A Dynamic Network Analysis of the World Oil Market: Analysis of OPEC and Non-OPEC Members

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Abstract

We characterize the dynamic network structure of major oil producing countries. We examine the oil production coordination of 13 Organization of the Petroleum Exporting Countries (OPEC) and 17 non-OPEC members. We construct the dynamic network structure using the network connectedness measure of Diebold and Yilmaz (2009). We investigate the structural changes in connectedness of OPEC and non-OPEC members. Additionally, we study how the influence of OPEC members, non-OPEC countries and major oil producers evolves over time. We find that the network structure of major oil-producing countries changes significantly over time. Specifically, the impact of changes in oil-production of all OPEC members on global oil production declines, whereas the impact of non-OPEC on global oil production increases. OPEC's "increase" decisions have a significant and positive impact on OPEC and non-OPEC coordination but "cut" decisions does not affect coordination. We find that OPEC countries and developing countries have significantly higher levels of connectedness. Additionally, countries with high oil production levels have significantly more influence. The empirical results provide intuition about the recent developments in global oil production.

Keywords: Global Oil Production, Coordination, Networks, OPEC
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"Russia and other oil producers agreed on Saturday to join OPEC nations in a rare, ***coordinated*** reduction in oil output meant to lift petroleum prices and revenues to shore up their sagging government budgets." **New York Times, December 11, 2016**

1 Introduction

Fluctuations in oil prices have caused oil-producing countries to design policies to control the global oil production and increase oil prices. The Organization of the Petroleum Exporting Countries (OPEC) regularly takes action to coordinate its members' oil production decisions and influence oil prices. As stated by Loutia et al. (2016), "The impact of OPEC decisions about the production level (increase, cut or maintain) on oil prices is a controversial issue among policymakers, regulators, and academics in particular." (page 262) To be able to affect oil prices, the OPEC and non-OPEC should have high levels of oil production coordination. In this paper, we gauge the time-varying oil production coordination of 30 major oil-producing countries: 13 OPEC and 17 non-OPEC.[1] To that end, we calculate the dynamic interaction between these countries and construct the network structure.

We quantify the dynamic network structure of these countries by calculating the time-varying interdependence of oil production levels. Specifically, we implement the network econometrics methodology of Diebold and Yilmaz (2009) (DY) and calculate the time-varying "connectedness" measure for each country. The connectedness measure, $C_{a \leftarrow b}$, provides us the direction and magnitude of the effect each country in the oil production network. For example, we can measure the monthly effect of a change in the oil production of Saudi Arabia

[1]We present the country list in the appendix.

on Russian oil production ($C_{Russia \leftarrow SArabia}$) and vice versa ($C_{SArabia \leftarrow Russia}$). Connectedness provides information about the relative importance of each country in affecting oil production of other countries. When two countries, a and b, take coordinated oil production actions, country a takes into account the change in the oil production of country b. Similarly, oil production of country b will be significantly affected by the change in oil production of country a. Therefore, the connectedness measures of countries a and b ($C_{a \leftarrow b}$, $C_{b \leftarrow a}$) which gauge their level of influence in the oil-production network will be high. Consequently, countries with high levels of coordination will have high connectedness levels. We calculate monthly "connectedness" measures for all country pairs and gauge the change in the influence of a specific country on OPEC and non-OPEC members over time.

Using the connectedness measure, we construct the network structure of oil-producing countries and study the following research questions:

- **What is the coordination level of oil-producing countries (network structure)? Does the network structure change over time?**

We construct the dynamic network structure of oil-producing countries using the connectedness measure. The connectedness measure is calculated monthly. Thus, we can gauge the structural changes in the impact of each country on others. This allows us to examine the network dynamics. We conduct structural break analysis to investigate whether the network structure changes over time and determine the exact structural change dates. We find that the network structure varies significantly over time. Specifically, the impact of changes in oil-production of all OPEC members on global oil production declines, whereas the impact of non-OPEC on global oil production increases.

- **Are OPEC countries more coordinated compared to non-OPEC countries?**

We find that until 2012, the oil production coordination of OPEC and non-OPEC was similar. After 2012, the total coordination level of OPEC decreased substantially. The monthly average connectedness of OPEC decreased from 40.48% in 2012 to 33.14%. The coordination level of non-OPEC did not change significantly during the 2002-2016 period.

- **What is the effect of changes in oil production of OPEC members on non-OPEC oil production?**

Changes in OPEC oil production have significant effects on non-OPEC oil production. The effect is the highest during the August 2010-November 2012 period, with a monthly average connectedness level of 37.18%. Structural break tests confirm that the average connectedness measure is significantly higher in this time period. However, the impact of OPEC on non-OPEC oil production decreased significantly after 2012. The directional connectedness of the effect of non-OPEC on non-OPEC is 46.57% after May 2013. For the same time period, the directional connectedness of the effect of OPEC on non-OPEC is 33.27%.

- **How influential are major countries in the global oil production network? Does their network strength change over time?**

We specifically examine the network strength of Russia, Saudi Arabia and the

Unites States. As stated by the US Energy Information Administration (EIA)[2], these are the largest oil producers.[3] We find that the influence of Russian and US oil production on both OPEC and non-OPEC increases over time. Currently, the effect of Russia on OPEC and non-OPEC is 4.4% and 5.9%, respectively. The average effect of changes in US oil production on OPEC oil production is 3.78%. The effect of the US on non-OPEC is 3.11%. In contrast, the effect of Saudi Arabia is declining significantly. In the 2005-2007 period, the average network strength of Saudi Arabia was 7.66%. Recently, the total effect of Saudi Arabia on the oil production of other OPEC members was 2.63% the and effect of Saudi Arabia on non-OPEC oil production was 2.13%. We conduct structural break tests to identify the dates with significant changes in network strength of these major oil-producing countries. These results suggest that dramatic increases in US shale oil and Russian oil productions have significantly affected the strength of Saudi Arabia in the oil production network.

- **Do OPEC oil production decisions affect the coordination level of OPEC and non-OPEC oil production?**

We construct a data set of OPEC oil production decisions and examine the effect of such decisions on the coordination level of OPEC and non-OPEC. In other words, we investigate whether OPEC manages to coordinate their oil production. We conduct an event-study analysis to examine the effects of the "cut" and "increase" decisions taken at OPEC meetings. We conclude that cut decisions do not have any effect on OPEC and non-OPEC coordination. Therefore, oil-

[2]Statistics are available at https://www.eia.gov/beta/international/rankings/#?prodact=53-1&cy=2016.

[3]In 2016, the US produced 14.9 million barrels per day whereas Saudi Arabia and Russia produced 12.4 and 11.2 million barrels per day respectively. Fourth largest producer is China with a production of 4868 thousand barrels per day.

producing countries do not act in line with the cut decisions. Increase decisions have a significant and positive impact on OPEC and non-OPEC coordination. OPEC and non-OPEC countries increase their oil production coordination level and act inline with increase decisions.

- **What are determinants of connectedness?**

We conduct a panel regression analysis to examine the factors that affect the level of coordination among two oil producing countries. We examine the impact of country characteristics on connectedness. Being a OPEC member is one of the major determinants among many economic and structural factors. The level of connectedness among OPEC members are significantly higher compared to non-OPEC oil producing countries. Oil production of an OPEC country is mostly affected by changes in oil production of other OPEC countries. Furthermore, we find that countries with higher levels of oil production have significantly more network power to affect the production of other countries.

