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Oil Market Stabilization: The Performance of OPEC and Its Allies

Hossa Almutairi,[a] *Axel Pierru,*[b] *and James L. Smith*[c]

ABSTRACT

We examine the influence of OPEC+ on the level and volatility of oil prices. By extending Pierru et al.'s (2018, 2020) modeling framework, we are able to distinguish OPEC's particular role and impact from that of its Allies—those countries who joined with OPEC at the end of 2016 in the attempt to stabilize the market. In addition to corroborating earlier results regarding the impact of OPEC's management of spare capacity prior to 2017, we now present an analysis of how the concerted actions by the larger community of OPEC+ members have affected prices, including during the tumultuous period in which the COVID-19 pandemic took hold. We find that OPEC+'s efforts to stabilize the market reduced price volatility by up to one half, both before and during the pandemic. We attribute most of that reduction to OPEC's own actions whereas the impact of the Allies' efforts was mostly to support the price level. In that vein, OPEC+'s management of spare capacity barely impacted the average price over the pre-pandemic period, but, by countering the price collapse caused by the pandemic demand shock, lifted the average price by $35.70 from May 2020 through August 2021.

Keywords: OPEC+, Oil price, Volatility, Spare capacity, Market stabilization, COVID-19

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1. INTRODUCTION

This paper assesses OPEC's success in stabilizing the price of oil during the so-called OPEC+ era and compares the results with OPEC's performance in earlier periods.[1] We also estimate the separate contribution of the so-called Allies who joined with OPEC in December 2016 to create OPEC+, and we contrast the success of pre-pandemic stabilization efforts with results from the unprecedented pandemic period that followed. The two main contributions of our analysis are (1) measuring the extent to which cooperation provided by non-OPEC oil producers impacted OPEC's ability to stabilize prices, and (2) assessing the extent to which OPEC was able to offset the unprec-

1. OPEC+ refers to the combination of OPEC members and ten non-members (Azerbaijan, Bahrain, Brunei, Kazakhstan, Malaysia, Mexico, Oman, Russia, South Sudan, and Sudan) who were parties to the Declaration of Cooperation announced on December 10, 2016. In this paper, we refer to these ten non-OPEC countries as the Allies.

a King Abdullah Petroleum Studies and Research Center (KAPSARC), P.O. Box 88550, Riyadh 11672, Saudi Arabia. E-mail: hossa.mutairi@kapsarc.org.

b Corresponding author. King Abdullah Petroleum Studies and Research Center (KAPSARC), P.O. Box 88550, Riyadh 11672, Saudi Arabia. E-mail: axel.pierru@kapsarc.org.

c Edwin L. Cox School of Business, Southern Methodist University, Dallas, TX 75275. E-mail: jsmith@smu.edu.

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edented demand shocks related to COVID-19. Both contributions are achieved via the specification and estimation of a structural model of the interaction between OPEC and its Allies. Our analysis extends from 2001 to 2021, which is an eventful interval that allows us to contrast the implications of cooperative and non-cooperative behavior on the part of the Allies and also allows us to compare OPEC's success in stabilizing prices before and during the pandemic. To our knowledge, this is the first paper to address these questions.

The economic significance of any attempt to stabilize the price of oil derives from the extremely inelastic global demand for, and supply of oil. Any shock to oil supply or demand requires a relatively large price adjustment to effect a response that is sufficient to restore market equilibrium. The economic impact of the price jumps that result is amplified by oil's position as the leading commodity in international trade (Smith, 2009). Jaffe and Soligo (2002), Parry and Darmstadter (2003), Kilian (2008), Baumeister and Gertsman, (2013), and Brown and Huntington (2015) are but a few of the many papers that describe the economic costs due to volatile oil prices. Although OPEC's attempt to stabilize the price of oil is but one part of a larger effort that includes private inventories, corporate hedging, and various consuming-country government stockpiles, nevertheless OPEC's role is unique 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.

Recent developments have complicated OPEC's long-standing attempt to stabilize the price of oil. In particular, we mention the surprising and ample volumes of new low-cost unconventional oil coming from non-OPEC producers, the willingness of new Allies (OPEC+) to cooperate with OPEC's efforts to balance supply and demand, and the very disruptive effects of the global pandemic that not only depressed demand for oil to an unprecedented degree but also challenged, at least temporarily, continued cooperation among the members of OPEC+. Although Pierru, Smith, and Zamrik (2018) found that OPEC managed to substantially reduce price volatility prior to 2015 by using its spare capacity to offset market shocks, further investigation is required to know whether this remains to be the case, and to determine how much the cooperation of the Allies has contributed to the effort. Therefore, we present here a substantial extension of this line of research that incorporates each of the new complexities and examines how they have impacted the success of OPEC's continued efforts to stabilize market prices.

The most fundamental extension we provide is to incorporate the participation of the Allies that since January 2017 have formed part of OPEC+. As in Pierru, Smith, and Zamrik (2018), we model OPEC as attempting, albeit imperfectly, to offset perceived monthly shocks to the global demand and supply of oil.[2] But, the impact of the Allies' shut-in capacity on OPEC's own production decisions, and ultimately on the market price, is now represented explicitly within the model. We also incorporate the impact of OPEC's historical decision to not offset shocks in April 2020 when renewal of the OPEC+ agreement was delayed by the onset of the pandemic. These extensions to the model, along with a longer time series through August 2021 for estimation of model parameters, allow us to contrast the success of efforts by OPEC+ to stabilize prices before the pandemic and after, and also to distinguish the stabilizing impact of OPEC's own production decisions from that of its Allies. Thus, we do not model OPEC+ as a homogeneous aggregate, as it is usually discussed, but instead differentiate the separate role and market impact of OPEC from those of its Allies. To our knowledge, this is the first paper to do so.

Our analysis distinguishes four market regimes that have prevailed during the past two decades: First, the Commodity Boom (September 2001-February 2015) during which OPEC alone

2. See also Pierru, Smith, and Almutairi (2020), and Almutairi, Pierru, and Smith (2021).

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attempted to stabilize price, then the Market Share Campaign[3] (March 2015-December 2016 + April 2020) during which OPEC openly refrained from price stabilization, followed by the Pre-Pandemic era of OPEC+ (January 2017-February 2020) which saw OPEC and its Allies acting together for the first time to offset weakening global demand and surging supply, and concluding with the Pandemic era of OPEC+ (March 2020-August 2021) during which OPEC and its Allies have tackled the unprecedented disruptions caused by Covid-19. The actual volumes of spare capacity held by OPEC and its Allies[4] during these periods are shown in Figure 1, which illustrates the dramatic increase in spare capacity during the pandemic. Our monthly data on oil production comes from IEA. We also use IEA's monthly reports of spare capacity held by OPEC members. The monthly spare capacity of Allies, beginning in 2017, was provided by Energy Intelligence.

Figure 1: Monthly spare Capacity held by OPEC+

Source: 1) OPEC's spare capacity: until October 2019: IEA's data used in Pierru et al. (2020), November 2019–August 2021: IEA's Oil Market Reports and email exchanges with the IEA. 2) Allies' spare capacity: email exchanges with Energy Intelligence.

We analyze each of these four regimes through the lens of a single underlying structural model—which we estimate from monthly data spanning the entire period, September 2001–August 2021. The long time series allows us to reliably measure OPEC's ability (albeit imperfect) to per-

3. There has been some debate about the onset of OPEC's Market Share Campaign. Arezki and Blanchard (2014) cite Saudi Arabia's October 2014 decision to not offset increasing output from other producers, and OPEC's subsequent decision to maintain production, as a major cause of the late-2014 drop in the price of oil. Baffes et al. (2015) and Khan (2017) voice similar opinions. However, Baumeister and Kilian (2016) show that most of the price decline that occurred in the second half of 2014 was already predictable as of June—and by implication could not have been caused by the later announcements of Saudi Arabia and OPEC. OPEC's production actually declined by 1.3% between October 2014 and February 2015 as the global economy weakened, which is consistent with efforts to stabilize the price and which raises the question of when OPEC's so-called "Market Share" campaign actually began. Only in March 2015 did OPEC's production rise to the previous level of October 2014, after which OPEC output increased by 13.5% through November 2015. Based on these considerations, we treat March 2015 as the beginning of the Market Share Campaign.

4. Note that analysts have traditionally considered that non-OPEC production and capacity have been closely aligned. For this reason, until the COVID-19 crisis the IEA had not had historical spare capacity figures for non-OPEC countries (source: email exchange with IEA on August 19, 2020). This view is consistent with information provided by S&P Global Platts (email exchange on December 10, 2020) which shows zero spare capacity for OPEC's Allies prior to January 2017.

ceive shocks and to offset them using spare capacity. The model also facilitates the calculation of various counterfactual pricing scenarios that show the implications if OPEC, or the Allies, or both, had failed to participate in the effort to stabilize the market at various times.

