OPEC's Pursuit of Market Stability

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ABSTRACT

We investigate attempts by the Organization of Petroleum Exporting Countries (OPEC) to stabilize the price of oil during the past fifty years. We first develop a novel decomposition of shifts in global demand and non-OPEC supply. This decomposition provides a fresh perspective on the debate over the relative importance of demand versus supply factors as determinants of previous price movements. When factoring in OPEC's production, the analysis suggests market stabilization efforts by OPEC. Using more detailed monthly data available only since 2001, we extend and refine Pierru, Smith, and Zamrik's (2018) analysis of OPEC's management of spare capacity to offset shocks to demand and supply. Although OPEC's attempt to identify and offset shocks has not been perfect, we nevertheless conclude that, overall, OPEC's use of spare capacity has achieved a significant reduction in the volatility of the price of oil. This has been particularly true during the recent OPEC+ period. We also provide an estimate of welfare gains to the global economy that result from OPEC's effort to reduce price volatility and show how these gains have been distributed geographically.

Keywords: OPEC, spare capacity, oil, price volatility, demand and supply shocks

https://doi.org/10.5547/2160-5890.9.2.apie

1. INTRODUCTION

Many economists believe that the Organization of Petroleum Exporting Countries (OPEC) wields considerable market power over the price of oil. Strong support is provided by the fact that OPEC members have produced 42% of all crude oil supplied to the market during the past fifty years and yet control more than 70% of remaining proved reserves (*BP Statistical Review of World Energy, 2019*). Recognizing this power, OPEC members meet regularly in the attempt to regulate production in line with their objectives, with an eye on potential price impacts and inventory movements. Indeed, maintaining stability in the world market is a prominent component of OPEC's self-stated mission.[1] In this paper, we examine the extent to which OPEC has succeeded in this mission.

Cursory inspection of historical price movements hardly suggests market stability. Figure 1 contrasts the evolution of the real price of oil during the past fifty years with corresponding changes in the volume of OPEC production. While the price has varied considerably from one

1. In OPEC statute: "The Organization shall devise ways and means of ensuring the stabilization of prices in international oil markets with a view to eliminating harmful and unnecessary fluctuations." Source: https://www.opec.org/opec_web/static_files_project/media/downloads/publications/OPEC_Statute.pdf

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year to another (coefficient of variation = 55%), its relation to the variation in OPEC output (which has also been substantial) is not clear. The simple correlation between annual changes in OPEC output and price is only 20% and not statistically significant. Of course, this abstracts from many other relevant factors that impact price, such as fluctuations in global oil demand and non-OPEC supply. Therefore, a deeper analysis is required to understand whether OPEC's adjustments to output have, in fact, damped variations in price that otherwise would have occurred.

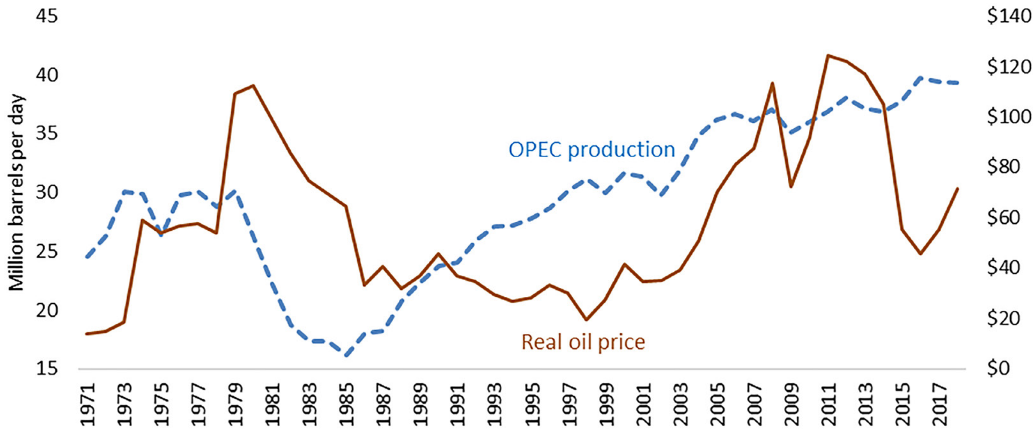

FIGURE 1

Movements in OPEC Production and the Real Price of Oil

Source: IEA's Oil Information Database (OPEC crude oil and natural gas liquids production), *BP Statistical Review of World Energy 2019* (real oil price in $2018).

Pierru, Smith, and Zamrik (2018), hereafter PSZ, were the first to provide a formal analysis of this question, by estimating a structural model that indicated the value of an additional barrel of OPEC's spare capacity and quantified the extent to which OPEC's management of spare capacity reduced price volatility. In this paper, we provide a novel decomposition of shifts in demand and supply that forms the backdrop for OPEC's attempts to stabilize the market. We then proceed to extend PSZ's analysis in two ways. First, by including the tumultuous years, 2015–2019, we update the counterfactual exercise that PSZ used to measure the success of OPEC's attempt to offset perceived shocks to demand and supply. In particular, we now incorporate the period beginning in 2014 when OPEC adopted a "market share" strategy, and check to see how it impacted market volatility, and we then compare that episode with the so-called OPEC+ regime of expanded producer coordination that followed. Second, in a major extension to PSZ, we provide an estimate of the value of OPEC's spare capacity to the global economy and report region-specific estimates of welfare gains that have resulted from OPEC's attempt to stabilize the market and reduce price volatility.

2. LITERATURE REVIEW

Few papers have attempted to assess OPEC's performance as a stabilizing force on the oil market, and those few do not focus on OPEC's use of spare capacity to offset shocks. Indeed, in arguing that OPEC production quotas contributed to price volatility, De Santis (2003) assumes the absence of spare capacity. In contrast, the papers by Nakov and Nuño (2013) and

Golombek, Irarrazabal, and Ma (2018) assume that OPEC output is chosen strategically in the manner of a Stackelberg or dominant firm. It is well known that such a firm finds it profitable to increase production when output from the competitive fringe goes down. These output adjustments are therefore a stabilizing factor, but that stabilization comes as a by-product of an ulterior motive, not by design. And, unlike our analysis, those papers do not discuss the cost or size of spare capacity that is required to implement this strategy.

Ratti and Vespignani (2015) discuss evidence that variation in OPEC production tended to offset supply shocks from non-OPEC producers prior to 1997 but not thereafter. They interpret this as OPEC's move to a more "market-oriented" strategy. They do not, however, investigate the size, cost, or management of OPEC's spare capacity during those years, nor its impact on price volatility. Fattouh (2006) and Difiglio (2014) recognize the potential impact of OPEC's spare capacity on price volatility but make no formal attempt to model or quantify its effect. Behar and Ritz (2017) and Baumeister and Hamilton (2019a) also recognize[2] the tendency by OPEC in general, and Saudi Arabia in particular, to offset demand and supply shocks, but do not analyze those efforts in detail. The most recent example of such behavior is Saudi Arabia's intent to cut production to offset falling demand due to the novel Coronavirus, as reported by Raval, Brower, and Sheppard (2020).

