OPEC’s Impact on Oil Price Volatility: The Role of Spare Capacity

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Abstract

OPEC claims to hold and use spare production capacity to stabilize the crude oil market. We study the impact of that buffer on the volatility of oil prices. After estimating the stochastic process that generates shocks to demand and supply, and OPEC’s limited ability to accurately measure and offset those shocks, we find that OPEC’s use of spare capacity has reduced volatility, perhaps by as much as half. We also apply the principle of revealed preference to infer the loss function that rationalizes OPEC’s investment in spare capacity and compare it to other estimates of the cost of supply outages.

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1. Introduction

Spare production capacity plays a central role in the world oil market, and the spare capacity held by OPEC members in particular is significant for its potential ability to stabilize the market price. Indeed, to "ensure the stabilization of oil markets" is part of OPEC's statutory mission[1]. Often, the question has been raised whether OPEC's spare capacity is large enough—or too large (Fattouh, 2006; *Petroleum Economist,* 2008a,b; *Saudi Gazette*, 2013). Our purpose in this paper is to shed light on the factors that have influenced OPEC's calculation of the volume of spare capacity required to achieve its mission, and to estimate the extent to which OPEC's utilization of spare capacity has stabilized the price of crude oil.

Looking beyond OPEC as a whole, we also focus on the spare capacity held by four OPEC members: Saudi Arabia, Kuwait, Qatar, and the UAE. For lack of a better name, like Reza (1984) and Alhajji and Huettner (2000) we will refer to these four as the OPEC Core (Jacoby and Paddock (1983), Karp and Newberry (1991), and Gately (2004) use other definitions for the Core). They are distinguished by a perception that, unlike many other members, they have engaged most purposefully in attempts to balance the market by adjusting their production to offset demand and supply shocks. Although the four Core members do not necessarily act in unison to develop and manage spare capacity as a homogeneous unit, they appear individually at least to have taken seriously the responsibility to help stabilize price. In any event, the volume of spare capacity held by the Core comprises the largest portion of OPEC's total, averaging 85% during the period of our study.

The significance of efforts to stabilize the price of oil hardly requires explanation. The market is exposed to substantial shocks that disrupt both supply and demand. Whether from war, natural disasters, labor strikes, port closures, political sanctions, or terrorism, the

[1] The complete mission statement is available at: http://www.opec.org/opec_web/en/about_us/23.htm (accessed on July 28, 2015).

production and delivery of oil to the market is insecure and subject to frequent and unpredictable outages. The demand for oil responds fitfully to the vagaries of the global business cycle and financial markets, and suffers as well from other types of disruptions (e.g., the short-term substitution of diesel for nuclear energy after Fukushima, or diesel for coal prior to the 2008 Summer Olympics). The impact of each disruption is further magnified by relatively low elasticities of demand and supply, which means sharp price movements may be required—especially in the short term—to restore equilibrium in the market.

Previous research (Jaffe and Soligo, 2002; Parry and Darmstadter, 2003; Kilian, 2008; Baumeister and Gertsman, 2013; Brown and Huntington, 2015) has identified various economic costs associated with oil price volatility. Some of these costs are borne directly by the consumers and producers of crude oil and related products. They take the form of shocks to factor prices and revenue streams that make long-term business planning more difficult but also more important. Many private remedies exist to mitigate these shocks, including precautionary inventories, hedging, and long-term contracts. Such measures impose costs of their own, but for many it is the lesser of two evils. Rational consumers and producers are guided by internal incentives that reflect their particular vulnerabilities, and these private incentives are reflected in the extensive scope and diverse form of private risk management programs that target the price of oil. Less direct is the impact of oil price shocks on the business cycle and overall health of the economy. Viewing macroeconomic stability and national security as a public good, national governments and various multilateral agencies have attempted to manage these costs collectively, one example being the International Energy Agency's strategic petroleum reserve program that requires member nations to maintain 90 days of net oil import volumes in public storage. The European Union's program, which is more stringent, requires all members to maintain in public storage a volume equivalent to 90 days of domestic oil consumption.

In light of the various private and public incentives that motivate multiple entities to manage oil price risks, it is clear that OPEC's mission to stabilize the oil market is but one part of a larger picture. OPEC's role is unique, however, because it aspires to reduce price volatility directly—by acting as a swing producer that offsets physical shocks to supply and demand—rather than simply mitigating the cost of price shocks after they have occurred. This strategic capability to reduce price volatility at its source is lacking in private commercial inventories and government stockpiles. No privately-owned inventories are large enough to impact the market price (and if several private entities collaborated in the effort, they could be charged with illegal efforts at price fixing). Moreover, the public-good aspect of price stabilization transcends the incentives of individual economic agents. Government stockpiles, although certainly large enough (if released) to impact the price, are seldom used, perhaps because they tend to be reserved for use during "emergencies" and because the rules for releasing volumes to the market (or taking volumes off the market) are vague and controversial[2].

Recent suggestions that privately-produced shale oil has taken OPEC's place as the new swing producer are misguided. The producers of shale oil do not regulate their output to offset shocks to demand or supply, nor do individual shale oil producers have the ability or desire to attempt to "defend" any particular price level. Even though it may represent something like an expansion of privately owned and production-ready inventory, shale oil is produced subject to the profit motive where the market price determines the quantity supplied, not vice versa. In contrast, as we will show below, OPEC's spare production capacity appears to be managed

[2] Enabling legislation for the US Strategic Petroleum Reserve (Public Law 94-163-Dec. 22, 1975) states its purpose as being to reduce "the impact of severe energy supply interruptions." Recent press reports indicate that the Obama administration has suggested the President be given the authority to release barrels not only in reaction to likely economic harm caused by a supply disruption, but also in anticipation of such developments. Those same reports indicate, however, that the administration is very sensitive to suggestions that its focus on energy security amounts to managing markets (*Petroleum Intelligence Weekly*, 2015). The International Energy Agency is very clear that the purpose of its emergency stockholding program is not to manage oil prices. See http://www.iea.org/topics/energysecurity/subtopics/energy_security_emergency_response/ (accessed July 29, 2015).

actively (albeit not perfectly) to offset short-term fluctuations in demand and supply whether or not that effort contributes to the profits of its members.

Before proceeding further, it is well to consider whether the purpose of OPEC's spare capacity is indeed to stabilize the market price. We find support for this proposition not only in OPEC's own mission statement, but also in the obvious and persistent efforts by some OPEC members to raise or lower production to offset unexpected shocks to global demand and supply. Many examples can be cited (e.g., production cuts during the global economic downturn in 2001, production increases which accompanied the unusual buildup of global demand in 2003-2004 and supply disruptions in 2011-2012).

Such examples are typical of a "swing producer" and are indicative of the organization's commitment to stabilize the market. Khalid Al-Falih, then Saudi Aramco CEO, acknowledged as much when reporting (*Petroleum Economist*, 2013) that "in the past two years alone, we have swung our production by more than 1.5 million barrels a day (mmb/d) in order to meet market supply imbalances." Quite often Saudi Arabia is singled out as the ultimate swing producer, the supplier of last resort with sufficient wherewithal (physical and financial) to assume this duty[3]. Accordingly, in addition to studying the impact of OPEC and its four Core members, we also perform a separate analysis of Saudi Arabia's role in stabilizing the market.

In principle, spare capacity could be used to advance objectives besides price stabilization. One potential use would be to make opportunistic sales from spare capacity when the market is tight—cherry picking to enhance sales revenue. We do not believe the evidence supports this view. If demand for OPEC oil is inelastic, it is true that taking oil off the market

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[3] See, for example, Fattouh and Mahadeva's (2013) review of the literature, in which Saudi Arabia is singled out as the dominant swing producer. Nakov and Nuño (2013) show that both the size of Saudi Arabia's spare capacity and the volatility of its monthly output greatly exceed that of other OPEC members.

when prices are low would increase revenue. But raising production when prices are high would decrease revenue. In other words, opportunistic behavior must be asymmetric. In reality, OPEC's behavior appears to be more or less symmetric—not only raising output when the market is tight but also cutting output when the market is weak. This pattern contradicts the notion that spare capacity is held for the purpose of making opportunistic sales. If demand is elastic, then taking oil off the market when prices are low would reduce sales revenue. Given OPEC's historic tendency to decrease production when facing surplus, this again contradicts the hypothesis that OPEC's spare capacity is managed opportunistically.

