



Long run dynamic volatilities between OPEC and non-OPEC crude oil prices[☆]



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HIGHLIGHTS

- We investigate asymmetric-dynamic mechanisms of OPEC and non-OPEC crude oil prices.
- Such dynamics are explored using original ECM within threshold cointegration modeling and CGARCH errors.
- OPEC couldn't drive down (up) crude oil prices with alike speed for all producers.
- Conditional volatility has long memory and shocks on long run component decay slowly.
- The speed-adjustments show evidence for distinct competitive behaviors between OPEC and non-OPEC.

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ABSTRACT

Understanding the long-run dynamics of OPEC and non-OPEC crude oil prices is important in an era of increased financialization of petroleum markets. Utilizing an ECM within a threshold cointegration and CGARCH errors framework, we provide evidence on the cointegrating relationship and estimate how and to what extent the respective prices adjust to eliminate disequilibrium. Our findings suggest that the adjustment process of OPEC prices to the positive discrepancies is slow which implies that OPEC producers do not prefer moderate oil prices; however, the reverse holds for non-OPEC producers. These results reflect distinct competitive behaviors between OPEC and non-OPEC producers.

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1. Introduction and literature review

The increasing growth in demand for crude oil from economies such as China, India and the Middle-East has had an impact on the prices of oil, which reached a record level of \$145 per barrel in 2008. Changes in the price of oil are increasingly significant and have influenced every economy around the world. The analysis of oil prices has always been of considerable interest to all people. Established in September 1960, the Organization of Petroleum Exporting Countries (OPEC) exercises enormous influence on the world prices of oil due to many factors, particularly its spare oil capacity of roughly 4 million barrels per day in 2014, based on

an assumed 85% utilization rate.¹ Additionally, according to the International Energy Agency (IEA), non-OPEC countries had an excess demand of 35.5 million barrels per day in 2013²; this gap is satisfied with the oil supplied by the 12 members of OPEC.³ In 2013, the non-OPEC share of global oil production was approximately 59.8% of the total world production of oil. Due to the non-OPEC excess demand-supply, it is a common belief that non-OPEC producers behave as price takers and that OPEC may play a central role in the world oil market by adjusting its production and setting the prices of oil. However, it remains the case that the dynamics in

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¹ Source: 2014 World Oil Outlook. OPEC, Austria. www.opec.org.

² Source: Oil Market Report, Annual Statistical Supplement, IEA. www.oilmarketreport.org.

³ Filling such a gap requires OPEC members to coordinate their oil production policies through incremental capacities; these reactions help avoid sudden increases in crude oil prices. In addition, if supply outruns demand, over time OPEC will manage the excess capacity to avoid sudden decreases in oil prices. According to Smith [1], the oil demand and supply curves are highly inelastic in the short-run; shifts in the curves can lead to excessive price volatility.

crude oil markets depend on their different market fundamental situations [2,3]. These dynamics are attributed to their price regimes such as Brent, West Texas Intermediate and OPEC Reference Basket. The oil market itself appears to be in charge of pricing.

There is a vast literature on the price of oil. Gately [4] establishes that the reductions in the world demand for oil following the increase in oil prices in the 1970s have not been completely reversed by the price cuts of the 1980s. De Santis [5] explains the volatility of crude oil prices by focusing on the quota regime as a primary characteristic adopted by OPEC agreements. Recently, Nakov and Nuño [6] incorporated the ample spare capacity and the volatile domestic production, as features of Saudi Arabia, into a general equilibrium model where the global oil market is modeled as a dominant producer with a competitive fringe. They find that Saudi Arabia produces a smaller amount of oil than its capacity given the oil price, allowing it to charge a markup over its marginal cost. Lin [7] finds oligopolistic behavior among non-OPEC producers and collusion among OPEC producers during the period 1970–2004. Hamilton [8] investigates the factors responsible for changes in crude oil prices by reviewing the statistical behavior of oil prices and the key features of crude oil supply and demand. He concludes that there is an increasing contribution of scarcity rent to the petroleum price. Li [9] shows that the non-OPEC production Granger-causes world oil prices and that the causation runs from the refiner acquisition cost of imported crude oil to OPEC production. He concludes that it is not appropriate to treat OPEC as a dominant firm. Additionally, Ji and Guo [10], using an event study methodology and an AR-GARCH model, show that the reactions of oil price returns to different OPEC production announcements are inconsistent.

Few of the previous works assume that the adjustment process is asymmetric. Moreover, a number of studies claim that there is an asymmetric relationship between the oil price followed by OPEC and non-OPEC countries [11–15]. Chen et al. [11] document new supportive evidence for asymmetric adjustment in United States retail gasoline prices. The asymmetric transmission is found to occur through the spot markets of crude oil and refinery gas and their future markets. A number of empirical studies have also been performed on price asymmetry for the North American markets, but the findings of these studies are mixed [16,17,18]. According to Borenstein [19], oil price increases do not reflect a compensation mechanism for the weakness in the US dollar featured in a long-run declining trend of its purchase power. He indicates that, during 2007, the dollar lost approximately 10% against others major currencies whereas the price of crude oil in dollar increased roughly 50%, with oil prices being set based more on the balance of worldwide supply and demand. The existing empirical evidence in favor of (or against) price asymmetries in oil markets is skillfully summarized by Perdiguero-García [15], who conducts a meta-analysis of the related contributions and concludes that the smaller (higher) level of competition in the market displays higher (smaller) degree of price asymmetries. He states that asymmetries are more difficult to detect in analyses that cover a long period of time.

The variability in the crude oil price can be explained by OPEC and non-OPEC crude oil price volatilities and by their oil production variability. Nevertheless, even if financial trader activities are confined to the oil futures market, their speculative trading in spot markets can provoke oil price volatility [1,20,21]. According to Smith [1], the oil market share of financial traders increased between 2004 and 2008; meanwhile, the share of oil producers

decreased during that span. Many authors (e.g., [1,22,23]) consider that non-fundamental factors such as speculative activities in the crude oil future markets, financial market risks and geopolitical conflicts may drive the short and long-run volatility of international crude oil prices. Based on fundamental factors, Wu and Zhang [23] question the effects from October 2005 to November 2013 of China's real crude oil net imports⁵ and real monthly Brent oil spot price changes. They find that, in the short- and long-run, China's crude oil net imports do not significantly affect Brent price changes. However, using variance decomposition, they show that China's crude oil net imports contribute to Brent price volatility approximately 10%, that is, less than the US dollar exchange rate. Zhang and Wei [22] empirically analyze the asymmetric and dynamic impacts of various risk factors from January 1997 to July 2007 based on the weekly average returns in the US, UK, and Japan stock markets on the weekly US WTI futures oil price changes. They use the time-varying Capital Asset Pricing Model (CAPM) and Arbitrage Pricing Theory (APT) to develop a dynamic factor model.⁶ They find that the three stock market risks have significant time-varying effects and can exert asymmetric linear and non-linear shocks to the crude oil market in their up and down conditions and that the dynamic risk of the US stock market on the oil market has the largest volatility compared to the British and Japanese markets. By considering US fundamental oil macro-variables and the US industrial production index, Zhang et al. [24] find that rational bubbles⁷ exist in the short-run dynamic of WTI crude oil prices, mainly around 2008. They explain that their findings are closely related to the new changes in international crude oil markets since the end of 2004, which consist of a vast number of investment hedge funds with implications for the financial feature of crude oil assets.

The changes in crude oil prices over time may be analyzed through the dynamic volatilities in the short and long-run. The hypothesis that we will evaluate is that the increase in OPEC crude oil price volatility can be attenuated by the decrease in non-OPEC oil price volatility and vice versa. We expect that the OPEC dynamic volatilities of oil prices cannot be the main source of price variability in comparison to the non-OPEC prices. We explore the magnitude of the extent to which the OPEC and non-OPEC price series mutually interact to reveal the competitive nature in the oil market by using nonlinear cointegration and determining their reactions to positive or negative discrepancies (i.e., oil prices that are too high or too low) in the short and long-run. Considering the dynamic volatilities in short and long-run, we suppose that the permanent component of volatility is more persistent than the transitory volatility, even if the latter has higher volatilities. However, it remains the case that these transitory volatilities impact the long-run oil price process. According to Mensi et al. [2], the presence of structural breaks reduces the persistence of volatility and improves the understanding of such volatility in oil markets.

