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A Structural Model of the World Oil Market: The Role of Investment Dynamics and Capacity Constraints in Explaining the Evolution of the Real Price of Oil

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Abstract

Using novel measures that decompose oil supply shocks into its exogenous supply (driven by exogenous geopolitical events in OPEC countries) and endogenous supply (driven by investment dynamics within the oil sector) components, this paper offers a fresh perspective on the role of supply, flow demand and speculative demand shocks in explaining the changes in the real price of oil over the last three decades. We show that while exogenous supply shocks are non-negligible, endogenous supply shocks have generated larger and more persistent price responses than previously thought. Earlier studies have consistently shown that positive shifts in the flow demand for oil were responsible for most of the oil price surge between 2002-2008. But this paper shows that endogenous production capacity constraints, which restricted the ability of producers to ramp up production to meet the unexpected increase in demand, added at least \$50/barrel to the real price of oil. More recently, endogenous oil supply shocks alone accounted roughly for twice as much as any other supply or demand shock in explaining the 2014 oil price collapse. Specifically, of the \$64 per barrel cumulative decline in the real price of oil from June 2014 to January 2015, our model estimates that \$29 have been due to endogenous oil supply shocks, \$13 have been due to exogenous oil supply shocks, and \$12 have been due to flow demand shocks. The paper concludes by demonstrating that forecasting models that are able to distinguish between exogenous and endogenous supply shocks generate more realistic out-of-sample estimates of the sequences of the structural shocks, thus resulting in higher real-time predictive accuracy than forecasting models that use a collective measure of a flow supply shock.

Keywords: Oil price; crude oil market; supply; demand; inventories; production capacity; OPEC; shale oil; oil production; economic activity; oil shocks; forecast; structural model; VAR; identification.

1. Introduction

Understanding the evolution of the oil price is important to consumers, firms and policymakers because oil price fluctuations affect economic decisions across all segments of the global economy (Barsky & Kilian, 2002, 2004; Hamilton, 2009a; Kilian, 2008a, 2014). Oil price fluctuations, however, are difficult to anticipate due to unexpected shifts in supply and demand (Baumeister & Kilian, 2016a). In practice, the oil price will only be as predictable as its determinants, implying that the better one can identify and understand the determinants of past oil price fluctuations, the more realistic interpretations and better forecasts one can make (Alquist, Kilian & Vigfusson, 2013; Baumeister & Kilian, 2012, 2014). The unexpected component of a change in the price of oil is referred to as an *oil price shock*, defined as the difference between the expected price of oil and its eventual realisation.

Just a few years ago, it was commonly believed that all major oil price shocks could be attributed to oil supply disruptions triggered by exogenous geopolitical events in oil-producing countries, such as wars and revolutions, and/or by some other disruptive supply-based factors, such as a shift in OPEC's oil policy (Hamilton, 1983, 1985, 2003).¹ Today, this view has little empirical support. Not only do direct measures of exogenous oil supply disruptions have little explanatory power (see, for example, Kilian, 2006, 2008b), but also structural vector autoregressive (VAR) models of the world oil market that focus on the supply-demand determinants of the oil price show that oil supply shocks overall have had little impact on the real price of oil since 1973 (Baumeister & Peersman, 2013a, 2013b; Kilian, 2009a; 2009b; Kilian & Murphy, 2014; Kilian & Hicks, 2013; Peersman & Van Robays, 2009). In contrast, there is now widespread recognition that changes in crude oil demand best explain most major oil price fluctuations since the 1970s. Demand shocks driven by shifts in the global business cycle are now seen as the primary driver of oil prices, with shocks to physical speculative (or inventory) demand arising from shifts in market participants about future supply-demand tightness playing a much lesser part (see also Baumeister & Hamilton, 2015; Baumeister & Kilian, 2016b; Kilian & Lee, 2014; Lippi & Nobili, 2012; Melolinna, 2012).

Although traditional supply-side explanations of the real price of oil have come under extreme scrutiny during the past decade, there is still good reason to be sceptical of the assertion that the supply determinant is not as important as originally thought. The classical notion of an oil supply shock as discussed in the literature (also referred to as *flow supply shock*), corresponds to an exogenous disturbance to the flow supply that shifts the upward-sloping oil supply curve along the downward-sloping oil demand curve and hence, results in an opposite movement in global oil production and in the real price of oil (see, for example, Baumeister & Peersman, 2013b; Kilian, 2009a; Kilian & Murphy, 2014). Recent experience, however, with regards to the oil price collapse in the second half of 2014, when the monthly average real price of oil plunged by -44%,² has shown that oil supply shocks can generate abrupt changes in the real price of oil without large quantity movements, if at all, in the observed global oil production. For example, Baumeister & Kilian (2016b) argue that to the extent that oil supply shocks mattered for the 2014 oil price collapse, the question of interest is not whether oil production moved or not, but whether it moved relative to what it was expected to be. The authors go further and suggest (p. 135): "*If oil production was expected to decline, for example, but did not because of a positive oil supply shock, then this shock would trigger an additional [downward] adjustment of the price of oil without a change in observed oil production*". In a falling market characterised by relative oil abundance, such expectations could arise by beliefs that OPEC oil

¹ Exogeneity here means that these events did not occur in response to the current or past state of the crude oil market and the global economy.

² The real price of oil in this paper refers to the Brent price deflated by the US consumer price index in August 2016 USD, unless otherwise stated. The Brent price is the most widely traded global crude oil benchmark and refers to a light-sweet grade of crude oil produced from several separate crude streams in the North Sea.

producers will pursue an aggressive pricing strategy by curbing their output and/or non-OPEC oil producers whose long-run marginal costs exceed the current price of oil will exit the market. An opposite situation arises when the market is tight. If oil production is expected to increase, but does not because of a negative oil supply shock, then this shock would trigger an additional *upward* adjustment of the price of oil without a change in observed oil production (see, for example, Hamilton, 2009a). This phenomenon became self-evident during the 2003 and mid-2008 surge of the monthly average real price of oil from \$41/b to \$147/b, driven by a series of stronger-than-expected flow demand shocks in conjunction with a stagnating global oil production from 2004 onwards (Hamilton, 2009b, 2013a, 2013b; Kilian, 2009b, 2010a, 2010b; Lombardi & Van Robays, 2011; Nakov & Pescatori, 2010). In both cases the heart of the problem is not the unexpected disruptions of global oil production, but instead is the limited ability of oil producers to adjust oil supplies in response to demand-driven shocks to the real price of oil, due to the presence of capacity constraints in crude oil production (see Baumeister & Kilian, 2016a; Kilian, 2008b; Mabro, 1998, 2006; Smith, 2009). Indeed, there is a consensus in the literature that the absence of surplus production capacity since the early-1990s may have contributed to higher oil price fluctuations, albeit quantifying the extent of these changes has proved hard to empirically pin down (see, for example, Baumeister & Peersman, 2013a).

Traditional oil market VAR models implicitly assume that existing production capacity in oil producing countries is fixed over time, while the ability or willingness of oil producers to adjust production to smooth out price changes is observationally equivalent to a shock to the flow supply of crude oil, as measured by global crude oil production (see, for example, Kilian & Murphy, 2014).³ Capacity constraints however are not fixed over time and the outcome of a given exploration effort are not related to prices; in contrast the investment decision is (Favero & Perasan, 1991; Mabro, 1992). As noted by Fattouh and Mabro (2006) a number of uncertainties pertaining to geological, political, economic and technological factors have an impact on the investment decisions of oil producers, that affect oil supply and can lead to inefficiencies. On the one hand, considering the long lead times and long gestation periods from the point at which a Final Investment Decision (FID) is made and the start of first-production, underinvestment in upstream oil can generate large oil price spikes due to the inability of oil producers to maintain and expand production. On the other hand, considering that once costs have been sunk producers are unlikely to reverse an investment decision on a project, as well as shutting-in operating capacity is costly, overinvestment in upstream oil can depress the price of oil due to the unwillingness of oil producers to defer excess production. Even OPEC will find it difficult to maintain its role as a market stabilizer in an oversupplied market because of the uncertainty pertaining to the responsiveness of oil demand and non-OPEC supply to a higher price, as well as the cost of losing market share in favour of restoring its revenue (Fattouh & Sen, 2015). Taken together, whereas both risks of either under- or over-investment can result to capacity constraints in crude oil production, their effect on the real price of oil would be markedly different. This point is displayed in Figure 1 that shows the annual worldwide active rig counts (i.e. drilling activity) as one of the primary indicators for investment activity in the oil sector and the global capacity utilisation rates for the period 1990-2016. As is evident from both graphs, the presence of capacity constraints due to underinvestment refers to a situation where the current or future production capacity is unable to meet the current or expected increases in global oil demand (as observed by the profound year-on-year increases in drilling activity during 2003-2008), generating thus abrupt and persistent increases in the real price of oil. In contrast, the presence of capacity constraints due to overinvestment refers to a situation where the current and future operating capacity runs ahead of the current and expected increases in oil demand, thus severely depressing the real price of oil and producing an environment conducive to low investment rates affecting supply conditions in the next cycle (as observed by the more-than-halve displacement of drilling rigs during 2014-2016). Such asymmetric responses are not

³ Production capacity is the sum of operating and spare (or surplus) capacity. Operating capacity is defined as the maximum sustainable amount of capacity that is in operation at the beginning of a period. Spare capacity is defined as the component of production capacity that is not in operation but can be brought online within one month; or not in operation but under active repair that can be completed within three months.

allowed for in the existing VAR literature in modelling the world oil market, which implies that this type of oil supply shocks cannot be identified from traditional observables of flow supply. This observation raises the question of how reliable is the comparative lack of explanatory power of the supply determinants in favour of the demand-driven explanations of major fluctuations in the real oil price.

Figure 1: Worldwide drilling activity and global capacity utilisation rates, 1975-2016

Notes: The real price of oil refers to the West Texas Intermediate price deflated by the US consumer price index in 2016 USD. The red shaded bars indicate the periods 2003-2008 and 2014-2016.

Data source: Federal Reserve Bank of St. Louis; Baker Hughes GE Database; US Energy Information Administration.

