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BI Norwegian Business School — Thesis

The U.S Shale Oil Boom: The Impact of U.S. Supply Shocks on the Global Oil Price

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Abstract

We examine the role of the U.S. shale oil boom in driving global oil prices. We give a brief discussion of the recent developments in the oil markets, paying special attention to the U.S. shale oil boom. We estimate a series of SVAR models which identify supply-related shocks from the U.S. and use a constructed U.S. imports variable which only reflects the state of domestic supply. Our results suggest that the U.S. has indeed exerted considerable negative pressure on the price. More specifically, we find that the U.S. explains up to 15.54% of its variation, considerably more than what has been found in other studies. However, this pressure on prices did not manifest itself until 2015. This delay implies a temporary friction in the transmission of U.S. supply shocks which we theorise is caused by incompatible processing facilities in the downstream supply chain.

Contents

1 Introduction

Few other commodities enjoy the same level of attention as crude oil. It serves as an important input for a large share of economic output. It has also been the centre of war and conflict, and can be a contributing factor to political turmoil and geopolitical tensions. It is not surprising that a significant change in the price of oil spurs interest and debate.

The summer of 2014 marked the end of a period characterised by remarkably high oil prices. From fluctuating around \$120 per barrel, the price hit the \$28 mark in January 2016 — the lowest level in more than 10 years. While the oil industry scrambles to recover profitability, researchers and analysts engage in heated discussions about the origins and implications of the plunge. Academics have emphasised demand-side innovations as the main drivers of oil prices, implying slowing growth in emerging markets as a plausible explanation. We believe there to be differences between the current and previous episodes of oil price fluctuations in that the U.S. experienced an unprecedented surge in shale oil production during the run-up to the recent price drop.

In this thesis, we analyse the impact of the U.S. shale oil boom on global oil prices. Our hypothesis is that additional oil production coming from the U.S. has been able to drive down the prices in recent years. Our methodology allows us to assess the magnitude of this effect.

To find evidence for our hypothesis, we employ a structural vector autoregression (SVAR) model which includes a measure of U.S. crude oil supply, in addition to OPEC production, a measure of global economic activity and the real price of oil. Novel in our approach is the use of a constructed U.S. imports variable which exclusively captures changes in U.S. supply. We thereby get the effect of U.S. supply increases on the oil prices through their lowered demand for foreign oil. Our model is built on Kilian (2009) where identification is accomplished by imposing exclusion restrictions.

Our results give strong support for our hypothesis. The United States explains up to 15.54% of the variation in the real price of oil according to our model. When the U.S. and OPEC are taken together, this figure grows even larger, to 27.6%. This is considerably higher than what has been found in the literature up until this point and reintroduces supply as an important driver of oil prices.

The rest of the thesis is structured as follows: Section 2 gives a narrative of the U.S. shale oil boom and the plunge in the oil price during 2014 and 2015. Section 3 concerns the ongoing debate in the literature with respect to the relative importance of demand and supply as drivers of oil prices. Section 4 opens with a motivating exercise and proceeds by describing the background for our SVAR analysis. This is followed by a description of the specifications in addition to the results derived from our three main models. We conclude by summarising our findings and give suggestions for further work in section 5.

2 The U.S. Shale Oil Boom

2.1 Background

The United States is no stranger to oil booms. The inception of the modern petroleum industry happened as a result of the 1859 Titusville, Pennsylvania oil rush. Beginning that year, the U.S. output of crude oil swelled from 2 thousand barrels per year to 4 million barrels ten years later, before reaching 10 million barrels in 1873 (Toyoda 2003). The attention shifted to Oklahoma and Texas after the 1901 discovery of the Spindletop gusher in Beaumont, Texas. 30 years had to pass before it got established as the centre of oil production in the United States following huge discoveries in Kilgore (Hinton and Olien 2002). The abundance was so large and prices so low that the Texas Railroad Commission (TRC) was urged to establish quotas on production. Since then, the output in the United States grew until the early 1970s when production reached its peak. Today, almost 40 years later, observers are talking about the oil boom in North Dakota, but this time around, there are no gushers to be seen. The oil is hidden away in the shales.

Box 1: Shale oil and extraction technologies

Extraction of conventional oil resources has traditionally entailed simply drilling for it. The same cannot be said for unconventional oil resources such as shale oil. With conventional oil, we drill through rocks that trap concentrated reserves of hydrocarbons. The change in pressure due to the drilling is usually enough to make these reserves flow to the surface (Robbins 2013). The geological particularities of oil shales is not as straight-forward and makes techniques such as *hydraulic fracturing*, *horizontal drilling* and *in-situ detortion* essential for recovery.

Shale oil is found in sedimentary rock formations, or shales. These shales have extremely low permeability due to the way in which they got formed. They are comprised of very fine-grained sediments which accumulated horizontally in quiet waters. In between these layers which over time solidified into rocks, organic materials from plant- and animal-life got trapped. The low permeability makes it virtually impossible for the hydrocarbons to flow within the shales (DoE 2009). Hence, extraction is not just about drilling — the well also needs to be stimulated for the hydrocarbons to flow freely. This is where *hydraulic fracturing* (or "fracking") comes into play. Fracking is a way to break up and create fissures in the rock formations. After drilling, the well is pumped with *fracking fluid* — a liquid mostly containing water, sand and chemicals under high pressures. Sometimes, other larger particles are used in addition to sand to make sure that the fissures do not close after the process is done. The chemicals are added to perform a variety of functions during the process, mostly to reduce friction so that the fluid can hit the target area more efficiently and with less pressure (Arthur, Bohm and Layne 2009). The reserves trapped in the shale layer are more easily accessed after the fracking process is completed.

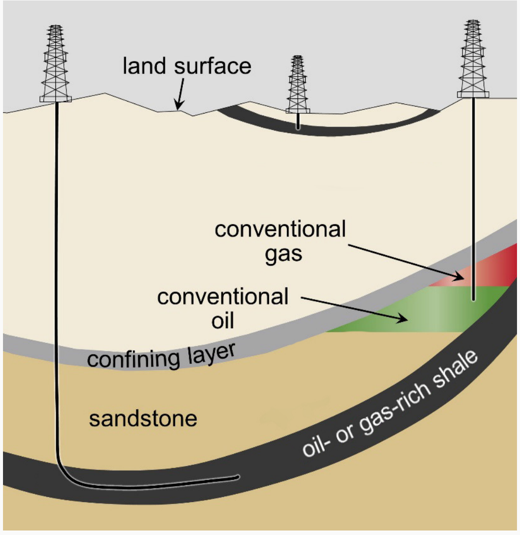

Figure 1: An adapted illustration of different sources of petroleum and their respective extraction methods. Source: U.S. Environmental Protection Agency.

However, while fracking makes the reserves more accessible, it makes little economic sense to drill vertically. The returns from stimulating a vertically drilled well are simply not large enough. This is where *horizontal drilling* becomes important. The shale layer is thin, but can span over vast areas. By drilling first vertically and then turning horizontally when the shale deposits are reached, a much larger area of the shale can be fracked at once. Between 2007 and 2009, the horizontal reach of drilling increased by a factor of four (Jaffe, Medlock and Soligo 2011), effectively reducing the average cost of extraction.

After having drilled horizontally and fracked the shales, there is still a crucial step left before the oil can be extracted. Due to the geological process creating these sedimentary rock formations, the hydrocarbons are still in a pre-petroleum state known as kerogen (Bussell 2009). In a process known as *retorting*, the kerogen is distilled by heating it up to about 500°C. This can either be done above ground (requiring that the shales are mined instead of drilled for) or *in-situ*. The latter is done by mining an underground chamber where the retort is placed (Bussell 2009).

From this summary, it becomes apparent that the exploitation of unconventional oil brings about a chain of costly additional steps in the extraction process compared to conventional oil.

The excitement surrounding U.S. shale oil is understandable for many reasons when put into a historical perspective. Until recent years, the notion of having passed *peak oil* in the United States was prevalent. Hubbert (1949) presented a framework to assess developments in the supply of different fossil fuels. His observations led him to believe that these developments followed a bell-shaped pattern where the supply of a particular resource would move asymptotically towards zero after the peak level had been reached. Almost Malthusian in nature, this implied that reserves over time would be so depleted and costly to extract that it would seize to be a viable source of energy[1]. Applying his own framework, he predicted that *peak oil* for the United States would occur around the year 1970 (see figure 21 in Hubbert 1956). While acknowledging the existence of substantial shale reserves, Hubbert disregarded these as unimportant for the timing of the peak. At best, shale oil would slow the rate of decline, making the right tail of the bell-curve longer. However, the recent developments in the U.S. oil industry is a clear departure from Hubbert's prediction and a sign that a *Malthusian catastrophe* in crude oil is not imminent — alas, at least not for a couple of decades (see e.g. Miller and Sorrell 2013).

2.2 The boom

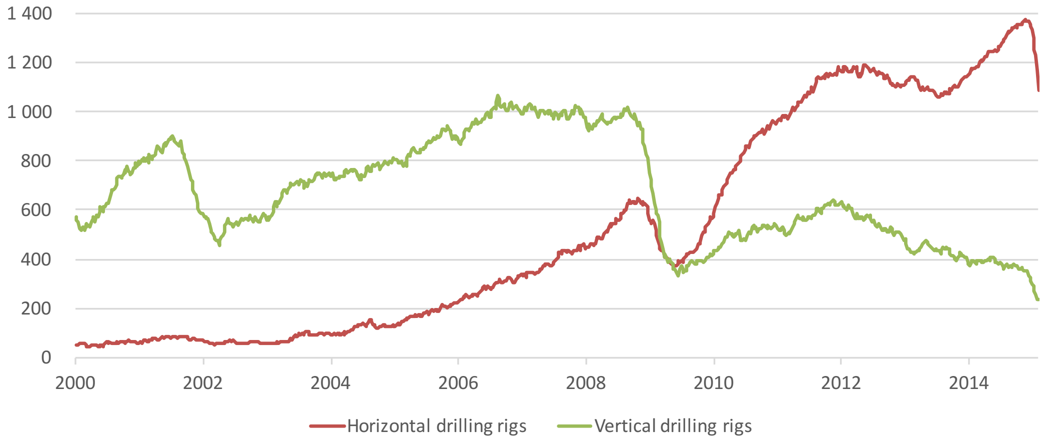

Figure 2: U.S. rotary rig count by drilling type, showing the increase in the use of horizontal drilling techniques. Source: Baker Hughes

Shale oil is petroleum found in rock formations of low permeability. In contrast to conventional oil, e.g. from gushers, the oil cannot be extracted by traditional drilling methods. A combination of horizontal drilling and hydraulic fracturing enables the oil to escape these rock formations (Box 1). The boom in shale oil production in the U.S. was enabled by the continued development of these

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[1] The Malthusian school of thought stems from the original work by Thomas Malthus (1798), predicting the eventual peak in the global population as growth in food supply would be insufficient to sustain a continued population growth.

extraction technologies. While they had been around for a long while, the per barrel cost of extraction had simply been too high. Development of the technology was fuelled by a period of high oil prices (Alquist and Guénette 2014; Kilian 2016; Maugeri 2013). Unconventional oil thus became competitive against conventional techniques, and investments in shale oil production in the U.S. consequently started increasing (figure 2). We can see from figure 3 that, by 2015, the U.S. shale oil production had increased sixfold since 2010. Between 2011 and 2012, over 4000 new shale oil wells had already been brought on-line — more than in the rest of the world when not considering Canada (Maugeri 2013). A clear advantage of the shale wells compared to conventional ones are the relative small initial investment and a short span of time needed to bring a new well online after discovery (Gold 2015). In theory, this implies a more elastic supply in the short run.

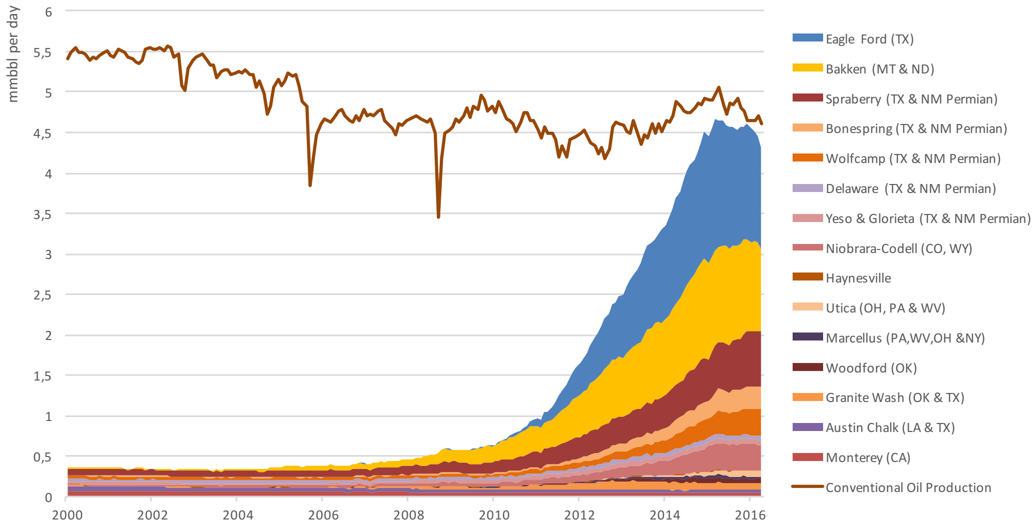

Figure 3: U.S. shale oil production per field juxtaposed with the country's conventional oil production (estimated as total crude oil minus tight oil production). Source: EIA, based on data from DrillingInfo and LCI Energy Insight

The largest bulk of shale oil comes from two shale oil plays in North Dakota and Texas. These are the Bakken and Eagle Ford shale formations respectively (figures 3 and 4). In the Bakken fields alone, the production started out at a few thousand barrels in 2007 and reached 770 000 barrels per day in December 2012 in addition to 23 billion cubic metres of natural gas per day (Maugeri 2013). For the United States, the boom in shale oil has had positive effects on employment and personal income in the areas surrounding the production sites (Fetzer 2014). North Dakota has been the highest ranking U.S. state in terms of net population growth during the last 4 years[2], a common trait among areas experiencing a boom.

A combination of different factors were necessary to set up the conditions

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[2] As evident by 2015 population data retrieved from the U.S. Census Bureau.

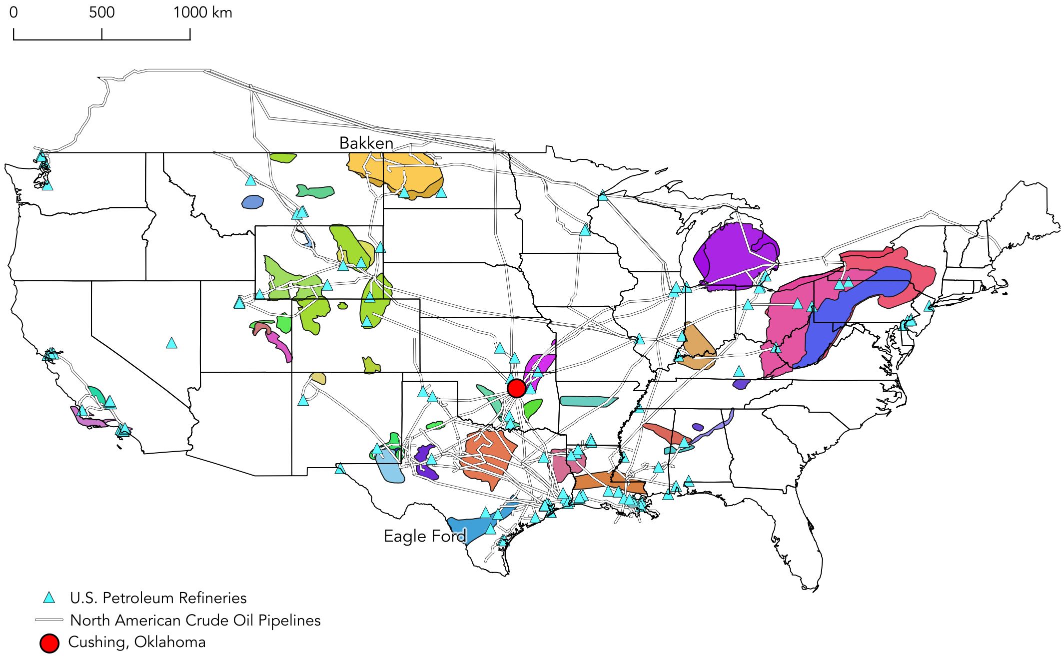

Figure 4: A map of U.S. shale oil plays, petroleum refineries and crude oil pipelines. Coordinates are gathered from EIA and the U.S. map data is created by Charlie Fitzpatrick at the Environmental Systems Research Institute.

for a boom in unconventional drilling activity (Alquist and Guénette 2014; Kilian 2016; Maugeri 2013). There were, of course, large reserves of tight oil available just waiting to be exploited. Drilling for oil is not a new industry in the United States. Hence, the investments needed to support this new endeavour were smaller compared to having to start out from scratch. The pre-existing drilling rigs, downstream supply chain and support services for the conventional oil industry formed the absorptive capacity for the development of unconventional oil production. While a positive force in terms of local economic activity and employment, the exploitation of shale has met resistance — most importantly due to worries concerning water contamination and other environmental issues possibly caused by the practice of fracking (McDermott-Levy, Kaktins and Sattler 2013). However, states like North Dakota have a low population density, leaving the areas affected less prone to opposition from the local populace. Other circumstances also contributed to the boom. The U.S. shale oil industry mostly consists of small independent firms. These firms have a large focus on high-risk, high-return projects, which generate cash flow quickly (Maugeri 2013). U.S. domestic financial institutions, venture capital and private equity are all eager to supply capital to finance independent companies. Finally, a legal framework making it straightforward to acquire mineral rights coupled with the factors mentioned above, made the expansion in unconventional oil difficult to replicate elsewhere in the world (Maugeri 2013).

Looking at figure 2, following the financial crisis of 2008, one might ask why conventional oil did not experience the same booming production. The data might mistakenly be interpreted as a drop in conventional oil production that never recovered after the initial drop. However, horizontal drilling techniques are increasingly being utilised in development of conventional wells, so the graph might not be as informative as it first appears[3]. Nonetheless, after the U.S. reached peak production in 1970, the production of conventional oil has been on a steady decline, and between 2011 and 2014, its production experienced only a slight increase (figure 3). The boom in shale was more dramatic as it was mainly due to technical innovations which directly contributed to more efficient extraction. Suddenly, there was profit to be made in shale oil and the industry did not hesitate to exploit it.