To sum up, we implement a novel methodology to construct the dynamic network of oil-producing countries. We define the strength of an individual country in the network by measuring the effect of significant changes in oil production levels of that country on the production of other countries. The dynamic network structure allows us to examine how the network strengths of individual countries evolve over time. We conduct structural break tests to determine the dates of significant changes in network dynamics. Finally, we contribute to the literature by examining the effectiveness of OPEC by studying the effect of OPEC decisions on coordination level of OPEC and non-OPEC.

The paper is organized as follows: Section 2 provides an overview of OPEC. We review the literature and state the contribution of the paper in Section 3. Section 4 describes the data and methodology. Section 5 constructs the dynamic network structure and investigates the network strength of OPEC and non-OPEC countries. Section 6 conducts an event-study analysis of the effect of OPEC decisions on the oil-production network. Section 7 implements a panel regression analysis to examine the determinants of connectedness and Section 7 concludes the paper.

2 Overview of OPEC

The OPEC was established in Baghdad in 1960. The founding members were Iraq, Iran, Kuwait, Saudi Arabia and Venezuela. Later on, the following members joined the organization: Qatar, Indonesia, Libya, United Arab Emirates (UAE), Algeria, Nigeria, Ecuador, Angola, Gabon and Equatorial Guinea. OPEC aims at coordinating and harmonizing the petroleum policies of oil-exporting countries in order to ensure fair and stable prices for producers and adequate return on oil investments (OPEC: Brief History).

OPEC produces around 43% of the world's total crude oil and more than 20% of the world's natural gas. OPEC possesses approximately 80% of the world's crude oil reserves and 48% of the world's natural gas reserves. In 2015, OPEC produced around 38.2 million barrels of crude oil, out of which Saudi Arabia, the largest producer within OPEC, contributed 12 mb/d. Most of OPEC production is exported to the Asian-Pacific region, while the US imports around 34% of its total oil imports from OPEC members. The OPEC References Basket (ORB) plays an important role in oil pricing. The basket consists of 12 oil blends from member states (OPEC - Statistics & Facts). In 2016, the EIA estimated that OPEC members received about $433 billion in net oil exports revenues, compared to $509 billion in 2015, a decline ascribed to lower oil prices and, to a lesser extent, decrease in OPEC exports (OPEC net oil export revenues).

Since the 1970s, OPEC has gained power by the virtue of its size, controlling around 50% of the global crude oil production. Therefore, it was in a position to influence prices through manipulation of production. Fattouh (2007) argues that the OPEC pricing power is not unconstrained, with its ability to influence oil prices varying according to market conditions. Moreover, he found that OPEC's influence is affected by geographic location, for example, where member states develop reserves and gain larger market share. However, some empirical investigations show that OPEC is a price taker and acts as cartel only with a subgroup of its members. Nevertheless, the results indicate that OPEC influence underwent variations over time in tandem with changes in the oil pricing system (Bremond et al., 2012). While some researchers consider OPEC as a textbook model of cartels, others consider it a fringe of non-cooperative producers led by Saudi Arabia. Some structural factors make the coordination of OPEC members difficult, for instance, given individual differences in characteristics, fiscal stance and reserves and the absence of compensation and enforcement mechanisms. These factors are instrumental in determining the scope for coordination (Behar and Ritz, 2016).

Within the network of oil production, some countries assume more prominent roles than others. The Saudi role, for instance, was not undermined by the re-emergence of Russia and Iraq, underpinning factors such as capacity- increasing investments aimed at preserving spare capacity, which is essential for stabilizing the international oil market and maintaining Saudi Arabia's leadership in the oil arena and its role as price maker (Fattouh, 2007). Manescu and Nuno (2015) employed a general equilibrium model of the global oil market, where Saudi Arabia assumes the dominant firm position vis-a-vis other producers who are considered the competitive fringe. As far as the impact of unconventional oil is concerned, the results suggest that the bulk of anticipated rise in US oil supply from the shale revolution has already been absorbed in oil prices. Around the end of 2014, OPEC adopted a new strategy to increase its market share, a step that analysts perceived as an endeavor to drive shale oil producers with high costs out of the market. However, research shows that four factors to rationalize OPEC's new strategy: the US shale oil production growth, slackening international oil demand, decline in OPEC's integration as a cartel, and upsurge of non-OPEC's production (Behar and Ritz, 2016).

Although the non-OPEC states produce around two-thirds of the world's total oil production, they are not as influential as OPEC for reasons such as lack of coordination with market variables in the absence of spare capacity, to make up for short supply, and high production (Khadduri, 2013). Ratti and Vespignani (2015) employ Granger causality to test for the impact the non-OPEC oil production growth on the OPEC oil production growth to find causality during 1974-1996; that is, OPEC production declined with positive shocks in non-OPEC production. However, this is not valid for the period 1997-2012. They also found that between 1997 and 2012, the "cumulative effects of structural shocks to non-OPEC oil production and to real oil price on OPEC oil production are large, and that the cumulative effect of structural shocks to OPEC production and real oil price on non-OPEC production are small."

OPEC and non-OPEC countries started coordination in the late 1980s, with the objective of reducing production. However, this coordination did not reap fruits because of disagreement on quotas, parities, and ceiling. During the 1998-1990 crisis, Mexico and Venezuela conformed with Saudi Arabia, and after the 1999 meeting, which was attended by Algeria and Iran, an agreement was reached to cut production by more than 4 mb/d. Thus, there was a price hike in the same year and years after. The agreement was supported by other OPEC and non-OPEC countries. Another recent example of successful cooperation between OPEC and non-OPEC is the December 2016 agreement led by Saudi Arabia, Russia, Qatar, and Algeria and joined by another 19 countries. The agreement resulted in cutting the production by 1.8 mb/d, and then the first ever joint monitoring system was introduced (Al Muhanna, 2017). The future of oil will be driven by factors such as growth in world population, technology, and renewable energy. By 2040, the world population is expected to increase by 1.7 billion. This increase will be reflected in higher demand for oil. Therefore, fossil fuel will continue to play a prominent role in economic welfare (OPEC Bulletin, 2016). Renewable energy is growing at a very fast pace (7.1% p.a.). Its share in primary energy is forecast to rise from 3% in 2015 to 10% by 2035. China is expected to continue as the largest source of this growth over the next two decades (BP Energy Outlook, 2017).

3 Literature Review and Contribution

A broad literature conducts theoretical and empirical analysis to study the world oil market. We primarily contribute to the empirical literature investigating the time-varying structure of the oil market. Hamilton (2013) singles out five distinct eras when oil prices have witnessed substantial changes, namely, 1859–1899, 1900–1945, 1946–1972, 1973–1996, and 1997 to the present. He names the 1973-1996 era as "The age of OPEC" in connection with the upsurge in oil prices and the influential role of OPEC and the 1997-to the present era as "A new industrial age" in connection with the industrial revolution in many emerging countries including India and China. Lin (2009) confirms these results and determines that the market was heavily influenced by OPEC during the 1973-1990 period. She claims that it became very competitive during 1990-2006. Rati and Vespignani (2015) investigate the real oil pricing behavior and the OPEC and non-OPEC production behavior during those two eras. They find that non-OPEC oil production growth Granger causes the growth in OPEC oil production during "the age of OPEC era". While during the "new industrial age", OPEC oil production upswings meaningfully with a noticeable upsurge in oil prices, the main justification is the increase in global demand supported by industrial growth in many emerging countries.