This paper quantifies the role of investment dynamics and capacity constraints in crude oil production in determining the real price of oil, by redefining oil supply shocks in terms of exogenous geopolitical disruptions in crude oil production (henceforth referred to as *exogenous supply shocks*) and the presence of capacity constraints in crude oil production due to investment dynamics (henceforth referred to as *endogenous supply shocks*). The identification of the newly proposed oil supply shocks rests on the availability of two time series due to Economou (2016). One is a measure of exogenous production shortfalls of crude oil due to geopolitical events in OPEC producing countries. The other is a newly constructed time series intended to capture any positive (oversupply) and negative (stagnant supply) deviations of production capacity from the equilibrium production path that arise due to risks of either over- or under-investment, respectively, and due to the presence of capacity constraints in crude oil production. Accordingly, the analysis in this paper builds on a fully specified structural vector autoregressive (VAR) model of the world oil market, in the tradition of Kilian and Murphy (2014), that decomposes the real price of oil as follows:

- (1) shocks to oil supply that are caused by exogenous geopolitical events in OPEC countries (*exogenous supply shocks*);
- (2) shocks to oil supply that arise within the crude oil market due to investment inefficiencies in upstream oil that result to capacity constraints (*endogenous supply shocks*);
- (3) shocks to oil demand associated with the global business cycle (*flow demand shocks*);
- (4) shocks to stock demand arising from the forward-looking behaviour of the market participants (*speculative demand shocks*); and

- (5) other idiosyncratic oil demand shocks not otherwise captured by the preceding structural shocks (*other demand shocks*).

Our analysis provides estimates of the dynamic effects of supply and demand shocks on the real price of oil and by how many dollars each structural shock contributed to the real oil price evolution from February 1992 to August 2016. The central message of the paper is that while there is overwhelming empirical evidence that most large and persistent fluctuations in the real oil price have been driven by the cumulative effects of oil demand, the robustness of this evidence crucially depends on the rigorous identification of oil supply shocks.

The rest of the paper is organised as follows. Section 2 reviews the alternative oil supply shock measures, available in the empirical literature, that can be used in modelling the supply side of the crude oil market. Section 3 introduces the structure and identifying assumptions of the proposed structural VAR model of the world oil market. In Section 4 we quantify the oil supply and oil demand shocks in the crude oil market and estimate their dynamic effects and historical contribution to the real price of oil. Discussion is built on an empirical comparison with the conventional framework, by comparing our results with those obtained by re-estimating a structural VAR model of flow supply, flow demand and speculative demand within the theoretical framework proposed by Kilian and Murphy (2014). The analysis concludes by assessing the real-time forecasting performance of each structural model in predicting the June 2014 oil price collapse and the subsequent evolution of the Brent price up to December 2016. Section 5 draws the conclusions.

2. A Review of the Supply Shock Measures of Crude Oil

Considering the rich record of geopolitical episodes in oil-producing countries since the 1970s-oil crisis, numerous studies concerned with the effects of exogenous supply shocks on the price of oil and other macroeconomic aggregates introduce measures that control explicitly for these shocks (Dotsey & Reid, 1992; Hamilton, 2003; Hoover & Perez, 1994; Kilian, 2008). Exogeneity here means that these events did not occur in response to the current or past state of the crude oil market and the global economy. Historical examples of such exogenous geopolitical events in the modern OPEC period that began in the early-1970s, include: the Arab oil embargo of 1973, the Iranian Revolution of 1978, the Iran-Iraq War of 1980, the Gulf War of 1990, the Venezuelan oil crisis of 2002, the Iraq War of 2003 and the Libyan Civil War of 2011, among other episodes. During these geopolitical events, crude oil production from key oil-producing regions has been severely curtailed, withholding the growth of global oil production and thus affecting the flow supply of crude oil. While this distinction was originally thought important in assessing the effects of supply and demand shocks on the real price of oil, recent empirical evidence demonstrate that commonly used measures of exogenous supply disruptions explain little about major oil price shock episodes post-1974 (Kilian, 2008b). Furthermore, Kilian (2009a) finds that utilising measures that distinguish between exogenous and endogenous production responses among oil producers to the exogenous supply disruptions (through their effect on price), in comparison to changes in global oil production per se, makes no difference to the observed lack of a significant response of the real price of oil to supply shocks.⁴ As a result, subsequent empirical studies on the causes of oil price shocks drop these explicit oil supply shock measures and instead rely on the observed monthly changes in global oil production to identify shocks to the flow supply of oil collectively (see, for example, Kilian & Murphy, 2014). This approach, however, points to a potential limitation of modelling the supply-side of the oil market, which does not differentiate between supply shocks originating from outside and within the crude oil market, or recognise the differences associated with the responses of oil production, real economic activity, inventories, and hence the real price of oil to these shocks over time.

⁴ The author compares the results from the structural VAR model introduced in Kilian (2009a) with an earlier version of the model that distinguishes changes in global crude oil production between shocks to oil production that are driven explicitly by exogenous political events in the Middle East, building on the exogenous supply shock measure proposed by Kilian (2008b), and other supply shocks (see Kilian, 2006).

In addressing these problems, recent empirical work by Economou (2016) introduces a new set of oil supply shock measures that distinguish between changes in crude oil production that arise due to exogenous geopolitical events in OPEC producing countries, such as wars and civil unrests, and capacity constraints in production capacity that arise due to market-specific innovations associated with the investment dynamics in upstream oil. The key insight on which the proposed measures are built is that any attempt to identify the timing and magnitude of these distinct oil supply shocks requires explicit assumptions about the counterfactual path of oil production in the absence of an exogenous event in question on the one hand and conditional to the equilibrium production path on the other hand. The methodology for constructing the exogenous oil supply shock measure generalises the approach introduced by Kilian (2008b) and is designed to capture the timing, the duration, the magnitude and the sign of all exogenous changes in OPEC crude oil production driven by major geopolitical events. The newly proposed measure of endogenous supply shocks builds on the explicit assumption that oil supply shocks can also be determined endogenously with respect to the cumulative amount that could eventually be extracted and the projected time path of the demand function (Adelman & Watkins, 2008; Smith, 2009, 2012). The reasoning underlying this assumption follows the logic that just as the interaction of supply and demand determines the equilibrium price path, these market forces determine also the equilibrium production path (Adelman, 1993). Accordingly, the endogenous oil supply shock measure is designed to capture the timing, the magnitude and the sign of any positive or negative deviations of production capacity from the equilibrium production path that arise due to inefficiencies in the investment decisions of oil producers. These measures allow us to evaluate the quantitative importance of the exogenous and endogenous supply components in the real price of oil at each point in time since January 1990. This is a period of academic and policy interest, as the supply-side of the oil market experienced a structural shift away from the problem of availability towards the problem of deliverability⁵ and the investment challenge that dictate oil price dynamics to date (Fattouh & Mabro, 2006).

2.1. Measure of flow supply shocks to global crude oil production

The classical notion in the literature of shocks to the flow supply of crude oil, associates these shocks with disruptions in global oil production driven by exogenous geopolitical events in oil-producing countries, as well as politically motivated decisions by OPEC members and other flow supply-related shocks (Kilian & Murphy, 2014, p. 458). Figure 2 plots the monthly percent changes in global crude oil production from February 1973 to August 2016, using data compiled by the US Energy Information Administration (EIA). From the figure, it is shown that major historical movements in crude oil production reflect largely key exogenous geopolitical events in OPEC countries (indicated by the vertical lines in the plot), which are associated with wars and political unrests, politically motivated supply decisions and internal OPEC power struggles observed during periods of high volatility such as in the mid-1980s (see Gately, Adelman & Griffin, 1986). It can also be seen that, by historical standards, there have been no substantial fluctuations in global oil production after 1990, with the largest changes corresponding to the Gulf War of 1990, the Venezuelan Oil Crisis of 2002 and the Iraq War of 2003.⁶ Indicatively, from January 1990 to August 2016, shocks to the flow supply of oil accounted for 0.8% of the variability in global oil production changes, compared to 4.8% in the previous period of the sample (February 1973 to December 1989). Finally, a visual examination of the series seems to belie any obvious relationship to endogenous shocks in crude oil production after 2003. Yet a large body of the recent literature postulates that major oil price developments after 2003 were partly driven by capacity constraints in crude oil production associated with the long run

⁵ Naimi (2005) defines deliverability as a measure of effective capacity that the oil industry needs to develop, produce, refine and deliver to end-consumers, as to meet the actual and expected oil demand.

⁶ The volatility starting from mid-1990s till the early-2000s is largely driven by the fluctuations in Iraqi oil production associated with the gradual erosion of the U.N. Oil-for-Food-Programme and the Iraqi oil exports bans that served as a negotiating tactic against the uneven enforcement of the U.N. sanctions (Katzman, 2003).

challenges of depletion, the erosion of spare capacity, the economic viability of new sources of supply such as US shale oil and Canadian oil sands, as well as shifts in OPEC oil output policy (Alquist & Guenette, 2014; Arezki, 2016; Fattouh & Sen, 2015; Hamilton, 2013a, 2014; Sandrea, 2014).

A case in point is the 2003-2008 episode, during which the strong demand growth from the non-OECD economies had caught up with the decade-long structural underinvestment in the upstream sector of the 1990s, the maturity of legacy oil fields and the long lead times associated with the development of new production capacity. Between 2004 and 2007, oil consumption in emerging economies increased on average by a 4.3% annual growth rate, whereas global oil production between 2005 and 2007 unexpectedly halted.⁷ Although there have been other episodes when global oil production stagnated over a two-year period, these were inevitably either responses to falling demand during recessions or to exogenous supply disruptions (Hamilton, 2013b). During this episode, however, the strength of global demand growth caught oil producers by surprise. By 2007, crude oil production outside OPEC was 0.73 mb/d lower from its levels in 2004, as important contributors to the growth of non-OPEC oil supply (e.g. the US, the North Sea and Mexico) failed to maintain and expand production. Fattouh & Mabro (2006) attribute this stagnation of crude oil production to a number of economic, political and geological factors, as well as other relating to corporate behaviour, that predominated in the oil industry since the 1980s. These factors combined produced a long-lasting environment conducive to low investment rates in the upstream sector at the expense of maintaining and developing new crude capacity. Most importantly, the main impact of the generalised structural underinvestment in the upstream sector over the previous two decades was felt on the erosion of spare capacity that between 2002 and 2005 collapsed by 4.15 mb/d, down to 1.02 mb/d (Fattouh, 2006). Hamilton (2009b, p.10) characterises the 2003-2008 oil price surge as a new era for oil price dynamics, according to which without the willingness or the ability of Saudi Arabia to adjust production to smooth out price changes, any disturbance to supply or demand had a significantly bigger effect on price after 2005.