Another possibility is that OPEC employs its spare capacity to stabilize its own export revenues. But then, assuming that demand is elastic, the prescribed course would be to decrease production when an outage occurs. The logic here is simple: if a shock drives the market price up (which ceteris paribus would increase OPEC revenue), then production must be decreased to restore the previous (lower) level of revenue. This is not consistent with observed behavior. Only if demand is inelastic would revenue stabilization and price stabilization dictate similar actions. But then, even if the actual motive were to stabilize its own export revenues, by so doing OPEC would also tend to stabilize the price.

After reviewing some related literature in Section 2, we develop in Section 3 a structural model of a producer using his spare capacity to stabilize the market price of its output. We estimate the model's parameters using observed price and spare capacity data for three groups of producers: Saudi Arabia, OPEC Core, and OPEC. In section 4, based on our model, we derive an analytical formula for the marginal value of spare capacity. In Section 5, we adopt the assumption that OPEC has equated the marginal costs and perceived benefits of its spare capacity and invoke the principle of revealed preference to calibrate the loss function that appears to have motivated OPEC's investment in spare capacity. In section 6, our estimate of OPEC's loss function is compared to the estimated size of economic losses due to oil supply disruptions derived from a well-known macroeconomic model of the global economy. The extent to which each group of producers' intervention has damped price volatility during the past fifteen years is examined in Section 7, through both an analytical approach and a counterfactual reconstruction of "unstabilized" price. Concluding observations are presented in Section 8.

2. Related Literature

Here we discuss only the few papers that have previously addressed OPEC's role in stabilizing the price of oil and leave aside countless others that focus mainly on the level rather than stability of price. De Santis (2003) attributed price volatility under OPEC's old production quota regime specifically to the inelasticity of Saudi Arabian supplies. Any physical disruption, he argued, would create a short-term price spike that could only be dissipated by longer term supply adjustments. De Santis assumed the absence of spare capacity which begs the question of how such a precautionary buffer would be sized and managed—or what would be its impact on price volatility.

Nakov and Nuño (2013) take the opposite approach, assuming that Saudi Arabia can and does adjust its output in response to each monthly demand shock in the manner of a Stackelberg dominant producer. By offsetting positive (negative) shocks with an increase (decrease) in its own output, Saudi Arabia effectively reduces price volatility, although that result is a by-product and not the objective of its behavior. The Stackelberg framework is a very insightful approach that seems appropriate to the structure of the world oil market, but one that presumes the dominant producer can perfectly anticipate the magnitude of each shock. Substantial misjudgments in that regard, if acted upon, could in fact lead to an increase in volatility, and the possibility of mistakes may hold the producer in abeyance.

Fattouh (2006) provided evidence that an increase in volatility and the frequency of price spikes are in a general way due to reduced spare capacity held by OPEC and other producers, but he did not pursue the argument to the point of a formal model or empirical estimates. Kilian (2008) argues that large oil price increases were caused by the conjunction of demand shifts and capacity constraints due to low OPEC and world spare capacity. Baumeister and Peersman (2013) attribute the observed increase in volatility to substantial reductions in short-run demand and supply elasticities post-1985. Difiglio (2014) recognizes OPEC's role in stabilizing prices via spare capacity and reviews reasons why similar efforts to offset disruptions using consuming nations' own strategic petroleum reserves have not been very successful. However, he provides no model or structural framework by which the effectiveness of releases from consumer stockpiles can be measured. More generally, the stockpile valuation literature has applied a mixture of dynamic programming and more heuristic analysis to size reserves designed to be used in disrupted periods only (see for instance Murphy and Oliveira (2010) for a survey of the literature). The literature has not so far provided any formal model of a buffer capacity that is used to continuously stabilize the price of oil, which is the goal of our paper.

3. A Model of price stabilization using spare capacity

3.1 Model assumptions

Since there is nothing specific to OPEC in the structure of the model, we develop the framework in the context of a generic oil Producer who elects to develop and deploy spare capacity to stabilize the market price of his output. Implicit is the notion that Producer has sufficient production to impact the market price. We assume that demand for Producer's output in any period follows a lognormal distribution due to the arrival of shocks that follow a known autoregressive process. We further assume that Producer wishes to stabilize price around a certain target level and that he creates a buffer of spare capacity (to be maintained going forward) to be used in this endeavor, but he is unable to accurately estimate the size of the shocks. As stressed by Mabro (1999): "In a market that naturally causes prices to collapse or to explode in response to either ill-informed expectations or small physical imbalances between supply and demand, production policies are unlikely to yield the desired price effect. Exporting countries, unhappy about a particular price situation, may change production volumes by too little or too much. The price target will therefore be missed."

Let $Q_t(P)$ represent the demand for Producer's output given price P. We assume:

$$Q_t(P) = a_t P^{\varepsilon} e^{S_t} \tag{1}$$

where a_t is an exogenous scaling parameter, ε is the short-run elasticity of residual demand for Producer's oil (its calculation will be discussed later in the paper), and S_t represents random shocks that affect the demand for Producer's crude.

The stochastic component e^{S_t} reflects the size and likelihood of shocks to global demand and non-Producer supply. For application to monthly data, some shocks are likely to persist beyond 30 days. Accordingly we consider that the shocks S_t follow a first-order autoregressive process:

$$S_{t+1} = \kappa S_t + \sigma_S u_t \tag{2}$$

where $u_t \sim i.i.d. N(0,1)$, σ_S represents the standard deviation of innovations on the shock to the call on Producer's crude, and κ is the shock persistence (note that $\kappa = 1$ implies a random walk). The lower κ, the faster shocks dissipate. This implies that S_t follows a normal law and that, for a given market price P, Q_t follows a log-normal law.

Let P_t^* represent Producer's target price for the period t. It is assumed that the target price vector is determined exogenously according to many criteria that lie outside the scope of our analysis. Given the price target, Producer adjusts output each period to mitigate losses caused by deviations of the market price from P_t^*. In the vernacular of the oil market, P_t^* is the price that Producer chooses to "defend." And, let Q_t^* be the volume that Producer expects to have to produce in period *t* to defend the target price P_t^* in the absence of shocks (i.e. if $S_t = 0$). From (1) we have:

$$Q_t^* = a_t(P_t^*)^\varepsilon \tag{3}$$

We assume that, in order to absorb shocks, Producer adopts a policy of maintaining a buffer sized as a fixed proportion of Q_t^*. Letting C_t represent production capacity at period t, we have:

$$C_t = BQ_t^* \tag{4}$$

Our goal is to identify the value of constructing a buffer and to identify its optimal size.

When estimating the size of the shock, Producer makes the error $\sigma_z z_t$, where z_t is uncorrelated with S_t and $z_t \sim i.i.d. N(0,1)$. The shock perceived by Producer is therefore $S_t + \sigma_z z_t$. Given the target price, Producer thus perceives the call on its crude to be:

$$\tilde{Q}_t = a_t(P_t^*)^\varepsilon e^{S_t+\sigma_z z_t}. \tag{5}$$

From (3) and (5) we have:

$$\tilde{Q}_t = Q_t^* e^{S_t+\sigma_z z_t}. \tag{6}$$

The resulting price P_t is such that: $a_t P_t^\varepsilon e^{S_t} = \tilde{Q}_t$. Figure 1a illustrates the price formation when the buffer size allows for absorbing the shock on the call on Producer's crude. P_t^0 represents the (undamped) price that would have been obtained if Producer had not used spare capacity to offset shocks, with $a_t(P_t^0)^\varepsilon e^{S_t} = Q_t^*$. Figure 1b illustrates the price formation when the buffer size is not sufficient to fully absorb the shock on the call on Producer's crude, with $a_t P_t^\varepsilon e^{S_t} = C_t$.

