05$, and + $p < .10$.
# ADF statistic does not have a trend or a constant. Significance level calculated based on functions in MacKinnon (1996) using the number of observations. Asymptotic values have a higher significance level.

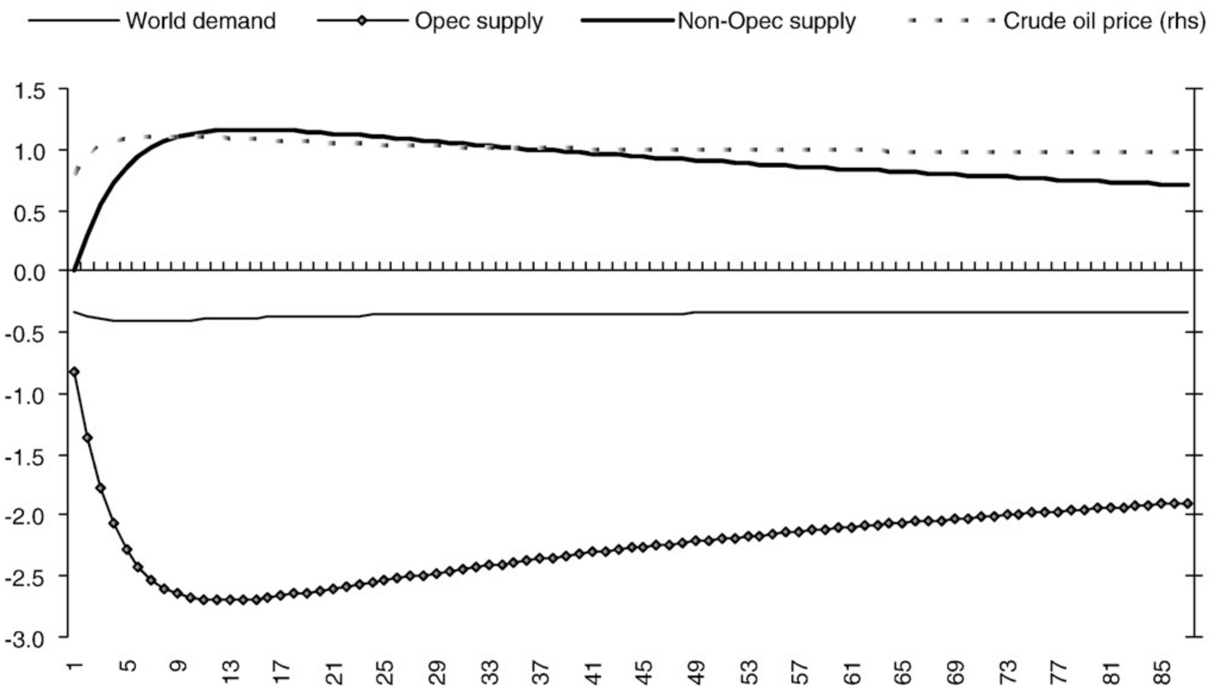

Fig. 2. Impact of a 5% decrease in refinery utilization as measured by the percentage changes from the baseline scenario.

evidence that higher refinery utilization rates raise the price of lighter crude oils. As such, these results are consistent with the results generated by Eq. (1), which indicate that higher refinery utilization rates reduce the average price of crude oil.

To assess further the effects of the refinery utilization on the oil market, we simulate a five percentage point reduction in the refinery utilization rate with the model by Dees et al. (2007) as supplemented with Eqs. (1) and (2). Fig. 2 shows that a 5 percentage point reduction in refinery utilization rate would increase crude oil prices by around 20%, which would depress world demand by about 0.5%. Higher oil prices increase non-OPEC production (about 1%), which combined with lower demand, reduce OPEC production by about 2.5% after two years (2% in the long-run).