A broader literature has focused on the measurement and classification of oil market shocks that create unexpected price movements—the very phenomenon that stabilization would presumably address. These analyses, although varied in detail, all utilize Structural Vector Autoregressions (SVAR) to model expected market developments, as in Kilian (2009). The estimated residuals from structural equations are regarded as unexpected shocks to supply, demand, inventories, etc. However, identification of the structural parameters in these models has been tricky. Although each SVAR represents a structural economic model, estimation is actually performed on the reduced form of that structural model.[3] Therefore, structural parameters (i.e. elasticities, etc.) must be inferred from the estimated values of reduced form parameters. But if the model is under-identified, various combinations of structural parameters are equally consistent with the reduced form. Identifying restrictions are imposed to eliminate all but the "true" set of structural parameters. Exclusion restrictions take the form of assuming certain structural parameters are zero, and with a certain pattern in the case of recursive systems. Sign and set restrictions comprise assumptions about infeasible values of the structural parameters.

Caldara, Cavallo, and Iacoviello (2019) note that models with different identifying restrictions reach conflicting conclusions on the relative importance of supply and demand shocks. Kilian and Murphy (2012) show that models with different combinations of restrictions also produce very different dynamics. Baumeister and Hamilton (2019a, 2019b) also discuss limitations of the identifying assumptions in these models. One manifestation of weak identification has been the apparent over-estimation of the short-run elasticity of demand for oil.

2. Saudi efforts to stabilize the market have also been acknowledged in international forums, as shown by the 2012 G20 Leaders Declaration: "We welcome Saudi Arabia's readiness to mobilize, as necessary, existing spare capacity to ensure adequate supply." (http://www.g20.utoronto.ca/2012/2012-0619-loscabos.html). This statement was issued after Saudi Arabia increased its production in mid-2011 to compensate for the collapse in Libyan oil production.

3. Structural economic models reflect prior theoretical considerations that describe explicitly, via a set of equations (e.g. demand function, supply function), how economic agents or sectors react to their objectives and constraints. Such models are valuable because they identify the causal links that are believed to connect economic variables. The associated reduced form is an algebraic rearrangement of these equations that facilitates unbiased estimation, but to achieve that goal, only the impact of changes in a subset of the variables (i.e., exogenous variables whose values are determined outside the model) is considered. The estimated parameters that describe these impacts are combinations of the full set of underlying structural parameters; hence the need for identification.

According to Baumeister and Hamilton (2019a), SVAR estimates of the demand elasticity are "implausibly large," a conclusion with which we agree. However, even after they introduce techniques designed to strengthen identification, Baumeister and Hamilton's (2019a) own SVAR-based estimate of the short-run demand elasticity remains implausibly large.[4]

Much of the discussion in Caldara et al. (2019) and Baumeister and Hamilton (2019a, 2019b) regarding the estimation of SVAR models of the oil market pertains to the choice of priors for parameters and data series for the included variables. We suspect that a fruitful direction for future research would be to focus on the structural specification of the model itself. For example, existing SVAR studies do not allow emerging and developed economies to respond differently to oil market shocks. Aastveit, Bjørnland and Thorsrud (2015) and Gundersen (2020) suggest this may be responsible for the otherwise puzzling result that predicts a rise in global activity following an adverse oil price shock. Also, SVAR analyses do not typically include any modeling of OPEC; all suppliers are presumed to react to prices in the same way. This is not how energy economists have viewed the world oil market. Very likely, many supply "shocks" emanating from OPEC are endogenous (to offset anticipated price movements) whereas the "shocks" emanating from non-OPEC members are exogenous. We are aware of only three studies, Kolodziej and Kaufmann (2014), Ratti and Vespignani (2015), and Gundersen (2020) that estimate SVAR models where OPEC production is distinguished from that of non-OPEC producers, but they do not report an estimate of the implied demand elasticity to compare with models that aggregate OPEC and non-OPEC output. Kolodzeij and Kaufmann (2014) note that failure to distinguish between the two will lead to underestimation of the impact of supply shocks on the price of oil. Proper identification of shocks, and their impact on price, requires proper specification of market structure.

In response to the ongoing debate about how to identify shocks in SVAR models, Güntner and Henßler (2020) attempt to identify oil supply shocks based directly on historical episodes where production shortfalls in individual countries have arguably been due to truly exogenous events (e.g., strikes, wars, hurricanes, etc.). Their method, like the method we introduce in the next section, does not depend on the kind of identifying assumptions inherent in multivariate time-series models. Unlike us, however, their analysis attempts to identify only shifts that occurred unexpectedly, and only on the supply side of the market. Notably, their results are significantly and positively correlated with the results of state-of-the-art SVAR models, but they acknowledge that the correlation is modest, roughly 0.20 at monthly frequency.

3. HISTORICAL DECOMPOSITION OF SHIFTS IN SUPPLY AND DEMAND

The call for OPEC's oil at a given price equals the global quantity of oil demanded less the quantity that would be supplied by non-OPEC producers at that price. These two quantities, demand and non-OPEC supply, shift throughout time for various reasons (such as population and income for demand, depletion and technological innovation for supply). If OPEC were attempting to stabilize the price of oil, it would have to adjust its production to meet the ever-changing call for its oil. We begin our analysis by identifying, from a long-term perspective, the shifts in demand and non-OPEC supply that have impacted the call on OPEC.

4. Rather than basing the ensuing analysis on doubtful SVAR estimates of demand and supply elasticities, we directly impose values from the literature that seem reasonable to us.

To do so, we extend the decomposition suggested by Smith (2009). We first offer a general formulation of this procedure, which differs in several important ways from existing decompositions of oil demand and supply shocks found in the SVAR-based literature.

Let Q_t be the quantity variable of interest (global oil demand or non-OPEC supply) in year *t*. Q_t is assumed to depend on the current price of oil and the *K* previous prices, and on a scaling factor, d_t, whose variation through time captures the shifts we want to identify:

$$Q_t = d_t f\left(P_t,\ P_{t-1}, \ldots, P_{t-K}\right) \tag{1}$$

… where P_t is the price of oil in year *t*, and f is a function that captures the price effects.

If throughout time the oil price were to remain constant at a fixed level, P_f, it follows from Equation (1) that the quantity in year *t* would be $\bar{Q}_t$, with:

$$\bar{Q}_t = d_t f\left(P_f,\ P_f, \ldots, P_f\right) = Q_t \frac{f\left(P_f,\ P_f, \ldots, P_f\right)}{f\left(P_t,\ P_{t-1}, \ldots, P_{t-K}\right)}. \tag{2}$$

Let us select a base year *b* to serve as a benchmark and choose P_f to match the relevant price of that base year: $f\left(P_f,\ P_f, \ldots, P_f\right) = f\left(P_b,\ P_{b-1}, \ldots, P_{b-K}\right)$. Using Equation (2), the series of counterfactual quantities $\bar{Q}_t$ associated with P_f can be calculated, and the index $\frac{\bar{Q}_t}{Q_b}$ can be constructed. Because $\frac{\bar{Q}_t}{Q_b} = \frac{d_t}{d_b}$, this index measures the magnitude of shifts in demand or supply relative to the base year. To be clear, the index measures shifts in the demand or supply function itself, not the change in the quantity demanded or supplied in any particular year due to a change in price.