2. LITERATURE REVIEW

This paper contributes to a line of research that attempts to measure the success of OPEC's proclaimed mission[5] of stabilizing the price of oil. Pierru, Smith, and Zamrik (2018) introduced a simpler version of the model we use here that indicated the extent to which OPEC successfully deployed spare capacity to offset perceived shocks to global oil demand and supply during the period 2001–2014. Pierru, Smith, and Almutairi (2020) and Almutairi, Pierru, and Smith (2021) applied that model—still using parameter estimates based on the 2001–2014 data—to confirm OPEC's retreat from stabilization during the so-called Market Share Campaign. They also estimated the value of OPEC's spare capacity buffer by calculating the expected increment to global GDP generated by OPEC's attempt to stabilize the oil price. In this paper, we not only extend the period of estimation by seven years and test the robustness of the model and earlier conclusions against the severe challenge posed by the coronavirus pandemic, but most importantly we now also include data on volumes of production that were shut-in by OPEC's Allies since the OPEC+ agreement was reached in December 2016. We produce three new counterfactual price series that indicate the extent to which OPEC's actions, and those of its new Allies, have impacted oil prices both before and during the pandemic.

Much has been written about the circumstances that led to the formation of OPEC+, but there have been very few attempts to quantify its subsequent impact on the level and volatility of the price of oil. The agreement that brought OPEC+ into existence was adopted in late 2016 (OPEC 2016a, OPEC 2016b) in response to a prolonged decline that saw the spot price of Brent crude oil fall by 52% between June 2014 ($111.80) and December 2016 ($53.31).[6] That decline has been attributed in part to the impact of the U.S. shale oil boom but also to the unexpected softening of global demand for crude oil (Baffes et al. 2015, Baumeister and Kilian 2016, Kilian 2017, Frondel and Horvath 2019). It has also been suggested that OPEC's internal decision to maintain production in the face of low prices (OPEC 2014) created dismal expectations in late 2014 that contributed further to the price decline (Arezki and Blanchard 2014, Baffes et al. 2015, Khan 2017). Some of these points have been debated, however: Kilian (2016) finds no evidence that U.S. fracking was a major cause of the decline in oil prices that occurred during the last half of 2014, and Baumeister and Kilian (2016) find no evidence to support the claim that OPEC's November announcement contributed to the price decline.

Market analysts have put forward several possible explanations of OPEC's decision to maintain output in 2014 and let prices slide. One hypothesis is that, by maintaining a low price, OPEC hoped to squeeze high-cost oil producers, notably U.S. shale oil (Behar and Ritz, 2017). Dale (2016) and Ansari (2017) reject the argument that OPEC's objective was to "wage war" on U.S. shale, positing instead that OPEC recognized shale oil to be a permanent shock of a lasting type that it could not offset in the same manner that a short-term shock would be treated. But Ansari (2017)

5. In OPEC statute: "The Organization shall devise ways and means of ensuring the stabilization of prices in international oil markets". Source: https://www.opec.org/opec_web/static_files_project/media/downloads/publications/OPEC_Statute.pdf.

6. U.S. Energy Information Administration. The series of spot Brent crude oil prices is available at https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=M.

also suggests that OPEC may have been simply taking some time to learn about the resilience of shale oil output to low prices—that is, observing an experiment to generate knowledge that would be important to the success of any long-term strategy.

Many observers have described OPEC's acquiescence in low oil prices during 2014–2016 as a defense of "market share,"[7] but that period ended abruptly with the formation of OPEC+ at the beginning of 2017. Based on game-theoretic considerations, Volkmar (2019) concludes that due to the increased price responsiveness of non-OPEC supplies (particularly shale oil) and constraints faced by some OPEC members, market stabilization became impossible by 2017 without the participation of Russia. Using a different approach, Gundersen and Hvinden (2021) rationalize the formation of OPEC+ in 2017 on the basis of a Markov-switching model that accounts for cooperative versus non-cooperative operating modes. Behar and Ritz (2017) also identify factors they believe rationalize OPEC's switch from cooperative to non-cooperative behavior at the onset of the market share campaign, but their analysis ends before the subsequent switch back to cooperative behavior with the formation of OPEC+ at the end of 2016.

Fattouh and Mahadeva (2013), Ansari (2017), and Gundersen and Hvinden (2021) emphasize the difficulty of successfully capturing OPEC behavior with a unified model over any long period of time, primarily due to changing market conditions and the resulting evolution of OPEC behavior. However, Dale (2016), Ansari (2017), and Khan (2017) also argue that, despite changing market conditions, it appears that OPEC's fundamental objective of stabilizing the market has never changed during the past 20–30 years. As will become clear in the next section, we agree with both points of view. By incorporating four distinct regimes in our analysis that account for changing market conditions and temporary shifts in OPEC's behavior, we are able to specify an otherwise unified model of OPEC's effort to offset market shocks, and obtain robust and stable estimates based on twenty years of heterogeneous but informative data.

Almost all of the research we have identified above attempts to identify the factors that led to OPEC's decision to launch the market share campaign in 2015 and to the subsequent formation of OPEC+, but there has been little research regarding the actual impact of OPEC+ on the market price. Indeed, we are aware of only one paper that attempts to do so. Based on two variations of a SVAR model of the world oil market, Quint and Venditti (2023) calculate counterfactual price scenarios that suggest that the production cutbacks achieved by OPEC+ increased the average price of oil by 6% during the pre-pandemic period of 2017–2020. However, they do not examine the impact of OPEC+ agreements during the pandemic, when production cutbacks by the OPEC+ members reached an unprecedented magnitude, nor do they report the impact of OPEC+ on price volatility.

Economou and Fattouh (2021) also construct a counterfactual scenario, based on the assumption that all of OPEC's available capacity (including the buffer of spare capacity) had been put on the market during 1990–2018. Although OPEC+ was formed toward the end of this interval, the authors do not consider the potential impact of the Allies' additional spare production capacity on the counterfactual price. Of course, the resulting counterfactual price series is lower than the observed historical price due to the incremental volumes of OPEC's oil the market has to absorb, and the counterfactual price volatility is higher than actual. However, Economou and Fattouh's counterfactual exercise assumes that OPEC would have created the same capacity whether or not it intended to serve as a market stabilizer, which begs the question whether OPEC would indeed have created all that capacity if it had not intended to maintain a buffer stock. This is particularly true given the

7. Although its connotations may vary among authors, the term "market share" has frequently been used to describe OPEC's strategic decision in 2014 to not reduce output. See Lawler et al. (2014), Ansari (2017), Behar and Ritz (2017), Kahn (2017), Argus (2020), S&P Global (2020), and U.S. Energy Information Administration (2020).

intent stated in OPEC's (2010) long-term strategy to "continue making investments to expand its production capacity to not only meet perceived demand for its crude, but also maintain an adequate level of spare capacity."

3. THE MODEL

Our point of departure is the model of OPEC's spare capacity and production decisions presented in Pierru et al. (2018). In that model, the demand for OPEC's oil in any period is assumed to follow a lognormal distribution due to the arrival of shocks to global oil demand and non-OPEC oil supply that follow an autoregressive process. It was further assumed that OPEC wishes to stabilize the oil price around a certain target level and creates a buffer of spare capacity to be used in this endeavor, but OPEC is unable to accurately estimate the size of the shocks and makes execution errors when implementing its production decisions. Pierru et al. (2018) estimated that model based on data that extended from 2001 to 2014, and found that, despite the inherent difficulties, OPEC's utilization of spare capacity did tend to offset market shocks and achieved a substantial reduction in the volatility of oil prices.

Based on the additional data that have since become available, including data that reflect the contributions of the Allies that joined in OPEC's effort to stabilize the price of oil, as well as data that incorporate the unprecedented demand shocks occasioned by COVID-19, that model is now extended as follows. The residual demand for OPEC oil but for the OPEC+ agreement is given by the same function as before: $a_t\left(\prod_{k=0}^{K} P_{t-k}^{\omega_k}\right)e^{S_t}$, where P_{t-k} is the oil price in period $t-k$. This expression gives the residual demand for OPEC if its Allies produce at full capacity. It implicitly assumes that all non-OPEC producers behave in a competitive way. Their competitive behavior is captured by the price elasticity of non-OPEC supplies that enters into the calculation of the ω_k. ω_0 is the short-run (monthly) price elasticity of the residual demand for OPEC's oil, $\sum_{k=0}^{K}\omega_k$ is the long-run elasticity. e^{S_t} is a lognormally distributed random variable representing the effects[8] of the short-term shocks to the demand for OPEC's crude oil; a_t is an exogenous, time-varying scaling factor that represents secular change (e.g., growth in population or income) that proceeds at a steadier and more predictable rate than the random short-run shocks that are not secular but idiosyncratic in nature. The demand curve for OPEC's oil shifts throughout time due to both long-run and short-run changes, represented by the term $a_t e^{S_t}$.

