The Shale Revolution and the Dynamics of the Oil Market

Shale and the Global Oil Market

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Abstract: We build and estimate a dynamic, structural model of the world oil market to quantify the impact of the shale revolution. We model the shale revolution as a decrease in shale production costs and find that the resultant increase in shale production lowers oil prices by 21% in the short run and 46% once the shale oil transition is complete. Oil price volatility is lowered by 9 to 22% depending on the horizon. We also find OPEC Core acts to keep its market share constant in the face of the dramatic increase in shale production.

Keywords: oil price, oil price volatility, shale, OPEC

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1 Introduction

The U.S. shale revolution, the increase in U.S. crude oil production brought about by the technological developments in hydraulic fracturing and horizontal drilling, has brought long-lasting changes to the world oil market. U.S. oil production, which had been declining since 1970, nearly doubled from 2008 to 2021, with all of the increase coming from shale. The dramatic increase in shale production seen thus far is likely to be only a precursor of future shale production as improvements in shale production techniques continue and the diffusion of these techniques spreads worldwide. The increase in shale production has implications beyond just the increase in oil production. Shale producers appear to be more flexible than conventional producers in their responsiveness to price changes (see (Bornstein et al., 2022; Newell and Prest, 2019; Smith and Lee, 2017; Vatter et al., 2022; Walls and Zheng, 2022)). The increase in shale production is likely to alter how sensitive overall market supply is to oil price changes.

Shale's substantial growth also has implications for the strategic calculus of OPEC. Figure 1 displays shale's share of global output along with that of OPEC Core (Saudi Arabia, Kuwait, UAE, and Qatar) and the rest-of-world conventional oil production. Shale oil started from less than one percent of the market in 2005 and grew to roughly 10 percent of the global oil market by 2021. Yet, despite shale's dramatic rise in market share, OPEC Core's market share has been largely unchanged. From the 1980s onward Saudi Arabia had been seen as the 'swing producer' in OPEC; it is the OPEC producer with the highest output, largest excess capacity, and the most flexibility.[1] The rise of shale may alter the extent to which OPEC and Saudi Arabia, in particular, can exert its market power.[2]

Figure 2 displays the real oil price (Brent crude price divided by U.S. CPI). Interestingly, while shale production has risen steadily (with exception of the 2015 period), its effect on the real oil price and world oil production is less evident. Oil prices have risen and fallen substantially over our sample but the timing of these changes is not tightly linked to the steady rise in shale production. Similarly, the increase in shale production has not been reflected in a one-for-one increase in world oil production. Together these suggest that despite the dramatic increase in shale production, other factors play important roles in the fluctuations of oil price and output.

In this paper, we build and estimate a dynamic structural model of the oil market in order to quantify the impact of the emergence of shale production on oil prices and production over our sample and in the future. First, we model the dynamic supply decisions of conventional competitive fringe producers, shale producers, and a dominant oil producer that acts strategically when setting oil production. In this application, we take the dominant producer as OPEC Core.[3] We assume that OPEC Core acts strategically and takes into account how its production decision affects both the market price and the competitive fringe's (both conventional and shale) production. Our structural model implies decision

[1] '.. the Kingdom of Saudi Arabia, ... will act as a swing producer to supply the balancing quantities to meet market requirements.' ('Communique by OPEC', (New York Times, 1983)).

[2] The Saudi oil minister Ali al-Naimi stated in February 2016: 'We are leaving it to the market as the most efficient way to re-balance supply and demand. It is a simple case of letting the market work. The producers of those high-cost barrels must find a way to lower their costs, borrow cash or liquidate. It is the most efficient way to re-balance markets. Cutting low-cost production to subsidise higher cost supplies only delays an inevitable reckoning.' (IHS CERAWeek, 2016). The trade press reported his views as 'Naimi declares price war on U.S. shale.' (Oil Daily, 2016)). Oil prices fell to $30 by February 2016.

[3] In section 3, we argue that OPEC Core rather than all of OPEC should be considered as the dominant producer in the world oil market. In section 9, we discuss our analysis when OPEC as a whole is taken to be the dominant producer.

rules for short-run, medium-run, and long-run production for these three types of producers, which in turn, determine the short-run, medium-run and long-run supply responses to changes in market conditions. Second, we model the transition from the pre-shale revolution oil market to the post-shale revolution oil market as a gradual but permanent decrease in shale production costs that raise shale's market share from 0.5% of the market to 20% of the market.[4] We take this transition into account when solving and estimating the model. We also allow shocks to demand, conventional and OPEC Core supply, as well as temporary shocks to shale oil supply, to account for other sources of oil market fluctuations.

We use Bayesian methods to estimate our model: combining oil market data over the period 1991-2021 with priors informed by previous micro-level as well as market-level studies of oil producers. These prior studies suggest shale supply elasticities to be substantially higher than those of conventional producers. We do indeed find that the estimated short-run supply elasticity of shale producers is substantially higher than those of conventional fringe producers. However, in contrast to the short-run supply elasticities, the data are less informative about long-run supply elasticities; posterior distributions of the long-run supply elasticities are largely determined by the prior distributions for these parameters. Interestingly, the implicit supply elasticity of OPEC Core is substantially lower than would be the case if OPEC Core were a price-taker, suggesting that OPEC Core restrains its production response to changing oil market conditions. We estimate that shale's increasing market share increased the price elasticity of market supply by 13 to 31 percent depending on the horizon.

[4]Technological innovations will likely lead to additional shale development not just in the U.S. but in the rest of the world where shale is present, such as Argentina, China, etc.

We examine the sources of fluctuations in oil prices and output over our sample and conduct a counterfactual analysis to determine the contribution of shale to oil price and output fluctuations. Up until around 2010, we find that the shale transition or shale cost shocks contributed little to oil price movements; oil specific demand shocks and conventional fringe supply shocks drive most of the movements in oil prices and output. Toward the end of our sample, we find increasing evidence that shale has had a significant effect on the oil market. In particular, we find that the shale revolution contributed to a 21% decline in the real price of oil and a 3% increase in global output by the end of 2021. In the long-run, once the shale transition is over, we estimate that the price of oil would be nearly 46% lower (and output 11% higher) than if the shale revolution had not occurred (see Table 5 below). Not only does shale revolution affect the market price and output, but it will lower the market power of the dominant producer–halving the price to marginal cost ratio of OPEC Core.

In addition, our analysis suggests that as of 2021 shale oil has lowered conditional forecast error variance of the real oil price by 9%-22% depending on the horizon and that eventually the conditional forecast variance of oil prices is expected to decline by 17%-35% once the shale revolution is complete.[5] While shale's market share has risen substantially over the sample, we find that OPEC Core's output share is little affected by the increase in shale output; most of shale's growth is at the expense of conventional producers in the rest of the world. Finally, we use the model to examine how the presence of shale alters the impact of supply disruptions originating outside the shale sector. In particular, we examine the implication of a conventional fringe shock similar to that which occurred as a result of the

[5]These numbers are calculated using the conditional forecast error variances presented in Table 6.

Russian invasion of Ukraine in 2022. We find that without shale, the resulting oil price increase would have been 30% higher.

Overall, our paper contributes to the literature on shale's effect on the oil market in several ways. First, to our best knowledge, ours is the first paper that models the dynamics of the ongoing shale revolution and to allow for shocks in demand and supply along the transition path. This allows us to examine shale's current contribution to global oil market fluctuations while allowing the contribution of shale to be substantially larger in the future. Second, we use actual price and output dynamics in the oil market to estimate key parameters in our structural model and combine that with prior information informed by previous micro-level studies of the oil market. Third, by building a dynamic structural model and including in our estimation sample periods in which shale production was virtually nonexistent, we can plausibly ask the counterfactual 'what would the oil market be like if the shale revolution had not occurred.' For example, our model is ideally set up to investigate the effects of a demand or supply disruption in the oil market (for example, the Russian invasion of Ukraine) and the role shale has played in mitigating the effect of those disruptions.

There are two papers that take very similar approaches to the one that we take in this paper. Manescu and Nuno (2015) utilise the model of Nakov and Nuno (2013) to analyse the effect of the increase in shale production. Their model is a calibrated general equilibrium model of the world economy that includes an oil sector. As in our model, producers choose utilisation and capacity, however in their model Saudi Arabia takes into account how its production decisions affect the fringe's utilisation, but not capacity. They find that as of 2014, the shale revolution had relatively modest effects on world oil prices and that non-Saudi supply shocks were the main reason for the oil price decline experienced in 2014. Our analysis differs from theirs in that we model both the short-run (utilisation) and long-run (capacity) strategic decisions of the dominant producer. We also find that as of 2014, shale had only moderately affected outcomes in the oil market. But we also show that shale's impact is currently non-negligible and will be substantially greater in the future.

Bornstein et al. (2022) have a model of the oil market which includes both conventional and non-conventional (shale) oil producers, with OPEC behaving as a cartel that acts strategically both in the short-run and the long-run. Assuming a steady state 20% share for non-conventional oil production, they find that the volatility of oil price changes is reduced by 43% when shale firms are included in the model. Our analysis differs from theirs in that they use firm-level data to estimate the key parameters governing supply. Our estimation, on the other hand, uses actual time series dynamics in the oil market to estimate key market parameters, along with prior information based largely on micro-level studies. Furthermore, our estimation and analysis explicitly takes into account the stochastic nature of demand and supply (i.e., allows for random shocks to demand and supply) along the transition path from a pre-shale steady state to a post-shale steady state. Hence, we account for the continually growing share of shale production over our estimation sample and also, changing oil price volatility as shale production grows. Despite using different data and estimation methods, our results are largely consistent with Bornstein et al. (2022) with respect to the reduction in oil price and volatility and elasticities of demand and short-run supply. Our results further complement theirs by shedding light on the dynamics and decomposition of the variability in oil prices at different time horizons along the transition path.

The rest of the paper is organised as follows. Section 2 describes how shale oil production is different from conventional oil production and reviews some of the burgeoning literature on shale oil. In section 3, we argue that OPEC Core rather than OPEC as a whole, better fits the dominant producer with competitive fringe market structure we use to model the oil market. In section 4, we develop the dynamic model used to quantify the effects of the shale revolution. Section 5 discusses how the model is solved and estimated. In section 6, we discuss our empirical results and assess shale's effect on OPEC Core's production and the elasticity of supply for the market as a whole. In section 7, we examine the model's predictions about the real oil price and the volatility in price during the shale revolution transition. In section 8, we conduct a counterfactual analysis of the shale revolution never occurring. We also examine how the oil market might react to a supply disruption similar to the one that occurred as the result of the Russian invasion of Ukraine in February 2022. Section 9 discusses some robustness analysis including using OPEC as a whole as the dominant producer. Section 10 concludes.