A merit of this simple decomposition procedure is its transparency. The only assumption that matters is that demand and supply functions are time invariant except for the shift in the scaling factor d_t that affects all quantities proportionately (i.e., the function *f* remains the same over time). Functions for which the elasticity is constant along the curve and time invariant, for example, satisfy this condition. Whereas papers in the SVAR-based literature also typically assume that model parameters are time-invariant, they require many additional and varied assumptions to define model structure and identify parameters. As we discussed previously, those assumptions and the resulting estimates have been problematic. Further, whereas our decomposition identifies historical shifts whether they were anticipated or not, the SVAR-based literature focuses on unexpected shifts and attempts to quantify the relative contribution of supply and demand shocks to the fluctuations of the oil price. This distinction is reasonable and important because shifts in oil supply and demand are sometimes expected and sometimes not. There may be good reasons why policymakers would want to know about the price impact of unexpected shifts in demand and supply. However, to gain a retrospective understanding of the main drivers of observed price movements, it does not really matter if a historical shift was anticipated or not. The market will clear, and the price must adjust to restore equilibrium.

To perform our historical decomposition, we follow the same implementation procedure as Smith (2009), by assuming a constant elasticity functional form with Q_t depending on the average price observed during the last three years:

$$f\left(P_t,\ P_{t-1}, \ldots, P_{t-K}\right) = \left(\frac{P_t + P_{t-1} + P_{t-2}}{3}\right)^{\varepsilon} \tag{3}$$

… where ε denotes the long-run price elasticity for the quantity variable of interest. And like Smith (2009), we assume that the long-run price elasticity is –0.3 for global oil demand and 0.3 for non-OPEC supply.[5] Figure 2 shows the resulting global demand and non-OPEC supply indices, $\overline{Q}_t / Q_b$, with base year 1976, over the 1971–2018 period.

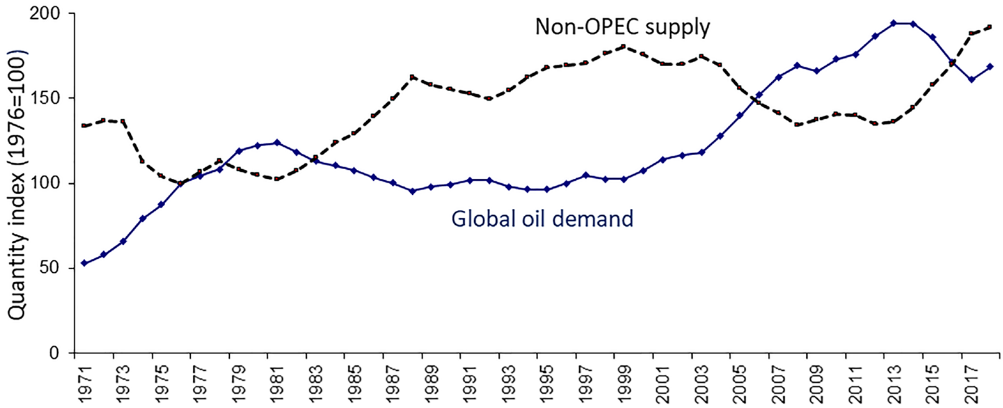

FIGURE 2

Estimated Shifts in Oil Demand and Non-OPEC Supply

Source: Authors' calculations (see discussion in text). IEA's Oil Information Database (world total oil demand, world and OPEC crude oil and natural gas liquids production), *BP Statistical Review of World Energy 2019* (real oil price in $2018).

This historical decomposition highlights several major cycles that have affected prices, and presumably OPEC production decisions. For example, between 1971 and 1981, demand grew by 134% whereas non-OPEC supply shrank by 23%. This put strong potential upward pressure on the price of oil, of which we know in retrospect OPEC took advantage. The pattern reversed between 1981 and 1988, during which time demand shrank by 23% while non-OPEC supply grew by 58%. Between 1989 and 1998 the market remained fairly stable, with demand growing by 5% and non-OPEC supply growing by 12%. Then, between 1999 and 2013 the pattern reversed again: demand grew by 90% (largely fueled by China and the developing economies) while non-OPEC supply shrank by 24%. As in the cycle of 1971–1982, this pushed the real price of oil to unprecedented heights, as seen in Figure 1. Finally, during the most recent cycle, demand fell by 17% between 2014 and 2017, whereas non-OPEC supply grew by 30% (due mostly to the development of unconventional oil resources in the United States). The influence of other notable events can also be discerned in Figure 2, like the temporary decrease in demand due to the Great Recession in 2009, and the impact of the Asian financial crisis during 1997–1998. Overall, by the end of 2018, global demand for oil had more than tripled relative to 1971, whereas non-OPEC supply had grown by only 43%.

These results provide a fresh perspective on the debate over the relative importance of demand versus supply factors as determinants of previous price movements. For example, based on their SVAR analyses, Kilian and Murphy (2012, 2014) and Baumeister and Kilian (2016) contend that the price increase of 2003–2008 was caused almost entirely by shifts in

5. Our assumption regarding the long-run demand elasticity is consistent with estimates of the annual demand elasticity (–0.18, –0.32) reported by Kheiravar, Lawell, and Jaffe (2019), and with the range of estimates of the long-run elasticity of demand for oil by the G7 countries (–0.18, –0.45) reported by Cooper (2003). In any event, our conclusions are robust with respect to reasonable variations in the assumed elasticities.

global oil demand. However, according to Baumeister and Hamilton (2019a), supply shocks that accumulated during 2007–2008 accounted for much of that price increase. According to our analysis, global demand increased by 43% during 2003–2008, whereas non-OPEC supply decreased by 23%. Over that period, OPEC production rose by 17%, not enough to compensate for the combined shifts in demand and supply. And between 2006–2008, we find that global demand grew by 11% whereas non-OPEC supply fell by 9%, which is consistent with Baumeister and Hamilton's (2019a) conclusion that supply shocks during 2007–2008 accounted for much of the price increase.

Regarding the decrease in oil prices observed post-2014, our results occupy middle ground. In contrast to Caldara et al. (2019) and Gunderson (2020) who emphasize the increasing role of shale oil, Baumeister and Hamilton (2019a) conclude that supply shocks comprised less than half the story behind the price collapse observed between 2014 and 2016. Our decomposition shows that global demand decreased by 11% between 2014 and 2016 whereas non-OPEC supply increased by 18%. We conclude that both demand and supply were instrumental in the price decrease, but the impact of shale oil appears to have been the larger factor.

We now look at the gap, implied by Figure 2, between the global quantity of oil demanded and the quantity supplied by non-OPEC producers, assuming hypothetically that the real price remained constant and equal to the average level recorded during the whole period. Taking 1976 as the base year fixes the real price at $56.43 a barrel (i.e., the average price over 1974–1976), which is almost the same as the average price over the entire period 1969–2018 of $56.69 a barrel. The gap represents the call on OPEC that would have been required to keep the price of oil fixed at the historical average. This means that the indicated call on OPEC, shown in Figure 3, represents the quantity of oil that OPEC would have had to produce to eliminate price variability, while keeping the same average level of oil price. It is a simple matter to see how OPEC's actual output compared to this call. Were the call ever to exceed (fall below) OPEC's actual output, the market price would exceed (fall below) the average level. In those instances, the implication is that OPEC could perhaps have done more to stabilize the price (if it so desired) by adjusting output accordingly.