Figure 2: World crude oil production in monthly percent changes, 1973.2-2016.8

⁷ Calculations in this section are based on publicly available data from the US Energy Information Administration, unless stated otherwise. Available at: <https://www.eia.gov/petroleum/data.php>

Another case of interest, is the unprecedented growth of US shale oil production and its importance to recent price dynamics which shifted market perceptions from oil scarcity to oil abundance. Between 2009-2015, US oil production grew on average at a sustained annual rate of 9.6%, while US shale oil production alone grew on average by a remarkable annual rate of 22.3%. Alquist and Guenette (2014) attribute this unprecedented growth in US shale oil production to the persistent high oil prices in the past decade, the transfer of technological expertise and knowledge from the exploitation of shale gas that had been developed in the US since the 19th century, as well as the legal incentives, access to finance and advanced infrastructure available to US oil producers. Nevertheless, despite US oil production accounting on average for 9% of total world output (between 2009-2015), the immense growth of US production had no obvious impact to the growth of global oil production, at least not until 2014. Many observers have suggested that this paradox can be explained by the fact that from December 2010 to March 2014, the 3.2 mb/d of new production originating from the US were exactly matched by exogenous disruptions in oil production in the Middle East and North Africa (Stevens, 2015, p. 6). Only in the second half of 2014, when the earlier geopolitical production shortfalls unexpectedly receded and OPEC decided not to cut output to counter the excess supply that had been muted for years, did the supply-demand imbalance materialise, generating a very significant price response to the downside (Baffes et al. 2015). By 2015, the annual average real price of oil halved from \$100/b down to \$53/b, as global oil production continued to grow at an annual average rate of 2.8% driven by an increase in OPEC and US crude oil production by 4% and 7.4% respectively, while global oil consumption grew by a comparably weaker annual average rate of 1.6%.

Evidently, there is a good reason to suspect that modelling shocks to the flow supply of oil collectively, based on changes in global oil production per se, may render recent structural VAR models of the world oil market informationally misspecified. One important implication is that critical information about the underlying supply conditions of the crude oil market are not contained in the shock measure of flow supply available to the econometrician (e.g. oil production might be subject to capacity constraints). An additional implication is that exogenous shocks in crude oil production would be expected to have a markedly different effect on the real price of oil, as on the rest variables of the model, compared to shocks to crude oil production within the confines of the world oil market. To the extent that this assumption is valid, estimates of the dynamic effects of flow supply shocks on the real oil price are potentially misleading, especially at increasingly distant horizons. The reason is that, on the one hand, geopolitical shortfalls in crude oil production tend to be resolved in the short-run by spare capacity releases when excess production is available, which explains why recent empirical studies find that exogenous supply shocks have little systematic impact on the real price of oil (see, for example, Kilian, 2008b). On the other hand, unless oil demand deteriorates, capacity constraints due to underinvestment can only be resolved in the long-run by adding new capacity in the oil market, which is a process associated with long gestation periods and lead times of optimal investment decisions and planning (Fattouh & Mabro, 2006). Similarly, unless oil demand recovers or OPEC collectively decides to balance the market, the only way to resolve capacity constraints due to overinvestment hitting the market, is for oil producers whose long-run marginal cost exceeds the current price of oil to exit the market, which can take months or years (Baumeister & Kilian, 2016b).⁸ This line of reasoning suggests that while exogenous oil supply shocks are non-negligible, capacity constraints in crude oil production may have generated larger and more persistent price responses in recent years than previously thought.

⁸ In his regard, Adelman (1962) notes that, under competition, when demand falls short of operating capacity the price must fall so low until it is clearly below the current extractive operation costs of many wells producing a sizeable fraction of output, for the market oversupply to be resolved.

2.2. Measure of exogenous shocks to OPEC crude oil production

Many studies have proposed measures of exogenous oil production shortfalls (see Dotsey & Reid, 1992; Hamilton, 2003; Kilian, 2008b). More recently, Economou (2016) proposes a monthly measure of exogenous shocks to OPEC crude oil production that takes full account of the timing and the actual duration of the shock, as well as of variations over time in its magnitude and sign. Building on the work of Kilian (2008b), the author generates the counterfactual production level for an OPEC country associated with an exogenous geopolitical episode, by extrapolating its pre-shock production level based on the average growth rate of production in other OPEC countries that are subject to similar governance, operational and investment performance but not in any way associated with that episode or any other exogenous episode of their own. Incorporated into the counterfactual underlying the construction of the series, is a monthly dummy variable that identifies the actual duration of an exogenous shock to crude oil production on a case-by-case basis. This approach allows for the counterfactual production level to normalise relative to actual production, given that the initial exogenous event has expired and is not followed by another episode. Explicit in the methodology is the role of Saudi Arabia which is the only producer that has an official policy of maintaining spare capacity and has historically acted as a swing producer filling the gaps at times of oil disruptions (Fattouh & Mahadeva, 2013). In this case, the counterfactual production series identifies the timing, the magnitude and the sign of a Saudi oil production response to an exogenous production shortfall elsewhere in OPEC, over an extended period of adjustment and not strictly temporary. The measure of exogenous oil supply shocks reflects changes in OPEC crude oil production driven explicitly by geopolitical events and not by collective output adjustment decisions in response to the state of the crude oil market or by other oil market-specific factors (e.g. geological depletion or investment decisions).⁹

Figure 3: Exogenous disruptions and offsets in OPEC crude oil production in thousand barrels per day, 1990.1-2016.8

⁹ For a detailed discussion on the methodology and construction of the counterfactuals on a country-basis the reader is referred to Economou (2016).

Figure 3 shows the OPEC-wide exogenous shortfalls and offsets in crude oil production driven by major geopolitical events for the period January 1990 to August 2016. These are computed on a country-basis by subtracting from the actual production levels the constructed counterfactual levels at monthly frequency. The negative production levels at each point in time may be viewed as the true shortfalls in crude oil production from a given country as a response to a major exogenous event, indicated by the vertical lines in the plot; namely from Iran, Iraq, Kuwait, Venezuela, Nigeria and Libya. The positive production levels at each point in time may be viewed as the true oil production responses from Saudi Arabia that are triggered in response to an exogenous event elsewhere in OPEC. The actual duration of each exogenous shock to crude oil production is part of the propagation mechanism to be estimated by the dummy series underlying the construction of the counterfactuals. By summing all OPEC country-specific shortfalls in oil production and the Saudi production increases as a response, it is possible to construct an aggregate time series of changes in OPEC crude oil production caused explicitly by exogenous geopolitical events. The change over time in the series provides a natural measure of the exogenous oil supply shocks at monthly frequency, shown in Figure 4. The series is expressed as a percent share of global production capacity.

Figure 4: Measure of exogenous supply shocks to OPEC crude oil production in first-difference, 1990.2-2016.8

Figure 4 shows that exogenous oil supply shocks range from -7.5% to +4.5% of global production capacity. These are associated with large negative and positive swings in OPEC crude oil production that by construction reflect a production shortfall driven by an exogenous event and the degree of a reversal of that shortfall either by releases of spare capacity from Saudi Arabia, or by the gradual recovery of the initial shortfall following the expiration of the exogenous episode, or both. Exogenous oil supply shocks from February 1990 to December 2003 account for 1.6% of the variability in global production capacity changes, following the outbreak of major geopolitical events such as the Gulf War of 1990, the Iraqi Oil Embargos during 1997-2002, the Venezuelan Oil Crisis of 2002 and the Iraq War of 2003. From January 2004-onwards, however, the movements in the exogenous oil supply shock measure are comparably weaker and less persistent, accounting for only 0.6% of the variability in global production capacity. Overall, these exogenous movements exhibit a similar pattern with shocks to the flow supply of oil as shown in Figure 2, the latter accounting for 1.2% and 0.4% of the variability in world output at the same intervals, while a preliminary statistical comparison shows that the two

measures are relatively close with a correlation of about 60%. This statistically significant relationship further strengthens our concerns that measures of flow supply shocks may have become less informative in recent years. One possible explanation is that they largely reflect changes in global oil production that are brought about by exogenous events, thus neglecting important information about innovations to oil production that arise within the crude oil market. Another explanation *ex ante* is that to the extent that measures of flow supply shocks fail in practice to model the supply-side of the oil market collectively, recent VAR models of the world oil market may ignore the endogenous channel of transmission of supply shocks to the real price of oil, in favour of other demand-related channels. Therefore, of equal importance to a measure that controls explicitly for all exogenous shocks to crude oil production, is an explicit measure of shocks to global production capacity that operate within the crude oil market.

2.3. Measure of endogenous shocks to global production capacity

Exogenous shocks to global crude oil production constitute only one type of oil supply shock. There also may be shocks to global production capacity due to a number of uncertainties impacting the investment decisions of oil producers and hence affecting the oil supply. This type of oil supply shocks (referred to as *endogenous oil supply shocks*) arises within the crude oil market and implicitly reflects the rate of investment in new production capacity, conditional to the expectations of oil producers regarding future market conditions and the likelihood of price (Adelman, 1993; Mabro, 2006). Accordingly, recent empirical work by Economou (2016) introduces a novel methodology for constructing a monthly measure of endogenous oil supply shocks that takes full account of the timing, the magnitude and the sign of any supply-related deviations from the equilibrium production path driven by oil market-specific factors. The newly proposed measure implicitly equates new additions in production capacity with oil production based on the critical assumption that just as the growth rate of production capacity must be equal to that of oil production, the growth rate of oil production must be approximately equal to that of petroleum consumption. Having adjusted the actual oil production levels insofar as all exogenous shocks are accounted for (due to the measure of exogenous supply shocks),¹⁰ the author generates the counterfactual production path for selected oil producers that are net importers and net exporters by country, by extrapolating their adjusted production levels based on the growth rate of their domestic consumption. The latter is weighted according to the percent contribution of domestic production and imports drawn by origin to the total consumption of the net importers, and the percent contribution of total production from the net exporters to domestic consumption and exports by destination. The assignment of weights ensures that the counterfactual production levels do not overstate the true endogenous shortages or surpluses in global oil production, given that operating capacity is predetermined. The strategy is to estimate that amount of oil production that the net importers need to cover by imports drawn to meet total domestic consumption on the one hand, and that amount that is available for exports given that the net exporters cover their domestic consumption on the other hand. The intuition is that through petroleum inter-regional movements they should offset one another, thus determining the equilibrium production path, from which it is possible to observe the timing, the magnitude and the sign of any oil market-specific supply deviations over time (see Economou, 2016).