Our contribution to the recent related literature consists of exploring, through a new modeling approach, the ECM-TAR (MTAR)-CGARCH analytical framework.⁸ This approach investigates whether the prices of oil for both groups are cointegrated, with the

⁴ They study the implications of spatial crude oil price divergence for the price of refined products in the US. By using monthly spot crude oil prices, they conclude that the transport constraint has caused a large price differential in crude oil. They show that the decrease in the US Midwest crude oil price has not been passed through to the refined product prices, namely, gasoline and diesel.

⁵ According to the US EIA (Short-Term Energy Outlook, May 2015), China is the top annual world oil net importer.

⁶ The influence of stock market risk is based on the excess oil price return defined as weekly US WTI oil price returns minus the risk-free returns approximated by weekly returns of 3-month US T-bills. Also, the excess stock market return is calculated by subtracting the weekly return of 3-month US T-bills from the stock market return.

⁷ According to Lammerding et al. [25], Zhang et al. [24] define a bubble as an asymmetric, non-linear and non-stationary deviation of crude oil prices from the fundamental values.

⁸ This new framework combines the ECM with the asymmetric cointegration and CGARCH errors structure (more details are in Appendix A.1.2). It leads to a parsimonious representation of some stylized features of the OPEC and non-OPEC prices, such as the time-varying volatility and volatility clustering.

price adjustment process being either symmetric or asymmetric, and determines whether any interaction exists between the two different oil prices. Empirically, we explore the asymmetric cointegration first by using the threshold autoregressive (TAR) and momentum threshold autoregressive (MTAR) methods of adjustment suggested by Enders and Siklos [26]. They argue that the standard cointegration test and its extensions are misspecified if the adjustment is asymmetric.

The findings are that OPEC prices adjust more slowly than non-OPEC prices when they differ from their thresholds and that there is evidence of asymmetry in both the non-OPEC and OPEC price series. The negative MTAR-deviations of crude oil prices from the long-run equilibrium are corrected at moderate rates at a similar magnitude for both OPEC and non-OPEC countries. OPEC cannot drive crude oil prices down (up) at a similar speed for all producers; thus the speed adjustments show evidence of competitive behaviors between OPEC and non-OPEC countries. However, because the conditional volatility has a long memory [2] and shocks on the long-run component decay slowly, all producers in crude oil markets will face not only persistent shocks but also high short-run volatilities in the transitory variance [27]. This outcome is corroborated by the results of Ji and Guo [10], who indicate that crude oil price returns, induced by oil-related events, exhibit a stronger persistent effect. The implication of these results is that there is not a unique market scheme but instead diverse pricing behavior related to economic and geo-political factors between OPEC and non-OPEC countries. Indeed, when the price increases, non-OPEC countries correct any market imbalances that may occur due to the slowness of the response of OPEC countries through a unified strategic reaction. However, when the price decreases, OPEC countries adjust any market imbalances that may occur due to the tardiness of non-OPEC producer reactions through multiple strategic responses. The paper is organized as follows: Section 2 reports the description of the data and the cointegration tests, Section 3 presents and discusses the empirical findings of the error correction model, and Section 4 concludes.

2. Data and cointegration tests

2.1. Data and preliminary tests

The data are based on the per barrel price of crude oil in US Dollars at the monthly frequency for both OPEC and non-OPEC countries. The advantage of the monthly frequency is that there are no missing observations and, according to Baumeister et al. [28], there is no gain from switching to mixed data sampling (MIDAS) models and the monthly model is preferred to an infra-month-frequency. In a future paper, we expect to investigate the available weekly or daily frequency data of crude oil prices to detect whether dynamic volatility will be more amplified. The averages of the OPEC and non-OPEC prices are based on the affiliations of the countries for the stated period, which may differ from current affiliations. The most commonly used primary benchmarks of crude oil prices are the West Texas Intermediate (WTI), Brent Blend, and Dubai Crude. As such, the OPEC Reference Basket⁹ is among the other well-known blends, including the Tapis Crude, Bonny Light and the Urals. Following the construction of the U.S. Energy Information Administration (EIA), monthly oil prices variables are constructed as averages of daily data over the month. The monthly data are based on FOB prices from the first business day of the first week. OPEC and non-OPEC prices are calculated as the average

price (FOB) weighted by the export volume. To include the structural changes that occurred in the history of the international oil market, our sample monthly data cover the period January 1973 to April 2013 (Fig. A1).¹⁰ This figure strikingly shows how all these prices move closely together. The two variables are converted into natural logs and labeled LOPEC and LNOPEC. The mean-to-median ratio of each variable suggests that the distribution of the variable is not far from a symmetrical distribution, given that this ratio is close to one (Table 1). Using the Van Der Waerden normal scores test, as nonparametric test statistics in the one-sample test framework, to test the null hypothesis of the equality of median to mean, we accept the alternative hypothesis. In addition, the D'Agostino-Pearson (DP) omnibus test for both skewness and kurtosis conducts to reject the null hypothesis of the normality assumption: for OPEC and non-OPEC prices, we obtain $P(\chi^2 > 43.75) = 3.16E - 10$ and $P(\chi^2 > 32.51) = 8.73E - 08$, respectively. Consequently, the distribution of the logged OPEC and non-OPEC prices cannot be normally distributed. In addition, to check whether the underlying data are normally distributed, we use the Quantiles-plot. The results indicate that the QQ-plots do not lie in a straight line because the two distributions for each series deviate from the linearity pattern and visually there are fat tails.

According to Horn [29], we expect that the crude oil prices do not follow an independent and identical distribution. If the random variables are independent, then the unconditional distribution is equal to the conditional distribution. However, temporal dependence doesn't allow the independence feature even in the normal distribution; it becomes more interesting for the conditional distribution. Thus, the empirical analysis is focused on the unconditional distribution of crude oil prices, based on past information and requiring stable processes. From Table 1, the standard deviation, skewness, and kurtosis fail to confirm the normality of each variable. The distribution of the crude oil prices at monthly data exhibits a positive skewness and an excess kurtosis, indicating price volatility; thus, we have a platykurtic distribution. Also, the statistics of the parametric Jarque-Bera test strongly reject the null hypothesis of normal distribution.

To obtain the integration order, the oil prices were initially tested by the ADF and ADF-GLS with constant and trend using traditional and modified AIC and SIC [30] to improve the size and the power of the test. These statistics suggest that OPEC and non-OPEC prices have a unit root process but are stationary in their first difference. As a reversed test because it also rejects the null hypothesis of level stationarity of the crude oil prices, the outcome of KPSS Lagrange Multiplier test confirms the ADF test decision. When the variables are $I(1)$, the unconditional distribution may not exist; the underlying stochastic process cannot lead to the platykurtic unconditional distribution if the process is not strictly stationary.

The plots of the first difference of the logged crude oil prices indicate conditional heteroscedasticity, but that does not necessarily mean that the series are from a platykurtic conditional distribution. Thus, the unconditional platykurtosis could reflect conditional heteroscedasticity. A GARCH model may be sufficient to address this purpose by capturing the peakedness and the fat-tailedness of the unconditional distribution [31]. The motion of non-OPEC prices does not occur in isolation; instead the prices cluster dynamically with OPEC prices (Fig. A1). The existence of volatility clustering would justify the CGARCH framework [32].¹¹ The conditionally platykurtic

¹⁰ The data are gathered from the US Energy Information Administration; the links used to collect these data are the following: <http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=1060000004&f=M> (for OPEC). <http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=1070000004&f=M> (for non-OPEC).

¹¹ Volatility shocks lead to an uncertain future evolution, indicating the presence of volatility clustering [32], which means that when negative news occurs during price increases, volatility also increases. This phenomenon appears when the differences in the interpretability of information from the crude oil market amplify competition between OPEC and non-OPEC producers.