The spare capacity X_t is the difference between the total installed capacity and the perceived call on crude:

$$X_t = max\{0, C_t - \tilde{Q}_t\} \tag{7}$$

3.2 Estimating the estimation error based on observed price volatility

To stabilize the price, Producer supplies $\tilde{Q}_t$, i.e. the perceived call on its output. The resulting price P_t is therefore such that: $a_t P_t^\varepsilon e^{S_t} = a_t(P_t^*)^\varepsilon e^{S_t+\sigma_z z_t}$, which gives: $P_t = P_t^* e^{\frac{\sigma_z z_t}{\varepsilon}}$, or equivalently:

$$ln(P_t) = ln(P_t^*) + \frac{\sigma_z z_t}{\varepsilon} \quad (8)$$

In other words, in the absence of outages, the deviation of the oil price from the target price is attributable to the estimation error. We will therefore use the observed price volatility to estimate the observation error. The conventional measure of volatility, vol, is based on the variance of returns (percentage change in price). From (8) we therefore have:

$$vol^2 = var\left[\ln\left(\frac{P_t}{P_{t-1}}\right)\right] = \sigma_{TP}^2 + 2\left(\frac{\sigma_z}{\varepsilon}\right)^2 \quad (9)$$

The first term in this expression is the variance of the periodic percentage changes in Producer's target price: $\sigma_{TP}^2 = var\left(ln\left(\frac{P_t^*}{P_{t-1}^*}\right)\right)$. Solving (9) for the standard deviation of Producer's estimation error gives:

$$\sigma_z = \frac{|\varepsilon|}{\sqrt{2}}\sqrt{vol^2 - \sigma_{TP}^2} \quad (10)$$

Assuming that $\sigma_{TP}^2 = 0$ therefore provides an upper bound on σ_z. Of course, the term σ_{TP}^2 would vanish if the target price were increasing by a constant percentage each month. Upon reviewing the development of the crude oil market during our sample period, it may not be unreasonable[4] to assume $\sigma_{TP}^2 \cong 0$. This assumption, along with an estimate of the residual demand elasticity, allows us to approximate the standard deviation of Producer's estimation error:[5]

$$\hat{\sigma}_z = vol \times \frac{|\varepsilon|}{\sqrt{2}} \quad (11)$$

For our purposes, we use the average monthly Brent crude oil spot price series published by the U.S. Energy Information Administration and estimate vol as the standard

[4] After allowing for the disruption caused by the 2008/2009 financial crisis, the change in annual average oil price shows an underlying trend that suggests that the target price may have been rising fairly steadily over time.

[5] Let λ measure the portion of observed volatility due to changes in the target price. Thus, $\sigma_{TP}^2 = \lambda \times vol^2$, in which case (11) takes the general form: $\hat{\sigma}_Z = vol \times \frac{|\varepsilon|}{\sqrt{2}} \times \sqrt{1-\lambda}$. As we show later, however, our main results and conclusions are robust with respect to the presumed value of λ.

deviation of the log-returns of the average monthly price over our sample period (which goes from September 2001 to October 2014). This gives $vol = 8.58\%$.

ε, the short-run (monthly) elasticity of residual demand for Producer's oil, is by construction equal to $[\varepsilon_D - (1-\rho)\varepsilon_S]/\rho$, where ε_D and ε_S represent the short-run elasticity of global demand and non-Producer supplies, and ρ is the Producer's market share of global output.

Our estimation procedure is therefore sensitive to ε_D and ε_S, the presumed elasticities of demand and non-Producer supply. Given the range of estimates found in the literature, our analysis will be subjected to sensitivity analysis. The literature traditionally sees both global demand and non-OPEC supply to be highly inelastic in the short-run. Hamilton (2009) proposed a short-run global demand elasticity of -0.06, but noted that it might be higher or lower. Based on observed price movements following specific disruptions of the market, Smith (2009) suggested short-run demand and supply elasticities of –0.05 and 0.05, which together produce a "ten-times" multiplier that translates physical outages into price spikes. Baumeister and Peersman (2013) provide corroborating evidence based on a time-varying parameter vector autocorrelation analysis of global crude oil demand and supply. Their estimates of the quarterly demand elasticity fall between –0.05 and –0.15 throughout our sample period, and their estimates of the quarterly supply elasticity are of the same magnitude. Because our data are monthly, we consider a global demand elasticity ranging from -1% to -5% to be consistent with this literature (for values within this range we take $\varepsilon_S = |\varepsilon_D|$). Kilian and Murphy (2014) derive a much higher estimate of the short-run elasticity of demand (–0.26) from a structural vector autoregression that takes into account estimated monthly changes in the global volume of speculative crude oil inventories. Therefore, we also include a sensitivity case where the monthly demand elasticity is –0.26 and the monthly supply elasticity is 0, per Kilian and Murphy.

For each group of producers, we compute the average crude oil supply per month and global market share over the sample period. Our crude oil supply data are from the IEA Monthly Oil Data Service; production from the Neutral zone is not included in Saudi production (but included in OPEC Core production); for OPEC, we use the "OPEC Historical Composition" series. Table 1 provides the implied elasticities of residual demand. Table 2 provides the corresponding standard deviation of the estimation error, in both relative and absolute terms, calculated from (11). The absolute estimation errors (barrels per day) attributed to Saudi Arabia, the Core, and OPEC are roughly equal in size. The values range between 0.07 and 1.16 mmb/d, with all values below or equal to 0.4 mmb/d if global demand elasticity does not exceed -5%, which appears sensible to us. Since Saudi production is smaller than that of the Core, which in turn is smaller than that of OPEC, the relative size of the error (% of producer's output) respectively decreases, as shown in Table 2.

The precision of $\hat{\sigma}_z$ can be estimated using the Chi-Square distribution. A 95% confidence interval for σ_z^2 is given by: $\left[\frac{(n-1)\hat{\sigma}_z^2}{K_{.975}}, \frac{(n-1)\hat{\sigma}_z^2}{K_{.025}}\right]$, where $K_{.975}$ and $K_{.025}$ are cutpoints from the Chi-Square distribution with $n-1$ degrees of freedom. Based on the 158 monthly observations in our sample, the 95% confidence interval for σ_z is: $[0.901\hat{\sigma}_z, 1.124\hat{\sigma}_z]$.

3.3 Estimation of other parameters based on spare capacity

Because $C_t = \tilde{Q}_t + X_t$, after using (4) and (6) to substitute for C_t, we have:

$$-ln\left(1 + \frac{X_t}{\tilde{Q}_t}\right) = S_t + \sigma_z z_t - ln(B) \qquad (12)$$

The left-hand side of (12) is observable. The right-hand side represents the perceived autoregressive shocks to Producer's demand (cf. (2)) with unknown parameters B (buffer size), σ_S (volatility of demand shocks), and κ (shock persistence). Given monthly data on actual production and spare capacity, along with our previous estimate of σ_z, maximum likelihood estimates of B, σ_S, and κ, along with the covariance matrix, are obtained by the procedure described in Appendix 1. We here ignore the data censoring represented by (7) which occurs whenever the shock exceeds the size of the buffer capacity (i.e., when there is an outage). However this should not matter since in our sample only the Saudi data exhibit spare capacity equal to zero (during three months only). The historical monthly frequency of outage is therefore very low (1.9% for Saudi Arabia, zero for OPEC and OPEC Core), which simply reflects the fact that the spare capacity has almost always been sufficient to meet the perceived call on production. This remark also applies to the previous section where we attribute all the price volatility to the observation error.

Figure 2 shows the monthly variation in reported spare capacity of OPEC, Saudi Arabia, and the OPEC Core. Our data come from the International Energy Agency (IEA) and represent what the IEA calls "effective" spare capacity.[6] The monthly spare capacity data for Saudi Arabia and OPEC were provided directly by IEA in an Excel file[7]. To build the series for the OPEC Core, we collected[8] the data for Kuwait, UAE and Qatar from monthly issues of IEA's *Oil Market Report*. Because spare capacities are not reported on a regular basis prior to September 2001, our sample extends from September 2001 to October 2014 (158 observations for each series). These are the primary data with which we estimate the stochastic process governing shocks to the call on OPEC production. The estimates and their standard errors are reported in Table 3 for the case where the global demand elasticity is assumed to be -0.01. The estimates and standard errors corresponding to the other elasticity cases are nearly identical to

[6] According to the IEA, spare capacity is defined as "capacity levels that can be reached within 30 days and sustained for 90 days." Effective spare capacity captures the difference between nominal capacity and the fraction of that capacity actually available to markets (Munro, 2014).
[7] Email from Steve Gervais (IEA) on January 7th, 2015.
[8] We had five missing data for the non-Saudi members of OPEC Core. We consider that, because of a typo, the values for November 2002 and 2010 are those reported for October in the December's Oil Market Report (as these values differ from those reported for October in the November's report). The three other missing data are for June 2002, April 2003 and March 2007. We interpolate the missing values with the formula: $X_{c,t} = X_{S,t} + \frac{X_{O,t}-X_{S,t}}{2}\left[\frac{X_{C,t-1}-X_{S,t-1}}{X_{O,t-1}-X_{S,t-1}} + \frac{X_{C,t+1}-X_{S,t+1}}{X_{O,t+1}-X_{S,t+1}}\right]$, where $X_{S,t}$, $X_{c,t}$ and $X_{O,t}$ represent the spare capacity of Saudi Arabia, OPEC Core and OPEC, respectively, in month t.

these and therefore remanded to the appendix.