But, given that Allies agree to hold oil off the market in certain periods, we now let Q_t represent the residual demand for OPEC's output in period t conditional on Allies' choice of spare capacity E_t:

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

Because of their cooperation with OPEC, the Allies produce less than what they would if they were behaving competitively. Therefore, the demand for OPEC's crude oil that balances the market at a given price is increased by the quantity E_t. A related interpretation is that OPEC may need to reduce its production to attain its target price. However, the production cut E_t provided by the Allies reduces the cut required of OPEC (compared to the case where all non-OPEC producers would behave competitively). As a result, the residual demand for OPEC's oil increases by the amount E_t.

8. The shock to the residual demand for OPEC oil is net of inventory adjustments and other measures taken by other participants in the market.

In other words, by providing the spare capacity E_t, the Allies alleviate OPEC's burden in its market-management efforts.

The stochastic component e^{S_t} is caused by shocks to global demand and non-OPEC supply. We consider these shocks to follow the first-order autoregressive process:

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

where $u_t \sim iid\ N(0,1)$, σ_S represents the standard deviation of innovations on the shock, and κ is the shock persistence.

Let P_t^* represent OPEC's target price[9] for period . And, 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 (i.e., $S_t = 0$) and given Allies' commitment. From (1) we have:

$$Q_t^* = a_t P_t^{*\omega_0} \prod_{k=1}^{K} P_{t-k}^{\omega_k} + E_t. \tag{3}$$

In the market-share regime, during which OPEC may directly target a production volume to achieve a desired market share, Eq. (3) still applies but the right-hand-side then defines the corresponding implicit target price.

OPEC knows that shocks to global oil demand and non-OPEC supply will occur and influence the call on its production. To have the ability to offset these shocks in order to stabilize the price, it creates a buffer of spare capacity. We assume OPEC's total capacity includes a buffer sized as the fixed proportion $B-1$ (with $B>1$) of its expected call net of Allies' behavior. And we introduce a binary variable, $\lambda_t \in \{0,1\}$, that indicates whether OPEC elects to offset the shock in the current period $(\lambda_t = 1)$ or not $(\lambda_t = 0)$ as in the Market Share Campaign.

Letting C_t represent OPEC's total production capacity at period t, we have:

$$C_t = B^{\lambda_t + (1-\lambda_t)e^{-rv_t}} \left(Q_t^* - E_t\right) + E_t. \tag{4}$$

While acting to stabilize $(\lambda_t = 1)$, OPEC's buffer is assumed to be the fixed proportion $B-1$ of its expected call net of Allies' behavior. But during the Market Share Campaign $(\lambda_t = 0)$, the buffer is assumed to be the proportion $B^{e^{-rv_t}} - 1$ of its expected call net of Allies' behavior, where v_t is the time elapsed since the switch to the market-share regime. This recognizes that OPEC may gradually decrease its desired buffer during the Market Share Campaign, in the limit to the point where no buffer is needed ($\lim_{v_t \to \infty} B^{e^{-rv_t}} - 1 = 0$) because there is no attempt to offset shocks in this regime. OPEC's willingness to maintain its buffer is thus assumed to erode progressively, which is in line with the steady decline in its ratio of capacity to production observed during the 2015–2016 market-share episode. The parameter r measures the speed of the relaxation of the buffer policy, the buffer size being halved after approximately $\frac{ln(2)}{r}$ periods (if r equals zero, the buffer size remains at B).

Eq. (4) recognizes that OPEC's policy of holding spare capacity impacts its choice of total production capacity. This view is consistent with OPEC's stated long-term strategy (OPEC, 2010): "The Organization will continue making investments to expand its production capacity to not only meet perceived demand for its crude, but also maintain an adequate level of spare capacity." Eq. (4)

9. Like Pierru et al. (2018, 2020), we do not take any particular stance about the level of the target price and how it is determined. In the model, it serves as an (unobserved) reference level for OPEC's market stabilization efforts each month. Neither the estimation of the model's parameters nor the formulas derived from the model require specifying the level of the target price.

also implies that spare capacity is only used to offset shocks and that anticipated shifts in the demand function $\left(\text{in } Q_t^*\right)$ are compensated by changes in total production capacity.

Given the target price, Allies' behavior, and OPEC's decision whether to offset perceived shocks, OPEC's production is given[10] by:

$$\tilde{Q}_t = a_t P_t^{*\omega_0}\left(\prod_{k=1}^{K} P_{t-k}^{\omega_k}\right)e^{\lambda_t\left(S_t+\sigma_z z_t\right)+\left(1-\lambda_t\right)\sigma_y y_t} + E_t. \tag{5}$$

When attempting to stabilize $\left(\lambda_t = 1\right)$, OPEC makes the error $\sigma_z z_t$ in offsetting the shock, where z_t is uncorrelated with S_t and $z_t \sim iid\,\mathrm{N}\left(0,1\right)$. Some degree of error is unavoidable when judging the size of shocks to be offset, despite OPEC's best efforts to track inventory movements, futures prices, and other sources of market intelligence.[11] In addition, various internal factors (e.g., political, operational, logistical, etc.) may constrain the execution of OPEC's production decisions. z_t is therefore the composite of the estimation error made by OPEC when measuring the size of the shock to offset and an execution error that may affect OPEC's production in any given month. When attempting to stabilize, OPEC's resulting production level simplifies to:

$$\tilde{Q}_t = a_t P_t^{*\omega_0}\left(\prod_{k=1}^{K} P_{t-k}^{\omega_k}\right)e^{S_t+\sigma_z z_t} + E_t \tag{5a}$$

If not stabilizing $\left(\lambda_t = 0\right)$, OPEC's production decision is assumed to be impacted by an execution error,[12] denoted by $\sigma_y y_t$, where y_t *~iid N(0,1)*[13] and is assumed to be uncorrelated with S_t. OPEC's resulting production level during the Market Share Campaign simplifies to:

$$\tilde{Q}_t = a_t P_t^{*\omega_0}\left(\prod_{k=1}^{K} P_{t-k}^{\omega_k}\right)e^{\sigma_y y_t} + E_t \tag{5b}$$

For the general case, we have from (3) and (5):

$$\tilde{Q}_t = \left(Q_t^* - E_t\right)e^{\lambda_t\left(S_t+\sigma_z z_t\right)+\left(1-\lambda_t\right)\sigma_y y_t} + E_t \tag{6}$$

OPEC's spare capacity X_t is the difference between OPEC's total installed capacity and the volume it elects to produce:

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

3.1 Estimating the composite error $\left(\sigma_Z\right)$ based on observed price volatility

When OPEC supplies $\tilde{Q}_t$, the resulting price P_t is such that:

$$a_t\left(\prod_{k=0}^{K} P_{t-k}^{\omega_k}\right)e^{S_t} + E_t = \tilde{Q}_t,$$

10. $\tilde{Q}_t$ is formally equal to $min\left(C_t, a_t P_t^{*\omega_0}\left(\prod_{k=1}^{K} P_{t-k}^{\omega_k}\right)e^{\lambda_t\left(S_t+\sigma_z z_t\right)+\left(1-\lambda_t\right)\sigma_y y_t} + E_t\right)$; we here drop the minimum operator, which does not impact the estimation of the parameters since OPEC's output is always less than production capacity over our period sample.

11. As reported by IHS Markit (2020), the OPEC Secretariat has paid particular attention to crude oil stock levels and their relationship to price.

12. A more restrictive formulation for Eq.(5) would be: $\tilde{Q}_t = a_t P_t^{*\omega_0}\left(\prod_{k=1}^{K} P_{t-k}^{\omega_k}\right)e^{\lambda_t\left(S_t+\sigma_e e_t\right)+\sigma_y y_t} + E_t$, where $\sigma_e e_t$ is OPEC's estimation error when measuring the shock. This formulation assumes the same size for the execution error in both regimes, and, therefore, is equivalent to Eq. (5) if the estimated execution error σ_y is smaller than σ_z (with $\sigma_y^2 + \sigma_e^2 = \sigma_z^2$). Our estimation results show it is the case when the price elasticities assumed for global demand and non-OPEC supply are sufficiently high, for instance –8% and 3% (Table A2). Alternatively, less cohesion and discipline within OPEC during the market-share regime could, for instance, cause the typical size of the execution error to increase.