Barros et al. (2011) focus on the time series behavior of OPEC oil production. They implement a fractional integration model to find that OPEC oil production has a mean reverting persistence behavior with occasional structural breaks. Alkhathlan et al. (2014) focus on Saudi Arabia's behavior. They argue that Saudi Arabia's production behavior significantly varies over time. Specifically, it coordinates production cuts with the rest of OPEC when the oil demand is decreasing, but increases its production when other OPEC members do not coordinate. Alkhathlan et al. (2014) claim that Saudi Arabia takes strategic action considering the coordination level of OPEC and oil market conditions.

Several studies conduct theoretical analysis to investigate the OPEC pricing and production behavior. The seminal paper of Griffin (1985) tests alternative theories of OPEC. Using annual data for 1971-1982, he concludes that the partial market-sharing cartel model cannot be rejected for all countries. Huppmann and Holz (2012) discuss the changes in crude oil market behavior using a game theoretical approach. They present their findings on three important issues: (i) there is no global agreement on the structure of crude oil market, notably with the empirical literature suggesting conflicting outcomes; (ii) the price formation process is partly affected by price indices and liquid spot markets; and (iii) it is difficult to know what motivates each country or oil company. They conclude that OPEC members have been witnessing a decreasing market power since 2008. Hochman and Zilberman (2015) develop a political economy model to describe OPEC pricing behavior. They conclude that political considerations might cause countries to deviate from OPEC decisions. Behar and Ritz (2016) construct an equilibrium model and show that it can be optimal for OPEC to drive up production and induce high-cost producers like shale producers, to exit the market. Fattouh and Mahadeva (2013) compares theoretical models of OPEC and argue that they do not perform well because they do not consider OPEC's varying conduct. Almoguera et al. (2011) estimate a structural model and find that OPEC's oil production can be described as " Cournot competition in the face of a competitive fringe constituted by non-OPEC producers."

A closely related literature examines OPEC's cartel power by analyzing the effect of OPEC decisions on oil prices. Loderer (1985) studies the OPEC meeting decisions during 1974-1983 and provides inconclusive evidence about the effect of OPEC on oil prices. Alhajji and Huettner (2000) study alternative models for OPEC behavior and conclude that OPEC is not a "dominant producer in the world crude oil markets." Kaufmann et al. (2004) revealed that OPEC plays a key role in the determination of oil prices. Moreover, Kaufmann et al. (2008) expose oil prices as an important driver of the production behavior of OPEC members.

Lin and Tamvakis (2010) conduct event-study analysis to investigate the effects of OPEC announcements on oil price returns. They conclude that the cut decisions of OPEC meetings result in positive and significant oil price returns. Bremond et al. (2012) study the Granger causality between oil price and production for OPEC oil production. They divide the 1973-2009 period into 5 sub-periods and conclude that price Granger causes production in all sub-periods after 1982, whereas production Granger causes price only during 1986-1993. Accordingly, they conclude that OPEC members are price takers for most periods and do not have cartel power to influence oil prices. Loutia et al. (2016) conduct event-study analysis to investigate the effect of OPEC production decisions on oil prices. They find that the impact of OPEC's announcements on oil prices is more significant for cut and maintain decisions. Schmidbauer and Rosch (2012) employ GARCH models and conclude that OPEC decisions have a significant impact on oil price volatility and expectations. We provide empirical results that are in line with Lin and Tamvakis (2010). We find that the OPEC network is significantly stronger and takes more coordinated production actions after OPEC cut decisions.

In this paper, we separately investigate OPEC and non-OPEC countries, as is usually the case in the related literature (Rati and Vespignani, 2015). For example, Kolodzeij and Kaufmann (2014) investigate the effects of representing oil supply with the aggregate of OPEC and non-OPEC production. They suggested that this practice could lead to misleading results and policy implications, especially because OPEC and non-OPEC decisions on oil output are based on different criteria (Ramcharran, 2002). Using a quarterly econometric model, Dees et al. (2007) distinguish between non-OPEC and OPEC production behaviors. They indicated that non-OPEC behavior is presumed to be competitive even though subject to geological and institutional constraints, but OPEC production can be modeled in different way including cartel modeling, among others. Further, they stated that non-OPEC oil demand and supply are rather inelastic to changes in price. However, OPEC agreements on oil supply with member countries have a substantial and instantaneous influence on oil prices. Smith (2005) provides an interesting literature review on the possible behavior of OPEC. Moreover, applying a production approach, he found strong evidence of cooperative behavior between OPEC members.

We contribute to the literature summarized above by constructing and analyzing the dynamic network structure of the world oil market. Using the novel methodology of DY, we calculate the level of interaction between the major OPEC and non-OPEC oil producers' production cycles using monthly data. We conduct structural break analysis to determine significant change in the dynamic network structure of world oil production. We examine several research questions on the dynamic effect of OPEC, non-OPEC and major oil producers. These empirical analysis uncover the time-variation in influence of OPEC, non-OPEC, and major oil-producing countries.

4 Data and Methodology

We implement the methodology developed by DY to calculate the connectedness measures of oil-producing countries.[4] This measure provides us the direction and magnitude of the effect of changes in oil production of a country on other countries. DY build the connectedness measure using the variance decomposition matrix of a vector-autoregressive (VAR) model of oil production cycle, S_t. We use the Hodrick-Prescott (1997) (HP) filter as suggested by Ewing and Thompson (2007). The HP filter calculates stationary cyclical deviations from a trend. We construct a VAR model using the monthly cyclical components of oil-production by each country.[5] We obtain the monthly oil-production data from the US EIA website for years 1996-2016.

The $VAR(p)$ model can be presented as

$$S_t = \sum_{i=1}^{p} \Psi_i S_{t-i} + \varepsilon_t, \quad (1)$$

where S_t is the vector of the oil production cycles of 30 major oil pro-

[4]Recently, Awartani at al. (2016) used the connectedness measure to investigate the transmission of volatility from the oil market to US equities, exchange rates and other commodity indices.

[5]We examine the stationarity of production data for each country by employing Augmented Dickey-Fuller and Phillips-Perron unit root test. We display the test results in the new online appendix table OA.1. Both tests conclude that the cyclical components of oil production that we use in the VAR analysis do not have a unit root.

ducers measuring significant deviations from the oil production trend. Ψ_i is the 30×30 companion matrix containing the coefficients. The moving average representation is $x_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i}$. A_i is the recursive form of $A_i = \Psi_1 A_{i-1} + \Psi_2 A_{i-2} + \ldots + \Psi_p A_{i-p}$, where A_0 is the 30×30 identity matrix and $A_i = 0$ for $i > 0$. We estimate a VAR(1) model as selected by the Schwarz criteria.