The question of continued profitability relies heavily on the per barrel marginal cost. While this cost is expected to fall as the deployment of and continued improvements to the technology continues, it is believed that the cost is higher than for conventional oil. Maugeri (2013) gives an upper bound of $80 and argues for the costs being as low as $40. This $40 limit is supported by statements made by the oil industry itself (Gold 2015). If this lower threshold is correct, unconventional oil could continue to be profitable despite prices being significantly lower than they were in 2010. It seems that the longer tail Hubbert (1956) speculated that shale oil would cause does not look like a tail at all. Production levels in the U.S. have returned to what was previously considered *peak oil* in the United States.

2.3 The recent price drop

While the significance of the U.S. shale oil boom on oil prices remains to be uncovered, there is no doubt that the steep decline in prices that occurred during the summer of 2014 and onwards has had considerable consequences for oil exporters and importers alike. Figure 5 shows the magnitude of the drop. Going from a price well above $100, the Brent Crude dropped to the $28 mark in January 2016, severely cutting into the industry's profit margins. For oil exporters, it meant a loss of income, more unemployment and attempts at cost reductions in the affected sectors of their economies (BBC News 2016; Toronto Star 2015).

A similar drop in prices has not been seen since the mid-80s when oil from outside the Middle East was brought to the market and OPEC chose to stand

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[3] For more on the differences between unconventional and conventional extraction technologies, Verdon (2013) provides a useful write-up, but focuses more on shale gas. See also Box 1.

idly by, not willing to lose market share (Gold 2015). This time around, the media and experts bring up remarkably similar explanations. A higher supply from non-OPEC countries such as Russia and the U.S. coupled with the apparent unwillingness to curb production among OPEC members have led to oversupply. Analysts point to a possible attempt by low-cost producers such as Saudi Arabia to push prices below the marginal cost of other suppliers as an explanation for OPEC's lack of action. As shale continues to emerge as a viable source of oil, expectations regarding total untapped reserves also affects the overall price level. Additionally, the slowing growth in emerging markets — China in particular — only adds to the overall outcome (The Economist 2015; The Economist 2016; The New York Times 2016; Vox Media 2016). The importance of emerging markets as the main demand-side driver of oil price fluctuations has been suggested by Aastveit, Bjørnland and Thorsrud (2015). They show that emerging economies can account for more than twice as much of the variance in the oil price as developed economies. While the U.S. dollar appreciated in the run-up to the mid-80s price drop, the Plaza Accord of 1985 stopped this development. This time around, the role of an appreciating U.S. dollar cannot be left out of the list of possible explanations (World Bank Group 2015). Since crude oil is quoted in U.S. dollars, an appreciating dollar is bad news for all buyers holding other currencies, and demand for it weakens as a result.

Baumeister and Kilian (2016) seek a more quantitative approach in order to assess the competing explanations. They deploy VAR forecasts with models containing the real price of oil, global production, changes in inventories and Kilian's own measure of real activity. The authors manage to forecast over half of the oil price decline during the second half of 2014, implying that the fall was predictable with data available before July. By looking at the forecast errors, they argue that OPEC's decision not to curb production in November and positive supply shocks after July 2014 are not causes supported by the data. Instead, they argue for changing expectations in July causing a decline in storage demand and an unexpected weakening of the global economy in December. Opposing popular opinion, they also raise doubts as to the effect of the dollar appreciation.

2.3.1 The Cushing cushion

For observers of the oil markets, it is easy to justify an assertion that the fall in global oil prices, at least to some extent, was due to the U.S. shale oil boom. However, the swelling U.S. supply of a type of crude oil with a different chemical makeup and geographical origin makes this explanation less convincing. American refineries were not prepared to process this new type of crude oil at first. As shale oil got transported to the market in Cushing, Oklahoma (see figure 4), and with no buyers with the appropriate processing facilities, a crude oil glut started to develop. The emergence of this glut can be seen in figure 5 as a price spread widening between the Brent crude and the West Texas Intermediate (WTI) benchmarks. While some refineries along the Gulf Coast in Texas had appropriate processes in place, the lack of southbound pipelines from Cushing made it impossible for this oil to cater to this demand, only adding to the spread (Kilian 2016). The lower prices quoted in Cushing created incentives for refineries to build new facilities or adjust their existing equipment to take advantage of this new source of supply. Over time, pipelines were constructed from the storage facilities in Cushing to the refineries along the Gulf Coast in Texas. Since the oil prices started dropping, the Brent–WTI spread narrowed.

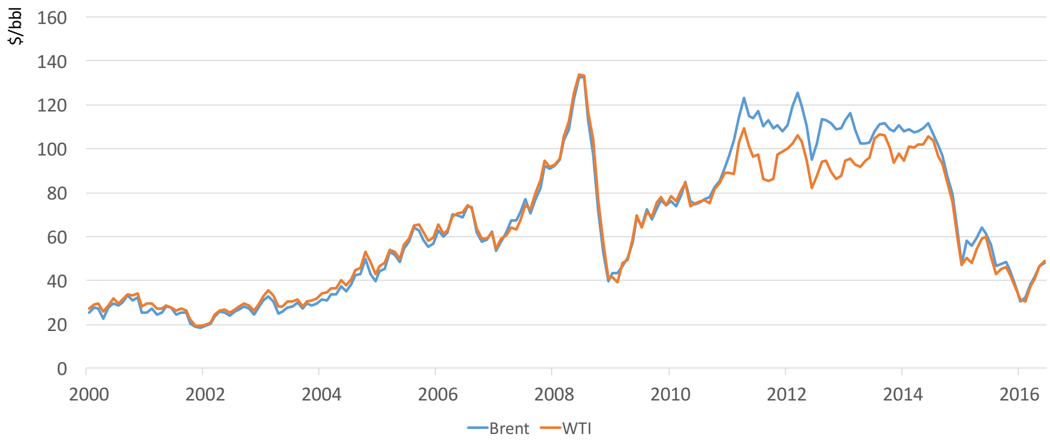

Figure 5: Brent crude and West Texas Intermediate prices, 2000–2016 with monthly frequency. The financial crisis of 2008 and the rapid oil price decline as of mid-2014 are notable. Source: Federal Reserve of St. Louis Economic Data (FRED)

The consequence of the glut in Oklahoma was a temporary friction in the transmission of booming shale oil supply in the U.S. to the oil prices globally. While the inventories of shale oil continued to build in Cushing, the refineries had to continue importing crude from abroad in order to satisfy demand for petroleum products. In other words, as the U.S. oil supply was booming, the impact on global prices got cushioned by the glut until downstream buyers were able to adapt their refining processes and utilise domestic shale oil to a greater extent, thereby increasing U.S. self-sufficiency.

3 Demand vs. supply

The recent oil price drop makes analysis on what determines the oil price as relevant as ever. Before we begin our investigation of the U.S. shale oil boom's effect on prices, it will be useful to do a review of what the literature has considered as the main drivers behind oil price fluctuations.

When it comes to the theoretical explanations for oil price shocks and their origins, there are two prevailing views in particular to consider: (1) The supply-side view of explaining oil price shocks originates from the work of Hamilton (1983; 1985), where exogenous supply disruptions are found to be the culprit of oil price shocks in post-war data. (2) More recently, Kilian (2009) employed a structural vector autoregression (SVAR) method which indicated that supply was not important in explaining the oil price fluctuations after the 1970s. Demand from global real activity and what he coined *oil-specific demand* were much more successful in explaining the oil price movements from the 70s onwards.

The competing explanations have to be viewed with the time-varying structure of the global oil markets in mind.

3.1 Hamilton and post-war oil shocks

In an attempt to find an explanation for why the oil price somewhat consistently spiked right before U.S. recessions in post-war data, Hamilton (1983; 1985) proposed that these spikes were not due to the U.S. business cycle, but rather exogenous oil supply disruptions, e.g. wars and conflicts in oil-producing locations.

Hamilton underpins this argument by pointing to the Texas Railroad Commission (TRC), an important institution which imposed *de facto* price controls during the period of analysis. The TRC would forecast crude oil demand month by month and plan production in Texas accordingly. With this institutional filter, the oil price would seldom deviate much from the posted or targeted price, effectively filtering out endogenous business cycle movements. Since exogenous supply disruptions could not be predicted, the crude oil price could not be shielded from these events, causing oil price hikes or rationing. Thus, this unique institutional arrangement allowed these exogenous supply shocks to be identified, as any innovations on the demand side were controlled for. The TRC's influence on the global oil price is likely to have deteriorated after the establishment of OPEC in the 1970s. This means that the plausibility of Hamilton's hypothesis of supply-side disruptions causing oil price shocks gets challenged in the post-OPEC environment. Giving support to Hamilton's case, Danielsen and Selby (1980) argue that OPEC established a price-targeting regime not unlike the one organised by the TRC, where oil price increases would only be sought if it was justified in OPEC meetings or by supply disruptions. However, it is unlikely that they would plan supply following projected U.S. demand. After the establishment of OPEC, endogenous demand forces should then have started to play a larger role in the determination of oil prices.

While Hamilton gives support to a supply-side explanation for oil price fluctuations, his analysis only considers exogenous negative supply shocks. If what we have observed recently is in fact due to a positive shock, it is not obvious that the implications of his results are analogous to our investigation of recent events. Large and persistent increases in supply require investments which are unlikely to be exogenous like the geopolitical events described in Hamilton's research. However, the TRC served as a filter for positive supply shocks in the pre-OPEC oil markets and the same could possibly be true for the OPEC-period. On the other hand, OPEC's lack of an effective market intervention mechanism to curb supply and control prices, i.e. OPEC being unsuccessful in maintaining control over its member countries[4], makes it more plausible than before that negative movements in the oil price could originate from a rapid endogenous increase in supply. Research on recent OPEC behaviour is scarce.

3.2 Kilian and demand shocks

By estimating structural VAR models, Kilian (2009) manages to establish recognition for demand-side forces' influence on the crude oil price. Kilian identifies three orthogonal shocks: supply, demand and what he coined oil-specific demand — the latter reflecting changing expectations of future supply shortfalls or other factors not captured by the first two shocks. Based on these, he finds that supply disturbances over the sample period 1973–2007 were, for the most part, transitory. In contrast, the estimated contribution of the demand- and oil-specific demand shocks on the oil price were pronounced, reflecting changes in global activity and shifts in expectations of the future oil supply, respectively. Even when there are physical supply disruptions, he argues that it is mainly the precautionary demand component which drives the prices up, and not the supply shock itself. Kilian and Murphy (2012) confirms

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[4] The effectiveness of OPEC as a cartel has been a controversy in the literature. Griffin (1985) found that OPEC in 1971–83 acted like a collusive cartel while non-OPEC suppliers did not. Almoguera, Douglas and Herrera (2011) find that OPEC did not act like a cartel on average over the full 1974–2004 sample period while Alhajji and Huettner (2000) reviewed several studies where 11 out of 13 dismiss OPEC as a functioning cartel.

the results in Kilian (2009) using a more sophisticated strategy involving sign-restrictions rather than exclusion restrictions to achieve identification.

Kilian's results imply that no oil price shocks are the same and that there is a two-way causality between the macro economy and the oil price. A negative supply shock will lead to higher prices and lower real activity. A positive demand shock will cause higher prices, but only dampened real activity as the decrease is cushioned by the shock itself. Depending on the type of shock, the policy implications for the economy will be different. More importantly, his results run in contrary to Hamilton's, rendering the supply side unimportant. For the case at hand, Kilian's findings hint to the possibility of the recent oil price drop being caused either by slowing global demand or a mix of less demand and more supply.

3.3 Recent discussions

Countering Kilian (2009), Hamilton (2009a) attempts to reinforce his supply-side view by looking at the period after the establishment of OPEC. Hamilton argues that Kilian's oil-specific demand shocks ought to manifest themselves as changes in inventories. More specifically, precautionary demand should incentivise hoarding behaviour and inventories should increase. Looking at the months following negative oil supply shocks, he observes that they actually tend to decrease. The implication is that changes in inventories serve to mitigate rather than worsen the shocks, smoothing the flow of oil in case of gluts or shortages.

Kilian's explanation favouring the demand side succeeds in explaining why the pre-2008 oil price hike did not cause the recession that followed[5]. Commenting on Hamilton, Kilian (2009b) argues that he fails to account for the crucial point that commonly used measures of oil supply only explain up to 20 percent of oil price increases. By construction, the rest can only be explained by demand factors[6]. Kilian goes so far as to say that the 1973 oil shock was in fact driven by demand. A surge in global real activity predates the oil price shock and, since the oil price prior to OPEC did not reflect the true market price due to interventions by the TRC, the oil price should have been much higher in the period prior to the shock. Further, the prices in other raw materials increased during the same period, but do not point to any contemporaneous disruptions

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[5] It is worth noting that the financial crisis of 2007–2008 is well understood and was not caused by variations in the oil prices (see Blundell-Wignall, Atkinson and Lee 2008; Crotty 2009; Foster and Magdoff 2009).

[6] Here, Kilian does not take into account the fact that, in his model, oil-specific demand can be affected by supply disruptions as well.

in supply. The oil price increase observed is only moderately higher than the price increases of other raw materials and commodities.

In a recent working paper by Baumeister and Hamilton (2015), the authors revisit the results employed in Kilian (2009) and Kilian and Murphy (2012). Using Bayesian techniques, they are able to confirm that these results are robust. Baumeister and Hamilton's results show that an oil price hike as a result of a negative supply shock leads to lowered economic activity after a significant lag while a price hike due to a demand shock does not exhibit the same response. It seems that Hamilton implicitly acknowledges the importance of demand shocks in this paper as he is not arguing otherwise.

Significant amounts of attention has been directed towards estimating the demand- and supply elasticities in the oil markets (see among others Baumeister and Peersman 2013; Hamilton 2008; Krichene 2002). These have important implications for how to understand oil price fluctuations. However, a SVAR might pick values for demand and supply elasticities which do not match those found in studies. In addition, for any particular value of the demand elasticity, the system might yield an implausible value for the supply elasticity and the other way around. Caldara, Cavallo and Iacoviello (2016) solves this issue by using prior information in the form of exclusion restrictions in addition to restricting the elasticities using a minimisation problem to get as close to the consensus in the literature as possible[7]. Combining this with a similar approach as Aastveit et al. (2015) with demand being split up into developed and emerging economies, the authors can trace up to 50 percent of the oil price fluctuations back to supply shocks over the 1985–2015 sample period. This is significantly more than what we have seen in the oil market SVAR literature up until now. Baumeister and Kilian (2016) also mentions the supply side of the oil markets as a major contributor to oil price fluctuations, specifically with regards to the 2014 decline.

While the debate is yet to be resolved, Kilian has managed to present compelling evidence showing that demand is important when assessing oil price shocks after the 70s, contrary to Hamilton's earlier findings. It is worth noting that Kilian does not cover the pre-1970s period. As we have just experienced a major fall in the oil prices, researchers have been busy attempting to understand its causes. Caldara et al. (2016) and Baumeister and Kilian (2016) give renewed confidence for supply-side explanations though most of the literature still favours demand.

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[7] While the median elasticities among studies reported in the literature were 0.13 and −0.13 for supply and demand respectively, the closest ones admitted by the SVAR were 0.11 and −0.11. See Caldara et al. (2016)

For our investigation, the discussion opens up a range of possible explanations for the recent oil price decline of which we deem these the most important: (1) A lower demand for oil through slowing global activity in emerging markets, (2) a larger supply through increased U.S. production and (3) OPEC's inability or unwillingness to curb production among its members. For us, the main goal will be to find evidence for (2). A natural step in this endeavour would be to find indications of the supply-side forces being the main drivers in the most recent data before delving into more sophisticated analysis.

4 Methodology

Here, we present our formal analysis of the oil market with particular emphasis on the relationship between U.S. supply and the oil price. This is primarily done through the use of structural vector autoregressions (SVARs).

This segment is organised as follows: We begin by doing a decomposition of the West Texas Intermediate (WTI) in order to further motivate a supply-side angle. We then briefly present the mathematics behind our structural VAR methodology in section 4.2. This is followed by a preliminary SVAR analysis in section 4.3 which uses a similar specification to the one employed by Kilian (2009). We then shorten the sample to only include observations from the last 13 years. The results of this baseline model are presented in section 4.4. Based on what we learn from these, we continue by exploiting the relationship between United States crude oil imports and the oil price. This leads us to our final SVAR model in section 4.5.

4.1 Decomposing the West Texas Intermediate into demand and supply components

The discussion in the previous sections presented the possibility of both supply and demand factors being behind the recent oil price drop. Much attention has been directed towards explaining the high oil prices during the run-up to the 2008 financial crisis and the factors which contributed to them (see among others Hamilton (2011), Tang and Xiong (2012), Kilian and Hicks (2013), Kilian and Murphy (2014) and Aastveit et al. (2015)). However, significantly less has been said about the period following the crisis. In order to motivate an investigation into our hypothesis, we need to find support in recent data for the supply side being a plausible explanation for the price drop observed during the second half of 2014. If both slowing demand and booming supply work at the same time to give a significantly lower price level, it can be a useful exercise to approximate how much of the change can be attributed to the respective forces.

Following the example of Hamilton (2014), we seek to estimate the change in the WTI exclusively with demand-side independent variables. More specifically, we estimate a model to predict the weekly log change in the oil price given the log change in the price of copper, the change in the 10-year U.S.

Treasury bond yield and the log change in the U.S. dollar exchange rate[8]. The reasoning behind the choice of variables is as follows: the price of copper is not influenced by the amount of oil extracted from the wells, but is at the same time highly sensitive to a changing global activity level. A lower price of copper could help us estimate the lower price of oil if both are driven by lower demand for these commodities. Both copper and oil are important inputs in pro-cyclical industries such as construction, the electric power industry and electronics manufacturing. The 10-year U.S. Treasury bond yield reflects the demand for this asset. As demand increases, the prices for these bonds go up and the yield necessarily must come down. A decline in the 10-year Treasury bond yield can be a sign of increased pessimism regarding future global activity as investors move their funds into less risky and long-maturity assets. Finally, an appreciating U.S. dollar exchange rate can be a sign of a weakening global economy as foreign currencies depreciate accordingly.