2 How is Shale Different from Conventional Oil?

The 'shale revolution' has significantly increased oil production in the U.S. in a very short period of time. U.S. oil production had declined from a high of 10 mb/d in 1970 to a low of 4.9 mb/d by mid-2007. With the advent of hydraulic fracking and horizontal drilling in shale formations, U.S. output reached 13 mb/d by the end of 2019. This increase of 8 mb/d since 2007 has all come from shale.

Conventional oil is produced by vertically drilling in relatively permeable formations (meaning once the well is drilled the oil flows relatively easily through the well). Shale or tight oil comes from very low-permeability rock that requires hydraulic fracturing in order for oil to flow out of the well Schlumberger (nd)).[6] The combination of hydraulic fracking with horizontal drilling has unlocked a vast oil resource in these formations that were not previously accessible.[7] With horizontal drilling, the well is first drilled vertically, to a depth of 5,000 to 10,000 feet and then turned horizontally for another 5,000 to 10,000 feet.[8] The well is then fracked by pumping sand, water and chemicals at high pressure to crack open the rock. The sand particles keep the fissures open, releasing the oil and gas (Dunn, 2016). Horizontal drilling exposes the well to much greater length and surface of rock, increasing production levels.

Horizontal drilling and hydraulic fracking are not new technologies. The first commercial application of hydraulic fracking was done in 1949 (Aoghs, 2007), but horizontal well construction and large-scale hydraulic fracking were developed and field tested in the 1970s through a project funded by the U.S. government, called the 'Eastern Shales Program' (Kleinberg and Fagan, 2019). George Mitchell, who was an industry participant in the program, successfully applied it to the Barnett shale in the early 2000s, starting the 'shale boom'.

Shale production costs have fallen dramatically over the years. Initially, production costs from shale oil reservoirs were significantly higher than from conventional reservoirs. As a result, shale's share of oil production worldwide was very small. However, through technological developments and learning-by-doing, these costs have come down considerably. Technological advances in drilling methods have reduced both the time and cost of drilling. For example, pad drilling allows for multiple wells to be drilled from a single well pad in a

[6] For example, conventional reservoir permeability is in the 10 -100 milliDarcies range (unit of permeability), while tight oil reservoir permeability is in the one millionth of a milliDarcy. (See Canadian Society for Unconventional Resources (2019))

[7] Much of the tight oil in the U.S. comes from shale formations and has been called shale oil. We will use the term shale oil throughout this paper.

[8] The lateral section of a well can be as long as 20,000 feet. The average length of a lateral was 9,000 in 2019.

short amount of time. This reduces nonproductive times for rigs and simplifies the infrastructure and supply chains (Kleinberg et al., 2018). Newer rigs have additional features such as top drivers, Measurement-While-Drilling tools, and more advanced motors, all contributing to increased efficiency and lower costs (Siegel, 2013). Other techniques such as zipper fracking and stacked laterals in multiple shale layers have all helped to increase production from shale fields (Badiali, 2014). Figure 3 shows the dramatic increase in productivity for the three major U.S. shale basins. This increase in productivity translates into reduced costs and greater production in the shale sector and is a feature of the data that we want our model to reflect.

In addition to increased productivity and lower costs, the new technologies have also greatly lowered drilling and production times. Despite longer laterals and increased well depth, the average time to drill has declined from 32 days in 2008 to 18 days in 2013 (Siegel, 2013).[9] The decline in drilling times, together with increased productivity have lowered costs and enabled shale producers to respond faster to changes in oil prices, hence the 'short cycle' moniker for shale oil production.[10] The market structure of the U.S. oil industry may be another factor in the quicker response of shale producers to oil price changes. U.S. shale producers are typically small and very nimble: 70 percent have 1-9 employees, and 18 percent have 10-49 employees (Bureau of Labor Statistics, 2022). These producers typically act independently and as price takers (Kleinberg et al., 2018). All this suggests that shale producers behave as a competitive fringe. However, unlike conventional producers, they have higher supply elasticities, faster response times, and rapidly increasing productivity.

[9] Recently, some companies, such as Diamondback, have reduced the drilling time to 10 days. (Motley Fool, 2021)

[10] New adjustable-rate pumps allow producers to restrict flow rates up to 25% without damaging the wellbore.

The onset of the shale boom and the availability of micro data sets covering the oil industry brought forth a multitude of studies about the impact of shale production on the oil market. Papers studying the effects of the shale boom on the U.S. economy and importer/exporter GDP and oil revenues include Kilian (2017), Manescu and Nuno (2015), Mohaddes and Raissi (2019), and Cakir Melek et al. (2021), among others. Recent academic studies show the supply elasticities from shale are quite a bit higher than from conventional oil. Newell and Prest (2019) show that the price responsiveness of U.S. supply is 13 times that of the pre-shale era. Walls and Zheng (2022) find high supply elasticies for shale, especially in the long run. Similarly, Vatter et al. (2022) in a Bakken Case study, find much higher supply elasticities for shale. Their three-month elasticity is 0.23, the one-year is 1.14 and the eight-year is 1.95. Bjornland et al. (2021) with a model using spot prices conditional on fixed future prices, find very high short-run elasticities of supply for shale wells, with no significant supply response from conventional wells. As to shale's effect on the market as a whole, Frondel and Horwath (2019), with a reduced form dynamic OLS model, show that WTI prices would have been \$40 - \$50 higher without the shale boom. Gundersen (2020) shows that oil prices would be \$10 higher in 2014-2015 without US shale. As mentioned previously, Bornstein et al. (2022) also find that the shale revolution has had important consequences for the oil market.

3 OPEC market structure

Analysing the effect of the shale revolution would be much more straight forward if the oil market could be characterised by a competitive market structure. However, there are many studies that have extensively analysed the oil market and OPEC market structure, most of which find evidence of strategic behaviour (non-price taking) on the part of OPEC. Salant (1976) and Pindyck (1978) were the earliest papers modelling the oil industry as a dominant producer with a competitive fringe. Econometric models testing for OPEC market structure, began with Griffin (1985), followed by Salehi-Isfahani (1987), Jones (1990), Dahl and Yucel (1991), Spilimbergo (2001) among others. While there is a wide array of alternative models, ranging from a market-sharing cartel, revenue-targeting cartel, loose cooperation and non-collusive behaviour, there is no clear consensus among all these studies about OPEC's market structure (see Smith (2005)), except that none conclude that OPEC and particularly Saudi Arabia is acting as a price taker.

The most common market structure for modelling oil supply is that of a dominant producer with a competitive (price-taking) fringe. The dominant producer is typically modelled as a Stackelberg leader and internalises the responses of consumers and the competitive fringe responses to oil prices. In our empirical analysis below, rather than taking all of OPEC as the dominant producer, we take a subset of OPEC: Saudi Arabia, Kuwait, UAE, and Qatar, which we call OPEC Core, to be the dominant producer.[11] Among OPEC members, these four countries have 60% of OPEC's total production and 85% of OPEC's spare capacity (see Pierru et al. (2017)). Together, they are large enough to influence oil prices and have substantial excess capacity that allows them more production flexibility with which they can act strategically. Furthermore, OPEC Core producers tend to have much lower extraction costs

[11] Other studies have used the assumption that a subset of OPEC acts as the dominant producer. Alhajji and Huettner (2000) suggest that Saudi Arabia was the dominant producer with the rest of OPEC behaving as a competitive fringe. Huppmann and Holz (2012) find that observed prices are very close to those from a Stackelberg model, with Saudi Arabia acting as the Stackelberg leader. Nakov and Nuno (2013) model Saudi Arabia as the dominant producer and the rest of oil producers as a competitive fringe. While the Bornstein et al. (2022) benchmark model assumes OPEC is a cartel facing a competitive fringe, they also consider a case where a subset of OPEC producers deviate from the dominant producer's decision rule and act as price takers.

than other OPEC producers. Asker et al. (2019) examine detailed cost data from oil fields around the world and find OPEC-Core producers are producing at levels where marginal costs are substantially lower than those of the rest-of-OPEC producers. We take this as consistent with OPEC Core exercising its market power by restricting output so that price exceeds marginal cost, while the remaining OPEC members act more like competitive fringe producers that equate marginal cost to market price.[12]

4 Dynamic Model of the Oil Market

In this section we develop a dynamic model of the oil market that is rich enough to match actual market outcomes and reflects the ongoing shale revolution. We model world oil supply as composed of a dominant producer along with the competitive fringes of conventional and shale producers. $Q_{o,t}$ denotes the dominant producer which we take as OPEC Core, $Q_{f,t}$ is conventional fringe production, and $Q_{s,t}$ is shale fringe production. We assume the dominant producer takes into account how the competitive fringe (both shale and conventional) will respond to market prices. We allow the elasticities of supply and demand to be different in the short- versus the long-run. In particular, we view production as having two margins of adjustment: production capacity provides the long-run margin, while capacity utilisation provides the short-run margin. The costs of adjusting capacity result in medium-run supply elasticities that are a weighted average of short and long-run supply elasticities.

[12] Asker et al. (2019) examine production cost data from over 13,000 oil fields around the world and find that unit costs for the production fields in Saudi Arabia and Kuwait are substantially lower than other prominent non-core OPEC producers. In addition, Asker et al. (2019) conduct a competitive market counterfactual where producers set production so that marginal cost equals price and show that OPEC Core producers would substantially increase their production while most of the rest-of-OPEC would cut back on production.

4.1 Dynamic demand

We consider a simple dynamic demand function which incorporates long-term and short-term demand:[13]

$$Q_t = Q(p_t, Q_{t-1}, x_{d,t})$$

where Q_t is the quantity demanded in time period t, and $x_{d,t}$ represents a non-price demand shifter. This results in an inverse demand curve of the form

$$P_t = P(Q_t, Q_{t-1}, x_{d,t}) \tag{1}$$

whose specific functional form will be discussed in detail later. The total supply of oil is

$$Q_t = Q_{o,t} + Q_{f,t} + Q_{s,t}. \tag{2}$$

Substituting (2) into (1), yields the market clearing equation:

$$P(Q_{o,t} + Q_{f,t} + Q_{s,t}, Q_{o,t-1} + Q_{f,t-1} + Q_{s,t-1}, x_{d,t}) = P_t. \tag{3}$$

4.2 Dynamic supply

Conventional oil production typically has a lengthy initial development phase. This limits producers' ability to adjust production in the short-run in response to market forces. Over the long run, producers can explore, appraise and develop more oil fields. As noted previously, shale production technology tends to shorten the development phase, and suggests that shale

[13] Atkeson and Kehoe's (1999) Putty-Clay technology suggests a demand for oil whose short-term and long-term price elasticities are different.

producers differ from conventional producers in how quickly they can respond to changing market conditions.