We follow DY and implement the generalized orthogonalization approach of Koop et al. (1996) and Pesaran and Shin (1998) when estimating the parameters of the VAR,Ψ_i, and calculating variance decompositions. This approach is independent of the ordering of variables and accounts for correlated shocks. Accordingly, variable j's contribution to the H-period-ahead generalized error variance of variable i is

$$d_{ij} = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e_i^{'} A_h \Sigma e_j \right)}{\sum_{h=0}^{H-1} \left(e_i^{'} A_h \Sigma A_h^{'} e_i \right)}, \tag{2}$$

where σ_{jj} is the standard deviation of ε_j , Σ is the covariance matrix of shock vector in the non-orthogonalized VAR, and e_i is the selection vector with i^{th} element unity and zeros elsewhere. d_{ij} is the fraction of the H-step-ahead error variance of i from shocks to j. DY defines the pairwise directional connectedness from j to i using d_{ij}, $C_{i \leftarrow j} = d_{ij}$. For example, the average impact of changes in Saudi Arabia's oil production on non-OPEC oil production,$C_{non-OPEC \leftarrow SArabia} = d_{non-OPEC,SArabia}$, was 5.72% before October 2005, as presented in Table 5. This directional network measure provides both the direction and strength of Saudi Arabian oil production's deviation on non-OPEC oil production. The highest connectedness measure score is 100 since we derive d_{ij} using the variance decomposition matrix. Consequently, DY use the well-established VAR and variance decomposition methodology to construct an eloquent measure to gauge the interconnection between time-series variables.[6] As stated by DY, this approach is intentionally nonstructural. DY (2015) state that "we remain agnostic on *how* connectedness arises; rather, we take it as given and seek to measure it correctly for a wide range of possible underlying structures ... we prefer an approach that achieves much under minimal assumptions, in contrast to an approach that in principle could achieve more, but only under heroic assumptions ..." (page 11)

There are $N^2 - N$ separate pairwise directional connectedness measures. Accordingly, we calculate the total directional connectedness to obtain concise oil production coordination measures. The total connectedness from others to i is

$$C_{i \leftarrow \bullet} = \sum_{\substack{j=1 \\ j \neq i}}^{N} d_{ij}$$

The total connectedness from j to others is

$$C_{\bullet \leftarrow j} = \sum_{\substack{i=1 \\ i \neq j}}^{N} d_{ij}$$

Finally, we calculate the total connectedness, C, to study the total coordination level in the network of 30 major oil producers. We calculate C by taking the average of total connectedness from others, $C_{i \leftarrow \bullet}$.

$$C = \frac{\sum_{i=1}^{N} C_{i \leftarrow \bullet}}{N} \tag{3}$$

Finally, we examine the major oil producers' time-variation in world oil market coordination and network structure. We follow DY and implement a 72-month rolling-window estimation methodology to calculate the connectedness measure, d_{ij}^t, for each month, t. We use the end date of the window as t. Accordingly,

[6] Vector autoregressive models and variance decomposition are regularly used in the literature. Therefore, we do not explain them in detail and refer to excellent description of Hamilton (1994) chapter 11 and Diebold and Yilmaz (2015) chapters 1 and.2.

we obtain the connectedness measure for the June 2002- November 2016 period. After calculating d_{ij}^t, we investigate the structural change in coordination. We determine the structural break dates using the Bai and Perron (1998) (BP) methodology in the regression setting

$$C_t = \beta_1 constant + \nu_t \tag{4}$$

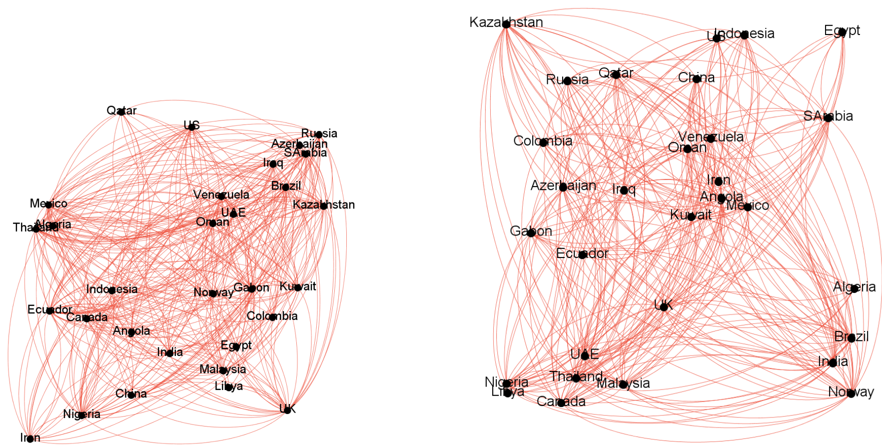
β_1 is the mean of C_t. Structural changes in β_1 measure the differences in the mean of total connectedness, C_t, over time. v_t is the error term. We determine the structural break dates of β_1 using BP to avoid the endogeneity problem pointed out by Hansen (1992).[7] A common criticism of empirical structural change analysis is the possible endogeneity of the structural break date. Hansen (1992) argues that "... the date of structural change may be selected by appeal to events known a priori. ... it is essential that the researcher can argue that the events are selected exogenously." BP allows for multiple *unknown* breakpoints. We do not impose a known structural break date. Instead, the methodology determines the break dates by iteratively examining the likelihood function over different sub-samples.

5 Dynamic Network Structure of Oil-Producing Countries

5.1 Total Connectedness and Network Structure

Figure 1 below displays the complex network structure of all oil-producing countries before and after 2009.

[7] We test the connectedness measures that we present in Figures 3-7 for a unit root using Augmented Dickey-Fuller and Phillips-Perron tests. We display the test results for each connectedness measure in the online appendix table OA.2. Both tests conclude that the connectedness measures that we present in Figures 3-7 do not have a unit root.



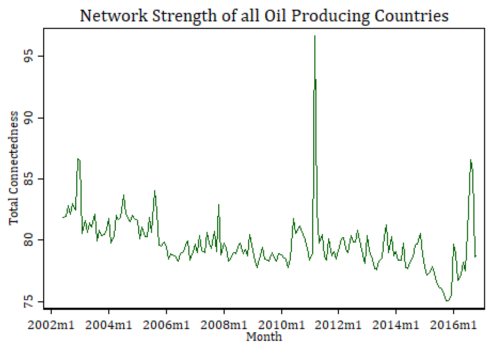
Before 2009 After 2009

Figure 1: Network Structure of Oil-Producing Countries

Figure 1 provides a glimpse of the dynamic and complex nature of the network structure of oil production. We cannot obtain any meaningful results by just observing figure 1. Thus, we examine the network structure through several empirical analyses to identify the changes over time and the causes for these changes.

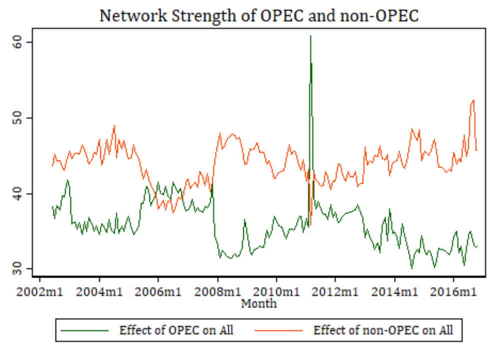
5.2 Network Strength

We calculate the time-varying total network strength of oil-producing countries using the DY methodology. We implement equation 3 and calculate total network strength (total connectedness) by taking the average of total connectedness from others, $C_{i\leftarrow\bullet}$. Figure 2 below displays the time variation in total connectedness of all countries.