4.2. Non-linearities in supply conditions and dynamics in crude oil prices

To evaluate the importance of non-linearities in the relationship between price and OPEC supply, we use several tests to evaluate the inclusion of non-linear terms in Eq. (1). First, values for β_3 and β_4 that are significantly different from zero give preliminary support for a non-linear relationship. Second, we test whether non-linear combinations of the estimated values help explain the dependent variable (Ramsey, 1974). This procedure is based on the notion that if non-linear combinations of the independent variables have any power in explaining the dependent variable, then the linear model is misspecified. Test statistics indicate that a linear version of Eq. (1) is indeed misspecified, which confirms the role of non-linear terms of Caputil in determining real oil prices (Table 4). Finally, we evaluate the role of non-linearities using *F*-tests for omitted and/or redundant variables. The former checks whether additional variables (here the non-linear terms) explain a significant portion of the variation in the dependent variable; the latter tests whether a subset of variables (here the non-linear terms) all have zero coefficients and may be deleted from

Table 4
Ramsey test for non-linearities in the oil price equation

Reset 1	15.04 (0.000)
Reset 2	7.38 (0.001)

The p-value associated with the statistic is in parenthesis.
Note: The Ramsey RESET tests 1 and 2 use the fitted values squared, the fitted values squared and cubed as explanatory regressors respectively.

Table 5
Tests for non-linearities in the oil price equation (Omitted and redundant variable test)

Omitted variables, *F*-stat	3.87 (0.027)
Redundant variables, *F*-stat	11.99 (0.000)

The *p*-value associated with the statistic is in parenthesis.

the equation. Both tests confirm the validity of the non-linear specification for the effect of OPEC capacity utilization on real oil prices (Table 5).

To assess the impact of a non-linear relationship between oil prices and OPEC supply, we introduce Eqs. (1) and (2) in the model by Dees et al. (2007) to assess a demand shock (rise by 1% in world real GDP). We simulate two scenarios: the first assumes that OPEC operates at 96% of its capacity (i.e. broadly the highest level of OPEC capacity utilization that was reached in 2005Q3); the second case assumes that OPEC operates at 87% of its capacity (Fig. 3). The price increase is more rapid at higher rates of utilization. As the model equilibrates, the long-term response is the same; non-linearities affect the dynamics of convergence. This simulation illustrates that high rates of OPEC capacity utilization amplified the price effects of demand growth after 2004.

4.3. Contango, backwardation and speculation

The change from backwardation to contango may represent a change in expectations for long-run prices. Both backwardation and contango are stable market conditions that are maintained by self-reinforcing positive feedback loops and significant shifts between these two states may be triggered by an exogenous shift in expectations.

The market was in a general period of backwardation between 1998 and 2005. During this period, prices were relatively low and demand was relatively weak. Under these conditions, OPEC tried to maintain prices by keeping supply and demand in near balance. By pumping just enough oil to cover demand, there was no oil "left over" to build stocks and low levels of stocks supported higher prices in the near month. Prices were lower farther in the future because OPEC had plenty of spare capacity—the market expected OPEC cooperation to break down, production to exceed quotas, and excess supply to depress price. Backwardation is maintained via the incentive to hold stocks and speculative behaviors. So long as the market is in backwardation, there is no incentive to build stocks because future deliveries can be purchased

