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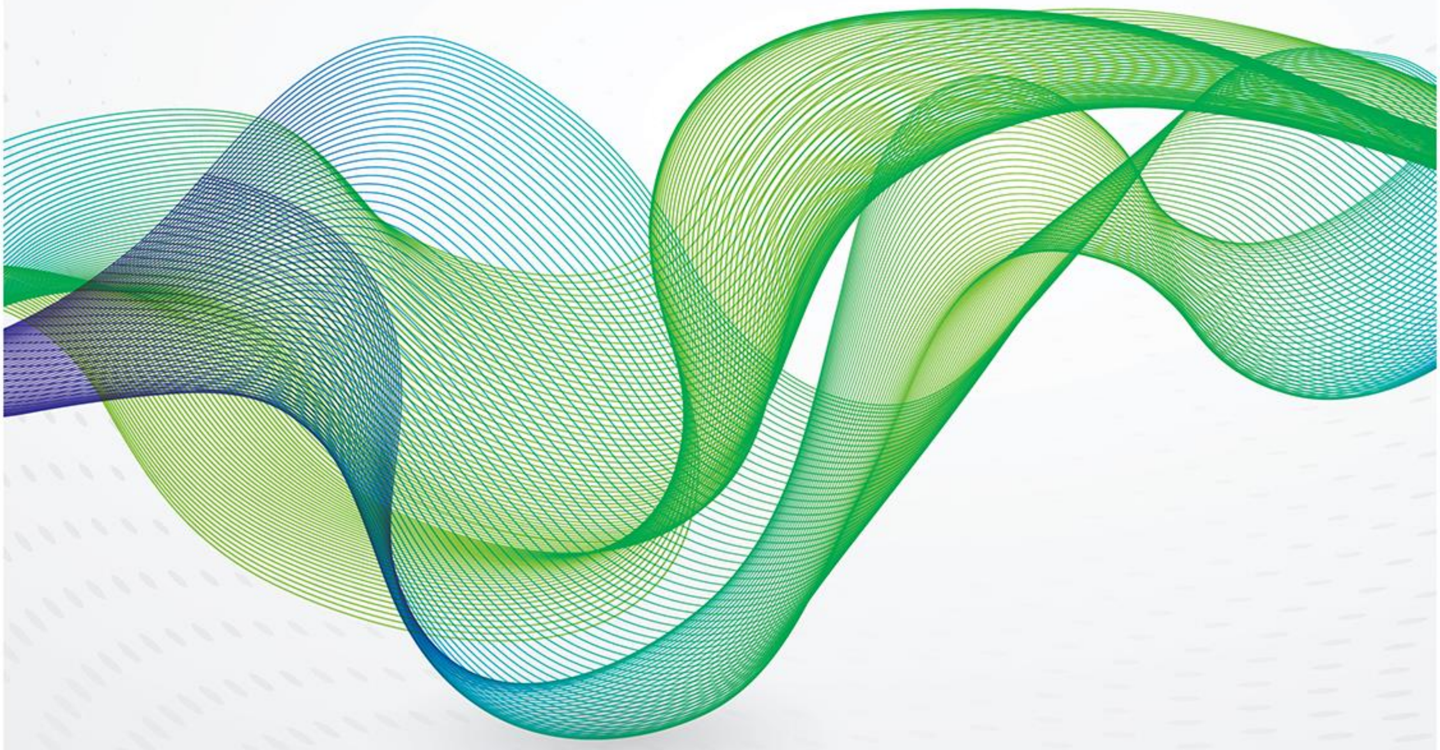
Oil Price Shocks:
A Measure of the Exogenous and Endogenous Supply Shocks of Crude Oil



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Andreas Economou*

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* Andreas Economou, OIES–Saudi Aramco Fellow, Oxford Institute for Energy Studies, Oxford, UK. Corresponding author. Email: andreas.economou.13@ucl.ac.uk

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Abstract

The paper introduces a new measure that jointly identifies and disentangles the oil supply shocks of crude oil into exogenous and endogenous, by quantifying the positive and negative shocks to oil production caused by events outside the oil market (exogenous) or as a consequence of the normal functioning of the oil market (endogenous). The objective is to examine how the use of alternative measures of oil supply shocks affects our assessment of the dynamic effects of supply shocks on the real price of oil since 1990. Results show that for most of the 1990s, shortfalls in oil production that were brought about by geopolitical episodes accounted for about 7% of the variability in global crude oil production. However, this pattern reverses after 2000 onwards, as fluctuations in global oil production are largely attributed to market-specific events (6%). We show that oil supply shocks may have very different effects on the real price of oil, depending on the underlying specification of the shock. In particular, the measures that capture market-driven shifts in oil supply are found to be more plausible than the rest in explaining the variability of the real price of oil, especially when compared with flow supply shocks. In fact, analysis suggests that flow supply shocks underestimate the historical contribution of oil supply shocks to changes in the real price of oil, in contrast to total supply shocks that appear to have exerted significant upward pressure in the real price of oil especially between 2003 and mid-2008. Overall, endogenous supply shocks play an increasing important role in the historical evolution of the oil price, but it must be noted that oil price developments after 2010 are largely attributed to exogenous supply shocks. We conclude that historically the supply side of the market has been an important determinant of the real price of oil after all.

Keywords: oil price, oil supply, shocks, oil market, crude oil production

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1. Introduction

The crude oil price path has evolved *vis-à-vis* the structural changes of the oil market: (1) from the integrated and regulated market that prevailed until 1971; (2) to the transitional period in the aftermath of the first and second oil shocks (1973-1984); and (3) the commodity and deregulated market (1986-ongoing), in which prices are determined today, conditional to expectations about supply-demand tightness (Mitchell, 2002; Yergin, 1992). On the supply side, expectations are primarily influenced by the physical availability of crude oil supply and the uncertainty pertaining to the future availability of production capacity (Fattouh, 2007; Hamilton, 2009a; Kilian, 2008). On the demand side, expectations shift in accordance with fluctuations in the global business cycle (aggregate demand shocks) and the uncertainty associated with unanticipated shortfalls of the levels of available supply relative to the anticipated levels of petroleum demand (precautionary demand shocks; Hamilton, 2013a; Kilian, 2009a). Taken together, these market imbalances correspond to a rich record of episodes in the form of 'oil price shocks' that are thought to reflect disruptions in oil production caused mainly by exogenous geopolitical events, e.g. wars or civil unrests in OPEC[1] countries (Hamilton, 2009a). In principle, oil price shocks are unanticipated components of a substantial change in the price of oil, defined as the difference between the expected and realised oil price (Baumeister & Kilian, 2016a).

In the aftermath of the 1970s oil crisis there has been a growing interest in understanding the dynamic effects of crude oil production shortfalls on changes in the real oil price. Whereas such exogenous political events were initially thought to have played a significant role during the historical oil price shocks in 1973-74, 1980-81, 1990-91 and 2002-03, recent empirical findings indicate a decrease in the explanatory ability of the supply side of the oil market (Kilian, 2008, 2009a). Several studies have appeared in recent years supporting the claim that exogenous production shortfalls are of limited importance in explaining oil price shocks during crisis periods, as most of the oil price changes in historical episodes are largely explained by demand-specific shocks, i.e. a combination of global aggregate and precautionary demand shocks (Baumeister & Kilian, 2016a; Baumeister & Peersman, 2013; Kilian, 2009a; Kilian & Lee, 2014; Kilian & Murphy 2014). Examining for similarities between the oil price shocks of the past and recent years, it is observed that major geopolitical events are present in all events except the period of the build-up to the 2008 oil shock (2004-08); whilst the physical supply disruptions since 2011 onwards were largely matched by gains in non-OPEC supply (Hamilton, 2014; Stevens, 2015). First, it has been widely documented that the sharp increase in the price of oil beginning in 2003 and accelerating sharply until the 2008 price collapse, was caused by stagnating global production levels confronted by the strong demand growth that originated from the non-OECD[2] countries (Coleman, 2012; Hamilton, 2013a, 2014; Kaufmann, 2011; Kilian & Hicks, 2013).[3] Second, consensus dictates that the 2014 price collapse was materialised by the timely synergy of the unprecedented positive shocks to actual and expected non-OPEC oil production confronted by the unexpectedly weak growth of global petroleum demand (Baumeister & Kilian, 2016b; Manescu & Nuno, 2015).

An alternative theoretical view following the 2008 oil price shock postulates that supply shocks may also be determined endogenously with respect to the cumulative amount that could eventually be extracted and the projected time path for the demand function (Smith, 2009, 2012). This theoretical premise follows the logic that just as the interaction of supply and demand determines the equilibrium price path in a market economy, these market forces determine also the equilibrium production path (Smith, 2012,

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[1] Organisation of the Petroleum Exporting Countries.
[2] Organisation for Economic Cooperation and Development.
[3] In these studies, and in related references it is also debated that financial bubbles may have emerged just prior to and during the oil price shock of 2008 (see Hamilton, 2009b; Kilian, 2009b).

p. 4). A rule of thumb is that price uncertainty prompts oil producers to delay investment and decrease capital spending, because upstream projects are particularly capital intensive and large capital outlays are committed prior the resolution of uncertainty regarding the likelihood of production and price (Mabro, 2006; Pindyck, 1991). Oil producers will not invest to new projects today if they expect that the investment costs of doing so will be cheaper tomorrow. Yet, they must constantly drill new wells or seek for new discoveries in order to maintain and expand production, conditional to the projected growth of global demand (Adelman & Watkins, 2008). Accordingly, expectations of future oil supply availability alone are argued to have exerted significant influence over recent major oil price shocks, i.e. 1990-91, 2003-08, 2009, 2014 (Fattouh, 2010; Hamilton, 2013a, 2014; Kilian, 2008, 2014). The interpretation of this new evidence points towards a structural innovation of the supply determinant from an endogenous perspective, which still lacks attention from the existing framework for the empirical analysis of oil price shocks.

This paper introduces a new methodology that jointly identifies and disentangles the supply shocks of crude oil into exogenous and endogenous, by quantifying the positive and negative shocks of oil production caused by events outside the oil market (exogenous) or as a consequence of the normal functioning of the oil market (endogenous). Exogenous supply shocks originate mainly from geopolitical and political episodes in oil producing countries that lead to the actual disruption in oil drilling and extracting operations of oil facilities. The endogenous supply shocks are associated directly with substantial positive or negative changes in available production capacity[4], relative to demand, as a result of geological, economic and technological stimulus or constraints, respectively. The objective of this paper is to consider a structural vector autoregressive (VAR) model of the world oil market that for the first time incorporates this endogenous aspect of oil supply shocks and to examine the extent to which the supply-side of the oil market under the new specification can explain changes in the real oil price since 1990 (1990.1–2015.6). By quantifying the dynamic effects of endogenous supply shocks to price changes during crisis periods, allows for a robust analysis of the role of capacity shifts in crude oil production, relative to demand, which is not linearly related to changes in actual oil production, and puts into test the conventional approach of recent studies in the analysis of oil prices using fundamental measures.

The rest of the paper is organised as follows. Section 2 locates the study in time and reviews the current empirical understanding on the causes of historical oil price shocks in the scope of the study. Section 3 introduces the new measure of monthly exogenous and endogenous supply shocks of crude oil that quantifies the timing, magnitude and the sign of each discrete category of supply shocks. The sum of the two measures results to an aggregate measure of total supply shocks. Section 4 presents the structural VAR models of the world oil market under the different specifications of the supply shocks and examines how the use of the new measures affects the assessment of the dynamic effects of supply shocks on the real price of oil. Discussion is built on an empirical comparison of the supply shock measures. Section 5 draws the conclusions.

[4] Production (or operable) capacity is the sum of operating and idle capacity, defined as the maximum sustainable amount of capacity that is in operation; not in operation but can be brought online within thirty days; or not in operation but under active repair that can be completed within ninety days (Access: http://www.eia.gov/tools/glossary/).

2. Causes of historical oil price shocks

Figure 1 presents the evolution of the real oil price[5] along with key oil market events in the period 1990 to 2015. Oil price shocks are represented by plotting the net real Dated Brent price changes, which isolate from the series corrections from earlier oil price increases and declines.[6] As follows from the figure, it is possible to identify three distinct but interrelated oil price intervals throughout: (1) the 1990-99 price depression around $29/bbl; (2) the 2000-10 price surge, during which the price of oil had risen on average by 109% ($62/bbl), from its average value in the 1990s; and (3) the 2011-14 price stability close to $110/bbl. The latter was followed by the 2014 oil price collapse, during which prices fell by 73% to $48/bbl in January 2015, down from $111/bbl in June 2014. Three important observations follow throughout the entire period. First, the oil price has shown significant volatility, while there is no obvious long run trend (upward or downward). Second, the one geopolitical event throughout the entire period that produced the most significant increase in the price of oil was the Gulf War in 1990, during which the oil price spiked by 53% in the course of three months (August to October 1990). During the rest major geopolitical episodes, namely the 2002-03 Venezuelan crisis and Iraq War (13%), and following the events of the 2011 Arab Uprisings (35%) the oil price increases were only modest due to the offsets by gains in oil production elsewhere. Third, several other oil market-specific events produced larger and comparable price shocks related to the underlying supply and demand conditions, i.e. the 1999-2000 strong global industrial growth (77%), the great commodities surge of 2003-08 (145%), the Global Financial Crisis of 2008 (-102%) and the oil market imbalance of 2014-15 (-73%).

Table 1 summarises the key contributing factors of oil price shocks at certain chronological oil market events along with estimates of the rate of the positive or negative oil price changes. Many of these episodes were associated with supply shocks arising out of geopolitical conflicts, even though their frequency and amplitude have been progressively in decline through time. Demand specific shocks had become increasingly important contributors in the late 1990s and are primarily associated with major global economic expansions and contractions. Moreover, there is a strong presence of precautionary demand shocks in several episodes that reflect shifts in the demand for oil associated with the forward-looking behaviour of the market participants. Notwithstanding, episodes that are associated with market imbalances, i.e. positive shifts in the demand for oil confronted by limited oil supply response and with strong supply growth confronted by stagnant demand, produced the most substantial oil price shocks by historical standards. It follows that neither of the market fundamentals can be an important determinant *per se*, but it is rather the catalytic interaction of both supply and demand that has historically driven the real oil price.

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[5] Oil prices used in the text are expressed in real terms and refer to the inflation-adjusted Dated Brent price in June 2015 USD, unless it is stated otherwise.

[6] Hamilton (1996, 2003) suggests that an accurate measure of changes in the oil price should compare the current price with its levels over the previous year and not during a previous period alone, e.g. a month or quarter. In this manner price corrections to earlier increases or decreases from an episode are eliminated.

Figure 1: Timeline of oil market episodes since 1990

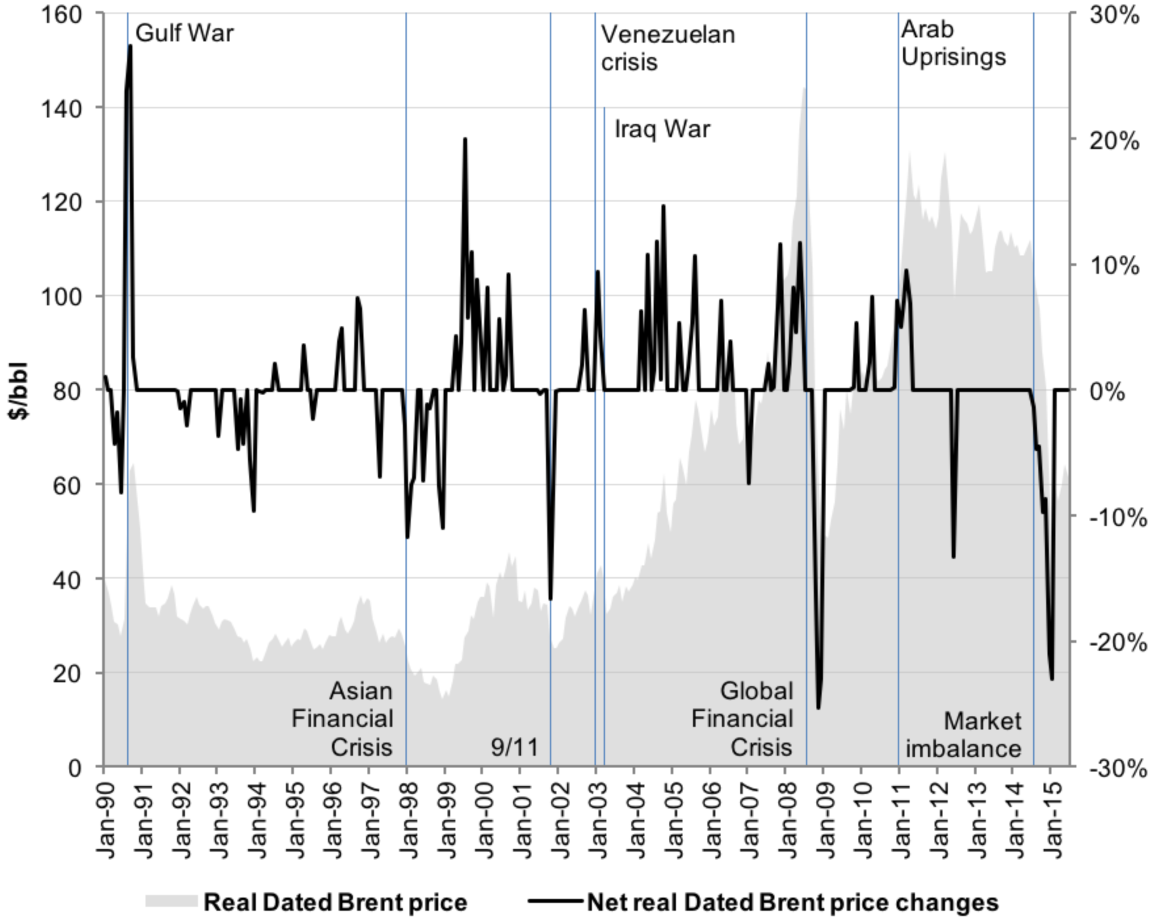


Table 1: Summary of the key factors of historical oil price shocks

Oil price shock (Chronology)	**Key Factors**
53% (Aug 90 – Oct 90)	*Gulf War*; Supply shock and precautionary demand shock
- 57% (Dec97-Dec98)	*Asian Financial Crisis*; Demand shock
77% (Jun 99 – Sep 00)	*Strong global industrial growth*; Supply cuts and strong demand
13% (Dec02–Mar03)	*Venezuelan crisis and Iraq War*; Supply shock
145% (Jan03–Jun 08)	*Commodities supercycle*; Strong demand and s*tagnant* supply, precautionary demand shock
- 102% (Jul08–Dec08)	*Global Financial Crisis*; Demand shock
35% (Dec10–Apr11)	*Arab Uprisings*; Supply shock
- 73% (Jul14–Jan15)	*Excess capacity*; Strong supply and *stagnant* demand, precautionary demand shock

2.1. Supply shocks

In pursuit of modelling the historical oil supply shocks and examining their impact on the relationship between oil and the US macroeconomy, Hamilton (2003) proposes first a measure of exogenous oil supply shocks by developing a quantitative version of the dummy-variable approach introduced by Dotsey and Reid (1992) and Hoover and Perez (1994). The strategy is to compute the counterfactual production path for a given country associated with an exogenous event by explicit assumptions about what that country's production levels would have been in the absence of the event. Hamilton extrapolates the counterfactual production level of a given country by the level of production in the month prior the exogenous event and compares that level to the lowest level of production that is observed subsequently. The difference in physical production levels over the period in question results to the estimation of the magnitude of an exogenous shock to the supply of oil, for selected geopolitical events from 1949 to 2001 (Hamilton, 2003, p. 373). The author concludes that historical oil price shocks were primarily caused by significant disruptions in crude oil production that were brought about largely by exogenous geopolitical events, indicatively the 1956 Suez Crisis, the 1973 Arab Embargo, the 1979 Iranian Revolution, the 1980 Iran-Iraq War and the 1990 Gulf War (Hamilton, 2009a, 2014).

