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Non-Linear Unit Root Properties of Crude Oil Production

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Abstract

While there is good reason to expect crude oil production to be non-linear, previous studies that have examined the stochastic properties of crude oil production have assumed that crude oil production follows a linear process. If crude oil production is a non-linear process, conventional unit root tests, which assume linear and systematic adjustment, could interpret departure from linearity as permanent stochastic disturbances. The objective of this paper is to test for non-linearities and unit roots in crude oil production. To realize our objective, this study applies a threshold autoregressive model with an autoregressive unit root to monthly crude oil production levels for 16 OPEC and non-OPEC countries over the period January 1973 to December 2006. Specifically, first we test for the presence of non-linearities (threshold effects) in the production of crude oil in two regimes. Second, we test for a unit root against a non-linear stationary process in two regimes and a partial unit root process when the unit root is present in one regime only. We find that crude oil production is characterized by threshold effects. We find that for ten of the countries a unit root was present in both regimes, while for the others a partial unit root was found to be present in either the first regime or second regime.

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1. Introduction

Crude oil production can be characterised by seasonal fluctuations, structural breaks and abrupt changes in demand and has limited capabilities for expansion in terms of reserves. The objective of this paper is to test for non-linearities and unit roots in crude oil production. Stationarity properties of crude oil production are extremely important in economic modelling. Models which assume stationarity and linearity such as real business cycle models and dynamic equilibrium models (Wilder, 1999) will not be appropriate if the data violate these principles. As noted by Wilder (1999), if production is non stationary, any shock to production will permanently affect the equilibrium path of the crude oil market. This will affect energy prices, which in turn will affect real income and hence substantially change the underlying characteristics of the business cycle. In this case "business cycle theories describing output fluctuations as temporary deviations from long-run growth would loose their empirical support" (Narayan et al., 2007, p.14).

The issue of stationarity is important for modelling peak and post-peak oil production and forecasting as well as developing national energy models such as the Oil and Gas Supply Module (OGSM) in the United States. OGSM is developed as a part of the National Energy Modelling System (NEMS) in which future oil and gas production is determined on the basis of oil and gas reserves and previous production levels. Therefore, patterns in crude oil production, including whether crude oil production is stationarity, will affect the projections of OGSM. Whether there is a unit root in crude oil production also has implications for modelling and forecasting production levels and prices of products that are produced with oil as an input. Crude oil is used in many sectors of the economy including plastics, cosmetics, transportation and many others. In some cases such as jet fuel and plastics, crude oil is a primary input which does not have any substitutes.

This study was motivated by the striking neglect in earlier studies devoted to the stochastic properties of crude oil production to the possibility of non-linearities. This can be partly explained by the availability of data required for unit root tests. Unlike most financial data which is readily available at daily and intra-day frequencies, it is impossible to find daily production volumes for the majority of oil producing countries. In fact, it can be problematic to draw inferences about unit root behaviour or non-linearities in oil production if the data is sampled at annual frequency and is only available over 30-40 year intervals. Most publicly available data sets such as the BP Statistical Review of World Energy or EIA datasets only contain data going back to the 1960s and 1970s (Brandt, 2007). We use EIA data, which contain monthly observations from January 1973 until December 2006, which is a total of 408 observations.

The implications of non-linearities in crude oil production when testing for a unit root are potentially very serious. First of all, conventional unit root tests assume the data process is linear. If oil production can be described by a linear stationary process, conventional tests such as Dickey Fuller (DF), Augmented Dickey Fuller (ADF) and Phillips Perron (PP) unit root tests can be used without substantial loss of power. However, as Choi and Moh (2007, p. 83) noted, given that these conventional unit-root tests are constructed under the assumption of linear and symmetric adjustment, "a departure from linearity through curvature or kinkidness could lead the tests to misinterpret [departure] as permanent stochastic disturbances". If production is a non-linear process, conventional unit root tests will provide a misleading outcome even if production is stationary.

It is reasonable to expect crude oil production to be non-linear. Much peak oil modelling literature such as Hubbert (1959), Wood et al. (2000), Hirsh (2005), Bardi (2005) and Brandt (2007) is based on the assumption of non-linear production and assumes that oil production can be represented by a bell-shaped curve. For example, Hubbert (1959) and Wood et al. (2000) assumed exponential growth and decline in oil production over time. In terms of modelling, Hubbert proposed linearization of the US production data such that it fits a logistic function. However, it is likely that traditional linear modeling techniques which are used to forecast energy demand or supply are not very useful because "the economic and energy systems are chaotic and nonlinear" due to uncertainty and imperfect information about future economic growth and energy developments (Dong, 2000, p. 443). As noted by Koop and Potter (2001), "if departures from linearity exist, it is important to know whether these are endogenously generated (as in, for example, a threshold autoregressive model) or whether they merely reflect changing structure over time." In oil production, it is possible that both these factors play a role.

Finally, energy production can be prone to non-linearities due to the nature of production. That is oil fields do not produce oil in a linear increasing or decreasing fashion. The life of any oil field is cyclical and can be decomposed into six main stages, which are buildup, reaching a peak and plateau, decline, reserve addition and reduction in operating costs and expenses (OPEX) (Gluyas and Swarbrick, 2004). Each of these production stages depend on the nature of the field (offshore versus onshore), its size (giant fields versus small fields) and other characteristics. Modern technologies facilitate a rapid buildup stage, which is quickly transformed to peak production. Once the peak is reached, production will plateau followed by an exponential decline. For example, the Prudhoe Bay field in the US reached its peak in 1987 and has been in continuous decline ever since (Blum, 2005). At this stage reserve additions may be possible. Take, for example, offshore deepwater oil fields. Once production starts to decline from the main field, new supporting fields will be drilled to obtain oil from the surrounding reservoirs. Finally, reducing the costs of operations will allow production to continue beyond its original economic limits (Gluyas and Swarbrick, 2004). Typically, an oil field is abandoned before reaching its zero production point where the decision to abandon is determined by the "cross-over between the value of produced oil and the cost of producing it" (Gluyas and Swarbrick, 2004, p.272).

At any of these six stages, the level of production will be affected by many factors such as seasonality, temperature, wind speed and technology. For example, extreme weather conditions in the North Sea during winter make it impossible to extract oil. Therefore, it is not viable to model the entire production life-cycle using linear modelling techniques. It is possible to use linear techniques applied to one stage at a time. The problem, though, is that it is very hard to distinguish between the stages before the peak in production has been reached. Because modern oil production techniques, including horizontal drilling and multi-lateral wells, allow rapid extraction of oil, there can be a very rapid decline in production with fast well closure. Thus, linear modelling techniques will not describe the data correctly if applied over the entire production cycle.