In order to capture the different responsiveness of short and long-run supply across different producers, we assume that all three types of producers make two choices that jointly determine output: production capacity and capacity utilisation. Specifically, $Q_{j,t} = u_{j,t}k_{j,t-1}$, $j = o, s, f$, where one can think of $k_{j,t-1}$ as the production capacity available in t which is predetermined in time period t and $u_{j,t}$ is the current utilisation rate of capacity. In each period, producers choose their current utilisation rate, $u_{j,t}$, and next-period's capacity $k_{j,t}$. This "time-to-build" feature of capacity reflects that substantial resources must be spent before production is realised. We take the time interval in the model to be a quarter; thus, within the quarter changes in supply can only occur by changing utilisation.

Oil producers incur two types of costs. The first is the direct operating cost or "production cost". This cost reflects the cost of current production given current capacity. The second is the cost of changing capacity. This second cost reflects the costs of exploration and developing new oil fields. Shale and conventional producers will differ both in their production cost and their costs of changing capacity.

We model oil producers as intertemporal profit maximisers where $\pi_{j,t}$ is the profit of supplier "j" with intertemporal profits given by:

$$\underset{t}{E}\sum_{i=0}^{\infty}\beta^{i}\pi_{j,t+i} \tag{4}$$

where β is the discount factor and

$$\pi_{j,t} = P_t u_{j,t}k_{j,t-1} - C_j(u_{j,t}, k_{j,t-1}, k_{j,t}) \tag{5}$$

where $C_j(u_{j,t}, k_{j,t-1}, k_{j,t})$ is the sum of production and development costs. Profit in time period t is revenue from current production less the costs of current production and the costs of changing capacity and is affected by current capacity, $k_{j,t-1}$, utilisation, $u_{j,t}$, and next-period capacity, $k_{j,t}$.

4.2.1 Competitive fringe and OPEC Core

Both conventional and shale fringe producers ($j = f, s$) are competitive price takers and choose $u_{j,t}$ and $k_{j,t}$ to maximise the present value of profits. The first order conditions for fringe producers are given by:

$$\frac{\partial \pi_{j,t}}{\partial u_{j,t}} = 0 \tag{6}$$

$$\frac{\partial \pi_{j,t}}{\partial k_{j,t}} + \underset{t}{E}\left[\beta \frac{\partial \pi_{j,t+1}}{\partial k_{j,t}}\right] = 0 \tag{7}$$

where $\pi_{j,t}$ is period t profits defined by equation (5). By choosing $u_{j,t}$, the fringe equates the marginal cost of increasing current utilisation to price. Similarly, by choosing $k_{j,t}$ the fringe producer is trading off the costs of changing capacity against its effect on $t+1$ revenue. Equation(7) describes the intertemporal trade-off between the costs of changing capacity ($\frac{\partial \pi_{j,t}}{\partial k_{j,t}}$) and future revenue ($\frac{\partial \pi_{j,t+1}}{\partial k_{j,t}}$).

We distinguish between OPEC Core and the competitive fringe by allowing OPEC Core to take its market power into account when making its production decision. We assume that OPEC Core is acting strategically as a Stackelberg leader. OPEC Core chooses $u_{o,t}$ and $k_{o,t}$ to maximise the present value of profits and considers how prices (current and future) and the competitive fringe (both conventional and shale) respond to its production decisions. In each period OPEC Core anticipates that its choice of current utilisation and next-period's capacity will affect current and next period's price and, hence, influence the competitive fringe's decisions about its current utilisation and next-period capacity.

Formally, we set up OPEC Core's problem as a constrained optimisation problem where the market clearing conditions and the fringe's optimality conditions enter as constraints.[14] The choice variables will include not only $u_{o,t}$ and $k_{o,t}$ but also market price, P_t and both conventional and shale fringes' utilisation and capacity, $u_{j,t}$ and $k_{j,t}$ for $j = f, s$. Thus, we can think of the dominant firm solving the following dynamic problem:

$$\max_{u_{o,t},\ k_{o,t},\ P_t,\ u_{j,t},\ k_{j,t},\ j=f,s} \underset{t}{E} \sum_{i=0}^{\infty} \beta^i \pi_{o,t+i} \tag{8}$$

subject to constraints given by the market clearing condition (equation (3)) and the first-order conditions of the fringe producers (equations (6), and (7) for $j = f, s$). We consider time consistent choices on the part of the dominant producer, so that the first order conditions that characterise time t decisions will also characterise future decisions.[15] Appendix A presents the detailed first-order conditions for OPEC Core.

4.3 Specific functions for Oil Demand and Production Costs

In order to take the above model to the data, we must assume particular functional forms for oil demand and for the various production costs.

[14]This model uses a very similar structure to that in the Ph.D. dissertation of Jin (2013). Bornstein et al. (2022) also approach the dominant producer's optimisation problem in similar way as we do. See Appendix A for fuller description of OPEC Core's optimisation problem.

[15]In general, the dominant producer's optimal price path is not time consistent. While the dominant producer might want to set a particular future price in order to influence the competitive fringe's choice of future capacity, the dominant producer has an incentive to change its mind and select a different price when the "future arrives", since the fringe's capacity is already set. Thus, the original price path is not time consistent. Here we consider the case where the dominant producer cannot credibly commit to the optimal price path and follows a time consistent pricing strategy. Jin (2013) considered the commitment case but preliminary analysis found little empirical difference between the commitment and the time consistent models in our application.

4.3.1 Oil Demand

We assume that the current period demand for oil has the following form

$$Q_t = x_{d,t} \left(\frac{Q_{t-1}}{x_{d,t-1}} \right)^{\rho_d} P_t^{-\eta_d (1-\rho_d)} \tag{9}$$

where Q_t is quantity demanded in time t. $x_{d,t}$ is an exogenous demand shifter. Our demand function implies a long-term elasticity of demand of $-\eta_d$ and a short-term elasticity of demand of $-\eta_d(1 - \rho_d)$ where ρ_d reflects the inertia in demand's response to price changes in the short-run.

We assume that $x_{d,t}$ in turn is given by:

$$x_{d,t} = x_{b,t} x_{c,t} x_{i,t} \tag{10}$$

where $x_{b,t}$ is a deterministic balanced growth trend, $x_{c,t}$ reflects demand for oil arising from cyclical fluctuations in world economic activity, and $x_{i,t}$ reflects demand changes that are idiosyncratic to the world oil market. In the data, there is a clear steady upward trend in oil production but no such trend is discernible in oil prices. To capture this feature of the data, we include a balanced growth trend component which will affect both oil demand and oil supply proportionately so that oil output is affected but oil prices are not. We model the balanced growth as a deterministic trend (in logarithms) that implies world oil output would be growing roughly 0.9% per year, absent the shale revolution.

In our empirical analysis below, we model the cyclical component of oil demand as:

$$log(x_{c,t}) = \eta_y log(WEA_t) \tag{11}$$

where η_y is the elasticity of oil demand with respect to world economic activity and $log(WEA_t)$ is a measure of world economic activity. In turn, we assume that $log(WEA_t)$ follows an AR(2) process. Finally, we model the oil specific demand component $log(x_{i,t})$ as an AR(1) process.[16]

4.3.2 Cost Functions for Oil Production

We specify the cost functions in order to capture the different responsiveness of oil supply in the short, medium, and long runs. This reflects differences in the direct production cost for field operations and investment costs of development of new fields. As world oil production has grown steadily over our sample, we do not model the extraction and depletion of oil reserves. The relatively steady increase in world oil production suggests that not modelling these elements is unlikely to be an important oversight when modelling oil market dynamics over our sample period.

We model production costs as:

$$C_j(u_{j,t}, k_{j,t-1}, k_{j,t}) = (c_j(u_{j,t}) + \phi_j(k_{j,t-1}, k_{j,t}))\ \ z_{j,t}\frac{k_{j,t-1}^{(1+\frac{1}{\eta_{k,j}})}}{(1+\frac{1}{\eta_{k,j}})} \tag{12}$$

Producers' ability to adjust output in the short-run is limited. Given current capacity, producers can only adjust the utilisation rate $u_{j,t}$ within the current period. The cost associated with the choice of utilisation rate is given by $c_j(u_{j,t})$ where

$$c_j(u_{j,t}) = c_{0,j} + c_{1,j}u_{j,t}^{(1+\frac{1}{\eta_{u,j}})}. \tag{13}$$

[16]See Appendix A for a fuller description of the demand processes.

The parameters $c_{0,j}$ and $c_{1,j}$ are chosen to normalise utilisation and the cost function $c_j(u_{j,t})$ to be one in the steady state ($u_{j,ss} = 1$ and $c_j(1) = 1$).[17] The costs of adjusting capacity are given by $\phi_j(k_{j,t-1}, k_{j,t})$. Here we assume these are quadratic:

$$\phi_j(k_{j,t-1}, k_{j,t}) = \frac{\kappa_j}{2}\left(\frac{k_{j,t}/x_{b,t}}{k_{j,t-1}/x_{b,t-1}} - 1\right)^2 \tag{14}$$

We normalise the adjustment costs in capacity so that in the balanced growth steady state those costs are zero. This ensures that long-run costs are determined solely by $z_{j,t}\frac{k_{j,t-1}^{(1+\frac{1}{\eta_{k,j}})}}{(1+\frac{1}{\eta_{k,j}})}$.

Appendix B derives the short, medium, and long-run supply elasticities for price-taking producers. For price-taking producers the long-run (balanced growth steady state) elasticity of supply is given by $\eta_{k,j}$. The parameter $\eta_{u,j}$ is the short-run (within a period) elasticity of supply. For the case of a permanent increase in price, our specification of adjustment costs implies that the medium term supply elasticity is a weighted average of the long-run and short-run supply elasticities: $\frac{dlog(Q_{t+n})}{dlog(P)} = (1 - \phi_{1,j}^n)\eta_{k,j} + \phi_{1,j}^n\eta_{u,j}$. Since $0 < \phi_{1,j} < 1$, the further in the future, the greater the weight on the long-run elasticity of supply. As the adjustment cost parameter κ_j approaches zero, $\phi_{1,j}$ approaches zero while as κ_j approaches infinity, $\phi_{1,j}$ approaches one. As a result, three parameters, $\eta_{u,j}, \eta_{k,j}$, and κ_j, effectively govern the medium-run elasticity of supply.