All Countries

Figure 2a



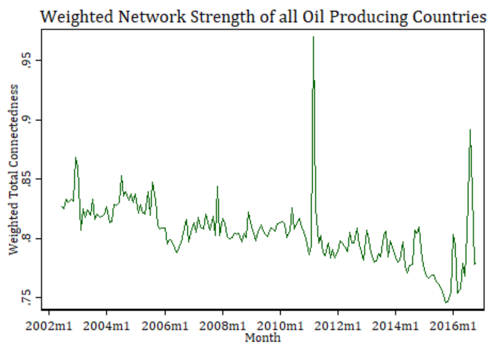
OPEC and non-OPEC

Figure 2b

Figures 2a and 2b show that although the total connectedness measure of all countries does not change significantly over time, the effect of OPEC and non-OPEC countries on all countries shows significant time variation. As in DY, figures 2a and 2b do not consider the total amount of oil production affected by actions of other countries. Alternatively, we calculate a weighted measure of total connectedness by taking into account the changes in quantity of oil production caused by other countries.[8] Both methods provide very similar results.[9]

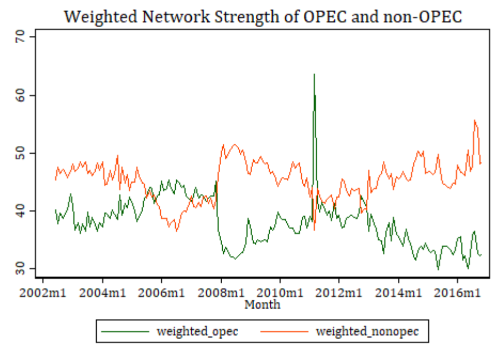
[8]For example, in June 2006 the effect of Saudi Arabia on Algeria is 2.36%. In figures 2a and 2b, we use these percentage values obtained from variance decomposition analysis as in equation 3. The total connectedness values in figures 2c and 2d are calculated using values weighted by quantity of oil produced. Algeria produced 1595.27 thousand barrels in June 2006. Therefore, 37.65 thousand barrels are caused by Saudi Arabia. We weighted the oil production of all countries and calculated the weighted total network strength by dividing the total world oil-production.

[9]The network strengths of OPEC and non-OPEC nations in figures 2b and 2d are mirror images. This is caused by the fact that total connectedness is a summation of OPEC and non-OPEC connectedness. Accordingly, a decrease in OPEC network strength means that the total strength of non-OPEC nations is increasing.



All Countries

Figure 2c



OPEC and non-OPEC

Figure 2d

We estimate equation (4) and investigate the structural break dates for the total effect of both OPEC and non-OPEC on all oil-producing countries using the BP methodology. For OPEC, BP determines December 2007 and May 2014 as structural break dates. BP determines May 2005 and December 2007 as the structural break dates for the effect of non-OPEC countries. Table 1 below displays the average connectedness measures for the determined structural break dates.

Time Period	Average Effect of OPEC	F-Statistics	Time Period	Average Effect of non-OPEC	F Statistics
June 2002-December 2007	37.69	47.61	June 2002-April 2005	45.32	19.27
January 2008-April 2014	35.45	16.8	May 2005-November 2007	40.59	25.55
May 2014 – November 2016	32.61	2.35	December 2007-November 2016	44.48	7.83

Table 1: Structural Break Tests of OPEC and non-OPEC on All Oil Producing Countries

5.3 Total Directional Connectedness

The previous section examined the coordination level of oil-producing countries by studying the changes in total connectedness levels. In this section, we focus on the directional connectedness of OPEC and non-OPEC countries. Directional connectedness provides information about the effect of a shock to the oil production of a certain country (or group of countries like OPEC) on other countries (or group of countries like non-OPEC). For example, the directional connectedness of UAE on Qatar (Q) in January 2010 is displayed as $C_{Q \leftarrow UAE,2010m1} = d_{Q,UAE,2010m1}$. We sum the directional connectedness of UAE on all other OPEC members and calculate the effect of UAE on OPEC for January 2010, $C_{OPEC \leftarrow UAE,2010m1} = d_{OPEC,UAE,2010m1}$. Accordingly, the directional connectedness we calculate using the VAR structure described in Section 4 allows us to examine the effects of individual countries or group of countries on the oil production of other countries.

5.3.1 Total Effects of OPEC and non-OPEC Countries on Global Oil Production

In this section, we examine the effect of OPEC and non-OPEC separately. Figure 3 below displays the dynamic effect of OPEC on OPEC and non-OPEC.

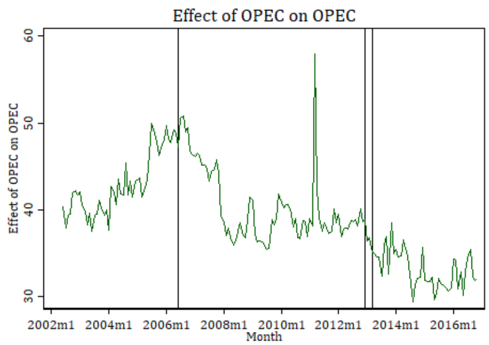


Figure 3a

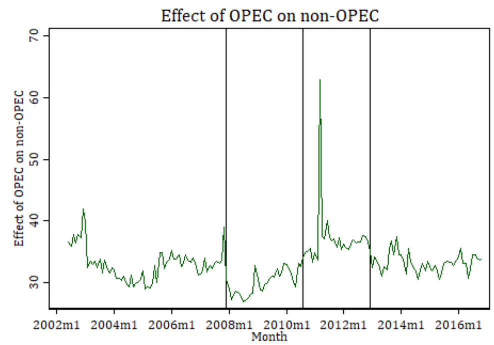


Figure 3b

Figure 3 shows that the influence of OPEC measured as the total connectedness of OPEC on OPEC changes significantly over time. Specifically, we calculate the effect of each OPEC member on other OPEC members. Then, we sum the monthly effect of all OPEC members to obtain the monthly connectedness measure presented in figure 3a. Accordingly, we characterize the monthly effect of OPEC on total OPEC oil production. Similarly, figure 3b presents the connectedness measure constructed by summing the effect of each OPEC member on non-OPEC oil production. We implement equation (3) and investigate the structural break dates for the total effect of OPEC on both OPEC and non-OPEC using the BP methodology. For figure 3a, BP determines June 2006, December 2012 and March 2013 as structural break dates. BP determines December 2007, and July 2013 as structural break dates for the effect on non-OPEC countries. Table 2 below displays the average connectedness measures for the determined structural break dates. Ansari (2017) confirms the lower OPEC coordination levels by stating that "missing coordination had been a central issue ..." (page 172) for the OPEC until a deal has been reached in December 2016.

Time Period	Average Effect on OPEC	F-Statistics	Time Period	Average Effect on non-OPEC	F Statistics
June 2002 -May 2006	42.9	170.89	June 2002 -November 2007	33.06	27.4
June 2006 -November 2012	40.48	84.65	December 2007 - July 2010	30.04	28.66
December 2012- February 2013	37.37	102.52	August 2010 – November 2012	37.18	23.49
March 2013 – November 2016	33.14	3.66	December 2012 – November 2016	33.27	3.6

Table 2: Structural Break Tests of Impact of OPEC on OPEC and non-OPEC

Figures 4a and 4b display the dynamic effect of non-OPEC countries on the oil production of OPEC and non-OPEC.