Equation 1 shows the estimation results for a sample with weekly observations running over the period 2007:M04–2015:M05. The t-values in parenthesis are calculated with HAC-robust standard errors which were adjusted using the Newey-West estimator with 7 lags[9]. In this exercise, let t_c be the sample cutoff and $t_c + k$ be the observation k weeks from the cutoff. By calculating the log changes in the independent variables between t_c and every $t_c + k$ observation, and fitting these changes to the model, we get a new demand-only oil price series, $\widehat{\Delta p^d_{oil,t_c+k}}$, which we can use to back out the supply-effect by comparing it to the observed oil price for every $t_c + k$. By construction, the share of the oil price change not explained by demand, i.e. $1 - \frac{\widehat{\Delta p^d_{oil,t_c+k}}}{\Delta p_{oil,t_c+k}}$, has to be attributed to supply innovations.

$$\Delta p_{\text{oil,t}} = \underset{(1.86^{*})}{0.118}\Delta p_{\text{copper,t}} - \underset{(-3.56^{**})}{1.389}\Delta p_{\text{dollar,t}} + \underset{(4.12^{**})}{0.145}\Delta r_{\text{10y,t}} + \hat{e}_t \quad \bar{R}^2 = 0.24 \quad (1)$$

From the beginning of July 2015 (t_c) to the end of January 2016 ($t_c + k$) the copper price fell by approximately 23%, the dollar exchange rate appreciated by 6.6% and the yield on the 10-year Treasury bond decreased by 41 basis points. Plugging the numbers into equation 1, we estimate the log change

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[8] All the data used is gathered from the FRED Database, courtesy of the Federal Reserve Bank of St. Louis, apart from the copper prices which were gathered from `http://www.investing.com/commodities/copper-historical-data`. The exchange rate is a trade-weighted basket of major currencies.

[9] Heteroscedasticity and autocorrelation (HAC) robust standard errors are used to make statistical inference such as hypothesis testing valid if the standard OLS assumptions regarding the error terms are violated (i.e. that they are not independently and identically distributed). Without lags in the specification, there are likely autocorrelated residuals making them non-independent. Having a non-constant variance makes them non-identically distributed. Estimating with non-HAC robust standard errors makes the parameters much more significant, likely due to underestimated standard errors. See Bjørnland and Thorsrud (2015 p. 33) for a summary of these issues.

in the oil price to be approximately $\widehat{\Delta p^{d}_{oil,t_c+k}} = -18\%$. Over the same time period, the observed decline in the WTI was 45%. It then follows that the share of supply explaining the price over this period is approx. 65%. The average of the share of supply explaining the oil price for every observation following the sample cutoff is at 67% with a standard deviation of about 5%.

By calculating $\widehat{p^{d}_{oil,t_c+k}} = p_{oil,t_c} + \widehat{\Delta p^{d}_{oil,t_c+k}}$ for each k to recover levels, we can graphically represent the decomposition, shown in figure 6. The dotted line shows the result of an estimation done on an earlier sample and attributes 58% to supply factors. Details for this estimation can be found in appendix A.1.

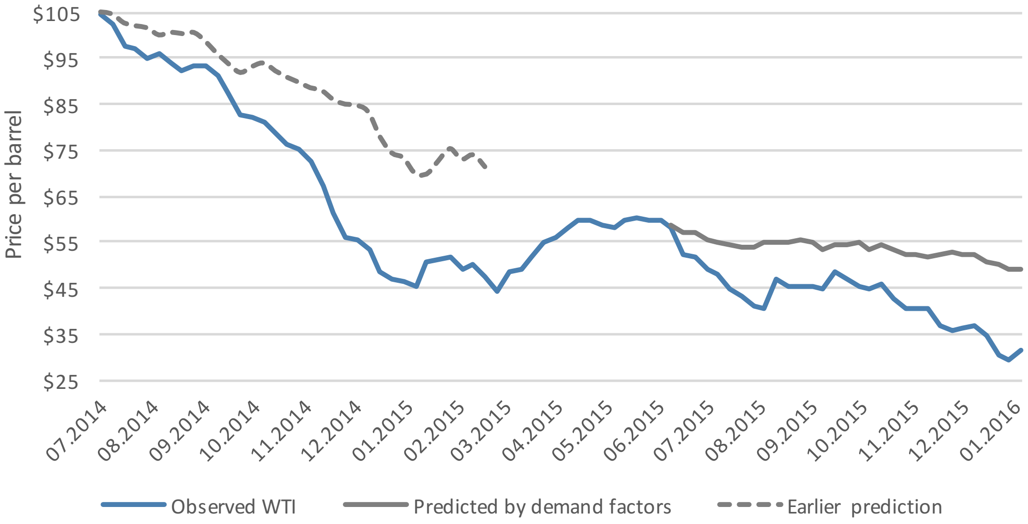

Figure 6: Two decompositions of the WTI into demand and supply components, 2014:M07–2015:M03 and 2015:M06–2016:M01.

If we are to take our two predictions in figure 6 at face value, the initial drop starting in the summer of 2014 seems to be driven more by demand than the drop which occurred during the summer one year later, as seen by comparing the slopes of the two grey lines. Additionally, the dotted line seems to track the observed WTI to some extent in contrast to the prediction from the latest sample. This may imply that the short-run volatility of the oil price during the first drop was caused mainly by demand-side factors, and the unexplained portion (supply) merely gives us the magnitude of the drop. This runs contrary to the later prediction where the supply-side seems to account for both the long-run level decline and most of the short-run volatility. Examining the three independent variables more closely, there seem to be breaks present between March and June 2015. In March, the European Central Bank was about to initiate its quantitative easing programme, causing the U.S. dollar to appreciate relative to the euro. In June, the Federal Reserve signalled to the market the possibility of increased interest rates, heightening optimism. This likely caused the 10-year bond yield to increase relative to short-term instruments. Following these events, the series stabilised on new levels, with less steep trends and less volatility than before the breaks. As the estimated coefficients did not change much between the two models, the underlying data series must be the cause of the differences in the predictions. In other words, demand-side developments stabilised after the breakpoints in the respective series making them less able to explain the fall in the oil prices.

While the exercise is illustrative in its simplicity, we cannot rule out the possibility of overestimating the importance of demand. It is unlikely that the implicit assumption of constant coefficients holds as we get further away from the sample cutoff. Our analysis implies with some degree of confidence that supply has been the larger force in driving the oil price down during the latter part of 2014 and 2015. As expected from the discussion in section 3.3, we cannot disregard the developments on the demand side as the exercise gives merit to both views. On the other hand, it gives the necessary motivation to continue looking at the U.S. shale oil boom and other supply-side explanations as possible drivers of the recent oil price decline with more sophisticated tools.

4.2 The general SVAR setup and identification strategy

There is no consensus in the oil literature on how to model the global oil markets (Kilian and Murphy 2014). However, since the seminal paper of Kilian (2009), deploying structural VARs in order to model the oil market with new identification strategies and variables is an ever-increasing part of the field.

The structural VAR methodology builds on the work by Sims (1980) and stems from a time when the validity of traditional large-scale dynamic simultaneous equation models and the exogeneity assumptions came under scrutiny. There is a large literature on the estimation of reduced form VAR models (see e.g. Lütkepohl 2005, 2011; Watson 1994). Their performance in forecasting and descriptive analysis in macroeconometrics is also well recognised (Kilian 2011). However, while the structural forms of VAR models have become popular tools in answering causal questions, it is still contested whether these provide true causal inference, mostly due to the need for identifying assumptions.

Structural VAR models have several appealing properties which will be useful to us. Firstly, they allow us to generate impulse response functions, i.e. the average response of a variable to a structural shock given the structural errors in the system. With this, we can make causal inference about the path and persistence of variable responses following specific shocks. Secondly, we can generate variance decompositions which allow us to assess the relative contribution of a shock to the variance of the variables. Finally, by using the cumulative contribution of the identified shocks, we can generate a historical decomposition to determine how they have influenced each variable over the sample period (Kilian 2011).

The remainder of this section will outline the statistical framework deployed in the rest of this thesis. In the reduced form VAR in equation 2, let Y_t be our vector of endogenous variables, μ a vector of constant terms, A_p the coefficient matrix relating the vector Y_t with its p lags, and e_t the reduced form errors. It is assumed that $e_t \overset{iid}{\sim} N(0, \Sigma_e)$ where Σ_e is positive semi-definite and symmetric.

$$Y_t = \mu + \sum_{p=1}^{P} A_p Y_{t-p} + e_t \tag{2}$$

By using the lag operator, we can write it more compact as

$$A(L)Y_t = \mu + e_t$$

where $A(L) = (I - \sum_{p=1}^{P} A_p L^p)$. Pre-multiplying this with $A(L)^{-1}$ gives us the moving average representation of the reduced form VAR

$$Y_t = \nu + B(L)e_t$$

where $B(L) = A(L)^{-1}$ and $A(L)^{-1}\mu = \nu$. The inverse of $A(L)$ exists if all of its eigenvalues are less than unity in absolute value and the VAR is then also considered stable. Given that this stability condition is fulfilled, estimating a VAR in the reduced form is straightforward (see Lütkepohl 2005, p. 22). However, the covariance matrix of e_t is likely not diagonal, i.e. a shock in this system is unlikely to come alone which makes causal inference impossible. However, we can write the reduced form errors as a linear combination of a matrix describing the structural relationships between the uncorrelated (structural) shocks or $e_t = S\varepsilon_t$, where we assume that $E[\varepsilon_t \varepsilon_t'] = I$ (see appendix A.2). Let $B(L)S = \Theta(L)$. We then get

$$Y_t = \nu + \Theta(L)\varepsilon_t \tag{3}$$

Identifying S lets us compute $\Theta(L)$ through the reduced form $B(L)$[10].

As discussed in appendix A.2, S needs to be lower triangular in order for the $E[\varepsilon_t \varepsilon_t'] = I$ assumption to hold. In addition to this, we are yet to identify the structural parametres in Θ_j. To achieve identification we need at least $K(K+1)/2$ restrictions, where K is the number of variables in the system (Kilian 2011). By imposing exclusion restrictions (sometimes referred to as

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[10] It can be shown that $B_0 = I$, leaving us with $\Theta_0 = S$ and $\Theta_j = B_j S$ for $j > 0$.

zero-restrictions or short-run restrictions) on S, we can achieve both uncorrelated structural errors and unique identification of the structural parameters. This, however, implies that our identification strategy must entail making assumptions about the contemporaneous structural relationships between the shocks and the variables through $\Theta_0 = S$. S needs to be lower triangular. This means that we need to impose a recursive structure where the variables ordered at the top in Y_t will respond to the ones ordered beneath them with a one period delay for $j = 0$. This, however, does not necessarily apply for the periods following ($j > 0$) as those are given by $\Theta_j = B_j S$ where B_j is not subject to restrictions. Cooley and Leroy (1985) criticised the "atheoretical" assumptions sometimes imposed by researchers as the validity of structural VAR models hinges on sound identifying assumptions motivated by economic theory. See Kilian (2011) for suggestions for such assumptions.

In the sections that follow, each SVAR specification will include a description of the rationale used to justify the orderings of the variables.

4.3 1974–2015 preliminary SVAR

Our point of departure is an augmentation of the work by Kilian (2009). The variables he used are global crude oil production, his self-constructed index of real activity, and the real price of oil at monthly frequencies. His sample spans from 1973:M01–2007:M12.

Our specification mirrors his, but there are two important differences. Firstly, we augment the model by adding U.S. production into the mix. By doing this, we are hoping to assess the importance of U.S. crude oil production in the oil market. Secondly, OPEC crude oil production is used in place of global production. The reason for this is twofold. The first is due to a possible simultaneity issue, as U.S. oil production is a component of global production. The second reason has to do with the data itself. We suspect there might be a lack of variation due to production decreases in one location being matched by production increases elsewhere within a month, hence neutralising fluctuations. OPEC production is an interesting candidate as it represents a large bulk of global production and possibly captures some interesting dynamics between itself and the U.S. Details about our data set can be found in appendix A.3.

4.3.1 Model specification

Equation 4 describes the structural VAR specification. The sample size is 1974:M01–2015:M09[11]. For the transmission of oil price shocks, it is important to allow for a multitude of lags. As discussed in Hamilton and Herrera (2004), the effects of oil price shocks first appear after about a year. Kilian (2009) specifies 24 lags in his model. With the monthly frequency of our data set, adding this many lags is unproblematic. Thus, our model includes two years worth of lagged endogenous variables.

$$\begin{bmatrix} \Delta opecprod \\ \Delta usprod \\ rea \\ lrpo \end{bmatrix}_t = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix} + \begin{bmatrix} \theta_{11} & 0 & 0 & 0 \\ \theta_{21} & \theta_{22} & 0 & 0 \\ \theta_{31} & \theta_{32} & \theta_{33} & 0 \\ \theta_{41} & \theta_{42} & \theta_{43} & \theta_{44} \end{bmatrix} \begin{bmatrix} \varepsilon^{\Delta opecprod} \\ \varepsilon^{\Delta usprod} \\ \varepsilon^{rea} \\ \varepsilon^{lrpo} \end{bmatrix}_t + lags \tag{4}$$

The ordering of the variables in the system above follows Kilian (2009). Supply variables are ordered at the top, followed by global demand and, lastly, the oil price. Oil supply shocks are defined as unexpected changes in oil production in OPEC member countries and the U.S. We thus get an OPEC and a U.S. supply shock. By placing OPEC and U.S. production at the top, we impose a short-run vertical supply curve. Hence, OPEC members and the U.S. do not adjust production within a month after shocks to aggregate demand, nor after shifts in beliefs about the state of future oil markets (oil-specific demand shocks). Taking into consideration the adjustment costs of changing their production schedules, but also a lack of information regarding business cycle movements in real time, oil producers are likely to respond to these innovations with a lag. We place OPEC above U.S. production, assuming OPEC members cannot react instantaneously to U.S. supply shocks, while the U.S. is able to react instantaneously to OPEC supply shocks. We find this to be plausible as shale oil has a higher supply elasticity compared to conventional oil, implying that their production schedules are more flexible (Bjørnland, Nordvik and Rohrer 2016). OPEC also makes up a relatively large chunk of the global oil market and consists of many member countries. Thus, it can be argued that it would be harder for OPEC as one coordinated body to track U.S. production figures within a month due to necessary cartel coordination[12].

An abrupt change in global real activity is here represented by a shock to the demand of industrial commodities, henceforth called an aggregate demand

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[11] The data available at EIA only goes as far back as 1974. We deem this satisfactory as our period of interest is the latter part of our data set and not the 1970s. To investigate this particular period, Barsky and Kilian (2002) extended the data backwards.

[12] Switching around the ordering between OPEC and the U.S. does not change our results notably.

shock. Our exclusion restriction implies that global real activity takes one month to adjust to shocks inherent to the oil markets. While oil prices are observable daily, economic agents are slow to change their behaviour, and the effect on the level of real activity is therefore delayed. This is consistent with the historical relationship between oil prices and business cycle movements (see e.g. Hamilton (1985)). We leave the real price of oil unrestricted.

4.3.2 Discussion of results

Impulse responses generated from the system described in equation 4 are shown in figure 7. We proceed by analysing these results.

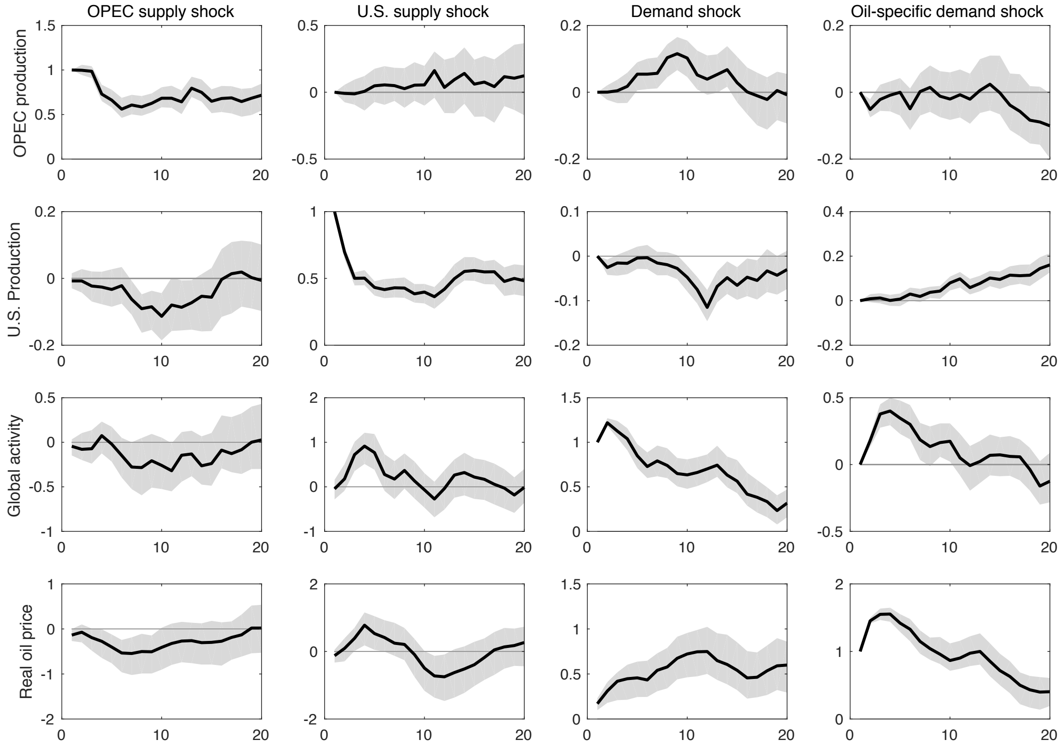

Figure 7: Impulse responses generated from the preliminary model described in equation 4. They are all in levels of the variables. Shocks are normalised to unit shocks, i.e. 1% for the OPEC supply shock, U.S. supply shock and aggregate demand shock while one log-unit for the oil price. The shaded areas represent 68% confidence bands calculated using a bootstrap with 2000 draws.

A sudden increase in OPEC supply leads to a persistent increase in their level of production, while the United States responds by outputting less. This might be because of a downward pressure on the oil price. However, this result is only significantly different from zero around period 10. Global activity does not seem to respond significantly to the OPEC supply shock, but the oil price predictably does so by falling.

As with the OPEC supply shock, a U.S. supply shock causes persistent increases in the level of U.S. production. In contrast to the OPEC shock to U.S.

production, OPEC does not seem to change their production notably after the U.S. shock. The shock heats up the economy during the first 5 periods, and global activity increases. So does the oil price, before going negative after about 10 periods.

After a shock to aggregate demand, it takes more than 20 periods for the effect on global activity to abate. OPEC ramps up production for about 10 periods before slowing down, while the U.S. seems to start contracting production after about 5 periods. The latter might stem from the fact that the U.S. has enforced an export ban in the past (more on the ban later in section 4.5) and therefore has not been as sensitive to changes in global activity. As expected, the real price of oil reacts by increasing.