The estimates for B, the size of the buffer, and σ_S, the magnitude of the innovations on the shock exhibit a common pattern: the greatest values are obtained for Saudi Arabia, and the lowest for OPEC. This is consistent with the (traditional) view that Saudi Arabia is the swing producer and absorbs more shocks than the other OPEC producers (relatively to the size of the residual demand for its crude). In all cases, the estimated size of the Saudi buffer is about 21% of the expected call on Saudi Arabia's output, whereas for the Core (15%) and OPEC as a whole (9%) it is smaller.

To better understand the absolute size of the estimated buffers, we first determine Q^*, the average call on Producer's crude in the absence of shocks. Q^* is the average of $Q_t^* = \frac{\tilde{Q}_t + X_t}{B}$. For an elasticity of global demand of -1%, this gives Q^* = 8.82 mmb/d for Saudi Arabia, 14.91 mmb/d for the Core, and 30.02 for OPEC as a whole. The average size of the buffer in absolute terms is then calculated by multiplying Q^* by $B - 1$. As one would expect, the larger is the group of countries, the bigger is the average size of the buffer: 1.94 mmb/d for Saudi Arabia, 2.27 mmb/d for OPEC Core, and 2.64 mmb/d for OPEC. The Saudi figure is consistent with the various official pronouncements that have emanated from the Kingdom, which says their intended buffer has ranged between 1.5 and 2 mmb/d (see for instance *Petroleum Economist* (2005, 2012) and H.E. Ali Al-Naimi's address at CERAWeek (2009) and remarks at the 12th International Energy Forum (2010)). When considering the estimated speed at which shocks dissipate (Table 3), the estimated half-life is roughly 25 ($\kappa = 0.973$) months. Although the differences in the estimated κ appear small and are not statistically significant across all the elasticity cases, the implied half-life is considerably shorter (15 months) for the case of -0.26 demand elasticity (see appendix).

4. Incremental value of spare capacity

We assume that Producer incurs costs in any period when the perceived call exceeds production capacity. Such outages are denoted by $O_t \stackrel{\text{def}}{=} max\{0, \tilde{Q}_t - C_t\}$. The outage equals the portion of the call that Producer is not able to meet. From (4), (6) and (7), the outage can be written equivalently as $O_t = max\{0, (e^{S_t+\sigma_z z_t} - B)Q_t^*\}$. An outage occurs whenever the perceived shock exceeds the size of the buffer.

The probability of an outage depends on the size of the buffer and is given by:

$$\varphi_t(B) \stackrel{\text{def}}{=} pr(O_t > 0|B) = \int_{ln(B)}^{\infty} g_t(\xi)\, d\xi \tag{13}$$

where $g_t(.)$ represents the marginal density of $S_t + \sigma_z z_t$ based on the information set at time $t = 0$.

The expected size of the outage is:

$$E[O_t|B] = \int_{ln(B)}^{\infty} \left(e^{\xi} - B\right) Q_t^* g_t(\xi) d\xi \tag{14}$$

whereas the conditional expectation, given that an outage occurs, is:

$$E[O_t|B \cap O_t > 0] = \frac{E[O_t|B]}{\varphi_t(B)} \tag{15}$$

We postulate a quadratic loss function that reflects the present value of Producer's damages that result from all future outages:

$$L = \alpha \sum_{t=1}^{T} \frac{(O_t)^2}{(1+r)^t} \tag{16}$$

where r is the real risk-adjusted periodic discount rate and α is a latent preference parameter that reflects the weight that Producer attaches to outages. The loss function is increasing in the square of the size of individual outages and additive regarding their occurrence. The planning horizon is defined by T. We treat T as the service life of a designated production facility kept for spare. The value of the buffer to Producer is determined by its ability to reduce the expected loss resulting from outages. As shown in Appendix 3, the incremental value, v, of spare capacity is given by:

$$v = -\frac{\partial E[L|B]}{\partial B} = 2\alpha \sum_{t=1}^{T} \frac{E[O_t|B]Q_t^*}{(1+r)^t} \quad (17)$$

Note that the value of expanding the buffer does not depend on the functional form of $g_t(.)$, only on $E[O_t|B]$, which is itself the product of $\varphi_t(B)$ (the probability of an outage) and $E[O_t|B \cap O_t > 0]$, as well as the length of the planning horizon, the expected call, and α. In the next section, we show how all of these parameters can be estimated from existing data. Of particular interest is the estimated value of α because that will allow us to calibrate Producer's loss function and compare the cost of outages as perceived by Producer (whether OPEC, OPEC Core, or Saudi Arabia) to independent estimates of the global economic cost of outages. That comparison, in turn, will provide an indication of the extent to which OPEC's stabilization policy addresses the interests of the global economy.

As shown in Appendix 3, an immediate implication of (17) is that the expected loss and the value of incremental spare capacity are both decreasing in the size of the buffer. To evaluate (17), we shall need to calculate:

$$E[O_t|B] = Q_t^*(E[e^{S_t+\sigma_z z_t}|S_t + \sigma_z z_t > ln(B)] - B) \times \varphi_t(B) \quad (18)$$

Since we are considering a long-term policy of maintaining a buffer of optimal size, we will use the covariance-stationary process that satisfies (2) (see Hamilton (1994) p. 53). $S_t + \sigma_z z_t$ therefore follows a normal law with mean zero and variance $\sigma^2 = \sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2}$. We make the additional assumption that the call on Producer's crude in the absence of shocks remains stable and equal to Q^*.

We now use the following fact about the mean of a truncated lognormal distribution (Johnson et al., 1994, p.241):

$$E[e^{S_t+\sigma_z z_t}|S_t + \sigma_z z_t > ln(B)] = e^{\sigma^2/2} \frac{\Phi(\sigma - ln(B)/\sigma)}{\varphi(B)} \quad (19)$$

where: $\varphi(B) = 1 - \Phi(\ln(B)/\sigma)$ and where $\Phi(\cdot)$ represents the cumulative distribution of the standard normal law.

From (14) we therefore have:

$$E[O_t|B] = Q^* \left(e^{\sigma^2/2}\, \Phi\left(\sigma - \frac{ln(B)}{\sigma}\right) - B\left(1 - \Phi\left(\frac{\ln(B)}{\sigma}\right)\right)\right) \tag{20}$$

Upon substituting (20) into (17), we obtain the parametric form of the incremental value of spare capacity:

$$v = \left(e^{\sigma^2/2}\, \Phi\left(\sigma - \frac{ln(B)}{\sigma}\right) - B\left(1 - \Phi\left(\frac{\ln(B)}{\sigma}\right)\right)\right) \sum_{t=1}^{T} \frac{2\alpha(Q^*)^2}{(1+r)^t} \tag{21}$$

5. Revealed Preference for Spare Capacity

We now show how (21) and the principle of revealed preference can be used to infer the value of α, the behavioral parameter that reveals how much importance Producer attaches to outages.

Denote by h the marginal cost to provide 1 barrel per day of additional spare capacity. This is the capital expenditure to construct the capacity, plus maintenance cost, less any net revenue generated when that incremental barrel of spare capacity is used. If it is known that the cost is K to construct a production facility with peak production rate R, then the capital cost per daily barrel of spare capacity is given by $k = K/R$. In addition, for the additional spare capacity we have to account for the periodic maintenance costs (which are incurred even when spare capacity is not in use) and net financial gains (which are generated only when barrels are released from spare capacity). Any release generates marginal revenue that may be either positive or negative depending on the elasticity of residual demand. The net financial gain from each release is the marginal revenue minus the operating cost of producing the barrel. Over the life of the facility, the present value of the periodic maintenance costs is represented by m, while the present value of expected net financial gains is represented by f. Therefore, from the Producer's perspective the present value of total outlay for an incremental barrel of spare capacity is $h = k + m - f$.