All three producers are periodically hit with cost shocks that change the cost of production. We assume that this cost shock consists of two components:

$$z_{j,t} = \frac{v_{j,t}}{x_{b,t}^{\frac{1}{\eta_{k,j}}}} \tag{15}$$

[17] This implies $c_{0,j} = \frac{(\frac{1}{\eta_{u,j}} - \frac{1}{\eta_{k,j}})}{1+\frac{1}{\eta_{u,j}}}$ and $c_{1,j} = 1 - c_{0,j}$.

where $v_{j,t}$ is a producer j specific cost shock and $x_{b,t}$ is the balanced growth trend that is common to all producers. Note that the balanced growth trend will affect the output of all producers as well as demand proportionately; an increase in the balanced growth variable increases market output but has no affect on the market price. Furthermore, as all producers' costs are affected proportionately, the balanced growth trend will not affect the relative market share of producers in the long run.

4.4 The shale revolution

We model the shale revolution as a dramatic and permanent decrease in the cost of shale production and investment. In our model, this takes the form of a permanent decrease in $v_{s,t}$. As the increase in shale production has been gradual over our sample, we will model the transition from the originally low shale production to a substantially higher production in the future. We take the advent of the shale revolution to be in 2005 quarter 1, when shale's share of global production was less than 0.5 percent. We take the ultimate shale share of global production to be 20 percent.[18] We assume an "S" shaped transition curve from the low shale steady state to the high shale steady state. Specifically, we set

$$log(v_{s,t}) = log(v_{s,t}^{temp}) + log(v_t^{perm}) \tag{16}$$

where $log(v_{s,t}^{temp})$ is a temporary cost shock for shale production (which follows an AR(1) process) while $log(v_t^{perm})$ is the permanent transition from the old steady state to the new

[18] The consulting firm Rystad predicts that shale's share of global production will be 20 percent in 2050, Rystad (2022).

steady state. For t < 2005, $log(v_t^{perm}) = log(v_{old\ ss}^{perm})$. For t $\geq$ 2005Q1,

$$log(v_t^{perm}) = log(v_{new\ ss}^{perm}) + 2\rho_{v_s}(log(v_{t-1}^{perm}) - log(v_{new\ ss}^{perm})) - \rho_{v_s}^2(log(v_{t-2}^{perm}) - log(v_{new\ ss}^{perm})) \tag{17}$$

The values of $v_{old\ ss}^{perm}$ and $v_{new\ ss}^{perm}$ are chosen so that shale's share in global oil production is 0.5 and 20 percent, respectively. The value of ρ_{v_s} controls the shape of the transition from the old steady state to the new steady state. Values in the range (0.90, 1.00) imply an "S" shaped transition in (log) shale's share of world production. We estimate the value of ρ_{v_s} in our empirical analysis below.[19]

5 Empirical model

In this section, we derive the model that we will use in our empirical analysis. We also describe the Bayesian estimation method and the prior distributions over the parameters. One of the innovations in our analysis is that we take the transitional nature of the dynamics into account, both in terms of the dynamic evolution of shale costs but also in the solution of the model. Appendix C contains a detailed description of our solution technique.[20]

5.1 Model solution and approximation

The model outlined in Section 4 can be written as a system of nonlinear difference equations:

$$\underset{t}{E}\left[g(\boldsymbol{X_t}, \boldsymbol{X_{t+1}}, \boldsymbol{X_{t-1}}, \boldsymbol{e_t}, v_{old\ ss}^{perm}, \Theta)\right] = 0, \quad t < 2005Q1 \tag{18}$$

[19]S-shaped diffusion curves have been used widely in the literature to model technology adoption. See Comin and Mestieri (2014).
[20]We use a combination of modified Dynare subroutines and our own custom written matlab scripts to solve and estimate the model. These are available upon request.

and

$$\underset{t}{E}\left[g(\boldsymbol{X_t}, \boldsymbol{X_{t+1}}, \boldsymbol{X_{t-1}}, \boldsymbol{e_t}, v^{perm}_{new\ ss}, \Theta)\right] = 0, \quad t \geq 2005Q1 \tag{19}$$

where $\mathbf{X_t}$ is $n \times 1$ vector of endogenous variables, $\mathbf{e_t}$ is $p \times 1$ vector of exogenous, i.i.d. N(0,1) shocks, and Θ are structural parameters of the model. $\mathbf{X_t}$ includes variables such as market price, the decision variables of the three producers, and the current values of demand and production cost shifters. The vector e_t contains shocks to oil specific demand, to world economic activity, and to the three producers' costs. $v^{perm}_{old\ ss}$ is the steady state of shale producers' production cost before the shale revolution while $v^{perm}_{new\ ss}$ is the post-shale steady state production cost. The only difference between the system of equations given by (18) and (19) is the steady state of shale's production cost. From the perspective of time periods before 2005, the success of the shale revolution has been almost certainly a surprise. However, once the revolution began, it is likely that market expectations about the long-run prospects of shale increased dramatically, so that the market expects shale's share in the future to be substantially higher that its current share. To capture this potentially changing view of the importance of shale oil, we assume that market participants changed expectations about shale in 2005Q1 and have perfect foresight about the transition path of shale costs given by equation (17).

Typically, a model such as implied by equation (18) or equation (19) would be approximated linearly around a deterministic steady state and the resulting linear rational expectations equations solved using standard methods. In our case, a substantial component of the dynamics once the shale revolution begins (t>2005Q1) will reflect the transitional dynamics of moving from the old steady state to the new steady state. The variable that governs the transition from the old steady state to the new steady state is largely the permanent component of shale production costs, v_t^{perm}. Recall that we set the original steady state value, $v_{old\ ss}^{perm}$ so that shale's share of the world oil market is 0.5% while the new steady state value results in a shale market share of 20%. A linear approximation around the old steady state might be appropriate early in the transition but less appropriate later in the transition. Similarly, a linear approximation around the new steady state might be appropriate late in the transition but less so early in the transition. Because the transition path implies shale's share of global output is gradually rising, we take a sequence of first order approximations as shale costs transition toward the new steady state. That is, the sequence of linear approximations depends on the value of the transition variable, v_t^{perm}. We assume that economic agents are anticipating the continuing transition to shale and so will know the future values of v_t^{perm}. We start with the model evaluated at the new shale steady state, then work backwards in time updating the approximation periodically based on the transition variable, v_t^{perm}. See Appendix C for a fuller description of the solution method.[21]

The resulting solution implies a time varying parameter model of the following form:

$$\mathbf{X_t} = \mathbf{G^{[t]}} + \mathbf{P^{[t]}}\mathbf{X_{t-1}} + \mathbf{Q^{[t]}}\mathbf{e_t} \tag{20}$$

The matrices $\mathbf{G^{[t]}}, \mathbf{P^{[t]}}$, and $\mathbf{Q^{[t]}}$ depend on the deep model parameters such as elasticities of supply and demand, the adjustment cost parameters and the parameters of the shock processes along with the values of $\log(v_t^{perm})$ used to approximate the model along the transition path. One can view the solution to the model as time-varying VAR(1) whose parameters change along the transition path. Finally, with the exception of shale transition

[21] Our approach is similar to the piece-wise linear approximation of Guerrieri and Iacoviello (2015).

costs, all demand and producer cost shocks in the model are treated as stochastic. This allows us to evaluate the model's implications for the volatility of oil prices along the transition path.

5.2 Estimation equations

One can think of the empirical model as a state space model with observation equations given by:

$$\mathbf{Y_t^{obs}} = \mathbf{HX_t} \tag{21}$$

where $\mathbf{Y_t^{obs}}$ is the vector of observable variables and $\mathbf{H}$ is a selector matrix that pulls the observable variables from the variables in the model. Since we assume the transition from the pre-shale steady state to the post-shale steady state is deterministic and known to economic agents, we can use a standard Kalman filter to evaluate the model likelihood. Recall that there are five structural shocks: oil specific demand shocks, shock to world economic activity, and costs shocks to conventional fringe, shale, and OPEC Core producers. As a result, we will use five observables when estimating the model.

5.3 Data

Table 1 lists the observable variables in our empirical analysis. Along with real oil price and world oil production, we include the share of OPEC Core and US shale's share of world oil production. The data for the project were downloaded from the Haver Analytics Database. Haver Analytics is a private database with data sourced from both private and public resources. The oil production data are crude oil and lease condensate, sourced from the EIA's Petroleum and Liquids: International data, Energy Information Administration

(2022a). The shale data are sourced from the EIA's Drilling Productivity Report, Energy Information Administration (2022b). Given that the focus of our analysis is the effect of shale oil's development on the world oil market, we use market level data rather than individual firm data to estimate the parameters of cost functions of the various oil producers. We use the Brent oil price, as it is the benchmark price that is used most widely around the world, and deflate it by the U.S. CPI.[22] The Brent price is sourced by Haver from the EIA: Petroleum and Other Liquids, Spot prices- Brent, Energy Information Administration (2022c). The CPI is CPI-U: All Items (NSA, 1982-84=100), sourced from the Bureau of Labor Statistics, Bureau of Labor Statistics (2022). As an indicator of world economic activity, We divide Brent oil price by the CPI and normalise the resulting real price series to be 100 averaged over the 1991-2005 time period. Similarly, for output we normalise output so that its is equal to 100 over the 1991-2005 time period. As an indicator of world economic activity, we include de-trended log world industrial production from Baumeister and Hamilton (2019).[23] Our data are quarterly and the sample period runs from 1991Q1 to 2021Q3. We treat shale share observations before 2009 as missing when estimating the model. Before 2009, the infrastructure for shale production was not fully developed suggesting shale data before 2009 is not likely to be as good an indicator of shale's key cost parameters as data after 2009.[24]

[22]WTI and Brent have historically moved together, but there was a divergence between these prices in 2011 due to the shale boom and pipeline bottlenecks. See (Buyuksahin et al., 2013; Bornstein and Kellogg, 2014; Agerton and Upton, 2019; Langer and Lemoine, 2020; Plante and Strickler, 2021)

[23]We use a linear time trend to de-trend log world industrial production.

[24]We thank an anonymous referee for pointing this out to us. This is also consistent with Walls and Zheng (2022) who find a structural break-point in overall U.S. shale supply in 2008. Plante and Strickler (2021) also find a structural break in price differentials among global crude around 2008. They note that one reason is a fundamental, long-lasting change in the global oil market due to the shale oil boom.