13. The attack on Abqaiq in 2019 suggests that large technical disturbances can be addressed quickly. We therefore do not assume an autoregressive process for the execution error.

which, after using (5) for the market-stability regime $(\lambda_t = 1)$, gives: $P_t = P_t^* e^{\frac{\sigma_z z_t}{\omega_0}}$. Equivalently:

$$ln(P_t) = ln(P_t^*) + \tfrac{\sigma_z z_t}{\omega_0}, \quad (8)$$

from which it follows:

$$vol^2 = var\left[\ln\left(\tfrac{P_t}{P_{t-1}}\right)\right] = \sigma_{TP}^2 + 2\frac{\sigma_z^2}{\omega_0^2} \quad (8a)$$

The first term on the right is the variance of the periodic percentage changes in the target price: $\sigma_{TP}^2 = var\left(ln\left(\frac{P_t^*}{P_{t-1}^*}\right)\right)$. Solving (8a) for the error variance, we obtain:

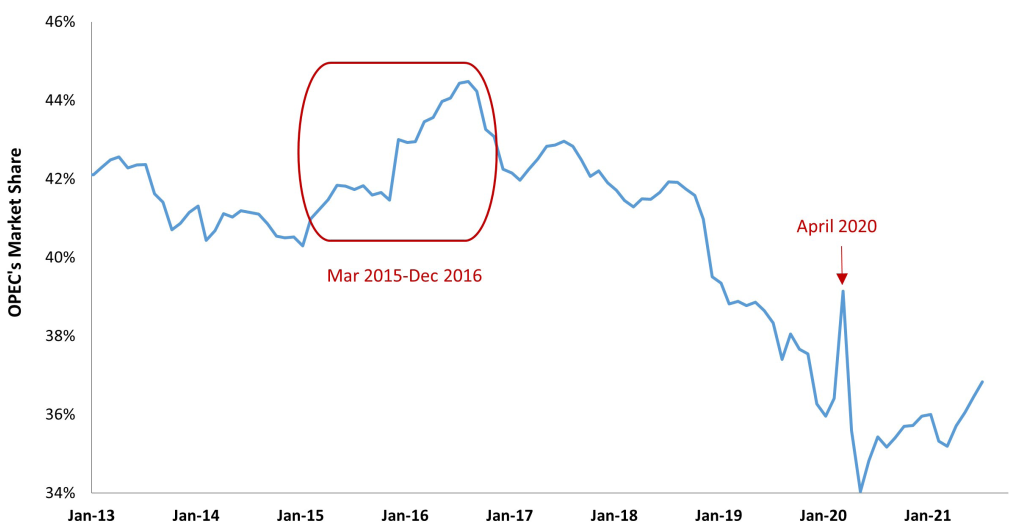
$$\sigma_z^2 = \tfrac{\omega_0^2}{2}\left(vol^2 - \sigma_{TP}^2\right). \quad (8b)$$

Following Pierru et al. (2018, 2020), we assume that $\sigma_{TP}^2 = 0$, which provides an upper bound on σ_z^2. We perform the estimation excluding data from the Market Share Campaign (March 2015—December 2016 plus April 2020). Since (8b) requires considering log-returns of price when $\lambda_t = 1$ we do not consider the change in price from March 2020 to April 2020 or the change in price from April 2020 to May 2020. We therefore use 214 data points (161 until February 2015, 53 after January 2017). We estimate *vol* (standard deviation of log-returns of the average monthly price[14]) to be 9.7%

The monthly price elasticity of residual demand for OPEC's crude oil, ω_0, is by construction equal to $\left[\varepsilon_D - (1-\rho)\varepsilon_S\right]/\rho$, where ε_D and ε_S represent the monthly price elasticity of global demand and non-OPEC supply, and ρ is OPEC's market share of global output. We use IEA's "OPEC Historical Composition" series and since OPEC's crude oil supply does not include condensates, we have deducted condensates from global crude oil supply for consistency. OPEC's average market share is 40.9%, with monthly variation through time as shown in Figure 2.

To complete the estimation of ω_0, we use monthly elasticity values from Caldara et al. (2019), whose broad instrument specification yields an estimate of –0.055 for ε_D (when using the

Figure 2: OPEC's Monthly Market Share (Market Share Campaign indicated in red)



14. Source: U.S. Energy Information Administration (average monthly Brent crude oil spot price).

mean group estimator of Pesaran and Smith) and of 0 for ε_S.[15] These elasticity values are used for the results presented in the main body of our paper, but we provide sensitivity analyses in Appendix 2. Based on these values, we obtain $\omega_0 = -0.134$ and then from (8b) $\sigma_z^2 = 8.44 \times 10^{-5}$, which implies $\sigma_z = 0.92\%$.

3.2 Estimation of other model parameters

For the other model parameters, we produce maximum likelihood estimates over the September 2001 – August 2021 sample period. Combining (4), (6) and (7) we obtain:

$$-ln\left(1+\tfrac{X_t}{\tilde{Q}_t - E_t}\right) = \lambda_t\left(S_t + \sigma_z z_t\right) + \left(1-\lambda_t\right)\sigma_y y_t - \left(\lambda_t + \left(1-\lambda_t\right)e^{-rv_t}\right)ln\left(B\right) \tag{9}$$

The left-hand side of (9) is observable, and when OPEC attempts to offset shocks $\left(\lambda_t = 1\right)$ the right-hand side reduces to give:

$$-ln\left(1+\tfrac{X_t}{\tilde{Q}_t - E_t}\right) = S_t + \sigma_z z_t - ln\left(B\right) \tag{9a}$$

Eq. (9a) is a modified version of (12) in Pierru et al. (2018) adjusted for the support provided by OPEC's Allies.

Alternatively, during the Market Share Campaign $\left(\lambda_t = 0\right)$:

$$-ln\left(1+\tfrac{X_t}{\tilde{Q}_t - E_t}\right) = \sigma_y y_t - e^{-rv_t} ln\left(B\right) \tag{9b}$$

Eq. (9b) shows that the difference between the intended buffer size and the percentage of unused capacity (adjusted for Allies' support) is due to OPEC's execution error.

Appendix 1 shows how the log-likelihood function is derived from (9a) and (9b). The log-likelihood function is the natural logarithm of the density of a 237-dimension normal law (using 214 conditional observations in the market-stability regime and 23 observations in the market-share regime). The estimates are the parameter values that maximize the log-likelihood function and their standard errors are derived from its Hessian matrix.

Table 1 presents the estimates and standard errors. In addition to accounting for the Allies' spare capacity, our study extends Pierru et al.'s (2018) sample period by almost 7 years. Despite that extension of the data, our estimates remain close to those obtained previously and with smaller standard errors, as shown in Table 1. Therefore, despite introducing new market regimes and the impact of Allies' support, the underlying model remains remarkably stable.

Table 1: Maximum Likelihood Estimates

Parameters	This study	Pierru et al. (2018)
Shock persistence, κ	0.966 (0.008)	0.971 (0.017)
Buffer size, B	1.099 (0.007)	1.085 (0.033)
Volatility of shocks, σ_S	1.16% (0.08%)	1.1% (0.1%)
Volatility of execution errors, σ_y	1.57% (0.24%)	—
Decay rate, r	1.47% (0.58%)	—

Note: standard errors in parentheses; Pierru et al.'s (2018) estimates come from their Table A2 where elasticity of global demand is –0.05

The parameter r is estimated to be 0.0147, which means that OPEC would halve the size of its buffer after almost 4 years of market-share regime.

15. Caldara et al. (2019) find a non-significant value of –0.004 for the group of non-OPEC countries.

Appendix 2 provides a sensitivity analysis of these estimates with respect to the assumed elasticity values. Tables A1 and A2 give the estimates obtained when the monthly price elasticity of global demand is either –0.031 or –0.08 and the monthly price elasticity of non-OPEC supply is either 0 or 0.03. These values for the monthly elasticity of global oil demand capture the dispersion of estimates that Caldara et al. (2019) obtained using alternative identification strategies, whereas the values for the non-OPEC supply elasticity correspond to the narrower range of estimates obtained by Pesaran (1990), Anderson et al. (2018), Caldara et al. (2019), Newell and Prest (2019), and Bjornland et al. (2021). Tables A1 and A2 show that the parameter estimates are not sensitive to the assumed elasticity values.

4. OPEC AND OPEC+'S IMPACT ON PRICE VOLATILITY

In this section we compare actual and counterfactual volatilities during each of the four regimes (Commodity Boom, Market Share Campaign, Pre-Pandemic OPEC+, and Pandemic OPEC+). We also measure the Allies' relative contribution to the reduction in volatility during the OPEC+ period. We would expect the Allies' contribution to the reduction in volatility to be small if their use of spare capacity was not tailored to offset monthly shocks, but rather to compensate for the overall level of demand destruction and price collapse. In that case, their contribution would be to lift prices (first moment of price distribution), but not necessarily to stabilize the price from month to month (second moment). However, the role of the Allies most likely goes beyond this since OPEC's willingness to stabilize the market may have been contingent on getting Allies' support.

Our three counterfactuals are respectively based on the assumptions that (1) the Allies provide spare capacity but OPEC elects not to offset perceived shocks, (2) the Allies do not provide spare capacity but OPEC elects to offset perceived shocks, and (3) Allies do not provide spare capacity and OPEC elects not to offset perceived shocks. Speaking informally, we could say that Counterfactual 1 represents the case where only the Allies have pitched in, Counterfactual 2 represents the case where only OPEC has pitched in, and Counterfactual 3 represents the case where nobody has pitched in. Note that during the Commodity Boom regime (Sep. 2001–Feb 2015), Counterfactual 1 coincides with Counterfactual 3 because the actual level of spare capacity provided by the Allies during that period was zero, which means that no one pitched in (as assumed under Counterfactual 3). For the same reason Counterfactual 2 is not actually counterfactual during the Commodity Boom but reverts to the historical price because OPEC was in fact the only party providing spare capacity during that period, as assumed in Counterfactual 2.