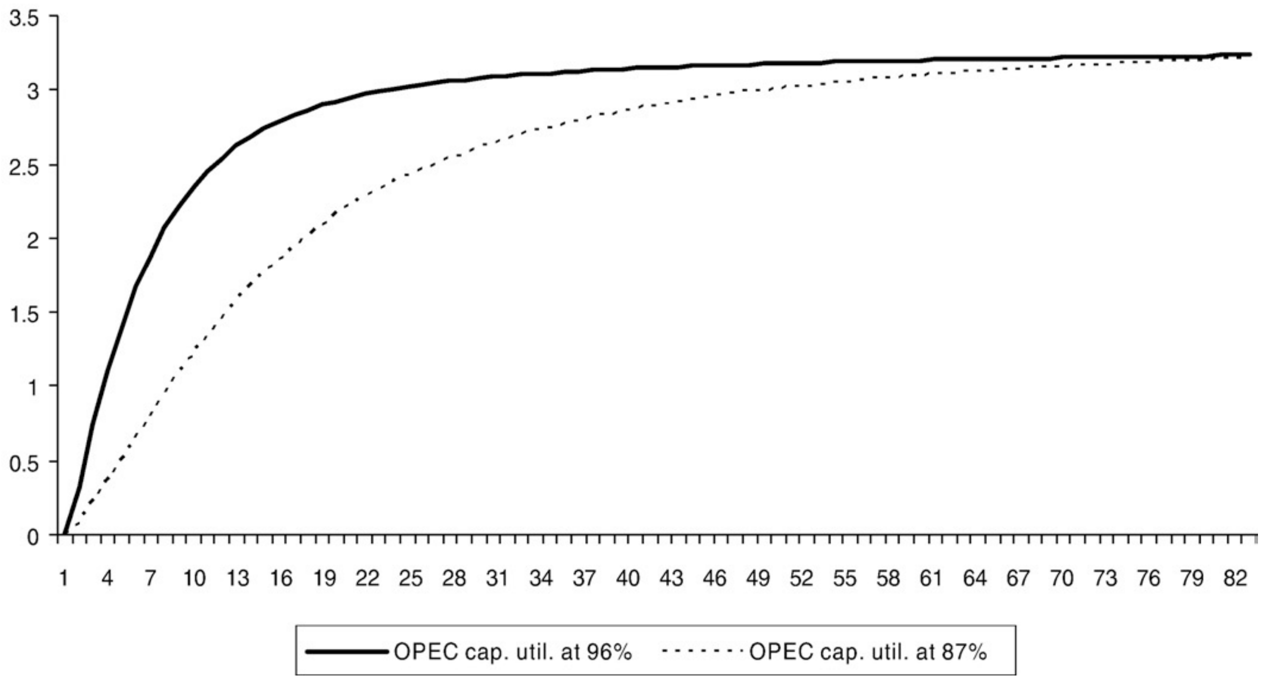

Fig. 3. Impact of a 1% increase in world real GDP on oil prices as measured by the percentage change from the baseline scenario.

at a lower price and do not carry the economic costs of physical storage. Backwardation can be broken only if OPEC produces quantities of oil well beyond its quota, raises its production quotas beyond immediate market demand, or if demand starts to grow faster than trend growth.

Since 2005, the market has entered a period of contango, in which prices on contracts for future deliveries are higher than prices on contracts for current deliveries. Under these conditions, stocks of crude oil build if the price difference between far-month and the near-month contract is greater than the economic cost of physically storing oil. Financial gains are available to those who can store oil, purchase prompt-month contracts, and sell contracts dated further in the future. The stock build reinforces contango by lowering near month prices. Contango can be broken if the market perceives a long-term slow down in demand growth or a long-term increase in production growth.

Given the positive feedback loops that maintain backwardation and contango, significant shifts between these two stable states probably are driven largely by exogenous events. To date, analysts have not isolated an exogenous event that changed the market from backwardation to contango. Failing this, the switch may be associated with a change in long-run perceptions for oil prices. Specifically, the lack of significant additions to OPEC capacity, continued discussion about a peak in global oil supply, and strong growth in oil demand despite higher prices, may have raised the far-end of the price curve in a way that moved the market from backwardation to contango.

4.4. Forecasting performance and factors explaining the recent rise in oil prices

To assess the degree to which the 2004–2006 price rise can be explained by Eqs. (1) and (2), we use them to generate a one step ahead out-of-sample forecast. The forecast is compared to those implied by the futures market and a random walk. To facilitate comparisons with alternative forecasts, Eqs. (1) and (2) are re-estimated using the price for the near-month contract of WTI on the NYMEX as the dependent variable. By doing so, the one step ahead out-of-sample forecast can be compared directly to that implied by the futures market, which is the price for the four-month contract (there is no equivalent set of potential forecasting variables for the average FOB price used as the dependent variable in the previous section). The forecast implied by a random walk is the current price for the near-month contract applied to the next quarter.