If, consistent with the principle of revealed preference, we assume the historical size of the buffer has been optimized, then the marginal cost of the buffer must equal the incremental benefit. Since v is derived for a buffer defined in relative terms, at the optimized buffer size we must have: $hQ^* = v$,[9] which implies:

$$k + m - f = \left(e^{\sigma^2/2}\,\Phi\left(\sigma - \frac{ln(B)}{\sigma}\right) - B\left(1 - \Phi\left(\frac{ln(B)}{\sigma}\right)\right)\right)\sum_{t=1}^{T}\frac{2\alpha Q^*}{(1+r)^t} \tag{22}$$

A rational agent therefore sizes the buffer based on four factors: the size and frequency of shocks to demand, the precision with which agent can estimate those shocks, the importance attached to resulting outages (as represented by the parameter α of the loss function), and the cost of developing, maintaining, and operating spare capacity (including potential financial gains or losses). Given the estimated size of the buffer, (22) allows us to infer the loss function that would rationalize OPEC's investment in spare capacity:

$$\alpha = \frac{k+m-f}{\left(e^{\sigma^2/2}\,\Phi\left(\sigma - \frac{ln(B)}{\sigma}\right) - B\left(1 - \Phi\left(\frac{\ln(B)}{\sigma}\right)\right)\right)\sum_{t=1}^{T}\frac{2Q^*}{(1+r)^t}} \tag{23}$$

To investigate this issue empirically, the call on Producer's crude in the absence of shocks (Q^*) is estimated using the average values calculated previously in Section 3.3. We have previously discussed all other parameter estimates that appear in the denominator of (23), and now turn to the cost parameters in the numerator. The spare capacity that exists within OPEC can be drawn from many sources, including increased liftings from producing fields as well as additional production from idle facilities (if any). We assess the costs associated with incremental production via the simplifying assumption that it all comes from a dedicated buffer facility that is reserved for that specific purpose. Although this may depart somewhat from

[9] $h = k + m - f$ represents the cost of expanding the buffer by one barrel per day, which on average corresponds to $1/Q^*$ in percentage terms, whereas v represents the benefit from expanding the buffer by 1 percent.

reality, it provides a useful proxy for the more complicated and diffuse costs that may actually be incurred.

The capital cost of spare capacity (k) can be estimated using data from the most recent oil field development in Saudi Arabia, the Manifa field that is located in a shallow offshore setting. According to Henni (2013), the total capital cost to develop Manifa's production capacity of 900,000 barrels per day (which corresponds to our parameter R) is \$15.8 billion (which corresponds to our parameter K). Therefore, the capital cost per daily barrel of production capacity is given by $k = K/R =$\$17,500.

We assume that the maintenance cost remains constant throughout time and take it from QUE\$TOR, IHS's cost estimating software package that is a petroleum-industry standard. For an idle facility located in Saudi Arabia with 40 wells and combined production capacity of 200,000 barrels per day, QUE\$TOR estimates annual maintenance cost to be \$410 per daily barrel, or \$34.167 on a monthly basis. Thus, for an annual real discount rate of 4% in line with Pierru and Matar's (2014) findings for Saudi Arabia, the present value of maintenance costs over the 240-month life of the facility (which corresponds to our parameter m) would be: $\sum_{t=1}^{240} \frac{34.17}{(1.04)^{\frac{t}{12}}}$, which gives $m = \$5{,}670$ per daily barrel of capacity.

The incremental barrel of buffer capacity would only be used when there is an outage. For each group of producers, we consider the average price (\$45.24 per barrel) observed during the three Saudi outage months (from August to October 2004) and use that price (along with the usual formula for marginal revenue) to determine the parameter f as the sum of expected monthly net financial gains over the 240-month life of the facility discounted at 4%, assuming \$2 production cost per barrel[10]. We thus have:

[10] *Petroleum Intelligence Weekly* (2011) reports Saudi Aramco's group-wide average production cost as falling between \$2.00 and \$3.00 per barrel. Also note that we assume that the marginal revenue is received for each of thirty days within any month affected by an outage.

$$f = \sum_{t=1}^{240} \frac{\varphi(B)30\left(\left(1+\frac{1}{\varepsilon}\right)45.24-2\right)}{(1.04)^{\frac{t}{12}}}$$

The resulting estimates of the financial gains due to an incremental barrel of buffer are given by Table 4. f is negative when the residual demand is inelastic.

6. Assessment and discussion of the implicit loss function

After substituting the parameter estimates discussed above into (23), we obtain the estimated values of α shown in Table 5. These values represent the inferred weight that Producer attaches to outage events.

Using the estimated values of α, it is possible to evaluate the loss function that rationalizes Producer's choice of the buffer. Consider, for example, OPEC Core, for whom the expected size of an outage (when one occurs) is roughly half a million barrels per day.[11] By substituting the estimated values of α from Table 5 into the loss function (16), we can calculate the cost that the Core attaches to an outage of half a million barrels per day that lasts for 6 months. We get a cost of \$24.87 billion if the elasticity of global demand is assumed to be –1%, \$12.80 billion if elasticity is –3%, \$8.38 billion if elasticity is –5%, and \$1.34 billion if elasticity is –26%.

These results mean little when standing alone, but are of considerable interest when compared to other informed estimates of the economic cost that such an outage would impose on the global economy. For this purpose, we have applied Oxford Economics *Global Economic Model* to simulate the impact on global GDP of outages of varied size and duration. Appendix 4 provides the information on the model and the procedure we followed, and the

[11] From (15) and (20) we derive the expression of the (conditional) expected outage size: $E[O_t|B \cap O_t > 0] = \frac{Q^*}{\varphi(B)}\left(e^{\sigma^2/2}\,\Phi(\sigma - \ln(B)/\sigma) - B\varphi(B)\right)$. For OPEC Core this gives a size ranging between 0.50 and 0.53 mmb/d when global demand elasticity is lower or equal to -5% (0.82 mmb/d when elasticity is -26%).

results obtained are given in Table A4. According to the Oxford Economics model, a six-month outage of 0.5 mmb/d that is assumed to occur at the beginning of 2015 would reduce the present value of global GDP over the next five years by some \$22.36 billion, relative to the reference scenario. This loss lies near the top of the range of perceived costs that we believe the OPEC Core may have attributed to such an outage. Similar results hold for Saudi Arabia and for OPEC as a whole.

For differently sized six-month outages, Figure 3 compares the global cost inferred from the Oxford Economics model and the inferred cost that rationalizes OPEC Core's choice of buffer (assuming different values for elasticity of global oil demand). Even if global demand is assumed to be relatively elastic in the short term (-5%), the costs that rationalize OPEC Core's buffer comprise 40% of the "global" costs. This does not imply that the buffer is too small, only that the OPEC Core may for whatever reason be motivated[12] to address only a portion of the damage caused by oil shocks. We repeat an earlier point: the OPEC Core is but one piece of a much larger picture when it comes to neutralizing the impact of oil shocks. Whether it is reasonable to believe that 60% of the burden should be left for individual consumers, producers, government agencies, and multilateral organizations, (not to mention the other members of OPEC) to deal with, we are unable to say. We leave that debate to others. However, if global demand is assumed to be highly inelastic in the short term (-1%), the costs that rationalize the size of the Core's buffer actually exceed the level of global costs projected by the Oxford Economics model.

[12] Note that whatever motivated OPEC Core's decision to build its observed buffer, that decision has sheltered the global economy from potential outages. Let us for instance consider $\varepsilon_D = -5\%$. According to (19) and (20), if there had been no buffer ($B = 1$), the outage probability and conditional expected size would have increased from 3.3% to 50% and from 0.53 mmb/d to 1.09 mmb/d, respectively.