While recognizing that OPEC may not have wanted to maintain a constant market price over the entire interval, it is still possible to identify three "epochs" that appear in Figure 3. During the first epoch, 1978–1985, OPEC consistently produced less than the call, which raised the real price of oil above its long-run average. During the second epoch, 1987–2005, OPEC production consistently exceeded the call, which depressed the real price below the long-run average. During the third epoch, 2006–2016, OPEC again consistently produced less than the call, which again pushed the real price of oil above its long-run average. We also note that in the two most recent years, 2017–2018, OPEC's output has been roughly equal to the call, which had the effect of returning the real price of oil to its long-run average.

Are the two series shown in Figure 3 related? The ADF and KPSS unit root tests conclude that both series are non-stationary in level and stationary in first difference. A battery of statistical tests (trace test, maximum eigenvalue test, small sample corrected trace test, bootstrapped trace test, Engle-Granger test, bounds test) collectively reject the hypothesis that the series are cointegrated in levels. However, we find Granger causality running from the annual change in the call on OPEC to the annual change in OPEC production, a predictive relationship significant at the 2% level. Moreover, a variance decomposition analysis using different forecast horizons shows that on average 19% of the annual change in OPEC production is due to the change in the call on OPEC.

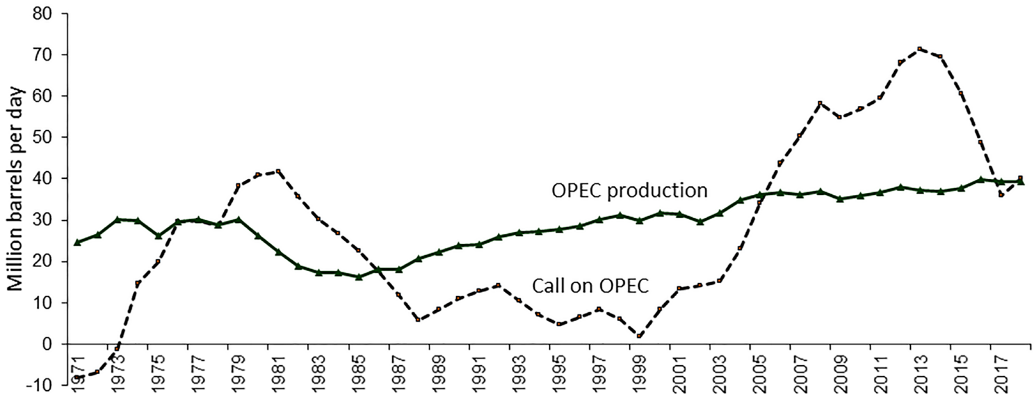

FIGURE 3
The Call on OPEC (holding price constant)

Source: Authors' calculations for the call on OPEC (counterfactual global demand less counterfactual non-OPEC supply, based on Equation (2) giving $\overline{Q}_t$ and assuming that the price remained constant and equal to its long-run average).

This result provides support to the hypothesis that, to a certain extent, OPEC has adjusted its production in response to changes in the call on its oil. It therefore suggests market stabilization efforts by OPEC during the past fifty years. There are many possible reasons why the link would not have been stronger. For example, it seems unlikely (and inconsistent with anecdotal evidence) that OPEC would have chosen to defend a single constant real price of oil over this entire historical interval. Rather, OPEC may have attempted to stabilize the price at varying target levels during certain subintervals. The imperfect correlation can also possibly be attributed to OPEC's inability to accurately anticipate or respond to each of the shifts. To better understand OPEC's reaction to the call, we now turn to PSZ's analysis, which incorporates these complicating factors.

4. THE ROLE OF SPARE CAPACITY IN STABILIZING THE MARKET

The demand for OPEC oil equals, by definition, global demand less non-OPEC supply. PSZ assume OPEC demand to be a constant elasticity function of current and past prices:

$$Q_t\left(P_t, P_{t-1}, \ldots, P_{t-K}\right) = a_t\left(\prod_{k=0}^{K} P_{t-k}^{\omega_k}\right)e^{S_t} \tag{4}$$

where ω_0 is the short-run (monthly) elasticity[6] of demand, $\sum_{k=0}^{K}\omega_k$ is the long-run elasticity, a_t is an exogenous, time-varying scaling factor, and e^{S_t} is a lognormally distributed random variable representing the effects of the shocks affecting the demand for OPEC's crude oil. S_t is assumed to follow a first-order autoregressive process:

$$S_{t+1} = \kappa S_t + \sigma_S u_t \tag{5}$$

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

where $u_t \sim iid\, N(0,1)$, σ_S represents the standard deviation of innovations on the shocks, and κ is the shock persistence. OPEC is assumed to form an unbiased but noisy estimate of the shock, given by $S_t + \sigma_z z_t$, where z_t is independent of S_t and $\sim iid\, N(0,1)$. This "estimation error" recognizes that the economic, industrial or geopolitical information necessary to accurately judge the size of shocks is never fully available and limits OPEC's ability to stabilize the price. Although OPEC may track inventory movements, futures prices, and many other sources of market intelligence in order to identify shocks to demand and supply, there will always remain some estimation error. As part of our research, we obtain an estimate of σ_z, which governs the size of these errors. In fact, z_t may be a composite of various factors (e.g., political, operational, logistical, etc.) that, in addition to estimation error, influence OPEC's production in any given month. If OPEC wishes to achieve a particular target price, P_t^*, given what has gone before, it would choose to produce the quantity:[7]

$$\tilde{Q}_t = a_t \left(P_t^{*\omega_0} \prod_{k=1}^{K} P_{t-k}^{\omega_k} \right) e^{S_t + \sigma_z z_t}. \tag{6}$$

Based on their analysis of production and spare capacity data over the period from September 2001 through October 2014 (the IEA does not report spare capacities on a regular basis prior to September 2001), PSZ estimate that, on average, OPEC holds production capacity that exceeds its expected call by 9%. This is the size of the buffer required to avoid outages, i.e., episodes where unexpectedly high demand would exceed OPEC's ability to tame the market and defend its target price. But, due to the stochastic nature of the demand for OPEC oil—sometimes exceeding and sometimes falling below the expected call—the actual amount of spare capacity (production capacity not in use) fluctuates from month to month. In addition to OPEC's spare capacity, many private remedies exist to mitigate oil market shocks, including precautionary inventories, strategic reserves, hedging, and long-term contracts. We do not attempt to model any of these factors that are external to OPEC but recognize that the shock to the residual demand for OPEC oil is net of adjustments and measures taken by other participants in the market.

This paper extends the period studied to include the tumultuous years 2015–2019. The amount of spare capacity held collectively by members of OPEC, and by Saudi Arabia individually, is shown in Figure 4. According to the International Energy Agency (IEA), these data represent effective spare capacity: i.e., defined as incremental production volumes that can be reached within 30 days and sustained for 90 days. The majority of OPEC's spare capacity has been held by Saudi Arabia, and apart from September 2019 (following the attacks on Saudi Aramco's facilities) and a brief period in late summer of 2004, it appears that OPEC's spare capacity has been sufficient to avoid outages.