To realize our objective, this study applies threshold unit root tests proposed by Caner and Hansen (2001) to crude oil production. Specifically, first we test for the presence of non-linearities (threshold effects) in the production of crude oil including Lease Condensate for 16 countries that include both OPEC and non-OPEC members. Second, we test for a unit root against a non-linear stationary process and a partial unit root process when the unit root is present in one regime only. Foreshadowing the main results, we find that crude oil production is characterized by non-linearities. For ten countries a unit root was present in both regimes, for four countries there is a partial unit root in the first regime and for two countries there is a partial unit root in the second regime.

2. Existing literature

Few studies have tested for the presence of a unit root in energy production or consumption, particularly crude oil production. Among the few studies to test for a unit root in either energy production or crude oil production are Hutchison (2004), Kaufmann and Cleveland (2001), Ileader and Olatubi (2006) and Narayan et al. (2007). Related studies that have tested for a unit root in energy consumption are Al-Iriani (2006), Chen and Lee (2007), Hsu et al. (2007), Joyuex and Ripple (2007), Lee (2005), Lee and Chang (2007, 2007a) and Narayan and Smyth (2007). This section is divided into two parts. First, we examine the literature that has tested for the presence of a unit root in crude oil production and second, we briefly discuss the existing literature that has applied the Caner and Hansen (2001) methodology to test for a unit root in other variables.

Presence of a unit root in crude oil production

Most existing studies that have tested for a unit root in crude oil production have used conventional unit root tests such as DF, ADF and PP. These studies have not been able to reject the unit root null. Hutchison (2004) tested for the presence of a unit root in total energy production for Norway, the Netherlands and the UK. Data was sampled at quarterly frequency over the period 1960 to 1987. Based on both the DF and PP tests he was not able to reject the unit root null. Studies by Kaufmann and Cleveland (2001) and

Ileader and Olatubi (2006) applied the ADF unit root test to US crude oil production. Kaufmann and Cleveland (2001) tested for a unit root in crude oil production in the lower 48 states of the US over the period 1938 to 1991. Ileader and Olatubi (2006) tested for the presence of a unit root in Gulf of Mexico Outer Continental Shelf (OCS) quarterly petroleum production. For shallow water production the period of analysis covered was from 1948 to 2000 and for deep water production, the data spanned the period between 1979 and 2000. Both studies were unable to reject the unit root null.

These studies potentially suffer from loss of power, which can be addressed through allowing for the possibility of structural breaks in the data and/or exploiting the panel properties of the data. To address this issue, Narayan et al. (2007) applied a wide range of univariate and panel unit root tests, with and without structural breaks, to test the stationarity properties of crude oil production for 60 countries over the period 1971 – 2003. Overall, they found that the panel Lagrange (LM) unit root test with one structural break provided strong evidence in favour of joint stationarity of crude oil production. For most of the countries in the sample, structural breaks were found to be statistically significant and corresponded either to the second oil price shock of 1979 or the first Gulf war in 1990. However, there are no existing studies of the stationarity properties of crude oil production that allow for the possible presence of non-linearities in the data.

Previous studies applying the Caner and Hansen methodology

In this section we briefly discuss studies which have applied the Caner and Hansen methodology to exchange rates and stock prices. Basci and Caner (2005) applied the Caner and Hansen methodology to test for a unit root in the post-float real exchange rates for 17 OECD countries. They found that for most countries the partial unit root hypothesis was valid. Alba and Park (2005) applied the Caner and Hansen methodology to test for a unit root in Turkey's real exchange rate over the period 1975 to 2005. They found strong support for a Threshold Autoregression (TAR) model and the presence of threshold effects. They also found support for a partial unit root process, when real exchange rates were stationary in the first regime and non-stationary in the second.

Another study that applied the Caner and Hansen methodology to real exchange rates is Ho (2005). He investigated the threshold effects of inflation on Purchasing Power Parity (PPP) for low- and high-inflation developed OECD economies and 36 developing economies, over the period 1980 to 2001. The results obtained were mixed. Some real exchange rates were found to be non-linear stationary and, for some, particularly the high-inflation exchange rates, partial unit roots were found. Two studies that have applied the Caner and Hansen methodology to the stock market are Narayan (2005, 2006). Narayan (2005) tested for the presence of a unit root in the monthly ASX All Ordinaries Index and NZSE Capital Index over the periods 1964 to 2003 and 1967 to 2003 respectively. He reached the conclusion that stock price indices in both countries were non-linear with a unit root. Similar results were obtained by Narayan (2006), who applied the Caner and Hansen methodology to test whether real US stock prices can be described by non-linear unit root processes over the period 1964 to 2003. He found that US stock prices have threshold effects. This finding can be interpreted as an indication of the presence of non-linearities in stock prices. The null hypothesis of a unit root was not rejected and, in addition, he also found support for the partial unit root hypothesis.

3. Methodology

In this paper we use the TAR unit root methodology developed by Caner and Hansen (2001). This methodology is applicable if a non-linear process has a unit root. The TAR model was first introduced by Tong (1979). Among the advantages of this model is the ability to capture jumps and limit cycles in the data (Ho, 2005, p. 928). The main contribution of Caner and Hansen (2001) is that their methodology allows testing for non-stationarity and non-linearity in data simultaneously (Alba and Park, 2005, p. 993).

Caner and Hansen (2001) proposed a set of Wald tests to check for the presence of a unit root and a non-linear threshold. They suggested an unrestricted two regime TAR model, with an autoregressive unit root, specified with the following data generating process:

$$\Delta y_t = \theta_1' x_{t-1} 1_{\{Z_{t-1} < \lambda\}} + \theta_2' x_{t-1} 1_{\{Z_{t-1} \geq \lambda\}} + e_t \qquad (1)$$

where $t = 1, \ldots\ldots, T$ and $x_{t-1} = (y_{t-1} r_t' \Delta y_{t-1} \ldots\ldots\ldots \Delta y_{t-k})'$, $1_{\{.\}}$ is the indicator function, e_t is an iid error, $Z_t = y_t - y_{t-m}$ for some $m \geq 1$ and r_t is a vector of deterministic components including an intercept. The threshold parameter is given by λ. λ takes values in the interval $\lambda \in [\lambda_1, \lambda_2]$ and is chosen so that $P(Z_t \le \lambda_1) = \pi_1 > 0$ and $P(Z_t \le \lambda_2) = \pi_2 < 1$. The parameters of the model, θ_1 and θ_2 can be partitioned as:

$$\theta_1 = \begin{pmatrix} \rho_1 \\ \beta_1 \\ \alpha_1 \end{pmatrix}, \qquad \theta_2 = \begin{pmatrix} \rho_2 \\ \beta_2 \\ \alpha_2 \end{pmatrix}$$

where ρ_1 and ρ_2 are the slope coefficients of y_{t-1}, β_1 and β_2 are the slopes of the deterministic components, and α_1 and α_2 are the slope coefficients on $(\Delta y_{t-1, \ldots\ldots\ldots\ldots,} \Delta y_{t-k})$ in the two regimes. The TAR model is estimated in two steps using Ordinary Least Square (OLS). In the first step of estimating Equation (1), for each $\lambda \in \Lambda$, the threshold λ is selected by minimizing $\sigma^2(\lambda)$. The OLS estimates of other parameters are found in the second step by inserting the point estimate $\hat{\lambda}$, viz. $\hat{\theta}_1 = \hat{\theta}_1(\hat{\lambda})$ and $\hat{\theta}_2 = \hat{\theta}_2(\hat{\lambda})$. The threshold effect in Equation (1) has the null hypothesis $H_0 : \theta_1 = \theta 2$, which is tested using the Wald Statistic, W_T, given by:

$$W_T = T\left(\frac{\hat{\sigma}_0^2}{\hat{\sigma}^2} - 1\right)$$

where $\hat{\sigma}^2$ is defined as the residual variance from Equation (1) and $\hat{\sigma}_0^2$ is the residual variance from the OLS estimation of the null linear model. The stationarity of the process can be inferred from the parameters ρ_1 and ρ_2. The stationarity of the series can be characterised in two ways i.e. a complete unit root (a unit root in both regimes) or a partial unit root (unit root in only one of the regimes). The null is the same in both cases i.e. $H_0 : \rho_1 = \rho_2 = 0$, but the alternative in the complete unit root case is:

$$H_1 : \rho_1 < 0 \text{ and } \rho_2 < 0$$

In the case of a partial unit root, the alternative is specified as:

$$H_2 = \begin{cases} \rho_1 < 0 \quad and \quad \rho_2 = 0 \\ \qquad\quad or \\ \rho_1 = 0 \quad and \quad \rho_2 < 0 \end{cases}$$

The null, H_0 is tested against the alternative of H_2 using a two-sided Wald statistic:

$$R_{2T} = t_1^2 + t_2^2$$

where t_1 and t_2 are the t ratios for $\hat{\rho}_1$ and $\hat{\rho}_2$ from the OLS regression. As the alternatives H_1 and H_2 are one sided, the two sided Wald statistic may be less powerful than a one sided version. Caner and Hansen (2001) suggest a one sided version of the test statistic which focuses on negative values of $\hat{\rho}_1$ and $\hat{\rho}_2$, given as:

$$R_{1T} = t_1^2 1_{\{\hat{\rho}_1 < 0\}} + t_2^2 1_{\{\hat{\rho}_2 < 0\}}$$

To distinguish between the alternative of complete stationarity (given by H_1) and partial stationarity (given by H_2), individual t statistics (t_1 and t_2) are used. If only one of $-t_1$ or $-t_2$ is statistically significant, the series has a partial unit root. Critical values are generated via 10,000 bootstrap simulations as proposed by Caner and Hansen (2001) using their Gauss program, which was modified for the present exercise.

4. Data

The data studied in this paper are the physical production levels of crude oil including Lease Condensate (in thousand barrels of oil per day) for 16 OPEC and non-OPEC countries. Data was sampled at monthly frequency over the period January 1973 to December 2006. The source of the data is the Energy Information Administration (EIA) of the US Department of Energy. The OPEC countries included were Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia and Venezuela. The non-OPEC countries included were China, Egypt, Canada, UK, US, Mexico and Norway.

Several of the series are characterised by a dominant upward or downward trend in crude oil production. Countries with an upward trend are China, Mexico and Canada, while the US has a downward trend in oil production. There is a cyclical pattern in production in the UK and Norway where production of crude oil increased, but is now on a steady decline. None of the countries mentioned above belong to OPEC. Of the non-OPEC countries, the major producer is the US (5000 thousand of barrels per day) although its level of production now is only half what it used to be in 1975. The US is followed in production by China and Mexico and the lowest oil producer among the non-OPEC countries in the sample is Egypt. Of particular interest are country differences in the minimum and maximum levels of production, which are summarized in table 1.

INSERT TABLE 1

When considering table 1, a word of caution is in order. It is possible that some countries reached maximum production levels before the start of our sample. For example, a number of studies (see, for instance, Simmons, 2007) suggest that the peak in crude oil production for the US was reached before 1973. Therefore, we treat all maximum levels as local maxima. It is possible that a local maximum in production could be reached in the first or second regime or both. For the OPEC countries the maximum production level does not necessarily imply the peak in production because countries have to comply with the OPEC specified quota. In this case, whether the peak in oil production was reached can be indirectly inferred form comparison with production levels and the production quota. Table 2 contains a summary of recent OPEC quotas. We do not show the whole history of these production allocations because compliance among OPEC members has been very low since the 1980s. However, over the past few years, and particularly in 2005 and 2006, compliance with production quotas has been less of an issue since "the production ceiling itself pushed the limits of each member's available production capacity" (Smith, 2007). Iraq is excluded from this table because OPEC did not allocate it a production level from March 1998. In other countries, such as Iran and Venezuela, levels of production are consistently below quota, indicating either that the peak has already been reached or that some political factors prevented production up to the quota.

INSERT TABLE 2

INSERT FIGURE 1

Figure 1 shows OPEC and non-OPEC production in thousand barrels per day from January 1973 to December 2006. These figures were calculated based on the countries in our sample and do not represent total OPEC or total non-OPEC production. Eyeballing figure 1 shows that neither series is characterised by a linear pattern through the entire sample period. For OPEC members, there is no clear cut single trend in production. In fact, production levels have been quite volatile and can be described by large swings, which occurred prior to the 1990s. These swings can be attributed to political instability, such as the first Gulf war, which adversely affected production levels in Iraq and Kuwait in the early 1990s and the Iran-Iraq war in the 1980s. The only exceptions here are Venezuela and Iraq, where extreme lows in production of crude oil could be attributed to the general strike of 2003 and the second Gulf war respectively. Starting in the early 1990s, there have been both upward and downward trends in oil production across the developing countries in the sample. For example, starting from the early to mid 1990s, production levels in Nigeria, Qatar and Iran increased while Indonesian production of crude oil experienced a downward trend. There are no clear cut tendencies for Kuwait and Libya where production levels were between 1500 and 2500 and 1200 and 1800 thousands barrels per day respectively. Among OPEC countries, the major producer is Saudi Arabia, followed by Iran. Iraq is the only country in our sample, where production of crude oil was relatively stable for almost five years after the first Gulf war when the UN's resolution 96 and oil for food program was in place. For developed countries, such as the UK, we also observe an expansion in production levels; however, this expansion was relatively moderate compared to that in the developing countries in the sample.