Kilian (2008), however, identifies three distinct shortcomings in Hamilton's (2003) widely used approach: (1) the method imposes the implicit assumption that the level of oil production would never have changed in the absence of the exogenous event; (2) it does not allow for the response of oil production to the exogenous event to be immediate or delayed; and (3) it does not allow the response to be long lasting, time- and sign-varying. To solve these issues, Kilian (2008) introduces an alternative measure of exogenous supply shocks by computing the counterfactual production level for a given country by extrapolating its production level in the month just before the event in question, based on the average growth rate of production in other countries that are subject to similar macroeconomic conditions and are not involved into an exogenous episode. This method allows the construction of a monthly time series of exogenous production shortfalls that takes full account of the timing of the shock and of variations over time in its magnitude and sign. The author's objective is to analyse the predictive content of exogenous oil supply shocks for changes in the real price of oil since 1973.

Kilian's (2008) findings differ from the general consensus in the literature along a number of dimensions, as he draws the following concluding remarks: (1) the exogenous oil production shortfalls are found to be of limited importance in explaining oil price changes during crisis periods; (2) of the episodes studied, only the 1980-81 oil price increases can be attributed to exogenous oil supply disruptions, although small by the historical standards; and (3) the presence of capacity constraints in crude oil production amid large increases in oil demand has generated large oil price increases, especially in 1973, 1979 and 2004-05. Kilian argues that there is no indication that the supply side of the oil market has been a key factor affecting the real price of oil, *per se*, nor did it play a catalytic role during the oil price shocks of the 1970-80s. He notes, however, the importance of capacity constraints in crude oil production as these are found important in his analysis and urges the need to identify observables that are likely to drive expectations of future oil supply availability (p. 234). Later studies drop the counterfactual approach of representing shocks to the physical availability of oil and instead utilise estimates of the percentage changes in global crude oil production (Coleman, 2012; Baumeister & Kilian, 2016b; Kilian, 2009a; Kilian & Lee, 2014; Kilian & Murphy, 2014; Manescu & Nuno, 2015).

2.2. Demand shocks

The empirical literature has widely documented that demand shocks play an important role to changes in the price of oil (Coleman, 2012; Dées *et al.*, 2007; Fattouh, 2007; Kaufmann, 2011). However, the task of quantifying these demand shocks has for years puzzled researchers because there are no readily available indices that capture shifts in the demand for industrial commodities driven by the global business cycle. Kilian (2009a) introduces a measure of the changes in global real activity that affects the demand for crude oil, using a monthly index of dry cargo bulk freight rates; namely a monthly measure of global real economic activity. The measure is a business cycle index that is designed to capture shifts in the global use of all industrial commodities. The author uses the newly constructed index in order to examine its effects on the real price of oil along with other fundamental measures. He classifies the key determinants of the real price of oil into: (1) shocks to the current availability of oil, namely flow supply shocks; (2) shocks to the current demand for crude oil driven by fluctuations in the global business cycle, namely aggregate demand shocks; and (3) shocks driven by shifts in the precautionary demand for oil, namely precautionary demand shocks. His results show that aggregate demand shocks tend to raise the oil price levels significantly and support that the previous oil shocks were as much demand-driven as the 2008 shock.

In pursuit of a more robust examination of historical demand shocks, Kilian and Murphy (2014) and Kilian and Lee (2014) generalise the structural oil market model pioneered by Kilian (2009a) and Baumeister and Peersman (2013), and examine the contribution to changes of the real price of oil from flow supply, flow demand, physical speculative demand and other idiosyncratic demand shocks[7] between 1973 to 2012. The models include the real price of crude oil, extensions of the variables used in previous models representing supply and demand, and a newly constructed proxy of above ground global crude oil inventories under different specifications, designed to capture shocks to the speculative demand for oil above ground. Both studies conclude that the oil price surge in recent years has been driven by the market fundamentals and that flow demand shocks have been the primary driver of the real oil price. Indicatively, results show that in the period 2003-12 out of the cumulative $65/bbl oil price increase, $38-40/bbl (or 58-60%) are attributed to the effect of flow demand shocks, $5-21/bbl (or 7-32%) to the effect of supply shocks and $-2 to $11/bbl (or 0-16%) to precautionary demand shocks, depending on the model's specification. Evidently the importance of demand shocks in the recent empirical literature has been more robust, while the authors confirm that there is no indication that the supply side of the market has been a key determinant of the real oil price in recent years. More recently, Baumeister and Kilian (2016b) draw similar conclusions with regard to the causes of the 2014-15 oil price collapse.

2.3. Other demand shocks

Building on the work of Barsky and Kilian (2002, 2004), there has been an increasing recognition that shocks in precautionary demand for oil driven by the uncertainty about shifts of expected supply relative to expected demand are important in modelling the real price of oil. Much of the early literature associates these shocks with the convenience yield from having access to oil inventory holdings that can serve as a buffer against unexpected oil supply disruptions caused either by unexpected oil production outages, by unexpected growth of demand, or by both (Alquist & Kilian, 2010). However, modelling the expectation shifts underlying precautionary demand shocks has proven trivial, as the uncertainty about future oil supply shortfalls is not directly observable and highly non-linear. Kilian (2009a) addresses this issue by modeling these shocks as a residual, which is specified to capture innovations to the real oil price that cannot be explained based on oil supply or demand shocks. The author finds evidence that precautionary demand shocks play an important role in explaining oil price changes, but treats this finding with caution by suggesting that such expectations shifts are limited on the basis of information contained only in the past data on oil production, real economic activity and the real oil price available to the econometrician. On the contrary, market expectations that are formed on the basis of information signals related to future demand and supply conditions are omitted.

More recently, several studies have appeared documenting that the forward-looking behaviour of the market participants is associated with changes in crude oil inventories, according to which oil inventories fall following an unexpected reduction in storage demand in anticipation of a future oversupply; and oil

[7] Idiosyncratic (or Other) oil demand shocks are defined as innovations to the real price of oil that cannot be explained based on oil supply shocks or aggregate demand shocks.

inventories rise due to an unexpected decline in demand or increase in supply (Baumeister & Peersman, 2013; Fattouh, Kilian & Mahadeva, 2012; Kilian & Murphy, 2014; Knittel & Pindyck, 2013). On this basis, Kilian and Murphy (2014) propose and construct a new proxy named physical speculative demand, using data for global above ground oil inventories. The term 'physical speculative demand' is defined as anyone buying and storing crude oil for future use rather than current consumption, based on expectations about future price movements (Alquist & Kilian, 2010). Following the empirical literature, the authors build their model framework on the assumption that shifts in the expectations of forward-looking traders are reflected in changes in the real price of oil and changes in oil inventories. Their results rule out physical speculative demand as a cause of the surge in the real price of oil between 2003-08, but they conclude that movements in oil inventories played an important role in several earlier oil price shocks, notably in 1979, 1986, 1990 and 2002.

Similarly, Fattouh, Kilian and Mahadeva (2012) search for evidence of physical speculation on the basis of data on oil inventories and they conclude that the oil price-inventories relationship explains little about the quantitative importance of speculation on oil prices. Kilian and Lee (2014) re-estimate the structural VAR proposed by Kilian and Murphy (2014) by constructing an alternative proxy which provides detailed accounts of oil inventories by region and indicator (i.e. includes stocks at sea and in transit) and they explore how the use of the original proxy from Kilian and Murphy (2014) and the newly constructed proxy, affects the empirical evidence for physical speculative demand. Comparing the results from the two proxies, the authors observe that there is evidence of physical speculative demand raising the oil price by $5-14/bbl only in mid-2008, depending on the inventory specification. They too confirm that there is no evidence of significant physical speculative demand-pressures on oil price changes, especially since 2003 onwards.

3. Constructing a measure of the exogenous and endogenous supply shocks of crude oil

Analysis of oil supply shocks focuses on the period 1990.1–2015.6. In principle we utilise monthly proprietary production data for all OPEC producers by member country, the US, China, Russia, Canada, Mexico, the North Sea and on aggregate Rest of World that are available from the *Oil and Gas Journal Energy Database* since January 1990. Additionally the proposed methodology utilises monthly fitted proprietary petroleum consumption and imports/exports data for the preceding countries and group of countries available from the *International Energy Agency* (IEA) since January 1990.[8] The criteria for selecting the above specific list of countries were based on their individual involvement in an exogenous event and the average percentage share over 1990-2014 of a number of selection criteria as summarised in Appendix A.

The proposal is to jointly identify and disentangle the supply shocks of crude oil into exogenous and endogenous, by quantifying the positive and negative shocks of oil production caused by events outside the oil market (exogenous) or as a consequence of the normal functioning of the oil market (endogenous). Exogenous supply shocks originate mainly from geopolitical and political episodes in oil producing countries that lead to the actual disruption in oil drilling and extracting operations of oil facilities. The proposed methodology builds on the approach introduced by Kilian (2008) that identifies the timing, magnitude and sign of a production shortfall from a given country associated with an exogenous event, through explicit assumptions about what would have been that country's production level in the absence of the event. The strategy is to generate the counterfactual production level for this country by extrapolating its production level in the month right before the geopolitical event in question,

[8] Data for petroleum consumption and imports/exports include also Japan, India and IEA Europe, excluding the UK and Norway.

based on the average growth rate of production in other OPEC countries that are subject to similar governance, operational and investment performance (see Appendix B); and not in any way associated with that episode or any other exogenous episode of their own. The change over time in the aggregate exogenous oil production series provides a natural measure of fluctuations in global oil production caused explicitly by exogenous political events.

Endogenous supply shocks are associated directly with substantial positive or negative changes in available operable capacity, relative to demand, as a result of geological, economic and technological stimulus or limitations, respectively. The main theoretical premise underlying this newly proposed methodology is based on Adelman's (1993) economic principle of petroleum supply, according to which oil production depends on the continued renewal of proved reserves as these are extracted, conditional on the best time profile of the relationship between prices, costs and investments. The logic of this relationship unfolds so that the higher the expected oil price, the more it pays to invest into plays with higher discovery and extraction costs per unit that generate long-term value under present conditions of knowledge (positive shock). On the other hand, if oil prices are expected to remain low for a prolonged period of time, the incentive to explore and build new reserves decreases, and supply shrinks as a minimum level of profit on investments can no longer be covered (negative shock; Adelman, 1970, 2002). Accordingly, the study puts forth the explicit assumption that as the growth rate of operable capacity must equal that of oil production, the growth rate of oil production must be approximately equal to that of petroleum consumption.

The proposal is to quantify the endogenous supply shocks by generating the inverse counterfactual path of production both for selected petroleum net importers and net exporters by country, identifying the timing, magnitude and sign of any supply shocks under normal market conditions. The objective is to compute the counterfactual production path for a given net importer or net exporter through explicit assumptions about what that country's production levels would be if these were to grow at a rate approximately equal to its domestic consumption growth. The term *inverse counterfactual* defines the proposed strategy, which in the case of a given net importer is to estimate that amount of supply that needs to be met by its respective exporters and not by its own means. Conversely for the net exporters the strategy is to estimate that amount of supply that is available to be exported to its respective importers, given that its production covers in principle its own domestic needs. The intuition is fairly straightforward: that is, through petroleum inter-regional movements they should offset one another, thus bringing the market fundamentals into equilibrium. This method allows the construction of a monthly time series that takes full account of the timing of oil supply related deviations from the market equilibrium and of variations over time in its magnitude and sign. The change over time in the aggregate endogenous oil production series provides a natural measure of operable capacity shifts in crude oil production, relative to demand, that are explicitly associated to market-specific events. Correspondingly, the sum of the two measures results to an aggregate measure of the total supply shocks.

Over the sample period the task of disaggregating successfully the supply shocks, requires a rigorous identification of all exogenous shocks to the actual production levels of the examined countries, which in contrast to any endogenous event are discernible from empirical observations. The significance of this task is twofold. First, the principal objective is to identify and quantify shocks to OPEC oil production that are exogenous with respect to the normal functioning of the oil market. Second, in order to investigate any supply deviations from the market equilibrium under normal market conditions, the actual oil production levels across all examined OPEC and non-OPEC producers must be adjusted insofar as all exogenous events are isolated. A natural starting point is to consider all geopolitical and political events that caused a physical disruption of oil production in OPEC countries since 1990. Primary candidates are the Gulf War of 1990, the Venezuelan crisis of 2002, the Iraq War of 2003, the Iranian oil sanctions of 2011 and the Libyan Civil Wars of 2011-13. Secondary and other minor geopolitical outages, intermittent in nature, occurred in Iraq and Nigeria. These were associated with the Nigerian oil strikes of 1994, the Iraqi oil embargos under the UN Oil-for-Food Programme (OIP) of 1997-2002, the counterinsurgency in Iraq of 2003-09 and the Nigerian oil crisis of 2005-09. It follows that the construction of the measure of exogenous supply shocks focuses explicitly on all OPEC producers, while other non-OPEC exogenous events[9] are accounted for and isolated accordingly in the computation of the measure of endogenous supply shocks.

3.1. Exogenous supply shocks of crude oil

The counterfactual production level of a given country involved in an exogenous episode is computed by the following general form equation (1):

$$CFS_{\mathrm{i,t}} = S_{\mathrm{i,t-1}} + \left[S_{\mathrm{i,t-1}} * \frac{\sum_{j \epsilon B} \left(S_{\mathrm{j,t}} - S_{\mathrm{j,t-1}} \right)}{S_{\mathrm{j,t}}} \right] \qquad (1)$$

where the counterfactual production level of a country i involved in an exogenous shock at time t, $CFS_{i,t}$, is a function of its production level prior to the event, $S_{i,t-1}$, and the average growth rate of production $S_{\mathrm{j,t}}$ in all countries not involved in an exogenous episode, indicated by j belonging to the benchmark group of these countries B. Analysis of exogenous supply shocks is focused explicitly on all crude oil production shortfalls associated with a geopolitical event, originating from individual OPEC members during the period 1990.1–2015.6; namely Iraq, Iran, Kuwait, Venezuela, Nigeria and Libya. At any point in time, if any of the preceding countries is not involved in an exogenous episode, that country belongs to the benchmark group along with the remaining OPEC producers; namely Algeria, Angola, Ecuador, Gabon, and Indonesia. Explicit in the analysis is the role of Saudi Arabia, which is the only producer that has an official policy of maintaining spare capacity that can be utilised within a relatively short period of time (Fattouh & Sen, 2015). On many occasions Saudi Arabia acted as a swing producer, filling the gap at times of oil disruptions, and a supplier of last resort, adjusting its output intertemporally to balance the market (Fattouh & Mahadeva, 2013). The Saudi output is found to be negatively correlated and highly volatile in comparison to that of other OPEC producers, even though it has not been directly associated with any geopolitical events of its own (Alkhathlan, Gately & Javid, 2014). Accordingly, Saudi Arabia is excluded from the benchmark group for the entire period. Qatar and the United Arab Emirates (UAE) are also excluded from the benchmark, because their operational and investment performance differs from the rest OPEC producers (see Appendix B).

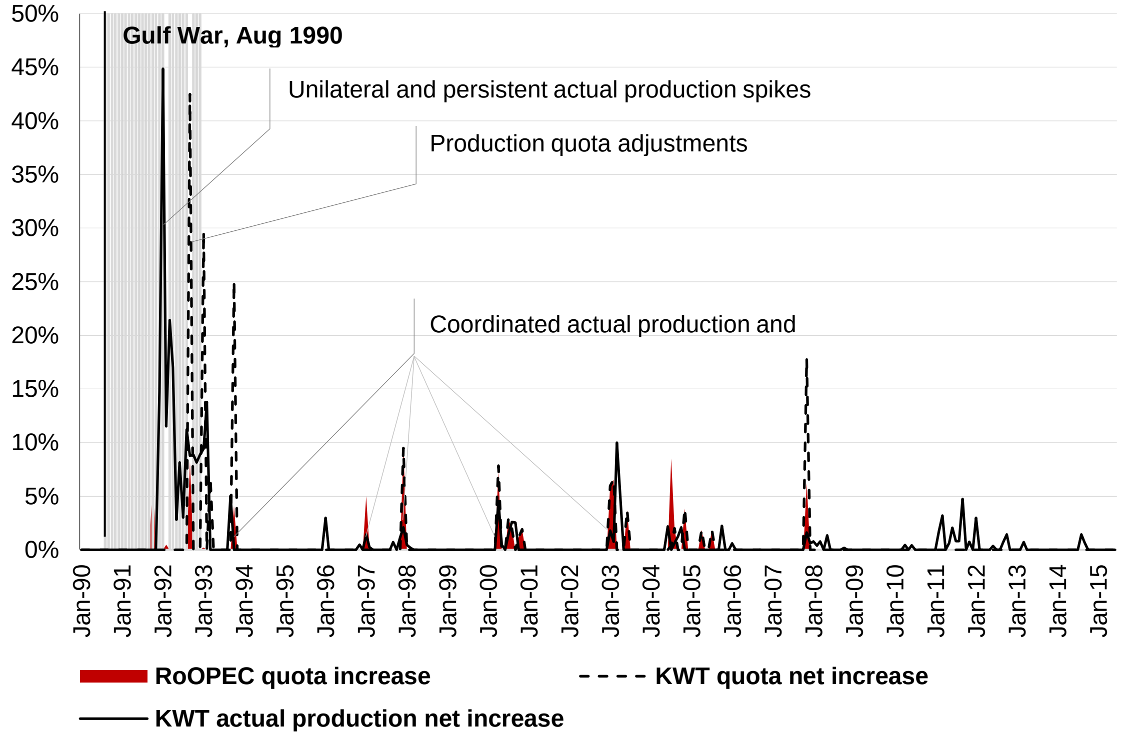
An important concern raised by Kilian (2008) is that the counterfactual of a given country may become less plausible, the further it is extrapolated beyond the most recent exogenous event of a given country.[10] This concern is particularly relevant in this study, in the sense that oil production shortfalls are lasting throughout the entire sample period. The significance is that this would cause the shortfall implied by the aggregate measure of exogenous supply shocks to overstate the true shortfall, a condition that violates the primary assumption underlying the proposed theory for computing the endogenous supply shocks measure. To overcome this shortcoming, we compute a dummy variable to identify the actual duration of all exogenous supply shocks on a country basis. The objective for a country associated with an exogenous event, is to allow for the counterfactual to normalise relative to actual production, given that the initial exogenous event has expired and is not followed by another

[9] In general, these were associated with seasonal weather-related disruptions mainly affecting offshore operations in the US Gulf Coast (USGC), Mexico and the North Sea. Geopolitical outages of 800,000 bpd combined are also observed in Egypt, Syria, Sudan and Yemen following the 2011 Arab Uprisings, which are accounted for in the aggregate Rest of World. All the while, the 2014 Western sanctions on Russia's financial and energy sectors had no apparent effect on the producer's oil production and exports levels.