Not surprisingly, a demand shock intrinsic to the oil markets causes the oil prices to increase, the effect slowly weakening as time passes. While OPEC's response to an oil price hike is indeterminate, the U.S. responds by gradually increasing their production. Rather unexpectedly, global activity increases, which is counter-intuitive as we would expect higher prices to dampen the activity level. However, this is a similar result as seen in Kilian (2009), later attributed to not allowing different regions to respond differently to oil market shocks (see Aastveit et al. (2015)).

It is the response of the real price of oil to a U.S. supply shock that interests us. Even though the initial increase in prices might reflect a delay in the transmission from production to delivery, the eventual dip below the pre-shock level is also small and transitory, lasting for about 8 periods. Figure 8 shows a historical decomposition of the real price of oil. As was seen in Kilian (2009), the importance of supply shocks to variations in the oil price has been minuscule over the sample period. Only two abrupt dips in oil production stand out (also observable in figure 3), while the aggregate demand and oil-specific demand shocks explain the largest bulk of fluctuations in the sample. The latter can also be seen in the model's variance decomposition in appendix A.4, where a shock in U.S. supply only explains up to 3.46% of the variation in the oil price.

While the results presented in this section parallel those of Kilian (2009), they are not encouraging with respect to the United States' ability to affect global oil prices during the most recent period. Looking at the data, we would expect the influence of the U.S. on prices to increase to some degree in the last few years. The weakness of our structural VAR methodology is that it does not allow for coefficients to change over time. They are simply averages over the sample and fail to take into account the possible time-varying structure of

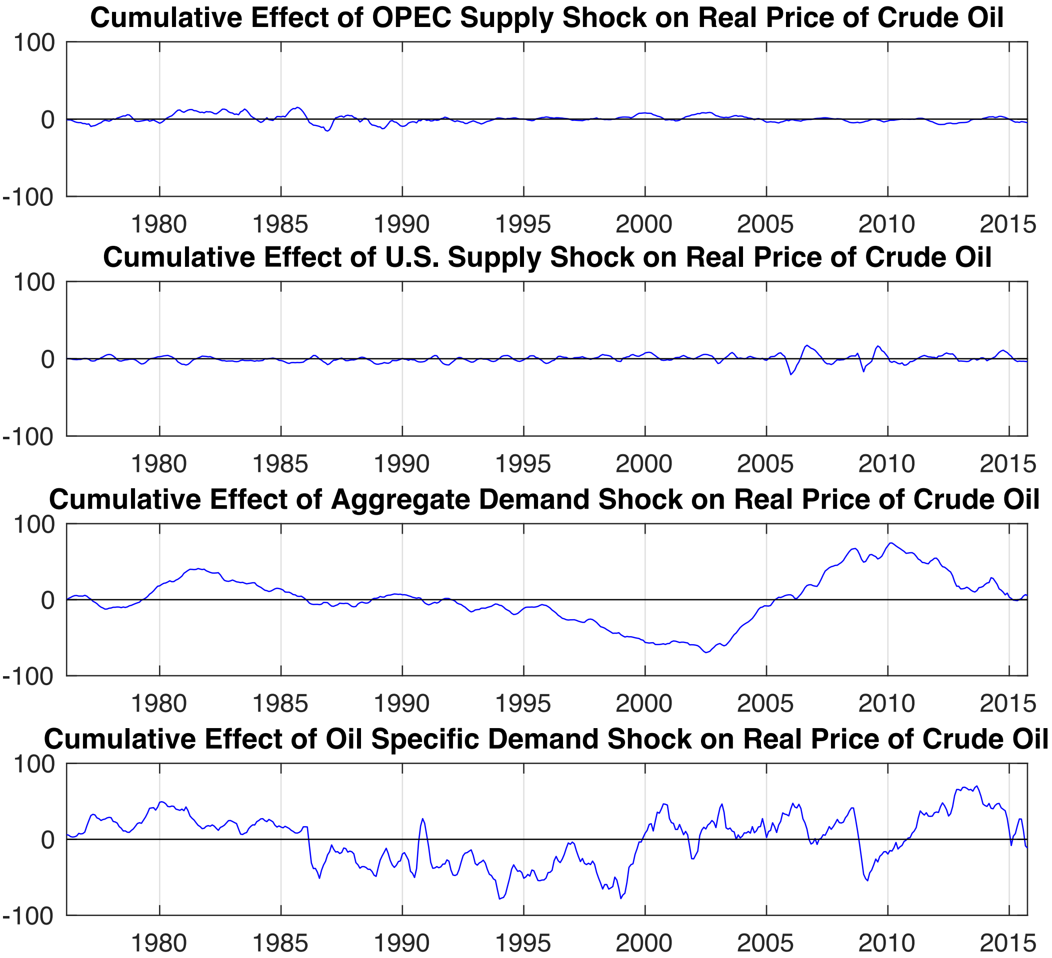

Figure 8: Historical decomposition of the real price of oil derived from the preliminary model described in equation 4.

the oil markets[13]. If the oil markets have in fact changed, it is a reasonable assumption that it can be remedied by restricting the sample. This is what we do in the next section.

4.4 Baseline SVAR model with U.S. crude oil production

The SVAR specification and variable ordering justifications in this section remain identical to the ones presented in the preceding section. The sample is now restricted, however, so that it spans the period 2003:M01–2015:M09. To achieve stability, the lag order has been reduced to 19.

The impulse responses generated from this system are qualitatively similar, though there are some notable differences (see figure 9). Firstly, the oil-specific demand shock now causes OPEC to temporarily increase output and global

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[13] We could have deployed a Markov-switching technique to allow for regime shifts, but that is outside the scope of this thesis. See Krolzig (2013).

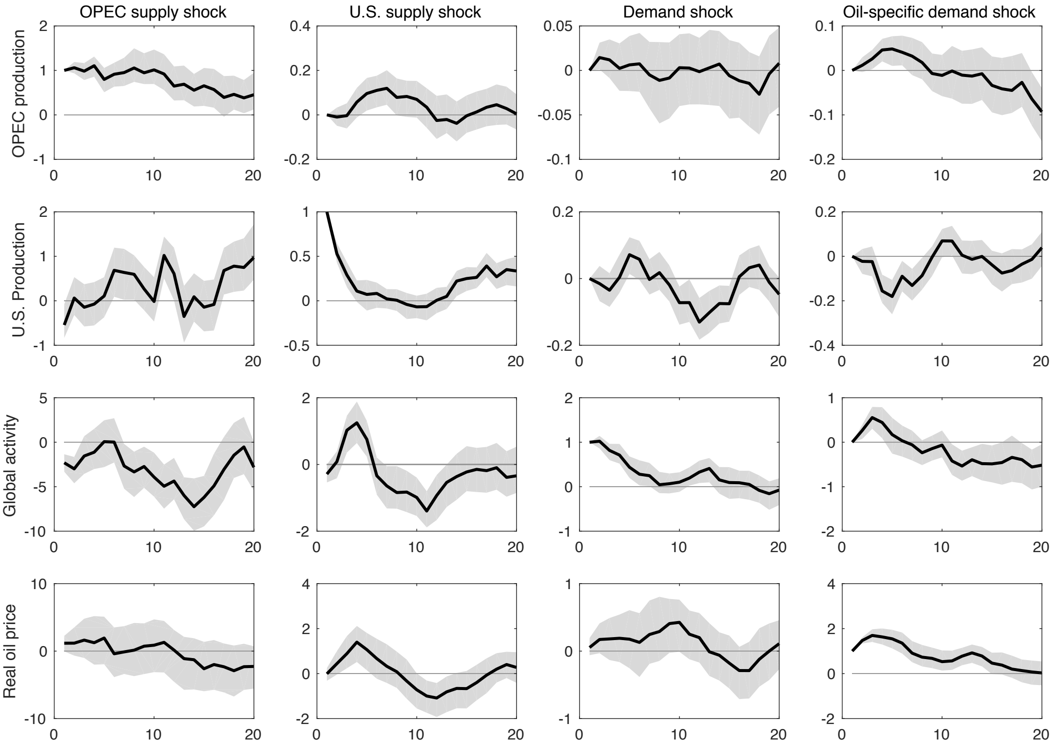

Figure 9: Impulse responses generated from the baseline model described in equation 4, but with the sample 2003:M01–2015:M09. They are all in levels of the variables. Shocks are normalised to unit shocks, i.e. 1% for the OPEC supply shock, U.S. supply shock and aggregate demand shock while one log-unit for the oil price. The shaded areas represent 68% confidence bands calculated using a bootstrap with 2000 draws.

activity to decrease below zero after the initial bump. This is more in line with what we would expect. U.S. production, however, now drops initially and exhibits more volatility in general. Secondly, the interaction between OPEC and the U.S. has changed. Following the respective supply shocks, the oil producers now respond by increasing their outputs. The U.S. response to an OPEC supply shock is slightly more erratic than what was the case in our preliminary model. Lastly, the response of global activity to an OPEC supply shock has now become statistically significant, but exhibits a clear negative development.

The response of the oil price to a U.S. supply shock has now become slightly more significant and has increased in magnitude. However, the shape of the impulse response remains the same, reflecting the delay between when a barrel is produced and when it is offered in the marketplace. The OPEC supply shock now has an indeterminate impact on the oil price and the aggregate demand shock does not give the same upward pressure in the first periods.

The historical decomposition of the real price of oil also exhibits promising changes. The large and persistent cumulative effects of aggregate demand have now been greatly reduced, and the United States' recent contribution to the downward pressure on the oil prices is now visible (see figure 18 in appendix A.5). The variance decomposition described in table 3 of appendix A.5 now attributes 12.62% of the variation in the oil price to U.S. supply shocks which is a marked increase from our previous model. Restricting the sample further to 2005:M01–2015:M09 only magnifies these results, but also makes them less reliable (see appendix A.5.1 for the impulse responses). The variance decomposition in this restricted sample shows us for instance that a U.S. supply shock explains up to 27.84% of the variation in the oil price, but the confidence intervals are wide[14].

While restricting the sample to begin at 2003:M01 likely solved the largest issue with our preliminary model, we would still like to see the oil price respond to a U.S. supply shock in a more direct way, without the initial increase in prices. So far, we have assumed that merely including U.S. oil production *ad hoc* in a structural VAR would reveal results which support our hypothesis. We are yet to examine possible transmission mechanisms through which the U.S. affects the global oil markets. We turn to this in the subsequent section.

4.5 SVAR with U.S. imports of crude oil

While our results from our baseline model in section 4.4 gave promising indications of the U.S. being able to affect the global oil prices, there might be better ways to capture the effect we are looking for. Our estimated VAR contained the U.S. production of crude oil, and the structural shock and responses generated from that system are likely to be influenced by the time-delay between a barrel of oil is produced and that same barrel being transported to and offered in the marketplace. An important notion is that the increased supply of U.S. crude will only affect prices globally if it displaces foreign sources of oil. Hence, the only way that the U.S. can affect the global oil price is by changing their net exports. We can take advantage of this idea and try to capture shifts in U.S. demand for foreign crude oil that occur due to a higher availability of domestic supply, i.e. shifts in imports due to higher U.S. production. We might be able to achieve this by substituting our U.S. production variable with U.S. imports.

Equation 5 explains the relationship between U.S. self-sufficiency, net exports

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[14] The confidence interval around this estimate is [15.31;43.54] at the 20 period forecast horizon.

and changes in inventories.

$$\underbrace{\text{U.S. Production} - \text{U.S. Consumption}}_{\text{Self-sufficency}} = \underbrace{\text{Exports} - \text{Imports}}_{\text{Net exports}} + \Delta\text{Inventories} \tag{5}$$

We are fortunate enough that U.S. energy policy makes this relation much simpler. After the enactment of the Energy Policy and Conservation Act of 1975, the U.S. government banned exports of crude oil and natural gas[15]. However, with appropriate permissions, exports could still be carried out. This has been done on a very small but increasing scale to Canada and from production sites in California and Alaska (EIA 2014b; 2015). Luckily, the extent of this flow is negligible relative to total U.S. oil production[16]. This means we can simplify the equation and say that imports can only be caused by a changing degree of self-sufficiency or through changes in inventories. We can simplify further by looking at the inventories. Are there other reasons for holding inventories besides smoothing out gluts or shortfalls in the flow of oil? If not, then build-ups of inventories should be transitory and even out over time. Indeed, looking more closely at U.S. inventory data, the monthly changes create a covariance stationary process with a mean close to zero[17]. We are then left with the following identity, rearranging and leaving out exports and changes in inventories:

$$\text{Imports} = \text{U.S. Consumption} - \text{U.S. Production} \tag{6}$$

The demand for oil which is not satisfied by domestic production thus has to be covered by changes in imports.

Looking at figure 10, we can see that there is a clear negative correlation between U.S. oil production and imports in the long run. However, the decline in imports after 2005 precedes the boom in domestic supply, meaning that the initial fall in imports must be due to lower U.S. consumption. This leaves us with a challenge: making sure that the variations in the import variable are

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[15] This clause was repealed in the Consolidated Appropriations Act of 2016, which got signed into law in January. Crude oil exports are once again legal in the United States. Fortunately, our sample ends in September 2015, so this will not affect our analysis.

[16] On average, exports relative to U.S. production have been around 1% from 2003 to 2015 with a peak at 6% in April 2015. The vast majority of U.S.-sourced crude goes to Canada (EIA 2014b), but starting in 2014, some crude leaving the Gulf was shipped to Europe and Asia. However, this is Canadian oil re-exported by the United States (EIA 2014a). This might help explain the growth in U.S. exports relative to U.S. production starting in 2014.

[17] The mean of the log change in inventories from 2003:M01–2015:M09 was 0.18% with a standard deviation of 1.03%. Stationarity of the series was found when deploying the Augmented Dickey-Fuller test (details in appendix A.6.1). The results from a SVAR estimation with U.S. inventories as an exogenous variable can be found in appendix A.6.2. These do not differ from our main results found later in section 4.5.2 in any important way and do not change our conclusions.

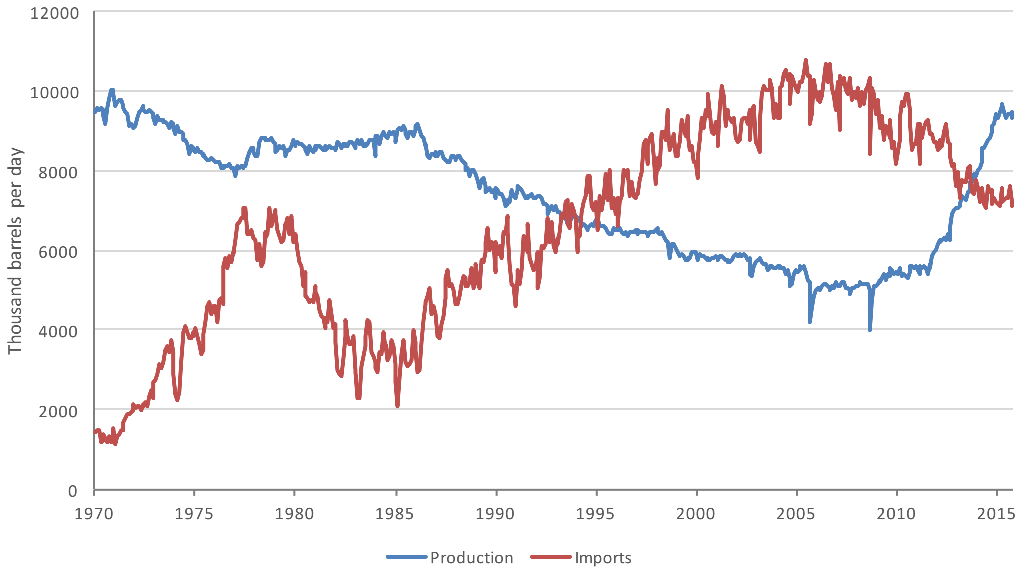

Figure 10: U.S. crude oil production and imports, 1970–2015. Source: EIA

exclusively due to changes in U.S. supply, i.e. getting rid of U.S. consumption from equation 6. We attempt to achieve this using simple OLS.

Our candidate variable for our VAR model should have the U.S. imports be made orthogonal to shifts in domestic demand for crude oil, but still correlated with domestic supply. To accomplish this, we will have to regress the imports on variables which reflect demand for oil and are correlated with imports but not U.S. production. The residuals of this regression will optimally reflect the variation in the import variable which is not due to demand for crude oil. Two variables with the appropriate monthly frequency and sample availability were chosen for the regression: *Vehicle miles travelled* captures domestic demand for petroleum products through the use of road vehicles. It includes cars and larger diesel vehicles used in freight transportation. More traffic on U.S. roads implies a higher demand for petroleum products which induces demand for crude oil from refineries. The refineries can choose to import the oil or use what is produced domestically. However, the mileage on the U.S. vehicles each month does not affect the amount of oil extracted from the ground directly. *Petroleum product exports* captures demand for American crude oil abroad through exports of refined products from U.S. refineries[18]. Again, the refineries have to make use of imports or domestic supply. How much is refined and exported does not directly determine how much crude oil is taken up from the ground[19].

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[18] The U.S. became a net exporter of petroleum products in 2011 (EIA 2015))

[19] *Vehicle miles travelled* is compiled by the U.S. Federal Highway Administration by using automatic traffic recorders and is retrieved from the FRED Database at `https://fred.stlouisfed.org/series/TRFVOLUSM227SFWA`. *Petroleum product exports* data come from EIA.

$$\Delta usimp_t = \underset{(2.49^{**})}{1.7}\,\Delta vmt_t + \underset{(3.30^{***})}{0.098}\,\Delta petrolexp_t + \hat{e}_t \quad \bar{R}^2 = 0.11 \qquad (7)$$

Equation 7 describes the regression. All variables are in log-differences and the t-values are shown in parenthesis. $\hat{e}_t = \Delta \widehat{usimp^S}_t$ will be the candidate variable to include in our SVAR analysis. It will represent only the supply effect on oil imports as it should now be close to orthogonal to demand innovations. In other words, a negative shock to our modified U.S. imports variable can be interpreted as a decision by refineries to import less crude because of an abundance of domestic supply. Here, we need to assume that U.S. refineries always prefer to use domestic supply rather than imports. A positive shock will reflect the need for more imports because of less domestic production. The impulse responses generated by this shock should be appropriate to answer our research question.