7. The Impact of Spare Capacity on Price Volatility

We evaluate the counterfactual price, P_t^0, that would have been obtained if Producer had produced Q_t^* instead of using spare capacity to offset shocks:

$$a_t(P_t^0)^\varepsilon e^{S_t} = a_t(P_t^*)^\varepsilon$$

It follows that:

$$ln\left(\frac{P_t^0}{P_{t-1}^0}\right) = ln\left(\frac{P_t^*}{P_{t-1}^*}\right) + \frac{S_{t-1}-S_t}{\varepsilon},$$

which implies:

$$var\left(ln\left(\frac{P_t^0}{P_{t-1}^0}\right)\right) = \sigma_{TP}^2 + \frac{1}{\varepsilon^2} var(S_t - S_{t-1}) \quad (24)$$

The covariance stationary process satisfying (2) is such that:

$var(S_t) = var(S_{t-1}) = \frac{\sigma_S^2}{1-\kappa^2}$, with $cov(S_t, S_{t-1}) = \frac{\kappa\sigma_S^2}{1-\kappa^2}$. Eq. (24) therefore gives:

$$var\left(ln\left(\frac{P_t^0}{P_{t-1}^0}\right)\right) = \sigma_{TP}^2 + \frac{2\sigma_S^2}{(1+\kappa)\varepsilon^2} \quad (25)$$

Producer's action stabilizes the price if $var\left(ln\left(\frac{P_t^0}{P_{t-1}^0}\right)\right) > var\left(\ln\left(\frac{P_t}{P_{t-1}}\right)\right)$. According to (9) and (25), this will occur if and only if:

$$\frac{2\sigma_S^2}{(1+\kappa)\varepsilon^2} > \frac{2\sigma_z^2}{\varepsilon^2}$$

This requires:

$$\sigma_S^2 > (1+\kappa)\sigma_z^2 \quad (26)$$

This condition highlights the fact that the Producer's ability to stabilize the price depends only on the precision of its estimate relative to the volatility and persistence of shocks; it does not depend on the elasticity of demand. Our estimate of the precision of Producer's estimate, however, is conditioned on the presumed elasticity, as shown in Table 2. Condition (26) therefore appears to be satisfied under certain of our elasticity scenarios (e.g., Saudi Arabia and OPEC Core when the price elasticity of global demand is presumed to be -1%, and for OPEC when the elasticity is presumed to be -1% or -3%), but not in others (see Table 3 and Appendix Tables A1-A3).

We now conduct an independent counterfactual experiment to examine the actual impact that Producer's utilization of spare capacity has had on price volatility over our sample period. This counterfactual experiment does not use any of our previous estimates or results. If Producer were content to produce only to meet its expected call, Q_t^*, then the quantity $\frac{\tilde{Q}_t+X_t}{B}$, instead of $\tilde{Q}_t$, would have been put on the market in each period. The counterfactual price must therefore satisfy:

$$a_t(P_t^0)^{\varepsilon}e^{S_t} = \frac{\tilde{Q}_t + X_t}{B}$$

After substituting for $a_t e^{S_t}$ using $a_t P_t^{\varepsilon_t} e^{S_t} = \tilde{Q}_t$, this gives:

$$ln\left(\frac{P_t^0}{P_{t-1}^0}\right) = ln\left(\frac{P_t}{P_{t-1}}\right) + \frac{1}{\varepsilon}ln\left(1 + \frac{X_t}{\tilde{Q}_t}\right) - \frac{1}{\varepsilon}ln\left(1 + \frac{X_{t-1}}{\tilde{Q}_{t-1}}\right) \quad (27)$$

Conditional on the presumed elasticity of demand, which is the only unobservable variable on the right-hand side, the volatility and trend of the counterfactual price series can be calculated from (27). The results are given in Table 6.

All the counterfactual volatilities exceed the historical volatility of 8.58%, which is to say that it appears OPEC's utilization of spare capacity has damped price movements. This indicates that condition (26) must be satisfied in practice. It also casts doubt on the presumption that the short-run elasticity of global demand deviates much from zero, since values that exceed $|\varepsilon_d| = 0.03$ produce estimates of σ_z that fail condition (26), which would be a contradiction of Table 6.[13] Our counterfactual experiment does not, of course, reveal the true identity of the

[13] Even if we treat the reported values of σ_Z as upper bounds on the estimation error and factor out the contribution due to volatility of the target price, per footnote 5, the adjusted estimates of σ_Z would still violate condition (26) and contradict the results shown in Table 6 unless the elasticity of global demand is close to zero. We note that Nakov and Nuño (2013) experience similar difficulty simulating historical price and output volatilities when a high demand elasticity (–0.26) is imposed on their model.

"Producer" whose actions have succeeded in stabilizing the market, be it Saudi Arabia, the Core, or OPEC acting all together. Based on other evidence, however, one may doubt that OPEC as a whole has played this role. Many OPEC members are reported to produce continuously at full capacity. Whether it has been Saudi Arabia or the OPEC Core acting as swing producer makes little difference, at least according to the estimates shown in Table 6. The counterfactual volatilities and trends are similar in both scenarios. Our estimates indicate that Saudi/Core intervention has damped oil price volatility by some 23% to 30% if the monthly elasticity of global demand is thought to be -0.03, or by 56% to 65% if the elasticity is thought to be -0.01.[14] Differences in assumptions regarding the elasticity of global demand and non-OPEC supply translate into big differences regarding the extent to which OPEC appears to have stabilized the market price. One's view of the impact of OPEC's efforts to stabilize the price clearly runs inversely to one's opinion about short-run elasticities of demand and supply, which makes the elasticity a worthy subject of further research.

8. Concluding remarks

We believe the present paper is the first attempt to fit a structural model to the behavior of OPEC's spare capacity. Although discussions of oil price dynamics frequently mention the influence of this factor, as yet there has been no quantitative investigation of the determinants of the size or impact of spare capacity. To that end, we have constructed a model having three main components: an autoregressive stochastic process by which the residual demand for OPEC oil is shocked, a separate stochastic process by which OPEC attempts to estimate the size of such shocks and offset them by regulating production from its buffer stock, and finally, a loss function which describes the benefits that rationalize the observed size of OPEC's chosen buffer—and which can be compared to independent assessments of the global economic cost of oil supply disruptions.

[14] The 23% reduction in volatility is calculated from Table 6 as (11.1%-8.6%)/11.1%, etc.

By estimating the parameters of this model using monthly data, we obtain plausible results regarding the size and persistence of demand and supply shocks that impact the global oil market, plausible estimates of the precision (or lack thereof) of OPEC's ability to estimate and offset shocks, and plausible estimates of the scope of OPEC's concern for the economic costs that oil price shocks impose on the global economy. We also perform a counterfactual experiment to calculate the apparent impact of OPEC's use of spare capacity during the past fifteen years. Depending on one's particular beliefs regarding the short-run elasticity of global demand and supply for oil, OPEC's impact may be viewed as large or small—but in all cases having at least partially offset shocks and stabilized the price. Under plausible assumptions regarding the elasticity of demand, OPEC's stabilizing influence appears to have been very substantial, with indications that Saudi Arabia may have acted as a supplier of last resort and, relative to the size of the residual demand for its oil, absorbed more shocks than the other OPEC members.

In this paper, we are abstracting from the impact of volatility on the formation of production capacity outside OPEC and on fuel substitution in demand. In addition, our study has focused on the past. There are many who would argue that OPEC has done little, of late, to stabilize the price of oil in the short term. We do not deny the many indications of a strategic change within OPEC in late 2014, following the end of our sample period. What remains to be seen is whether the market, and OPEC's role, has changed forever, or whether the market will gradually adjust to a new equilibrium in which OPEC continues to pursue its goal of market stabilization, albeit at a lower target price.

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Figure 1a: Price formation when buffer is sufficient to fully absorb shocks