5.4 Prior distribution of parameters

Given shale oil's recent emergence as an important factor in the world oil market, there is a limited sample period over which to estimate market-level shale supply elasticities. However, as noted above, there is a growing literature that makes use of micro or firm-level data to assess the responsiveness of shale (and conventional) oil production to market prices. Bayesian methods provide a way of drawing on this growing literature as well as using oil market data to estimate the parameters of the model. We use recent research to inform the prior distributions of supply elasticities for shale and non-shale producers.

As is well known, shale oil production is called 'short-cycle' compared to conventional oil.[25] This characteristic of shale oil leads to much higher elasticities of supply, especially in the long run.[26] In a recent paper, Walls and Zheng (2022) estimate short and long run elasticities for shale and non-shale regions in the U.S. using monthly data. After controlling for endogenous oil prices, they find the short-run shale elasticity for a price rise to be 0.12 and the long-run elasticity to be 1.67. Their elasticities for a price cut are somewhat smaller, with 0.07 for the short-run and 0.993 for the long-run elasticity. Similarly, Vatter et al. (2022) in a Bakken Case study, find much higher supply elasticities for shale than for conventional oil. Their three-month supply elasticity is 0.23, the one-year is 1.14 and the eight-year is 1.95.

[25] Conventional production 'stands in stark contrast to modern unconventional extraction from shale, which is commonly said to resemble a 'manufacturing process' in that operators have much more flexibility and can control their production levels' (Newell et al., 2019). Hydraulic fracturing has 'a qualitatively, materially different temporal and physical scale of production compared to new conventional wells-one that allows for short, granular investment opportunities that new conventional production does not', according to Eckhouse (2021).

[26] For example, Newell and Prest (2019) note that the price responsiveness of post-shale U.S. supply is 13 times that of pre-shale supply.

Conventional oil production is less responsive to price changes and, hence, estimated elasticities in the literature are lower. Walls and Zheng (2022) find that supply elasticities for non-shale, conventional oil in the producing areas of the U.S. are smaller than those for shale. The short-run elasticity for a price rise is 0.035 (0.044 for a price cut) and the long-run elasticity is 0.339 for a price rise (0.43 for a price cut). In a survey of several papers with structural vector-autoregressive models, Herrera and Rangaraju (2020) find very low short-run elasticities of supply ranging from 0.0 to 0.14 for global oil supply (which includes small amounts of shale, depending on the time-frame of the study). The supply elasticities found in Caldara et al. (2018) range from 0.021 to 0.081, depending on the specification of the model. Vatter (2017) estimates the non-OPEC elasticity of supply as 0.24 and Golombek et al. (2018) find the long-run non-OPEC supply elasticity to be 0.32.[27].

Table 2 displays the structural parameters along with their specified values or prior distributions. Based on the above studies, we choose the mode of the prior distributions for the short-run supply elasticity of shale ($\eta_{u,s}$) to be 0.2 and 1.0 for the long-run supply elasticity ($\eta_{k,s}$). As the medium-run elasticities of supply depend on the adjustment cost parameter (as well as the short- and long-run supply elasticities) we set the mode of the prior distribution for the adjustment cost parameter for shale, κ_s, so that at horizon of two years the mode of prior distribution of the shale supply elasticity is 0.5.[28] For conventional producers, we set the mode of the prior distributions of short-run, long-run, and medium-run supply elasticities to be half of those of shale, or 0.1, 0.5, and 0.25 respectively. We set the

[27] Again, non-OPEC includes shale in these papers.

[28] To calculate the prior distribution of the medium-run supply elasticities, we randomly draw from the prior distributions of $\eta_{u,s}$, $\eta_{k,s}$, and κ_s and use the formula for medium-run elasticity of supply derived in Appendix C. See Figure C2 in Appendix C for a box plot of the prior distribution of medium-run supply elasticites for shale, conventional fringe, and OPEC Core.

dispersion for these prior distributions to be fairly wide as there is a substantial range of estimates for the supply elasticities for shale oil and for the conventional fringe.

For OPEC Core, the cost parameters do not correspond directly to supply elasticities as OPEC Core is not a price taker. However, if costs are not responsive to production decisions, then in our framework, that would be equivalent to having high values of $\eta_{u,o}$ and $\eta_{k,o}$. Compared to conventional fringe producers, OPEC Core producers have more excess capacity and can be more responsive to oil prices than other conventional producers, if they choose to do so.[29] This flexibility and their share of world oil production gives them substantial market power. For the short-run, long-run, and medium-run elasticities of supply, we assume prior distribution for OPEC core to be the same as shale oil, roughly twice as high as conventional producers. Similar to shale and conventional fringe parameters, we set prior distributions that are fairly dispersed.

As for the other parameters in the model, the discount factor is not estimated but is set a priori. The deterministic balanced growth rate is set at a 0.22% quarterly growth rate. For shock parameters, such as the autoregressive parameters and the variances of the shock processes, the prior distribution is relatively uninformed. These parameters will largely be determined by the data. We set the mode of the prior distribution for the long run elasticity of demand to be -0.5 and the short-run elasticity of demand to be -0.1 which are within the bounds of demand elasticities found in the literature.[30]

[29] The EIA notes that Saudi Arabia, the largest oil producer within OPEC and the world's largest oil exporter, historically has had the greatest spare capacity. 'Saudi Arabia has usually kept more than 1.5 - 2 million barrels per day of spare capacity on hand for market management.' Energy Information administration (2022). Recall that President Biden traveled to Saudi Arabia in July 2022 in an attempt to coax the Saudis to increase their oil output to offset the disruption in world oil supply as a result of the Russian invasion of Ukraine.

[30] For example, Caldara et al. (2018) find short-run demand elasticities of -0.017 to -0.08. Herrera and Rangaraju (2020) document the wide distribution of short-run demand in the literature with demand elasticities ranging from -0.087 to -1.72.

6 Estimation results

We estimate the model using Bayesian methods similar to An and Schorfheide, (2007). We use a random walk, Metropolis-Hasting MCMC to simulate the posterior distribution of the parameters. We take 300k draws from the Markov Chain, discard the first 100K draws and take the last 200k to form an estimate of the posterior distribution of the parameters using every 10th draw.[31] From this posterior distribution, we calculate the posterior distribution of various functions of the parameters and the model such as steady state values implied by the model, impulse responses, medium-run supply elasticities, and conditional variance decomposition along the transition path, and historical decomposition of oil market variables.

6.1 Posterior distribution of model parameters

Table 3 displays the mode, mean, 5th and 95th percentiles of the posterior distribution of the structural parameters. The mean of the posterior distribution for the long-run elasticity of demand was estimated to be -0.17 and the posterior distribution for this parameter is relatively tight compared to the prior distribution. Somewhat surprisingly, given our priors, we estimate the short-run and long-run elasticity of oil demand to be very similar. While not differentiating between short- and long-run elasticities of demand, Bornstein et al. (2022) also estimate the elasticity of demand to be quite low (-0.15). The mean of the posterior distribution of the elasticity of oil demand with respect to economic activity is around 1.41 which is higher than that implied by the prior distribution.

[31]We first find the Θ that maximises $\log[l(\Theta|Y)p(\Theta)]$ where $l(\Theta|Y)$ is the likelihood and $p(\Theta)$ is the prior density of the parameters. Θ is used to initialise the MCMC. The inverse Hessian w.r.t. Θ is used to generate candidate draws in the MCMC. The scale parameter for the candidate distribution is set so that approximately 30% of the candidate draws are accepted.

The posterior distribution of the conventional fringe's long-run cost parameter (and its long-run supply elasticity), $\eta_{k,f}$, has a mean of 0.32 with the 5th to 95th percentile range of (0.16, 0.80). The posterior distribution is slightly shifted downward relative to the prior distribution for this parameter. The mean of the posterior distribution for OPEC Core's and shale's long-run cost parameters, $\eta_{k,o}$ and $\eta_{k,s}$, were 0.91 and 0.92, respectively. The 5th to 95th percentile ranges were also similar. For these parameters, the posterior and prior distributions are quite similar suggesting the data are not particularly informative about them. For shale, this is perhaps not too surprising given the relatively short sample period over which we estimate the model.

The posterior distribution of the short-run cost parameters are estimated to be substantially lower than the long-run cost parameters. Indeed, the posterior distribution suggests lower short-run cost elasticities than assumed by the prior distributions. In fact, most of the mass of the posterior distribution for conventional producers was on values less than 0.10. For OPEC core and Shale, the mean of the posterior distribution for the short-run cost parameter was nearly three times higher than that for the conventional fringe. The posterior distributions of the adjustment costs for OPEC Core and shale are substantially different from the prior distribution, suggesting relatively fast adjustment (particularly for OPEC core) than that implied by the prior distribution.

Finally, the parameters of the shock processes are fairly persistent and have much tighter posterior distributions than was assumed for the prior distributions of these parameters. The three cost shocks have similar standard deviations suggesting supply disturbances arising from the three types of producers of similar magnitudes. The posterior distribution of the shale cost transition parameter (ρ_{v_s}) is tightly centered around 0.96 which suggests a fairly slow transition to shale steady state.

6.2 Posterior distribution of medium-run elasticities of supply

While the structural parameters in the cost functions of different producers ($\eta_{k,j}$ and $\eta_{u,j}$, $j = f, s, o$) are the long-run and short-run supply elasticities for shale and conventional producers, for OPEC core they are not identical to the price elasticity of supply. Furthermore, the overall market supply elasticities depends on the individual producers' supply elasticities as well as their relative shares in market supply. In order to measure market supply's responsiveness to price changes from our dynamic model, we calculate pseudo-supply elasticities . Specifically, we take the response of log output to an oil-specific demand shock relative to the response of log market price to the same shock:

$$\frac{E[log(Q_{t+k})|e_{i,t}, \mathbf{Y_{t-1}}] - E[log(Q_{t+k})|\mathbf{Y_{t-1}}]}{E[log(P_{t+k})|e_{i,t}, \mathbf{Y_{t-1}}] - E[log(P_{t+k})|\mathbf{Y_{t-1}}]}. \tag{22}$$

where $e_{i,t}$ is the oil-specific demand shock. We do this at various horizons and extract the medium-run elasticities of supply. As oil-specific demand shocks are fairly persistent, the change in price and output are fairly long lasting and, thus, the ratio given by (22) is well defined.[32]

Table 4 displays the mean, 5th and 95th percentiles of the posterior distribution for pseudo-supply elasticities for various horizons. Panel A displays the supply elasticities in the pre-shale steady state, Panel B displays supply elasticities in 2021Q3 which is roughly

[32]When calculating expectations in equation (22), we took into account that the parameters of the state space model used to form expectations of price and output were changing over time as in equation (C.7) in Appendix C.

halfway through the transition from the pre-shale to the post-shale steady state, and Panel C displays the supply elasticities in the post-steady state. Shale supply elasticities are substantially higher and increase faster as the horizon lengthens compared to conventional producers. Shale supply elasticities are typically more than double those of conventional producers. Because conventional and shale fringe producers are price takers, the increasing share of shale in the world oil market does not appreciably affect their supply elasticities; hence, these supply elasticities are very similar across the three panels.[33]

On the other hand, the implied supply elasticity of OPEC Core and the overall market supply elasticity changes across the three panels, especially at longer horizons, getting larger as shale's share increases. Comparing pre-shale elasticities (Panel A) with those in 2021Q3 (Panel B), at horizon of a quarter OPEC Core's pseudo-supply elasticity rises from 0.105 to 0.117, a 12% increase. At longer horizons, the increase in elasticities is even larger. At a five year horizon, OPEC Core's pseudo-supply elasticity rises from 0.332 to 0.455, a 36% increase. Once the shale transition is complete, OPEC Core pseudo-supply elasticities rise by 26% (0.105 to .133) at a quarter horizon and by 65% (0.334 to 0.551) at a five year horizon. The increase in OPEC Core's supply elasticitiy suggests that OPEC Core's strategic calculus changes as shale's share gets larger, resulting in greater sensitivity to demand shocks.