4.1 Counterfactual 1 (only Allies pitch in)

In this scenario OPEC is assumed to produce the volume that, given Allies' commitment, would result in the target price in the absence of shocks. By comparing this counterfactual to actual, we can determine the extent to which OPEC's use of spare capacity has influenced price volatility both before and after the formation of OPEC+.

We first construct the price $\dot{P}_t$ that would have prevailed in month t if OPEC had not used its buffer to offset shocks (i.e., in the absence of OPEC's spare capacity policy). When OPEC attempts to stabilize $(\lambda_t = 1)$, as shown in Appendix 3 we have:

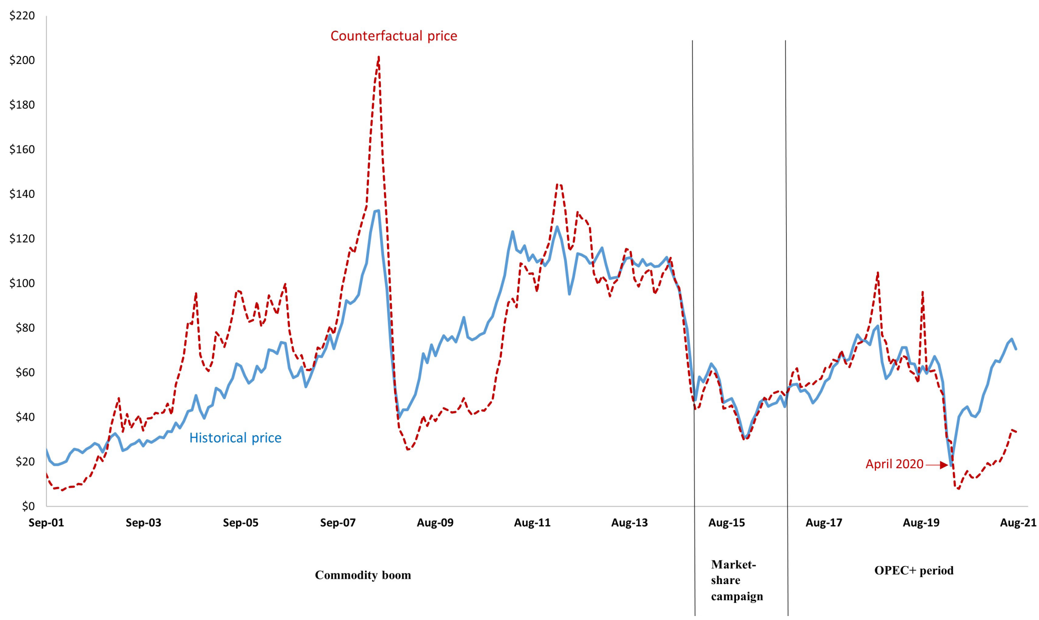
$$ln(P_t) = ln(P_t) + \frac{ln\left(1+\frac{X_t}{Q_t - E_t}\right) - ln(B)}{\omega_0} \tag{10a}$$

Eq. (10a) is a generalized version of Eq. (4) in Almutairi et al. (2021) that accounts for the support provided by OPEC's Allies. In its right-hand-side, the difference between the log terms can take any sign, which shows that the counterfactual scenario rules out not only upward production adjustments but also downward adjustments that would counter positive supply shocks or negative demand shocks. Therefore, as emphasized by Almutairi et al. (2021), Counterfactual 1 truly represents the price that would have prevailed in the absence of OPEC's attempts to stabilize the price, as shown in Figure 3. The counterfactual volatility is calculated by differencing Eq. (10a).

Alternatively, in the market-share regime $(\lambda_t = 0)$, as shown in Appendix 3 we have:

$$ln(\dot{P}_t) = ln(P_t) + \frac{ln\left(1+\frac{X_t}{\tilde{Q}_t - E_t}\right) - e^{-rv_t} ln(B)}{\omega_0}, \tag{10b}$$

Figure 3: Prices in Counterfactual 1 ($/barrel): OPEC Does Not Offset Perceived Shocks



Source for historical price: U.S. Energy Information Administration (average monthly Brent crude oil spot price,)

4.2 Counterfactual 2 (Only OPEC pitches in)

Next, we isolate the effect of OPEC's Allies on price during the OPEC+ period by computing the counterfactual price $\ddot{P}_t$ that would have prevailed if the Allies had produced at their full historical capacity ($E_t = 0$). We here assume that OPEC would have produced the same quantity as actual even without the support of its Allies, which would be the case if OPEC's historical production represents the maximum cuts that OPEC was willing to accept. We therefore assume that OPEC produces $\tilde{Q}_t$ and the Allies produce at $E_t = 0$ each month.

As shown in Appendix 3, these assumptions imply:

$$\ddot{P}_t = P_t\left(\frac{\tilde{Q}_t}{\tilde{Q}_t - E_t}\prod_{k=1}^{K}\left(\frac{P_{t-k}}{\ddot{P}_{t-k}}\right)^{\omega_k}\right)^{\frac{1}{\omega_0}} \tag{11}$$

Because $\ddot{P}_t = P_t$ until December 2016 (since $E_t = 0$), Eq. (11) provides a recursive calculation of $\ddot{P}_t$ starting in January 2017[16] and the resulting prices are shown in Figure 4 (for the OPEC+ Pre-Pan-

16. To calculate the price in this scenario (as well as in Counterfactual 3), like Smith (2009) and Pierru et al. (2018, 2020) we assume that the long-run price elasticity is –0.3 for global oil demand and 0.3 for non-OPEC supply.

demic Period) and Figure 5 (for the OPEC+ Pandemic Period). A possible interpretation of Counterfactual 2 is that although OPEC still uses its buffer to offset market shocks, without Allies' support OPEC might target a lower price $\ddot{P}_t^*$, with $\tilde{Q}_t = a_t \ddot{P}_t^{*\omega_0} \left(\prod_{k=1}^{K} \ddot{P}_{t-k}^{\omega_k} \right) e^{S_t + \sigma_z z_t}$. Combined with Eq. (A14) and (5a), this implies $\frac{\ddot{P}_t^*}{P_t^*} = \frac{\ddot{P}_t}{P_t}$, which means the ratio of the target prices implied by the model in the counterfactual and historical scenarios would equal the ratio of the counterfactual price to the historical price.

4.3 Counterfactual 3 (neither OPEC nor Allies pitch in)

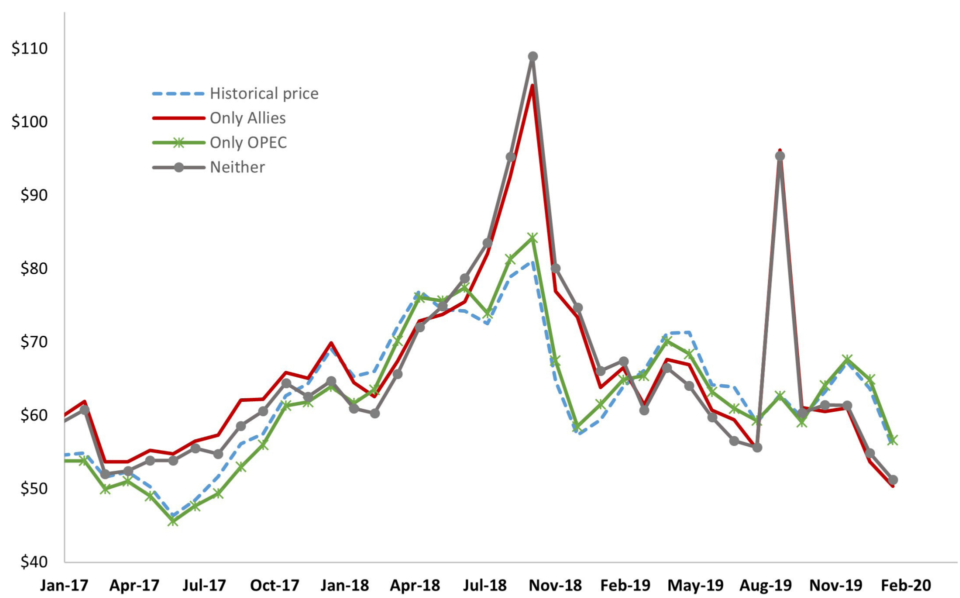
This counterfactual scenario assumes that no one within OPEC+ pitches in, i.e., OPEC has not used its spare capacity to offset shocks and OPEC's allies have not provided any support. As a result, each month OPEC produces $\dot{Q}_t^*$ as in Counterfactual 1 as defined in Appendix 3, and Allies produce at full capacity ($E_t = 0$).