4.5.1 Model specification

Equation 8 shows the new structural VAR specification. As was outlined in the previous section, the modified log-change in U.S. imports replaces U.S. production. Apart from this, the specification is identical to our baseline model. A shock to the altered U.S. imports variable can now be interpreted as an abrupt change in the import decision of U.S. refineries caused by a sudden change in the availability of domestically produced crude.

$$\begin{bmatrix} \Delta opecprod \\ \Delta usimp^S \\ rea \\ lrpo \end{bmatrix}_t = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix} + \begin{bmatrix} \theta_{11} & 0 & 0 & 0 \\ \theta_{21} & \theta_{22} & 0 & 0 \\ \theta_{31} & \theta_{32} & \theta_{33} & 0 \\ \theta_{41} & \theta_{42} & \theta_{43} & \theta_{44} \end{bmatrix} \begin{bmatrix} \varepsilon^{\Delta opecprod} \\ \varepsilon^{\Delta usimp^S} \\ \varepsilon^{rea} \\ \varepsilon^{lrpo} \end{bmatrix}_t + lags \qquad (8)$$

The ordering of the variables in the system is kept the same. OPEC is still ordered at the top and cannot respond to U.S. import shocks within one month. This is a plausible assumption as OPEC cannot observe the volumes imported by the United States in real time. Those data are published by the EIA and revised later on. Even if OPEC could, the production schedule is still costly to adjust.

U.S. importers are allowed, given what they know about domestic supply, to react contemporaneously to OPEC supply shocks. When the importers look for available supply abroad, a sudden increase in OPEC oil is likely not to go unnoticed.

In our model, U.S. imports are not allowed to respond to aggregate demand shocks right away. In our baseline model, U.S. producers could not adjust their production schedule within a month following this shock because they could not observe indicators of global activity in real time. Importers make their decision given what they know about domestic supply, hence their reaction will also be delayed[20].

Finally, refineries in the U.S. are assumed not to react to oil-specific demand shocks instantly. Although oil prices are observed in the market daily, the American suppliers are slow to ramp up their production due to adjustment costs. Hence, the effect of higher oil prices on imports when the U.S. supply situation is taken into account gets postponed.

4.5.2 Discussion of results

The impulse responses generated by the system can be seen in figure 11. In general, the results are in line with those of the baseline model, however the model now succeeds in creating a more nicely behaved set of responses in terms of what we would expect to see.

Following an oil-specific demand shock, both OPEC and the U.S. follow sound trajectories. OPEC starts to produce more while the Americans import less, implying that their domestic supply is higher. OPEC reacts more clearly in this model than what has been the case in earlier models, and the U.S. now increases production rather than decreasing it. The aggregate demand shock causes the oil price to increase significantly compared to the baseline model.

The negative shock to U.S. imports is caused by a more abundant supply of domestically produced crude oil. This shock dies out very quickly as U.S. imports return to pre-shock levels almost immediately. As the U.S. decreases their imports, global activity initially decreases as well. Finally, the oil price now exhibits an immediate and persistent decrease following a shock to imports. This is in stark contrast to the baseline model where it took almost 10 months for the price to drop below its initial level. When the U.S. reduces its imports by 1%, the oil price now falls by almost 2% after 10 months.

The reason for the missing delay is likely due to having moved the source of the shock closer to the global oil prices. U.S. production does not lower oil prices before the barrels are offered in the marketplace. In this case, however, given what the refineries know about the state of the domestic crude market, they choose immediately not to import. Since the price in this model reflects

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[20] We stress again that the importing decision is only based on information about the availability of U.S. domestic supply — the refineries in our model only care about domestic supply of crude in addition to foreign and domestic demand for petroleum products. The variations stemming from the latter two are controlled for. The only transmission mechanism left for an aggregate demand shock is indirectly through U.S. suppliers.

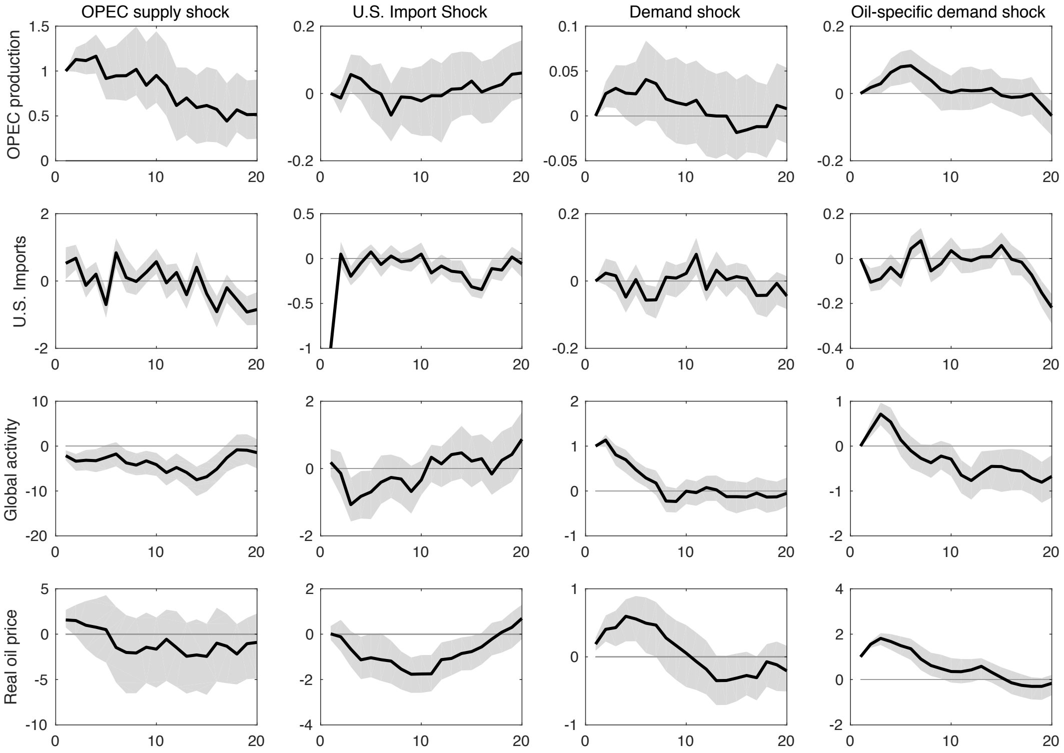
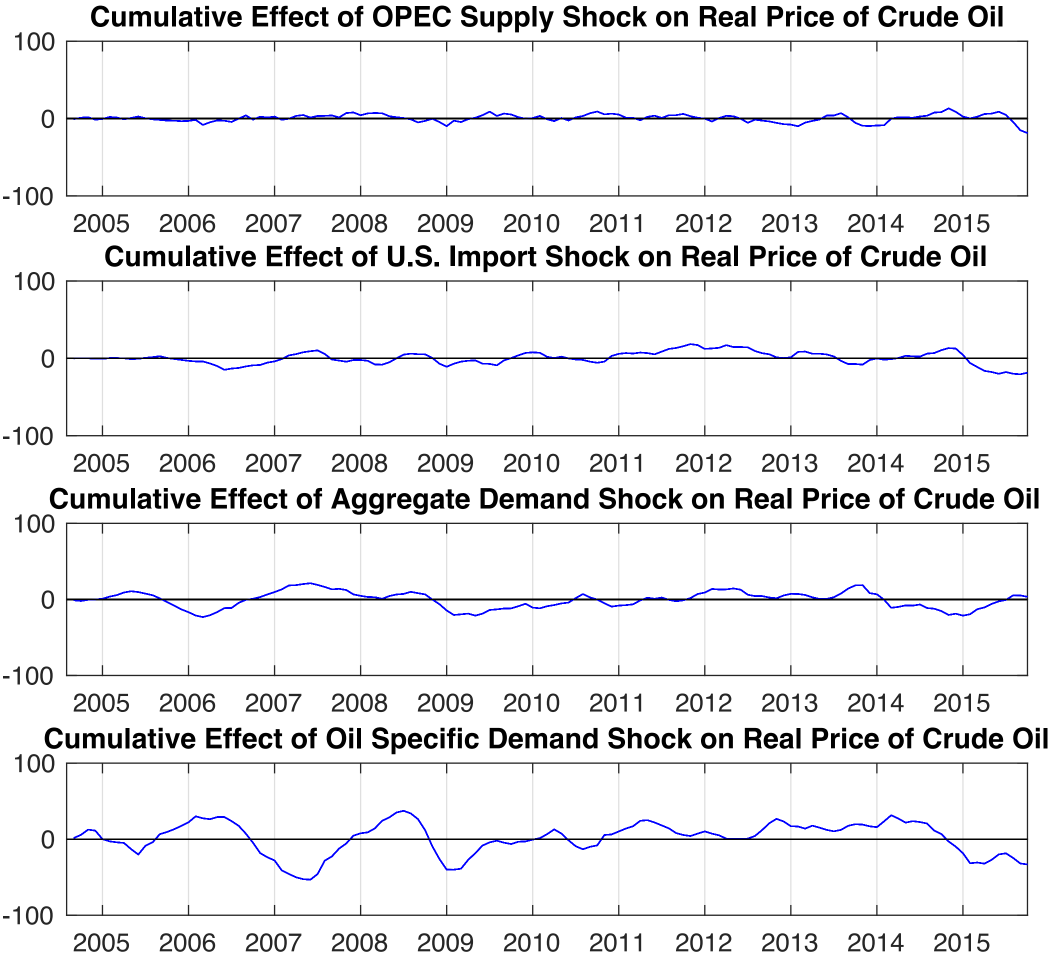


Figure 11: Impulse responses generated from the imports model described in equation 8. They are all in levels of the variables. Shocks are normalised to unit shocks, i.e. 1% for the OPEC supply shock, U.S. import shock and aggregate demand shock while one log-unit for the oil price. The U.S. import shock is negative. The shaded areas represent 68% confidence bands calculated using a bootstrap with 2000 draws.

the importer acquisition cost of U.S. refineries, the oil prices thus fall without the 10-month delay.

The new historical decomposition of the real price of oil is presented in figure 12. The cumulative effect of the U.S. import shock has since the beginning of 2015 contributed to push the oil price down. OPEC did so as well at the very end of the sample. Oil-specific demand has also contributed, possibly reflecting the expectations of an oversupply in the oil markets. Aggregate demand, on the other hand, had a negative effect on the price throughout 2014. The main results from our decompositions of the WTI described in section 4.1 make a reappearance. While supply forces still dominated, the prediction made for the 2014 oil price drop showed that demand was relatively more important in explaining it compared to the prediction made for the second drop in 2015. The influence of demand forces in the historical decomposition are greatly reduced during 2015, as was the case in the baseline model.

The variance decomposition of the real price of oil is presented in appendix A.6.3. U.S. supply-side innovations now explain up to 15.54% of the variation in the oil price compared to the 12.62% in the baseline model. In recent years, the literature has been giving supply-side explanations for oil price fluctuations an increasingly smaller role. We have, together with Caldara et al. (2016)


Cumulative Effect of OPEC Supply Shock on Real Price of Crude Oil

Cumulative Effect of U.S. Import Shock on Real Price of Crude Oil

Cumulative Effect of Aggregate Demand Shock on Real Price of Crude Oil

Cumulative Effect of Oil Specific Demand Shock on Real Price of Crude Oil

Figure 12: Historical decomposition of the real price of oil derived from the imports model described in equation 8.

found evidence giving more weight to supply. OPEC and the United States together account for 27.6% of the fluctuations in the oil price at the 20-period forecast horizon according to our model. This is significantly higher than those found for global production in other studies. Estimating an identical structural VAR as the one in Kilian (2009) over a 2003:M01–2015:M09 sample period for instance, we manage to attribute only 5% to supply-side innovations[21], while Aastveit et al. (2015) attributes even less. This could either be due to differing methodologies or possibly due to the drawbacks of using the aggregated global oil production variable as discussed earlier.

Our attempts to capture the effect of innovations to U.S. oil supply culminate in this model. Having both shortened the sample range and implemented the modified imports variable, which to our knowledge is novel in the literature, we have managed to come up with a model with few inconsistencies in variable responses and which provides convincing evidence for our hypothesis. In other words, our results imply that the U.S. shale oil boom has made a considerable

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[21] The model has 24 lags and endogenous variables $Y_t = \left[\Delta gprod \quad rea \quad lrpo\right]_t^{\prime}$ where $\Delta gprod$ is global production.

contribution to lowering the oil prices during 2015. However, we may be too early with the analysis as data availability restricts us from seeing the whole effect through. It is worth considering doing the same estimation on more data as it becomes available, though the repeal of the U.S. export ban might make this more challenging.

One question lingers: *why has the U.S. shale oil boom been so slow in making a measurable impact on the global oil prices?* As we have seen, the U.S. experienced the largest growth in shale oil output between 2012 and 2015 before starting to fade off. It therefore seems counter-intuitive that the prices would not get negatively affected until after the growth had subsided. However, as we have discussed before, the U.S. would only be able to affect oil prices globally if their new-found source displaced demand for foreign crude oil. The negative shock to imports in our model represents this sudden displacement. Hence, it must stand to reason that this displacement did not take place right away. We theorise that the initial inability to transport and process shale oil in the United States cushioned the transmission of this supply innovation until the issues got resolved. In the meantime, the U.S. had to rely on imports to cover their energy needs (see section 2.3.1).

5 Conclusion

In this thesis, we try to assess the impact of the U.S. shale oil boom on the global oil prices. This is done by employing a structural VAR based on the work of Kilian (2009) with OPEC production, a modified U.S. crude oil import variable, a measure of real economic activity and the real price of oil. The use of crude oil imports data in a structural VAR is to our knowledge new to the literature. It is modified so that it only captures U.S. supply innovations.

Firstly, we find that a 1% reduction in U.S. imports causes the oil price to decrease by almost 2% after 10 months. The U.S. import shock, reflecting the domestic supply environment, manages to explain up to 15.54% of the variation in the oil price in a sample starting in 2003. The U.S. and OPEC together account for over a quarter of the variation in the oil price. This is significantly more than what has been found in earlier studies. Secondly, our results show that the developments in the U.S. oil industry did not have a considerable effect on global prices until the beginning of 2015.

Our results suggest that the U.S. shale oil boom *has* in fact been able to affect the global oil prices negatively. While it did not contribute to the severe decrease in prices during the summer of 2014, it did so in 2015. The cause of the delay is puzzling considering how long U.S. production figures have been on the rise. We speculate that the oil glut in Cushing, Oklahoma, indirectly observable in the WTI-Brent price spread, was to blame for this delay.

Our results have implications for U.S. energy policy and underlines the importance of following future developments in the United States' oil industry. However, as more data becomes available, the full effect of the U.S. shale oil boom will be fully quantifiable. Our sample ends at a point in time where the impact of the shock originating in the U.S. has yet to die out. For further work, we propose repeating our analysis on a newer set of data at a future point in time. We have seen that splitting global production into two separate variables has remedied the issue of lack of variability on the supply-side of the oil markets. To take our analysis a step further, it would be interesting to include all oil producers in a similar fashion as done with demand in Aastveit et al. (2015). A final proposition would be to delve into regime-switching models, taking into account the time-varying structure of the oil markets.

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A Appendix

A.1 Section 4.1 — Decomposing the WTI: Early prediction

The following estimation in equation 9 was done on a sample over the period 2007:M04–2014:M06. The t-values were calculated using standard errors which were HAC-adjusted with the Newey-West estimator at 7 lags.

$$\Delta p_{\text{oil,t}} = \underset{(1.7^{*})}{0.11} \Delta p_{\text{copper,t}} - \underset{(-3.01^{***})}{1.348} \Delta p_{\text{dollar,t}} + \underset{(3.45^{***})}{0.142} \Delta r_{\text{10y,t}} + \hat{e}_t \quad \bar{R}^2 = 0.22 \quad (9)$$

Between June and December 2014, the copper price fell 10.4%, the dollar appreciated 8.9% and the yield on the 10-year U.S. Treasury bond fell by 49 basis points. The estimated change in the WTI is approx. −20% while the observed change in the WTI over the same period was closer to −48%, implying that supply explains close to 58% of the oil price decline over the period.

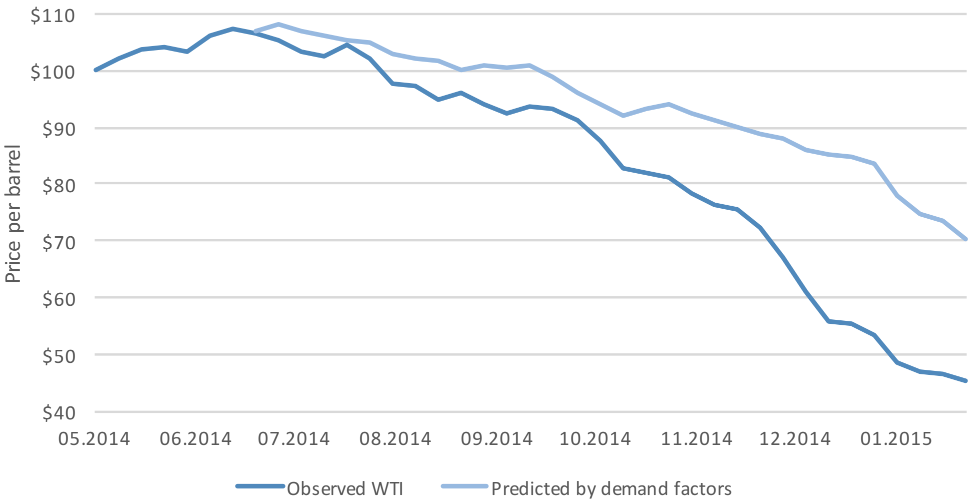

Figure 13: Decompositions of the oil price fall, 2014:M07–2015:M01. The light blue line is shown in figure 6 as "Earlier prediction".

In the same fashion as in section 4.1, the light blue line in figure 13 is generated by using the initial level at the sample cutoff.

A.2 Section 4.2 — Cholesky Decomposition

In the text, we assumed that having some matrix S will make the shocks in ε_t orthogonal to each other. The issue is then to identify this matrix. The most common way to achieve this is by using Cholesky decomposition. The Cholesky decomposition is a mathematical result in matrix algebra which says that any positive definite symmetric matrix can be written in terms of the product of a lower triangular with positive diagonal elements and its conjugate transpose, or $\Sigma_e = SS'$ where S is the Cholesky decomposition of Σ_e (Bjørnland and Thorsrud 2015). We can write the reduced form as

$$\begin{aligned} Y_t &= \nu + B(L)SS^{-1}e_t \\ Y_t &= \nu + \Theta(L)S^{-1}e_t \end{aligned}$$

where $B(L)S = \Theta(L)$. We use $S^{-1}e_t = \varepsilon_t$ to get

$$E[\varepsilon_t\varepsilon_t'] = S^{-1}E[e_te_t'](S^{-1})' = S^{-1}(SS')(S^{-1})' = I$$

It is then given that if S is lower triangular, the shocks in ε_t will be uncorrelated and of unit variance.