⁹ The OPEC Basket price is composed of 12 OPEC crude grades: Saharan Blend (Algeria), Girassol (Angola), Oriente (Ecuador), Iran Heavy (Iran), Basra Light (Iraq), Kuwait Export (Kuwait), Es Sider (Libya), Bonny Light (Nigeria), Qatar Marine (Qatar), Arab Light (Saudi Arabia), Murban (UAE) and Merey (Venezuela). Source: <http://www.energycharter.org/what-we-do/trade-and-transit/trade-and-transit-thematic-reports/putting-a-price-on-energy-oil-pricing-update-2011/>.

Table 1
Descriptive statistics and unit root tests of LOPEC = p_1 and LNOPEC = p_2 .

	Mean	Median	Std. Dev.	Skewness	Kurtosis	Jarque-Bera ^a	ADF ^b
LOPEC	3.186	3.046	0.677	0.729	2.727	43.30	-2.682
LNOPEC	3.174	3.086	0.660	0.626	2.739	32.20	-3.004

^a The p -value is 0.00.

^b The critical value at 1% is -3.98. Number of obs. is 472. $T = 1973-2013$.

and conditionally heteroscedastic properties may be mixed in a single model as a regime-switching model or multivariate distribution using mixed-normal conditional distributions [33,34]. These approaches will be explored in our next study.

2.2. Cointegration tests

To detect the long-run equilibrium relationship between OPEC and non-OPEC prices, we begin with Engle and Granger's [35] and Perron and Rodriguez's [36] cointegration test methods, assuming a symmetric adjustment. These tests have been implemented using GAUSS software. Each cointegration test includes a constant and trend as deterministic components because the visual data support a constant and trend. To run EG test, the lag order is chosen by using AIC and T -significance. The results in Table 2 show that EG test rejects the null hypothesis of no cointegration at 5% in accordance with AIC and T -significance criteria, evidencing that cointegration relationships exist between the oil selling price influenced and followed by OPEC and non-OPEC countries. By using a time-varying average distance measurement and an ECM combined with a directed acyclic graph technique, Ji and Fan [38] show that there is a long-run equilibrium relationship between the major crude oil prices (such as WTI, Brent Blend, Dubai Crude, Tapis Crude and Bonny Light). Additionally, PR test supports the results of EG test because it rejects the null hypothesis of no cointegration at 1% for both AIC and T -significance criteria. In EG test, if the variables are interchangeable and the sample size is sufficient, then the same test decision is attained (Table 2).

According to Horvath and Watson [39], when there is only one cointegrating vector, simple univariate tests provide an alternative to likelihood-based tests. The power trade-off between the multivariate and the univariate tests for cointegration is interesting in higher-dimensional systems. However, in our case, Johansen test explains that the OPEC and non-OPEC logged price series move together toward one stable long-run relationship. When the cointegrating vector is unique, EG test is validated. But, when the cointegrating vector is not unique, we may implement a VEC model. We find a significant trace-statistic of 25.35 and a significant Max-Eigen statistic of 24.14, with critical values of 19.94 and 18.52 at the 1% level, respectively. By using Granger causality/block exogeneity test, from the VEC model instead of the VAR model, using the χ^2 -statistic, we find bi-directional causality from OPEC prices to non-OPEC prices, where $\chi^2 = 32.07$ with a p -value equal to $9.06E-05$ and $\chi^2 = 225.59$ with a p -value equal to 0.00. Additionally, in the multivariate setting, the q_f statistic of Stock and Watson [40] tests the null hypothesis of the stochastic trends of series against their common trends, i.e., cointegrated series.¹² The test is based on filtering the data and using VAR representation. Testing for two versus one common trend using the $q_f(2, 1)$ statistic, the reported test using Camacho Gauss program leads to $q_f = -102.07$, which is more negative than the critical value of -39.2 at the 1% level (Table 3 of [40]). Thus, we reject the null

hypothesis in favor of a model in which the two crude oil prices contain a single common trend.

Johansen test uses sequential tests for determining the number of cointegrating vectors; its advantage over Engle-Granger (EG) cointegration test is that it can estimate more than one cointegration relationship, mainly if the data set contains more than two time series. But, the interpretation of the results becomes difficult when there are multiple cointegrating vectors. It is also invariant to the selection of the variable for normalization, whereas the results of EG procedure depend on how the single long-run equation is specified. In some cases, based on economic theory, it is possible to identify which variable is dependent on the left side of the equation. However, Johansen test often leads to a cointegrating vector without economic meaning [41]. The limitation of the Johansen procedure is that it assumes that the cointegrating vector remains constant during the sample period, which is not true due to technological progress, changes in people's preferences, economic crisis, policy or regime alteration and institutional development [8]. Such limitations are also valid for EG method. Threshold cointegration is more appropriate for crude oil prices processes.

Therefore, the residuals of the model $p_{1t} = \alpha + \beta p_{2t} + \varepsilon_t$, where p_1 and p_2 are the OPEC and non-OPEC logged crude oil price, respectively, are estimated by following TAR and MTAR models, where the lag order is chosen by using AIC and T -significance. Considering the TAR model with AIC, the point estimates are calculated to be $\rho_1 = -0.174$ and $\rho_2 = -0.322$, having the expected signs for convergence (Tables 3a and 3b). The statistic $\phi = 29.338$ is greater than the 1% critical value. This result implies that the null hypothesis of $\rho_1 = \rho_2 = 0$ can therefore be soundly rejected, indicating that the series are cointegrated. After confirming cointegration between OPEC and non-OPEC oil prices, the null hypothesis of no asymmetry ($\rho_1 = \rho_2$) can be tested by using the standard \mathcal{F} -distribution [42]. The sample value of $\mathcal{F} = 5.904$ with a p -value of 0.015 implies that we can also reject the null hypothesis and find evidence of asymmetric adjustment. The TAR model, following the T -significance test for lag selection, also supports these findings. Therefore, we can conclude that according to the TAR and MTAR tests, the oil prices followed by OPEC and non-OPEC countries are asymmetrically cointegrated. OPEC and non-OPEC crude oil market prices have a high asymmetric-cointegration through the TAR test than the MTAR test, which may be related to the natural flow of oil market prices information. The asymmetry feature may be used to stabilize crude oil prices at an acceptable level of increase or decrease in the main place of the crude oil market.

Turning to the MTAR and using AIC (Tables 3), the point estimates are found to be $\rho_1 = -0.164$ and $\rho_2 = -0.314$, which have the expected signs and suggest their convergence. The statistic ϕ of 29.556 clearly rejects the null hypothesis of no cointegration at the significance level of 1%. Given that the F value equals 6.296 with a p -value of 0.012, we can reject the null hypothesis of symmetric adjustment. The evidence of asymmetric adjustment in terms of F is further improved with the MTAR model.

The asymmetric adjustment is found in both the TAR and MTAR models using the AIC and T -significance criteria. The points estimate of ρ_1 and ρ_2 are found to be negative, suggesting convergence in both the TAR and MTAR models. As documented by Sichel [43], the threshold cointegration of LOPEC prices shows in all cases that

¹² They indicate that, if each n series is $I(1)$ but can be jointly characterized by $k < n$ stochastic trends, then the vector representation of these series has k unit roots and $(n - k)$ distinct stationary linear combinations, i.e., cointegrating vectors.

Table 2
Cointegration tests (Dependent variables LOPEC and LNOPEC).

	EG, LOPEC		EG, LNOPEC		PR, LOPEC = EG ^{GLS}		PR, LNOPEC = EG ^{GLS}	
	AIC	T-Sig.	AIC	T-Sig.	MAIC	T-Sig.	MAIC	T-Sig.
ρ	-0.138	-0.144	-0.152	-0.158	-0.131	-0.151	-0.129	-0.148
τ_ρ	(-3.432)	(-3.661)	(-3.659)	(-3.887)	(-3.359)	(-3.964)	(-3.293)	(-3.875)

Notes: For EG test: the one sided (lower tail) test of the null hypothesis is that the variables are not cointegrated; at the 1%, 5%, and 10% significance levels, the critical values are -4.02, -3.40 and -3.09, respectively [37]. For PR test: the one sided (lower-tail) test of the null hypothesis is that the variables are not cointegrated; at the 1%, 5%, and 10% significance levels, the critical values are equal to -3.33, -2.76 and -2.47, respectively [36].