Counterfactual 3 yields the counterfactual price $\ddot{P}_t$. Since the Allies start providing support in January 2017, $\ddot{P}_t = \dot{P}_t$ until December 2016, and the counterfactual price can be calculated recursively starting January 2017 according to Eq. (12) as shown in Appendix 3:[17]

$$\ddot{P}_t = \dot{P}_t \left(\frac{\prod_{k=1}^{K} \dot{P}_{t-k}^{\omega_k} + \frac{BE_t}{(C_t - E_t)} \prod_{k=1}^{K} P_{t-k}^{\omega_k}}{\prod_{k=1}^{K} \ddot{P}_{t-k}^{\omega_k}} \right)^{\frac{1}{\omega_0}}. \qquad (12)$$

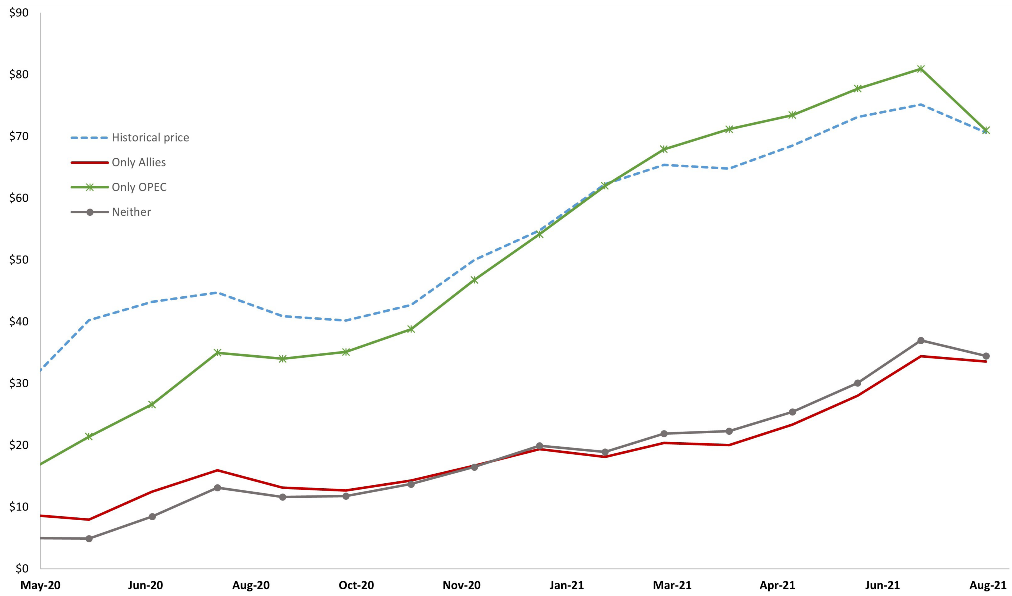
Figures 4 and 5 plot our three counterfactual price series calculated over the Pre-Pandemic and Pandemic OPEC+ periods, respectively, along with actual prices.

Figure 4: Counterfactual Prices ($/barrel), OPEC+ Pre-Pandemic Period



17. Note that if $E_t = 0$, Eq. (12) gives $\ddot{P}_t = \dot{P}_t$ (without support from Allies there is no difference between Counterfactual 1 and Counterfactual 3), and if $\tilde{Q}_t = Q_t^*$ then (12) reverts to (A14). Thus, when $\lambda_t = 0$, as during the Market Share Campaign, Counterfactuals 2 and 3 result in the same price.

Figure 5: Counterfactual Prices ($/barrel), OPEC+ Pandemic Period



5. DISCUSSION

Here we highlight the implications of our counterfactual analysis regarding the impact of OPEC and its Allies on the level and volatility of price. We begin by focusing on the impact of OPEC proper considered over the entire interval 2001–2021, then proceed to consider the combined impact that OPEC and its Allies acting in concert (as OPEC+) have had since January 2017. In addition to separately measuring those impacts before and during the pandemic, we also compare the separate impact of OPEC versus that of its Allies during these periods.

Table 2 shows the counterfactual volatility of oil prices over our full sample period assuming that OPEC had not used its spare capacity to buffer perceived shocks to the market. By comparison to the counterfactual, we estimate that OPEC's efforts to stabilize the price decreased average monthly volatility by one-third between September 2001 and August 2021 (10.8% versus 16.2%). This substantial reduction in volatility remains true when separately considering either the Commodity Boom (9.1% versus 13.8%) or the OPEC+ (8.2% versus 15.4%) periods. To be consistent with our subsequent calculations for the pre-pandemic and pandemic subperiods, the OPEC+ period considered in Table 2 excludes both March and April 2020, since March was the first pandemic month but immediately followed by a market-share-campaign month. Table 3 shows the sensitivity of our results to the inclusion of this transitional month of March. As expected, volatility does not appear to have been mitigated during the Market Share Campaign, with a counterfactual volatility (9.9%) slightly below the historical (10.4%) for this subperiod.

Table 2: Counterfactual 1: Volatility Had OPEC Not Attempted to Offset Shocks

	Commodity Boom	Market-Share Campaign	OPEC+	Overall
Period	Sep 2001-Feb 2015	Mar 2015-Dec 2016	Jan 2017-Aug 2021	Sep 2001-Aug 2021
Historical	9.1%	10.4%	8.2%	10.8%
Counterfactual 1	13.8%	9.9%	15.4%	16.2%

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For the OPEC+ period, Table 3 shows our computed volatilities and average price levels based on the three contrasting counterfactual assumptions about who joins the effort to stabilize the market. Over the full OPEC+ period, Counterfactual 3 (in which neither OPEC nor its Allies pitch in) produces a price volatility of 16.4%, whereas the historical volatility was 8.2%. Thus, we estimate that OPEC+'s management of spare capacity decreased monthly volatility by 50%. As indicated in Table 2 the actions of OPEC alone decreased volatility by 47% (8.2% vs. 15.4%); therefore it appears that the contribution of Allies' actions to the mitigation of volatility has been much below that of OPEC. This conclusion is confirmed by Counterfactual 2, which shows that OPEC acting alone (9.6%) would have nearly attained the observed volatility (8.2%). It is further corroborated by comparing Counterfactual 1, which shows that the Allies acting alone (15.4%) would have achieved only a small reduction relative to the unmanaged volatility of Counterfactual 3 (16.4%).

Table 3: Volatility and Average Price During OPEC+ period excluding March and April 2020

	Volatility			Average Price		
Scenario	Jan 2017–Aug 2021	Jan 2017–Feb 2020	May 2020–Aug 2021	Jan 2017–Aug 2021	Jan 2017–Feb 2020	May 2020–Aug 2021
Historical	8.2% (11.2%)	7.2% (11.3%)	9.3%	$60.40	$63.00	$54.10
Counterfactual 1 (Only Allies)	15.4% (16.8%)	14.5% (16.4%)	15.6%	$52.00	$66.10	$18.70
Counterfactual 2 (Only OPEC)	9.6% (12.3%)	7.1% (11.1%)	11.4%	$59.00	$62.50	$50.70
Counterfactual 3 (Neither)	16.4% (17.8%)	14.3% (16.2%)	17.8%	$51.60	$65.50	$18.40

Note: Values in parentheses are calculated excluding April 2020 only.

In Appendix 2 we provide a sensitivity analysis of OPEC+'s impact on volatility with respect to the assumed elasticities of demand and supply. There it is shown (Table A3) that OPEC+'s actions appear to have reduced oil price volatility by 25% to 70%, depending on one's assumptions, but in every case the results discussed above remain directionally true.

We now give separate consideration to the Pre-Pandemic and Pandemic subperiods in the life of OPEC+. Before proceeding, however, we note that if the Pre-Pandemic January 2017-February 2020 period is extended by just one month, to end with March, the historical volatility increases markedly from 7.2% to 11.3%. This is due to the steep and sudden price decrease that occurred in March 2020 when the potential impact of Covid-19 became manifest and lock downs were happening in various parts of the world. To judge the sensitivity of our results to the inclusion of this transitional month of March, we include in Table 3 counterfactual volatilities calculated for both time intervals. Over the Pre-Pandemic January 2017-February 2020 period, and based on Counterfactual 3, OPEC+'s spare capacity decisions appear to have cut volatility in half, from 14.3% to 7.2%. Including the transitional month of March, OPEC+ still appears to have achieved a significant reduction in volatility, from 16.2% to 11.3%, despite the turbulence caused by the onset of the pandemic. Counterfactual 2 suggests that over the Pre-Pandemic period the Allies' support of OPEC actions did not directly contribute to the mitigation of volatility—the whole reduction being attributable to OPEC's actions. This result is consistent with the assumption that the level of Allies' support is decided before the short-term shock to the demand for OPEC's oil is observed. Furthermore, it does not contradict the view that OPEC's willingness to stabilize the market might have been contingent on getting Allies' support.