Because patterns in production are different from country to country, we illustrate movement in production in Figure 2 through selecting the US, Iran and Saudi Arabia as representative countries. These countries have the largest volumes of production in our sample. It can be clearly seen that US production has been in steady decline since 1985, but it still higher than Iranian production. Of these three countries, Saudi Arabia is producing the most oil. Being a swing producer in OPEC, Saudi Arabian production is much more volatile than production in either the US or Iran. For example, there is a larger jump in production caused by the first and second Gulf wars in Saudi Arabia than either in the US or Iran.

INSERT FIGURE 2

The series on oil production for each of the countries in the sample exhibited non-normal distributions as depicted by QQ plots and kernel density plots. Kernel density estimation suggested that most of the series can be characterised by multi-modal distributions. The

Jarque-Bera test for normality was easily rejected at the 5% level of significance for each series. On the basis of the preliminary data analysis it is clear that linear statistical analysis is not appropriate for this dataset, which justifies our use of non-linear tests.

5. Results

First, we test for the presence of non-linearities in the production series based on the Wald test. Second, we examine the equality of the least squares estimates of the threshold model under both regimes. If non-linearities are detected, we proceed by testing whether the unit root null holds in both regimes by examining one-sided and two-sided Wald test statistics. Finally, we explore the possibility of a partial unit root, when a unit root is present in one regime only. However, it should be noted that regimes are not determined by a calendar but by changes in the levels of production. The regimes will be country specific. For example, it is possible that the Iraqi December 1993 production value belongs to the first regime and the January 1994 production figure is in the second regime. The cut-off between the regimes depends on the threshold parameter λ.

INSERT TABLE 3

The results for the threshold tests are summarized in table 3. Since the data is at monthly intervals, we set the maximum lag equal to 12. Caner and Hansen suggested choosing an optimal delay parameter m which maximizes the value of the Wald statistic W_T "since W_T is a monotonic function of the residual variance" (Alba and Park, 2005, p. 995). Therefore, this value of m minimizes the residual variance of the least squares estimates. In table 3, and throughout the paper, we report the results based on the endogenous choice of the delay parameter 'm' (using Caner and Hansen's (2001) terminology). In table 3 each of the series were found to be non-linear since the Wald statistics are significant at the 1% level indicating that simple linear models are inappropriate.

Second, we examine the least squares estimates of the TAR model at the endogenously determined value of the lag parameters for every country under analysis. Results for the optimal delay parameter (m) are reported in Table 3. For example, for Saudi Arabia, the optimal delay parameter is m=3 and the point estimate of the threshold parameter $\hat{\lambda}$ at m=3 is 513. This means that the TAR model divides the regression into two regimes depending on whether $Z_t = y_t - y_{t-3}$ lies above, equal to, or below 513 thousand barrels per day. This means that in the first regime, oil production has fallen, remained constant or increased by less than 513 thousand barrels per day within the period of 3 months ($Z_t < 513$). For Saudi Arabia 334 observations or 82% of the sample belong to this category. In the second regime, production levels rise more than or equal to 513 thousand barrels per day within the period of 3 months ($Z_t \geq 513$). Approximately 18% of the sample belongs to the second regime. For a second example, consider the US; the optimal delay parameter is m=6 and the point estimate of $\hat{\lambda}$ at m=6 is -244. That is over the period of six months in the first regime, the change in production was negative and production levels have fallen, remained constant or increased by less than - 244 thousand barrels per day. Only 16% of observations in the sample belong to the first regime.

Table 4 shows the regime corresponding to the local maximum production as set out in table 1. Some of the countries in our sample might have reached their maximum production rates (for example, Indonesia and the UK) and for some the peak is still in the future (for example, Qatar, China and Nigeria). For most of the countries the local minimum production levels corresponded to the first regime. The local maximum production levels for all countries apart from the US, Kuwait, Nigeria, Qatar and China corresponded to the second regime. For Nigeria the result is not clear because the production maximum was reached several times. Both Qatar and China have maximum levels of production which occurred later on in our sample indicating that the peak in production is still to come. For Qatar, on average during the sample period it was producing above the OPEC quota and there is spare capacity in terms of reserves. For the US and Kuwait, it is not possible to determine the regime at the optimal choice of m.

INSERT TABLE 4

Third, we examine which coefficients in Caner and Hansen’s (2001, p.1579) terminology "drive the threshold model". These can be determined by observing point estimates and Wald statistics on Least Squares Estimates from the threshold model. Tables 5 and 6 contain a summary of results for non-OPEC and OPEC countries respectively. Table 5 suggests that for all non-OPEC countries, apart from China and the US, the coefficient on Δy_{t-1} was very significant with very high Wald statistics and low p-values meaning that this is the driving force behind the threshold model. In the case of Mexico and Norway our results suggest that Δy_{t-1} is the only important variable. For the US, the most significant variable as indicated by the Wald statistic is Δy_{t-12}. For China all coefficients between Δy_{t-2} and Δy_{t-11} were found to be very important. For OPEC countries the results are different. In contrast with non-OPEC countries, Δy_{t-1} was found to be a driving force of the TAR model for Indonesia, Kuwait and Venezuela. No significant lag coefficient was found, which was true for most of the countries in the sample. At most, three countries shared significant coefficients. For example, Δy_{t-2} was significant for Indonesia, Iran and Nigeria and Δy_{t-11} was significant for Iran, Libya and Nigeria. This result can be partly explained by their membership of OPEC. While oil production is determined by both domestic and foreign demand in non-OPEC countries, in OPEC countries production is constrained by the OPEC quota. The special case is Iraq, where no significant variables were found with all Wald statistics low and insignificant.

INSERT TABLES 5-6

Fourth, having established that crude oil is a non-linear process for each of the countries we examine whether crude oil production contains a unit root. To examine the unit root properties we calculate the threshold unit root test statistics R_{1T}, R_{2T}, t_1 and t_2 for the optimal value of the delay parameter for each country. The R_{1T} and R_{2T} test results together with the bootstrap p values are reported in Table 7. At the optimal value of the delay parameter for each country, we are unable to reject the null of a unit root at the 5% level for Indonesia, Kuwait, Libya, Mexico, Qatar, Saudi Arabia, Venezuela, Canada, the UK and the US. Note that for Canada and Mexico R_{1T} and R_{2T} give conflicting results, but in this event Caner and Hansen (2001, p.1568) suggest following the one-sided alternative. The t_1 and t_2 test results together with the p values are reported in Table 8. For those countries for which the R_{1T} and R_{2T} test rejected the unit root, there is a partial unit root in the first regime for Iran, China, Egypt and Norway at the 5% level. Meanwhile, there is a partial unit root in the second regime for Iraq and Nigeria at the 5% level.