Figure 5 shows the vertical differences between actual and counterfactual production levels by country for selected oil producers that are net importers, namely for the US and China, and those that are net exporters, namely for aggregate OPEC, Russia, Canada, Mexico and the North Sea (i.e. the UK and Norway combined); along key oil market-specific events in the period January 1990 to August 2016. Incorporated into the weights underlying the construction of the counterfactuals for the net

¹⁰ Further to oil supply shocks that arise explicitly by exogenous events in OPEC countries, the author also controls for exogenous production shortfalls that occur outside OPEC, namely for Canada, Mexico, the North Sea, the US and Rest of World. These are primarily associated with natural disasters, such as the Katrina/Rita/Ivan and Gustav/Ike Hurricanes in the USGC of 2005 and 2008, as well as other geopolitical outages that occurred in the Middle East and North Africa following the 2011 Arab Uprisings.

exporters, is also demand for imports from Japan, India, IEA Europe and Rest of World.¹¹ Excluding the last aggregate, the selected sample combined represents on average a total of 81% of world oil output and 79% of world petroleum consumption, in the twenty-six-year horizon of the sample. The negative production levels at each point in time may be viewed as that amount of oil supply that the net importers need to cover by imports drawn and not from domestic production. The positive production levels at each point in time may be viewed as that surplus amount of oil supply that is available to be exported by the net exporters, given that they cover in principle their own domestic needs. The change over time in the series is driven explicitly by endogenous factors conditional to the current and past state of the crude oil market. For example, increasing production could be driven either by a significant oil discovery or by a past period of high investment rates in the upstream sector, or both. On the other hand, declining production could be driven by the natural declining rates of oil reserves or by a past period of structural underinvestment in the upstream sector, or both. In addition, these changes reflect collective OPEC (and non-OPEC) output adjustment decisions based on expectations about future market conditions and price. By summing all country-specific endogenous shortages and surpluses in oil production and further subtracting any amount of spare capacity over the buffer of 2.0 mb/d,¹² it is possible to construct an aggregate time series of imbalances in global production capacity caused explicitly by oil market-specific factors. The change over time in the series provides a natural measure of the endogenous oil supply shocks at monthly frequency as shown in Figure 6, expressed as a percent share of global production capacity.¹³

Figure 5: Endogenous cover/exposed levels of crude oil production in thousand barrels per day, 1990.1-2016.8

¹¹ 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.

¹² As an informal rule of thumb, oil market analysts suggest that OPEC needs to hold at least 5% of global oil demand in spare capacity to enable it to stabilise the market, which equals on average around 4.0 mb/d for the period 1990-2016 (McNally, 2012). However, Saudi Arabia's declared policy is to maintain a volume of spare capacity of 2-3 mb/d (Fattouh & Mabro, 2006, p. 125).

¹³ For more details on the rationale and construction of this measure the reader is referred to Economou (2016).

Endogenous oil supply shocks between February 1990 to August 2016 range from around +2.5% to -2.5% of global production capacity and account for 3.1% of the variability in the changes of the world series, compared to only 1.2% of the variability due to exogenous oil supply shocks (as shown in Figure 4). The movements in the baseline endogenous oil supply shocks measure can be reconciled with key market-specific oil dates, indicated by the blue vertical lines in the plot. For example, the initially negative and then positive swings exhibited in the shock measure in 1998, 1999, 2008 and 2009 are consistent with the collective OPEC-non-OPEC output adjustment decisions related to the market uncertainty in the aftermath of the Asian Financial Crisis of 1997 and the Global Financial Crisis of 2008. In addition, the negative spikes between 2002-2004 reflect the erosion of spare capacity amid the unexpected surge in non-OECD oil demand, owing to the generalised underinvestment in the oil sector in the 1990s. Finally, there are two periods of gradual fluctuations in the endogenous oil supply shock series that denote persistence: the 2005-2008 and the 2012-2015. The former reflects the global production stagnation associated with persistent declines in the series followed by temporary increases, while the latter reflects the US capacity expansions in unconventional oil production associated with persistent increases in the series followed by temporary declines. Overall, endogenous oil supply shocks from February 1990 to December 2003 account for 1.9% of the variability in global production capacity changes, compared to 4.2% from January 2004-onwards. A visual examination of the constructed series confirms that the measure is reasonably isolated from any exogenous events, as indicated by the absence of any significant shortfalls during key exogenous oil dates (e.g. Gulf War in August 1990). Furthermore, the correlation of the exogenous and endogenous shock series is weak at about 20%. Similar results also hold when the endogenous measure is compared with that of flow supply shocks (the correlation is weak at 21%). This evidence supports the robustness of the endogenous oil supply shock measure, while further strengthening the claim that traditional shock measures may neglect critical information about the underlying supply conditions of the crude oil market.

Figure 6: Measure of endogenous oil supply shocks to global production capacity in first-difference, 1990.2-2016.8

3. A Structural Model of the World Oil Market

The analysis in this paper builds on a dynamic simultaneous equation model in the form of a structural VAR that generalises the structural oil market model introduced by Kilian and Murphy (2014). The sample period extends from February 1990 to August 2016. The model is specified based on a monthly dataset that includes: (1) a measure of exogenous oil supply shocks; (2) a measure of endogenous oil supply shocks; (3) a measure of global real economic activity; (4) the real price of oil; and (5) a proxy of global crude oil inventories. Furthermore, we consider 24 autoregressive lags in line with the literature (Hamilton & Herrera, 2004; Kilian, 2009a), an intercept and seasonal dummies to remove the seasonal variations. The structural VAR model is set-identified based on a combination of sign restrictions, as well as bounds on the impact price elasticities of oil supply and oil demand.¹⁴ These identification restrictions constitute an essential component for the economic interpretation and causal meaning of the model estimates and they are motivated by economic theory, institutional knowledge and other extraneous information. The implementation of the identification procedure is described in Kilian and Murphy (2014, p. 463), while for a general exposition about the usefulness of set-identified VAR models the reader is referred to Kilian and Murphy (2012).

3.1. Data

Consider a VAR model based on monthly data for $y_t = (prod_t, cap_t, rea_t, \Delta rpo_t, \Delta stocks_t)'$. Accordingly, $prod_t$ is the measure of changes in OPEC crude oil production driven by exogenous geopolitical events in OPEC countries and cap_t is the measure of imbalances in global production capacity that arise within the crude oil market, as discussed in Section 2. Both these measures are expressed as a percent share of global production capacity and are stationary by construction. The rea_t denotes an updated measure of global real economic activity proposed by Kilian (2009a). This is a business cycle index of global real economic activity that is designed to capture shifts in the global demand for all industrial commodities. Moreover, it is widely characterised by the literature as one of the most suitable indices deemed appropriate for quantifying the effect of global economy on oil demand (see, for example, Baumeister & Peersman, 2013a; Kilian & Hicks, 2013). The index is expressed as percent deviation from a linear trend and is stationary by construction. The Δrpo_t refers to the real price of oil defined as the spot Brent price deflated by the US consumer price index and is expressed in log-differences. Finally, $\Delta stocks_t$ is the level-changes in closing OECD crude oil and other liquids inventories in million barrels, as reported by the EIA. Considering that there are no readily available data in the public domain for global oil inventories, we follow the literature in approximating the global stocks based on OECD oil inventories (see Hamilton, 2009b). Moreover, recent empirical studies that device alternative proxies for above-ground global crude oil inventories show that the use of these proxies in determining the real price of oil yields very similar results in general (see Kilian & Lee, 2014). This issue was addressed as part of our sensitivity analysis from which we concluded that the use of alternative inventory data does not change the main results of this paper.

3.2. Structural VAR model

Let y_t be a vector of the five observables, then the proposed structural VAR of the world oil market may be written as:

$$B_0 y_t = \sum_{i=1}^{24} B_i y_{t-i} + \varepsilon_t, \quad (1)$$

where B_i , $i = 0, \dots, 24$, denotes the coefficient matrices and ε_t is the vector of orthogonal structural innovations. The vector ε_t consists of five structural shocks. The first shock incorporates shocks to

¹⁴ Identification by sign restrictions in structural VAR models was pioneered by Faust (1998), Canova and De Nicolo (2002) and Uhlig (2005). The refinements of these sign restrictions to accommodate additional inequality restrictions for reducing the set of admissible structural models, as proposed in this paper, were introduced by Kilian and Murphy (2012).

crude oil production triggered by geopolitical events in OPEC countries that are exogenous with respect to the crude oil market (*exogenous oil supply shock*).

The second shock captures unexpected imbalances in production capacity, relative to the equilibrium production path, that reflect the failure of oil producers either to expand production due to underinvestment or to adjust excess production due to overinvestment, conditional on their expectations about future market conditions and the likelihood of price (*endogenous oil supply shock*).

The third shock corresponds to unexpected fluctuations in the global business cycle that drive demand for crude oil and other industrial commodities (*flow demand shock*).

The fourth shock captures changes in stock demand arising from forward-looking behaviour not otherwise captured by the model (*speculative demand shock*).

Finally, the fifth shock corresponds to other idiosyncratic oil demand shocks that cannot be classified as one of the preceding structural shocks (*other demand shock*). The latter is essentially a residual shock that escapes economic interpretation, but it implicitly represents other exogenous shifts in the demand for oil that can be driven by a myriad of reasons (e.g. weather-related shocks).

The preceding structural shocks are identified based on a set of key identifying assumptions that involve primarily restrictions on the signs of the impact responses of the five observables to each structural shock. These sign restrictions derive directly from the economic model, outlined as follows. First, conditional on all past data, an unanticipated exogenous shortfall in crude oil production raises the real price of oil and production capacity (through drilling activity), and lowers the real economic activity on impact. The impact effect on oil inventories is ambiguous *ex ante* because inventories could either be drawn down to mitigate the magnitude of the price increase (Hamilton, 2009b), or be built up driven by speculative demand in anticipation of the price increase (Alquist & Kilian, 2010). Therefore, we do not impose any restrictions on the sign of the impact response of oil inventories.

Second, an unanticipated endogenous contraction of production capacity causes the real price of oil to increase and the real economic activity to decrease on impact. We do not restrict the sign of the impact response of crude oil production and inventories because the former implicitly responds only to exogenous events and the latter is ambiguous *ex ante*.