Similarly, the overall market supply elasticity rises as shale's share increases. This is due to the declining share of low supply elasticity producers (conventional fringe), the increase in the share of higher supply elasticity producers (shale producers), and the increase in the supply elasticity of OPEC Core. Together these imply, once the shale transition is complete, increases in the market supply elasticity of 33% (0.073 to 0.097) at the one quarter

[33] Our estimates are very similar to those of Bornstein et al. (2022) who estimate the short-run elasticity of supply to be 0.05 using field-level data.

horizon and 59% (0.269 to 0.429) at the five year horizon. The transition period (Panel B) suggests increased elasticities of supply roughly halfway between the pre-shale and post-shale elasticities (increases of 13% to 0.083 at the one quarter horizon and 31% to 0.354 at the five year horizon), which implies that even now, shale production is substantially increasing the market elasticity of supply.

6.3 Posterior distribution of the new shale steady state

Table 5 displays the posterior distribution of the post-shale deterministic steady states for oil price, output, and output shares. The variability in the posterior distribution of these variables depends on the variability in the underlying structural parameters of the model. In the long-run, the model implies that the shale revolution will ultimately lower the real oil price by about 46% (evaluated at the posterior mean) and the 5th-95th percentile range suggests a 26%-56% decline in oil prices. Market output is expected to increase by roughly 11% (relative to the balanced-growth trend). By construction, shale's share is constrained to be 20% in the post-shale steady state. Conventional fringe producers' market share falls from around 80% of the market to around 60% of the market. Despite the dramatic increase in shale production, the model predicts that OPEC core will adjust its production to keep its market share steady. [34]

The shale revolution lessens the ability of OPEC Core to exert its market power. Panel B of Table 5 displays the markup of price over marginal cost in the steady state implied by

[34] Bornstein et al. (2022) find a 46% reduction in the price of oil in the steady state, although they predict the share of OPEC in oil production will fall from 42.3% to 40.1%.

the estimated model.[35] The price-marginal cost ratio implied by the model in the pre-shale steady state is around 11 with a 5th-95th percentile range of (6.9, 15.4). The estimates suggest that OPEC Core had substantial market power before the advent of shale oil production. These estimates are roughly consistent with price and cost data in Asker et al. (2019).[36] In the post-shale steady state, the price-marginal cost ratio is halved to around 5.4. As the elasticity of shale supply is higher than that of conventional oil producers, the increase in shale's market share raises the elasticity of effective demand for OPEC Core oil and, hence, substantially lessens OPEC Core's ability to exert market power.

6.4 Sources of oil market fluctuations

Our model has insights about the sources of oil price and quantity movements over the 1991-2021 sample period. In particular, we can decompose movements in our observable variables into movements due to the accumulated structural shocks (oil specific demand, world economic activity, and temporary cost shocks to shale, conventional fringe, and to OPEC Core). We can also back out the contribution of the shale transition variable (v_t^{perm}) as it transitions from the old steady state to the new steady state. Figures 4 - 7 display historical decompositions for the oil market variables.[37] The shaded regions show the contributions of the various shocks while the black line in the figures is the actual observations. The contributions of the

[35]In the steady state, the price over marginal cost ratio is given by $\frac{\eta_d \frac{(1-\rho_d)}{1-\beta\rho_d}+\eta_{u,s}s_s+\eta_{u,f}s_f}{\eta_d \frac{(1-\rho_d)}{1-\beta\rho_d}+\eta_{u,s}s_s+\eta_{u,f}s_f-s_o}$, where s_s, s_f, and s_o are the market shares of shale, conventional fringe, and OPEC Core, respectively. The term $\eta_d \frac{(1-\rho_d)}{1-\beta\rho_d} + \eta_{u,s}s_s + \eta_{u,f}s_f$ is the steady state elasticity of OPEC Core's effective demand.

[36]Asker et al. (2019) find price-unit cost ratios for Saudi Arabia and Kuwait in the neighbourhood of 10. Given that we were not targeting price-marginal cost, getting estimates of the pre-shale price-marginal cost ratio close to those seen in the micro-data analysed by Asker et al. (2019) provides additional validation for our analysis.

[37]In our model, fluctuations in world economic activity are due entirely to shocks in world economic activity; thus, we do not include that decomposition here.

various shocks nearly add up to the actual time series by construction except for early in the sample.[38]

Figure 4 displays the historical decomposition of the (log) real oil price. The figure implies that most of the oil price movements over the sample are driven by oil specific demand shocks and conventional fringe supply shocks. Positive shocks to demand and negative shocks to conventional supply contributed to much of the increase in oil prices from the mid-2000s to 2008 and then from 2008 to 2011. In the context of our model, the decline in conventional fringe supply relative to trend shows up as conventional fringe cost shocks. Some of the dramatic increases in oil prices in the mid-2000s as well as the dramatic decline in oil prices in 2008-09 shows up in our framework as being driven by increases and then declines in world economic activity. The large decline in oil prices during the 2014-2016 period is largely attributed in our model to a decrease in oil specific demand and an increase in conventional fringe supply. This is in line with increases in global supply outpacing consumption in 2014 and 2015 by a million barrels per day, leading to a large increase in global inventories.[39] The dramatic decline in oil prices in the 2nd quarter of 2020 is largely attributed to the decline in world economic activity due to the coronavirus pandemic. Compared to other shocks, the direct contribution of shale cost changes to oil price movements over our sample are relatively modest. In 2021Q3, the direct effect of the shale revolution transition variable is to lower the real oil price by approximately 20%.

Figure 5 displays the decomposition of oil output over the 1991-2021 period. Unlike oil prices, the balanced-growth trend has an important effect on oil output movements,

[38]Early in the sample, the initial conditions for the unobserved shock processes contribute as well, but as the sample progresses the contribution of the initial conditions dies out. We leave out the contribution of the initial conditions to lessen the clutter in the figures.

[39]From November 2014 to October 2016, Iran and Iraq increased their output by 2.2 mb/d, which in our framework would be an increase in conventional supply.

contributing to the steady upward trend in world oil production. Oil demand shocks and conventional fringe cost shocks are also large contributors to oil output fluctuations, although their contributions tend to offset one another. Specifically, world economic activity and oil specific demand shocks in the 2000s contributed to higher oil output, while conventional fringe cost shocks contributed to lower oil output. The decline in economic activity as a result of the coronavirus pandemic largely contributed to the decline in world oil production that occurred in 2020Q2. On the other hand, the direct effect of the shale transition as well as temporary shale supply shocks on world oil production are relatively modest but growing in most of the sample. As of 2021Q3, this direct effect was still relatively small.

Figures 6 and 7 display the decomposition of (log) shale's share and (log) OPEC Core's share of world oil production. Unlike market price and output, the shale transition variable has a very large direct effect on shale's share and is largely responsible for the increase in shale's share over our sample.[40] However, shale's share also responds to other shocks. In fact, Figure 6 suggests that some of the increase in shale's share in the early 2010s is the result of oil-specific demand shocks and conventional fringe supply shocks that drove up the price of oil. Recall that estimated parameters suggest shale output is more sensitive to prices than the conventional fringe. Early in the transition period, the model suggests shale cost shocks contributed to lower than expected shale production. This may reflect the fact that we only use data after 2009 to estimate shale's cost parameters. As we argued previously, early in the transition shale infrastructure had not yet been fully developed and there were substantial

[40] The model implies shale's cost (evaluated at the posterior mean) has fallen by a factor of 13 from 2008 to 2021. Output over that time period increased by nearly a factor of 11, which is consistent with the long-run elasticity estimated around 0.9 and the price of oil close to being unchanged. For the same period, when measured by oil production per new well, productivity in the Bakken rose by a factor of 14, the Eagle Ford by a factor of 57, and the Permian by a factor of 19. These numbers are not out of line with the implied decline in costs that the model suggests.

learning-by-doing improvements in productivity that had yet to be realised. These “growing pains" in shale’s early development are reflected as adverse shale cost shocks in our model that eventually dissipate.[41]

OPEC Core’s share (see Figure 7) has fluctuated around a constant mean over most of our sample. Changes in the share have been largely in response to fluctuations in conventional fringe cost shocks and OPEC Core cost shocks. One interpretation of these OPEC Core cost shocks is that they reflect OPEC Core supply considerations that our simple model of strategic behaviour does not capture.[42] The decline of OPEC Core’s share in 2001 and 2002 follows a decision by Saudi Arabia to cut output (see New York Times (2002)). Similarly, in the face of deteriorating demand from the Financial Crisis, OPEC decided to cut production by 1.5 mb/d in August 2008 (see New York Times (2008)). However, by February 2009, all the decline in output came from OPEC Core, namely Saudi Arabia, whose output dropped by 1.6 mb/d from August to February. The shale transition and shale costs shocks have virtually no impact on OPEC Core share over our sample period. As we see below, OPEC Core acts to maintain its market share in the face of shale production changes. This is consistent with Bornstein et al. Bornstein et al. (2022) who also find that OPEC maintains its market share throughout the transition.

[41] A referee pointed out that some of our inferred adverse shale cost shocks in the 2011-2014 period could be due to the divergence of West Texas Intermediate oil price (which is more relevant to U.S. shale production) from the Brent oil price used in the estimation.

[42] For example, the declines in (log) OPEC Core’s share that occurred in 2002-03, in 2008-09 and again in 2015-2016.