A.3 Section 4.3 — The Data

Variable	Description
$\Delta opecprod$	OPEC total crude oil production in thousands of barrels per day, log-differenced. Data from the U.S. Energy Information Administration (EIA), retrieved from Thomson Reuters Datastream (Code: OPPCOBD.P)
$\Delta usprod$	U.S. field production of crude oil in thousands of barrels per day, log-differenced. Retrieved from EIA
rea	Kilian's freight index as a measure of global real economic activity — represents monthly deviations from trend in percentages. Data available on Kilian's personal website: `http://www-personal.umich.edu/~lkilian/paperlinks.html`
$lrpo$	U.S. crude oil imported acquisition cost by refiners in dollars per barrel, deflated with the U.S. CPI to get the price in real terms, and then log'ed. Data retrieved from EIA

Table 1: Information on our data set, all in monthly frequency.

Kilian constructed his index based on representative freight rates. He accumulated their growth rates, deflated the result with the U.S. CPI and linearly detrended it. He describes the process in detail in Kilian (2009). The reason for using his index is that of convenience. There are few, if any, other data series which capture shifts in demand for industrial commodities through changing global activity and the business cycle at the right frequency.

We difference the production data in order to make sure the reduced form coefficient matrix is invertible and the VAR system stable.

The reason for using the import acquisition cost rather than the Brent or WTI benchmark prices is due to data availability. Using this price in oil market VAR models is not uncommon in the literature (see e.g. Aastveit, Bjørnland and Thorsrud 2015; Baumeister and Hamilton 2015; Kilian 2009).

See figures 14–17 for plots of the variables.

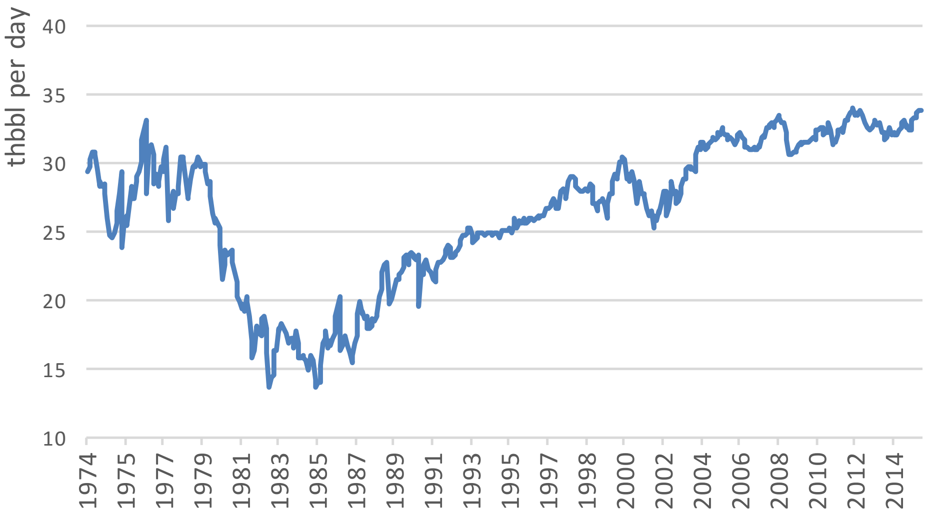

Figure 14: Plot of OPEC crude oil production, 1974:M01–2015:M09. Source: EIA (retrieved from Thomson Reuters Datastream)

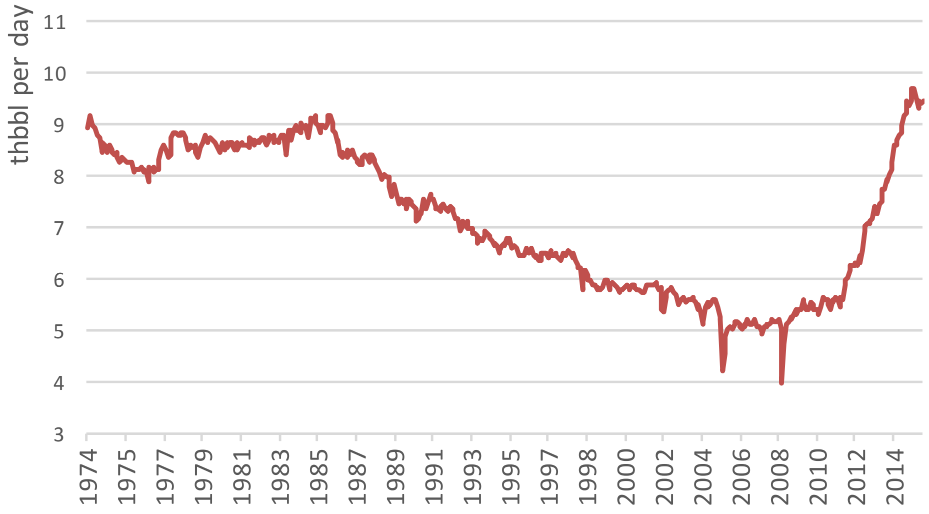

Figure 15: Plot of U.S. crude oil production, 1974:M01–2015:M09. Source: EIA

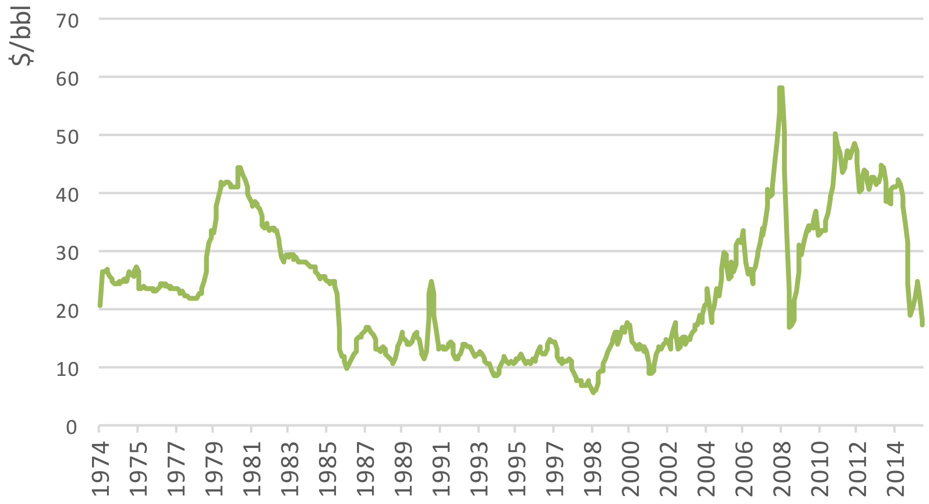

Figure 16: Plot of the deflated U.S. crude oil imported acquisition cost by refiners (the real price of oil), 1974:M01–2015:M09. Source: EIA

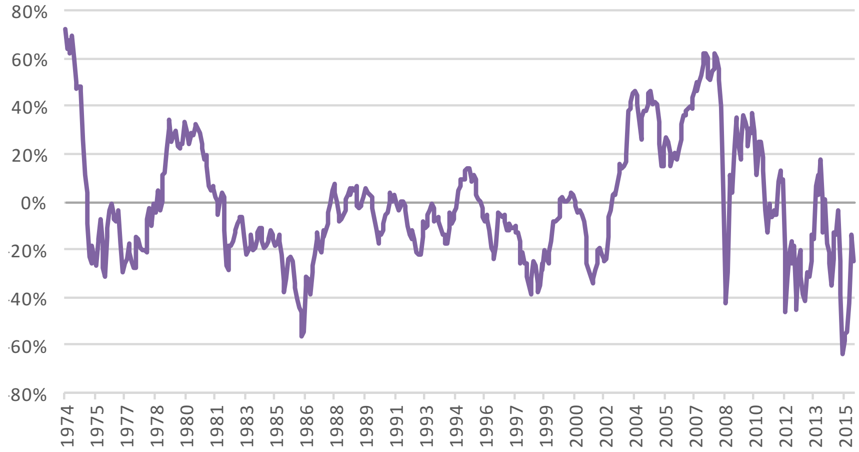

Figure 17: Plot of Kilian's index of real global economic activity in industrial commodity markets, 1974:M01-2015:M09

A.4 Section 4.3.2 — Preliminary SVAR results

Variance decomposition of the real price of oil

	Shocks			
	OPEC supply	U.S. supply	Aggregate demand	Oil-specific demand
1	0.52	0.35	2.37	96.00
	[0.06;1.80]	[0.03;1.43]	[0.87;4.45]	[93.40;97.98]
5	1.13	1.27	5.63	90.52
	[0.25;3.53]	[0.41;3.61]	[2.51;9.80]	[85.61;94.52]
10	2.96	1.83	12.42	80.88
	[0.73;7.38]	[0.76;4.23]	[6.10;20.03]	[72.91;87.96]
15	3.07	3.05	18.22	73.46
	[0.96;7.95]	[1.31;6.04]	[9.79;28.32]	[63.63;82.56]
20	3.63	3.46	22.00	68.45
	[1.37;8.80]	[1.65;6.79]	[11.61;33.53]	[57.29;78.89]

Table 2: Variance decomposition (in percentages) of the real price of oil for different time horizons, generated from the preliminary model in section 4.3.1. The confidence intervals (in brackets) are at the 68% level and computed using a bootstrapping method with 2000 draws.

A.5 Section 4.4 — Baseline SVAR results

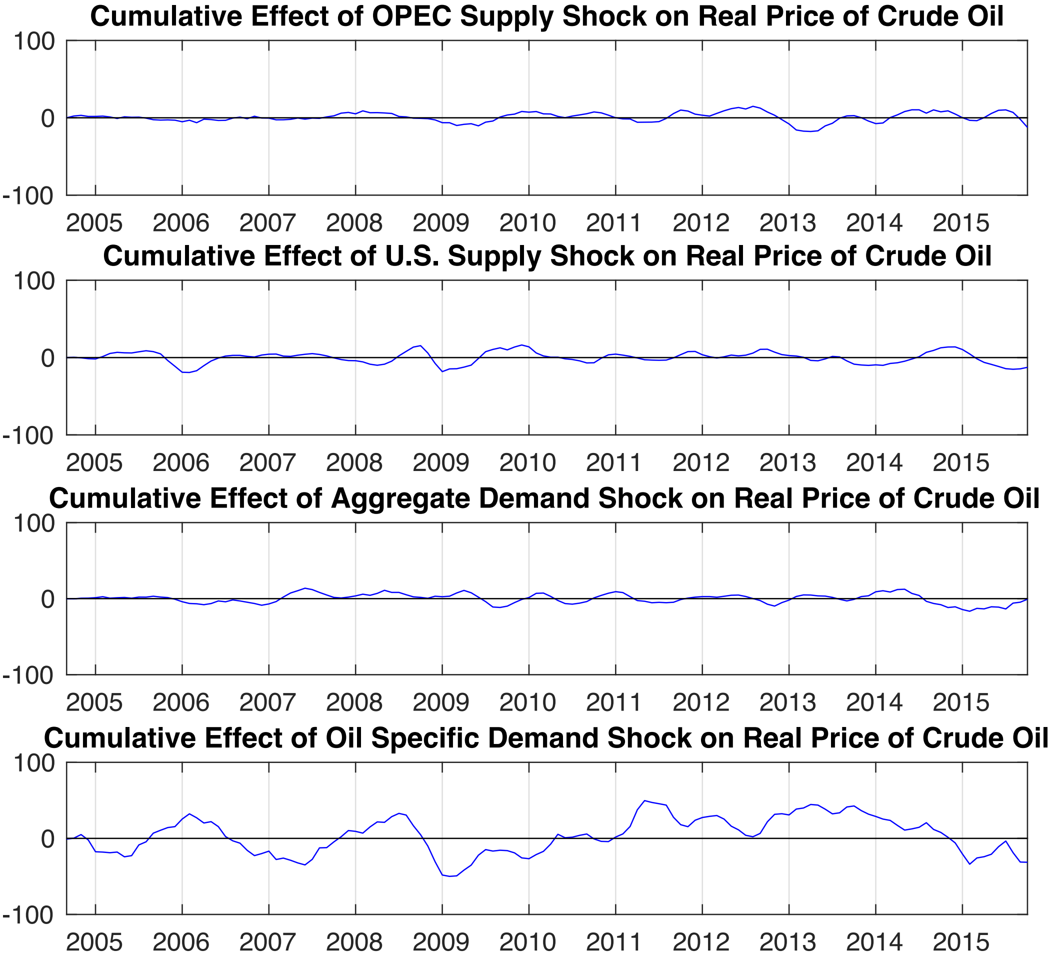

Figure 18: Historical decomposition of the real price of oil derived from the baseline model described in section 4.4.

Variance decomposition of the real price of oil

	Shocks			
	OPEC supply	U.S. supply	Aggregate demand	Oil-specific demand
1	2.90	0.94	1.18	91.96
	[0.33;10.08]	[0.06;4.32]	[0.10;4.68]	[84.26;97.06]
5	3.93	7.90	3.11	79.14
	[0.84;12.55]	[1.87;21.07]	[0.71;10.41]	[63.24;90.26]
10	6.45	9.41	7.79	69.22
	[2.22;17.36]	[3.76;21.19]	[2.34;21.42]	[50.06;82.60]
15	9.94	12.54	9.96	62.05
	[3.97;20.93]	[5.56;22.86]	[3.71;23.09]	[43.84;75.97]
20	13.38	12.62	12.28	56.15
	[5.58;25.83]	[5.97;22.67]	[5.21;24.32]	[39.06;70.93]

Table 3: Variance decomposition (in percentages) of the real price of oil for different time horizons, generated from the baseline model in section 4.4. The confidence intervals (in brackets) are at the 68% level and computed using a bootstrapping method with 2000 draws.

A.5.1 Baseline SVAR results with restricted sample

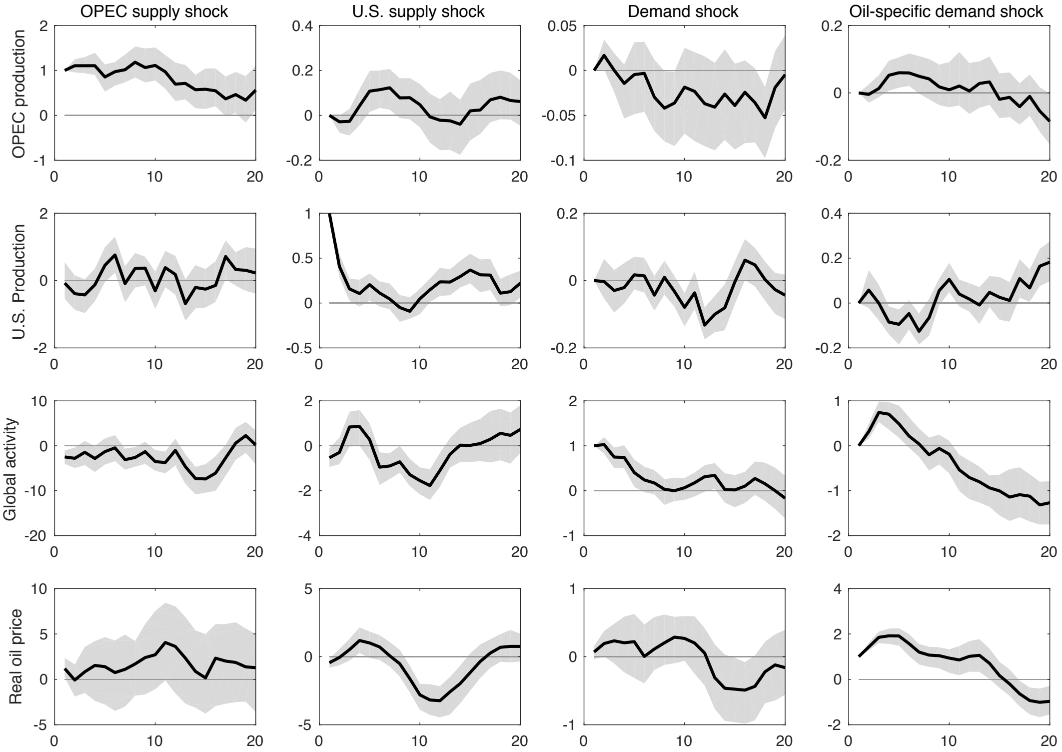

Figure 19: Impulse responses generated from the baseline model described in section 4.4, but with the sample restricted to 2005:M01–2015M09 and with 18 lags. They are all in levels of the variables. Shocks are normalised to unit shocks, i.e. 1% for the OPEC supply shock, U.S. supply shock and aggregate demand shock while one log-unit for the oil price. The shaded areas represent 68% confidence bands calculated using a bootstrap with 2000 draws. Note that the scaling of the axis might be different than in figure 9.

A.6 Section 4.5 — SVAR with U.S. imports

A.6.1 Augmented Dickey-Fuller test of U.S. Inventories

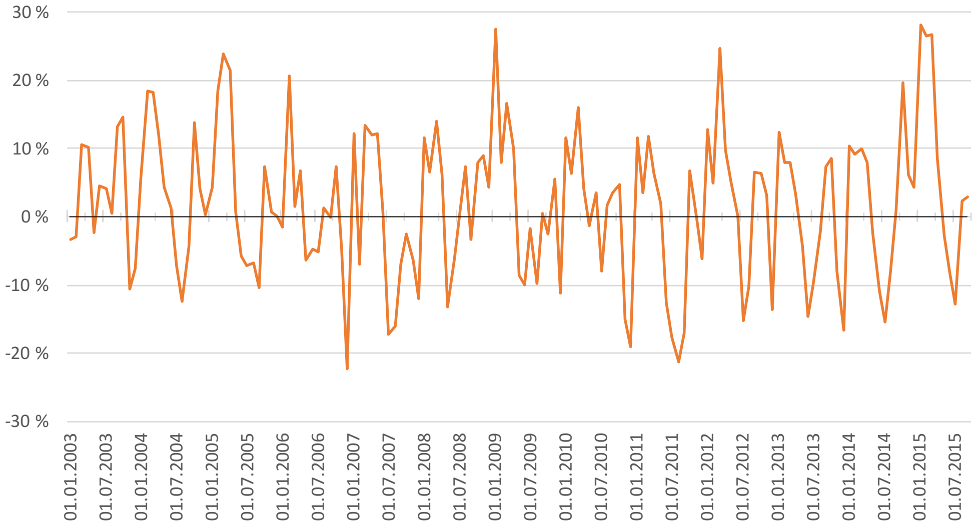

Figure 20: Plot of the log change in U.S. inventories over the sample 2003:M01–2015:M09. Data is retrieved from EIA.