INSERT TABLES 7-8

Table 9 presents a summary of the results. Overall ten of the 16 countries (or 62%) have a unit root in both regimes. Hsu et al. (2007) found that energy consumption was more likely to be non-stationary in countries which were large energy consumers. Our results suggest that is generally also true for oil producers. Each of the ten countries that have a unit root in both regimes either is, or has been, a major producer of crude oil. Table 10 shows the top 15 producers of oil in the world. Of the countries with a unit root in both regimes, six (Saudi Arabia, the US, Mexico, Canada, Venezuela and Norway) were among the top ten oil producers in 2006. Indonesia was a major producer of oil in the past, but its production is now in decline. Based on the official figures, in Indonesia the first peak in production was reached in 1977 and the second in 1995 at approximately 1.6 million barrels of oil per day (Prattini, 2007). Since 1995 the decline in production was so severe that in 2006 on average only 1 million barrels per day was produced (Prattini, 2007). For the past few years Indonesia was not able to meet the already reduced OPEC production targets due to maturing oil fields, lack of new discoveries and political instability (Powers, 2004). Recently, Indonesia started importing oil for domestic use and became a net oil importer.

INSERT TABLES 9-11

One would expect that in countries which have large proven oil reserves, crude oil production would be more likely to be stationary because such countries would be able to maintain constant supply in periods of economic or political turbulence. Hsu et al. (2007) found that energy consumption was more likely to be stationary in countries which exported energy. There is no clear cut evidence on the relationship between stationarity of production and proven oil reserves. Table 11 shows proven oil reserves. Of the OPEC countries with a unit root in both regimes, Kuwait, Saudi Arabia and Venezuela have vast oil reserves. Counties such as Libya and Qatar have much lower levels of proven quantities of oil reserves, while Indonesia has the smallest reserves of all OPEC countries in our sample. Of the non-OPEC countries, Canada has a lot of proven reserves, but most of these are oil sands which are difficult to extract and convert into low quality oil. Mexico, the UK and the US have relatively few proven reserves remaining.

For four countries (China, Egypt, Iran and Norway) there is a partial unit root in the first regime. For China 328 observations, or 80% of the sample, fall within regime 1. Thus, China crude oil production in China contained a unit root for most of the period studied. For Egypt, Iran and Norway only 12%, 11% and 19% of the sample fell within the first regime. Thus, for these countries crude oil production was stationary for most of the period under consideration. With the exception of China, these of countries reached a local maximum in regime 2. The results for Egypt, Iran and Norway are consistent with an exponential increase in crude oil production in regime 1, where there was a non-linear unit root and a plateau in regime 2 once the local maximum was reached. The exponential increase in crude oil production in each of these countries occurred over a relatively short period following the first oil price shock when energy prices increased.

For two countries (Iraq and Nigeria) there is a partial unit root in the second regime. For Iraq 379 observations, or 93% of the sample, occur in regime 2, while for Nigeria the breakdown is fairly evenly split with 218 observations or 53% of the sample occurring in regime 2. Both of these countries are politically troubled OPEC members that have been plagued by civil unrest or wars in the second regime. Nigeria has been unable to meet the OPEC quota, while, as stated earlier, Iraq is the only country in OPEC which is excluded from the quota allocations. In Nigeria, an inability to comply with OPEC quotas is because of worker’s strikes and conflicts between the indigenous people and the oil companies and continuing violence in the Niger Delta (Mouawad, 2007). In Iraq there are several factors adversely affecting supply, including the two Gulf wars, regulated production levels due to the United Nations oil for food program and current political instability. Both countries are capable of sustained growth in crude oil production, if not for political unrest and war. Iraq has the second largest proven oil reserves and Nigeria has the fifth largest proven oil reserves in OPEC. Narayan et al. (2007) found no clear relationship between the volatility and stationarity of crude oil production. In our study the second regime was characterized by higher volatility in production than the first regime. Our results are generally consistent with Narayan et al. (2007) on this point, given there are only four countries with a partial unit root in the first regime and two countries with a partial unit root in the second regime.

6. Conclusion

This paper has tested for non-linearities and unit roots in crude oil production, by applying a threshold autoregressive model with an autoregressive unit root to monthly crude oil production levels for 16 OPEC and non-OPEC countries over the period January 1973 to December 2006. Each of these countries either is, or has been, a major oil producer over the three decade period studied. We found that for ten countries there is a unit root in both regimes; for four countries there is a partial unit root in the first regime and for two countries there is a partial unit root in the second regime. China and Iraq has a partial unit root in crude oil production spanning most of the period. Thus, 12 of the 16 countries, or 75% of the sample, had a non-linear unit root in crude oil production for all, or most, of the period under consideration. Our finding that the countries in our sample contain a non-linear unit root in both regimes, or partial unit root in at least one of the regimes, has implications for the correct modelling and forecasting of crude oil production. In previous research Narayan et al. (2007) found that panel unit root tests provided strong evidence in favour of joint stationarity of crude oil production. Our results suggest that conventional unit root tests such as those employed in that study, which assume linear and systematic adjustment, can lead to misleading inferences because they may interpret departure from linearity as permanent stochastic disturbances.

Hamilton (2007) presents a simple factor share framework for examining the effects of energy supply disruptions on economic activity, which suggests that the elasticity of output with respect to a given change in energy use can be inferred from the dollar share of energy expenditure in total output. Hamilton (2007) postulates that in the US the dollar share of energy expenditure in total output is about 4 per cent. Thus, if there was a 10 per cent drop in crude oil production with a 4 per cent crude oil share, on the basis of the above relationship we would predict GDP would fall by 0.4 per cent. The effects of disruptions in crude oil production on economic activity are magnified if the assumptions of the factor share argument are modified, such as to allow for mark-up pricing rather than perfect competition or if there is modification of the capital utilization rate with perfect competition. Hamilton (2003) shows that the drops in real GDP in the US in response to various disruptions to crude oil production over the course of the second half of the twentieth century were greater than the factor share argument would predict. Thus, our results also have important implications for central tenants of macroeconomics such as business cycle theories. Hendry and Juselius (2000) suggested that “the impact of structural change in the world oil market is [a potential source] of non-stationarity”. If oil production contain a unit root, through the transmission mechanism to real income via energy prices, business cycle theories describing output fluctuations as temporary deviations from long-run growth would lose their empirical support. As Cochrane (1994, p. 241) noted, if real output contains a unit root, this “challenges a broad spectrum of macroeconomic theories designed to produce and understand transitory fluctuations”.