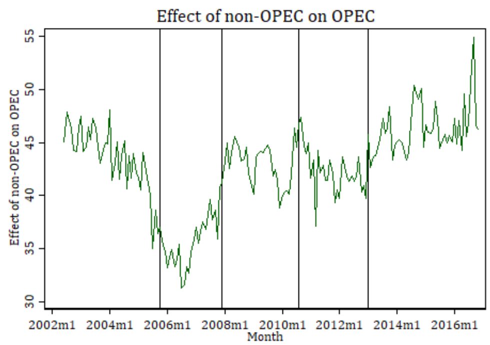


Figure 4a

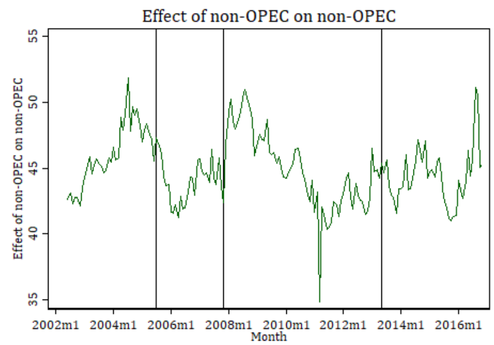


Figure 4b

Figure 4 shows the total effect of non-OPEC oil production on OPEC and non-OPEC. BP determines October 2005, December 2007, August 2010, and January 2013 as structural break dates for figure 4a. For figure 4b, BP determines July 2005, November 2007, October 2010 and January 2013 as structural break dates. Table 3 below displays the average connectedness measures for the determined structural break dates.

Time Period	Average Effect on OPEC	F-Statistics	Time Period	Average Effect on non-OPEC	F Statistics
June 2002 -September 2005	46.11	36.76	June 2002 -June 2005	44.18	64.21
October 2005 -November 2007	43.66	18.58	July 2005 -October 2007	35.56	39.11
December 2007- July 2010	47.19	21.49	November 2007- April 2013	42.69	111.17
August 2010 – December 2012	42.28	22.94	May 2013 – November 2016	46.57	4.37
January 2013 – November 2016	44.51	0			

Table 3: Structural Break Tests of Impact of non-OPEC on OPEC and non-OPEC

5.3.2 Time-Varying Network Strength of Major Oil-Producing Countries: Russia, Saudi Arabia and the US

In this section, we examine how the effect of major oil-producing countries changes over time. We specifically analyze the impact of Russia, Saudi Arabia, and the US on OPEC and non-OPEC. Ansari (2017) construct a quantitative model of the global oil market, and concludes that "... strategic substitution in the oil market takes place virtually between three players: Saudi Arabia, Russia and the US." (page 174) Figure 5 below displays the effect of Russia on OPEC and non-OPEC.

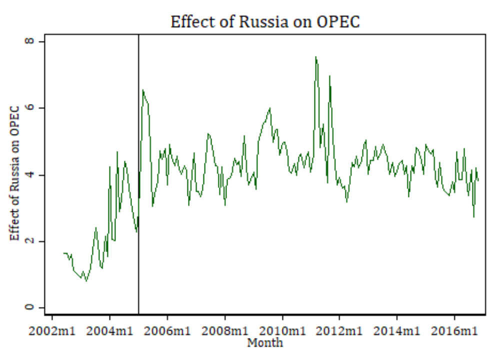


Figure 5a

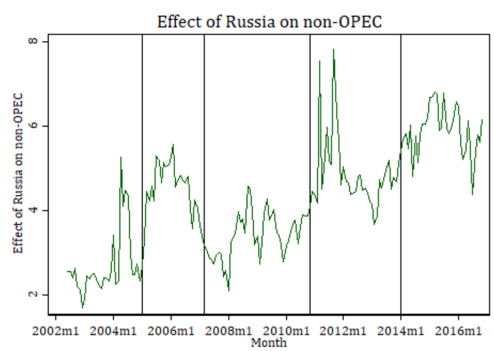


Figure 5b

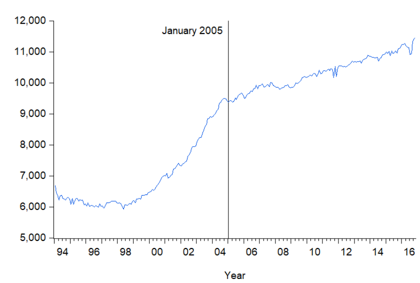


Figure 5c: Oil Production of Russia

Table 4 below displays the average connectedness measures for the determined structural break dates.

Time Period	Average Effect on OPEC	F-Statistics	Time Period	Average Effect on non-OPEC	F Statistics
June 2002 -January 2005	2.16	176.12	June 2002 -January 2005	2.7	185.6
February 2005 -November 2016	4.4	8.83	February 2005 - March 2007	4.48	43.99
			April 2007 – November 2010	3.43	28.93
			December 2010-January 2014	4.9	32.77
			February 2014 – November 2016	5.9	0

Table 4: Time-Varying Network Strength of Russia

We find that the effect of Russian oil production on especially non-OPEC has increased substantially over time. Figure 5c suggests that the significant increase in the influence of Russian oil production is related to the average daily production of Russia. Ansari (2017) theoretically justifies the dramatic change in impact of Russia. He finds that Russian oil production is above the equilibrium level and " Russia is voluntarily incurring losses for some of their sales." (page 174) Statements by the Russian Energy Minister Alexander Novak confirms that Russia prioritizes its market share. According to him, "If we cut, the importer countries will increase their production and this will mean a loss of our niche market." (BBC News, 2015)

Figure 6 below presents the effect of Saudi Arabian oil production on OPEC and non-OPEC.