Testing for stationarity: Augmented Dickey-Fuller

Variable	**Lags**	**Test statistics**
ΔU.S. inventories	2	-7.425^{***}
	4	-6.07^{***}
	6	-5.79^{***}
	8	-5.45^{***}
	10	-3.37^{**}
		Critical values
1%		-3.47
5%		-2.88
10%		-2.58

Table 4: An Augmented Dickey-Fuller test, checking for stationarity in U.S. inventory data. The series is tested with a constant term and in first differences after taking the natural logarithm. The sample range is 2003:M01–2015M09 with monthly observations. The null hypothesis is that the series is not stationary. The null hypothesis is rejected.

A.6.2 SVAR with U.S. inventories as exogenous variable

$$\boldsymbol{Y}_t = \boldsymbol{\nu} + \begin{bmatrix} \beta_{11} & \beta_{12} & \beta_{13} \\ \beta_{21} & \beta_{22} & \beta_{23} \\ \beta_{31} & \beta_{32} & \beta_{33} \\ \beta_{41} & \beta_{42} & \beta_{43} \end{bmatrix} \begin{bmatrix} \Delta inv_t \\ \Delta inv_{t-1} \\ \Delta inv_{t-2} \end{bmatrix} + \Theta_0 \boldsymbol{\varepsilon}_t + lags \tag{10}$$

Equation 10 is estimated over the sample 2003:M01–2015:M09 with 18 lags. The only difference from our final model presented in section 4.5.1, is the addition of U.S. inventories as an exogenous variable with two lags. The coefficients estimated for more than two lags of U.S. inventories were not statistically significant. The reasoning behind the exclusion restrictions remains the same.

We compare the output to our final U.S. imports SVAR. The generated impulse responses when including U.S. inventories (figure 21) do not deviate notably. When comparing the two variance decompositions, our SVAR with U.S. inventories gives the U.S. import shock an explanatory power of up to 15.74% over the oil price (table 5) while our U.S. imports model gives it 15.54%. Thus, we conclude that U.S. inventories do not help in explaining the variation in the global oil prices.

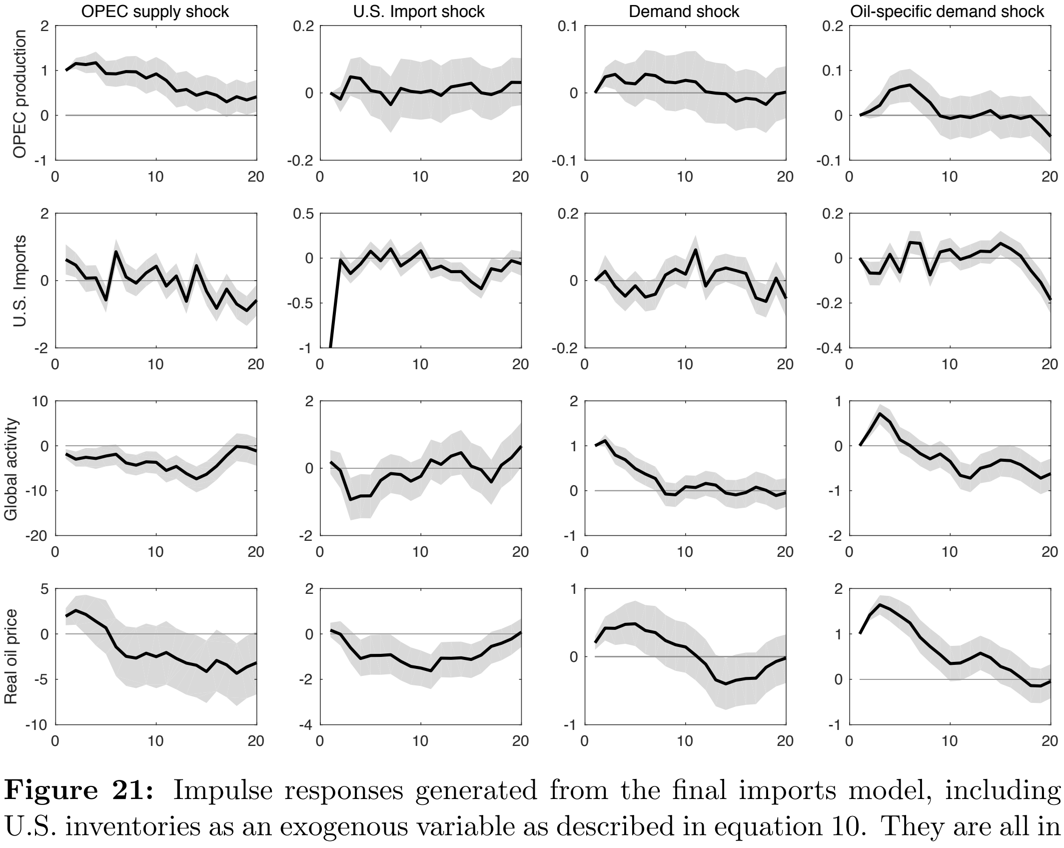

Figure 21: Impulse responses generated from the final imports model, including U.S. inventories as an exogenous variable as described in equation 10. They are all in levels of the variables. Shocks are normalised to unit shocks, i.e. 1% for the OPEC supply shock, U.S. import shock and aggregate demand shock while one log-unit for the oil price. The U.S. import shock is negative. The shaded areas represent 68% confidence bands calculated using a bootstrap with 2000 draws. Note that the scaling of the axis might be different than in figure 11.

Variance decomposition of the real price of oil

	Shocks			
	OPEC supply	U.S. imports	Aggregate demand	Oil-specific demand
1	6.77	1.15	5.72	83.04
	[1.90;14.54]	[0.10;4.76]	[1.58;12.98]	[73.55;90.65]
5	4.43	5.29	11.52	73.48
	[1.48;11.14]	[1.68;14.17]	[3.28;24.55]	[59.75;84.97]
10	9.14	12.05	12.08	60.10
	[3.72;19.27]	[4.58;24.65]	[4.30;26.35]	[43.94;73.34]
15	12.90	15.74	15.14	49.36
	[5.48;26.42]	[6.90;28.12]	[7.13;27.65]	[35.18;64.07]
20	17.22	15.42	16.28	43.73
	[7.67;33.53]	[6.96;27.47]	[8.34;29.10]	[30.34;58.78]

Table 5: Variance decomposition (in percentages) of the real price of oil as described in equation 10 for different time horizons. The confidence intervals (in brackets) are at the 68% level and computed using a bootstrapping method with 2000 draws.

A.6.3 Section 4.5.2 — U.S. Imports SVAR results

Variance decomposition of the real price of oil

	Shocks			
	OPEC supply	U.S. imports	Aggregate demand	Oil-specific demand
1	5.55	0.96	4.95	85.43
	[1.08;12.66]	[0.08;4.13]	[0.91;11.89]	[76.65;92.55]
5	3.05	4.23	11.05	76.67
	[0.91;9.30]	[1.02;13.00]	[2.67;24.46]	[60.70;87.98]
10	6.92	12.40	12.43	61.01
	[2.40;17.78]	[3.94;27.13]	[4.52;25.79]	[42.88;76.06]
15	10.01	15.54	17.24	50.65
	[4.10;21.79]	[5.74;29.48]	[7.93;29.54]	[33.78;66.02]
20	12.15	15.45	18.85	47.02
	[5.46;24.56]	[6.29;28.73]	[8.87;32.68]	[31.10;62.86]

Table 6: Variance decomposition (in percentages) of the real price of oil for different time horizons, generated from the final imports model in section 4.5.1. The confidence intervals (in brackets) are at the 68% level and computed using a bootstrapping method with 2000 draws.

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- The U.S. Shale Oil Boom -

The impact of U.S. supply shocks on the global oil price

GRA 19003 – Preliminary Thesis Report

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Programme:
MSc Business, major in Economics

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2 RESEARCH QUESTION

The United States of America has a long and proud tradition of being an oil producing economy. However, during the last 40 years, their position as a leading oil producer has diminished as other oil exporting economies developed and gained traction on the world market.

During the end of 2014 and ‘15 (and continuing throughout 2016) we have observed a steep decline in the oil price. As of the writing of this report, the Brent Crude has dipped below $30/bbl – the lowest level in more than 10 years. This has spurred debate, as the public, the media and researchers alike try to answer the question of where this oil price shock originated. Is slowing demand in China, the U.S. shale oil revolution or some other factor to blame? How large are the isolated effects of these factors?

It is the effect of the shale oil revolution that we wish to investigate further.

The literature has shifted from focusing on the supply side, starting with Hamilton in the 80s, to focusing on the demand side, revolving around Kilian’s work. Today, the supply story seems to be gaining traction once again.

There has been a major breakthrough in oil extraction technology in the U.S. during the last 15 years. Old oil wells, which were previously regarded as empty, have now been brought back to life as new technologies have been developed. The oil price increase observed during the last 10 years incentivised more investments, making new extraction techniques such as horizontal drilling and hydraulic fracturing profitable. These advancements in technology made it more cost-effective to access the shale oil reserves.

The question is then whether or not the increased production in the U.S. is the main culprit of the recent fall in the global oil price. Although this may be a plausible explanation *ex ante*, we are yet to quantify this effect. Naturally, demand also plays a role in determining the price. Because of this, our methodology needs to account for both forces.

Our contribution to the literature will be to assess the impact of the recent take-off in U.S. oil production on the global oil price.

3 THE U.S. SHALE OIL REVOLUTION

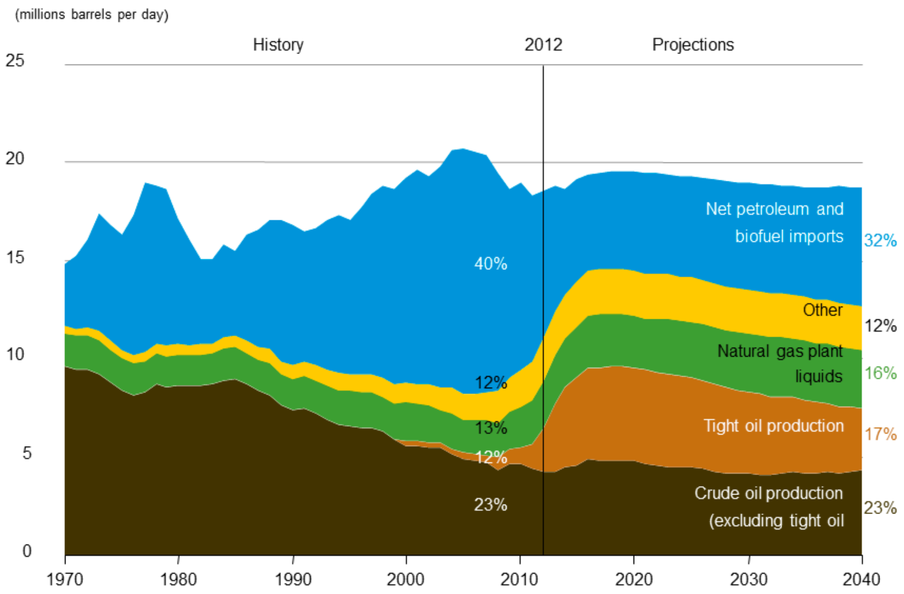

Figure 1: U.S. petroleum and other liquid fuel supply by source, 1970-2040

Shale oil (used here interchangeably with tight oil) is petroleum found in unconventional rock formations of low permeability. The boom in shale oil production in the U.S. (Fig. 1) was facilitated by the high oil price which made the new extraction methods available financially viable (Kilian 2014). After 2003, this combination of hydraulic fracturing and horizontal drilling thus became competitive, and investments in shale oil production in the U.S. consequently started increasing (Fig. 2).

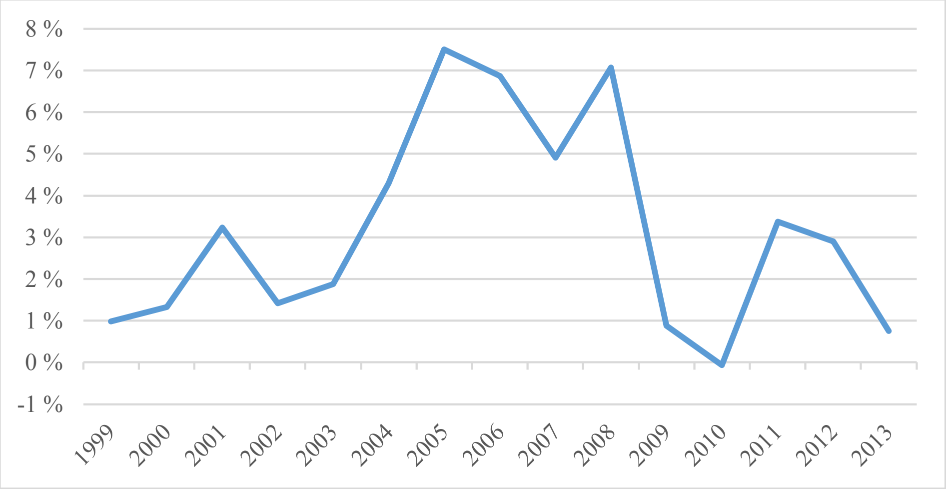

Figure 2: Percentage changes in private fixed investment: Mining and oilfield machinery (Source: FRED)

The centres of the shale oil boom were in Texas and North Dakota, with Eagle Ford in the former and the Bakken shale oil formation in the latter state. Maugeri (2013) argues that there was a combination of different factors that set up the conditions necessary for the shale oil revolution to take place: (1) a low population density in affected areas, (2) a large supply of oil and pre-existing drilling rigs and lastly, (3) the Americans' entrepreneurial spirit. In 2012, over 4000 shale oil wells were brought online – more than in the whole rest of the world (excl. Canada). This high drilling intensity coupled with the adaptability of U.S. firms and the other aforementioned factors, made this expansion difficult to replicate elsewhere.

In the Bakken Three-Forks fields alone, the production started out at a few thousand barrels in 2007 and reached 770 000 barrels per day in December 2012 in addition to 23 167 million cubic meter of natural gas per day (Maugeri 2013).

4 SUPPLY VS. DEMAND: HAMILTON VS. KILIAN

The efforts to explain oil price fluctuations have mostly concentrated around two prominent figures in academia. On the one side, James D. Hamilton has been promoting the supply-side view. In his research conducted in the 80s, he found evidence for the post World War II oil price shocks being caused by exogenous disruptions to the supply of oil. This was the prevailing view until recent years when Lutz Kilian published his game-changing research employing structural VARs. Contrary to Hamilton's view, Kilian found compelling evidence for demand forces being much more important than what had been previously believed.

4.1 HAMILTON AND POST-WAR OIL SHOCKS

Hamilton (1983, 1985) attempts to find links between macroeconomic variables and the oil price. In the post-war data, he observes that prior to recessions, the price of oil tends to spike. The probability for the oil price and the business cycle to move in this pattern is too low for it to be caused by randomness. Hence, it cannot be coincidental.

He also tests whether or not the business cycle can predict the oil price behaviour, i.e. whether demand drives the oil price up before the business cycle ends. He is not able to confirm this as key macroeconomic figures have no predictive power on the oil price (U.S. output, unemployment, wages, commodity price indices, monetary aggregates, interest rates or stock prices). This does not imply, however, that the demand story is ruled out. He simply states that these factors cannot explain how the oil price spikes right before an output slump. Hence, it makes Hamilton propose that the shocks to the oil price since the last World War have been caused by exogenous events unrelated to U.S. business cycle movements. To further elaborate on this proposition, he proceeds to identify these exogenous events (Table 1) leading to oil price shocks and whether or not they lead to a recession. He mentions oil supply disruptions in particular as a recurring culprit of either a subsequent recession or an oil price hike, depending on whether price controls are in place.

Table 1. Principal Causes of Crude Oil Price Increases, 1947 – 1981

Oil Price Episode	*Principal Factors*
1952 – 1953	Iranian nationalisation Strikes by oil, coal and steel workers Import posture of Texas Railroad Commission
1956 – 1957	Suez Crisis
1970	Rupture of Trans-Arabian pipeline Libyan production cutbacks
1973 – 1974	Stagnating U.S. production Arab-Israeli war
1978 – 1979	Iranian revolution
1980 – 1981	Iran-Iraq war Removal of U.S. price controls

Source: (Hamilton 1985)

With this proposition, he claims to be able to explain the oil price shocks in the post-war data, yet to be accomplished by models focusing on resource exhaustion or cartel behaviour optimisation. Hence Hamilton's proposition implies that the oil price shocks are due to exogenous disruptions to the global supply of oil.

He underpins this argument by pointing to the Texas Railroad Commission (TRC), an important institution which imposed *de facto* price controls during the period of analysis. TRC would forecast oil demand month by month and plan production in Texas accordingly. Because of this, the oil price would seldom deviate much from the posted or targeted price, effectively filtering out endogenous business cycle movements. Since exogenous supply disruptions could not be predicted, the crude oil price could not be shielded from these events, causing oil price hikes or rationing. Thus, this unique institutional arrangement allowed these exogenous supply shocks to be identified, disregarding any innovations on the demand side completely.

TRC's influence on the global oil price is likely to have deteriorated after the establishment of OPEC in the 70s. OPEC enabled innovations on the demand side to affect the oil price level more directly than had been the case before. This meant that the plausibility of Hamilton's hypothesis of supply-side disruptions causing oil price shocks got challenged. Giving support to Hamilton's case, Danielsen and Selby (1980) argue that OPEC established a price targeting regime not unlike the one organised by the TRC where oil price increases would only be sought if it was justified in OPEC meetings or by supply disruptions. However, it is unlikely that they would plan supply following projected U.S. demand. After the establishment of OPEC, endogenous demand forces should then play a larger role in the determination of the oil price.