Eqs. (1) and (2) (hereafter termed oil price model) are used to generate a recursively expanding, one-step ahead forecast from the second quarter of 1999 through the first quarter of 2007. Visual comparison indicates that Eqs. (1) and (2) are able to generate an accurate one-step ahead out-of-sample forecast (Fig. 1). The single notable exception is the forecast for the third quarter of 2003, when the model under predicts the observed value. The third quarter coincides with the start of the US occupation of Iraq, and the model may not be able to capture its effect on global oil prices. The model's ability to reconstruct the recent price rise is not solely due to the one-step ahead nature of the forecast. If we start the simulation in the first quarter of 1999 and do not update the observed prices for crude oil, the model still captures much of the recent rise in oil prices (Fig. 1).

To compare the oil price model's forecast to the futures market and a random walk, the accuracy of the forecasts is assessed using the following loss function:

$$d_t = \left[P_t - \hat{P}_{\mathrm{Et}}\right]^2 - \left[P_t - \hat{P}_{At}\right]^2 \tag{7}$$

in which P_t is the observed price for crude oil at time t, $\hat{\mathrm{P}}_{\mathrm{Et}}$ the one-step ahead out-of-sample price forecast generated by the econometric model (Eqs. (1) and (2)) and $\hat{\mathrm{P}}_{\mathrm{At}}$ is the price forecast by the alternative model, either the futures market or a random walk.

Values of d_t are used to calculate the sign test ($S_{2\mathrm{a}}$) test statistic as follows:

$$S_{2a} = \frac{\sum_{t=1}^{N} I_+(d_t) - 0.5N}{\sqrt{0.25N}} \tag{8}$$
$$I_+(d_t) = 1 \quad \text{if } d_t > 0$$
$$= 0 \quad \text{otherwise}$$

in which N is the number of observations (32) (Lehmann, 1975). The $S_{2\mathrm{a}}$ statistic tests the null hypothesis that the price forecasts generated by the two models are equally accurate and is asymptotically standard normal under the null. A negative value for the S_{2a} statistic that exceeds the $p = .05$ threshold (− 1.96) would indicate that the one-step ahead out-of-sample forecast generated by the econometric model is closer to the observed value of price than the alternative forecast more often than expected by random chance. Under these conditions, we would conclude that the econometric model generates a more accurate price forecast than the futures market or a random walk.

Results indicate that the econometric model performs relatively well. The one-step-ahead forecast generated by the econometric model is statistically indistinguishable from the forecast implied by far month contracts on the NYMEX. The forecast generated by the econometric model is closer to the observed value for sixteen of the thirty-two out-of-sample observations, hence the zero value ($p = 1.0$) for the S_{2a} statistic. On the other hand, there is some indication that the one-step ahead forecast based on the notion that oil prices are a random walk is more accurate than the forecast generated by the oil price model. The value of the S_{2a} statistic is 1.77, which indicates that that the random walk is closer to the observed value than expected by random chance at the 10% level ($p < .086$). The superior performance of a random walk is consistent with previous studies that indicate the price forecasts implied by futures contracts perform poorly relative to random walks (Abosendra and Baghestani, 2004).

The oil price forecasts also can be compared using the econometric concept of encompassing. For competing forecasts, a finding of encompassing means that relative to a first forecast, a second forecast provides no further useful incremental information for prediction (Newbold and Harvey, 2002). In other words, the second model contains no information not already contained in the first model, which makes the second forecast inferentially redundant.

Our analysis of encompassing is based on the notion that the three models can be thought of nested versions of the other. The econometric model includes the difference of the near and four-month contract on the NYMEX, and so forecasts based on the four-month contract or a random walk can be thought of as restricted versions of the econometric model.