Table 3a
Threshold cointegration tests (Dependent variable LOPEC, p_1).

		ρ_1	ρ_2	ϕ	F (p-value)	τ, γ
		TAR	AIC	-0.174 (-4.923)	-0.322 (-6.177)	29.338**
	T-Sig.	-0.088 (-1.783)	-0.192 (-3.725)	7.312**	2.795 (0.095)	-0.0514
MTAR	AIC	-0.164 (-4.426)	-0.314 (-6.491)	29.556**	6.296 (0.012)	-0.0318
	T-Sig.	-0.102 (-2.326)	-0.240 (-3.696)	7.928**	3.995 (0.046)	-0.0318

Notes: The values corresponding to ϕ are compared to the ϕ -tables computed by Enders and Siklos [26]. The t -values are in parentheses in the 3rd and 4th columns. The Threshold Auto-Regressive (TAR) model is $\Delta \hat{e}_t = \rho_1 I_t \hat{e}_{t-1} + \rho_2 (1 - I_t) \hat{e}_{t-1} + u_t$, where I_t is the indicator function, $I_t = 1$ if $\hat{e}_{t-1} \geq \tau$, and 0 if $\hat{e}_{t-1} < \tau$. For the Momentum TAR, we use $\Delta \hat{e}_{t-1}$ instead of \hat{e}_{t-1} to obtain the threshold γ . The threshold is estimated using Chan's methodology [44]. More technical details on threshold cointegration are available in Appendix A.1.1.

** Significance at 1% level.

$|\rho_1| < |\rho_2|$, which means that increases tend to persist whereas decreases tend to revert quickly toward equilibrium. By contrast, the threshold cointegration of LNOPEC prices notes three cases where $|\rho_1| > |\rho_2|$, indicating that increases tend to revert toward equilibrium, whereas decreases tend to persist and slowly return to the attractor. Hence, the results show that both the TAR and MTAR models provide evidence that there are asymmetric adjustments in oil prices between OPEC and non-OPEC countries. This asymmetric adjustment implies some asymmetries between the changes in OPEC oil prices versus non-OPEC oil price shocks and vice versa. Also, from Table 3a, we observe that the OPEC adjustment process is not persistent toward equilibrium above the threshold for both the TAR and MTAR models. However, the deviations from equilibrium are almost quickly eliminated when they are below the threshold parameter. Thus, the long-run equilibrium relationship between the OPEC and non-OPEC oil price, below the threshold parameter, is more stable with an asymmetric adjustment process.

3. Error correction model

From the results of the threshold cointegration between the two oil prices, it is possible to estimate the asymmetric error correction model. The findings for the ECM are reported in Table 4a, and both the TAR and MTAR models detect asymmetry in the oil price adjustment of OPEC and non-OPEC countries. The MTAR model, which has a consistent threshold estimate, yields the lowest AIC in comparison to the other models, and the MTAR specification exhibits greater power over the TAR specification [42].

Table 3b
Threshold cointegration tests (Dependent variable LNOPEC, p_2).

		ρ_1	ρ_2	ϕ	F (p-value)	τ, γ
		TAR	AIC	-0.305 (-5.847)	-0.189 (-5.290)	29.220**
	T-Sig.	-0.152 (-3.461)	-0.265 (-4.468)	13.482**	2.880 (0.090)	-0.0448
MTAR	AIC	-0.326 (-6.700)	-0.167 (-4.468)	31.141**	7.013 (0.008)	+0.0276
	T-Sig.	-0.320 (-4.983)	-0.167 (-4.082)	17.828**	4.739 (0.029)	+0.0329

The comparison between the transitory volatility persistence rate ($\alpha + \beta$), defined in Table 4b, and the permanent decay rate ρ , through the results of the ECM-Threshold-CGARCH model, shows that short-run volatilities are less persistent than long-run volatilities. The heteroscedasticity test indicates that the ARCH effect is largely reduced by using ECM-TAR-CGARCH (the last rows of Table 4b); this improvement in the regressions is explained by the diminution of the skewness and kurtosis coefficients. Nevertheless, these volatilities converge to the mean reversion ω_0 at speed ρ after an occurrence of shocks because $0.9 < \rho < 1$. Thus, q_t – the long-run component of σ_t^2 , the conditional variance – would move slowly toward the unconditional variance, ω_0 . Thus, the shocks to the long-run component do not decay quickly due to the slow adaptation to new events, given that the conditional volatility has a long-run memory feature (Figs. 1a and 1b). The decay rate of the permanent component ρ , i.e., the speed of the mean reversion (Fig. A2), is estimated for OPEC prices at a high rate of 97.0% using the Gaussian error distribution (GED) with the TAR-AIC error correction term. Therefore, these decay rates imply that approximately 78.6%, i.e., $\rho^8 = 0.9703^8$, of a shock remains even after eight trading months, and that 98.4% of the shock remains using Gaussian error and Student's distributions, respectively. For non-OPEC prices and when the error correction term is from TAR-AIC, the decay rate ρ is also high at 95.9% when we use the GED and 94.3% using the normal distribution. Hence, 71.4% and 62.7% of the effect of the shocks remains even after eight months using the GED and normal distribution, respectively. Using the AIC criterion for the threshold parameter, even after one year, the shocks to OPEC oil prices persist at 69.7%, i.e., 0.9703^{12} , whereas for non-OPEC oil prices, they are less

Table 4a
ECM-CGARCH applied to OPEC and non-OPEC prices, 1973.10–2013.01.

ECM-Threshold	OPEC Model_1	Non-OPEC Model_2	OPEC Model_3	Non-OPEC Model_4
1	6.6E–05 (0.27)	6.4E–04 (0.46)	–8.9E–04 (–2.61)	0.0016 (0.37)
ect_t^+	–0.188 (–15.23)	–0.547 (–6.68)	–0.144 (–7.38)	–0.517 (–6.04)
ect_t^-	–0.151 (–5.03)	–0.533 (–10.36)	–0.354 (–11.16)	–0.357 (–5.69)
$\Delta p_{1,t}$		0.798 (48.21)		0.771 (44.27)
$\Delta p_{1,t-1}$				0.172 (7.19)
$\Delta p_{1,t-2}$	–0.235 (–12.47)	0.312 (6.03)	–0.285 (–16.69)	0.317 (6.60)
$\Delta p_{1,t-3}$	–0.074 (–5.07)	0.051 (2.13)	–0.020 (–2.06)	0.052 (2.15)
$\Delta p_{2,t}$	0.843 (117.61)		0.856 (133.51)	
$\Delta p_{2,t-1}$		0.167 (6.27)		
$\Delta p_{2,t-2}$	0.159 (9.90)	–0.243 (–5.10)	0.205 (12.21)	–0.273 (–5.93)
$\Delta p_{2,t-3}$	0.013 (1.01)		–0.021 (–9.42)	
$\hat{\tau}, \hat{\gamma}$	–0.0514	+0.0471	–0.0318	–0.0448

Notes: Model_1 (OPEC_TAR_AIC, GED), Model_2 (non-OPEC_TAR_AIC, Gaussian), Model_3 (OPEC_MTAR_TSIG, GED) and Model_4 (non-OPEC_MTAR_TSIG, GED). Using VAR lag selection criteria, we find that the optimal lag is three following the sequential modified LR statistic test, the final prediction error and the AIC. The z-statistic is in parentheses. For the modeling details, see Appendix A.1.2: ECM-TAR-CGARCH.

Table 4b
Variance equation CGARCH applied to OPEC and non-OPEC prices 1973.10–2013.01.