Third, an unanticipated increase in oil demand for current consumption (i.e. flow demand for oil) raises the production capacity, the real economic activity and the real price of oil on impact. As in the case of a negative endogenous oil supply shock, we do not impose any sign restrictions on crude oil production and oil inventories.

Fourth, a positive speculative demand shock in equilibrium causes an accumulation in oil inventories, which requires oil production to increase and oil consumption to decrease (reflected by an increase in production capacity and a decline in real economic activity), as the real price of oil increases.¹⁵ By the same logic as before, we do not restrict the sign of the impulse response of crude oil production to a speculative demand shock.

Finally, these sign restrictions identify the fifth structural shock referring to other demand shocks not otherwise accounted for.

3.3. Identification

The usefulness of identifying assumptions is that they allow the model to distinguish between the unique patterns of the different oil supply and oil demand shocks, as well as they provide an economically meaningful interpretation of the model estimates when assessing the causal effect of these shocks to the model variables. Identification in set-identified models, however, can be problematic in that the lack of sufficient information about the values of the structural model

¹⁵ For more details on the motivation, rationale and economic interpretation of speculative demand shocks the reader is referred to Alquist & Kilian (2010) and Kilian and Murphy (2014).

parameters can lead to a wide range of admissible models (i.e. satisfying the identification restrictions), further complicating statistical inference (Inoue & Kilian, 2013). To overcome this problem, Kilian and Murphy (2012) suggest that when such information exists it is important to impose all credible identifying restrictions for the identification of the model estimates to be economically meaningful. In particular, the authors demonstrate that sign restrictions may be strengthened with the help of additional economically motivated inequality restrictions. In the context of a structural model of the world oil market, one such set of restrictions relates to empirically plausible bounds on the magnitude of the oil supply and oil demand elasticities on impact. Moreover, Kilian and Lütkepohl (2017) argue that it is possible to further reduce the set of admissible model solutions by imposing additional sign restrictions on the structural impulse responses beyond the impact period. However, because it is difficult to imply these dynamic sign restrictions directly from economic theory, these are often motivated based on some other extraneous information about the dynamic responses of the model variables (see, for example, Inoue & Kilian, 2013). Accordingly, our structural VAR model is identified based on a combination of static sign restrictions on the impact responses of the five observables to each structural shock, dynamic sign restrictions on the responses to an unexpected exogenous oil supply shock and bounds on the impact price elasticities of oil supply and oil demand.

Table 1: Sign restrictions on impact responses in VAR model

	Exogenous supply shock	Endogenous supply shock	Flow demand shock	Speculative demand shock
Oil production	–			
Production capacity	+	–	+	+
Real activity	–	–	+	–
Real price of oil	+	+	+	+
Inventories				+

Table 1 summarises the sign restrictions on the impact responses of crude oil production, production capacity, real economic activity, the real price of oil and oil inventories to each structural shock, as described in Section 3.2. All structural shocks have been normalised as to imply an increase in the real price of oil, while missing entries denote that no sign restrictions are imposed. In addition to these static sign restrictions, we also impose the restriction that the response of the real price of oil to a negative exogenous oil supply shock must be positive for at least one year beyond the impact period. This implies a joint set of sign restrictions such that the responses of oil production and real economic activity to an unanticipated exogenous oil supply shock are negative for the first twelve months, while the responses of the real price of oil and production capacity are positive. The inclusion of these dynamic sign restrictions follows the rationale in Kilian and Murphy (2014, p. 462), suggesting that these are necessary to rule out admissible models in which unanticipated exogenous shortfalls in crude oil production cause a decline in the real price of oil below its starting level. In contrast, we do not impose any sign restrictions on the impulse responses to endogenous oil supply shocks, flow demand shocks and speculative demand shocks beyond the impact period, because these shocks are associated with an expectational component which is not possible to determine ex ante at increasing horizons. For example, it is not possible to know how OPEC producers might resolve the uncertainty pertaining to the future state of the crude oil market, nor how traders will respond to the expectational shifts related to this uncertainty. These questions are instead treated as part of the propagation mechanism to be estimated by the structural model, conditional to additional inequality restrictions about the impact price elasticities of oil supply and oil demand.

The impact price elasticity of oil supply can be expressed as a function of the joint-ratio of the impact responses of oil production and production capacity to an unexpected exogenous demand shock (i.e. either in flow demand or in speculative demand), relative to the impact response of the real price of oil triggered by the same shock. In practice, oil producers will be slow, if at all, to respond to a flow demand shock on impact, given the costs of adjusting production and the uncertainty about the state of the crude oil market (Kilian, 2009a). In support to this view are empirical estimates of the short-run

price elasticity of oil supply that suggest a range between effectively zero and 0.27.¹⁶ Considering that there is little evidence to suggest that differences within this range have an important effect on inference about the relative contribution of oil supply and oil demand shocks on the real price of oil (see, for example, Baumeister & Hamilton, 2015), we impose the restriction that the impact price elasticity of oil supply falls within a lower bound of 0.00 and an upper bound of 0.02. This bound is consistent with conventional views in the literature that suggest a steep but not quite vertical short-run oil supply curve (Kilian & Murphy, 2014). We also examined the sensitivity of our main results to higher upper bounds, indicatively of 0.05 and 0.1, and found that there are no significant changes to the shape of the posterior distribution of the impulse responses, despite an increase in the set of the admissible models, in line with the wider consensus in the literature.

Finally, the model imposes the restriction that the long-run price elasticity of oil demand must at least weakly exceed on average the short-run price elasticity over the sample. Rather than associating this oil demand elasticity with its textbook definition (i.e. the ratio of the impact response of oil production and of the real price of oil to an unexpected oil supply shock), Kilian and Murphy (2014) propose a novel time-varying measure that estimates the responses of both oil production and oil inventories to an exogenous shift in the oil supply curve, called *oil demand elasticity in use*.¹⁷ The authors argue that this distinction is important because of the implied additions to inventory holdings that must be subtracted from the quantity of oil produced to depict the true amount of oil used. Thus, the impact price elasticity of oil demand in use can be constructed by evaluating jointly the ratio of the impact responses of oil production and production capacity minus the ratio of the impact response of oil inventories to the unexpected exogenous oil supply shocks, relative to the impact response of the real price of oil to these shocks. Because by construction our structural model disentangles the oil supply shocks into exogenous and endogenous (i.e. oil market-specific), we report the average oil demand elasticity in use as a function of the responses to the sum of both supply shocks. In addition, we impose the restriction that the impact price elasticity of oil demand in use should fall within a bound between -0.8 and 0, consistent with formal empirical estimates of the long-run price elasticity of oil demand available in the literature.¹⁸

4. Estimation Results

The structural VAR model is consistently estimated by the least-squares method, based on 10 million random draws for the rotation matrix that result to a set of candidate structural models. From this set we retain only those structural representations of the model that satisfy the identifying restrictions described in Section 3.3. Even though the range of admissible models is not very large, for expository purposes we report the results from the model that yields an impact price elasticity of oil demand in use closest to -0.29, which is the posterior median of this elasticity among all the admissible models. At the end of Section 4.2, we provide additional sensitivity analysis with respect to this elasticity and show that the model results are quite robust regardless of the elasticity range. It is important to note that qualitatively similar results are obtained from all the admissible response functions, with only a few admissible models assigning a higher predictive power for changes in the real price of oil to speculative demand shocks, at the expense of changes in oil inventories. These response estimates, however, are well outside the pointwise 68% posterior error bands at all horizons, suggesting that they are neither equally plausible nor economically credible compared to the rest admissible responses and thus are disregarded.

¹⁶ For a survey of this literature, see Caldara, Cavallo and Iacoviello (2016).

¹⁷ For a detailed discussion on how to construct the oil demand elasticity in use within a structural VAR model, the reader is referred to (Kilian & Murphy, 2014, pp. 477-478).

¹⁸ For a survey of this literature, see Caldara, Cavallo and Iacoviello (2016) and Fattouh (2007a).

4.1. Responses to oil supply and oil demand shocks

Figure 7 plots the responses of oil production, production capacity, real economic activity, the real price of oil and oil inventories to each structural shock along with the corresponding pointwise 68% posterior error bands obtained by drawing from the reduced-form posterior distribution (indicated by the shaded area).¹⁹ We note that all shocks have been normalised such that they imply an increase in the real price of oil. Recall that the feature that distinguishes oil production from production capacity, is that the former responds only to unanticipated exogenous oil supply shocks in OPEC producing countries, while the impact from these shocks to production capacity is channelled explicitly through their effect on the real price of oil. Furthermore, by construction, endogenous oil supply shocks reflect either an unanticipated stagnation in global production capacity (i.e. negative shock) or unanticipated expansions in global production capacity (i.e. positive shock), both of which arise explicitly within the crude oil market. This additional information would generate biases in the admissible impulse responses related to these observables, the extent of which hinges on the credibility of our underlying economic assumptions. For example, Figure 7 shows that apart from the exogenous supply shock, all remaining structural shocks have virtually no significant effect on oil production. Another example is the failure of production capacity to increase beyond impact of an unanticipated positive flow demand shock, despite a persistent increase in the real price of oil, once again supporting the robustness of the shock measures.

Figure 7: Structural impulse responses and corresponding pointwise 68% posterior error bands, 1990.2-2016.8

Notes: All responses but the inventory responses are expressed in percentages. The inventory responses are in million barrels.

¹⁹ We do not include the variable responses to a residual demand shock because this shock is found to be largely negligible. Results about the cumulative effect of other demand shocks are presented in Section 4.2.

The most striking result in Figure 7 is the fact that the relative importance of oil supply shocks for the real price of oil differs greatly, depending on the nature of the shock. On the one hand, a negative exogenous oil supply shock causes a sharp decline in crude oil production on impact, followed by the partial reversal of that decline within three months. The real price of oil temporarily rises on impact and after one year it gradually starts to decline towards its starting value, as oil production recovers near pre-shock levels. The price increase triggers endogenous expansions in production capacity that are proportional in magnitude to the exogenous shortfalls in oil production, but peak after half a year. The real economic activity drops slightly for less than a year, while oil inventories are persistently drawn down.