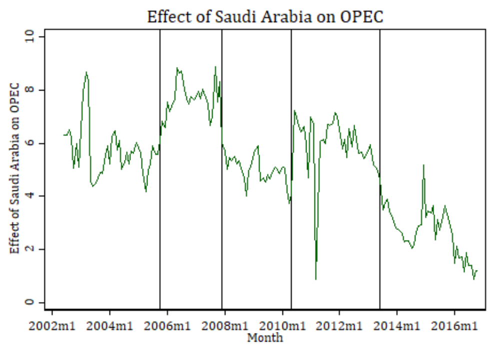


Figure 6a

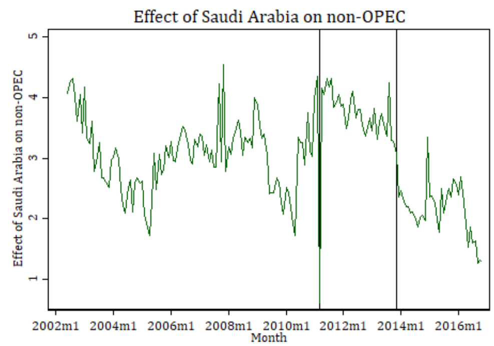


Figure 6b

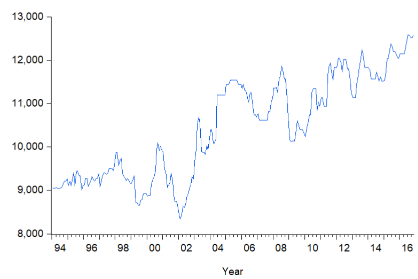


Figure 6c: Oil Production of Saudi Arabia

Table 5 below displays the average connectedness measures for the determined structural break dates. The effect of Saudi Arabia on OPEC and non-OPEC decreases significantly after 2013. Anecdotal evidence supports these empirical findings. According to Mohammed al-Sabban, a former adviser to the Saudi Arabian Minister of Petroleum and Mineral Resources Ali al-Naimi, "(Ali al-Naimi's) biggest move was the latest one of defending Saudi Market share, and abandoning the OPEC swing role." (The Wall Street Journal, 2015) Here, Saudi Arabia changed its oil production policy, especially after 2012, and focused on maintaining its market share despite the sharp decline in oil prices. Fattouh et al. (2016) state that Saudi Arabia faces a trade-off between maintaining its market share in the global oil market and maximizing its long-term oil revenue. They argue that US shale has made the trade-off more complicated.

Their game-theoretic analysis suggests that Saudi Arabia should not cut its oil production levels. Thus, the recent global market developments caused Saudi Arabia to diminish its role in the OPEC and focus on its oil revenues.

Time Period	Average Effect on OPEC	F-Statistics	Time Period	Average Effect on non-OPEC	F Statistics
June 2002 -October 2005	5.72	247.36	June 2002 -March 2011	3.03	85.3
November 2005 – December 2007	7.66	25.43	April 2011 - November 2013	3.75	41.25
January 2008 – May 2010	4.97	66.61	December 2013 – November 2016	2.13	6.58
June 2010 – June 2013	5.9	16.8			
July 2013 -November 2016	2.63	0			

Table 5: Time-Varying Network Strength of Saudi Arabia

Figure 7 below presents the US oil production effect on OPEC and non-OPEC.

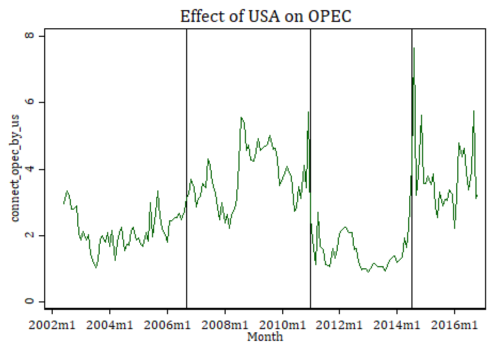


Figure 7a

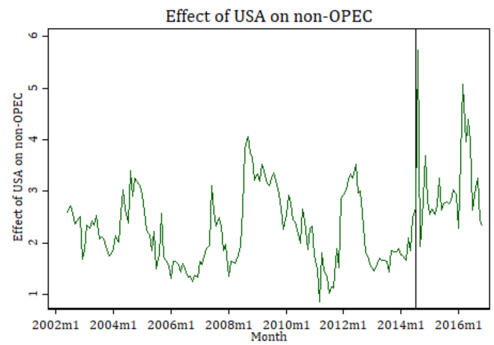


Figure 7b

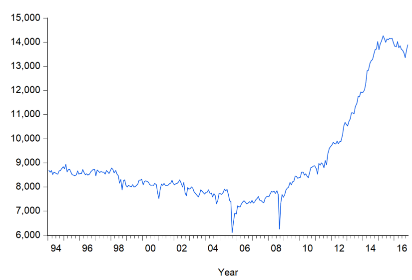


Figure 7c: US Total Oil Production

Table 6 below displays the average connectedness measures for the determined structural break dates. The US effect on non-OPEC increases significantly after July 2014. The US effect on OPEC rises significantly after July 2014 and returns to high levels of October 2006-January 2011 period.

Time Period	Average Effect on OPEC	F-Statistics	Time Period	Average Effect on non-OPEC	F Statistics
June 2002 -September 2006	2.16	27.27	June 2002 - July 2014	2.23	36.07
October 2006 – January 2011	3.78	70.66	August 2014 -November 2016	3.11	7.57
February 2011 – July 2014	1.46	118.86			
August 2014 -November 2016	3.78	11.81			

Table 6: Time-Varying Network Strength of United States

Figure 8 provides the weekly average oil production values.[10]

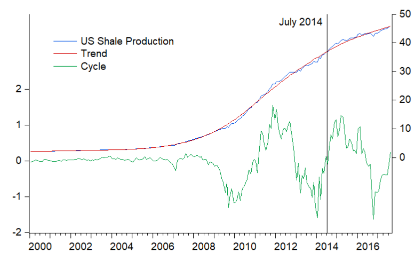


Figure 8a US Shale Production

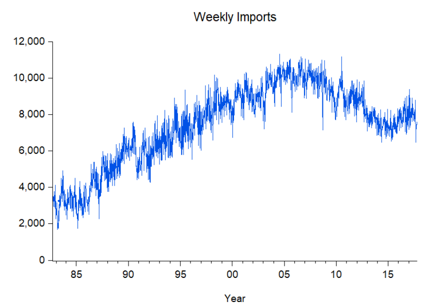


Figure 8b US Weekly Imports

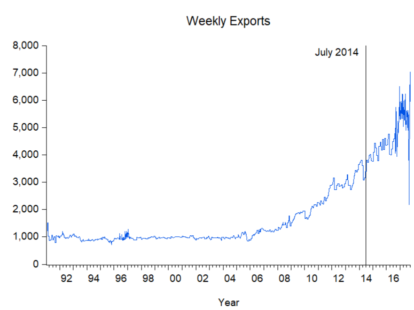


Figure 8c US Weekly Exports

Figure 8 suggests that the rise in US shale production and exports may explain the recent rise in the country's network strength. As shown by Baumeister and Killian (2016), the surge in US shale production has become one of the major price determinants of oil prices. Their empirical findings indicate that the US has taken "the traditional role of Saudi Arabia as the swing producer in global oil markets." (page 148) Accordingly, the efficiency and production increases in shale oil weakened OPEC's influence and OPEC members accepted the new oil market conditions.

[10]Weekly US oil statistics are available at https://www.eia.gov/dnav/pet/pet_move_wkly_dc_NUS-Z00_mbblpd_w.htm.

6 Event-Study Analysis of OPEC Decisions and Dynamic Network Structure

We conduct an event-study analysis to examine the effects of cut and increase decisions of OPEC. We collect and read all OPEC meeting minutes and construct a detailed data set of the meetings with cut, increase and maintain status quo decisions. We obtain 15 cut, 10 increase and 44 status quo decisions. We then examine the effect of cut and increase dummy variables on the change in connectedness levels of OPEC and all oil-producing countries. We conclude that cut decisions do not affect OPEC and non-OPEC coordination. Accordingly, oil-producing countries do not act in line with the cut decisions. Increase decisions have a significant and positive impact on OPEC and non-OPEC coordination. OPEC and non-OPEC countries increase their oil production coordination level and act in line with increase decisions.