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Figure 1

OPEC and non-OPEC production

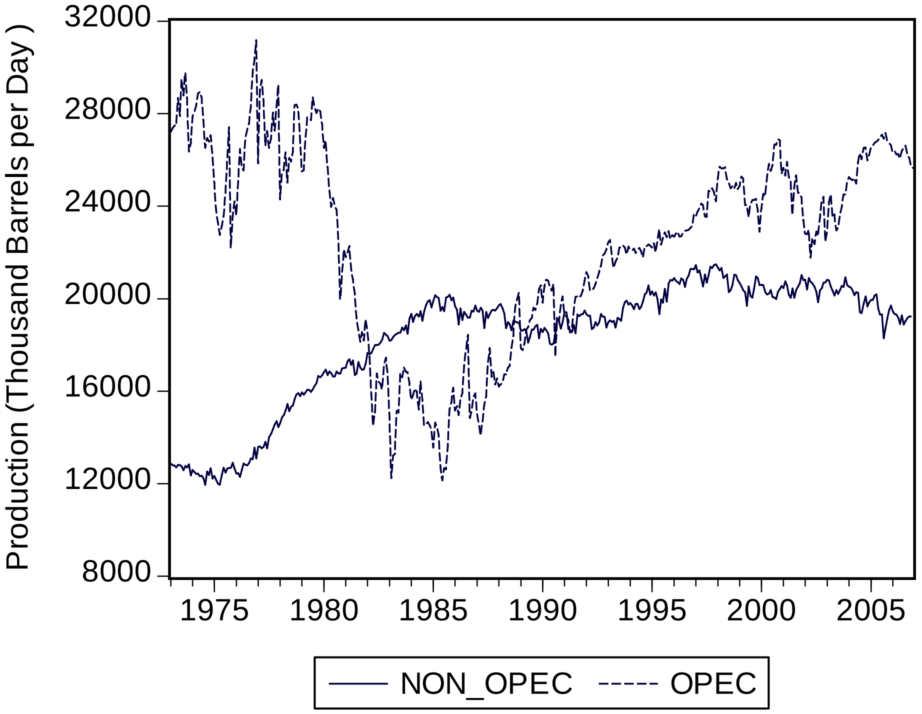

Figure 2:

Production of crude oil by the US, Iran and Saudi Arabia from 1973 to 2006

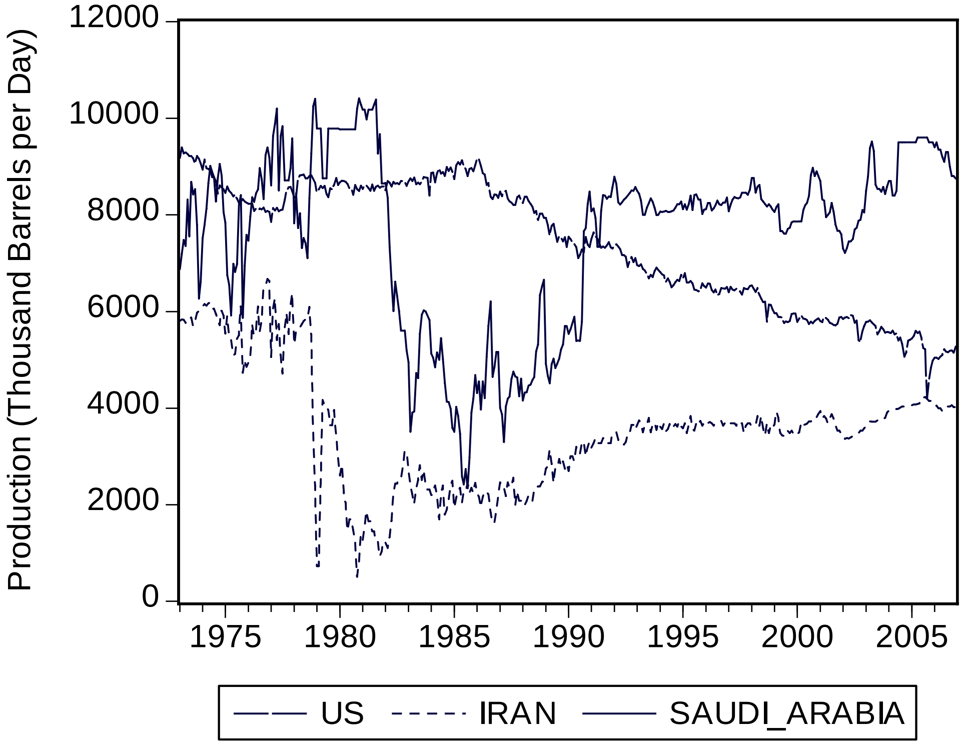

Table 1
Minimum and maximum production values: 1973-2006

Country	Minimum production (in thousands barrels per day)	Maximum production (in thousands barrels per day)
	OPEC	
Indonesia	1983 February, 984	1977 December, 1720
Iran	1980 September, 510	1976 November, 6677
Iraq	1991 February-May, 0	1979 November - December, 3728
Kuwait	1991 February-March, 0	1973 January, 3768
Libya	1981 August – September, 620	1973 October, 2370
Nigeria	1983 February , 675	2005 June-July, 2005 October-December, 2695
Qatar	1987 April, 145	2006 August – October, 885
Saudi Arabia	1985 August, 2340	1980 November, 10414
Venezuela	2003 January, 630	1997 December, 3453.26
	Non-OPEC	
Canada	1982 April, 955	2006 December, 2668.67
China	1973 January – June, 1012	2006 July, 3710
Mexico	1973 January, 453	2003 December, 3455
Egypt	1973 November - December, 28.66	1984 December, 942.55
Norway	1974 January, 2.018	2000 July, 3417.40
UK	1975 January – May, 1	1998 December, 2821
US	2005 September, 4203	1973 February, 9395

Table 2
OPEC crude oil production ceiling allocations in 1000 b/d.