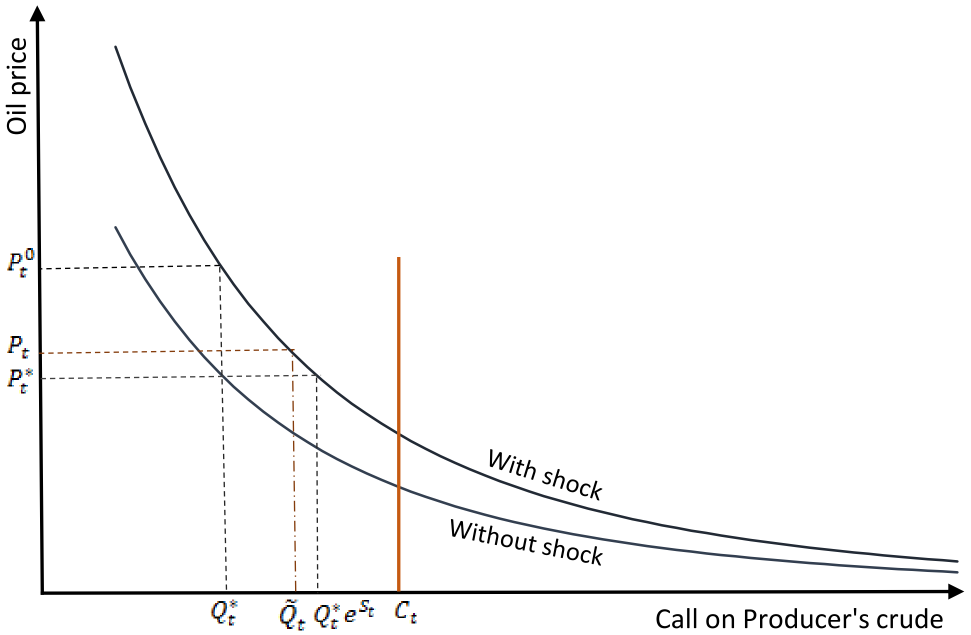


Figure 1b: Price formation when buffer is not sufficient to fully absorb shocks

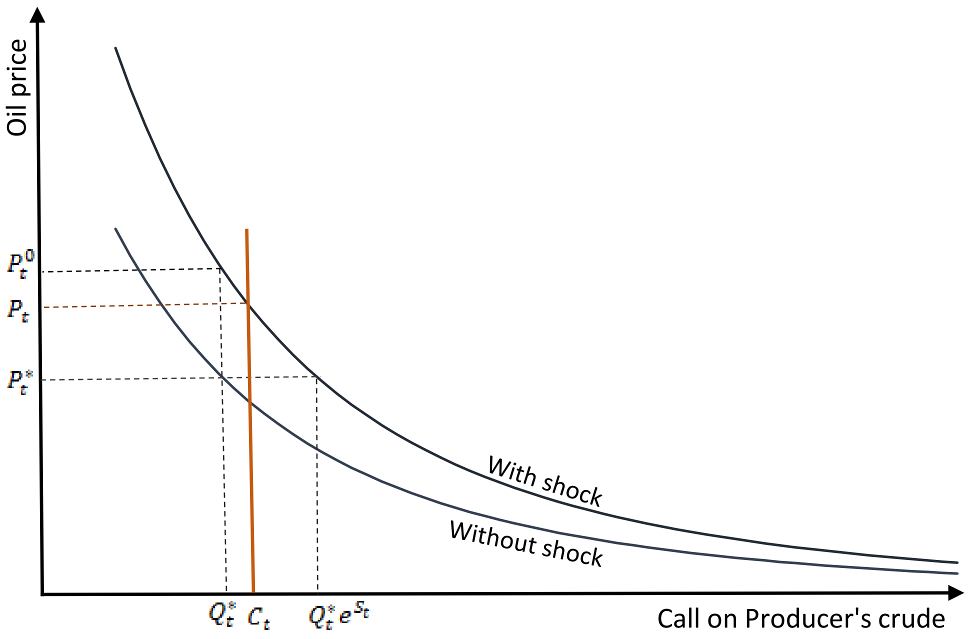


Figure 2: Spare capacity (million barrels/day)

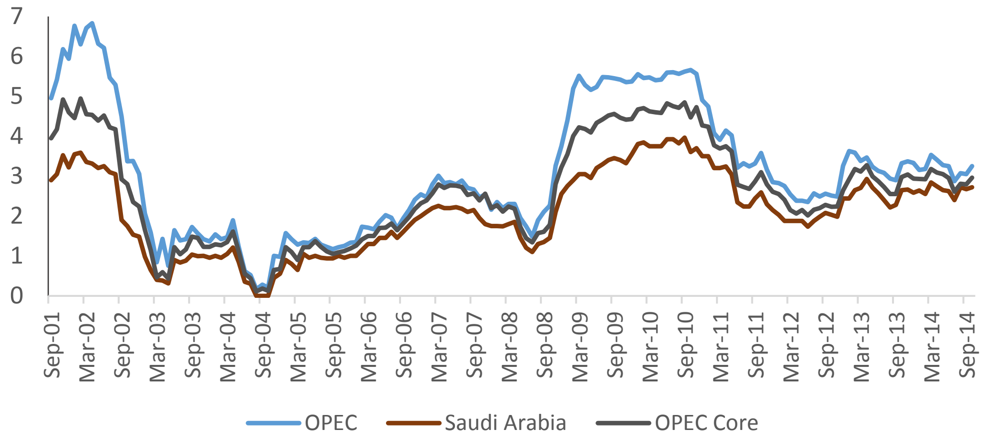
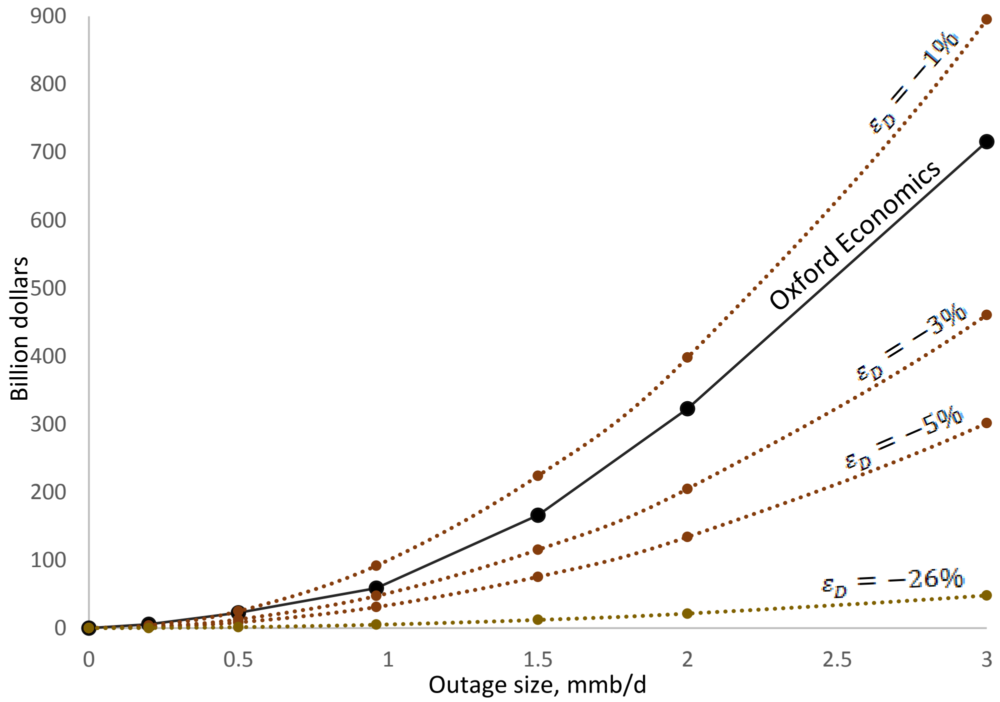


Figure 3: Estimated cost of oil supply outages

Dashed lines: inferred from OPEC Core's behavior; Solid line: inferred from Oxford Economics model.



	Saudi Arabia	OPEC Core	OPEC	Elasticity of global demand
Avg. production (mmb/d)	8.66	14.56	29.57	
Avg. market share	11.7%	19.7%	40.1%	
Implied elasticity of residual demand (ε)	-0.16	-0.09	-0.04	-1%
	-0.48	-0.27	-0.12	-3%
	-0.80	-0.46	-0.20	-5%
	-2.22	-1.32	-0.65	-26%

Table 1: Implied elasticity of residual demand (mmb/d=million barrels per day)

Elasticity of global demand	Saudi Arabia		OPEC Core		OPEC	
	$\hat{\sigma}_z$	mmb/d*	$\hat{\sigma}_z$	mmb/d*	$\hat{\sigma}_z$	mmb/d*
-1%	0.97%	0.084	0.55%	0.081	0.24%	0.072
-3%	2.92%	0.253	1.66%	0.242	0.73%	0.215
-5%	4.86%	0.421	2.77%	0.403	1.21%	0.358
-26%	13.47%	1.162	8.01%	1.162	3.94%	1.162

Table 2: Estimation error based on observed monthly price volatility
* $\hat{\sigma}_z$ times average own crude oil production.