To test whether one model encompasses another, we use a test statistic (ENC-NEW) developed by Clark and McCracken (2001). Their test statistic is given by:

$$\text{ENC}-\text{NEW} = P\frac{P^{-1}\sum_{i=t+1}^{N}\left(\hat{\mu}_{1,i}^{2}-\hat{\mu}_{1,i}\hat{\mu}_{2,i}\right)}{P^{-1}\sum_{i=t+1}^{N}\left(\hat{\mu}_{2,i}^{2}\right)} \tag{9}$$

in which P is the number of one-step ahead forecasts (32), $\hat{\mu}_1$ is the error of the one-step ahead forecast generated by the restricted model, $\hat{\mu}_2$ is the error of the one-step ahead forecast generated by the unrestricted model, $t+1$ is the date of the first out-of-sample forecast (1999Q2), N is the date for the last out of sample forecast (2007Q1). The null hypothesis is that model 2 nests the restricted model 1 such that model 2 therefore contains k extra parameters. Rejecting this null would indicate that the extra k parameters in model 2 are not redundant. This null hypothesis is tested against a non-standard distribution whose critical value depends on the number of extra parameters (k) and the ratio of out-of-sample observations to the number of in sample observations, which is termed r (.64 for this analysis).

We fail to reject the null hypothesis (ENC-NEW = 2.69, k=5, $p > .05$) that the econometric model contains five excess parameters (capacity utilization—together with its square and cubic terms, refinery utilization, and stocks) relative to the forecast generated by assuming that oil price are a random walk. This result is consistent with results that indicate the random walk generates a more accurate out-of-sample forecast than the econometric model. On the other hand, we reject (ENC-New = 7.7, $p < .01$) the null hypothesis that the four-month contract on the NYMEX nests the econometric model, which implies that the five parameters in the econometric model are not superfluous—they contain information not in the 4-month contract. This would imply that our model generates a more accurate forecast than indicated by the futures market.

Given the oil price model's ability to generate an accurate one-step ahead out-of-sample forecast, we use the econometric model to quantify the causes for the increase in the average FOB oil price for US oil imports between 2004Q1 and 2006Q3. To isolate the effects of individual variables, we simulate the model with historical observations for that variable and hold all other right-hand variables at their value in