During the Pandemic Period from May 2020 to August 2021, OPEC+'s management of spare capacity again appears to have cut volatility almost in half, falling from 17.8% in Counterfactual 3 to the historical volatility of 9.3%. The Allies' contribution to this reduction can be determined in two different ways, either by comparing Counterfactuals 1 and 3 (i.e., (17.8%−15.6%)/17.8%) or by comparing Counterfactual 2 with the historical volatility (i.e., (11.4%−9.3%)/17.8%). By either calculation, it appears that the Allies' support during the Pandemic Period decreased volatility by 12%, whereas OPEC's actions decreased volatility by an additional 36%. Allies' direct contribution to mitigating volatility may be due to the specific nature of the pandemic shock, with OPEC and Allies' decisions factoring in the market's realization that this shock would last.

Next, we examine the apparent impact of OPEC+'s spare capacity decisions on average price levels. By comparing the average historical price with the average price calculated under Counterfactual 3, we estimate that since inception and by acting in concert the members of OPEC+ have increased the average price of oil by $8.80 (January 2017 through August 2021). The Allies' particular contribution to this price increase can be inferred either from Counterfactual 2 (i.e., $1.40=$60.40-$59.00) or by comparing Counterfactuals 1 and 3 ($0.40=$52.00-$51.60), but in either case it is small.

It is evident from Figures 4 and 5, as well as the last two columns of Table 3, that OPEC+'s impact on the average price contrasts sharply between the Pre-Pandemic and Pandemic subperiods. During the Pandemic Period, OPEC+'s actions appear to have increased the average price by $35.70, whereas Pre-Pandemic the effect was actually to reduce the average price by $2.50. In both sub-periods, the Allies[18] actions tended to elevate the average price a bit: either by $0.60 ($66.10−$65.50) or $0.50 ($63.00−$62.50) Pre-Pandemic or $0.30 ($18.70−$18.40) or $3.40 ($54.10−$50.70) during the Pandemic Period—depending on whether the estimate is made by comparing Counterfactuals 1 and 3 or drawn from Counterfactual 2.

OPEC's particular actions in the Pandemic Period appear likewise to have raised the average price, and by an amount that exceeds $30 according to either Counterfactual 1 ($35.40=$54.10-$18.70) or a comparison of Counterfactuals 2 and 3 ($32.30=$50.70-$18.40). In contrast, while working alongside the Allies during the Pre-Pandemic period, it appears that OPEC's own use of its buffer to stabilize the market tended to reduce the price by a relatively small percentage (-$3.00=$62.50-$65.50 or -$3.10=$63.00-$66.10). This small reduction in the average pre-pandemic price indicates that, to stabilize the price at the target level, the spare capacity adjustments mostly served to offset positive short-term shocks to the demand for OPEC oil.

This reduction, although perhaps surprising to some, does not contradict the view that OPEC+ was formed to support the price relative to a desired target level. The reason can be inferred from Dale's (2016) suggestion that by 2016 OPEC had come to view the fracking boom not as a short-term shock, but as a permanent change in the balance of supply and demand—a shift that would negatively impact OPEC's target price and that, in reaction, led to the formation of the OPEC+ alliance.

In addition to the counterfactual analyses presented so far that focus on spare capacity management and market-stabilization efforts by OPEC+ members, we offer one further thought experiment that may help to illuminate the impact that the actions of OPEC+ have had on the average price of oil. Rather than looking through the lens of short-term variations in the output of the members

18. Our formulation of the residual demand for OPEC's oil captures dynamic long-term price effects (through the long-run elasticity). For a given volume of OPEC's production, the lower the past prices were, the higher is current demand and therefore the current price. For this reason, the price in Counterfactual 2 may sometimes exceed the historical price (e.g. after March 2021 in Figure 5). As expected, however, the average Counterfactual 2 price is below the average historical price.

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of OPEC+, as our counterfactuals have done, here we evaluate the overall impact if, hypothetically those countries had adhered to production levels that were determined prior to their December 2016 decision to collaborate in the stabilization effort. To this end, we calculate the prices that would have prevailed since January 2017 if the Allies had produced at full capacity while OPEC members maintained production not at the level required to support any particular target price, but rather held production constant at the reference level that was used as a benchmark for calculating subsequent production cuts. This reference level (33.2 million barrels per day) is based on the output of OPEC members in October 2016, except Angola for which the output in September 2016 is considered. An alternative interpretation is that we are assessing the price that would have prevailed if OPEC+ had not subsequently adjusted its production to long-term, anticipated changes in the demand for its oil (such as the fracking boom, as discussed above). In that event, we find that oil prices[19] would have averaged $5.40 lower than actual between January 2017 and January 2020. This estimate is roughly in line with Quint and Venditti's (2023) finding that production cuts by OPEC+ between January 2017 and January 2020 increased the average price by about $4 per barrel.

6. CONCLUSION

The formation of OPEC+ in December 2016 was a signal event in the history of the world oil market. It established for the first time in OPEC's sixty-year history an agreement by which non-members would cooperate with OPEC in the effort to stabilize the price of oil. The ensuing pandemic soon posed a great and unexpected challenge to this enterprise, one that tested both the limits of cooperation and the ability to overcome an unparalleled destruction of demand. The confluence of these events presents a unique opportunity to examine previously unknown and unobserved aspects of the world oil market. The objective of our research has been to examine these episodes to gain a better understanding of the Allies' role in the attempt to stabilize prices and to measure their impact on the outcome.

To that end, this paper extends the model of OPEC's behavior developed by Pierru et al. (2018, 2020) by incorporating the participation of Allies in the OPEC+ group. In addition, the model now embeds two different versions of OPEC's behavior (price stabilization versus defense of market share) in a unified formulation. Using monthly data from September 2001 through August 2021, we examine four successive regimes (Commodity Boom, Market Share Campaign, Pre-Pandemic OPEC+, Pandemic OPEC+) and obtain robust estimates of model parameters based on twenty years of heterogeneous but informative data. Despite the substantial extensions to the basic model and the extended period of observation, the new parameter estimates remain close to those obtained by Pierru et al. (2018).

The stability of our estimates tends to challenge the opinion of Fattouh and Mahadeva (2013), Ansari (2017), and Gundersen and Hvinden (2021) against the ability to maintain a consistent model of OPEC behavior over extended periods of time. And while our model does acknowledge, and our estimates do confirm OPEC's decision to defend market share for limited periods of time, our results do support the view expressed by Dale (2016), Ansari (2017), and Khan (2017) that OPEC's enduring objective has been to invest in and utilize spare capacity to offset shocks in order to stabilize the price of oil.

Based on the estimated model, we construct three counterfactual scenarios that distinguish the stabilizing impact of OPEC's own production decisions from that of its Allies. Like Pierru et al.

19. By denoting this price $\overline{P}_t$, we have: $a_t\left(\prod_{k=0}^{K}\overline{P}_{t-k}^{\omega_k}\right)e^{S_t}=33.2$. Using Eq. (A13), we obtain: $\overline{P}_t=P_t\left(\frac{33.2}{\tilde{Q}_t-E_t}\prod_{k=1}^{K}\left(\frac{P_{t-k}}{\overline{P}_{t-k}}\right)^{\omega_k}\right)^{\frac{1}{\omega_0}}$.

(2018, 2020), we find that OPEC substantially reduced oil price volatility during the Commodity Boom period but did not attempt to mitigate volatility during the Market Share Campaign. And when looking at more recent developments, we show that OPEC+'s management of spare capacity halved price volatility during both Pre-Pandemic and Pandemic periods. We also find that, although the Allies' actions in particular helped to decrease volatility during the Pandemic Period (albeit by a small amount, and with OPEC's own actions helping to reduce volatility by three times as much), the actions of the Allies had no discernable impact on volatility prior to the pandemic.

In addition, we find that since its inception, OPEC+'s management of spare capacity has increased the average price of oil by $8.80 per barrel (January 2017 through August 2021), but with the Allies' actions in particular responsible for no more than $1.40 of this amount. However, the Pre-Pandemic and Pandemic Periods differ fundamentally in this regard, where the market-stabilization efforts by OPEC+ appear to have increased the average price during the pandemic by $35.70, but to have decreased the average price before the pandemic by $2.50.

The most important take-away from our research is to confirm that OPEC, assisted by Allies, was able to substantially reduce the volatility of crude oil prices during the unprecedented disruption to the crude oil market caused by the COVID-19 pandemic. By any conventional macroeconomic measure, this reduction in volatility would have reduced the costs of adjustment to the pandemic and contributed to higher social welfare.

In our model, OPEC's ability to dampen price volatility is limited by the difficulty to precisely estimate the size of shocks to demand and supply, as well as potential execution errors in implementing production decisions. Future research could consider other potential obstacles to OPEC's price-stabilization efforts, such as the possibility that OPEC would base its decision making on a biased estimate of the price elasticity of the demand for its oil.