Variance equation	OPEC Model_1	Non-OPEC Model_2	OPEC Model_3	Non-OPEC Model_4
1_{ω_0}	0.0056 (0.47)	0.0011 (3.04)	0.0052 (0.43)	0.0013 (1.43)
$(e_{t-1}^2 - q_{t-1})_{\alpha}$	0.056 (1.42)	0.074 (2.19)	0.094 (1.05)	0.076 (1.81)
$(\sigma_{t-1}^2 - q_{t-1})_{\beta}$	–0.968 (–38.13)	–0.832 (–12.09)	–0.822 (–3.09)	–0.838 (–8.26)
$(q_{t-1} - \omega_0)_{\rho}$	0.970 (13.27)	0.943 (37.18)	0.959 (8.25)	0.969 (37.89)
$(e_{t-1}^2 - \sigma_{t-1}^2)_{\phi}$	0.187 (1.70)	0.168 (3.88)	0.220 (1.29)	0.161 (3.10)
AIC	–4.028	–4.098	–4.031	–4.207
SSR	0.035	0.034	0.034	0.032
ll	955.58	971.89	934.15	985.90
LM-ARCH Test	0.733 (1)	0.931 (1)	0.928 (1)	0.967 (1)
Ljung-Box Test	10.63 [0.56]	17.52 [0.13]	16.37 [0.18]	18.67 [0.13]
Wald Test for $\rho = 1$	0.1646 [0.68]	4.9801 [0.03]	0.1263 [0.72]	1.3747 [0.24]

Notes: The z-statistics are in parentheses. The LM-ARCH statistic tests of no ARCH effects in the residuals of the estimated equation; the number of lags is in parentheses. The Ljung-Box statistic tests whether there are no serial correlations in the residuals. The Wald test is run to test the unit value of the persistence parameter ρ using the χ^2 statistic. The p-values are in brackets.

persistent at 60.3%. By using the T-significance criterion, the results indicate that, even after one year, the shocks to OPEC oil prices persist at 41.7%, i.e., 0.9298¹², whereas for non-OPEC oil prices, they are more persistent at 74.8%.

The permanent component coefficients are well-defined for all variants of the ECM-TAR (MTAR)-CGARCH, i.e., models 1–4 (Tables 4a and 4b), implying the slow convergence of long-run volatilities to their mean levels, which explains the long-run stability of the underlying process. By contrast, given that the sum of the transitory component parameters through $(\alpha + \beta)$ is negative for both crude oil prices, there is no half-life defined for either the OPEC or non-OPEC oil prices. This result is due to the high short-run volatility in the transitory variance. Short-term oil price volatilities of reflect a transitory supply surplus and a sudden shift in the inelastic oil demand curve [1,19]. However, the long-run variability signals the overall regulation within the oil market through the stock of remaining proven crude oil reserves.¹³ Additionally, the long-run variation depends on real economic growth particularly in the advanced and emerging economies of the world.

A negative (positive) sign of ect_{t-1} signals an upward (downward) adjustment of the price starting from the next period and from the deviations around the long-run equilibrium [26]. A small (high) value of the long-run coefficient μ_t , which is associated with

OPEC prices (non-OPEC prices), indicates that the error correction term of the oil price process identifies a slight (sizable) speed of adjustment in the monthly disequilibrium correction to reach the long-run equilibrium, following its degree of dependency from non-OPEC prices (OPEC prices), with respect to the long-run relationship between OPEC and non-OPEC prices. The adjustment of the OPEC price process in relation to the positive (negative) discrepancies, i.e., after an external upward (downward) shock from hybrid events, in the long-run equilibrium shows the appropriate negative sign, and the slow adjustment indicates that the OPEC organization does not prefer moderate oil prices.¹⁴ By contrast, a rapid adjustment of the non-OPEC price process in relation to the positive (negative) discrepancies in the long-run equilibrium signifies a preference for moderate oil prices after they increase (decrease). This speed difference in the adjustment process between the OPEC and non-OPEC price processes is evidence of competitive behavior between OPEC and non-OPEC countries, where the OPEC countries appear to be a pseudo-leader in the crude oil market.¹⁵

¹⁴ This slowness or sticky oil price is partially due to the adjustment costs because OPEC producers adjust their crude oil production and storage. Other features of this stickiness can be explained by the market power of OPEC. This phenomenon is already indicated by Borenstein and Shepard [46] through the analysis of crude oil price shocks on the wholesale gasoline prices.

¹⁵ The US supply of light, sweet crude continues to outpace that of medium and heavy crude through 2015 and reduce the share markets of Russia and OPEC producers. According to the EIA (2015) approximately 90% of the growth of 3.0 million barrels per day in US production from 2011 to 2014 consisted of the light sweet type of oil. <http://www.eia.gov/todayinenergy/detail.cfm?id=21512>.

¹³ The proven crude oil reserves have increased remarkably from 700 billion barrels in 1980 to 1.7001 trillion barrels at the end of 2014 [45]. From such data and during the last decade, there is no geological reason that the prices of crude oil reach high and low record levels.

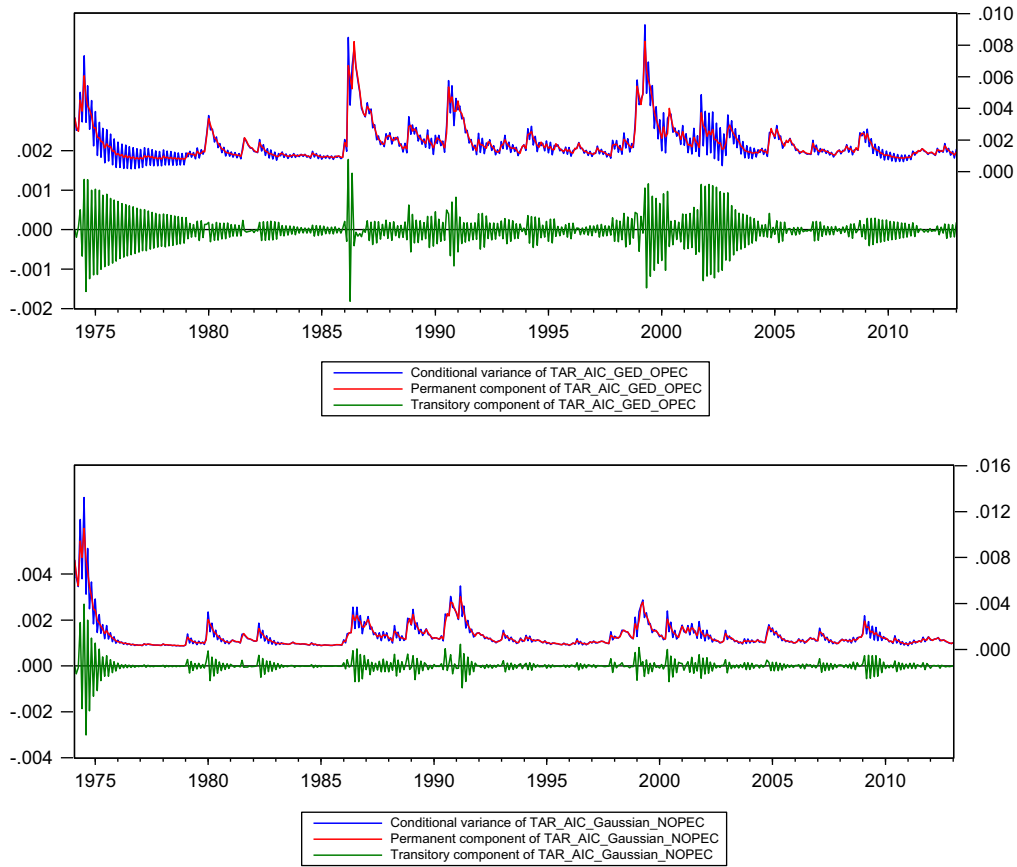


Fig. 1a. Conditional and permanent CGARCH-TAR of OPEC and non-OPEC prices.