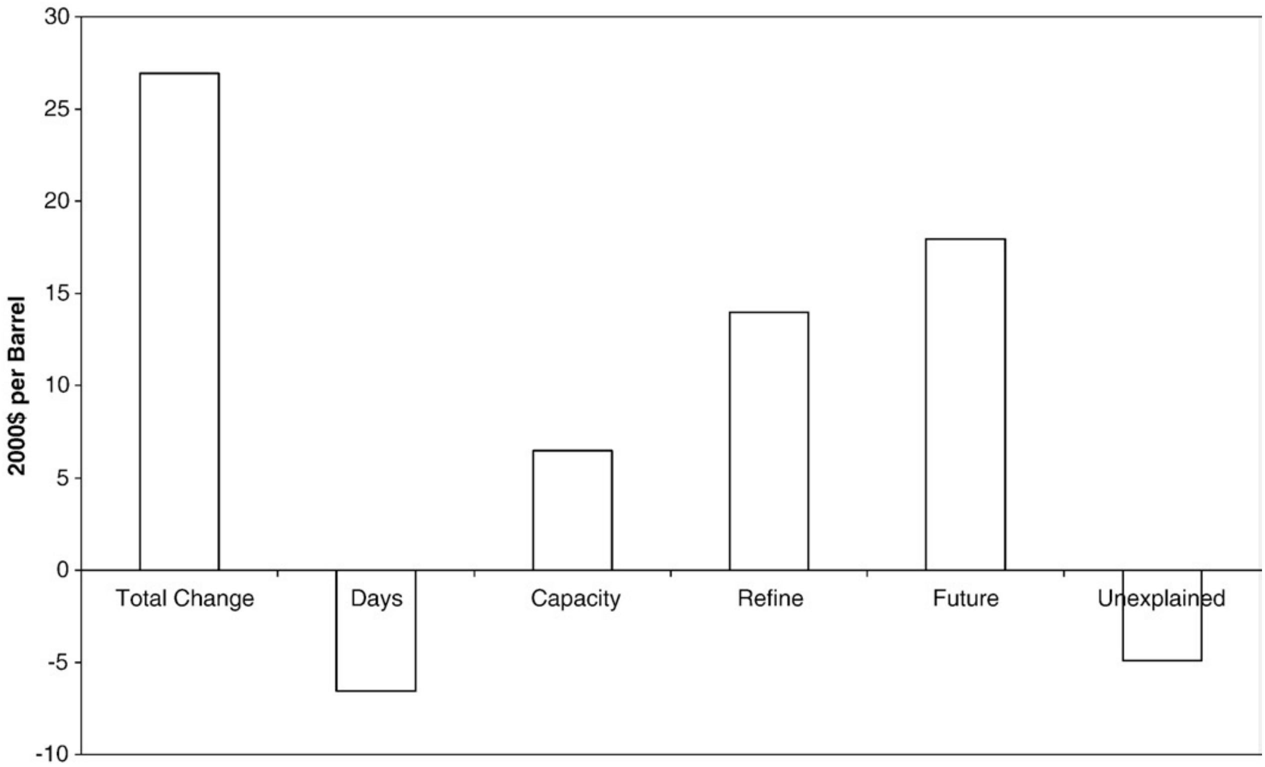

Fig. 4. The change in real oil price between the first quarter of 2004 and the third quarter of 2006 explained by individual variables in Eqs. (1) and (2).

2004Q1. The price change associated with that variable is the difference between the simulated value for the third quarter 2006 and the observed value for the first quarter 2004.

Results indicate that much of the $26.94 increase is associated with an increase in OPEC's capacity utilization, changes in refinery utilization rates, and changes in the futures market (Fig. 4). Specifically, the effects of the OPEC capacity utilization variable raised prices by about $6.49 largely because of a steady decline in OPEC cheating (Wirl and Kujundzic, 2004)—OPEC capacity rises from 94% in 2004Q2 to 96.3% in 2005Q3, but then drops back to 94.7% in 2006Q2. US refinery utilization rates drop from 95.2% in 2004Q2 to 90.7% in 2006Q2 and this decline is associated with a $13.97 price rise. The difference between the near-month and four month contract for WTI rises from −$0.96 in 2004Q1 to $2.39 in 2006Q2, which raises oil prices by about $17.93. Offsetting these increases, OECD stocks of crude oil rise from 81.7 days to 86.2 days and this reduces oil prices by $6.55. Together, these effects overstate the observed price rise by $4.90.

5. Conclusion

The rapid rise in the price of crude oil between 2004 and the summer of 2006 has been difficult to explain with the usual fundamentals related to the supply/demand balance. This paper investigates additional factors that might have contributed to the oil price increase. Most of the increase can be explained by concerns about future oil market conditions, as represented by the shift of the futures market from backwardation to contango, as well as changes in the refining sector, with a drop in the refinery utilization rate. Factors related to crude oil supply continue to be important when we account for non-linear relationships between OPEC supply behavior and oil prices.

Interestingly, results of this analysis indicate that there is little evidence that increasing refining capacity will lower crude oil prices. Of the variables identified by this paper to effect prices, only stocks of crude oil could effectively lower prices—each day of forward consumption reduces real oil prices by about $2 in the long run. Nonetheless, despite a recent upturn, days of forward consumption have generally declined over the last 20 years, from about 90–95 days of forward consumption to 78–82 days of forward consumption. Interestingly, this reduction is not due to a reduction in stock levels, but is due to the fact that the increase in storage capacity has been considerably slower than the increase in demand. This implies that market conditions may not provide the economic incentives needed to expand storage facilities with demand. Against this background, as long as demand remains robust, there are very few reasons to expect oil prices to return to levels observed before 2006.