7 Oil market in the transition to shale

In this section, we explore the model's predictions about transition path to the new shale steady state and the implications for oil price volatility along the transition path.

7.1 Expected transition path

Figure 8 displays the mean, 5th and 95th percentiles of the posterior distribution of projected log real oil price, log real output, the level of OPEC Core's share of the world oil market and the level of shale's share of the world oil market. The projection is based on the estimated model and data through 2021Q3. The figure includes the actual sample, which ends in 2021Q3, and projects the model predictions for the variables up to 2044.[43] Based on the estimated model and current value of the variables, the model predicts a gradual decrease in log real prices and a gradual increase in log output to the balanced growth trend. OPEC Core output share is expected to decrease slightly from its current levels while shale's share increases in an "S" shape transition to a permanently higher share.[44] Part of the decline in price and increase in oil production is the result of shale production increasing over the transition. But Figures 4 and 5 also suggest that some of the predicted decline in oil price and the increase in world oil production is the result of recent demand and conventional fringe cost shocks dissipating over time.

[43] Our solution technique assumes a log linear approximation around the deterministic steady state for time periods after 2045. The mean of the posterior distribution displayed in Figure 8 is based on the trimmed mean of the posterior distribution (2.5th-97.5th percentile range) to remove the effects of outliers. The posterior distribution for these calculations is based on 500 draws from the MCMC posterior distribution of parameters.

[44] We can compare our posterior distribution of future shale shares to those estimated by Rystad (see Bornstein et al. (2022), Figure 5.) Rystad estimates decadal averages of shale's share in the 2020s, 2030s, and 2040s are: 15%, 17%, and 19%, respectively. Our projection posterior mean [5th,95th percentiles] are 11.8% [10.0%,14.1%],17.4% [12.5%,24.6%], and 19.5% [12.5,27.3%], respectively.

7.2 Oil price volatility along the transition path

Above we saw that the shale revolution implies changes in the pseudo-elasticities of supply for OPEC Core and for the elasticity of supply for the oil market as a whole. This has ramifications for oil price variability that results from various shocks hitting the oil market. Increased elasticity of market supply would result in a reduction in price volatility in the face of demand shocks. Furthermore, a larger shale sector suggests that supply shocks originating outside of the shale sector would have smaller effects on market price, lowering price volatility, as shale producers can act as a buffer to these shocks. On the other hand, the shale oil sector could be an additional source of shocks that could result in more volatility in the oil market.

To determine the net effect of the increase in shale production on the volatility of the real oil price, we calculate the conditional forecast variance of log real oil price for various horizons implied by the model. Specifically, we calculate $\mathrm{var}(Y_{t+k} - E(Y_{t+k}|Y_t))$ where Y_t takes values along the deterministic transition path for t = 2006Q1, 2007Q1, ..., 2044Q1. We normalise this conditional variance by the conditional variance in the pre-shale steady state, $\frac{\mathrm{var}(Y_{t+k}-E(Y_{t+k}|Y_t))}{\mathrm{var}(Y_{oldss+k}-E(Y_{oldss+k}|Y_{oldss}))}$. Figure 9 presents the projected decline in log real oil price conditional forecast error variance (relative to the old steady state) along the transition path from pre-shale to a fully mature shale oil sector. As Figure 9 suggests, the conditional variance of log real oil prices falls as shale's share rises. The decline is larger, the longer the forecast horizon; ranging from around a 15% decline at a one quarter horizon to close to 30% decline at the five year horizon when evaluated in 2044Q1. The reduction, especially at the shorter horizon, is modest compared to the 42% long-run reduction in Bornstein et al. Bornstein et al. (2022)[45]. As we will explain below, this is because shale is an additional source of variability while buffering other shocks.

To obtain a sense of what shocks are contributing to the decline in the conditional forecast error variance implied by the model, Table 6 displays the mean of the posterior forecast variance decompositions of (log) real oil prices in the pre-shale steady state (Panel A), in the current transition period which is set to 2021Q3 (Panel B), and in the post-shale steady state (Panel C).[46] Comparing the reported variances at different horizons in Panel B to those in Panel A, as of 2021, shale oil has lowered the conditional forecast error variance of real oil prices by 9%-22%. The reduction will rise to 17%-35% once the shale revolution is complete (comparing Panel C to Panel A). As to the sources of oil price variability, all three periods suggest demand shocks are relatively more important at short horizons and supply (cost) shocks are more important at longer horizons. In all three time periods, the contribution of OPEC Core cost shocks is relatively small. While the shale revolution results in demand shocks having smaller effects on oil prices and, hence, contributing to the decline in overall variability along the shale transition path, the relative contribution of demand shocks to oil price variability is largely unaffected by the shale transition. This differs from Bornstein et al. (2022), whose model suggests that the shale transition will increase the importance of demand shocks in driving the volatility of prices to 98.4% (and lower that of supply shocks to 1.6%). In contrast, our model suggests the shale transition brings with it a substantial decline in the contribution of conventional supply shocks as well as an increase in the contribution of shale cost shocks to the variability of oil prices. This suggests that

[45] Bornstein et al. (2022) do not differentiate the price volatility at different horizons. They compare the pre-shale and post-shale steady state price volatility.

[46] The posterior distribution is based on calculating the conditional forecast error decomposition implied by the model at those particular dates for 5000 draws from the MCMC distribution of parameters.

as the shale sector grows, it becomes a greater source of shocks, but also causes the effect of conventional supply shock on oil prices to be dramatically lessened, resulting in relatively unchanged relative contribution of demand and supply shocks.

Shale's role as a buffer to conventional supply shocks may have implications beyond the oil market. Oil market disruptions have been a cause for much political and strategic concern for oil importing countries. For the U.S. and Europe, dependence on imported oil has included social costs over and above the market price for oil. These include not only the macroeconomic risks due to oil supply shocks but also to, as Brown and Huntington state, 'the costs to the United States to exercise market power in the oil market, the costs of maintaining a strong military presence in the Middle East and various other foreign policy factors'.[47] Shale's rise may lessen the strategic role oil plays in future international relations.

8 Counterfactual analysis of the oil market

In this section, we take advantage of interpreting our empirical model as structural to conduct several counterfactual exercises to assess the importance of the shale revolution. This includes the impact of the shale revolution on recent oil prices and outputs. We also examine a case study of how the existence of shale oil production alters the effects of conventional fringe supply disruptions.

8.1 The effect of the shale revolution on oil prices and outputs

As we saw above in the historical decompositions, Figures 4-7, the direct effect of the shale transition variable on market price and output is relatively modest compared to other shocks.

[47] See Brown and Huntington (2015) for a summary of the literature on the costs of oil import dependence.

However, this understates the full impact of the transition to shale. As the shale transition occurs, the reaction to market shocks (as reflected in the parameters of the state space model) changes as well. To get a sense of the overall effect of the on-going shale revolution, we conduct a counterfactual experiment where we take the parameters of the model and the implied structural shocks from the estimated model but assume the shale transition component of production costs remain at the their original values. Comparing the counterfactual outcome with the actual price provides an estimate of what the oil market would have been without the shale revolution. The red lines in Figure 10, display the mean of the posterior distribution of variables' paths over the sample for the counterfactual experiment along with the 5th and 95th percentiles of posterior distribution of the counterfactual experiment.

From the counterfactual, we observe in Figure 10 that the overall effect of the shale revolution begins to manifest itself around 2010 and gradually gets larger. As a consequence of the shale revolution, by 2021Q3 oil prices are 21% lower than the mean of the no-shale counterfactual, or alternatively, the mean of the no-shale counterfactual is 27% higher than the actual price level. The 5th-95th percentile range of the posterior distribution for the counterfactual does not include the actual value of (log) oil price variable in 2021Q3. Total oil output is 3% higher in 2021Q3 than the mean of the posterior distribution of the counterfactual and, again, the 5th-95th percentile range does not include the actual value of log output. Note that in the counterfactual, shale's output share is higher at the end of the sample than the beginning of the sample but is still small: 1% ($exp(-4.5)$) in the counterfactual versus approximately 10% ($exp(-2.5)$) in the benchmark model. The counterfactual model assumes that shale producers still respond more to oil prices than conventional producers despite their small market share. OPEC Core has roughly the same share, with and without shale, 22% versus 21%. This suggests that shale's growth has been at the expense of conventional producers in the ROW and not OPEC Core. OPEC Core acts as if it sets production to keep its market share constant.

8.2 Conventional fringe supply disruption

Our model is ideally set up to investigate how shale can dampen the effects of a conventional fringe supply disruption, such as occurred with the Russian invasion of Ukraine in February 2022. The invasion began at the end of February 2022 and world crude oil output fell 1.2 million barrels per day (mb/d) in the first quarter after the invasion.[48]. In terms of our model, this would be similar to a decline in conventional fringe supply. To study the effect of a shock similar to the Russian Invasion of Ukraine, we consider a supply shock of 2% to the conventional fringe that lasts 8 quarters.[49] We assume that, while the shock was initially unanticipated, the duration of the shock is correctly anticipated by market participants. We project the model forward taking the shale transition period to be 2022Q1. To see the impact of the shale revolution on the oil market's response to such supply disruptions, we also project the same shock for the pre-shale model and for the model after transition to the new shale steady state.

The results of our thought experiment can be seen in Figure 11. The results of our model are very similar to the initial impact of the Russian invasion on the world oil market. Starting in 2022Q1, our model suggests oil prices would increase 10% by the second quarter, which is similar to what happened with the invasion; Brent oil prices rose from $97 per

[48]See EIA International Energy Statistics, Energy Information Administration (2022a), Russian Crude Oil and Lease Condensate Production, May 2022

[49]Formally, we consider a cost shock to conventional fringe that results in a 2% decrease in conventional output at the original market price.

barrel in February to $113 in 2022Q2 (about a 14% increase in real terms). Figure 11 shows that global oil production would fall around 1.7% in the quarter after the supply disruption, which compares well to the actual decline of 1.6% in global oil production in 2022Q2. In our experiment, the invasion leads to an increase of 2.5% in shale output after the first quarter, rising to 4% in 5 quarters (compared to actual growth of 3% in the second quarter and 6.7% by 2022Q4).[50] Interestingly, as of the transition period 2022Q1, our model implies virtually no change in OPEC Core's output in response to the conventional supply disruption.