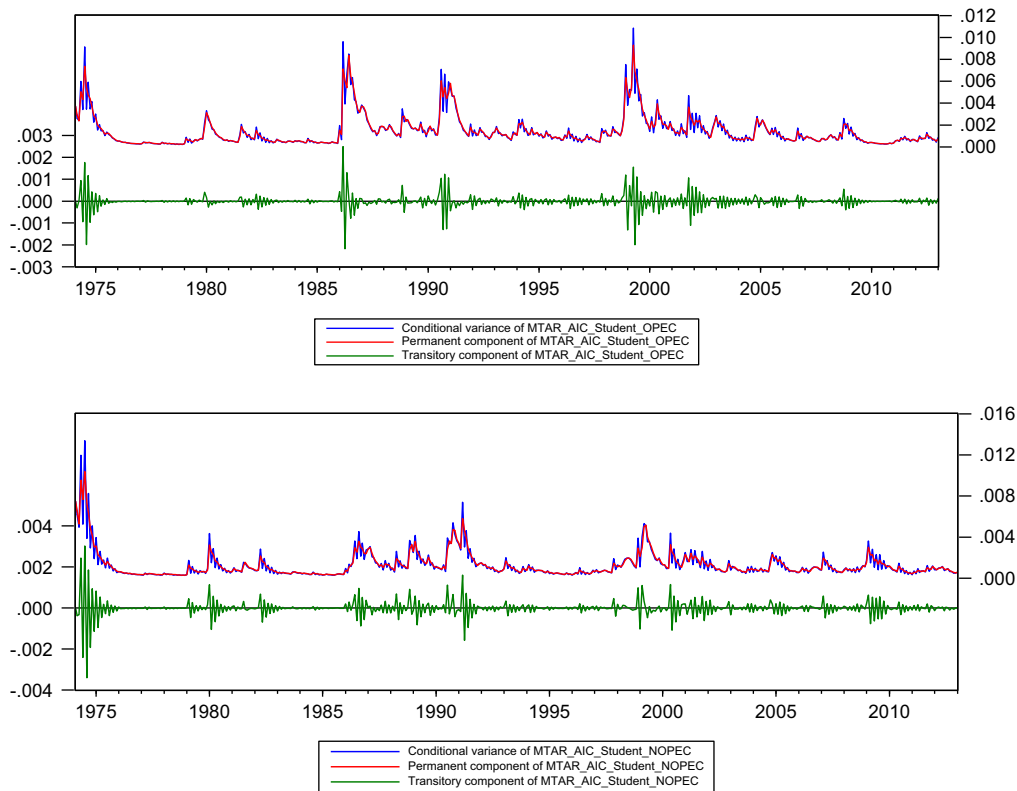


Fig. 1b. Conditional and permanent CGARCH-MTAR of OPEC and non-OPEC prices.

OPEC producers could not drive crude oil prices down (up) for all participants in the market. The market participants, assuming the OPEC actions, caused the price fluctuations [14,46]. However, our results show that non-OPEC countries do not strictly follow the OPEC strategies. The asymmetric adjustment provides evidence that the market participants sometimes misuse their market power in determining oil prices, in the sense that OPEC or to a lesser extent non-OPEC countries can influence oil prices by managing production quotas [48].

Describing the non-linear features of monthly oil price, the asymmetric adjustment means that hybrid events can impact the oil market environment turning into an open competitive behavior that influences the conditional variance [49]. Hybrid events depend on the factors behind the decreasing or increasing oil price process, and they are related to positive and negative discrepancies. These deviations work in the short and long-term and drive the movement of oil price. In the long-run, the deviations may occur based on fundamental factors mostly related to real macroeconomic variables [50] such as changes in crude oil inventories and oil demand due to the economic recovery (or crisis). They also come from non-fundamental factors particularly connected to speculation in oil futures markets [20,24], financial market risks [22], the US dollar exchange rate [23,50], and geopolitical or military conflicts [52].

The Wald test for the null hypothesis $\rho = 1$ shows that the unit root is rejected only for model 2, and accepted for models 1, 3, and 4 (Table 4b). For non-OPEC prices only, the conditional variance σ_t^2 mean-reverts to a long-run trend level q_t , with the speed determined by ρ . The CGARCH process is covariance stationary when conditional variance is stationary, then both the permanent and transitory components must be covariance stationary, which necessitates that $\alpha + \beta < 1$ and $\rho < 1$ [53]. Consequently, the permanent component q_t has a long memory, whereas the transitory component has a short memory [54,54]. However, in all other models, the volatility of a long-run process is $I(1)$, i.e., $\rho = 1$; thus conditional variance contains a unit root, and the persistence of shocks is infinite; also, unconditional variance does not exist i.e., there is no mean reversion, but a shock remains through conditional variance and impacts future volatility over an infinite horizon [56]. The LM-Arch and Ljung-Box tests reject the null hypotheses of the ARCH effect and the autocorrelation in the residuals (Table 4b). Thus, we should have correct estimates of the standards errors validating the statistical tests.

From TAR-models 1 and 2, the point estimates for ect_{t-1}^- , i.e., crude oil price undervaluation, are somewhat high, between -0.15 and -0.53 , suggesting that deviations between an increase in the long-run and reasonable crude oil prices are eliminated somewhat quickly. Also, from TAR-models 1 and 2, the point estimates for ect_{t-1}^+ , i.e., crude oil price overvaluation, are between -0.19 and -0.55 , indicating that an increase and a decrease in the long-run around the crude oil price equilibrium level have comparable magnitudes. The negative or positive level-discrepancies of OPEC prices from the long-run equilibrium are eliminated less quickly in comparison to non-OPEC prices. These results confirm that OPEC sets moderate oil prices and is less sensible to both the overvaluation and the undervaluation of crude oil prices compared to non-OPEC producers.

In contrast, from the MTAR-models 3 and 4 related to a margin behavior, the point estimates for ect_{t-1}^- are on the intermediate side, between -0.354 and -0.357 , and lead to the quasi-same marginal reactions of OPEC and non-OPEC countries. These findings suggest that the negative difference-discrepancies of the crude oil prices from the long-run equilibrium are corrected at moderate rates with quasi-similar magnitudes for both OPEC and non-OPEC countries to preserve their income from the international market.

But, the point estimates for ect_{t-1}^+ indicate that the positive difference-discrepancies of non-OPEC prices from the long-run equilibrium are quickly corrected at medium rates in comparison to OPEC prices. These results prove that OPEC sets moderate oil prices and is more sensible to the undervaluation than to the overvaluation of crude oil prices. It appears that both OPEC and non-OPEC countries have to learn more about the declining trend in oil prices. More importantly, the quick adjustments of non-OPEC prices to the long-run equilibrium appear to have a stabilizing effect and be less inflationist. In these cases, asymmetry is largely driven by a medium response to negative shocks, particularly from non-OPEC countries.

The negative discrepancies, with TAR or MTAR adjustments, are related to many factors, such as positive changes in crude oil inventories, economic recession, excess oil supply, decreasing oil demand, decreasing US dollar exchange rate, financial crisis, geopolitical and military conflicts, and shifting international sanctions. From the MTAR adjustment, such negative deviations are partially and moderately corrected with a similar magnitude by both OPEC and non-OPEC countries, which means that both OPEC and non-OPEC countries do not welcome a decreasing oil price tendency.

By contrast, the positive deviations could occur from negative changes in crude oil inventories, economic growth, decreasing oil supply, excess oil demand, increasing US dollar exchange rate, financial stability, geopolitical and military reconciliation, and international sanctions. From the TAR adjustment, such positive deviations are partially and fairly more corrected by non-OPEC countries than by OPEC countries; which mean that OPEC does not favor a moderate oil price tendency.

Overall, OPEC appears to have less aversion behavior to long-run changes in the crude oil price than the non-OPEC producers. The crude oil prices of non-OPEC countries would adjust upward at a quick rate to correct the imbalance with OPEC crude oil prices compared to OPEC prices if they were to adjust upward correcting the imbalance. The subdued adjustment of positive discrepancies to the long-run equilibrium may occur because OPEC countries want to control the high prices of oil, especially through the adjustment of negative discrepancies, and attempt to sporadically retain oil prices around an equilibrium level. Non-OPEC countries also provide visible support in this respect mostly through the adjustment of positive discrepancies. In the short-run, there is evidence of a causal flow of changes of contemporary oil prices from non-OPEC to OPEC countries and vice versa, with many discernible feedback relationships. The OPEC quota agreements contribute to this short-run price fluctuation. In particular, the \mathcal{F} -statistics corresponding to causality reveal that the price of each group, OPEC or non-OPEC producers, affect the movements in the other group's current price rate. It appears that the contemporaneous short-run variation of OPEC prices has a greater effect than the corresponding variation of non-OPEC prices. This result explains in the short-run that non-OPEC countries play a slightly more important role than OPEC countries for determining the crude oil prices in the international market.