References

Abosendra, S., Baghestani, H., 2004. On the predictive accuracy of crude oil production futures prices. Energy Policy 32 (12), 1389–1393.

Akaike, H., (1973), 2nd International Symposium on Information Theory, P.N. Petrov and F. Csaki, Eds., Akadacemiai Kiadaco, 267–281.

Annual Energy Review, 2006. US Energy Information Administration, Washington, DC.

Bachmeier, L.J., Griffin, J.M., 2006. Testing for market integration crude oil, coal, and natural gas. The Energy Journal 27 (2), 55–71.

Clark, T.E., McCracken, M.W., 2001. Tests of equal forecast accuracy and encompassing for nested models. Journal of Econometrics 105, 85–110.

Dees, S., Karadeloglou, P., Kaufmann, R.K., Sanchez, M., 2007. Modelling the world oil market, assessment of a quarterly econometric model. Energy Policy 35, 178–191.

Dickey, D.A., Fuller, W.A., 1979. Distribution of the estimators for autoregressive time series with a unit root. Journal of American Statistics Association 74, 427–431.

Engle, R.E., Granger, C.W.J., 1987. Cointegration and error-correction: representation, estimation, and testing. Econometrica 55, 251–276.

ENI Spa, 2006. World Oil and Gas Review.

Granger, C.W.J., Newbold, P., 1974. Spurious regressions in econometrics. Journal of Econometrics 2, 111–120.

Hylleberg, S., Engle, R.F., Granger, C.W.J., Yoo, B., 1990. Seasonal integration and cointegration. Journal of Econometrics 44, 215–238.

Johansen, S., 1988. Statistical analysis of cointegration vectors. Journal of Economic Dynamics and Control 12, 231–254.

Johansen, S., Juselius, K., 1990. Maximum likelihood estimation and inference on cointegration with application to the demand for money. Oxford Bulletin of Economics and Statistics 52, 169–209.

Kaufmann, R.K., submitted for publication. US refining capacity: implications for environmental regulations and the production of alternative fuels. Energy Policy.

Kaufmann, R.K., Cleveland, C.J., 2001. Oil production in the lower 48 states: economic, geological, and institutional determinants. The Energy Journal 22, 27–49.

Kaufmann, R.K., Dees, S., Karadeloglou, P., Sanchez, M., 2004. Does OPEC matter? An econometric analysis of oil prices. The Energy Journal 25 (4), 67–90.

Kilian, L., 2008. A comparison of the effects of exogenous oil supply shocks on output and inflation in the G7 countries. Journal of European Economic Asstion 6 (1), 78–121.

Lehmann, E.L., 1975. Nonparametrics, Statistical Methods Based on Ranks. McGraw-Hill, San Francisco.

MacKinnon, J.A., 1996. Numerical distribution functions for unit root and cointegration tests. Journal Applied Econometrics 11, 601–618.

Newbold, P., Harvey, D.I., 2002. Forecast combination and encompassing. In: Clements, M.P., Hendry, D.F. (Eds.), A Companion to Economic Forecasting. Blackwell Publishers, Malden, MA.

New York Times Record failures at oil refineries raise gas prices July 22, 2007.

Newey, W.K., West, K.D., 1987. A simple positive semi-definite heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica 55, 703–708.

Ramsey, J.B., 1974. Classical model selection through specification error tests. In: Zarembka, P. (Ed.), Frontiers in Econometrics. Academic Press, New York.

Schwarz, G., 1978. Estimating the dimension of a model. Annals of Statistics 6, 461–464.

Stock, J.H., 1987. Asymptotic properties of least squares estimators of co-integrating vectors. Econometrica 55, 1035–1056.

Stock, J.H., Watson, M.W., 1993. A simple estimator of cointegrating vectors in higher order integrated systems. Econometrica 61, 783–820.

Wirl, F., Kujundzic, A., 2004. The impact of OPEC conference outcomes on world oil prices 1984–2001. The Energy Journal 25 (1), 45–62.