Country	Jun03-	Nov03-	Apr04-	Jul-04	Aug04-	1Nov04-	17Mar05-	Jul05-	Nov-07-	Quota compliance
	Oct-03	Mar-04	Jun-04		Oct-04	16-Mar-05	30-Jun-05	Oct-06	Jan-07	
Indonesia	1,317	1,270	1,218	1,322	1,347	1,399	1,425	1,451	39	Below
Iran	3,729	3,597	3,450	3,744	3,817	3,964	4,037	4,110	176	Below
Kuwait	2,038	1,966	1,886	2,046	2,087	2,167	2,207	2,247	100	Comply
Libya	1,360	1,312	1,258	1,365	1,392	1,446	1,473	1,500	72	Comply
Nigeria	2,092	2,018	1,936	2,101	2,142	2,224	2,265	2,306	100	Below
Qatar	658	635	609	661	674	700	713	726	35	Comply
Saudi Arabia	8,256	7,963	7,638	8,288	8,450	8,775	8,937	9,099	380	Comply
Venezuela	2,923	2,819	2,704	2,934	2,992	3,107	3,165	3,223	138	Below

Source: OPEC retrieved from http://www.opec.org/home/quotas/ProductionLevels.pdf on May 30, 2007

Table 3
Threshold tests

Countries	Wald statistic	Bootstrap p- value	Optimal delay parameter m	Threshold parameter $\hat{\lambda}$
		OPEC		
Indonesia	91.4	0	8	-85.6
Iran	112	0	1	-216
Iraq	95.6	0.0002	1	-325
Kuwait	134	0	7	366
Libya	120	0	1	95
Nigeria	71	0	7	25
Qatar	54.5	0	1	65.5
Saudi Arabia	50.9	0.0018	3	513
Venezuela	68.9	0.0214	10	258
		Non-OPEC		
Canada	66.1	0	11	-13.7
China	129	0	12	157
Mexico	54.8	0.0081	6	-13.7
Egypt	123	0	3	-25
Norway	97.5	0	4	-90.2
UK	103	0	3	-167
US	68.7	0.0008	6	-244

Table 4
Regime corresponding to local maximum production

Country	Regime at endogenous choice of m
Indonesia	2
Iran	2
Iraq	2
Kuwait	could not be determined at optimal choice of m
Libya	2
Nigeria	1 (November-December 2005) and 2 (June, July, October 2005)
Qatar	1
Saudi Arabia	2
Venezuela	2
Canada	2
China	1
Mexico	2
Egypt	2
Norway	2
UK	2
US	could not be determined at optimal choice of m

Table 5
Least squares estimates for the threshold model for non-OPEC countries

	Canada	China	Egypt	Mexico	Norway	UK	US
Variables	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic
Intercept	13.9* (0.0174)	48* (0.0001)	1.33 (0.6)	0.648 (0.718)	0.00642 (0.965)	0.184 (0.842)	0.00574 (0.966)
y_{t-1}	16.2* (0.0064)	8.57 (0.077)	0.582 (0.662)	4.32 (0.23)	5.83 (0.13)	4.14 (0.209)	0.124 (0.843)
Δy_{t-1}	11.2* (0.0127)	7.19 (0.0566)	15.6* (0.0068)	12.9* (0.0118)	24* (0.0001)	24.6* (0.0001)	5.29 (0.116)
Δy_{t-2}	1.57 (0.391)	15.2* (0.0094)	59.2* (0)	5.17 (0.121)	7.07 (0.0586)	26.5* (0.0001)	1.26 (0.459)
Δy_{t-3}	4.77 (0.136)	56.3* (0)	28.1* (0.0008)	0.00675 (0.957)	4.17 (0.168)	9.55* (0.0316)	7.71 (0.0682)
Δy_{t-4}	0.423 (0.675)	36* (0.0003)	17.5* (0.0107)	0.391 (0.69)	0.0133 (0.936)	11.5* (0.0174)	1.35 (0.466)
Δy_{t-5}	3.13 (0.247)	23.9* (0.0022)	11.4* (0.0357)	3.94 (0.207)	1.65 (0.405)	2.13 (0.344)	0.769 (0.583)
Δy_{t-6}	22.4* (0.0002)	24.4* (0.0016)	0.602 (0.623)	8.06 (0.0832)	0.59 (0.619)	2.05 (0.365)	0.487 (0.664)
Δy_{t-7}	16.3* (0.0037)	39.9* (0)	5.57 (0.146)	3.58 (0.243)	0.138 (0.814)	17.8* (0.003)	4.76 (0.166)
Δy_{t-8}	6.19 (0.1)	59.7* (0.0001)	2.35 (0.332)	1.02 (0.53)	6.33 (0.0996)	0.0229 (0.925)	4.93 (0.172)
Δy_{t-9}	1.36 (0.465)	70.8* (0)	0.437 (0.669)	2.78 (0.309)	3.98 (0.204)	5.93 (0.11)	2.05 (0.378)
Δy_{t-10}	9.71 (0.0348)	25* (0.001)	5.31 (0.161)	8.41 (0.0848)	0.363 (0.717)	3.5 (0.235)	10 (0.0517)
Δy_{t-11}	3.75 (0.223)	28.3* (0.0014)	0.405 (0.686)	0.202 (0.787)	0.223 (0.769)	0.61 (0.62)	3.08 (0.285)
Δy_{t-12}	3.96 (0.188)	4.95 (0.13)	10.9* (0.0437)	8.67 (0.0752)	0.0132 (0.945)	5.24 (0.14)	22.5* (0.0036)

Note: Bootstrap p-values are given in parenthesis, * indicates whether the coefficient is significant