7. Like PSZ we do not take any particular stance about the level of the target price and how it is determined by OPEC. Implicit in our analysis is the notion that OPEC plays a dual role in managing the oil market—on one hand regulating production consistent with some target price level, on the other hand further regulating production (via spare capacity) to offset short-run shocks that would otherwise create deviations from that target price. These dual objectives are not completely unrelated because any decision to raise or lower the target price could temporarily increase price volatility. However, PSZ argues that OPEC has not changed the target price very frequently, which limits volatility emanating from that source. In any event, the results we report in the next section indicate that the overall impact of OPEC's market management has substantially decreased price volatility.

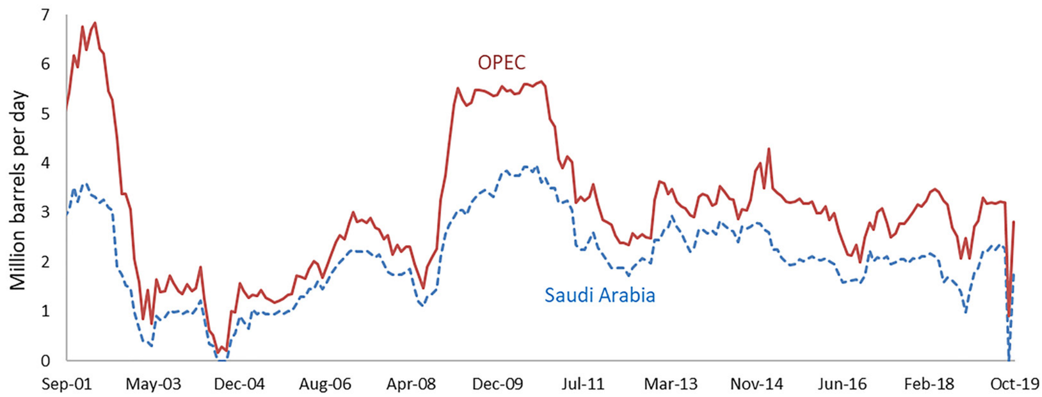

FIGURE 4
Monthly Variation in OPEC's Spare Capacity

Source: PSZ until October 2014, IEA Monthly Oil Market Reports.
Note: Spare capacity data were not reported in the Monthly Oil Market Reports during 2017, but we received those data by email (Peg Mackey, 30/09/2019).

If, hypothetically, OPEC had not employed its spare capacity to offset shocks to its demand, then its spare capacity would have remained unused, with volume equal to a constant 9% of the call in the absence of shocks. PSZ use this insight to build a counterfactual picture of OPEC monthly production during the period of 2001–2014 assuming there had been no attempt to stabilize the price. And, given an estimate of the elasticity of global demand for oil, a counterfactual history of price is obtained by calculating the price adjustments that would have been required for the market to absorb those incremental barrels, whether positive or negative. A comparison of the actual and counterfactual price series over our extended sample period is shown in Figure 5, based on the assumption that the monthly price elasticity of global demand for oil is –3% (the value found by Caldara et al. (2019) with a narrow instrumental variable panel regression).

Whereas the actual price volatility measured on a monthly basis from September 2005 through October 2014 was 8.4%, the volatility of the counterfactual price series over the same period is substantially higher; 13.3% if we assume the demand elasticity is –3%. This conclusion is robust with respect to the assumed elasticity of global demand, with the counterfactual volatility ranging between 10.7% and 36.8% if the demand elasticity is alternatively assumed to vary between –5% and –1%. The least of these results implies that OPEC's attempt to stabilize the market during 2001–2014 cut price volatility by at least one-fourth (10.7% ÷ 8.4% = 1.27), and the impact may be judged to have been much larger depending on one's opinion about the elasticity of short-run demand.

Figure 5 raises the question how prices might have behaved if OPEC had not initiated its "market share" strategy in late 2014. Many analysts interpreted this move as an attempt to squeeze high-cost U.S. shale oil out of the market. Behar and Ritz (2017) interpret it as a rational, profit-maximizing strategy for OPEC to pursue once U.S. shale oil output had reached a "tipping point." As a result of this strategy, OPEC production reached an all-time high by the end of 2016 and oil prices crashed. Not only did the price fall precipitously as OPEC pushed its oil on the market, but based on the data in Figure 5, price volatility also increased markedly: rising from 8.4% (before November 2014) to 12.5% for the duration of the market share campaign (November 2014-December 2016). The counterfactual price volatility, 12.1%, is

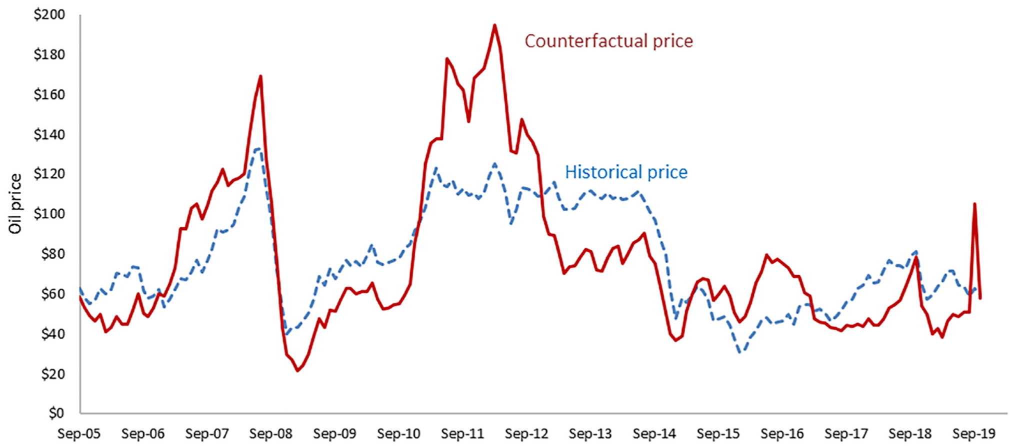

FIGURE 5
Comparison of Actual and Counterfactual Crude Oil Prices

Source: U.S. Energy Information Administration (average monthly Brent crude oil spot price) and authors' calculations. Prices are in nominal terms. The counterfactual price (with no spare capacity policy) assumes -3% monthly price elasticity and -30% long-run price elasticity for global demand (same absolute values for the elasticity of non-OPEC supply) and is computed using the equation on p.190 in PSZ. The initial counterfactual price determines the scale of the counterfactual series, but it depends on unknown long-term effects of (prior to sample) past changes in spare capacity. Since our goal here is to visualize the reduction in price volatility, we choose the initial counterfactual price so that the mean of the counterfactual price series is equal to the mean of the historical price series. Like PSZ we discard the first 48 monthly counterfactual prices to avoid short-term distortions.

almost identical, which suggests that there was no attempt to stabilize the price during the market share campaign.