[10] Kilian (2008, p. 227) conducts a sensitive analysis in order to explore this issue, according to which he derives very similar results to his constructed baseline measure of aggregate exogenous supply shocks.

episode; and insofar as shocks to the supply of oil are recovered from. The monthly dummy series computes the actual duration of the shock by identifying the time when a country enters unilaterally a period of sharp production increases beyond the original expiration of the exogenous episode, in order to recover the loss in output suffered by the event; followed by the gradual reinstatement of its production quotas according to actual production, after which it enters a post-shock period of coordinated increases along with the rest OPEC producers (see Figure 2 for an example). The latter signals the expiration of an exogenous supply shock. By contrast, given the unique ability of Saudi Arabia to act as a swing producer, the task is to allow for the Saudi counterfactual to offset a production

Figure 2: Actual duration of the exogenous supply shock of Kuwait (KWT)



shortfall associated with an exogenous event elsewhere in OPEC, over an extended period of adjustment and not strictly temporary. In this case the aggregate monthly dummy series indicates the actual timing when Saudi Arabia offsets a supply disruption elsewhere and the extent at which an increase in Saudi output is maintained.[11] Table 2 summarises the baseline framework that guides the computation of the exogenous counterfactuals for Iraq, Kuwait, Venezuela, Nigeria, Libya, Iran and Saudi Arabia.

3.1.1. Counterfactual for Iraq

The counterfactual for Iraq begins in August 1990 and is constructed by comparing the actual Iraqi oil output to the production level that would have prevailed following the month after the invasion of Kuwait, had Iraqi production grown at the same rate as that of total OPEC minus the combined production of Iraq, Kuwait, Saudi Arabia, Qatar and the UAE.

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[11] For example, in the face of the supply outages from Iraq and Kuwait during the 1990 Gulf War, the Saudis increased their output by 2.5 mmbpd (to 8.1 mmbpd), up from 5.6 mmbpd, and maintained that level of production for most of the decade (see for a discussion Alkhathlan, Gately and Javid, 2014, p. 212).

Table 2: Framework for the construction of the exogenous counterfactuals

EX		COUNTERFACTUALS						BENCHMARK					EXCLUDED		
Episodes		IRN	IRQ	KWT	VEN	LBY	NGA	ALG	ANG	IND	ECU	GAB	KSA	UAE	QAT
BAND		B	B	B	B	B	B	B	B	B	B	B	B	A	A
90	**[1]**		Aug	Aug											
91															
92															
93															
94	**[2]**						Apr								
95															
96															
97	**[3]**		Jun												
98															
99															
00															
01															
02	**[4]**				Dec										
03	**[5,6]**		Mar												
04															
05	**[7]**						Dec								
06															
07															
08															
09															
10															
11	**[8,9]**	Dec				Feb									
12															
13	**[10]**					May									
14															
15															

[**1**] Gulf War, 1990.8–1991.2
[**2**] Nigerian oil strikes, 1994.4-9
[**3**] Iraq OIP embargos, 1997.6–2002.4
[**4**] Venezuelan crisis, 2002.12–2003.2
[**5**] Iraq War, 2003.3–6
[**6**] Counterinsurgency in Iraq, 2003.7–2009.6
[**7**] Nigerian oil crisis, 2005.12–2009.10
[**8**] Libyan civil war, 2011.2-10
[**9**] Iranian oil sanctions, 2011.12–2015.6
[**10**] 2nd Libyan civil war, 2013.5–2015.6

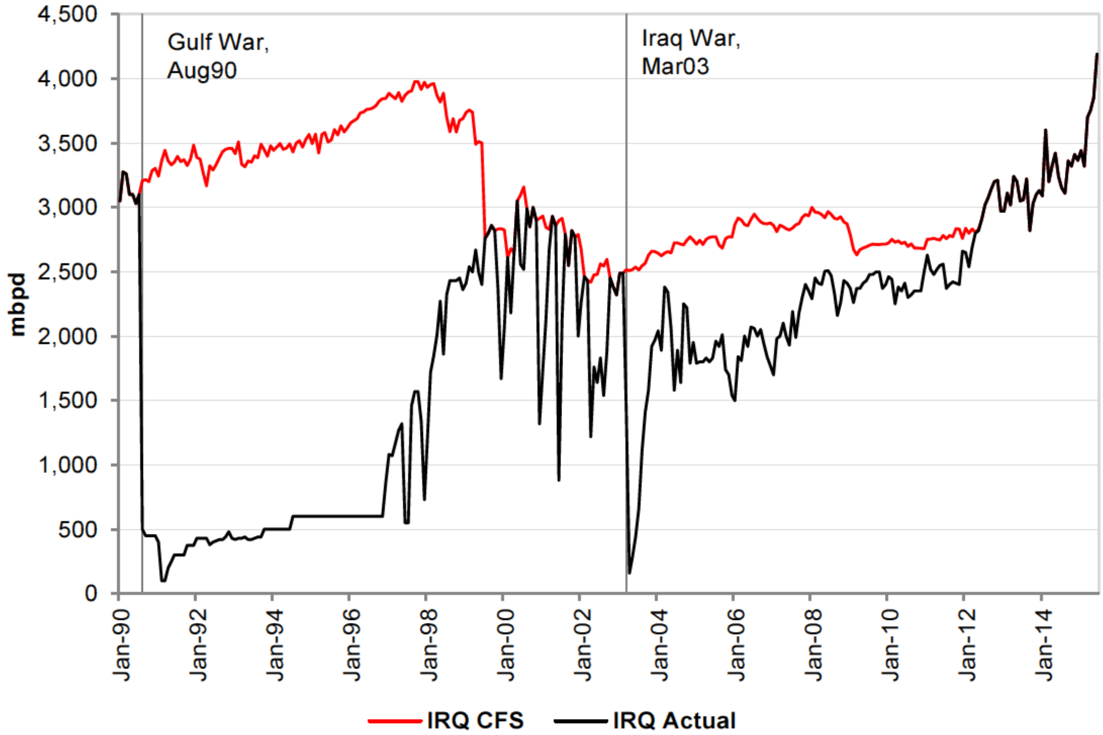
Notes: Red blocks indicate an exogenous event. Grey blocks depict the exclusion of a given producer from the benchmark countries. Ecuador is excluded from the benchmark for the period 1992.12-1997.10, during which the country suspended its membership. Gabon is also excluded from 1995.1, when the country terminated its membership. Angola is included in the benchmark only after 2007.1 when it joined OPEC. Finally, Indonesia decided to terminate its membership, effective on 2009.1 after becoming a net oil importer since 2003. Indonesia is excluded from the benchmark from 2002.1 and not 2009.1, because its declining rates should not be reflected on the production growth of any other OPEC member, as they depict a *prima facie* case of the country's failure to attract new investments confronted by its increasing domestic consumption.

Further adjustments of the counterfactual occur progressively as it is extrapolated, according to the baseline assumptions in Table 2. The complete actual and counterfactual production levels of Iraq are plotted in Figure 3. The vertical difference between the two series at each point in time may be viewed as a measure of the exogenous shortfalls of Iraqi oil production. From the figure it can be seen that Iraqi oil production remained largely subdued by 2.5 mmbpd[12] (at 500,00 bpd) for several years after the Gulf

[12] Million barrels per day.

War, owing to the severe destruction of Iraq's oil infrastructure during the war and the strict international sanctions and trade restrictions against Iraq, imposed by the United Nations (UN). Between 1997-98 production recovered sharply to 2.4 mmbpd after the implementation of the Oil-for-Food Programme[13] (OIP), but the recovery was accompanied by intermittent shocks of 1-2 mmbpd. These were associated with oil exports bans that served as Iraq's negotiating tactic against the context of the UN OIP resolutions. The counterfactual series breaks in July 1999 amid claims that Iraq had reached its operating capacity limit and thus it was unable to increase production much further.[14] In early-2000, Iraqi production grew near pre-shock levels (2.8 mmbpd), only to decline again in the wake of the Iraq War in March 2003. During the US-led military invasion of Iraq, the disruption in oil production was severe (2.9 mmbpd) but only temporary. Oil installations suffered little damage and production recovered rapidly by 2.0 mmbpd in the course of six months. Unfortunately, for Iraq, the end of the war and its consequent military occupation sparked an immediate counterinsurgency that led to the widespread sabotage of oil installations in the following years. The Iraqi oil production eventually recovered to pre-shock levels in late-2012, at 3.2 mmbpd, and gradually increased by more than 1.0 mmbpd towards 2015 (at 4.2 mmbpd as of June 2015).

Figure 3: Counterfactual production levels for Iraq (IRQ)



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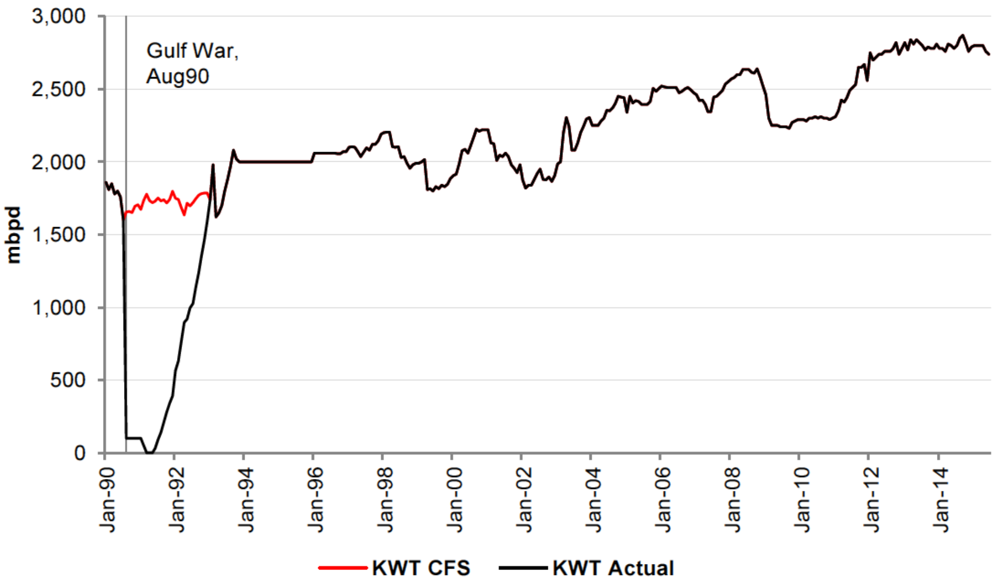
[13] The Oil-for-Food Programme was a temporary and limited exception to the comprehensive international trade embargo imposed on Iraq by the UN, as a consequence of its invasion of Kuwait, in order to alleviate human suffering in Iraq. The OIP was initially agreed upon in May 1996 and allowed Iraq to to sell up to $2.14 billion worth of crude oil in the world oil market, per six-month phase, in exchange for food, medicine and other humanitarian relief to its citizens (Katzman, 2003).

[14] In February 1998 the UN more than doubled the monetary ceiling of Iraqi oil exports at $5.26 billion over six months, but the Iraqi regime maintained that it only had the capability to export up to $4.0 billion over that period (Katzman, 2005). Subsequently, in June 1998 a new UN resolution allowed Iraq to spend $300 million on spare parts and oilfield equipment in order to help increase its capacity and meet its exports' target. A year later, however, the Iraqi output increased near 2.8 mmbpd (July 1999) around which level it plateaued until 2001.

3.1.2. Counterfactual for Kuwait

Figure 4 shows the counterfactual for Kuwait, which is based on total OPEC oil production minus the combined production of Iraq, Saudi Arabia, Qatar and the UAE, considering the rationale that follows from the preceding discussion. During the Gulf War, the extensive damage inflicted on Kuwaiti oil infrastructure resulted to a supply outage of 1.4 mmbpd. Adding to the problem were the Kuwaiti oil fires in February 1991 that led to the complete shutdown of Kuwait's oil production (UN, 1991).[15] Despite the devastation of the Kuwaiti oil industry during the war, its recovery proceeded with surprising speed and oil production recovered to its prewar levels, at 1.9 mmbpd, in less than three years (January 1993). In the remaining period, Kuwait was not associated with or affected by any other exogenous event and thus it returns to the benchmark.

Figure 4: Counterfactual production levels for Kuwait (KWT)



3.1.3. Counterfactual for Venezuela

Venezuela's exogenous supply shock is associated explicitly with its severe political instability. In 2001, the ongoing tensions between the president Hugo Chávez and his opposition erupted to a civil unrest with the passing of reforms directed at Venezuela's oil industry. In 2002 Chávez appointed a new board of directors for the country's NOC, the Petróleos de Venezuela (PDVSA), prompting a general strike that lasted almost two months. During that time, output fell by 2.0 mmbpd, down to 600,000 bpd, while the government fired nearly half of its thousands of PDVSA oil workers. That meant that the full recovery of production could not have been achieved. In fact, production only recovered to 2.2 mmbpd, 400,000 bpd below its pre-shock levels, at which level it plateaued for three years until thirty-two privately operated Venezuelan oil fields returned to state control and added 500,000 bpd of additional output (2006). Figure 5 presents the counterfactual for Venezuela, which lasts only for six months (2002.12-2003.5), as the events that follow after the oil strikes had been a product of ongoing reforms in Venezuela's oil sector and hence are not treated as exogenous.

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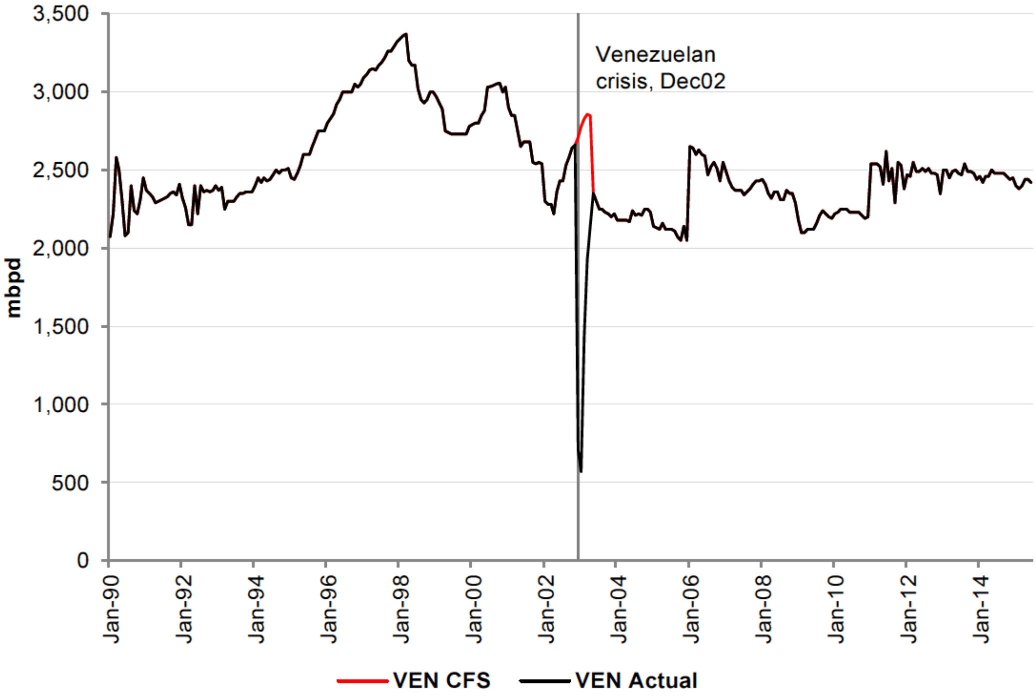
[15] As part of a scorched-earth policy while retreating from Kuwait in February 1991, the Iraqi military forces set to fire about 732 out of 1,330 active Kuwaiti oil wells. The high subsurface pressures kept the fires burning for more than eight months, consuming about 2% of the country's 1,000.0 mmbbls of proven reserves, until the last well was capped in November 1991 (UN, 1991).

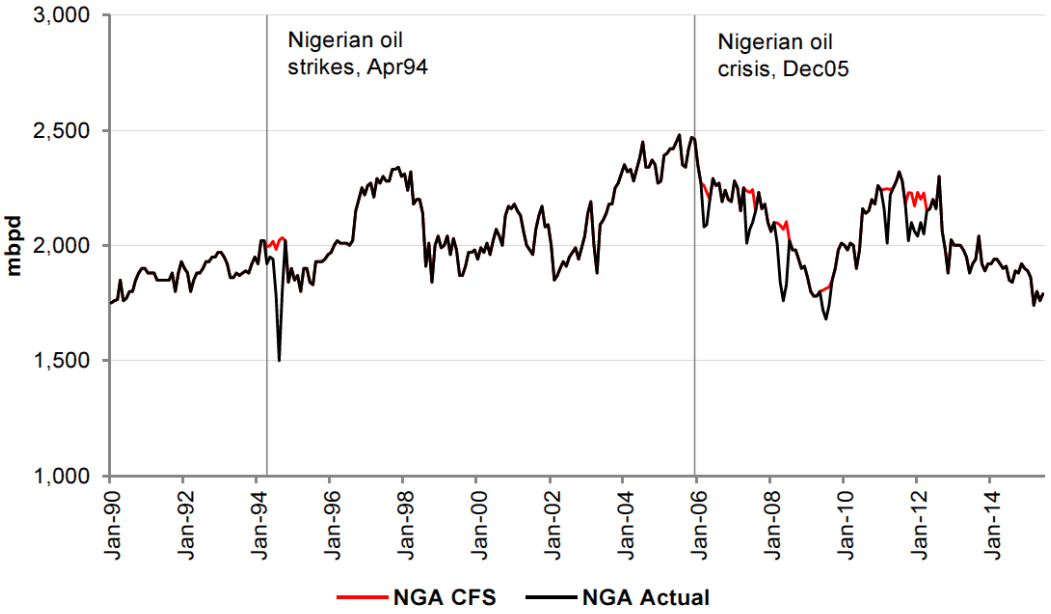
Figure 5: Counterfactual production levels for Venezuela (VEN)



3.1.4. Counterfactual for Nigeria

Nigeria's crude oil production suffers from chronic political instability, civil unrest, corruption and looting. Despite the fact that the exogenous shocks associated with Nigeria were less severe than those of any other country included in this analysis, we consider two exogenous episodes that in both instances removed 25% of the total Nigerian oil production. First, the Nigerian oil strikes of April 1994, in response to the imprisonment of the apparent winner of presidential elections, which paralysed the country for five months and led to a sharp decline of 500,000 bpd. Second, the Nigerian oil crisis that erupted in 2004 and escalated to an 'all-out-war' in 2005-06, when the Movement for the Emancipation of the Niger Delta (MEND) launched disruptive attacks in oil operations and facilities (Adams, 2014). By 2009 Nigerian output fell by 800,000 bpd from its value in 2005 (2.4 mmbpd), but recovered significantly in 2009-10 following the implementation of the amnesty program and the increased drilling efforts in new deepwater offshore production. Figure 6 shows the complete counterfactual for Nigeria.