Table 6
Least squares estimates for the threshold model for OPEC countries

	Indonesia	Iran	Iraq	Kuwait	Libya	Nigeria	Qatar	Saudi Arabia	Venezuela
Variables	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic	Wald Statistic
Intercept	0.0476	0.173	3.02	24*	2.65	12.1*	2.85	0.16	0.105
	(0.92)	(0.861)	(0.457)	(0.0034)	(0.469)	(0.0441)	(0.386)	(0.853)	(0.906)
y_{t-1}	0.582	7.89	8.54	0.124	0.0844	12.7*	3.95	0.0411	0.665
	(0.646)	(0.0925)	(0.0752)	(0.836)	(0.869)	(0.0167)	(0.221)	(0.902)	(0.664)
Δy_{t-1}	11.3*	0.292	1.62	17.3*	0.921	7.41	0.251	0.517	18.5*
	(0.0157)	(0.709)	(0.391)	(0.0058)	(0.494)	(0.0537)	(0.713)	(0.606)	(0.0131)
Δy_{t-2}	10.9*	32.3*	4.18	2.64	0.279	8.34*	2.07	0.775	6.46
	(0.0198)	(0.0002)	(0.193)	(0.284)	(0.716)	(0.0449)	(0.314)	(0.55)	(0.125)
Δy_{t-3}	0.0377	4.73	8.83	24.5*	4.06	5.14	6.13	0.516	10.1
	(0.896)	(0.145)	(0.0606)	(0.0038)	(0.169)	(0.138)	(0.0868)	(0.639)	(0.0678)
Δy_{t-4}	0.801	0.0199	9.1	65.9*	17.5*	0.827	1.54	1.8	2.52
	(0.569)	(0.926)	(0.0599)	(0.0001)	(0.0063)	(0.562)	(0.414)	(0.4)	(0.341)
Δy_{t-5}	0.0247	2.44	6.91	9.96	0.203	0.516	0.315	13.8*	0.0495
	(0.917)	(0.305)	(0.113)	(0.0557)	(0.765)	(0.642)	(0.721)	(0.0114)	(0.891)
Δy_{t-6}	13.8*	2.67	1.79	4.03	6.06	1.57	2.04	1.54	0.113
	(0.0135)	(0.296)	(0.404)	(0.228)	(0.12)	(0.438)	(0.357)	(0.435)	(0.842)
Δy_{t-7}	0.00453	6.15	5.87	28.2*	2.11	1.41	6.51	13.4*	11.6
	(0.964)	(0.116)	(0.136)	(0.0036)	(0.352)	(0.464)	(0.094)	(0.0164)	(0.0614)
Δy_{t-8}	2.5	0.713	1.56	1.13	0.517	15.7*	10.5*	3.68	3.57
	(0.321)	(0.602)	(0.43)	(0.532)	(0.644)	(0.0057)	(0.032)	(0.221)	(0.279)
Δy_{t-9}	4.75	0.409	10.1	1.07	17*	5.31	4.76	0.864	0.333
	(0.17)	(0.688)	(0.0545)	(0.525)	(0.0101)	(0.147)	(0.165)	(0.551)	(0.735)
Δy_{t-10}	0.647	2.39	6.19	1.68	10.6*	0.00158	2.93	2.82	2.46
	(0.613)	(0.329)	(0.139)	(0.431)	(0.0449)	(0.982)	(0.28)	(0.299)	(0.364)
Δy_{t-11}	0.206	35.3*	1.08	0.272	20.2*	9.4*	1.66	7.41	0.00191
	(0.784)	(0.0003)	(0.511)	(0.743)	(0.0061)	(0.0462)	(0.414)	(0.0828)	(0.983)
Δy_{t-12}	25.3	2.17	10.5	1.47	0.101	0.153	10.8*	3.36	0.466
	(0.001)	(0.351)	(0.0534)	(0.421)	(0.824)	(0.789)	(0.0235)	(0.228)	(0.682)

Note: Bootstrap p-values are given in parenthesis, * indicates whether the coefficient is significant

Table 7
One and two-sided unit root tests

Countries	Optimal delay parameter m	R_{1T} statistic	Bootstrap p-value	R_{2T} statistic	Bootstrap p-value
			OPEC		
Indonesia	8	1.23	0.832	1.23	0.871
Iran	1	18.6	0.0089	18.6	0.0095
Iraq	1	17.7	0.0181	17.7	0.0188
Kuwait	7	2.54	0.672	2.54	0.711
Libya	1	8.17	0.149	8.17	0.166
Nigeria	7	20.4	0.0032	20.7	0.0034
Qatar	1	3.55	0.523	4.25	0.464
Saudi Arabia	3	2.33	0.681	2.33	0.718
Venezuela	10	8.22	0.216	8.22	0.231
			Non-OPEC		
Canada	11	4.17	0.436	21.3	0.002
China	12	15.3	0.0176	15.3	0.0194
Mexico	6	12.1	0.0597	17.6	0.0171
Egypt	3	13.8	0.0351	13.8	0.0386
Norway	4	22.1	0.0013	22.6	0.0013
UK	3	11.3	0.0511	11.3	0.0557
US	6	0.17	0.96	0.17	0.982

Table 8
Partial unit root results

Countries	Optimal delay parameter m	t_1^2 statistic	Bootstrap p-value	t_2^2 statistic	Bootstrap p-value
		OPEC			
Indonesia	8	0.948	0.54	0.574	0.668
Iran	1	3.76	2.51	2.11	0.018
Iraq	1	3.38	0.032	2.5	0.108
Kuwait	7	1.29	0.409	0.941	0.57
Libya	1	2.82	0.0561	0.478	0.695
Nigeria	7	4.52	0.0015	-0.553	0.908
Qatar	1	-0.838	0.942	1.88	0.235
Saudi Arabia	3	1.29	0.414	0.821	0.594
Venezuela	10	2.86	0.0899	0.192	0.79
		Non-OPEC			
Canada	11	2.04	0.184	-4.14	1
China	12	0.849	0.582	3.82	0.0075
Mexico	6	2.24	0.151	2.67	0.0854
Egypt	3	1.41	0.385	3.44	0.0224
Norway	4	-0.742	0.937	4.7	0.0005
UK	3	2.4	0.11	2.35	0.119
US	6	0.407	0.714	0.07	0.809

Table 9
Summary of results

Decision	Countries
Unit root in both regimes	Indonesia, Kuwait, Libya, Qatar, Saudi Arabia, Venezuela, Canada, Mexico UK, US
Unit root in first regime	Iran, China, Egypt, Norway
Unit root in second regime	Iraq, Nigeria

Table 10
Top fifteen oil producers in 2006 (in thousand barrels of oil per day)

Rank	Country	Production
1	**Saudi Arabia**	10,719
2	Russia	9,668
3	**United States**	8,367
4	**Iran**	4,146
5	**China**	3,836
6	**Mexico**	3,706
7	**Canada**	3,289
8	United Arab Emirates	2,938
9	**Venezuela**	2,802
10	**Norway**	2,785
11	**Kuwait**	2,674
12	**Nigeria**	2,443
13	Brazil	2,163
14	Algeria	2,122
15	**Iraq**	2,008

Source: EIA: *International Energy Annual* (2000-2004), *International Petroleum Monthly* (2005-2006). Retrieved on June 30, 2007 from http://www.eia.doe.gov/emeu/cabs/topworldtables3_4.html

Table 11
OPEC and non-OPEC countries proven oil reserves as per 2006 (in billions barrels of oil)

OPEC		Non-OPEC	
Country	**Proven Reserves**	**Country**	**Proven Reserves**
Iran	132.5	Canada	179.2
Iraq	115	China	18.3
Kuwait	101.5	Mexico	12.9
Libya	39	Egypt	3.7
Nigeria	36.2	Norway	7.7
Qatar	15.2	UK	4.0
Saudi Arabia	260	US	21.4
Venezuela	79.7		
Indonesia	4.3		

Source: EIA, Country Analysis Briefs (2006-2007)