	Dependent Variable							
Variables	Connectedness of OPEC				Connectedness of All Countries			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Cut Dummy	-0.77	-1.57	-0.27	-0.69	1.14	0.45	1.25	1.24
	(0.40)	(0.73)	(0.13)	(0.35)	(1.42)	(0.52)	(1.44)	(1.52)
Increase Dummy	3.48	2.82	3.11	3.36	2.85	2.29	2.77	2.70
	(3.00)**	(1.96)*	(2.72)**	(2.80)**	(3.38)**	(2.98)**	(3.22)**	(3.22)**
Oil Price		-0.03				-0.03		
		(1.65)				(2.97)**		
First Difference of			0.11				0.02	
Oil Price			(1.04)				(0.77)	
Negative Oil Price				-0.43				-0.55
Change Dummy				(0.29)				(1.03)
Constant	39.55	41.73	39.27	39.74	79.47	81.33	79.47	79.72
	(45.72)**	(22.17)**	(45.67)**	(37.66)**	(285.58)**	(102.56)**	(283.22)**	(235.08)
R^2	0.06	0.09	0.08	0.06	0.23	0.34	0.24	0.25
N	50	50	50	50	50	50	50	50

Table 7: Event Study Analysis of Effect of OPEC Decisions

* p<0.05; ** p<0.01

We control for changes in oil prices when we conduct the event-study analysis. We employ oil price, the change in oil price measured as the first difference and a dummy variable which is 1 if the oil price drops (negative change from previous period.)

7 Determinants of Connectedness

In this section, we conduct a fixed effects panel regression analysis to examine the factors that affect the level of connectedness across countries. We construct a panel data set of 30 oil producing countries for years 2002-2016. We analyze the effects of oil-production capacity, real oil price, oil rent as percent of GDP and GDP per capita of each country.[11] We obtain annual oil reserves, oil production and real oil price data from the BP Statisticsl Review of World Energy 2017.[12] Pierru et al. (2018) argues that spare production capacity holds a key role in determining oil prices. With valuable spare capacity, OPEC members seem to have ability to mitigate volatility of oil price. Following Pierru et al. (2018), we examine the effect of total oil reserves on connectedness. Annual data about oil rent as percent of GDP and GDP per capita are from the WDI data base of the World Bank. Table 8 below displays the results of fixed effects panel regression analysis. Both OPEC variable is a dummy variable which is 1 if both affected (i) and affecting (j) countries are OPEC members. We also include year dummy variables.

[11] We present the summary statistics of these variables in the online appendix.
[12] The data is available online at: http://www.bp.com/statisticalreview

	Dependent Variable: Connectedness from Country j to Country i,($C_{i \leftarrow j}$)			
	(1)	(2)	(3)	(4)
Both OPEC	0.80	1.09	1.10	
	(13.37)**	(13.64)**	(13.72)**	
Both Developing				0.60
				(9.82)**
Total Oil Reserves	0.00	0.00	0.00	0.00
of Affected Country (i)	(0.05)	(0.56)	(0.53)	(0.08)
Total Oil Production	-0.04	-0.01	-0.01	-0.04
of Affected Country (i)	(1.04)	(0.17)	(0.16)	(1.02)
Total Oil Reserves	-0.00	0.00	0.00	0.001
of Affecting Country (j)	(0.19)	(0.21)	(0.70)	(2.17)**
Total Oil Production	0.05	0.09	0.08	0.07
of Affecting Country (j)	(4.68)**	(4.14)**	(4.06)**	(6.08)**
Real Oil Price	0.00	-0.00	-0.00	0.00
	(0.04)	(1.19)	(0.71)	(0.10)
Oil Rent (%GDP)		0.00	0.00	
of Affected Country (i)		(0.51)	(0.49)	
Oil Rent (%GDP)		-0.005	-0.01	
of Affecting Country (j)		(2.95)**	(3.33)**	
GDP Per Capita			-0.00	
of Affected Country (i)			(0.16)	
GDP Per Capita			-0.004	
of Affecting Country (j)			(3.22)**	
Constant	2.54	2.53	2.56	2.15
	(14.61)**	(8.27)**	(8.20)**	(11.84)**
R^2	0.02	0.04	0.04	0.01
N	12,180	8,112	8,112	12,180
Year Dummy Variables	YES	YES	YES	YES

Table 8: Determinants of Connectedness: Fixed Effects Panel Regression Analysis

* p<0.05; ** p<0.01

Table 8 shows that "Both OPEC" dummy variable is significant with a positive coefficient. Accordingly, level of connectedness among OPEC members are significantly higher compared to non-OPEC oil producing countries. This result extends the findings of Smith (2005) which states that a "core" group of producers including Kuwait, Saudi Arabia, and UAE have acted collectively and thus coordinate to mitigate production fluctuation arising from other OPEC members as well as non OPEC members. Additionally, the "Total Oil Production of Affecting Country (j)" variable is significant with a positive coefficient. Therefore, we conclude that countries with higher levels of production are able to affect the production of other countries. Finally, column 4 finds that connectedness among developing countries are significantly higher.[13]

8 Conclusion

We examine how the coordination level of major oil-producing countries changes over time. We calculate the DY connectedness measure for 13 OPEC and 17 non-OPEC countries and construct the dynamic network structure using that measure. We conduct several structural break tests to determine whether the coordination level of all countries and the impact of OPEC and non-OPEC countries change over time. We find that the network structure changes significantly over time. Specifically, the impact of OPEC on all oil-producing countries declines whereas that of non-OPEC on all countries increases. The total coordination of OPEC members decreases substantially after 2012. The monthly average connectedness of OPEC decreases from 40.48% in 2012 to 33.14%. The coordination level of non-OPEC did not change significantly for years 2002-

[13] We consider the definition of the World Bank. We identify Canada, Norway, USA and United Kingdom as developed countries and remaining oil producing countries as developing countries.

2016. The oil production changes of OPEC members have significant effects on non-OPEC oil production. The effect is highest for the August 2010-November 2012 period, with a monthly average connectedness level of 37.18%.

We find that the influence of Russian and US oil production on both OPEC and non-OPEC increases over time. In contrast, the influence of Saudi Arabia is declining significantly. Furthermore, we conduct an event-study analysis to examine the effects of OPEC's cut and increase decisions. We conclude that the cut decisions do not have any effect on OPEC and non-OPEC coordination. Accordingly, oil-producing countries do not act in line with the "cut" decisions. Increase decisions have a significant and positive impact on OPEC and non-OPEC coordination. OPEC and non-OPEC countries increase their oil production coordination level and act in line with the increase decisions. Finally, panel regression analyses conclude that level of connectedness among OPEC members are significantly higher compared to non-OPEC oil producing countries.

To sum up, we implement a novel methodology to construct the dynamic network structure of oil-producing countries. We define the strength of an individual country in the network by measuring the effect of significant changes in the country's oil production levels on the production of others. The dynamic network structure allows us to examine how the network strengths of individual countries evolve over time. We conduct structural break tests to determine the dates of significant changes in network dynamics. We examine the effectiveness of OPEC by studying the effect of OPEC decisions on the level of OPEC and non-OPEC coordination. The findings of the paper provide detailed information about the coordination level of OPEC and non-OPEC oil-production and how that coordination changes over time. Finally, we conclude that only increase decisions made in OPEC meetings are effective. The coordination level of global oil production significantly increases following such decisions.

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