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APPENDIX 1: MAXIMUM LIKELIHOOD ESTIMATION

From eq. (9), by setting $d_t = -ln\left(1+\frac{X_t}{\tilde{Q}_t - E_t}\right)$ we have:

$$d_t = \lambda_t\left(S_t + \sigma_z z_t\right) + \left(1-\lambda_t\right)\sigma_y y_t - \left(\lambda_t + \left(1-\lambda_t\right)e^{-rv_t}\right)ln\left(B\right) \quad \text{(A1)}$$

In periods of market-share regime $\left(\lambda_t = 0\right)$, (A1) becomes:

$$d_t = \sigma_y y_t - e^{-rv_t} ln\left(B\right) \quad \text{(A2)}$$

d_t follows a normal law of expected value $-e^{-rv_t} ln\left(B\right)$ and standard deviation σ_y.

In periods of market-stability regime $\left(\lambda_t = 1\right)$, by combining (A1) and (2) we obtain:

$$d_t = \left(\kappa - 1\right)ln\left(B\right) + \kappa d_{t-1} + \sigma_z z_t - \kappa\sigma_z z_{t-1} + \sigma_S u_t \quad \text{(A3)}$$

Let w_t be a standard normal variate. We have:

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

$$d_t = \left(\kappa - 1\right)ln\left(B\right) + \kappa d_{t-1} + W_t \quad \text{(A4)}$$

$$cov\left(W_{t-1}, W_t\right) = -\kappa\sigma_z^2 \quad \text{(A5)}$$

Therefore, d_t follows a normal law, with $E\left(d_t \mid d_{t-1}\right) = \left(\kappa - 1\right)ln\left(B\right) + \kappa d_{t-1}$ and standard deviation $\sqrt{\sigma_S^2 + \sigma_z^2\left(\kappa^2 + 1\right)}$.

Eqs. (A2), (A4) and (A5) allow for defining the log-likelihood function as the natural logarithm of the density of a 237-dimension normal law (using 214 conditional observations in the market-stability regime and 23 observations in the market-share regime). 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: SENSITIVITY ANALYSIS

Table A1: Maximum Likelihood Estimates if $\varepsilon_S = 0$

	Assumed elasticity of demand	
	$\varepsilon_D = -0.031$	$\varepsilon_D = -0.08$
σ_z	0.52%	1.3%
κ	0.964 (0.059)	0.965 (0.011)
B	1.099 (0.007)	1.098 (0.007)
σ_S	1.3% (0.08%)	1.1% (0.08%)
σ_y	1.57% (0.23%)	1.57% (0.23%)
r	1.48% (0.61%)	1.46% (0.58%)

Note: standard errors in parentheses

Table A2: Maximum Likelihood Estimates if $\varepsilon_S = 0.03$

	Assumed elasticity of demand	
	$\varepsilon_D = -0.031$	$\varepsilon_D = -0.08$
σ_z	0.81%	1.63%
κ	0.965 (0.001)	0.965 (0.002)
B	1.099 (0.006)	1.098 (0.007)
σ_S	1.2% (0.06%)	1.1% (0.13%)
σ_y	1.57% (0.22%)	1.57% (0.21%)
r	1.47% (0.55%)	1.46% (0.49%)

Note: standard errors in parentheses

Table A3: Volatility During OPEC+ period (Jan 2017–Aug 2021, excluding March and April 2020)

Assumed elasticities	Counterfactual 1 (Only Allies)	Counterfactual 2 (Only OPEC)	Counterfactual 3 (Neither)
$\varepsilon_D = -0.055$, $\varepsilon_S = 0$	15.4%	9.6%	16.4%
$\varepsilon_D = -0.08$, $\varepsilon_S = 0$	11.9%	8.7%	12.5%
$\varepsilon_D = -0.031$, $\varepsilon_S = 0$	25.1%	13.5%	27.5%
$\varepsilon_D = -0.08$, $\varepsilon_S = 0.03$	10.7%	8.5%	11.1%
$\varepsilon_D = -0.031$, $\varepsilon_S = 0.03$	16.5%	10.1%	17.5%

Note: historical volatility is 8.2%

APPENDIX 3: DERIVATIONS OF COUNTERFACTUAL PRICES

Counterfactual 1 (only Allies pitch in)

OPEC would have produced the volume $\dot{Q}_t^*$, with:

$$\dot{Q}_t^* = a_t P_t^{*\omega_0} \left(\prod_{k=1}^{K} \dot{P}_{t-k}^{\omega_k}\right) + E_t \tag{A6}$$

$\dot{P}_t$ is therefore given by:

$$a_t \left(\prod_{k=0}^{K} \dot{P}_{t-k}^{\omega_k}\right) e^{S_t} + E_t = a_t P_t^{*\omega_0} \left(\prod_{k=1}^{K} \dot{P}_{t-k}^{\omega_k}\right) + E_t \tag{A7}$$

Eq. (A7) gives: $ln\left(\dot{P}_t\right) = ln\left(P_t^*\right) - \frac{S_t}{\omega_0}$, which combined with Eq. (8) implies:

$$ln\left(\dot{P}_t\right) = ln\left(P_t\right) - \frac{S_t + \sigma_z z_t}{\omega_0} \tag{A8}$$

The general form of Eq. (8) is

$$ln\left(P_t\right) = ln\left(P_t^*\right) + \frac{(\lambda_t - 1)S_t + \lambda_t \sigma_z z_t + (1-\lambda_t)\sigma_y y_t}{\omega_0} \tag{A9}$$

Combining (A8) with (A9) gives

$$ln\left(\dot{P}_t\right) = ln\left(P_t\right) - \frac{\lambda_t S_t + \lambda_t \sigma_z z_t + (1-\lambda_t)\sigma_y y_t}{\omega_0} \tag{A10}$$

And combining (A9) and (A10) gives (A11), which allows us to compute $\dot{P}_t$:

$$ln\left(\dot{P}_t\right) = ln\left(P_t\right) + \frac{ln\left(1 + \frac{X_t}{\bar{Q}_t - E_t}\right) - \left(\lambda_t + (1-\lambda_t)e^{-rv_t}\right) ln(B)}{\omega_0} \tag{A11}$$

Eq. (10a) and (10b) are immediately derived from (A11).

Counterfactual 2 (Only OPEC pitches in)

We assume that OPEC produces $\tilde{Q}_t$ and the Allies produce at $E_t = 0$ each month. The counterfactual price $\ddot{P}_t$ must satisfy the counterfactual residual demand function as follows:

$$a_t\left(\prod_{k=0}^{K} \ddot{P}_{t-k}^{\omega_k}\right)e^{S_t} = \tilde{Q}_t \tag{A12}$$

The historical price is given by the historical residual demand function:

$$a_t\left(\prod_{k=0}^{K} P_{t-k}^{\omega_k}\right)e^{S_t} + E_t = \tilde{Q}_t \tag{A13}$$

By combining Eqs. (A12) and (A13) we obtain:

$$\prod_{k=0}^{K} \ddot{P}_{t-k}^{\omega_k} = \frac{\tilde{Q}_t}{\tilde{Q}_t - E_t}\prod_{k=0}^{K} P_{t-k}^{\omega_k}, \tag{A14}$$

Eq. (11) is derived from Eq. (A14).

Counterfactual 3 (neither OPEC nor Allies pitch in)

Counterfactual 3 yields the counterfactual price $\dddot{P}_t$. In the following, note that $\dot{P}_t$ still denotes the price determined in Counterfactual 1. We have:

$$a_t\left(\prod_{k=0}^{K} \dddot{P}_{t-k}^{\omega_k}\right)e^{S_t} = \dot{Q}_t^* \tag{A15}$$

By combining Eq. (3) and Eq. (A6), we have:

$$\dot{Q}_t^* = \left(Q_t^* - E_t\right)\prod_{k=1}^{K}\left(\frac{\dot{P}_{t-k}}{P_{t-k}}\right)^{\omega_k} + E_t$$

According to Eq. (4) we have $C_t = B\left(Q_t^* - E_t\right) + E_t$, which implies:

$$\dot{Q}_t^* = \frac{C_t - E_t}{B}\prod_{k=1}^{K}\left(\frac{\dot{P}_{t-k}}{P_{t-k}}\right)^{\omega_k} + E_t \tag{A16}$$

And, from Counterfactual 1 we have:

$$a_t\left(\prod_{k=0}^{K} \dot{P}_{t-k}^{\omega_k}\right)e^{S_t} + E_t = \dot{Q}_t^* \tag{A17}$$

By combining (A15) and (A17):

$$\prod_{k=0}^{K} \dddot{P}_{t-k}^{\omega_k} = \frac{\dot{Q}_t^*}{\dot{Q}_t^* - E_t}\prod_{k=0}^{K} \dot{P}_{t-k}^{\omega_k} \tag{A18}$$

Using (A16), (A18) becomes:

$$\prod_{k=0}^{K} \dddot{P}_{t-k}^{\omega_k} = \prod_{k=0}^{K} \dot{P}_{t-k}^{\omega_k} + \frac{BE_t}{(C_t - E_t)}\dot{P}_t^{\omega_0}\prod_{k=1}^{K} P_{t-k}^{\omega_k} \tag{A19}$$

All the elements in the right-hand side of (A19) are observed or already estimated. Eq. (12) is derived from Eq. (A19).

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