On the other hand, an unanticipated negative endogenous oil supply shock is associated with a significant contraction in production capacity on impact that persists at all horizons and relates to year-long stagnation periods. Notably, in the two-year horizon, the gains in production capacity reach only half the level of the initial shortage, consistent with the long lead times associated with the development of new capacity. This shock causes a steep and very persistent increase in the real price of oil that is twice as large in magnitude and duration compared with that caused by an exogenous supply disruption. Real economic activity is associated with large positive loops that progressively become more persistent to the downside. Oil inventories are temporarily drawn down and reverse near starting levels within one year. These estimates imply a larger role for shocks to oil supply that originate within the crude oil market than those driven by exogenous events, underscoring the importance of modelling explicitly each oil supply shock, as well as the central role of endogenous capacity pressures in determining the real price of oil.

At the same time, Figure 7 illustrates that a positive shock to the flow demand for oil is associated with a persistent and hump-shaped increase in real economic activity that causes an immediate jump in the real price of oil. The price increase remains large and persistent at all horizons. By construction, the effect on oil production is insignificant, while production capacity remains largely negative owing to the shortages in excess capacity. Oil inventories are persistently and significantly drawn down in an effort to smooth out consumption.

Finally, a positive speculative demand shock causes a persistent increase in oil inventories. The real price of oil temporarily rises on impact and reverts to its starting value after three months, before marginally declining further within one year. Production capacity slightly increases in the first half a year, while real economic activity remains largely in decline at all horizons. These estimates support some of the core insights provided by earlier studies, suggesting that flow demand shocks have large predictive power for changes in the real price of oil as opposed to speculative demand shocks that are largely negligible (see Kilian, 2014).

Figure 8: Historical decomposition of the real price of oil by structural shock in percent changes, 1992.2-2016.8

4.2. Historical decomposition of the real price of oil

Figure 8 shows the historical decomposition of the real price of oil from February 1992 to August 2016. Each panel in the figure plots the respective cumulative contribution of each structural shock to the real price of oil over time. The solid lines show how the real price of oil would have evolved, if all structural shocks but the shock in question had been turned off. The dashed lines show the cumulative change in the real price of oil caused by all structural shocks. The first panel indicates that exogenous oil supply shocks overall made little contribution to the real price of oil, especially after 2000. By far the biggest contribution is due to the endogenous oil supply shock and the flow demand shock. Endogenous oil supply shocks exerted significant upward pressure on the real price of oil between 2004 and mid-2007, while their increasing importance to the market imbalance that plunged the price of oil in June 2014 appears as early as mid-2012. Flow demand shocks are responsible for the bulk of the oil price collapse in 1997-1999 and largely for the price surge that preceded up to June 2008, but there is little evidence to suggest that the 2014 oil price collapse was demand-driven. To the extent that flow demand shocks mattered for the oil price slump of 2014-2016, they appear to be responsible for a sharp defined decrease in the real price of oil only after mid-2015. The final panel indicates that speculative demand shocks make no large systematic contribution to the evolution of the real price of oil. Notwithstanding these historical decompositions, it is instructive to focus on specific episodes since the early 2000s.

Figure 9 shows by how many dollars per barrel each oil supply and oil demand shock contributed to the cumulative change in the real price of oil over some period of interest. The results are broken down into three periods, representing: (a) the boom and bust of 2002-2009 (panel 1); (b) the oil price recovery of 2009-2014 (panel 2); and (c) the oil price collapse of 2014-2016 (panel 3). The real price of oil is inflation-adjusted in 2016.8 US dollars. The first five bars in each panel show the cumulative contribution of each structural shock to the cumulative change in the real price of oil over the period in question. The last bar indicates the actual cumulative change in the real price oil observed in the data. Starting with the results from January 2002 to June 2008 in the first panel of Figure 9 (indicated by the blue bars), we observe that out of the cumulative \$119/b increase in the real price of oil over this period, \$50/b are attributed to the cumulative effect of the endogenous oil supply shocks and \$48/b to flow demand shocks. An additional \$22/b are attributed to speculative and other demand shocks combined. On the contrary, the cumulative effect of exogenous oil supply shocks is negative but negligible, lowering the price of oil by \$1/b. What these results merely suggest is that despite popular belief that positive shifts in the flow demand for oil produced the bulk of the oil price surge between 2002-2008 (see Kilian, 2014, p. 6), if there was enough available production capacity to cover the unexpected rise in flow demand, the real price of oil would have been lower by at least \$50/b. This does not mean that the oil price would not have increased close to \$75/b (from \$26/b) driven explicitly by the growth of flow demand for oil, but endogenous capacity constraints in oil-producing countries amplified the effect of flow demand shocks on the real price of oil roughly by 104%. The same can be said for the subsequent plunge of the real price of oil by \$96/b, between June 2008 and February 2009 (indicated by the grey bars in the first panel). Endogenous supply shocks in conjunction with flow demand shocks accounted in total for 70% of the observed cumulative oil price decline, that is for \$36/b and \$32/b respectively. The difference in this episode is that OPEC oil producers were able (and willing) to adjust production to counterbalance the fall in flow demand and hence to smooth out the price collapse, which proved to be short-lived.

Figure 9: Contribution to the cumulative change in the real price of oil by structural shock, in 2016.8 USD per barrel

The second panel in Figure 9 focuses on the oil price recovery between February 2009 and June 2014 (indicated by the blue bars). We observe that out of the cumulative \$64/b increase in the real price of oil over this period, \$30/b are attributed to the cumulative effect of flow demand shocks and \$16/b are due to exogenous oil supply shocks following the outbreak of the 2011 Arab Uprisings. Speculative demand shocks accounted for an additional \$15/b, while endogenous supply shocks accounted only for \$4/b. It is useful to explore further the price dynamics over this period, especially between June 2012 and June 2014 (indicated by the grey bars in the second panel). A closer examination shows that even though the real price of oil was fairly balanced, associated with a minor cumulative decline by \$2/b, the underlying shocks in the oil market had been far more important. For example, we observe that endogenous oil supply shocks in the form of unanticipated capacity expansions exerted significant downward pressure on the real price of oil by \$11/b. However, the real price of oil response to these shocks have been small, as the excess supply was largely matched by positive shifts in the flow demand for oil that accounted for \$10/b of the cumulative price change. These estimates contradict earlier conjectures in the literature suggesting that the market oversupply at the time had been offset by unexpected exogenous shortfalls in crude oil production (see, for example, Stevens & Hulbert, 2012). This explanation is not supported by our results. On the contrary, out of the observed \$16/b cumulative contribution of exogenous oil supply shocks to the price increase between February 2009 to June 2014, these shocks account for at most \$1/b after June 2012.

Finally, the third panel in Figure 9 shows that of the \$64/b cumulative decline in the real price of oil from June 2014 to January 2015 (indicated by the blue bars), \$29/b are due to endogenous oil supply shocks, \$13/b are due to exogenous oil supply shocks and \$12/b are attributed to flow demand shocks. An additional \$12/b to the price collapse are attributed to speculative demand shocks. These estimates suggest that endogenous oil supply shocks alone roughly accounted for twice as much as any other supply or demand shock in explaining the oil price plunge during this episode, indicating that the persistence of the earlier capacity expansions were the dominant factor. On the contrary, an unexpected slowdown in global real economic activity affecting the flow demand for oil was the major contributor to a renewed price decline by \$22/b between January 2015 to January 2016 (observed by the grey bars in the third panel). Over this period, flow demand shocks accounted for an additional cumulative decline in the real price of oil by \$15/b, while endogenous oil supply shocks accounted only for \$1/b. The rest \$6/b of the additional price drop was due to receding exogenous supply disruptions. Thereafter, between January to August 2016 the real price of oil recovered from its earlier drop by a cumulative increase of \$14/b, of which over 95% is attributed to negative endogenous oil supply shocks driven primarily by a contraction in US shale oil production (see Figure 10).

Figure 10: Contribution to the cumulative change in the real price of oil by structural shock from January to August 2016, in 2016.8 USD per barrel
2016.1 - 2016.8

An obvious question that arises from these results is why did flow demand for oil unexpectedly fail to grow after June 2014, albeit a persistent decline in the real price of oil. Figure 11 illustrates how our response estimates of real economic activity and the real price of oil to a positive endogenous oil supply shock could help explain this paradox. We observe that whereas a positive endogenous oil supply shock causes a persistent decline in the real oil price, this shock causes almost no change in real economic activity on impact, followed by negative loops that progressively shift upwards (shown by the trendline in the plot). These findings suggest that despite the belief that an oil price fall has a net positive impact effect on global economy, the expected economic boost due to a market oversupply is far from smooth (through its effect on price). This view is consistent with recent empirical evidence in the literature suggesting that there appear no signs of economic growth picking up in the first year following the price collapse not only in 2014, but also in 1986 (see IMF, 2015). Both these episodes share two common and interrelated characteristics. First, a large persistent component to the oil price declines. Second, a large loss in oil revenues for the oil exporters as a response. Considering that oil exporting economies are heavily dependent on oil revenues and thus they present many fiscal and external vulnerabilities, an expected lower oil price is associated with adverse shocks to the economic growth of the oil exporters that pass-through to the global economy (IMF, 2016).

Figure 11: Responses of global real economic activity and the real price of oil to a positive endogenous oil supply shock

Notes: Both responses are expressed in percentages.