Thereafter, beginning with OPEC's decision to abandon the market-share campaign and the new agreement among the OPEC+ nations[8] to adopt production cuts as of January 2017, the historical price volatility dropped substantially during the January 2017–October 2019 period, to 7%, whereas counterfactual prices would have resulted in a much higher volatility of 19.3%. This shows that during the OPEC+ period, OPEC's management of its spare capacity has led to a substantial reduction in the volatility of the oil price.

It is also fair to ask how the result of OPEC's market share campaign differs from the counterfactual scenario in which OPEC would have held production and spare capacity steady. If indeed the purpose of the market share strategy was to squeeze some shale oil producers out of business, we should expect to see lower prices under that approach than under the benign alternative of steady production to meet OPEC's expected call. Figure 5 confirms this view, with actual prices falling significantly below the counterfactual prices from May 2015 through the end of 2016.

5. ESTIMATED VALUE AND ECONOMIC IMPACT OF OPEC'S SPARE CAPACITY

Investments in spare capacity provide value to the global economy because deploying the production held in response to disruptions saves costs that result from price volatility.[9] PSZ

8. OPEC+, also known as the "Vienna Group," refers to the combination of OPEC members and ten non-members (principally Russia, Mexico, and Kazakhstan) who were parties to the Declaration of Cooperation announced on December 10, 2016.

9. In addition to the value generated by offsetting shocks to the global oil market, OPEC's spare capacity may have certain

provide a formula for the marginal value of spare capacity, i.e. the incremental value generated by adding an additional barrel to the existing OPEC's buffer, and examine the magnitude of spare capacity. This is especially relevant given that the absolute level of spare capacity is now less than it was two decades ago, despite oil demand having grown 25 percent. The 'right size' for the buffer is when the cost of adding a marginal barrel per day of capacity is equal to the expected GDP loss without that additional barrel of capacity. PSZ's analysis confirms that OPEC's buffer, estimated at 2.64 million barrels per day (1.94 million barrels per day for Saudi Arabia), has been in line with global macroeconomic needs.

In this section, we provide an assessment of the value of OPEC's spare capacity, measured in terms of expected welfare gains, for some of the world's large economies. The formula giving the total value of the spare capacity buffer is derived in the appendix, by elaborating on PSZ's analytics. This value is calculated by subtracting the GDP losses that the economy under consideration would expect to suffer even when OPEC deploys the buffer from the expected losses without the buffer. The model does not differentiate between losses due to supply versus demand shocks. It is assumed that an outage of given size will cause the same loss of GDP whether it originates from a demand spike or supply shortfall. In principle, that assumption could be relaxed by a straightforward extension of the loss function (see Appendix equation A2). However, making that model operational would require detailed knowledge of the separate stochastic properties of global demand versus non-OPEC supply shocks. Given the ongoing debate within the profession regarding the proper identification and measurement of these shocks, we have not attempted to generalize our model in this direction. As a practical matter, we have calibrated the loss function based on a hypothesized outage due to a negative supply shock that emanates from non-OPEC producers.

The value of OPEC's buffer increases with respect to the buffer size, the magnitude and persistence of the shocks to offset, and the GDP losses incurred when there are production shortfalls. It is diminished by OPEC's estimation error which limits the efficiency of using spare capacity.

As discussed in the appendix, using data covering the period from September 2001 through October 2014, PSZ provide estimates for all the parameters mentioned above, except for the GDP losses incurred by the regional economies when there are production shortfalls (PSZ report figures aggregated at the world level only). The regional GDP losses are available in the simulations of the economic impact of oil supply shortfalls that were developed by PSZ using the Oxford Economics' Global Economic Model. The resulting annual value of OPEC's buffer is given by Table 1. Since the value also depends on OPEC's estimation error, it factors in possible miscalculations when measuring the shocks to offset.

The annual value of OPEC's buffer amounts to around 0.2% of the world's GDP in 2015. In terms of regional impacts, one suspects that the value of OPEC's spare capacity would be highest for economies that are oil-intensive and that import a large share of their total oil consumption. This is borne out in Table 1, which reports a much larger benefit accruing to the European Union than to China, for example. This is consistent with the fact that the European economy is significantly more oil-intensive than the Chinese economy and depends more heavily on imports to supply that oil than does China. The U.S. economy is more oil-intensive than either China or Europe, but also depends much less (during the years of our simulation)

indirect effects, for example by discouraging the development of high-cost substitutes for OPEC oil, or through its potential to discipline and maintain cohesion within OPEC. Although these additional impacts may be of significant value to OPEC, we do not include them in our assessment of the value of OPEC's spare capacity to the global economy.

TABLE 1
Annual Value of OPEC's Buffer (billion US dollars expressed in 2015 prices).

World	USA	China	EU
175.3	39.4	30.9	59.4

Calculations are detailed in the appendix. We use the parameters estimated by PSZ when the monthly price elasticity of global oil demand is assumed to be -3%.

on imports of crude oil and refined products than these other regions.[10] Other aspects of regional economies undoubtedly impact their vulnerability to oil shocks, but based on the Global Economic Model's simulation results, we believe these two factors play an important role.

6. CONCLUSION

The attempt to stabilize the world oil market is not a small or easy task. Disruptions to demand and supply are both large and frequent. Shocks come from many directions, including war, natural disasters, labor strikes, political and economic sanctions, financial crises, port closures, technological innovations, and the uneven pace of global economic growth. The market reaction to each shock is magnified by the highly inelastic nature of both crude oil demand and supply. This means that large price movements are required to close relatively small gaps that would otherwise develop between demand and supply. Conversely, even small mistakes in judging and attempting to offset such gaps can trigger large and unintended price movements that potentially undermine the attempt to reduce volatility.

OPEC's mission to stabilize the market is therefore difficult. Indeed, it is entirely possible that, despite best efforts, the attempt could fail. Our results indicate, however, that OPEC has succeeded to a limited but important degree in its attempt to employ spare capacity to offset shocks and stabilize the price of oil. Although the size of each monthly offset may have been subject to fairly large error (of estimation as well as execution), the magnitude of those errors has nevertheless been contained within the bounds necessary for stabilization to succeed. Although OPEC's adoption of a "market share" strategy did temporarily increase volatility beginning in late 2014, this was a purposeful departure from previous attempts to stabilize the market. During the previous fourteen years (2001–2014, for which data are available to permit an estimate), we conclude that OPEC's management of spare capacity decreased price volatility substantially, by at least 25% relative to what it otherwise would have been. In fact, the reduction may have been as much as 50%, depending on one's opinion regarding the price elasticity of short-run global demand and non-OPEC supply of oil.

How have OPEC's efforts to stabilize the market affected the world economy? Simulation of Oxford Economics' macro model of the global economy indicates that a single, sudden and unexpected loss of 1.5 million barrels per day from global supply, sustained for 6 months, would generate cumulative GDP losses of $166 billion over the next five years. Of course, shorter and/or smaller disruptions would impose smaller losses. After factoring in the estimated size, probability, and frequency of such shocks to global demand and supply and

10. During the period of our simulation (2015–2020), Europe consumed 12% more oil per dollar of GDP than did China. GDP data are from the World Bank's report of PPP GDP; consumption and import data are from *BP Statistical Review of World Energy 2019*.

allowing for the imprecision in OPEC's effort to offset them, we find that OPEC's attempt still produces an expected annual increment to global GDP equivalent to some $175 billion.