Figure 6: Counterfactual production levels for Nigeria (NGA)

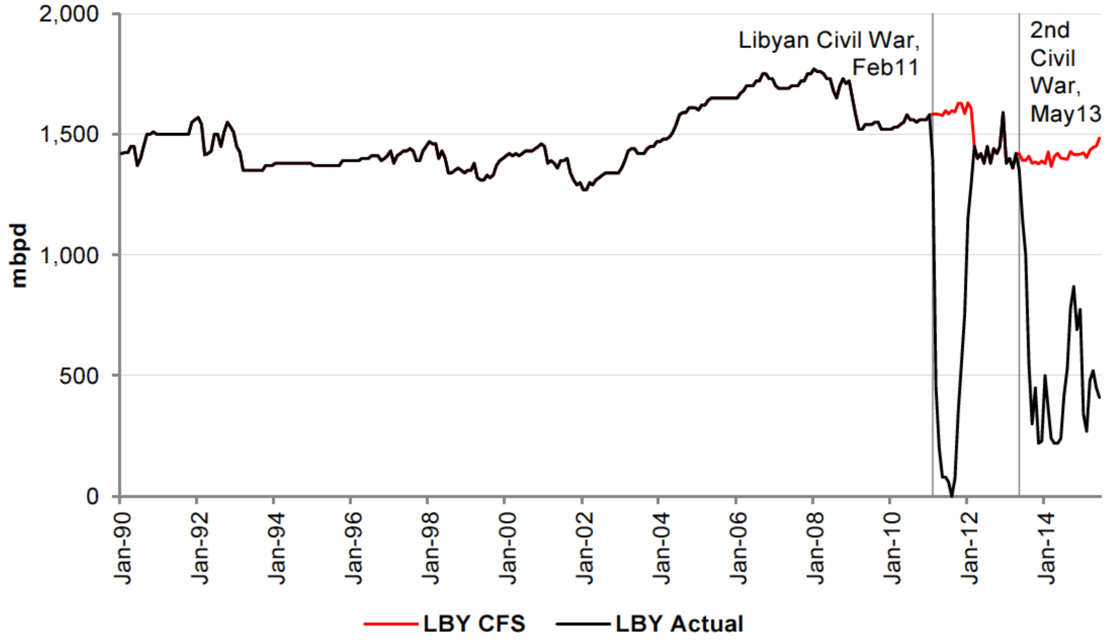


3.1.5. Counterfactual for Libya

The beginning of the 1st Libyan Civil War can be dated in February 2011, when violent protests erupted against the Qaddafi regime and escalated rapidly into conflict. NATO allies under the provisions of the UN Security Council attacked the regime and began a seven-month air campaign that eventually resulted to the regime's demise. The physical damage on oil infrastructure due to the conflict was relatively minimal, but oil production dropped precipitously to a mere 22,000 bpd, as a result of the fighting on the ground.[16] Immediately after the war, oil production recovered rapidly back to 1.4 mmbpd (March 2012), only to decline again in September 2013 as the control of oil had once more become a key factor in continuous regional and sectarian tensions. Oil facilities were taken over by armed forces causing the largest post-war drop in production, down to 160,000 bpd. In 2014, the proliferation of weapons, Islamic insurgencies, sectarian violence and lawlessness erupted to the 2nd Libyan Civil War, which is still ongoing. Most of the oilfields are completely or partially shut down as major refineries, oil loading ports and pipelines are seized by militants or not operating. Most importantly, due to the chaotic situation on the ground it is difficult to determine who's in control over Libya's oil and gas resources, let alone its NOC. The counterfactual for Libya is shown in Figure 7.

[16] From early on in the conflict, rebels controlled the east and south oil-rich provinces. Reports suggest that the low levels of physical damage were due to the fact that NATO planners went to great lengths to ensure that Libya's hydrocarbon industry was not seriously disrupted by military operations (Chivvis & Martini, 2014).

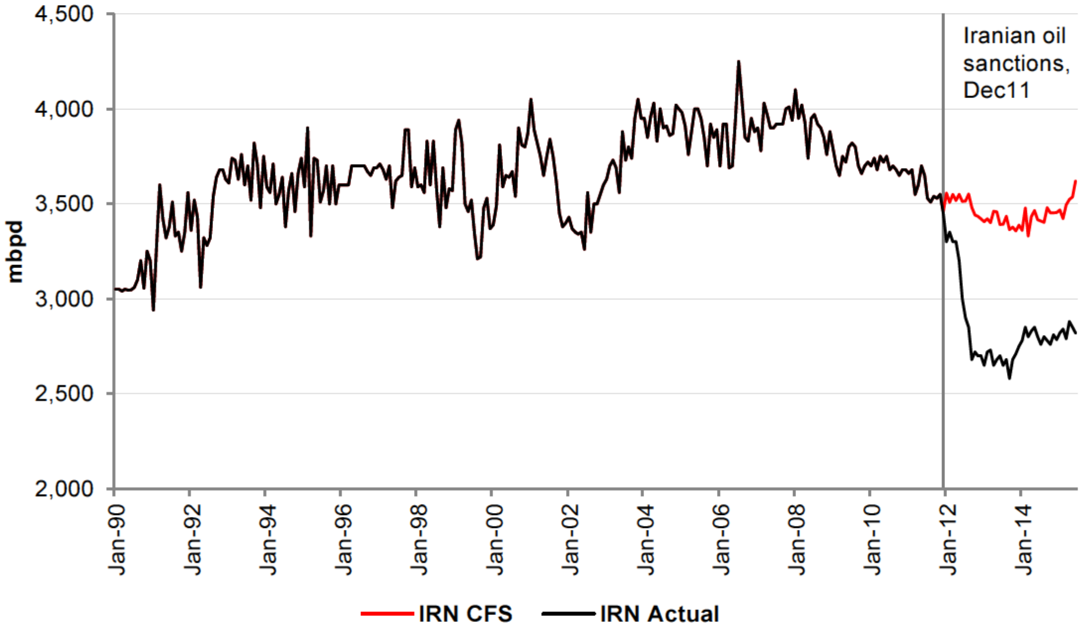
Figure 7: Counterfactual production levels for Libya (LBY)



3.1.6. Counterfactual for Iran

Iran had been under progressively strict US economic sanctions since 1996, which primarily targeted its energy and financial sectors but had no apparent effects on the Iranian output. In 2012, however, an EU imposed embargo over the Iranian nuclear program targeted Iran's oil exports, resulting to an output reduction of 800,000 bpd and a drop to Iranian exports by 1.3 mmbpd (1.6 mmbpd). Iran warned at the time that no other OPEC member should offset the loss of Iranian output in the oil market, but only for Saudi Arabia to disregard Iran's plea and replace the 800,000 bpd with its own production. Figure 8 plots the counterfactual for Iran, which is based on oil production from total OPEC minus the combined production from Libya, Saudi Arabia, Qatar and the UAE.

Figure 8: Counterfactual production levels for Iran



3.1.7. Counterfactual for Saudi Arabia

Considering that there is no explicit indication of the timing and duration of a Saudi exogenous supply response, the episodes that prompted an increase in Saudi production have been identified based on the dummy measure discussed above in corroboration with historical evidence. Figure 9 shows that there were three exogenous events during which the Saudis increased their output to offset the incipient shortfalls in production elsewhere in OPEC. The first relates to the 1990 Gulf War, when Saudi Arabia sharply increased its production by 2.5 mmbpd in the month right after the invasion of Kuwait, followed by another 700,000 bpd during the war (3.2 mmbpd). The Saudi response was maintained for several years and lapsed only in mid-1998 (by 825,000 bpd), as the Iraqi OIP exports' target was doubled and the trade restrictions on spare parts and oil equipment were relaxed (in February and June 1998, respectively).[17] The second relates to the 2002 Venezuelan crisis and the anticipated invasion of Iraq in March 2003.

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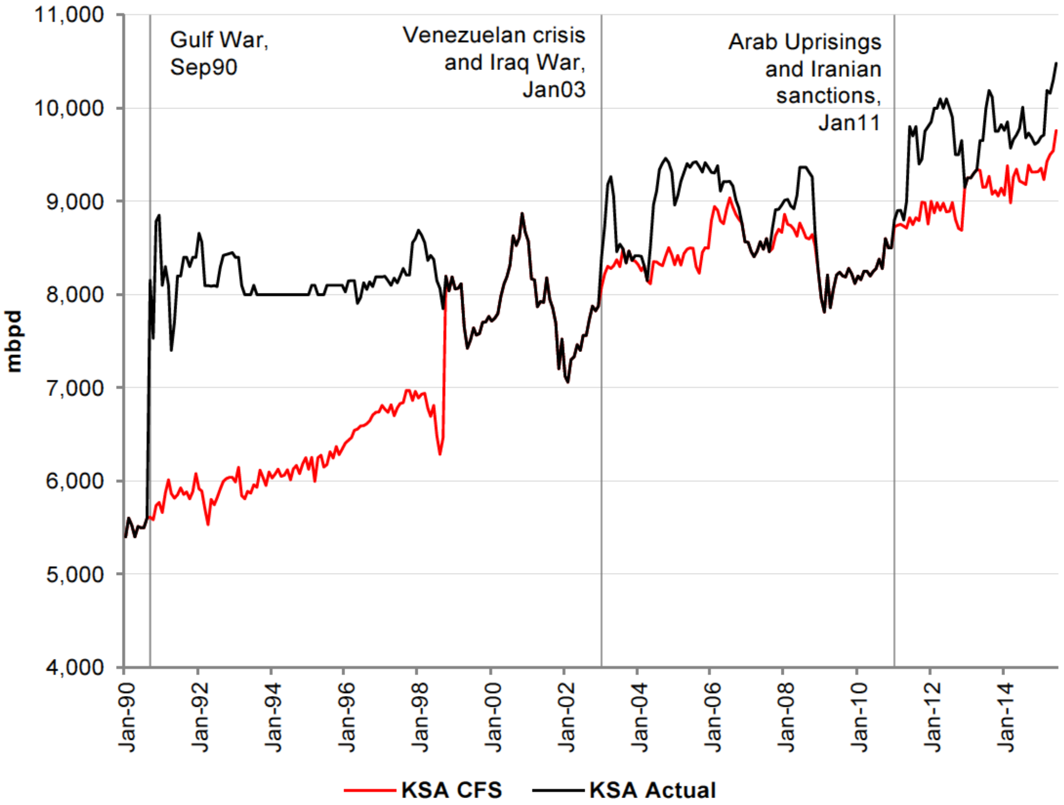
[17] It is important not to discount the events that followed the 1997 Asian Financial Crisis, when prices collapsed below $20/bbl as supply was growing in excess of consumption. Saudi Arabia was reluctant to cut production and pushed for a collective action with producers outside OPEC that materialised only in 1999, when Mexico, Norway, Oman and Russia pledged to contribute by 500,000 bpd. The Saudi production quotas were eventually curtailed in April 1999 by 600,000 bpd, and were matched by actual production a month later (7.4 mmbpd).

Figure 9: Counterfactual production levels for Saudi Arabia (KSA)

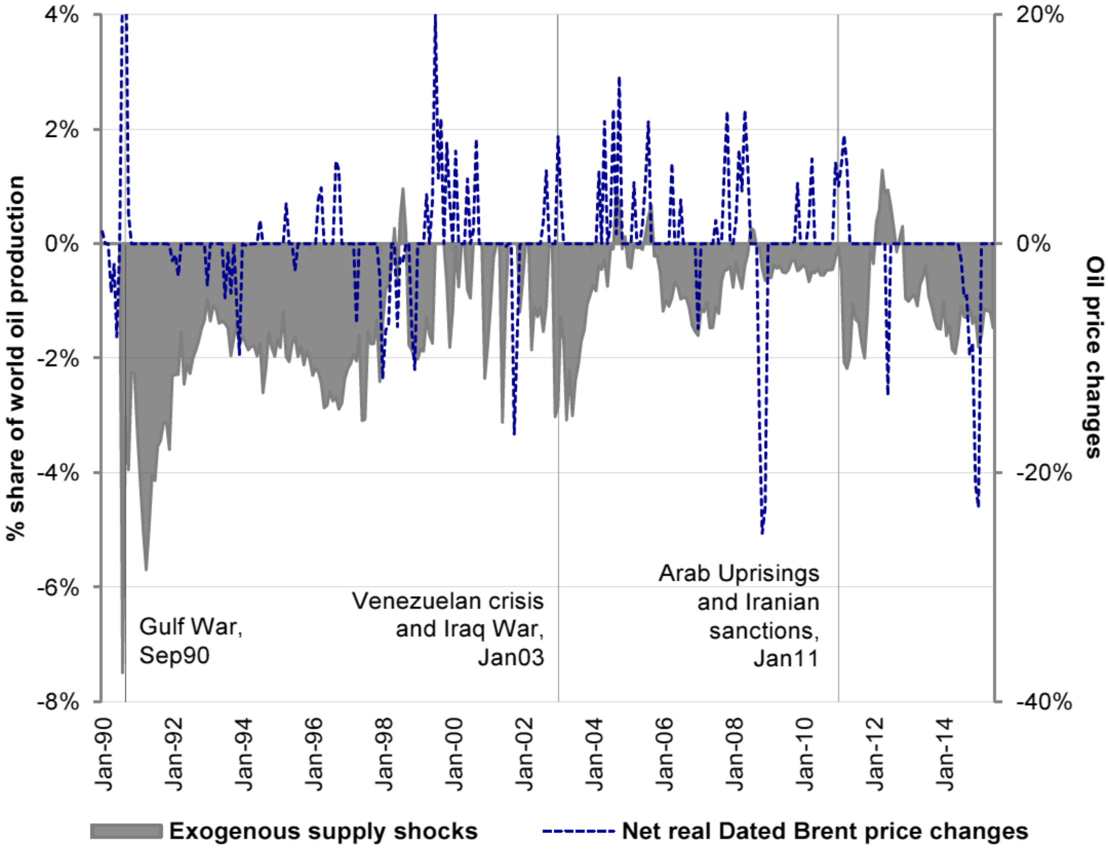


The Saudi output increases started in January 2003 by 520,000 bpd and reached at 1.3 mmbpd two months later. Initially, this increase appeared temporary and lapsed as soon as the Iraq War ended, but it was followed by another sharp increase of 1.0 mmbpd, nine months later. Whereas this increase was primarily motivated by the unprecedented demand growth at the time, the Saudi supply response absorbed the lost share of production from the Iraqi and Nigerian shortfalls (1.1 mmbpd), which is why it is treated as exogenous. However, during 2005-06 production from Saudi Arabia plateaued and declined progressively by 800,000 bpd as the Kingdom was closing to its capacity limit (9.3 mmbpd), at which point the counterfactual is dropped. The final episode relates to the revolutionary wave of demonstrations, protests, riots and civil wars that spread throughout the MENA region in December 2010. The Saudis needed to boost their oil production, and therefore their oil rents, in order to increase their public spending and meet the aspirations of their population (Stevens, 2012). Starting in January 2011, Saudi output gradually increased by 1.3 mmbpd as a response to the shortfalls in Libyan and Iranian oil production. The response is maintained in the remaining period, owing to the progressive disruptions in the Iranian output and the second wave of the Libyan Civil War.

3.1.8. Aggregate measure of exogenous supply shocks of crude oil

A monthly series of the aggregate measure of exogenous supply shocks is constructed by summing all OPEC country-specific shortfalls in oil production and the Saudi production increases as a response, in the period 1990.1–2015.6. The resulting plot is illustrated in Figure 10 and it is expressed as a percentage share of world oil production. Any negative change in the series indicates a production shortfall associated with an exogenous episode, which is expected *ceteris paribus* to have a positive signed effect on the real price of oil. By construction, the disruptions in oil supply are followed by positive changes that indicate the degree of reversal of a shortfall, owing to an offset from Saudi Arabia or the gradual recovery in oil supply, which is expected *ceteris paribus* to have a negative signed effect on oil prices. A zero value indicates that there was no supply shock related to an exogenous episode at that point in time. The movements in the baseline measure reflect the key historical events described in the preceding sections. Fluctuations in oil production caused by exogenous supply shocks range from approximately 1% to -7.5% of world oil production. Results show that for most of the 1990s, shortfalls in oil production that were brought about by geopolitical episodes accounted for about 7% of the variability in global crude oil production. By comparison, after 2000-onwards exogenous oil production shortfalls accounted only for about 2% of global supply. These findings indicate the absence of any significant physical supply disruptions since 2003, as one would expect, consistent with the view that recent oil price shocks cannot be explained by exogenous shortfalls in oil production but are largely attributed to market-specific events, i.e. 2000-01, 2004-07, 2009-10 and 2014-15.

Figure 10: Aggregate measure of exogenous supply shocks of crude oil



3.2. Endogenous supply shocks of crude oil

The newly proposed methodology utilises monthly oil production and consumption data for selected net importers/exporters by country since 1990, namely for all OPEC, the US, China, Japan, India, IEA Europe excluding UK and Norway, Russia, combined UK and Norway representing the North Sea, Canada, Mexico and on aggregate Rest of World.[18] Recall that the main theoretical premise for

[18] Excluding the last aggregate, the selected list of countries combined is a representative sample of 81% of the world's total crude oil production and 79% of the world's total petroleum liquids consumption, in the 25-year period (see Appendix A).

constructing a measure of endogenous supply shocks postulates that as the growth rate of operable capacity must equal that of oil production, the growth rate of oil production must be approximately equal to that of petroleum consumption. Accordingly, the inverse counterfactual production level of a given net importer is computed by the following general form equation (2):

$$CFSI_{\mathrm{i,t}} = S_{\mathrm{i,t-1}} + S_{\mathrm{i,t-1}} \left[\frac{D_{\mathrm{i,t}} - D_{\mathrm{i,t-1}}}{D_{\mathrm{i,t}}} - \sum_{j=1}^{J} w_{ij} \frac{S_{\mathrm{j,t}} - S_{\mathrm{j,t-1}}}{S_{\mathrm{j,t}}} \right] \quad (2)$$

where the counterfactual production level *CFSI* of a net importer at month *t* is equal to its production level in the previous month $S_{\mathrm{i,t-1}}$ and the rate of change in total domestic consumption D_{i} minus the change rate in production S_{j} in all countries *J* from which imports are drawn in month *t*, with the production from each importer weighted according to its contribution to the share of domestic consumption covered by all imported crude oil. This method allows for the counterfactual production level of a given net importer to grow at the rate at which its own production should increase in order to meet the growth rate of its total consumption. Following a counter-rationale, the inverse counterfactual production level of a given net exporter is computed by the following general form equation (3):

$$CFSE_{\mathrm{i,t}} = S_{\mathrm{i,t-1}} + S_{\mathrm{i,t-1}} \left[\frac{S_{\mathrm{i,t}} - S_{\mathrm{i,t-1}}}{S_{\mathrm{i,t}}} - w_i \frac{D_{\mathrm{i,t}} - D_{\mathrm{i,t-1}}}{D_{\mathrm{i,t}}} \right] \quad (3)$$

where the counterfactual production level *CFSE* of a net exporter at month *t* is equal to its production level in the previous month $S_{\mathrm{i,t-1}}$ and the rate of change in total production S_{i} minus the change rate in domestic consumption D_{i} weighted on the percentage share of total production covering its domestic demand. Hence the counterfactual production level of a given net exporter grows at the rate at which its production should increase in order to meet the consumption growth rates of its respective importers that correspond to its share, given that its production covers, in principle, its own domestic demand. This method allows the construction of a monthly time series that takes full account of the timing of any oil supply-related deviations from the market equilibrium and of variations over time in their sign and magnitude. It is thus possible to construct a measure of the aggregate endogenous supply shocks across all the selected countries as a percentage share of world oil production.

Prior to the commencement of the analysis, we need to assign weights, which are estimated by utilising monthly fitted proprietary petroleum consumption and imports/exports data for all countries available by IEA since January 1990. For the net importers we weight by country the percentage share contribution of domestic crude oil production and imports by origin to their total petroleum liquids consumption. For the net exporters we weight by country the percentage share contribution of total production to domestic demand and exports by destination. In all cases production refers to crude oil whereas consumption refers to all petroleum liquids. For this reason, we revert all petroleum liquids values to approximate crude oil equivalent values using the global average refinery yield of 43.1 US gallons or 1.062 boe suggested by EIA. In reality the refinery gain varies depending on the refinery equipment, its configuration and the type of crude oil. Table 3 summarises the baseline framework that guides the computation of the endogenous counterfactuals that follow for the US, China, OPEC, Russia, Canada, Mexico and the North Sea.