For example, Obstfeld, Arezki and Milesi-Ferretti (2016) argue that the oil exporting countries were the largest contributors to the slowdown of global economic growth during 2015-2016, despite their relatively small share of global GDP (about 15% based on purchasing power parity). In support to this evidence the European Central Bank (2016) finds that the oil exporting economies experienced substantial fiscal deficits, higher inflationary pressures and financial strains insofar as they exceeded the marginal consumption gains in oil importing countries, resulting to a net negative impact on the global economy. Furthermore, the absence of a balancing mechanism in the oil market (i.e. the unwillingness of OPEC producers to cut output) has led to a prolonged environment of higher price uncertainty that prompted oil producers to curtail capital investment in the upstream sector, weighing heavily on global economic activity and trade as a response. For example, Baumeister and Kilian (2017) show that because of the increased weight of oil-related investment in US real GDP growth due to the shale oil boom, the sharp decline in capital expenditure in the shale oil sector dampened the aggregate growth of the US economy. These examples highlight that the timing of the boost to

global economic activity amid a market oversupply (through its effect on price), depends on whether the latter is temporary or persistent. If temporary, oil exporters can draw on their financial reserves or increase borrowing to buffer their losses in oil rents, while upstream investment will remain robust as the oil price would be expected to recover. If persistent, the spending patterns of the oil exporters need time to adjust, while upstream investment will diminish once the expected price exceeds the long-run marginal cost of oil production, leading to a vulnerable macroeconomic environment and abrupt shocks to the flow demand for oil in both directions (see Figure 11).²⁰

As part of our sensitivity analysis, we address any concerns on whether our core conclusions are sensitive to allowing for the possibility of lower price elasticities of oil demand in use. Table 2 presents the minimum and maximum contribution of each structural shock based on all admissible models within a pre-specified range of this elasticity, over some period of interest. The resulting estimates are expressed in percent contribution of the total cumulative price change and they are rounded to the nearest integer. Table 2 indicates that regardless of the sample period, the endogenous supply shock and the flow demand shock account for the lion's share of the cumulative change in the real price of oil with only small quantitative differences across the elasticity ranges. For example, consider the results for the period January 2002 to June 2008. Regardless of the elasticity range, endogenous oil supply shocks accounted for anywhere between 34% and 49% of the cumulative price increase over this period, while flow demand shocks accounted for anywhere between 33% and 49%. The rest structural shocks combined accounted for anywhere between -3% and 30%. Likewise, regardless of the elasticity range, these two shocks combined accounted for anywhere between 67% and 79% of the cumulative price decline over June 2008 to January 2016, compared to the rest structural shocks that combined accounted for anywhere between 14% and 38%. These estimates imply that our main results are equally consistent regardless the choice of the admissible model.

Table 2: Minimum and maximum cumulative contribution to the real price of oil per range of price elasticity of oil demand in use, in percentages

Evaluation Period	Elasticity in use	Exogenous supply shock	Endogenous supply shock	Flow demand shock	Speculative demand shock	Other demand shock
2002.1 to 2008.6	[-0.30, 0]	[-2, 11]	[34, 47]	[33, 44]	[1, 13]	[-1, 4]
	[-0.25, 0]	[-2, 13]	[36, 49]	[37, 47]	[1, 13]	[-2, 2]
	[-0.20, 0]	[0, 13]	[36, 48]	[37, 48]	[1, 13]	[-1, 2]
	[-0.15, 0]	[1, 13]	[40, 48]	[37, 49]	[1, 11]	[-2, 3]
2008.6 to 2016.1	[-0.30, 0]	[12, 19]	[37, 41]	[32, 36]	[-2, 1]	[8, 11]
	[-0.25, 0]	[16, 18]	[38, 41]	[32, 38]	[-5, 6]	[8, 12]
	[-0.20, 0]	[16, 18]	[37, 41]	[30, 34]	[-6, 7]	[8, 12]
	[-0.15, 0]	[16, 18]	[38, 41]	[31, 34]	[-6, 7]	[8, 12]

4.3. Empirical comparison with a structural VAR model of flow supply, flow demand and speculative demand shocks

A central objective in this paper is to explore how the use of endogenous and exogenous supply shock measures potentially affects the conventional estimates of the effects of supply and demand shocks to the real price of oil obtained from structural oil market models that identify shocks to the flow supply of oil collectively (see Section 2.1). This section compares our baseline results to those obtained by re-estimating a structural VAR model of flow supply, flow demand and speculative

²⁰ It is worth emphasising that shale oil production is widely perceived as being more price sensitive than conventional production and thus shale oil investment is supposed to be more responsive in the short-run. However, there is still no empirical evidence to support this view which remains ambiguous.

demand in the tradition of Kilian and Murphy (2014). The model includes four monthly variables: (1) the percent change in global oil production; (2) the measure of global real economic activity due to Kilian (2009a); (3) the real price of crude oil; (4) and the proxy for changes in global oil inventories. Data on global oil production rely on monthly estimates as reported by the EIA, while the rest variables have been defined in Section 3.1. The sample extends from February 1990 to August 2016. The model is estimated recursively by least squares using 24 autoregressive lags and seasonal dummies.

Table 3: Sign restrictions on impact responses in the 4-variable SVAR model

	Flow supply shock	Flow demand shock	Speculative demand shock
Oil production	–	+	+
Real activity	–	+	–
Real price of oil	+	+	+
Inventories			+

The structural shocks are identified based on a combination of sign restrictions and bounds on the impact price elasticities of oil supply and oil demand, building on Kilian and Murphy (2014). Table 3 summarises the sign restrictions on the impact responses of the model variables to the four structural shocks, outlined as follows.²¹ A negative shock to the flow supply of crude oil lowers oil production and real economic activity on impact and raises the real price of oil. A positive flow demand shock raises oil production, real economic activity and the real price of oil on impact. A positive speculative demand shock in equilibrium raises oil production, oil inventories and the real price of oil, but lowers real economic activity. These restrictions implicitly identify the fourth residual demand shock. In addition, we impose the dynamic sign restriction that a negative flow supply shock does not lower the real price of oil for the first twelve months. Finally, the model bounds the impact price elasticity of oil supply by 0.02 and the impact price elasticity of oil demand in use between -0.8 and 0. To facilitate our comparison, we report the results for the model that yields an impact price elasticity of oil demand in use closest to -0.29 (henceforth referred to as *4-variable SVAR*), in line with the benchmark elasticity estimate obtained by our baseline model. The response estimates of each model variable to each structural shock are shown in Appendix A.

4.3.1. Responses of the real price of oil to oil supply and oil demand shocks

Figure 12 compares the responses of the real price of oil to each structural shock by model specification. All shocks have been normalised as to imply an increase in the real price of oil. For expository purposes, we also plot the aggregate oil price response to an exogenous and endogenous supply shock referred to as *total supply shock*. It can be shown that a flow supply disruption causes a temporary increase in the real price of oil that peaks after one year and then gradually starts to decline towards its starting value. This pattern is qualitatively (and even quantitatively) similar to the response of the real price of oil to an exogenous supply disruption, while it largely contrasts with the oil price responses to a negative endogenous supply shock and a negative total supply shock. The latter shock causes a steep and very significant increase in the real price of oil for the first six months that despite its partial reversal after a year and a half, it remains persistent at all horizons. These findings imply that flow supply shocks largely reflect disruptions in crude oil production that are brought about by exogenous events, neglecting important information about endogenous innovations to flow supply that arise within the crude oil market. We can observe that this missing information is instead transmitted to the real price of oil through demand-related channels. In particular, the 4-variable SVAR model attributes somewhat higher predictive power to the flow demand shock and the speculative demand shock for the changes in the real price of oil, than the baseline model. Given

²¹ All structural shocks have been normalised as to imply an increase in the real price of oil. Missing entries in Table 3 denote that no sign restrictions are imposed. For a detailed discussion see Kilian and Murphy (2014).

these differences it is worth examining further the cumulative effect of each shock on the evolution of the real price of oil by model specification.

Figure 12: Structural impulse responses of the real price of oil by model specification, in percentages, 1990.2-2016.8

4.3.2. Contribution of the structural shocks to oil price movements since 2002

Figure 13 plots the cumulative change in the real price of oil caused by each structural shock over January 2002 to August 2016, obtained from the 4-variable SVAR model (red bars) and the baseline model (blue bars). The first bar in each panel compares the cumulative contribution of flow supply shocks against that of total supply shocks, as specified in the previous section. It can be shown that regardless of the period in question, the 4-variable SVAR model attributes the bulk of the cumulative changes in the real price of oil to flow demand shocks, whereas the differences between the two models regarding the speculative demand shock are quite small. For example, of the \$119/b cumulative increase in the real price of oil from January 2002 to June 2008 (first panel), this model assigns \$90/b to the cumulative effect of flow demand shocks compared to \$48/b attributed by the baseline model. Likewise, of the \$99/b cumulative decline in the real price of oil from June 2008 to August 2016 (second panel), the 4-variable SVAR model assigns \$75/b to the cumulative effect of flow demand shocks compared to the baseline model that assigns only \$32/b to this shock. Evidently, these differences operate at the expense of the explanatory ability of the supply determinant, as flow supply shocks due to the 4-variable SVAR model are found to have played a limited role in explaining the evolution of the real price, compared to the more significant role assigned to total supply shocks due to the baseline model. The former assigns -\$1/b and -\$14/b to the cumulative contribution of flow supply shocks to the price changes over the two periods, against \$49/b and -\$52/b assigned by the baseline model to total supply shocks respectively.

Figure 13: Contribution to the cumulative change in the real price of oil by structural shock, by model specification, in 2016.8 USD per barrel

It is worth emphasising that the cumulative contribution of flow supply shocks is strikingly similar to that of exogenous supply shocks, that is of $-\$1/b$ and $-\$12/b$. These results underscore that the traditional emphasis on changes in global oil production, per se, for modelling the supply-side of the world oil market collectively is misplaced. Moreover, the claim that economic fundamentals in the form of flow demand and to a lesser extent speculative demand have been the main determinants of the real price of oil must be rethought. Much of the prima facie case against an important role of oil supply shocks rests on the fact that the traditional shock measures of flow supply are informationally inadequate. Whereas exogenous shocks to crude oil production are not negligible, endogenous shocks in global production capacity have been a far more important determinant for major oil price fluctuations in recent years.

4.3.3. Real-time forecasts of the Brent price as of June 2014

Given the differences between the two VAR models when it comes to the identification of the structural shocks that drive the price of oil and the overall importance of oil supply and oil demand shocks, it is useful to contrast their ability to predict the price of oil. This is an important test of the validity of our core conclusions. Recent studies have shown that suitably chosen reduced-form VAR models that include the key variables relevant to the determination of the real price of oil exhibit superior out-of-sample forecast accuracy than alternative forecasting models (see Baumeister & Kilian, 2012). Recall that a clear distinction between the competing forecasting models is that the baseline model decomposes the oil supply determinant into its distinct exogenous and endogenous components, whereas the 4-variable SVAR model does not. The question of interest is whether the inclusion of the proposed decomposition of oil supply shocks in a forecasting model of the price of oil potentially improves the real-time predictive accuracy of conventional VAR forecasts that model

shocks to the flow supply of oil collectively. This question may be addressed by generating real-time forecasts of the Brent price using the reduced-form representation of each structural VAR model (Baumeister & Kilian, 2014). The objective is to assess the real-time forecasting performance of each model in predicting the June 2014 oil price collapse and the subsequent evolution of the Brent price up to December 2016, converted to nominal US dollars.