Although it is possible to distinguish the contribution of individual OPEC members to the organization's effort to stabilize the market, we have not addressed that subject in the present paper—primarily to avoid an overly long and repetitious narrative. However, it is well known that the principal contributions have come from Saudi Arabia and other members of the "OPEC Core."[11] As PSZ demonstrated, most members outside of this core group have produced at full capacity almost continuously since 2001. PSZ therefore investigated specifications of the model used here that focus on the management of spare capacity held solely by Saudi Arabia or the OPEC Core and those results produce even stronger evidence of success in reducing price volatility.

By making non-OPEC supply more price responsive, has the rise of U.S. shale oil diminished the significance of OPEC's spare capacity for the oil market and the global economy? Because shale oil production comprises only a small fraction of total non-OPEC supply, 11% as of 2019,[12] its impact on the elasticity of that supply is limited, despite the fact that shale oil itself may have a much higher short-run supply elasticity than conventional oil. For example, if we assume that shale oil is five times more elastic than conventional, that would only raise the monthly elasticity of total non-OPEC oil from 3% to 4.3%, within the range of values considered by PSZ. Therefore, PSZ's results imply that the development of shale oil has not significantly reduced the need for and value of large buffer capacity by OPEC.

In recent years, as the oil market has expanded, stabilizing the price of oil has required more international cooperation. Our counterfactual scenario (assuming there had been no attempt to stabilize the price of oil) shows that during the agreement between the OPEC+ nations (the interval from January 2017 to October 2019 in our sample period) the management of OPEC's spare capacity has considerably reduced oil price volatility, from 19.3% to 7%. The demand shock caused by the coronavirus pandemic is not captured in our sample period. Countering such a large shock requires international collaboration much beyond OPEC producers.

ACKNOWLEDGMENTS

For comments on an earlier version of this paper, the authors are grateful to Bassam Fattouh, Mahmoud El-Gamal, James Hamilton, Amy Jaffe, participants in the journal's online symposium, "Brent, Oil Supply and Demand, and Geopolitics," and to three anonymous reviewers. The authors are also thankful to Abdulelah Darandary, Fakhri Hasanov and Jeyhun Mikayilov for their input. The views expressed herein are those of the authors and do not necessarily reflect the views or policies of KAPSARC, Southern Methodist University, or any other organization.

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11. As defined by PSZ and others, the "OPEC Core" includes Kuwait, the UAE, and, until December 2018, Qatar—in addition to Saudi Arabia.

12. This calculation is based on 2019 data from the U.S. Energy Information Administration, which reports U.S. tight oil production of 7.7 million barrels per day (mmb/d) and non-OPEC conventional production of 61.3 mmb/d.

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APPENDIX

We use PSZ's notations and definitions. The value $V(B)$ of the spare capacity buffer B is given by the expected loss without the buffer less the expected loss with the buffer:

$$V(B)=E[L\,|\,1]-E[L\,|\,B] \tag{A1}$$

(Note that the absence of a buffer translates into B = 1 since PSZ set OPEC's production capacity equal to B times the call on OPEC's oil in the absence of shocks.)

From Equation (16) in PSZ we have:

$$E[L\,|\,B]=\alpha\sum_{t=1}^{T}\frac{E\left[O_t^2\,|\,B\right]}{(1+r)^t} \tag{A2}$$

where r is the real risk-adjusted periodic discount rate and α is a parameter that reflects the economic losses caused by the outage O_t. The value attributed to α will depend on the regional economy that is considered. The loss function is increasing in the square of the size of individual shortfalls and additive regarding their occurrence.[13] Let Q_t^* be the volume that OPEC would have to produce in period t to defend the target price in the absence of shocks, as defined by Equation (3) in PSZ. The outage, O_t, is the difference between the quantity that should be put on the market to reach the target price, $Q_t^* e^{S_t}$, and the quantity that is actually put in the market, $min\left(Q_t^* e^{S_t+\sigma_z z_t}, Q_t^* B\right)$, when the latter is smaller than the former. We have:

$$O_t = max\left(Q_t^* e^{S_t} - Q_t^* e^{S_t+\sigma_z z_t}, Q_t^* e^{S_t} - Q_t^* B, 0\right)$$

The interpretation is that there are two possible sources of outage: when the buffer is not used efficiently (because of OPEC's estimation error) and when the buffer is not sufficient to avoid outages. We focus on supply outages and ignore potential impacts on the economy when OPEC puts more oil on the market than necessary (i.e., when $min\left(e^{S_t+\sigma_z z_t}, B\right) \geq e^{S_t}$).

$$\begin{aligned} E\left[O_t^2\,|\,B\right] &= Q_t^{*2} E\left[\left(e^{S_t}-B\right)^2 \,|\, e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right] \times pr\left(e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right) + \\ & Q_t^{*2} E\left[\left(e^{S_t}-e^{S_t+\sigma_z z_t}\right)^2 \,|\, e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right] \times pr\left(e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right). \end{aligned}$$

We introduce the following notations:

$$b_1 = \left(ln(B) - \frac{\sigma_S^2}{1-\kappa^2}\right) \Big/ \sqrt{\sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2}}\,,\; b_2 = ln(B) \Big/ \sqrt{\sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2}}\,,\; b_3 = 2b_1 - b_2\,.$$

13. Using the 17 values reported in PSZ's Table A4, we regress the cumulative GDP loss against both the size and the duration of the shock, with all variables in natural logarithm. The coefficient estimates are 2.22 for the constant, 1.84 for the slope coefficient of the size, and 1.24 for the slope coefficient of the duration. The adjusted R-squared is 99%. We do not here report the standard errors since the regression is performed on results of a deterministic model. With these estimates, we are comfortable with assuming in the analytical approach that the GDP loss depends on the square of the size of outage and is proportional to its duration.

$$b_4 = \left(\sigma_z^2 / \sqrt{\sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2}} \right) - b_3 \text{ , } b_5 = 2b_4 + b_3 \text{ .}$$

$$R = \begin{bmatrix} 1 & \frac{1}{\sqrt{1+\left(1-\kappa^2\right)\frac{\sigma_z^2}{\sigma_S^2}}} \\ \frac{1}{\sqrt{1+\left(1-\kappa^2\right)\frac{\sigma_z^2}{\sigma_S^2}}} & 1 \end{bmatrix}, U = \begin{bmatrix} 1 & \frac{1}{\sqrt{1+\frac{\sigma_S^2}{\left(1-\kappa^2\right)\sigma_z^2}}} \\ \frac{1}{\sqrt{1+\frac{\sigma_S^2}{\left(1-\kappa^2\right)\sigma_z^2}}} & 1 \end{bmatrix}.$$

We start by calculating $E\left[\left(e^{S_t} - B\right)^2 \mid e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B \right] \times pr\left(e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right)$. Since we are evaluating a long-term policy of maintaining a buffer, as PSZ (p.184) we use the covariance-stationary process that satisfies Equation (5), and S_t follows a normal law with mean zero and variance $\frac{\sigma_S^2}{1-\kappa^2}$.