Table 3: Framework for the construction of the endogenous counterfactuals

		COUNTERFACTUALS						
		NET IMPORTERS		NET EXPORTERS				
From	***To***	***US***	***CHI***	***OPEC***	***RUS***	***CAN***	***MEX***	***NS***
US		0.489	.	0.123	.	0.349	0.420	.
CHI		.	0.653	.	.	.	.	.
EUR		.	.	0.123	0.535	.	.	0.587
Asia/Pacific		.	.	0.493	0.120	.	.	.
OPEC		0.256	0.278	0.170	.	.	.	.
RUS		.	0.024	.	0.304	.	.	.
CAN		0.099	.	.	.	0.633	.	.
MEX		0.075	.	.	.	.	0.468	.
NS		.	.	.	.	.	.	0.326
ANG		0.017	.	.	.	.	.	.
RoW		0.050	0.045	0.082	0.013	0.018	0.105	0.065

Notes: The observed values denote the assigned weights which correspond to the percentage share allocation of production from a given country to domestic consumption and imports/exports flows, averaged for the entire period. The Asia/Pacific region refers to China, India and Japan. Europe includes Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, and Turkey; excluding Norway and the United Kingdom (North Sea).

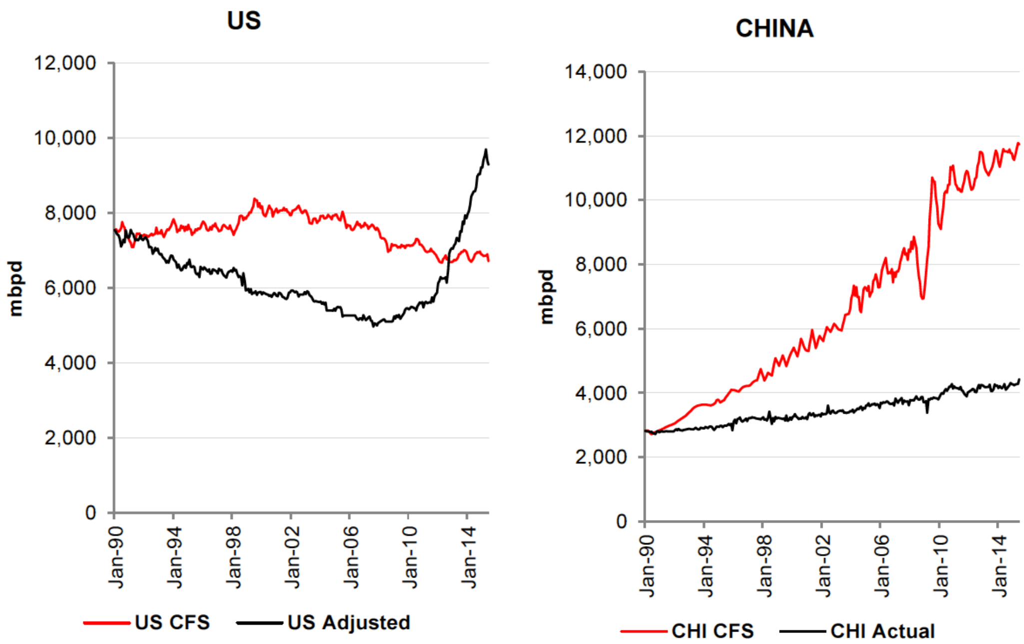
3.2.1. Counterfactuals for the net importers

Figure 11 shows the inverse counterfactual production levels for the US and China. The counterfactuals are constructed by comparing their actual oil output to the production level that would have prevailed, had production grown at an approximate growth rate as that of total consumption minus the weighted production growth rate of their respective exporters. The vertical difference between the two series at each point in time may be viewed as that amount of supply that needs to be met by imports drawn and not by their own means. For example, the counterfactual for the US is based on the growth rate of its total consumption minus the weighted production growth rate of total OPEC, Canada, Mexico, Angola until 2007 and the Rest of World. The actual US production has been adjusted insofar as all exogenous episodes are isolated. Two important observations follow. First, the US oil production had been in steady decline since 1990, until 2008, when the so-called “US unconventional revolution” experienced an unprecedented growth that reversed and tripled-up the US oil output quite smoothly. The huge growth in US shale supply has had a profound impact on the dependency of the US on oil imports, as import demand more than halved in the past decade from its peak in 2005 (12.0 mmbpd). Conversely, the Chinese import demand has risen dramatically in the 25-year period, from approximately 18% of China’s total consumption in 1990 to over 60% in 2014. This increase in oil demand outstripped Chinese supplies and exerted substantial pressure on oil exporting sources, especially OPEC.

3.2.2. Counterfactuals for the net exporters

Following a counter-rationale to the net importers logic, the inverse counterfactuals for the net exporters are constructed by comparing their actual oil output to the production level that would have prevailed, had production grown at an approximate growth rate as that of their weighted total domestic demand. Figure 12 illustrates the counterfactual production levels for total OPEC, Russia, Canada, Mexico and the North Sea respectively. The vertical difference between the two series at each point in time may be viewed as that surplus amount of supply that is available to be exported, given that production covers in principle their own domestic needs.

Figure 11: Counterfactual production level for the net importers



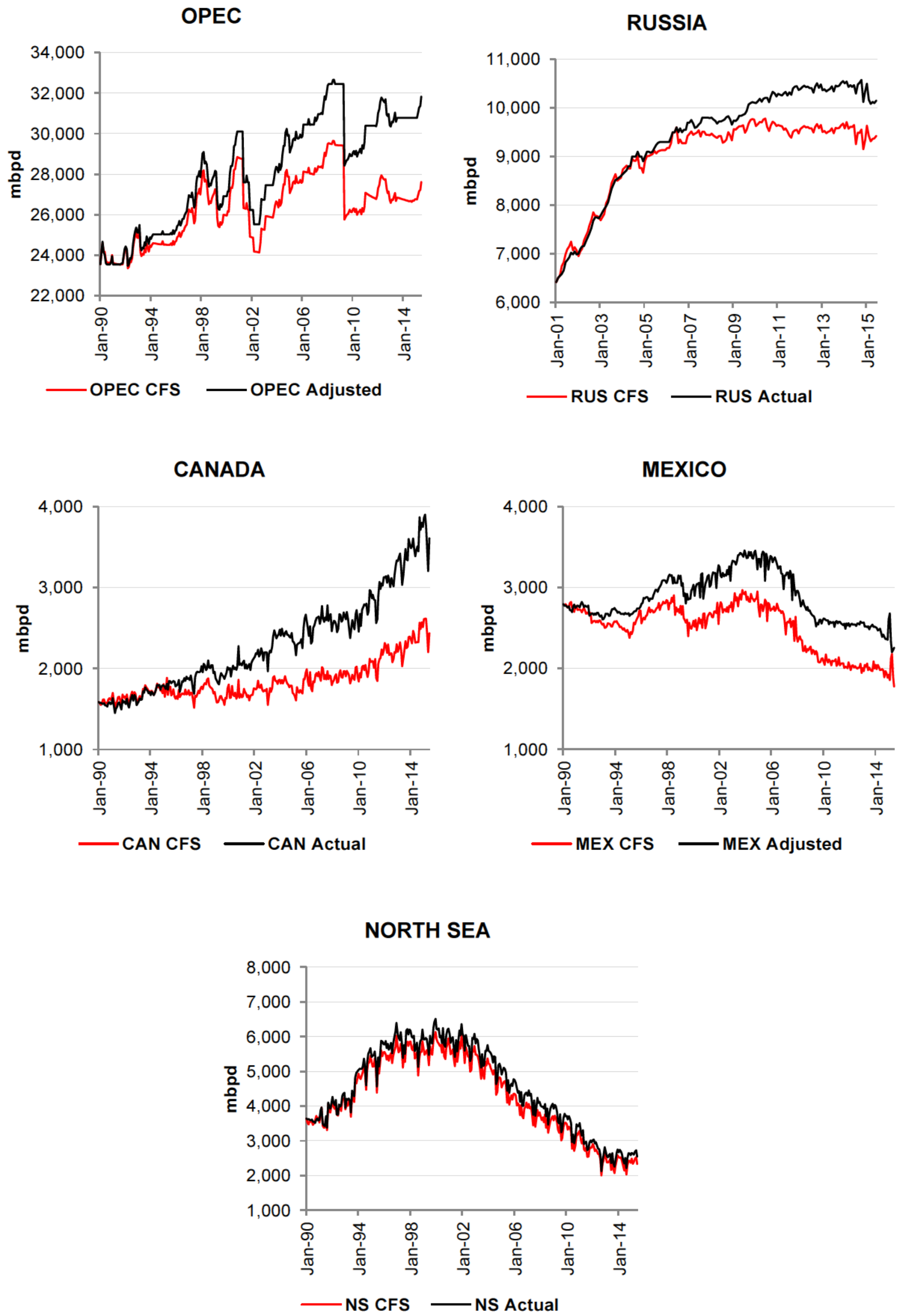
As can be seen from the figure, the largest contributors to productive capacity expansion in the previous decade had been OPEC (3.5 mmbpd), Canada (1.2 mmbpd) and at a lesser extend Russia (700,000 bpd). Oil production from Mexico and the North Sea, by contrast, had been in steady decline since the early-2000, while the tightness of 2000-06 had been apparent for all oil exporters. Strong capacity gains follow only after 2010, especially from Canada due to a rise in the extraction of the Canadian Oil Sands.

3.2.3. Aggregate measure of endogenous supply shocks of crude oil

An aggregate measure of the endogenous supply shocks across all OPEC and non-OPEC countries can be obtained by summing the time series of all country-specific supply shocks in the period 1990.1−2015.6 and further subtracting the available spare productive capacity, thus taking into account the total available operable capacity. We postulate that the amount of spare capacity to be subtracted from the constructed measure is any amount over the spare capacity buffer of 2.0 mmbpd, which is in line with OPEC's stated intentions.[19]

[19] As an informal rule of thumb, oil market analysts suggest that OPEC needs to hold at least 5% of global oil demand in spare production capacity in order to maintain stable prices and balance in the market equilibrium, which equals around 4.0 mmbpd on average for the period 1990-2015 (McNally, 2012). However, the 5% spare capacity rule applies best when geopolitical conditions are calm and thus it does not suit the specifications of this analysis.

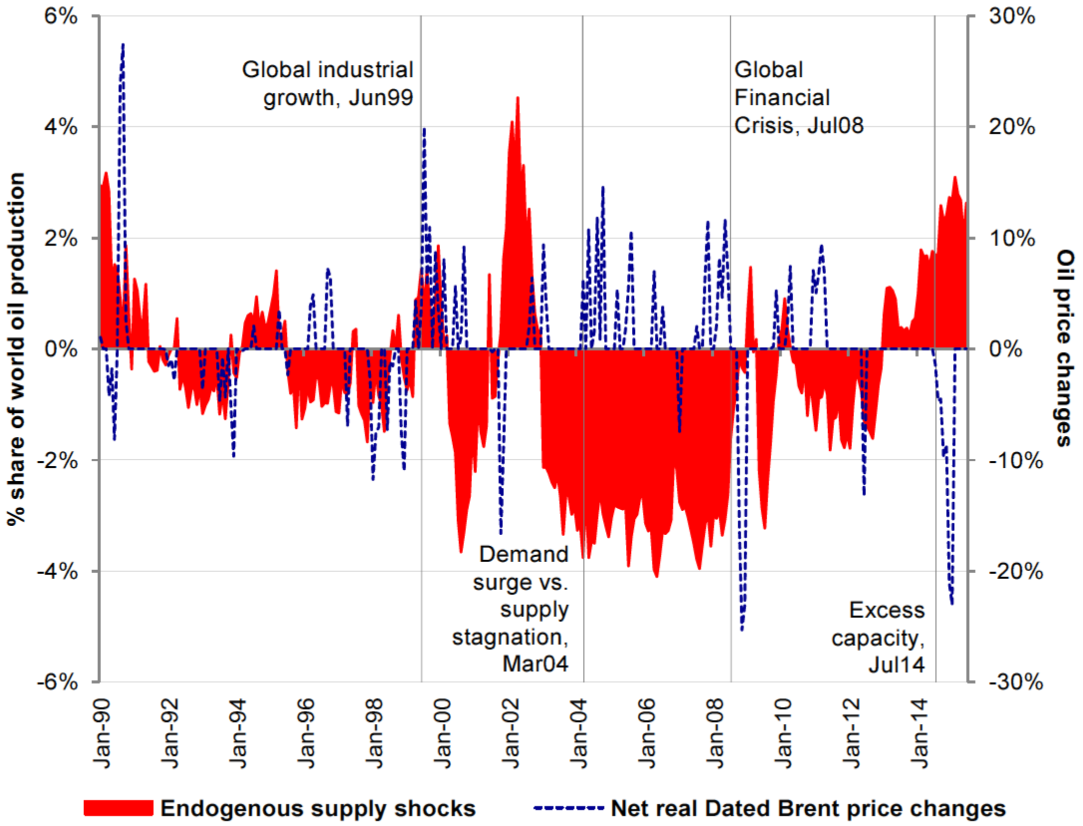
Figure 12: Counterfactual production levels for the net exporters



The resulting monthly series is expressed as a percentage share of world oil production. Any negative change in the time series indicates a negative deviation of supply from the market equilibrium due to capacity constraints associated with market-specific events, e.g. large shifts in demand amid stagnant production, which is expected *ceteris paribus* to have a positive signed effect on the real price of oil. By contrast, any positive change in the series indicates a positive deviation of supply from the market equilibrium in the sense that capacity expansion has run ahead of demand, which is expected *ceteris paribus* to have a negative signed effect on the real oil price.

Figure 13 shows that endogenous supply shocks range from approximately +4% to -4% of world oil production. The resulting plot shows that in the 1990s endogenous supply shocks accounted for a mere 1% of the variability in global oil production. However, this trend reverses after 2000 onwards, as fluctuations in global oil production can be largely attributed to market-specific events (accounted for 6%). For example, the initial negative shortfalls of operable capacity caused by endogenous supply shocks in 1999-2000 and 2002-08 are consistent with the literature in that these periods were characterised by booming demand and stagnant production as a result of the decade-long upstream underinvestment in the 1990s. The same is true for the period starting in mid-2012, when the oil price experienced the first signals of an oversupplied oil market. In early 2014, the supply-demand gap surpassed the barrier of 1.5 mmbpd and averaged close to 2.2 mmbpd for the rest of the period. A close examination of the constructed series allows for the following observations: (1) the relative absence of oil production disturbances in the 1990s, confirms that the series is free from exogenous shocks; (2) there appears little doubt that the prolong supply tightness starting in 2003 had been market-driven; and (3) the constructed series performs relatively well in relation to the timing of the oil price events and the magnitude of the shocks to oil supply.

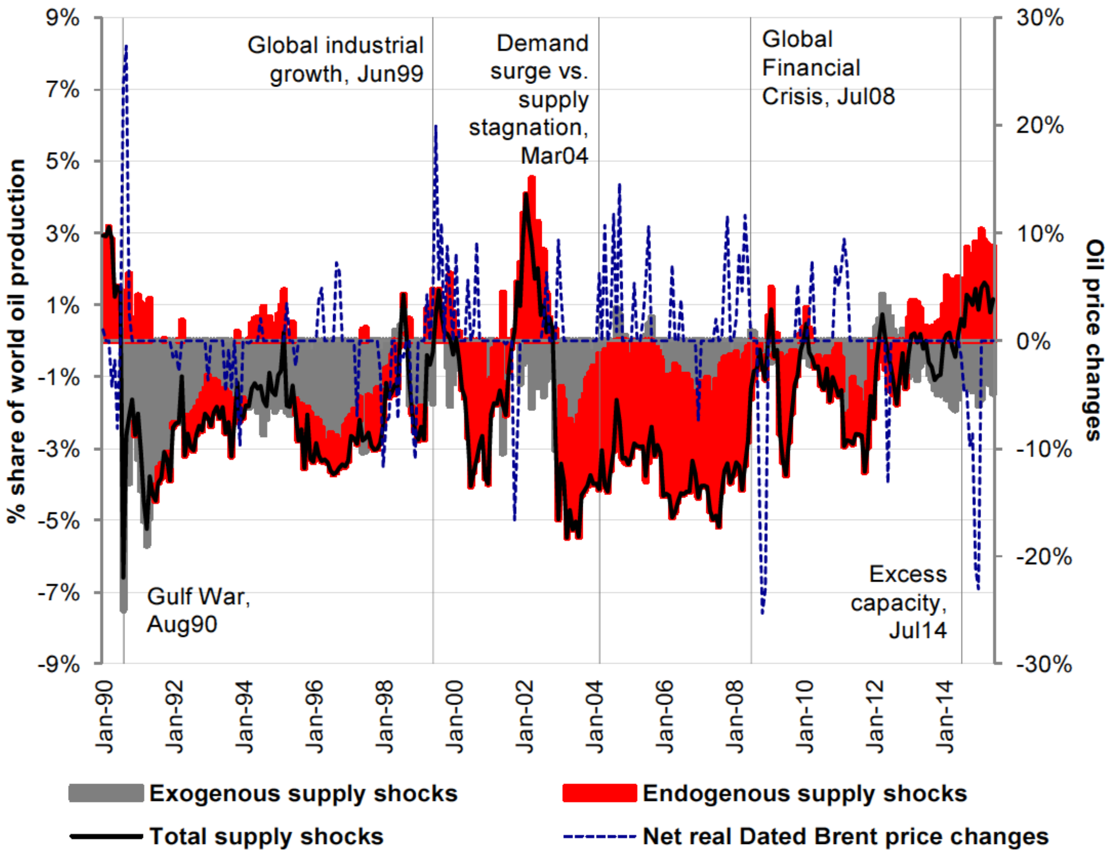
Figure 13: Aggregate measure of endogenous supply shocks of crude oil



3.3. Aggregate measure of total supply shocks of crude oil

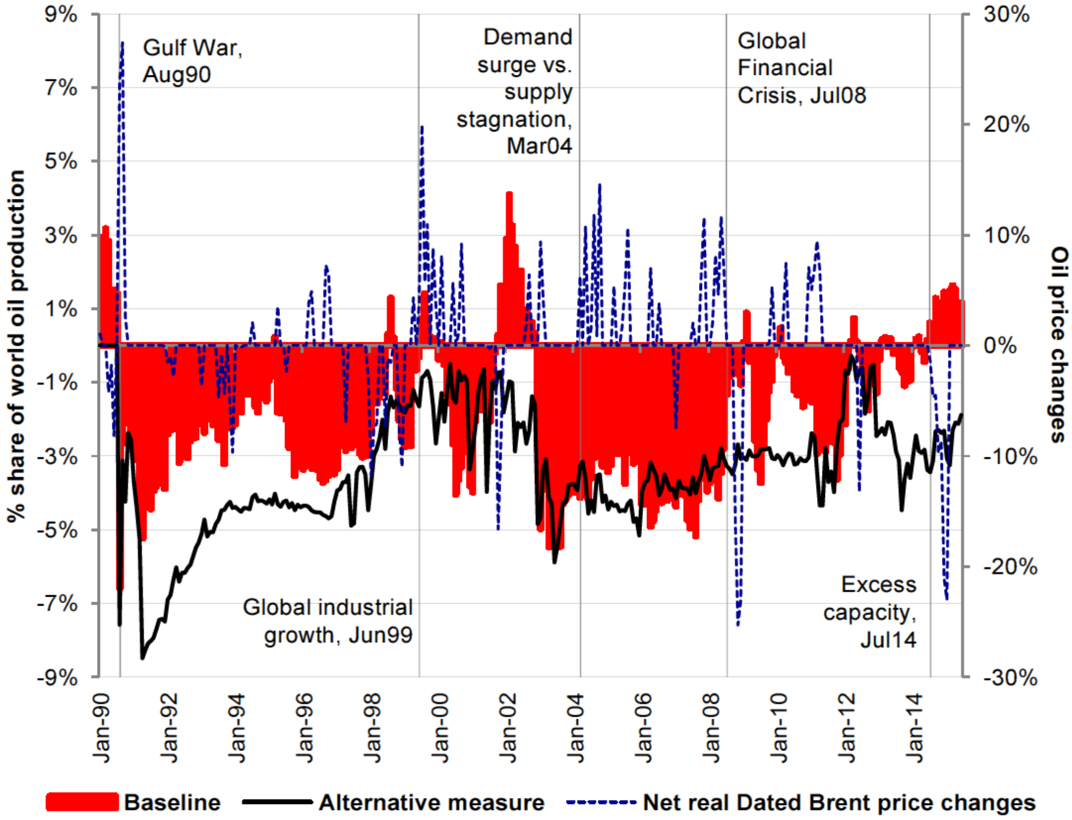
Figure 14 plots the combined total of supply shocks for the period 1990.1−2015.6, stacked with each discrete category of supply shocks, i.e. exogenous and endogenous supply shocks, while being related to the net oil price changes for the same period. The evidence so far suggests the following remarks. First, evidently the constructed measures are in good agreement with developments in the oil price and indicate that, in explicit terms of the supply side of the market, oil price shocks in recent years can be associated with endogenous innovations in crude oil production that were brought about largely by market-specific events, i.e. large shifts in demand hit the capacity constraints or capacity expansions run ahead of demand.