Figure 14: One-step ahead forecasts of the Brent price for July 2014 to January 2015, in nominal USD per barrel, 2014.1-2015.1

Figure 14 shows the evolution of the nominal Brent price from January 2014 to January 2015, along with the real-time forecasts obtained by the 4-variable SVAR model and the baseline model as of June 2014 (marked by the vertical line in the plot). For expository purposes, we focus on the one-step ahead forecasts. Each forecast is generated in real-time using only information as of the previous month (denoted by the black markers). As can be seen from Figure 14, the 4-variable SVAR model forecasts perform relatively poorly in predicting the one-step ahead directional change of the Brent price, with a success ratio of 43% (i.e. the fraction of times that the model correctly predicts the directional change of the oil price). Even though the forecasts in July and August are very close to the actual Brent price, the model systematically overpredicts the price of oil from the September forecast onwards by about \$13/b. On the contrary, the baseline model forecasts are much closer to the realisations of the Brent price, with a success ratio of 86%. Only the September 2014 and January 2015 baseline forecasts overpredict the Brent price by a more significant amount of \$7/b and \$10/b respectively. The consistency of this pattern, regardless of the model specification, raises the question of what are the causes of the competing forecast errors after August 2014, in the related context of supply and demand shocks to the price of oil.

Figure 15: One-step ahead forecast errors from September 2014 to January 2015
Brent price **Global oil production**

Notes: The forecast errors corresponding to the shock measures of crude oil supply due to the baseline model, are normalised as to reflect the aggregate forecast errors in global oil production.

Figure 15 traces the one-step ahead forecast errors by model specification from September 2014 to January 2015, for the Brent price, for global oil production, for global real economic activity and for changes in oil inventories. The first entry in each of the bar charts, corresponding to the errors in forecasting September 2014, shows large differences between the forecast errors of the two VAR models for global oil production and for oil inventories. The forecast errors for global real economic activity are largely in agreement in all months. The September forecast due to the 4-variable SVAR model generated a very large positive forecast error for global oil production (corresponding to about 3% of world oil output), which is lower by almost two-thirds due to the baseline model (corresponding to 1.2% of world oil output). The latter also attributed a small but non-negligible positive forecast error for the change in oil inventories (corresponding to 0.9% of OECD industry oil stocks). Thereafter, with the benefit of an additional month of information the one-step ahead forecast errors for the Brent price due to the 4-variable SVAR model persist well into October and November, while the errors due to the baseline model in the same months are largely corrected for. Considering that there are no large forecast errors associated with either an unexpectedly large supply or demand shock, a strong case can be made for the persistence of the forecast errors due to the 4-variable SVAR model being associated with the absence of critical information pertaining to the sequence of the earlier endogenous supply shocks. Likewise, despite both December forecasts attributing the forecast errors for the Brent price to large negative forecast errors for global real economic activity (compared with the actual index value of global real economic activity shown in Appendix B), the baseline forecast corrected this error by about one third at the expense of a large positive forecast error for global oil production (corresponding to about 1.5% of world oil output). Over 90% of the latter forecast error is

attributed to endogenous factors, due to the baseline model, which again appears to drive the mismatch between the January 2015 forecasts.

Figure 16: Real-time forecasts of the Brent price as of December 2014, in nominal USD per barrel, 2013.12-2016.12

In order to fully appreciate the implications of the informational inadequacy of flow supply shock measures at longer horizons, Figure 16 shows the evolution of the Brent price from December 2013 to December 2016 together with the real-time forecasts of the Brent price by model specification as of December 2014 (marked by the vertical line in the plot). Very similar results hold for both models regarding the directional accuracy of the December forecasts 24-months ahead, with a success ratio of 54% due to the 4-variable SVAR forecast and 50% due to the baseline forecast. However, by comparison, the baseline model forecast produced systematically lower real-time mean squared prediction errors (MSPEs), denoting higher predictive accuracy (Table 4). In most cases, MSPE reductions are higher than 40% relative to the 4-variable SVAR model forecast even at longer horizons.

Table 4: Recursive MSPE ratio of the baseline model forecast relative to the 4-variable SVAR model forecast

Month [Horizon]	Jan 15 [1]	Mar 15 [3]	Jun 15 [6]	Sep 15 [9]	Dec 15 [12]	Jun 16 [18]	Dec 16 [24]
MSPE	0.4043	0.4535	1.0587	0.6560	0.5781	0.5785	0.4437

Notes: Boldface indicates improvements relative to the 4-variable SVAR model forecast.

An intuitive way to put these results into perspective is to observe the bar charts in Figure 17 that compare the actual and predicted annual change of the key oil market indicators in 2015 and 2016, based on the real-time forecasts as of December 2014. Evidently, the main disagreement between the competing real-time forecasts is associated with the predicted annual growth of global oil production. On the one hand, the real-time 4-variable SVAR forecast predicted that global oil production in 2015 will marginally turn negative by -0.15 mb/d on average, before declining further in 2016 by -0.62 mb/d year-over-year (y-o-y). On the other hand, the real-time baseline forecast

correctly predicted that the annual growth of global oil production will persist well into 2015 and 2016, by 1.6 mb/d and 1.3 mb/d y-o-y, missing the average 2016 realisation only by 0.59 mb/d. As a result, in 2016, the 4-variable SVAR forecast predicted that the Brent price would rise at \$88/b year-end compared to \$53/b of the actual December price, whereas the baseline forecast predicted a price ceiling at \$66/b by the second half of the year (see Figure 16). These results are particularly informative given that the ability of the baseline forecasting model to distinguish between oil supply shocks that are different in nature has led to the much closer realisations of global oil production and hence of the Brent price over time. In support to the robustness of the baseline forecasting model, is also the fact that both forecasts detected an unexpected weakening of global economy and a stronger than expected growth of storage demand for oil.

Figure 17: Actual and predicted annual change of the key oil market indicators for 2015 and 2016, year-over-year

5. Conclusion

A recurring question in recent and past episodes of the crude oil market is how important are oil supply and oil demand shocks in explaining major oil price fluctuations. Advancements in theoretical and empirical work during the past decade made considerable strides addressing this question, enhancing our understanding of the determinants of oil price shocks. The conventional view today is that most major oil price shocks are explained by oil demand shocks collectively, rather than flow supply shocks, with a central role played by shifts in the global business cycle affecting the flow demand for oil. Traditionally, flow supply shocks were thought to reflect disruptions in crude oil production triggered by geopolitical events in oil producing countries and politically motivated OPEC decisions, both of which occurred outside the confines of the crude oil market. However, such exogenous shocks to global crude oil production constitute only but one type of oil supply shock.

There also may be shocks to global production capacity associated with the interaction of an array of geological, economical, regulatory and technological factors that combined can affect the supply of oil. This type of oil supply shocks arises endogenously with respect to the crude oil market and reflects the rate of investment to new production capacity and the lead times in bringing new capacity, conditional on the expectations of oil producers about future market conditions and expected price. This means that oil price shocks can only be understood with the help of structural models of the world oil market that jointly identify and estimate the exogenous and endogenous supply components in the real price of oil, along the components driven by flow demand and speculative demand. In this paper, we augmented the structural VAR model of flow supply, flow demand and speculative demand to allow for the decomposition of the supply determinant based on some novel approaches that in turn allow for the simultaneous identification of all four types of supply and demand shocks conditional on all past data.

There are two reasons why this decomposition is important. One is the fact that much of the *prima facie* case against an important role of oil supply shocks in explaining the evolution of the real price of oil rests on traditional measures of flow supply that are informationally inadequate. Our findings suggest that flow supply shocks largely reflect disruptions in crude oil production that are brought about by exogenous events, neglecting important information about endogenous innovations to flow supply that arise within the crude oil market. This missing information is instead transmitted to the real price of oil through demand-related channels at the expense of the explanatory power of the supply determinant. The second is that the relative importance of oil supply shocks for the real price of oil differs greatly, depending on the nature of the shock. For example, endogenous oil supply shocks appear to be associated with a markedly larger and more persistent impact on the real price of oil than exogenous disruptions in crude oil production. Furthermore, these shocks are also associated with important indirect effects on the real price of oil through other demand-related channels, such as their asymmetric impact effect on global economy.

The central message of the paper is that while there is overwhelming empirical evidence in the literature that most large and persistent fluctuations in the real price of oil have been driven by the cumulative effects of oil demand, the robustness of this evidence crucially depends on the rigorous identification of oil supply shocks. In general, our analysis showed that most large and persistent fluctuations in the real price of oil since the early-1990s can be explained either by large positive shifts in flow demand confronted by negative endogenous oil supply shocks or by persistent positive endogenous oil supply shocks confronted by unexpected negative shifts in the flow demand for oil. For example, our results suggest that despite the popular belief in the literature that the sustained run-up in the real price of oil between 2002-2008 was caused primarily by positive shifts in the global business cycle affecting oil demand, endogenous capacity constraints in oil-producing countries more than doubled the impact effect of flow demand shocks to the real price of oil. Likewise, while the 2014 oil price collapse was primarily triggered by the persistence of positive endogenous oil supply shocks, an unexpected downshift of the global business cycle in mid-2015 aggravated the recent price downcycle both in terms of magnitude and duration. On the contrary, there is little evidence to suggest that exogenous supply disruptions and shifts in speculative demand for oil contributed much to the evolution of the real price of oil over the sample period, confirming some of the core conclusions of earlier studies. Notwithstanding, both these shocks remain important components for the structural decomposition of the real price of oil. Finally, we demonstrated that forecasting models able to distinguish between oil supply shocks that are different in nature, produce more realistic out-of-sample estimates of the sequences of supply and demand shocks, thus enjoying higher real-time predictive accuracy than forecasting models that incorporate shocks to the flow supply of oil collectively. These findings underscore the importance of explicitly modelling endogenous supply shocks in structural models of the world oil market and the central role of production capacity pressures in understanding the evolution of the real price of oil.

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Appendix A

Figure A1: Structural impulse responses and corresponding pointwise 68% posterior error bands conditional on the estimate of the 4-variable SVAR model, 1990.2-2016.8

Notes: All structural shocks have been normalised as to imply an increase in the real price of oil. All responses but the inventory responses are expressed in percentages. The inventory responses are in million barrels.

Appendix B

Figure B1: Index of global real economic activity in percent deviations from trend, 2014.1-2015.1

Notes: This index is developed in Kilian (2009a) and is designed to measure the state of global economy. Negative index values represent recessionary phases of the economy and positive values expansionary phases. For a meaningful interpretation of the indicator, the magnitude of the deviations from zero should only be viewed in relation to the past.