	Saudi Arabia	*OPEC Core*	*OPEC*
σ_z	0.97%	0.55%	0.24%
κ	0.973 (0.017)	0.972 (0.016)	0.972 (0.018)
B	1.220 (0.082)	1.152 (0.061)	1.088 (0.037)
σ_S	2.3% (0.2%)	1.8% (0.1%)	1.2% (0.1%)

Note: standard errors in parentheses

Table 3: Maximum likelihood estimates if ε_D = -1%

Elasticity of global demand	Saudi Arabia	OPEC Core	OPEC
-1%	-$27,991	-$73,682	-$268,930
-3%	-$6,675	-$17,357	-$75,641
-5%	-$1,925	-$9,116	-$39,537
-26%	$11,784	$3,554	-$9,315

Table 4: Present value of net trading gains generated by holding an incremental barrel of buffer capacity (f)

Elasticity of global demand	Saudi Arabia	OPEC Core	OPEC
-1%	15.66	16.78	25.01
-3%	7.98	8.63	9.95
-5%	5.84	5.65	6.77
-26%	0.39	0.90	1.64

Table 5: Parameter α

	Saudi Arabia		OPEC Core		OPEC	
Elasticity of Global Demand	Volatility	Mean Return	Volatility	Mean Return	Volatility	Mean Return
-1%	19.4%	1.07%	24.3%	1.51%	33.2%	1.86%
-3%	11.1%	0.88%	12.3%	1.02%	14.7%	1.14%
-5%	9.9%	0.84%	10.4%	0.92%	11.6%	1.00%
-26%	8.9%	0.80%	9.1%	0.83%	9.2%	0.85%

Table 6: Counterfactual monthly volatility and mean price increase without OPEC buffer. Observed (factual) volatility = 8.6% and mean return = 0.78%.

Note: the following appendices are meant to be supplementary material in online-only form

Appendix 1. Log-likelihood maximization

From (12), by setting $d_t = -ln\left(1 + \frac{X_t}{\tilde{Q}_t}\right)$ we have:

$d_t = S_t + \sigma_z z_t - ln(B)$

$d_{t-1} = S_{t-1} + \sigma_z z_{t-1} - ln(B)$

Equivalently:

$S_t = d_t - \sigma_z z_t + ln(B)$

$S_{t-1} = d_{t-1} - \sigma_z z_{t-1} + ln(B)$

By replacing S_t and S_{t-1} in (2) we get:

$d_t - \sigma_z z_t + ln(B) = \kappa\big(d_{t-1} - \sigma_z z_{t-1} + ln(B)\big) + \sigma_S u_t$

which gives:

$$d_t = (\kappa - 1)ln(B) + \kappa d_{t-1} + \sigma_S u_t - \kappa\sigma_z z_{t-1} + \sigma_z z_t. \quad \text{(A1)}$$

We set:

$$W_t = \sigma_S u_t - \kappa\sigma_z z_{t-1} + \sigma_z z_t = w_t\sqrt{\sigma_S^2 + \sigma_z^2(\kappa^2 + 1)} \quad \text{(A2)}$$

where w_t is a standard normal variate.

(A1) can be rewritten:

$$d_t = (\kappa - 1)ln(B) + \kappa d_{t-1} + W_t \quad \text{(A3)}$$

with:

$$cov(W_{t-1}, W_t) = -\kappa\sigma_z^2 \quad \text{(A4)}$$

(A2), (A3) and (A4) allow for defining the log-likelihood function as the natural logarithm of the density of a multivariate normal law with a “tridiagonal” covariance matrix (variances on the main diagonal and covariance terms on the two adjacent diagonals). The estimates are the parameter values that maximize the log-likelihood function and their standard errors are derived from the Hessian matrix of the log-likelihood function. The MATLAB code is available upon request.

Appendix 2. Robustness of results to the value assumed for ε_D

	Saudi Arabia	OPEC Core	OPEC
σ_z	2.92%	1.66%	0.73%
κ	0.971 (0.018)	0.971 (0.016)	0.973 (0.016)
B	1.215 (0.077)	1.149 (0.058)	1.085 (0.036)
σ_S	2.3% (0.2%)	1.7% (0.1%)	1.1% (0.1%)

Note: standard errors in parentheses

Table A1: Maximum likelihood estimates if ε_D = -3%

	Saudi Arabia	OPEC Core	OPEC
σ_z	4.86%	2.77%	1.21%
κ	0.967 (0.019)	0.967 (0.018)	0.971 (0.017)
B	1.214 (0.070)	1.150 (0.053)	1.085 (0.033)
σ_S	2.3% (0.3%)	1.8% (0.2%)	1.1% (0.1%)

Note: standard errors in parentheses

Table A2: Maximum likelihood estimates if ε_D = -5%

	Saudi Arabia	OPEC Core	OPEC
σ_z	13.47%	8.01%	3.94%
κ	0.953 (0.027)	0.953 (0.023)	0.956 (0.021)
B	1.218 (0.055)	1.154 (0.041)	1.087 (0.026)
σ_S	2.4% (0.5%)	1.9% (0.3%)	1.2% (0.2%)

Note: standard errors in parentheses

Table A3: Maximum likelihood estimates if ε_D = -26%

<u>Appendix 3. Incremental value of spare capacity</u>

We calculate the expected loss as a function of the size of the buffer:

$$E[L|B] = \alpha E\left[\sum_{1}^{T} \frac{(O_t)^2}{(1+r)^t}\right] = \alpha\left[\sum_{1}^{T} \frac{E[max\{0,(e^{S_t+\sigma_z z_t} - B)Q_t^*\}^2]}{(1+r)^t}\right]$$

$$= \alpha \sum_{t=1}^{T} \frac{(Q_t^*)^2 \int_{ln(B)}^{\infty} \left(e^{\xi} - B\right)^2 g_t(\xi) d\xi}{(1+r)^t}$$

Let us now determine the value of increasing the size of the buffer. The incremental value, v, of spare capacity is given by the first derivative of the expected loss:

$$v = -\frac{\partial E[L|B]}{\partial B} = -\alpha \sum_{t=1}^{T} \frac{(Q_t^*)^2 \frac{\partial}{\partial B}\left(\int_{ln(B)}^{\infty} \left(e^{\xi} - B\right)^2 g_t(\xi) d\xi\right)}{(1+r)^t}$$

Since by application of Leibniz Rule:

$$\frac{\partial}{\partial B}\left(\int_{ln(B)}^{\infty} \left(e^{\xi} - B\right)^2 g_t(\xi) d\xi\right) = -2 \int_{ln(B)}^{\infty} \left(e^{\xi} - B\right) g_t(\xi) d\xi$$

We obtain (17): $v \;= 2\alpha \sum_{t=1}^{T} \frac{E[O_t|B]Q_t^*}{(1+r)^t}$

This implies:

$$\frac{\partial v}{\partial B} = 2\alpha \sum_{t=1}^{T} \frac{(Q_t^*)^2 \frac{\partial}{\partial B}\left(\int_{ln(B)}^{\infty} \left(e^{\xi} - B\right) g_t(\xi) d\xi\right)}{(1+r)^t} \;=\; -2\alpha \sum_{t=1}^{T} \frac{\varphi_t(B)(Q_t^*)^2}{(1+r)^t} \;< 0$$

Appendix 4. Use of Oxford Economics to simulate the impact of an oil supply shock

We use the Oxford Economics' Global Economic Model (http://www.oxfordeconomics.com/). The reference scenario is the version released in November 2014. To impose a supply shock of a given size and duration, we reduce the non-OPEC oil supply by the size of the shock for the duration considered, starting in the first quarter of 2015. In all scenarios, the OPEC Oil Supply is kept the same as in the reference scenario until the fourth quarter of 2016; i.e., OPEC is not allowed to make up the shortfall.

We observe global GDP for each quarter from 2015 to 2020 (virtually all impacts are realized during that interval) and the present value of cumulative GDP losses—relative to the reference scenario and expressed in real terms (2010 prices)—is computed using a quarterly discount rate corresponding to a 4% annual rate. The resulting cumulative GDP change is multiplied by Oxford Economics' world GDP deflator from year 2010 to year 2015 in order to be expressed in 2015 prices. The results are shown in Table A4.

Duration (Months)	Size (mmb/d)	Cumulative world GDP loss (Billion US dollars)
3	0.5	12.68
3	0.961	30.80
3	2	93.25
6	0.2	5.42
6	0.5	22.36
6	0.961	58.56
6	1.5	165.85
6	2	322.62
6	3	715.49
6	4	1239.94
6	5	1877.54
9	0.5	37.56
9	0.961	107.44
9	2	570.44
12	0.5	57.16
12	0.961	154.53
12	2	721.92

Table A4: Cumulative world GDP loss for various oil supply shocks (source: Oxford Economics)