Figure 14: Aggregate measure of total supply shocks of crude oil



Second, the robustness of the resulting plot can be reconciled with the actual episodes of the oil market in the sense that the timing, magnitude and sign of both measures are consistent with the actual oil price data, i.e. in 1990-91, 2000-01, 2004-08, 2009-10 and 2014-15. Third, oil price developments after 2012 are reflected explicitly on the cumulative effects of the aggregate supply shock series, as the two categories coexist and lead to the build-up of the 2014 oil price collapse. All the while, by construction, both categories of supply shocks play an equally important role in shaping expectations about future oil supply availability. For example, considering that during 1980-85 OPEC managed to build-up over 10.0 mmbpd of spare capacity due to global efficiency, a combination of the 1990s exogenous disruptions in oil supply and the large positive shifts in global demand starting in 2000, led to the disappearance of OPEC's excess capacity which meant that there was effectively no buffer against unexpected crude oil supply outages or unexpected shifts in demand. Relatedly, in the absence of any exogenous shortfalls in oil production after 2011-onwards, the supply-demand gap would have been much wider by more than 1.5 mmbpd. The constructed series illustrated in Figure 14 form the basis of the empirical analysis in the remainder of the paper.

Figure 15. Comparison of the baseline and alternative counterfactual series of total supply shocks



For our sensitivity analysis we explore three different scenarios: (1) supply shocks are caused explicitly by exogenous shortfalls in oil production; (2) the counterfactuals are by construction long-lasting throughout the entire sample period; and (3) the exogenous Saudi production responses are temporary. Figure 15 illustrates important qualitative and quantitative differences between our baseline series of total supply shocks and the alternative series arising from this exercise. First, the alternative counterfactual series of total supply shocks always stays below 0%, even during times when production recovered for exogenous reasons such as in the course of the 1990 Gulf War or when market-specific gains in production surpass the geopolitical outages in 2014. Second, the alternative measure indicates supply shocks of potentially very different magnitudes and persistence, typically for those following exogenous events, which in some cases are more than twice as large as the baseline measure. This is important especially in the period of 2003-08, when geopolitical outages had been relatively limited. Finally, the alternative series presents some ambiguities related to the timing of events and involves in a high degree assumptions that cannot always be verified. This fact makes it important to contrast the robustness of the baseline counterfactual series to that of the alternative series in the sense that it is easier to reconcile with actual data.

4. Quantifying the dynamic effects of supply shocks on the real price of oil

Analysis builds on the structural VAR model of the world oil market proposed by Kilian and Murphy (2014) in specifying four monthly reduced-form models under different specifications of the supply shocks. The sample period is 1990.1–2015.6. The models allow for 24 autoregressive lags consistent with the literature (see Hamilton & Herrera, 2004; Kilian 2009a). The set of variables consists of monthly data for three observables in each model. First, the oil supply observable conditional on the model's specification: (1) the percentage change in global crude oil production; (2) the constructed proxy of disruptions in global crude oil production that are explicitly caused by exogenous political events; (3) the constructed proxy of operable capacity shifts in crude oil production, relative to demand, that are explicitly associated with market-specific events; and (4) the constructed proxy of aggregate changes in total available operable capacity. The aforementioned proxies are expressed as a percentage share of world oil production. These variables have been defined and discussed in detail in the previous section. Second, a monthly global real economic activity index that is designed to capture shifts in the global use of all industrial commodities, expressed in percent deviations from trend, as developed in Kilian (2009a). Third, the real price of oil obtained by deflating the Dated Brent price by the US consumer price index, specified in percent deviations from its mean.

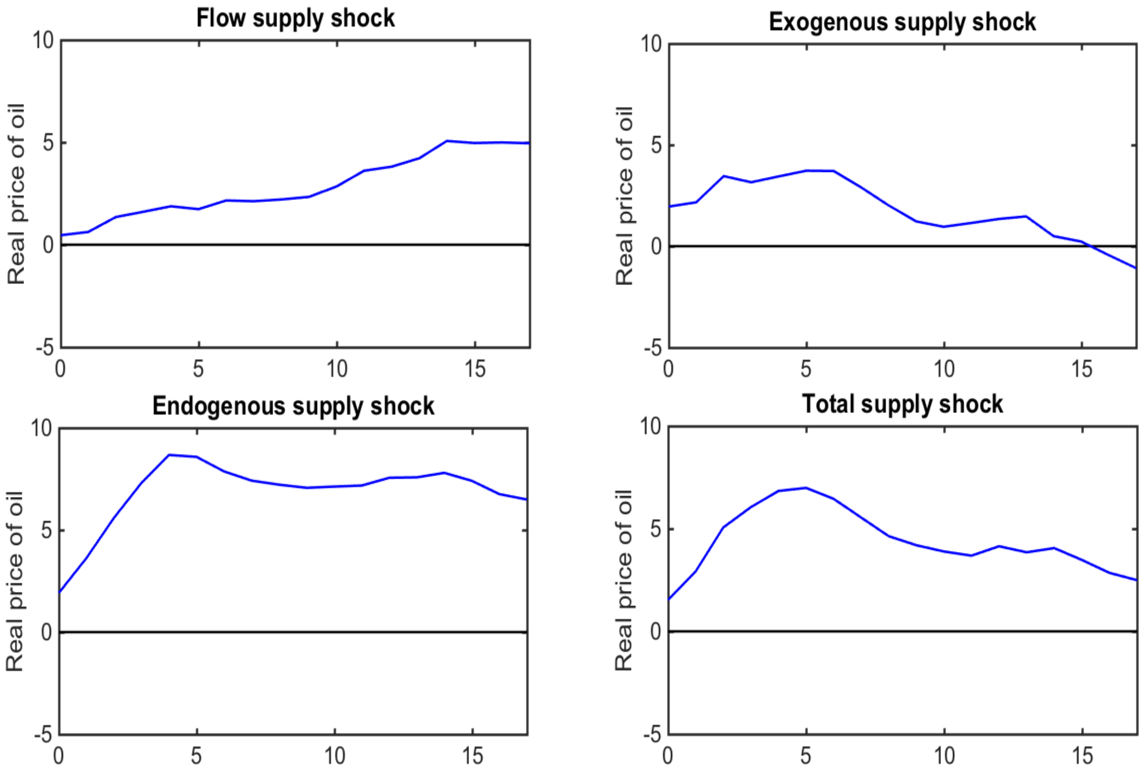
The first specification of oil supply shocks refers to the conventional notion of *flow supply shocks* discussed in the literature, defined as shocks to the amount of crude oil coming out of the ground associated with exogenous political events in oil producing countries as well as unexpected politically motivated supply decisions by OPEC members as well as other oil supply shocks (Kilian, 2009a; Kilian & Lee, 2014; Kilian & Murphy, 2014). The second specification refers to the *exogenous supply shocks*, which are defined as shocks to the physical availability of crude oil production that originate mainly from geopolitical and political episodes in oil producing countries that lead to the actual disruption in oil drilling and extracting operations of oil facilities. The third specification refers to the *endogenous supply shocks*, defined as shocks to the available operable capacity in crude oil production as a consequence of the normal functioning of the oil market. The final specification refers to the *total supply shocks*, defined as shocks to the total available operable capacity caused by a combination of both exogenous and endogenous factors. In addition to shocks to oil supply, the models allow for two more demand-related structural shocks. *Flow demand* shocks, defined as shocks to crude oil and other industrial commodities that are associated with unexpected fluctuations in the global business cycle, and *other demand shocks,* defined as idiosyncratic oil demand shocks that reflect changes in the demand for oil as opposed to changes in the demand for all industrial commodities. The latter category may also reflect shocks to stock demand driven by the forward-looking behaviour of the market participants.

The structural shocks are identified based on a combination of sign restrictions of the impact responses of the three observables to each structural shock and a bound on the impact price elasticity of oil supply, in line with the existing literature. Any unanticipated negative oil supply shock causes oil production and operable capacity to fall, the real economic activity to fall and the real price of oil to increase on impact. An unanticipated increase in the flow demand for oil associated with the global business cycle causes global oil production and the available operable capacity, global real economic activity and the real price of oil to increase on impact. Other positive demand shocks cause oil production and operable capacity to rise, global real economic activity to fall and the real price of oil to increase on impact. Second, we impose the restriction for the real price of oil to remain positive for the first twelve months in response to unanticipated negative oil supply shocks under any specification and in response to positive oil demand shocks. Finally we impose a bound on the impact price elasticity of oil supply by 0.025. For a detailed discussion of the above key identifying assumptions the reader is referred to Kilian and Murphy (2014), Kilian and Lee (2014), and Baumeister and Kilian (2014).

4.1. Responses of the real price of oil to supply shocks

The estimates of the responses of all three variables to each oil supply and demand shock as obtained by each model are shown in Appendix C. The focus in this paper is on the new measures of oil supply and how these affect our assessment of the dynamic effects of supply shocks on the real price of oil. Figure 16 shows the responses of the real price of oil to the four oil supply shocks by specification. The responses have been normalised such that oil supply shocks refer to an unanticipated disruption of oil production or an unanticipated contraction of operable capacity, depending on the specification of the model, and thus they imply an increase in the real price of oil. As can be seen from the figure, the role of oil supply shocks differs greatly depending on the specification of each shock. A negative flow supply shock causes a persistent and gradually increasing effect on the real price of oil that peaks after one year. However, much of the oil price increase triggered by the shock is delayed by about nine months. An exogenous supply disruption causes a temporary increase in the price of oil that persists for twelve months.

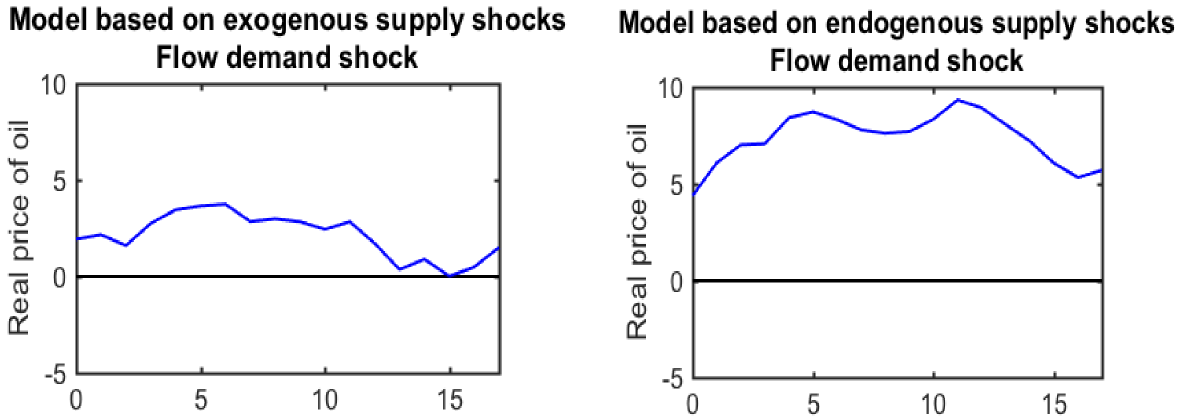
Figure 16: Responses of the real price of oil to supply shocks by specification



Notes: All responses are expressed in percentages. All structural shocks have been normalised such that they imply an increase in the real price of oil.

After one year, the oil price falls near its starting value and decreases below that level within fifteen months, as oil production shortfalls in one region tend to trigger production increases as a response elsewhere in the world. A negative endogenous supply shock, on the contrary, is associated with a steep and very persistent increase in the real price of oil. The real price response overshoots in the first six months and reverses only slightly after that, to remain largely positive throughout. This pattern is consistent with the view that unless oil demand deteriorates, the shock treatment for capacity contractions is associated with significant lags that reflect the long lead times from investment decisions to first oil. Finally, a negative total supply shock that combines both the exogenous and endogenous shocks of crude oil by construction causes a transitory and hump-shaped increase in the real price of oil that peaks in the first six months, after which it gradually reverses even though it remains largely positive for another year.

Figure 17: Responses of the real price of oil to flow demand shocks by model specification



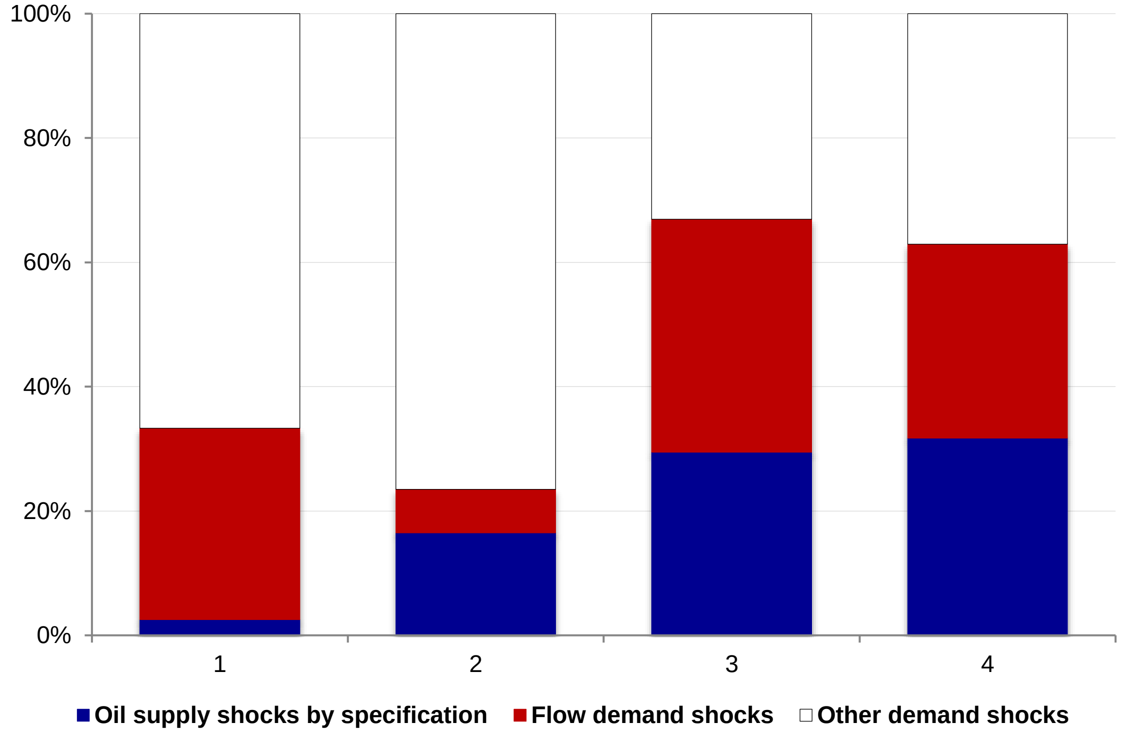
Notes: All responses are expressed in percentages. All structural shocks have been normalised such that they imply an increase in the real price of oil.

So far, these estimates imply a larger role for the effect of endogenous supply shocks on the real price of oil than exogenous supply shocks, illustrating the importance of modelling innovations to the supply determinant from an endogenous perspective. Even when considering the nature of flow supply shocks as defined by the existing literature, i.e. largely associated with disruptions in oil production caused by exogenous political events, there appears no evidence to support that on the basis of information contained in the data of global oil production, supply shocks are driven by exogenous factors. On the contrary, our estimates show that total supply shocks in recent years are more compatible with market-specific events. Another striking result obtained by these estimates is the fact that for the first time we provide robust empirical evidence to support the conjecture that unanticipated capacity constraints in crude oil production amplify the effect of demand shifts on the real price of oil. This is illustrated in Figure 17 that compares the responses of the real price of oil to flow demand shocks in the model based on exogenous supply shocks and that based on endogenous supply shocks. From this figure it can be seen that in the explicit presence of an unanticipated exogenous disruption of oil production, an unanticipated expansion of flow demand causes a relative increase on the real price of oil that is only temporary and expires within twelve months. Contrariwise, in the explicit presence of an unanticipated contraction of operable capacity the effect of an unanticipated positive shock of flow demand on the real price of oil is immediate, highly significant and very persistent. The robustness of these results confirms the widely documented view in the literature that the conjunction of capacity constraints amid increases in oil demand generates large oil price increases. This finding confirms that neither of the market fundamentals can be an important determinant *per se*, but it is rather the catalytic interaction of both supply and demand that has historically driven the real price of oil.

4.2. The role of supply shocks in explaining the variability of the real price of oil

Having shown that endogenous supply shocks of crude oil have a large effect on the real price of oil, we now turn to the related issue of measuring how well do the new measures of oil supply shocks explain changes in the real price of oil. Figure 18 shows the explanatory power of each structural shock in explaining the variability of the real price of oil, as obtained by each model. It can be shown that flow supply shocks have a negligible impact on the variation in the real price of oil with a mere 2%. The explanatory power of exogenous supply shocks somewhat increases to 16%, while endogenous supply shocks have a much larger role in explaining changes in the real price of oil with 30%. Much of this increase is drawn in expense of the explanatory ability of other demand shocks that decreases to 33%, compared with 67% in the model based on flow supply shocks and with 77% in the model based on exogenous supply shocks. The explanation is that in the presence of endogenous supply shocks, innovations to stock demand for crude oil do not necessarily reflect the forward-looking behaviour of the market participants but rather reflect a systematic contemporaneous effect owing to market conditions, i.e. stocks rise due to surplus capacity or stocks fall due to capacity shortages. Total supply shocks that combine both measures, i.e. exogenous and endogenous, account for 32% of the variation in the real price of oil. Finally, it is important to mention that the role of flow demand shocks remains robust with 31-37% depending on the specification of the model, except from the one based on exogenous supply shocks where their explanatory power falls to 7%.

Figure 18: Variation in the real price of oil by structural shock



Notes: 1 = Model based on flow supply shocks; 2 = Model based on exogenous supply shocks; 3 = Model based on endogenous supply shocks; 4 = Model based on total supply shocks.