4.2 KILIAN AND DEMAND SHOCKS

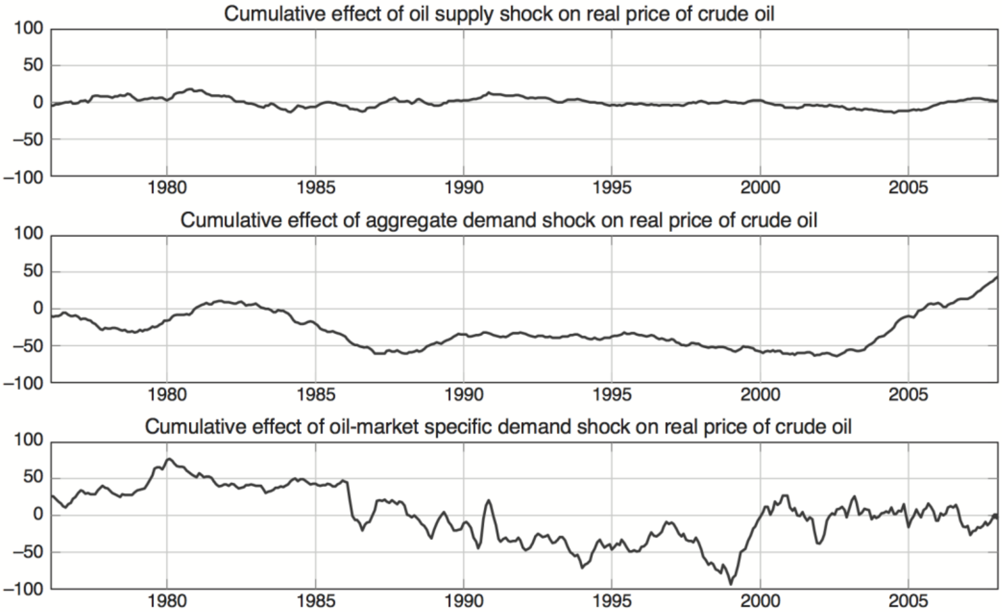

Figure 3: Historical decomposition of the real price of oil, 1976-2007 (Source: Kilian (2009))

By utilising structural VAR models, Kilian (2009) manages to establish recognition of demand-side forces. He decomposes the price shocks into three components – supply, demand and oil-specific demand (precautionary demand) (Fig. 3). He discovers that supply shocks between 1973 and 2007 were, for the most part, transitory (for up to 12 months) and had a far smaller impact on the real price of oil compared to the other two components. This might reflect production cuts being met with increased production elsewhere. In contrast, the cumulative contribution of the oil-specific demand on the real price has been pronounced, reflecting shifts in expectations of the future oil supply. Furthermore, he points out the increase in 1979 and 2003 in particular as driven by strong demand and precautionary demand forces, and not supply. Even when there are physical supply disruptions, he argues that it is mainly the precautionary demand component which drives the prices up and not the lack of supply itself.

Kilian’s results imply that no oil price shocks are the same and that there is a two-way causality between the macro economy and the oil price. Moreover, depending on the type of shock, the implications for the economy will be different. A negative supply shock will lead to higher prices and lower real activity. A demand shock will lead to higher prices, but only dampened real activity as the decrease is cushioned by the shock itself.

4.3 REACHING COMMON GROUND?

Following Kilian's seminal paper of 2009, Hamilton (2009) counters his findings by once again reinforcing his supply-side view, also after the establishment of OPEC. He argues that Kilian's oil-specific demand shocks need to manifest themselves as changes in inventories. More specifically, precautionary demand should incentivise hoarding behaviour and inventories should increase. Looking at the months following negative oil supply shocks, he observes that they actually tend to decrease. The implication is that changes in inventories serve to mitigate rather than worsen the shocks.

While Hamilton acknowledges that demand may have played some role in the price increase in the years following 2003, he does not elaborate on this point. However, Kilian's explanation favouring the demand side succeeds in explaining why this oil price hike was not immediately followed by a recession[1] (Fig. 3).

Commenting on Hamilton's 2009 paper, Kilian argues that Hamilton fails to account for the crucial point that commonly used measures of oil supply shocks only explain up to 20 percent of oil price increases. By construction, the rest can only be explained by demand factors.

Kilian goes so far as to say that the 1973 oil shock was in fact driven by demand. A surge in global real activity predates the oil price shock and – since the oil price prior to OPEC did not reflect the true market price (TRC) – the oil price should have been much higher in the period prior to the shock. Further, the prices in other raw materials increase during the same period but do not have any contemporaneous disruptions in supply. The oil price increase observed is only moderately higher than the price increases of other raw materials and commodities. Hence, it is plausible that demand can explain 80 percent of the price increase.

In a recent working paper by Baumeister and Hamilton (2015), the authors revisit the methodology employed in Kilian (2009) and Kilian and Murphy (2012).

---

[1] It is worth noting that the financial crisis of '07-08 is well understood and was not caused by variations in the oil price (Blundell-Wignall, Atkinson and Lee 2008; Crotty 2009; Foster and Magdoff 2009)

Using Bayesian techniques which do not require the Cholesky exclusion assumptions to achieve identification, they are able to confirm that the original results are robust.

Baumeister and Hamilton's results show that an oil price hike as a result of a supply shock leads to lowered economic activity after a significant lag while a price hike due to a demand shock does not exhibit the same response. It seems that Hamilton implicitly acknowledges the importance of demand shocks in this paper as he is not arguing otherwise. However, they do not explicitly mention precautionary demand as a significant factor.

Thus, while the Hamilton vs. Kilian debate is still not resolved, Kilian has managed to present compelling evidence showing that demand is important when assessing oil price shocks after the 1970s – contrary to what was believed earlier.

5 THE RECENT OIL PRICE DECLINE

The latest oil price drop whose endpoint still remains uncertain makes the above discussion as relevant as ever. The media has generally focused on the U.S. shale oil boom, OPEC's failure to curb production, and the weakening global demand as the main explanations for the fall. In addition, the newspapers highlight the higher-than-expected production of countries such as Iraq and Russia (Krauss 2016; Economist 2015; Plumer 2016). The World Bank (2015) also notes the reasons above, but adds the appreciation of the U.S. dollar to the list of important factors.

Baumeister and Kilian (2015) seek a more quantitative approach in order to assess the competing explanations. They deploy VAR forecasts with models containing the real price of oil, global production, changes in inventories and Kilian's measure for real activity. With data up until June 2014, the authors manage to predict over half of the oil price decline during the second half of the year. By looking at the forecast errors, they argue that the OPEC decision not to curb production and the U.S. shale oil boom are not causes supported by the data. Instead, they argue for changing expectations in July causing a decline in storage demand, and an unexpected weakening of the global economy in December. Opposing popular opinion, they also raise doubts as to the effect of the dollar appreciation.

5.1 DEMAND AND SUPPLY DECOMPOSITION

Rather expected, Hamilton (2014a) attributes the fall to surging U.S. production. However, he also acknowledges the role of slowing global demand for oil and seeks out to estimate the magnitude of this force (Hamilton 2014b).

He identifies three variables which may help explain a falling demand for oil as a result of slowing global activity. The first of these is the price of copper which is not influenced by how much oil is extracted from the wells, but is at the same time highly sensitive to changes in global activity. A declining price for copper could help to predict declining prices for oil if driven by falling demand. The second variable is the yield on a 10-year U.S. Treasury bond. A decline in the yield of such a long maturity bond can be a sign of increasing pessimism regarding global real activity. The last variable he suggests, is the dollar exchange rate measured as an index of other currencies. An appreciated U.S. dollar might be a sign of a weakening world economy, as foreign currencies depreciate accordingly.

With these three variables in hand, we build on Hamilton (2014b) and regress the log change in the West Texas Intermediate (WTI) on the log change in the price of copper and the exchange rate, as well as the change in the yield of the 10-year maturity U.S. Treasury bond. Using a weekly frequency, our sample begins in April 2007 and ends in June 2014. We can predict what the change in the WTI would have been given only the observed changes in the independent variables, i.e. the demand factors. By construction, the oil price decrease not predicted by the model can then be attributed to supply.

$$\Delta p_{\text{oil,t}} = \underset{(1.771^{*})}{0.111} \Delta p_{\text{copper,t}} \underset{(3.008^{**})}{-1.347} \Delta p_{\text{dollar,t}} + \underset{(3.454^{**})}{0.142} \Delta r_{\text{10y,t}} + \hat{e}_t$$

Equation 1: Estimation results – t-values (in parenthesis) computed using Newey-West robust SE w/ 7 lags

From June 2014 to December 11th 2014, the copper price was reduced by 7 percent, the dollar appreciated almost 9 percent, and the 10-year yield on U.S. Treasury bonds fell by 44 basis points. Given these observed figures, our model predicts that the oil price should have fallen by 19,2 percent. Observed data for the oil price reveal that the true decrease was 43 percent over the same period. Hence, approximately 44 percent of the price fall can be explained by demand factors. By construction, the remaining 56 percent must be due to supply. Figure 4 shows the predicted path of the oil price given only demand factors, and juxtaposes it against the observed price.

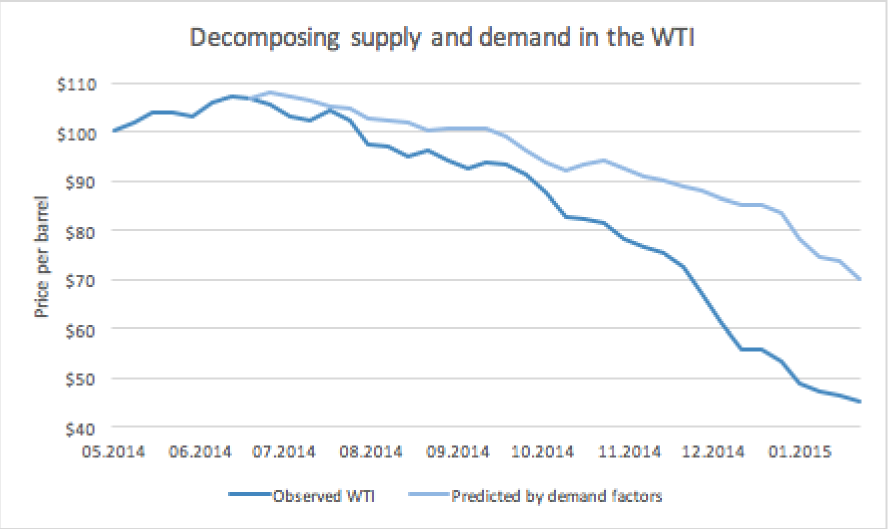

Figure 4: Predicted and observed paths of the WTI, 07.05.2014-28.01.2015

When expanding the forecast horizon by one week, we predict supply to account for almost 60 percent of the oil price decline. Expanding the forecast horizon further into 2015, we see that supply becomes less important, only accounting for 41 percent in January and eventually 37 percent in March.

While the exercise is illustrative in its simplicity, we cannot rule out the possibility that the model will overestimate the importance of demand, as the forecast horizon is extended. If there have been new supply shocks or structural changes in the relationships between variables occurring after the end of the estimation sample, the estimated coefficients will fail to account for this. We thus run the risk of potentially overestimating the magnitude of the predictive power the demand factors have on the oil price.

Although new estimations would have to be performed on a more recent sample, our analysis implies with some degree of confidence that the supply has been the larger force driving the oil price down during the latter part of 2014. However, demand side developments cannot be disregarded, giving merit to both sides of the discussion in the literature.

6 METHODOLOGY

Our preliminary approach will be to employ the SVAR-methodology, building on work done by Kilian (2009). As described previously, Kilian is able to separate the responses of the oil price after shocking different variables in the system. By adding U.S. supply to the mix, we are hoping to assess the responses of the variables in the system following a U.S. supply shock.

We are able to recreate Kilian's results and proceed with augmenting the model with data on U.S. crude oil production, gathered from the U.S. Energy Information Administration.

$$\begin{bmatrix} \Delta gprod \\ \Delta usprod \\ rea \\ rpo \end{bmatrix}_t = \Theta(L) \begin{bmatrix} \theta_{11} & 0 & 0 & 0 \\ \theta_{21} & \theta_{22} & 0 & 0 \\ \theta_{31} & \theta_{32} & \theta_{33} & 0 \\ \theta_{41} & \theta_{42} & \theta_{43} & \theta_{44} \end{bmatrix} \begin{bmatrix} \varepsilon^{\Delta gprod} \\ \varepsilon^{\Delta usprod} \\ \varepsilon^{rea} \\ \varepsilon^{rpo} \end{bmatrix} + lags$$

Equation 2: Kilian's 2009 SVAR specification augmented with U.S. oil production

The Cholesky ordering (Eq. 2) assumes that the real price of oil whose price can be observed on the market daily, responds to all shocks contemporaneously. It also takes time for real activity to absorb changes in the real price of oil. Hence, real activity is placed above it. Furthermore, it is safe to assume that oil producers are not able to observe the state of real economic activity in real time and thus react to them with a lag. This is because economic data is published and updated more than one month after they are observed. While the oil price can be observed by oil producers in real time, adjusting the supply accordingly cannot be done instantly as the production schedule does not allow for abrupt adjustments. We place global production above U.S. production since it is plausible that American producers will be able to respond quicker to changes on the global market rather than the other way around. However, this last assumption is not critical for the results. Whether U.S. production is placed first or second does not make a significant difference.

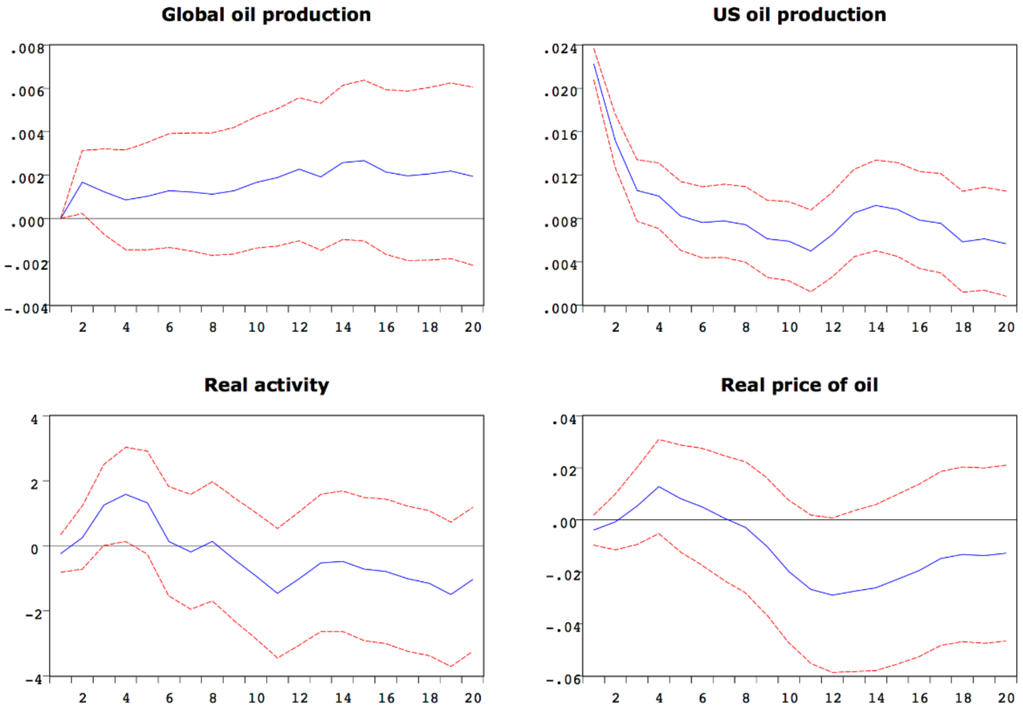

Figure 5: Impulse responses to a U.S. supply shock.

In Figure 5, we observe that the real price of oil increases in the months following the shock, eventually starting to decrease after six months. However, looking at Figure 6 reveals that the model fails to create a significant variation to shocks to U.S. production. Further, we suspect that a production increase in one location might be matched by a production decrease in another, thus neutralising any fluctuations in the global production variable. Finally, there might be simultaneity between global and U.S. production that can lead to incorrect inference.

If we wish to find meaningful results for our research question, we might need to find a different approach.

Going forward, we will attempt to find a suitable replacement for the global production variable. An interesting candidate is OPEC oil production, since it might help capture some of the dynamics between the two distinct crude oil suppliers. In order to better understand the effect of the U.S. shale oil boom on the global oil market, we need to look into the degree of The United States' self-sufficiency in terms of oil. If it turns out that the domestic oil market is completely insulated, it might provide a plausible explanation for the lack of variation between U.S. and global production data, as the U.S. may only affect the global price through the demand channel.

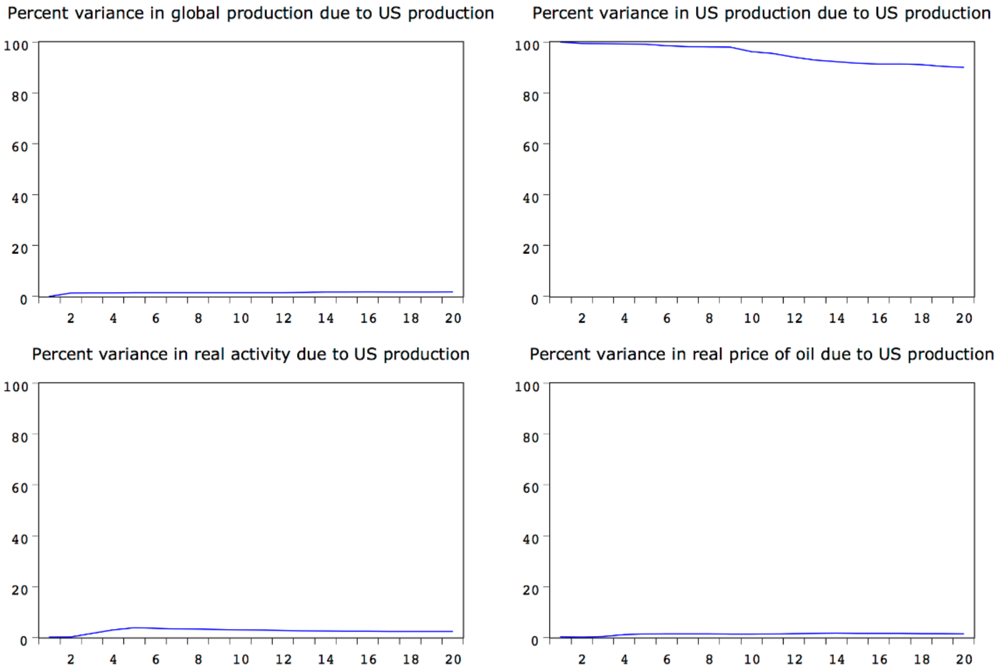

Figure 6: Variance decomposition of the SVAR system following a U.S. supply shock

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