4. Conclusions

We have examined the dynamics of OPEC and non-OPEC oil prices within an original TAR-Error Correction-CGARCH model, leading to a parsimonious representation of some stylized features for the period January 1973–April 2013. The results show that for both OPEC and non-OPEC producers, price shocks tend to be both persistent and volatile, indicating that there is a long memory in the volatility of international crude oil prices. Also, due to the high short-run volatility in the transitory variance, there is no half-life

defined for either OPEC or non-OPEC oil prices. More concretely, our findings suggest that the OPEC prices adjustment process in relation to the positive deviations from the long-run equilibrium is slow, implying that OPEC producers do not prefer moderate oil prices. However, the reverse holds for non-OPEC producers, which prefer rapid adjustment when oil prices are too high. These differences in speed between OPEC and non-OPEC price adjustments imply that there is evidence of a quasi-competitive behavior and different profit and pricing strategies between OPEC and non-OPEC countries. OPEC producers do not drive crude oil market prices up or down; to some extent, market traders and speculators assuming OPEC actions can cause oil price volatilities. The results also show that non-OPEC countries do not strictly follow OPEC strategies, except in the MTAR model with a negative error correction term. This exception means that both OPEC and non-OPEC producers react similarly to negative discrepancies when oil prices are too low.

Despite some differences in crude oil costs between OPEC and non-OPEC countries, threshold cointegration proves that there are small differences in crude oil prices. If OPEC appears to be well-integrated, then the crude oil market is a quasi-integrated market with a fringe competitive. Future market stability is related to the extent to which there is real collaboration between non-OPEC and OPEC countries in the international market. Non-OPEC countries may have a greater role in terms of a continuous increase in their supply and OPEC members must address a more reasonable price due to their increased spare capacity, mainly held by Saudi Arabia. In the future paper, we will extend the ECM-TAR (MTAR)-CGARCH model to capture leverage effects by adding the asymmetry parameters in the dynamic volatility. We expect to explore the asymmetric volatility effects on the permanent and transitory components and to detect whether dynamic volatility will be more amplified.

Due to the excessive volatilities during the last decade, there has been an emergency for policy makers in regard to how to reduce the economic impacts of the extreme price volatility from real market distortions or speculative trading. In addition, the main OPEC and non-OPEC producers have to develop a new organizational alternative to OPEC to face any expected positive or negative bubbles in the oil market and to diversify the pricing system to allow reasonable prices with respect to the quality, timing, and location of oil.

The economic growth of developed countries should be more accurately monitored by oil producers to avoid sudden shocks driven by the demand of oil. In parallel, technological, geopolitical, economic, and marketing challenges in oil markets will require massive investments by oil producers and a flexible regulation of the incremental production. To face the expected demand in the future, oil producers, and mainly OPEC must invest more in the petroleum sector. By preventing other spikes in crude oil prices, OPEC projects realizing massive investments of \$400 billion per year over the next 25 years, i.e., \$10 trillion from 2015 to 2040 ([57] World Oil Outlook, page 42). However, the excessively low price level does not support the expected oil investment perspective.

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Appendix A

A.1. Methodology

A.1.1. Threshold cointegration

Preliminarily, the two-step method by Engle and Granger [35] is employed to test cointegration between p_1 and p_2 the logged OPEC

and non-OPEC oil prices, respectively. By estimating the long-run relationship $p_{1t} = \alpha + \beta p_{2t} + \varepsilon_t$, we obtain the residuals $\hat{\varepsilon}_t$. Enders and Siklos [26] argue that the test for cointegration and its extensions are mis-specified if the adjustment is asymmetric. They propose the following asymmetric adjustment, known as the threshold autoregressive (TAR) model: $\Delta \hat{\varepsilon}_t = \rho_1 I_t \hat{\varepsilon}_{t-1} + \rho_2 (1 - I_t) \hat{\varepsilon}_{t-1} + u_t$, where ρ_1 and ρ_2 are the speed-adjustment coefficients and I_t is the indicator function, which is defined as the following: $I_t = 1$ if $\hat{\varepsilon}_{t-1} \geq \tau$ and $I_t = 0$ if $\hat{\varepsilon}_{t-1} < \tau$. The parameter ρ_1 means adjustments from below the threshold τ (widening), because the residual is greater than the threshold. The opposite holds true for ρ_2 , meaning that the adjustment is from above the threshold. They also suggest an alternative to the indicator function through the momentum TAR (MTAR), defined as the following: $I_t = 1$ if $\Delta \hat{\varepsilon}_{t-1} \geq \gamma$ and $I_t = 0$ if $\Delta \hat{\varepsilon}_{t-1} < \gamma$. According to Enders and Siklos [26], it is not necessary for the threshold to coincide with the attractor. Thus, the appropriate estimate of τ gives the lowest residual sum of the squares. If the system is convergent, then the long-run equilibrium value of the sequence is given by τ which can be 0. The sufficient conditions for the stationarity of $\hat{\varepsilon}_t$ are $\rho_1 < 0$, $\rho_2 < 0$ and $(1 + \rho_1)(1 + \rho_2) < 1$ [58]. In such a case, if $\hat{\varepsilon}_{t-1}$ is above its threshold value τ , then the adjustment is at the rate ρ_1 , and if $\hat{\varepsilon}_{t-1}$ is below τ , then the adjustment is at the rate ρ_2 . This adjustment will be symmetric if $\rho_1 = \rho_2$. However, if the null hypothesis $H_0: \rho_1 = \rho_2$ is rejected, then by using the TAR model, we can obtain the signs of asymmetry. As demonstrated by Sichel [43], a negative “deepness” i.e., $|\rho_1| < |\rho_2|$ of $\hat{\varepsilon}_t$ implies that increases tend to persist, whereas decreases tend to revert quickly toward equilibrium. For example if $-1 < \rho_1 < \rho_2 < 0$, then the negative phase of the $\hat{\varepsilon}_t$ series will tend to be more persistent than the positive phase. A searching method for a consistent estimate of the threshold was adopted by using a method proposed by Chan [44]. Besides, the MTAR model can be used to obtain different types of asymmetry. For instance, if $|\rho_1| < |\rho_2|$, then the MTAR exhibits little adjustment for positive $\Delta \hat{\varepsilon}_{t-1}$, but substantial decay for negative $\Delta \hat{\varepsilon}_{t-1}$. In other words, increases tend to persist, but decreases tend to revert quickly back to the attractor irrespective of where disequilibrium is relative to the attractor. The threshold is also estimated using Chan’s methodology.

By implementing the TAR and MTAR adjustments and defining the ϕ -statistic for the null hypothesis of non-stationarity of $\hat{\varepsilon}_t$, i.e., under $H_0: \rho_1 = \rho_2 = 0$, $\{\hat{\varepsilon}_t\}$ has a unit root, the value of ϕ -statistic is compared to the critical values computed by Enders and Siklos [26]. If we reject the null hypothesis, it is possible to test for asymmetric adjustment because ρ_1 and ρ_2 converge to a multivariate normal distribution [59]. The \mathcal{F} -statistic is used to test for the null hypothesis of symmetric adjustment $H_0: \rho_1 = \rho_2$.