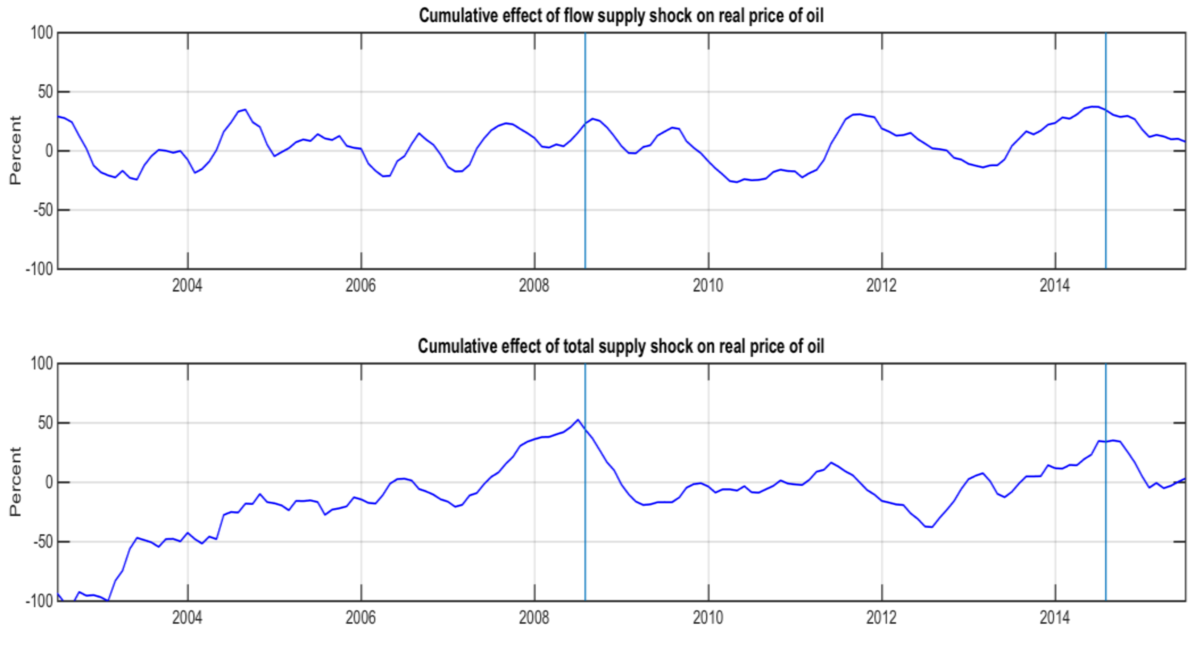
These findings suggest that oil supply shocks may have very different effects on the real price of oil, depending on the underlying specification of the shock. In particular, the measures that capture market-driven shifts in available operable capacity are found to be more plausible than the rest in explaining the variability of the real price of oil, especially when compared with flow supply shocks. One plausible explanation is that endogenous supply shocks are not linearly related to changes in crude oil production. An alternative and complementary explanation is that oil supply shocks conditional on information contained in past data of changes in global oil production have little systematic predictive power for changes in the real price of oil (see Kilian, 2008, p. 1062). That said, it is instructive to explore further the quantitative importance of oil supply shocks at each point in time since 2002.

4.3. Cumulative effect of oil supply shocks on the real price of oil

The cumulative change in the real price of oil caused by a given supply shock over some period of interest is a useful summary statistic because it measures the respective contribution of each oil supply shock to the historical evolution of the real price of oil. Figure 19 plots the respective cumulative effect of flow supply shocks and total supply shocks to the real price of oil, based on a historical decomposition of the data for 2002.6–2015.6. Recall that both supply shocks are aggregate by specification, in the sense that they are not explicit to either exogenous or endogenous innovations. Each panel in the figure shows how the real price of oil would have evolved in the absence of all demand-related structural shocks but the supply shock in question, based on estimates obtained by each model. Focusing first on the Great Surge of 2003-08, the first panel shows that flow supply shocks have made comparatively small contributions to the real price of oil between 2003 and mid-2008. This contrasts with a much larger role of total supply shocks that appear to have exerted significant upward pressure on the real price of oil over the same period (second panel). Thereafter, notwithstanding some differences in magnitudes, the two historical decompositions largely agree with each other with respect to the sharp swings in the real price of oil that preceded and followed the 2014 oil price collapse. These results emphasize the tenuous link between flow supply shocks and endogenous shifts in oil supply. With this evidence in mind, it is instructive to examine in more detail the underlying nature and timing of the supply shocks.

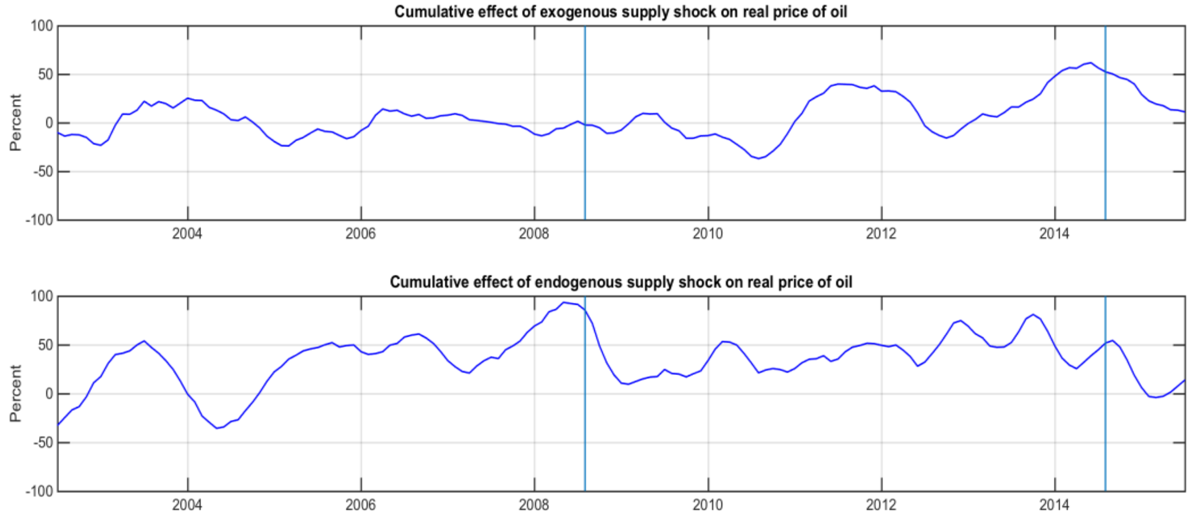
Figure 20 decomposes the cumulative effect of supply shocks to the real price of oil into exogenous and endogenous over the same period (2002.6–2015.6). Evidently, the bulk of the continued supply-related increase in the real price of oil starting in 2003 can be attributed explicitly to endogenous supply shocks. The increasing importance of oil market-specific supply shocks starting in mid-2004 is consistent with the unexpected halt of the growth of global oil production.

Figure 19: Historical decomposition of the real price of oil by flow supply shock and total supply shock for 2002.6–2015.6



Notes: The real price of oil is expressed in percent deviations from the sample mean. The vertical bars indicate the timing of specific oil market events, notably the Global Financial Crisis of 2008.7 and the oil market imbalance of 2014.7 respectively.

Figure 20: Historical decomposition of the real price of oil by exogenous supply shock and endogenous supply shock for 2002.6–2015.6



Notes: The real price of oil is expressed in percent deviations from the sample mean. The vertical bars indicate the timing of specific oil market events, notably the Global Financial Crisis of 2008.7 and the oil market imbalance of 2014.7 respectively.

Essentially the strong demand growth had finally caught up with the $1 trillion structural underinvestment in the upstream sector of the 1990s[20], the maturity of legacy oil fields and the long lead-times associated with the development and production of new capacity. Despite a substantial increase in exploration and drilling programs between 2000-08, OPEC failed to increase its production capacity, while many analysts even questioned the ability of Saudi Arabia to sustain its production levels after 2005 (Hamilton, 2013b). Saudi production in 2007 was 850,000 bpd lower than its levels in 2005 (9.55 mmbpd), initiating a strong debate on whether its massive Ghawar oilfield had peaked or if this was a deliberate strategy from OPEC's de facto leader (Gately, 2004; Alkhathlan, Gately & Javid, 2014). The persistent positive effect of endogenous supply shocks on the real price of oil overshoots in 2008, before declining sharply owing to the Global Financial Crisis. Exogenous disruptions in crude oil production appear only to amplify some of the short-run dynamics of the real price of oil in 2003, despite the fact that at the time the Venezuelan Crisis in 2002 and Iraq War in 2003 removed 4.3 mmbpd of oil production combined.

A common view in the literature is that oil market-specific supply developments in the form of unprecedented positive shocks to actual and expected non-OPEC oil production, were largely responsible for the oil price collapse of 2014. Our analysis does not support this conjecture *per se*. To the extent that oil supply shocks mattered for the real price of oil after 2010, these were largely driven by exogenous shocks in crude oil production that were explicitly associated with sharp swings in Libyan output staring in 2011. There is no evidence that the Iranian nuclear sanctions of 2012 exerted any sort of upward pressure on the real price of oil, consistent with the fact that the loss of the Iranian output was offset by higher production from Saudi Arabia. Contrariwise, the Libyan high-quality light and sweet crude oil is not interchangeable, i.e. Es Sider and El Sahara. This point is sustained by the fact that the majority of oil produced by OPEC is light sour, while there is limited available spare capacity of alternative compatible crude oil grades such as the Algerian Saharan Blend and the Nigerian Qua Iboe.

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[20] As reported by the *Oil and Gas Journal* of July 9, 2001.

The importance is that refining facilities are specifically designed to process only certain qualities of crude oil and hence short-term adjustments cannot be achieved. Even in the long-term, refining adjustments are very capital-intensive and require considerable amount of time. Accordingly, the timing of the oil price collapse in July-2014 is compatible with the sharp recovery of Libyan oil production by 700,000 bpd starting in June 2014, in conjunction with the presence of endogenous downward pressures on the real price of oil that began as early as mid-2013. It follows that the quantitative importance of exogenous disruptions in crude oil production to the real price of oil appears to be highly sensitive to the ability of other producers to find alternatives of similar quality to the grade of the missing crude oil and not to the magnitude of the shock *per se*.

5. Conclusion

Since the 1970s oil crisis there has been a growing interest in understanding the dynamic effects of oil supply shocks on the real price of oil. Traditionally, these shocks were thought to reflect disruptions to the physical availability of crude oil caused mainly by exogenous geopolitical events. Yet several studies have appeared in recent years supporting the claim that oil supply shocks are of limited importance in explaining changes in the real price of oil during crisis periods, as most of the oil price changes in historical episodes can be largely explained by demand-specific shocks. In this paper, we focused on the supply determinant from an endogenous perspective and examined how the use of alternative measures of oil supply shocks affects our assessment of the dynamic effects of supply shocks on the real price of oil since 1990. We introduced a new methodology that jointly identifies and disentangles the supply shocks of crude oil into exogenous and endogenous, by quantifying the positive and negative shocks of oil production caused by events outside the oil market (exogenous) or as a consequence of the normal functioning of the oil market (endogenous). Results show that for most of the 1990s, shortfalls in oil production that were brought about by geopolitical episodes accounted for about 7% of the variability in global crude oil production. However, this pattern reverses after 2000 onwards, as fluctuations in global oil production were largely attributed to market-specific events (6%). The interpretation of this new evidence points towards a structural innovation of the supply determinant from an endogenous perspective that should guide the existing framework for the empirical analysis of oil price shocks.

We provided empirical evidence to suggest that the supply side of the market has been an important determinant of the real price of oil after all. This result, however, is robust to the underlying specification of the supply shocks. For example, there exists a strong link between flow supply shocks and exogenous disruptions in crude oil production that filters out any endogenous innovations in crude oil supply. The importance is that flow supply shocks underestimate the historical contribution of oil supply shocks to changes in the real price of oil, in comparison with total supply shocks that appear to have exerted significant upward pressure in the real price of oil, especially between 2003 and mid-2008. Endogenous supply shocks play an increasing important role in the historical evolution of the oil price since 2000, but it must be noted that exogenous supply shocks were largely responsible for the oil price developments after 2010. That said the quantitative importance of exogenous disruptions in crude oil production to the real price of oil appears to be highly sensitive to the ability of other producers to find alternatives of similar quality to the grade of the missing crude oil and not to the magnitude of the shock *per se*. Finally, to our knowledge, this is the first study to provide empirical evidence that confirms the widely documented view in the literature that the conjunction of capacity constraints amid increases in oil demand generates large oil price increases. We conclude that neither of the market fundamentals can be an important determinant *per se*, but it is rather the catalytic interaction of both supply and demand that has historically driven the real price of oil.

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Appendix A

The criteria for selecting the specific list of countries for the construction of the counterfactuals were based on their individual involvement in an exogenous event and the average percentage share over 1990-2014 of a number of selection criteria as summarised in Table A1.

Table A1: Summary of the selection criteria

Selection Criteria	**OPEC (14)**	**US**	**China**	**Russia**	**North Sea**	**Canada**	**Mexico**	**Rest of World**
Involvement in Exogenous Episode	Yes	Yes	No	No	No	No	Yes	-
1P Reserves (%share of the total)	73.8%	2.1%	1.8%	4.9%	1.1%	7.3%	2.4%	**6.6%**
Crude Oil Production (%share of the total)	41.6%	9.0%	5.0%	11.6%	6.2%	3.3%	4.2%	**19.0%**
Petroleum Liquids Consumption (%share of the total)	7.8%	24.1%	7.2%	3.8%	2.5%	2.6%	2.5%	**21.8%** **IEA EU:** 18.2% **Japan:** 6.6% **India:** 2.9%
Exports / Imports (%share of the total)	*57.0%* 0.1%	*0.4%* 23.4%	*0.6%* 4.6%	*10.3%* 0.3%	*9.6%* 2.8%	*4.4%* 1.9%	*4.2%* 0.1%	***13.5%*** **21.8%** **IEA EU:** 30.7% **Japan:** 10.5% **India:** 3.9%
Status	Net Exporter	Net Importer	Net Importer	Net Exporter	Net Exporter	Net Exporter	Net Exporter	
Average %share per Destination/ Origin of Exports/ Origin of Imports	*To:* 60.0% Asia Pacific 15.0% US 15.0% Europe <10.0% Rest of World	*From:* 50.0% OPEC 20.0% Canada 15.0% Mexico <10.0% Rest of World	*From:* 80.0% OPEC 10.0% Russia <10.0% Rest of World	*To:* 80.0% Europe 18.0% Asia Pacific <2.0% Rest of World	*To:* 90.0% Europe <10.0% Rest of World	*To:* 95.0% US <5.0% Rest of World	*To:* 80.0% US <20.0% Rest of World	

Notes: OPEC 14 includes Saudi Arabia, Iran, Iraq, Kuwait, Qatar, UAE, Algeria, Nigeria, Libya, Venezuela, Ecuador excluding the period 1992.12–1997.10, Gabon until 1994.12, Indonesia until 2008.12 and Angola since 2007.1. The data for Russia are available only from 2001.1 because of the dissolution of the Soviet Union in 1991. IEA Europe includes Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, and Turkey; excluding Norway and the United Kingdom (North Sea).

Appendix B

Analysis of oil supply shocks will by construction involve a counterfactual. Notwithstanding, for the counterfactual production levels of any given country to grow based on the average growth rate of production in some other country or group of countries, their respective oil sectors must be subject to similar governance, operational and investment performance. The analysis employs annual findings from the *Fraser Institute's Global Petroleum Survey* 'All-Inclusive Composite Index'[21] launched since 2007, which surveys oil companies and support services providers regarding barriers to investment in oil and gas exploration and production in various countries around the globe. The index is designed to capture the opinions of the participants on sixteen factors that influence company decisions to invest in upstream projects around the world, thus allowing the construction of an aggregate indicator that covers government effectiveness, political stability, fiscal and taxation terms, rule of law, trade barriers and security. Estimates for the remaining period (1990-2007) are constructed by backcasting the performance of each country and investigating whether there were any historical accounts indicating a major setback or improvement on any of the factors examined by the survey.

All OPEC and non-OPEC producers are then grouped into two bands: (1) Band A, which indicates an overall normal to high investment climate (strong performance); and (2) Band B, according to which the overall investment climate is normal to low (poor performance). The results indicate an attractive operating and investment climate in all examined non-OPEC countries, except China, Mexico and Russia. These suffer primarily from regulatory uncertainty, concentration of powers in state-owned companies and restricted scope of foreign invested companies. On the other hand, all OPEC producers, excluding the UAE and Qatar, perform fairly weak mainly because of poorer marks on taxation and legal regulations in general, unattractive fiscal regimes and security issues. Qatar and the UAE are excluded from Band B, as both producers are characterised by fiscal and political stability, excellent operating environments with mature services and labour that offer access to new opportunities, and exploration success rates. The ranking scores and performance estimates per examined jurisdiction are presented in Table B1.

Table B1: Jurisdictional rankings according to the extent of investment barriers

	Estimates of Performance									
Country	**2014**	**2013**	**2012**	**2011**	**2010**	**2009**	**2008**	**2007**	**2000s**	**1990s**	**Overall**
OPEC											
Qatar	34.90	24.16	25.42	25.73	21.47	23.90	3.83	1.81	A	A	**A**
UAE	31.83	26.49	30.65	28.59	28.89	28.29	6.58		A	A	**A**
Kuwait	66.58	39.56	42.23	43.76	46.10	39.71	21.99	9.30	A	B	**B**
Gabon	66.84	57.85	59.15	60.23	52.10	48.74		12.13	B	B	**B**
Angola	69.92	60.14	69.84	72.70	52.65	58.72	8.79	49.16	B	B	**B**
Algeria	75.74	71.04	73.23	80.93	64.37	61.83	12.58	12.81	B	B	**B**
Indonesia	85.89	74.36	74.14	71.57	65.12	59.66	15.00	44.62	B	B	**B**
Nigeria	72.05	75.75	81.31	79.36	83.38	74.85	38.84	45.39	B	B	**B**
Iraq	88.59	82.88	82.60	83.95	81.41	70.09	41.84		B	B	**B**
Ecuador	96.79	97.97	85.34	96.27	85.59	87.80	83.42	86.00	B	B	**B**
Libya	85.43	79.98	85.55	83.69	76.60	58.95	3.15	27.97	B	B	**B**
Iran	93.78	97.17	88.44	92.50	87.93	69.29		61.43	B	B	**B**
Venezuela	100.00	100.00	97.09	100.00	97.18	91.86	81.27	94.45	B	B	**B**

Notes: A score over 50.0 indicates that oil companies and service providers regard a given country as relatively unattractive for investment, and vice versa. Saudi Arabia is excluded because upstream activities are mostly confined to government-owned companies. Estimates for Mexico are available only in 2014 (Data: Fraser Institute's Global Petroleum Survey 2007-2015, Oil and Gas Journal).

[21] Since 2013 the index has been renamed to 'Policy Perception Index'.