$\begin{pmatrix} S_t + \sigma_z z_t \\ S_t \end{pmatrix}$ follows the bivariate normal law $N\left(0,\Sigma\right)$, with $\Sigma = \begin{bmatrix} \sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2} & \frac{\sigma_S^2}{1-\kappa^2} \\ \frac{\sigma_S^2}{1-\kappa^2} & \frac{\sigma_S^2}{1-\kappa^2} \end{bmatrix}$.

R is the correlation matrix derived from Σ.

The formula for the truncated moments of a multivariate lognormal law is given by Arismendi (2013, p.53). We introduce the distribution function $\Phi_2\left(a_1, a_2, R\right)$ that gives the probability that $x_1 \geq a_1$ and $x_2 \geq a_2$ when $\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$ follows the bivariate normal law $N\left(0, R\right)$. We have:

$$\Phi_2\left(a_1, a_2, R\right) = \int_{a_1}^{\infty}\int_{a_2}^{\infty} \frac{e^{-\frac{1}{2}x'R^{-1}x}}{2\pi\left|R\right|^{\frac{1}{2}}} dx_1 dx_2$$

where $\left|R\right|$ is the determinant of R.

Using Arismendi's notation α for the order of the truncated moment, setting $\alpha = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ gives:

$$E\left[e^{S_t} \mid e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right] \times pr\left(e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right) = \Phi_2\left(b_1, \frac{b_1}{R_{1,2}}, R\right) e^{\frac{\sigma_S^2}{2\left(1-\kappa^2\right)}} .$$

Using Arismendi's notation, setting $\alpha = \begin{pmatrix} 0 \\ 2 \end{pmatrix}$ gives:

$$E\left[e^{2S_t} \mid e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right] \times pr\left(e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right) = \Phi_2\left(b_3, \frac{b_3}{R_{1,2}}, R\right) e^{\frac{2\sigma_S^2}{1-\kappa^2}} .$$

Using Arismendi's notation, setting $\alpha = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ gives:

$$E\left[B^2 \mid e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right] \times pr\left(e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right) = \Phi_2\left(b_2, \frac{b_2}{R_{1,2}}, R\right) B^2,$$

which gives:

$$E\left[\left(e^{S_t} - B\right)^2 \mid e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right] \times pr\left(e^{S_t+\sigma_z z_t} \geq B, e^{S_t} \geq B\right) =$$

$$\Phi_2\left(b_3, \frac{b_3}{R_{1,2}}, R\right) e^{\frac{2\sigma_S^2}{1-\kappa^2}} - 2B\Phi_2\left(b_1, \frac{b_1}{R_{1,2}}, R\right) e^{\frac{\sigma_S^2}{2\left(1-\kappa^2\right)}} + \Phi_2\left(b_2, \frac{b_2}{R_{1,2}}, R\right) B^2$$

We follow a similar procedure to compute $E\left[\left(e^{S_t} - e^{S_t+\sigma_z z_t}\right)^2 \mid e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right] \times$ $pr\left(e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right)$.

To apply Arismendi's formula, we note that the bivariate normal law $\begin{pmatrix} -S_t - \sigma_z z_t \\ -\sigma_z z_t \end{pmatrix}$ has the covariance matrix $\begin{bmatrix} \sigma_z^2 + \dfrac{\sigma_S^2}{1-\kappa^2} & \sigma_z^2 \\ \sigma_z^2 & \sigma_z^2 \end{bmatrix}$ and the correlation matrix U. We obtain:

$$E\left[e^{2S_t} \mid e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right] \times pr\left(e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right) = \Phi_2\left(-b_3, 0, U\right) e^{\frac{2\sigma_S^2}{1-\kappa^2}},$$

$$E\left[e^{2S_t+\sigma_z z_t} \mid e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right] \times pr\left(e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right) = \Phi_2\left(b_4, \sigma_z, U\right) e^{\frac{1}{2}\left(\sigma_z^2 + \frac{4\sigma_S^2}{1-\kappa^2}\right)},$$

and

$$E\left[e^{2\left(S_t+\sigma_z z_t\right)} \mid e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right] \times pr\left(e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right) = \Phi_2\left(b_5, 2\sigma_z, U\right) e^{2\left(\sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2}\right)}$$

This gives:

$$E\left[\left(e^{S_t} - e^{S_t+\sigma_z z_t}\right)^2 \mid e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right] \times pr\left(e^{S_t+\sigma_z z_t} \leq B, e^{S_t} \geq e^{S_t+\sigma_z z_t}\right) =$$

$$\Phi_2\left(-b_3, 0, U\right) e^{\frac{2\sigma_S^2}{1-\kappa^2}} - 2\Phi_2\left(b_4, \sigma_z, U\right) e^{\frac{1}{2}\left(\sigma_z^2 + \frac{4\sigma_S^2}{1-\kappa^2}\right)} + \Phi_2\left(b_5, 2\sigma_z, U\right) e^{2\left(\sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2}\right)}$$

We therefore have:

$$E\left[O_t^2 \mid B\right] = Q_t^{*2}\left(\left(\Phi_2\left(b_3, \frac{b_3}{R_{1,2}}, R\right) + \Phi_2\left(-b_3, 0, U\right)\right) e^{\frac{2\sigma_S^2}{1-\kappa^2}} + \Phi_2\left(b_5, 2\sigma_z, U\right) e^{2\left(\sigma_z^2 + \frac{\sigma_S^2}{1-\kappa^2}\right)} + \right.$$

$$\left. \Phi_2\left(b_2, \frac{b_2}{R_{1,2}}, R\right) B^2 - 2B\Phi_2\left(b_1, \frac{b_1}{R_{1,2}}, R\right) e^{\frac{\sigma_S^2}{2\left(1-\kappa^2\right)}} - 2\Phi_2\left(b_4, \sigma_z, U\right) e^{\frac{1}{2}\left(\sigma_z^2 + \frac{4\sigma_S^2}{1-\kappa^2}\right)}\right) \tag{A3}$$

The annual value of the buffer can be calculated using Equations (A1), (A2) and (A3). To compute the right-hand side of Equation (A3), we use the estimates provided by PSZ in Table A1 and p. 183: $\kappa = 0.973, \sigma_S = 1.1\%, \sigma_z = 0.73\%, B = 1.085, Q_t^* = 30$ mmb/d. To calculate the right-hand side of Equation (A2) we take $T = 12$ and, as in PSZ, $r = 0.04/12$. We also need an estimate of α for each regional economy. We use the GDP loss function obtained from the same simulations as in PSZ's Table A4. All regional costs of supply shortages are calculated using the same procedure as the one followed by PSZ for the world. To assess the coefficient α for each regional economy, we regress the cumulative GDP loss incurred by the regional economy against both the size and the duration of the shock, fixing the slope coefficients for the size and the duration to 2 and 1 respectively, with all variables in natural logarithm. α is the exponential of the estimated constant. We find $\alpha = 14.05$ for the world, $\alpha = 3.16$ for the USA, $\alpha = 2.48$ for China and $\alpha = 4.76$ for the European Union. The annual value of the buffer for each regional economy is determined with Equation (A1) and reported in Table 1.

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