A.1.2. ECM-TAR-CGARCH

The estimation of the following error correction model with a threshold adjustment is justified by the existence of a threshold cointegration:

$$\Delta p_{1t} = c_0 + \mu_1 \text{ect}_{t-1}^+ + \mu_2 \text{ect}_{t-1}^- + \sum_{i=1}^p \beta_i \Delta p_{1t-i} + \sum_{j=0}^q \beta_j \Delta p_{2t-j} + v_t \quad (1)$$

where the variables $\text{ect}_{t-1}^+ = I_t \hat{\varepsilon}_{t-1}$ and $\text{ect}_{t-1}^- = (1 - I_t) \hat{\varepsilon}_{t-1}$ are the error correction terms, defined based on the TAR and MTAR indicator functions I_t . The coefficient μ_i signifies the rate of convergence from gravitation-back toward the long-run equilibrium path. Given that the variable ect_{t-1}^- means an undervaluation of crude oil prices; we expect that the sign of the parameter μ_1 will be negative, therefore leading to a downward adjustment. The variable ect_{t-1}^+ indicates an overvaluation; we expect that μ_2 will be negative, which

drives to an upward adjustment converging to the long-run equilibrium. If the convergence condition is confirmed, we have $0 < |\mu_i| < 1$, driving to an upward or downward adjustment. The error term v_t is assumed to follow the specific component GARCH (CGARCH) errors distribution, used particularly in financial applications [55]; its structure is determined by the following equations:

$$v_t = \sqrt{\sigma_t^2} \xi_t = \sqrt{q_t + s_t} \xi_t \quad v_t | \Omega_{t-1} \sim \text{i.i.d.}(0; \sigma_t) \text{ and } \xi_t \sim \text{i.i.d.}(0; 1) \tag{2}$$

$$\sigma_t^2 - q_t \equiv s_t = \alpha(\varepsilon_{t-1}^2 - q_{t-1}) + \beta(\sigma_{t-1}^2 - q_{t-1}) \tag{3}$$

$$q_t = \omega_0 + \rho(q_{t-1} - \omega_0) + \varphi(\varepsilon_{t-1}^2 - \sigma_{t-1}^2) \tag{4}$$

Eq. (3) of the conditional variance σ_t^2 reveals the long-run component q_t and the short-run component ($\sigma_t^2 - q_t$). This transitory component s_t includes the deviations around the long-run component. Engle and Lee [53] point out that the CGARCH process, defined in

separated Eqs. (3) and (4), is weakly stationary if $\rho < 1$ and $\alpha + \beta < 1$. By combining the transitory and permanent equations, the model is reduced to a non-linearly restricted CGARCH (2, 2).

The CGARCH model captures the volatility persistence of the transitory and permanent dynamics. The long-run trend of the conditional variance shows the idea of time-varying long run volatility. The parameter ρ corresponds to the decay rate and determines the speed of the mean reversion, which assumes that the high and lower crude oil prices are temporary. Therefore, it is expected that the high and lower deviations, due to different shocks to the prices, will go back to an average price. The conditional variance shows the long-run mean reversion to a constant level, given by the unconditional variance ω_0 . The volatility prediction error ($\varepsilon_{t-1}^2 - \sigma_{t-1}^2$) has a zero-mean and is serially uncorrelated; it drives the dynamics of the permanent component [27]. The power of the shocks to the permanent component is defined by the first-order parameter φ . The shocks to the transitory component revert to the trend q_t , whereas in the GARCH model, the shocks decay to the unconditional variance $\omega_0 \equiv \sigma^2$. The strength

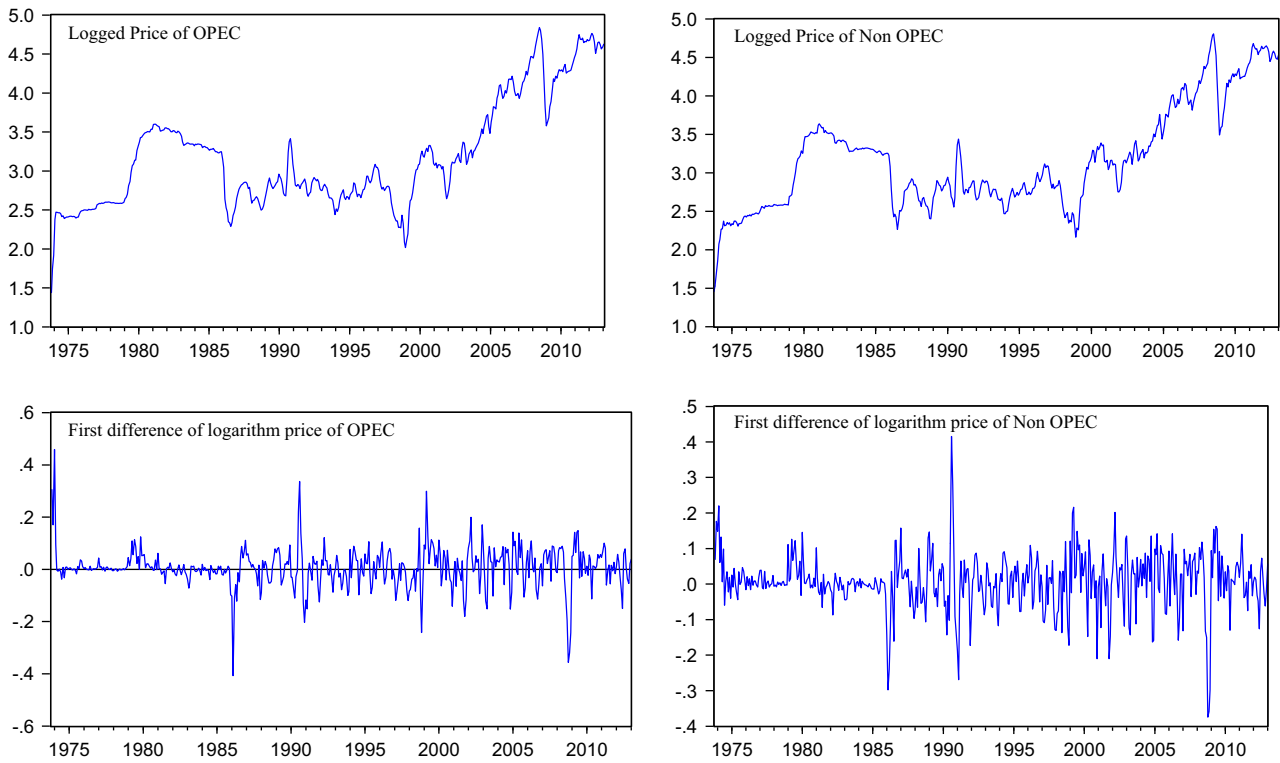


Fig. A1. Level and first difference of logarithm of OPEC and non-OPEC crude oil prices.

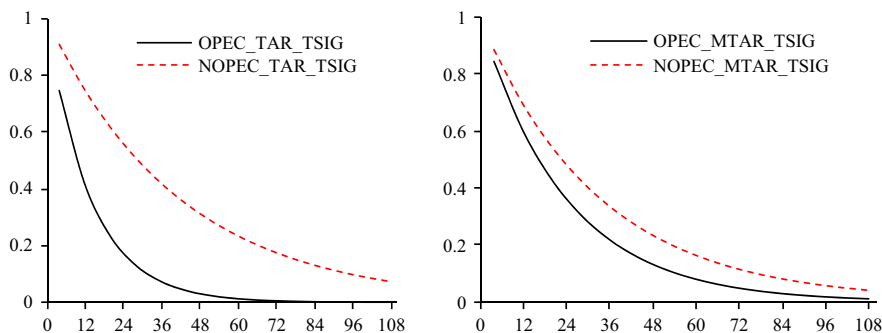


Fig. A2. ρ -GED Persistence shocks over month's horizon on OPEC and non-OPEC prices.

of the shocks to the transitory component is defined by the first-order parameter α . The permanent process q_t has a memory close to the unit root when ρ is close to 1. If $(\alpha + \beta) < 1$, then the transitory mean-reverting process s_t has a more rapid time decay, governed by $(\alpha + \beta)$. If $\rho < 1$, then the conditional variance σ_t^2 mean-reverts to a long-run trend level q_t at speed ρ . It is assumed that when $0 < \alpha + \beta < \rho < 1$, the permanent component is more persistent than the transitory component. The persistence in the transitory component is lower than the persistence in the permanent component, because $(\alpha + \beta) < \rho$. Consequently, the permanent component q_t has a long memory, whereas the transitory component has a short memory. The volatility persistence of transitory large shocks is shorter than shocks due to habitual news and events, but it remains the case that large shocks may have a permanent impact. However, with the CGARCH structure, the parameters do not have all non-negative signs. The transitory component may be negative, suggesting that shocks impact volatility during the convergence of the long-run trend.

A.2. Figures

See Figs. A1 and A2.

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