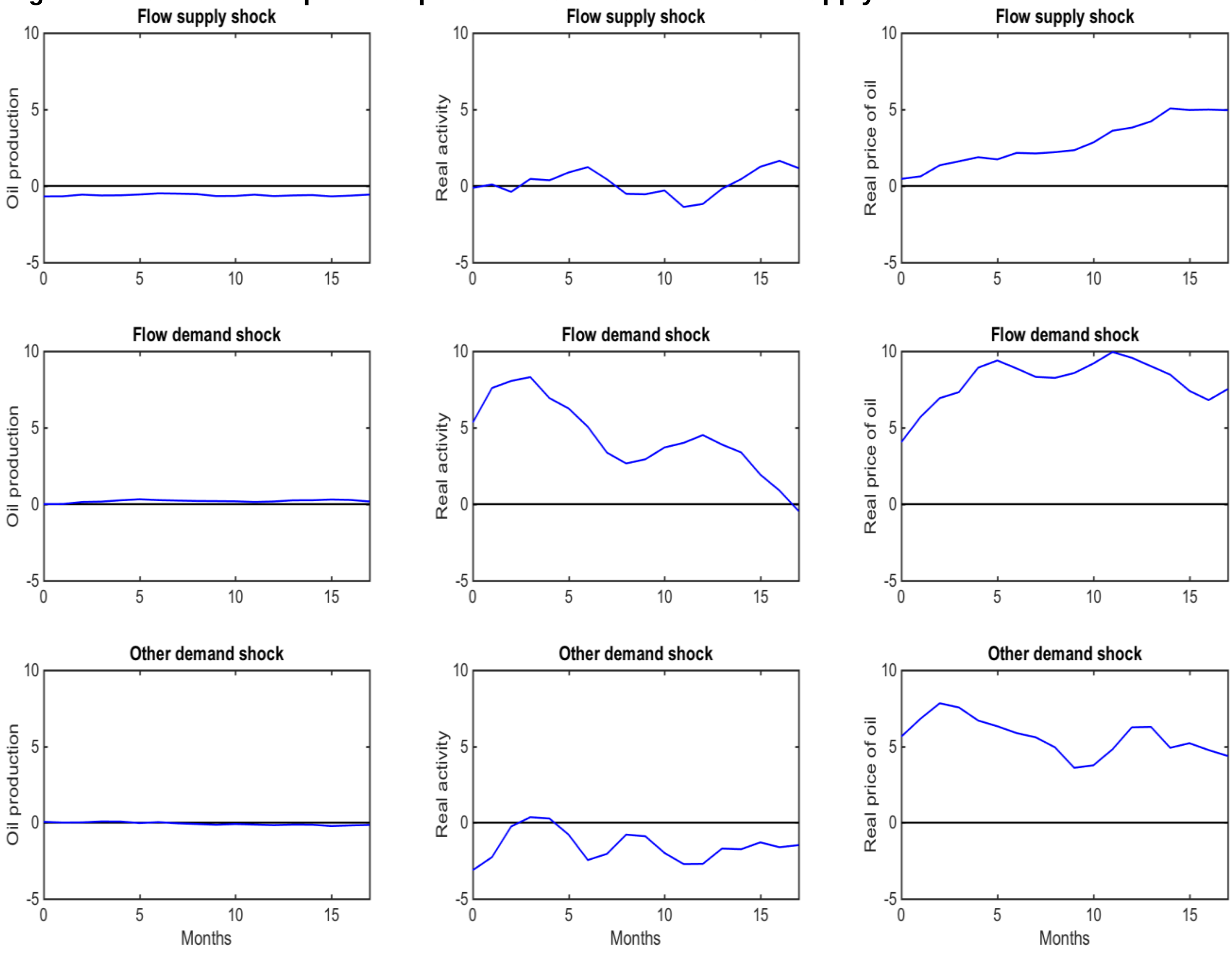
Table B1 (continued): Jurisdictional rankings according to the extent of investment barriers

Estimates of Performance											
Country	**2014**	**2013**	**2012**	**2011**	**2010**	**2009**	**2008**	**2007**	**2000s**	**1990s**	**Overall**
Non-OPEC											
US Overall	32.61	30.63	19.95	26.47	25.84	21.80	11.30	16.82	A	A	**A**
Wyoming	19.11	22.63	13.87	23.38	10.25	17.35	6.69	8.29	A	A	A
West Virginia	37.60	25.91	13.64	13.35	31.93	32.34	18.63		A	A	A
Utah	21.40	28.09	22.65	21.28	12.04	15.45	13.06		A	A	A
Texas	13.19	11.71	8.03	12.17	9.53	10.97	5.22	13.00	A	A	A
Pennsylvania	46.14	39.13	26.04	40.37	40.44	29.56	18.38		B	A	A
Oklahoma	7.02	9.84	4.71	11.81	13.00	11.30	3.93	14.80	A	A	A
Ohio	23.29	27.35	14.97	10.16	13.76	24.06	2.27		A	A	A
North Dakota	13.55	15.92	9.88	17.44	19.65	22.37	6.86		A	A	A
New York	64.68	64.20	44.08		59.34	22.73	1.26		A	B	B
New Mexico	30.70	30.36	11.92	28.79	34.27	26.75	13.32	19.67	A	A	A
Montana	28.62	25.89	22.17	29.74	24.26	25.74	16.45	50.75	A	A	A
Mississippi	7.25	11.19	6.30	4.89	11.65	9.88	10.77		A	A	A
Michigan	33.14	41.03	24.87	23.87	27.27	21.00	12.58		A	A	A
Louisiana	23.12	22.57	15.26	18.87	16.62	16.18	10.06	17.71	A	A	A
Kansas	12.82	12.64	12.32	11.70	18.80	8.93	7.59		A	A	A
Illinois /	36.51	32.51		17.75	9.65	15.26	28.62		A	A	A
Colorado	51.92	42.02	16.85	33.47	37.35	40.42	14.9	0.00	B	B	A
California	67.35	55.70	32.47	55.99	49.35	40.13	26.66	15.75	B	B	B
Arkansas	11.06	12.34		19.16	15.62	6.73	6.29		A	A	A
Alaska	52.52	49.70	40.16	50.84	41.80	39.75	18.17	11.42	B	B	A
Alabama	11.90	15.34		17.00	13.41	8.88	6.46		A	A	A
Offshore/Pacific	73.90	56.20		63.17	60.66	23.55	3.8		A	A	A
Offshore/GOM	40.61	33.07	22.89	36.38	13.44	15.96	7.82		A	A	A
Offshore/Alaska	55.24	49.70	35.92	47.23	36.20	37.92			B	B	A
Russia Overall	87.50	83.73	81.62	81.24	91.45	78.69	32.71	58.87	B	B	**B**
Other Offshore	82.11	81.62	82.33						B	B	B
Offshore											
Sakhalin	84.33	76.75	77.31						B	B	B
Eastern Siberia	92.66	85.80	85.91						B	B	B
Offshore Arctic	90.90	90.74	80.94						B	B	B
Other Russia				81.24	91.45	78.69			B	B	B
North Sea Overall	27.42	23.06	18.56	20.84	24.32	23.00	7.21	8.38	A	A	**A**
Norway Offshore	29.70	27.06	19.95	24.89	31.47	24.81	9.14	7.22	A	A	A
UK Offshore	33.18	23.47	21.44	21.77	21.23	25.02	5.28	9.54	A	A	A
China	72.37	57.23	62.53	55.43	51.66	44.86	16.35	31.70	B	A	**B**
Canada Overall	42.22	34.22	33.47	34.76	30.13	38.94	11.15	22.21	A	A	**A**
Yukon	52.59	31.99	38.04		25.50	54.05	5.91		A	A	A
Saskatchewan	10.29	11.43	14.60	17.48	17.63	25.02	2.37	10.23	A	A	A
Quebec	79.47	77.11	60.53	56.24	44.89	36.89			A	A	A
Ontario				22.57	21.22	33.30	11.19		B	B	B
Nova Scotia	48.96	27.52	26.17	26.64	33.28	30.37	11.88	24.07	A	A	A
Northwest Territories	53.12	40.84	39.62	64.84	44.08	62.84	24.36	21.39	A	A	A
Newfoundland & Labrador	39.06	26.43	33.78	32.34	32.39	40.87	18.38	46.94	B	B	A
New Brunswick	51.04	49.94	62.08	35.80					B	B	A
Manitoba	11.51	16.87	11.05	17.52	12.48	20.98	4.86		B	A	B
British Columbia	49.60	35.55	27.73	41.44	33.16	37.66	7.91	16.57	A	A	A
Alberta	26.57	24.47	21.08	32.73	36.70	47.46	13.48	14.07	A	A	A
Mexico	75.79										**B**

Notes: A score over 50.0 indicates that oil companies and service providers regard a given country as relatively unattractive for investment, and vice versa. Saudi Arabia is excluded because upstream activities are mostly confined to government-owned companies. Estimates for Mexico are available only in 2014 (Data: Fraser Institute's Global Petroleum Survey 2007-2015, Oil and Gas Journal).

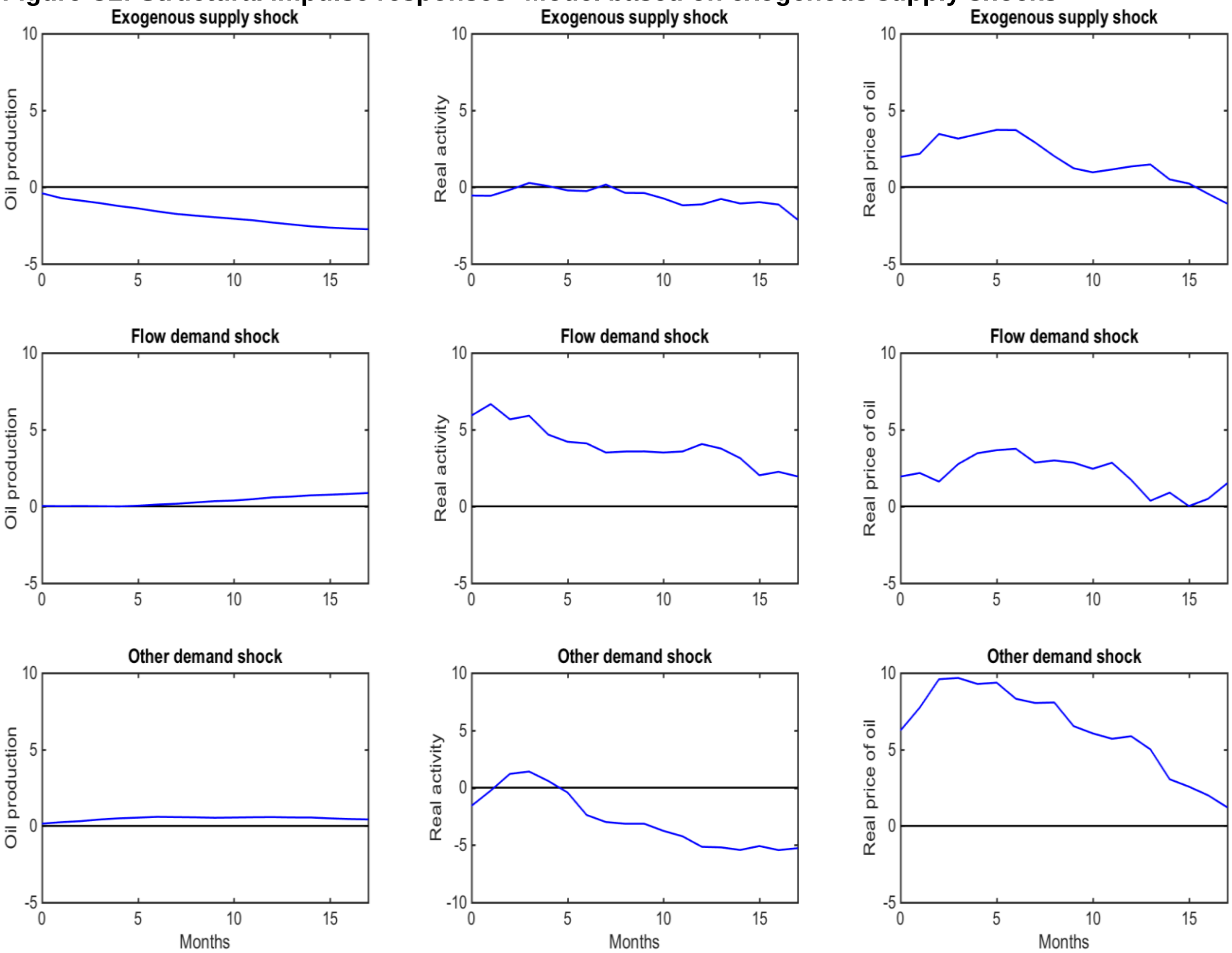
Appendix C

Figure C1: Structural impulse responses- Model based on flow supply shocks



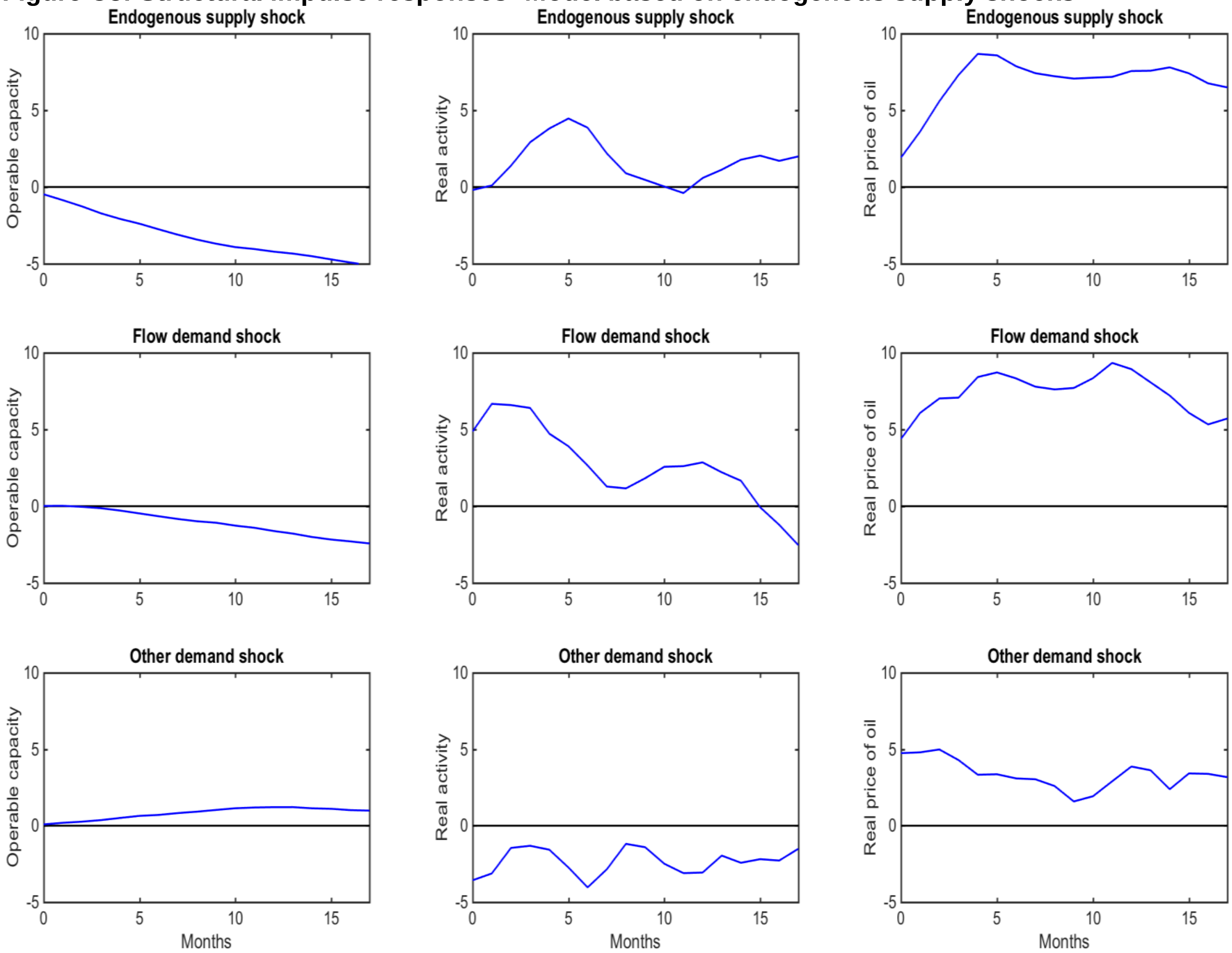
Notes: All responses are expressed in percentages. All structural shocks have been normalised such that they imply an increase in the real price of oil.

Figure C2: Structural impulse responses- Model based on exogenous supply shocks



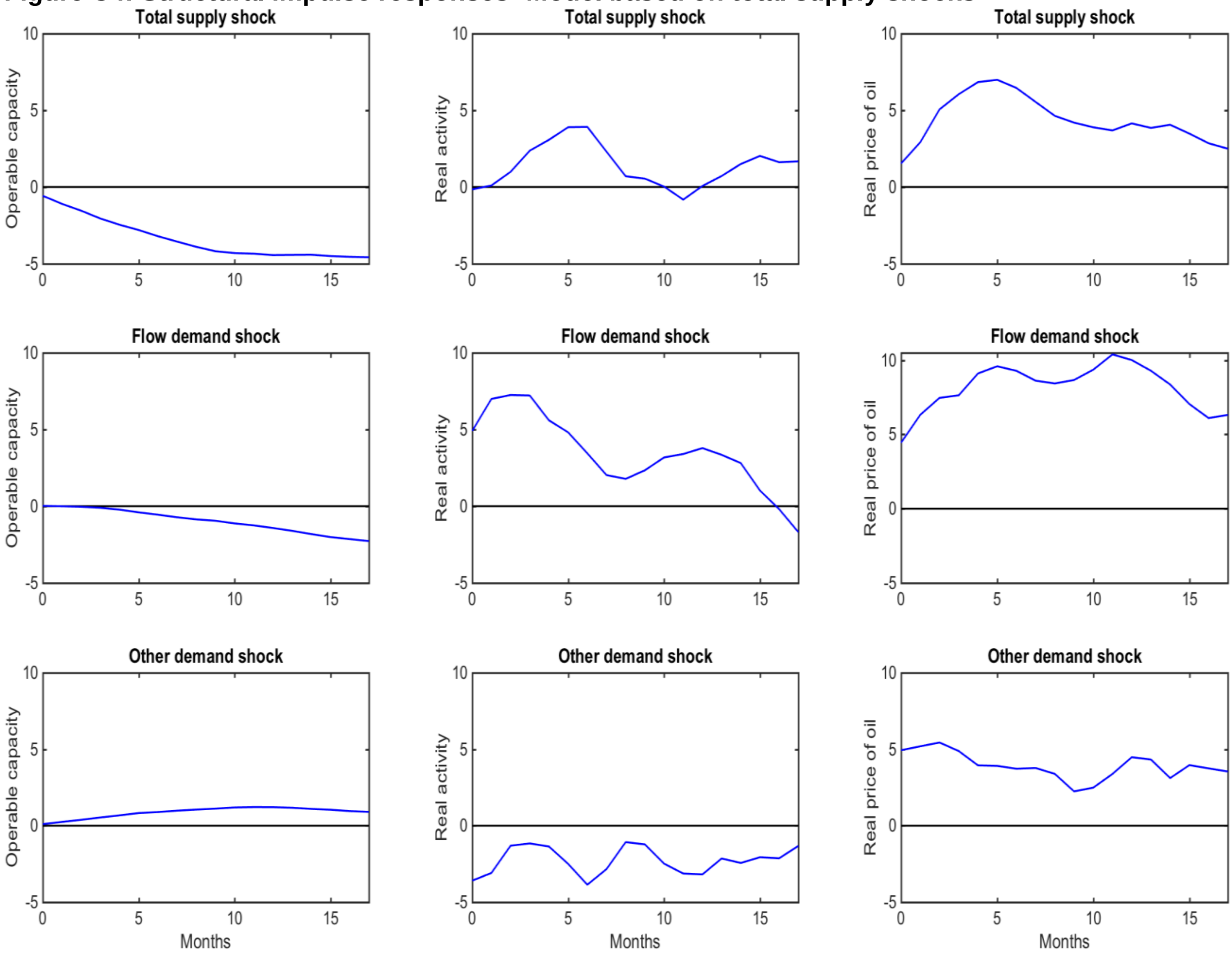
Notes: All responses are expressed in percentages. All structural shocks have been normalised such that they imply an increase in the real price of oil.

Figure C3: Structural impulse responses- Model based on endogenous supply shocks



Notes: All responses are expressed in percentages. All structural shocks have been normalised such that they imply an increase in the real price of oil.

Figure C4: Structural impulse responses- Model based on total supply shocks



Notes: All responses are expressed in percentages. All structural shocks have been normalised such that they imply an increase in the real price of oil.