For the counterfactual of no shale revolution, our model predicts that the conventional fringe supply disruption would increase real oil prices by roughly 13% (30% higher than the 10% with shale) and output would fall by 2.1%. In percentage terms, shale's response is greater in the no-shale-revolution counterfactual, but since shale's share of the world market is so small, it has little effect on the global oil market. Despite the rise in prices, OPEC Core decreases production in the no-shale counterfactual, exacerbating the decline in world supply. With the full transition to shale, the conventional fringe supply shock leads to a much smaller price increase and a smaller decline in global output. OPEC Core increases output to mitigate the conventional fringe supply shock. Fully transitioned shale output rises by 2.5%, less than in current transition period because oil prices do not rise as much in the full transition case. Although the percentage growth is low, recall that shale's share is 20% in the full transition so that the actual magnitude of the increase and its effect on world supply is substantial. Overall, the thought experiment suggests that the presence of shale production helps mitigate the effects of supply disruptions just as shale helps dampen the volatility due to demand shocks.

[50] See EIA Drilling Productivity Report, December 12, Energy Information Administration (2022b).

9 Robustness

We conduct several robustness exercises to study the sensitivity of the model to different modelling choices. A detailed discussion of these exercises can be found in Appendix D. First, we consider alternative values for shale's market share in the post-shale steady state. The benchmark model assumes a 20% market share for shale in the post-shale steady state. We experiment with a 15% share and a 25% shale share. Table 7 displays the posterior distribution of the deterministic steady state with the different shale market shares.[51] In both alternative scenarios, real oil prices fall and market output rises in the new steady state; the larger the increase in shale's share, the larger the effect on real oil price and market output. Regardless of the size of the increase in shale's share in the steady state, OPEC Core acts to keeps its market share relatively constant; the increase in shale's market share is at the expense of the conventional fringe. Within sample, the transition paths for the models with 15% and 25% shale shares are very similar to the benchmark model (see appendix D for details); the paths are similar in shape though slightly different in magnitude. Qualitatively, all the models with an increase in shale's share of output result in lower real oil price variability. The larger shale's share, the greater the reduction in the forecast error variance of log real oil price.

Second, while in our benchmark empirical model we take OPEC Core to be the dominant producer, we estimate the model using all OPEC members instead of just OPEC Core. The full set of results for this model are contained in Appendix D. With the exception of the elasticity of demand, the posterior distribution of the structural parameters were fairly

[51] We draw from the estimated posterior distribution of parameters discussed previously and find the level of shale cost so that shale market share is equal to the specified value. In a previous version of the paper, we re-estimated all the parameters of the model, but there were very little differences in the posterior distributions of the parameters across the various models.

similar across the OPEC and OPEC Core models.[52] Furthermore, inference about the effects of the shale revolution on oil price variability that were present in our benchmark model also hold for the model with OPEC as the dominant producer, with the exception that the decline in volatility tends to level off mid-way through the transition rather than continue to decline through out the transition to the new shale steady state. As in the OPEC Core model, the shale revolution lowers OPEC's steady state price-marginal cost ratio by roughly half, again suggesting the shale revolution dramatically lowers OPEC's market power. Lastly, the model with all of OPEC also suggests that the effect of a conventional fringe supply disruption is mitigated by presence of shale production.

On the other hand, the full OPEC version of the model does not do as well as the OPEC Core model in a few key dimensions. Unlike the model with OPEC Core, the implied price-marginal cost ratio for the model with OPEC was too large compared to the cost data analysed by Asker et al. (2019). The pre-shale price-marginal cost ratio implied by the full OPEC model was around 15 versus 11 for the OPEC Core model. Given that most non-Core OPEC producers have higher marginal costs than those in OPEC Core, the actual price-marginal cost ratios for OPEC overall should be substantially lower than that implied by the model.[53] Also, the model with all of OPEC implies that the supply disruption mirroring the Russian invasion results in an increase in the oil price of only four percent and a shale response of only one percent. This is substantially smaller than the actual experience during the Russian invasion of Ukraine. Taking these two results into consideration, our view is

[52]If the elasticity of demand (in absolute value) gets too low relative to dominant producer's market share, then in the steady state the dominant producer's markup over marginal cost will not be positive and the Stackelberg equilibrium will not exist. That OPEC's market share is around 40% compared to OPEC Core's market share of 20%, results in a higher estimated demand elasticity in the OPEC version of the model.

[53]Asker et al. (2019) find that most OPEC producers have substantially higher unit costs than Saudi Arabia and Kuwait whose price-marginal cost ratios averaged in the neighbourhood of 10. This means that OPEC overall would have price - marginal cost ratios that are substantially lower than that of OPEC Core.

that the baseline OPEC Core version of the model fits the dominant producer-competitive fringe framework better than that of using all of OPEC as the dominant producer.

10 Conclusion

In this paper, we build and estimate a dynamic model of the oil market to help quantify the impact of the shale revolution on oil prices and output. We model the short- and long-run production decisions of conventional and shale oil producers as well as the strategic production decisions of OPEC Core. We factor into our model solution and estimation that our sample period is one of transition from a steady state where shale oil production was virtually nonexistent to one where shale oil production is a substantial source of world oil supply. We use time series on oil prices and output to estimate key structural parameters in the model and then use these to identify the source of fluctuations in oil prices and production.

We find that the advent of shale lowered oil prices substantially, prices are approximately 22% lower in 2021Q3 as a result of the shale revolution. We also show that shale production acts as a buffer to demand and non-shale supply shocks, lowering the volatility of oil prices. Despite the entry of shale into the market, OPEC Core producers, by acting strategically, have maintained their market share, suggesting that shale's increasing share of the world oil production has come largely at the expense of other conventional producers.

The reduction in oil market volatility may help smooth the business cycles of oil exporting countries and lead to more stable growth paths. For the United States, the shale boom has important geopolitical and strategic consequences. The increase in U.S. oil production has enabled the U.S. to become a crude oil exporter, a net exporter of oil products and less dependent on politically unstable parts of the world for oil imports. Given the lower price volatility and higher oil production, the shale boom has made the U.S. less vulnerable to oil price shocks.

11 Figures and Tables

Table 1. List of observable variables

	Variable	Data Source
1.	$log(P_t)$	log of: Brent Oil Price divided by US CPI
2.	$log(Q_t)$	log of: world oil production
3.	$log\left(\frac{Q_{o,t}}{Q_t}\right)$	log of: OPEC Core production as a share of world oil production
4.	$log\left(\frac{Q_{s,t}}{Q_t}\right)$	log of: US shale production as a share of world oil production
5.	$log\left(WEA_t\right)$	log of: World industrial production

Table 2. List of parameters

	preset parameters	specified values			
1.	discount factor (β)	0.99			
		Prior Distribution:			
	estimated structural parameters	distribution	mode	5th	95th
1.	long-run demand elasticity (-η_d)	$beta(2.4, 5, 0.15, 1.5)$	0.50	0.27	0.98
2.	short-run demand elasticity (-$(1-\rho_d)\eta_d$)	$beta(3, 5, 0, 0.3)$	0.10	0.04	0.20
3.	oil demand elast. wrt world econ. activ. (η_y)	$N(1, (.5)^2)$	1.0	0.18	1.82
4.	long-run supply, conventional ($\eta_{k,f}$)	$beta(2.4, 5, .15, 1.5)$	0.50	0.27	0.98
5.	long-run supply, opec core and shale ($\eta_{k,o}, \eta_{k,s}$)	$beta(7.8, 5, 0.15, 1.5)$	1.00	0.67	1.25
6.	short-run supply, conventional ($\eta_{u,f}$)	$beta(3, 5, 0, 0.3)$	0.10	0.04	0.20
7.	short-run supply, opec core and shale ($\eta_{u,o}, \eta_{u,s}$)	$beta(9, 5, 0, 0.3)$	0.20	0.13	0.25
8.	adjustment costs, conventional (κ_f)	$\Gamma(1.36, 550)$	500.0	175.74	2527.6
9.	adjustment costs, opec core and shale (κ_o, κ_s)	$\Gamma(1.91, 550)$	200.0	74.57	2017.48
	shock process parameters	distribution	mode	5th	95th
1.	AR(1) coeff. for demand specific and cost shocks	$beta(1.05, 1.05, 0, 1)$	0.50	0.05	0.95
2.	std. dev. for demand specific and cost shocks	$\Gamma(1.01, 1)$	0.01	0.05	3.02
3.	AR(1) coeff. for World IP process	$N(.8, 1)^*$	0.80	-0.84	2.44
4.	AR(2) coeff. for World IP process	$N(0, 1)^*$	0.00	-1.64	1.64
5.	std. dev. for World IP process	$\Gamma(1.01, 1)$	0.01	0.05	3.02
6.	shale cost transition parameter (ρ_{v_s})	$beta(10.0, 10.0, 0.9, 1.0)$	0.95	0.932	0.968

* The roots of the AR(2) for World IP are restricted to be less than one in absolute value.

Table 3. Posterior distribution of parameters

	structural parameters	mode	mean	5th	95th
	demand elasticities:				
1.	long-run demand elasticity (-η_d)	-0.17	-0.17	-0.19	-0.16
2.	short-run demand elasticity (-$(1-\rho_d)\eta_d$)	-0.17	-0.17	-0.19	-0.16
3.	oil demand elast. wrt world econ. activ. (η_y)	1.42	1.41	1.17	1.66
	long-run cost elasticities:				
4.	Conventional fringe ($\eta_{k,f}$)	0.57	0.32	0.16	0.80
5.	OPEC Core ($\eta_{k,o}$)	1.00	0.91	0.59	1.21
6.	Shale fringe ($\eta_{k,s}$)	0.97	0.92	0.62	1.20
	short-run cost elasticities:				
7.	Conventional fringe ($\eta_{u,f}$)	0.06	0.06	0.05	0.08
8.	OPEC Core ($\eta_{u,o}$)	0.15	0.16	0.10	0.22
9.	Shale fringe ($\eta_{u,s}$)	0.16	0.16	0.12	0.20
	adjustment costs:				
10.	Conventional fringe (κ_f)	979.06	488.98	1.58	1951.1
11.	OPEC Core (κ_o)	5.05	22.78	0.73	68.81
12.	Shale fringe (κ_s)	63.51	95.20	32.46	206.85
	shock parameters	**mode**	**mean**	**5th**	**95th**
1.	AR(1) coeff. for oil specific demand shock	0.98	0.99	0.97	0.999
2.	AR(1) coeff. for OPEC core cost shock	0.80	0.83	0.74	0.92
3.	AR(1) coeff. for conv. fringe cost shock	0.95	0.97	0.93	0.999
4.	AR(1) coeff. for shale cost shock	0.93	0.96	0.90	0.999
5.	AR(1) coeff. for world IP shock	1.33	1.32	1.18	1.46
6.	AR(2) coeff. for world IP shock	-0.39	-0.39	-0.53	-0.25
7.	shale cost transition parameter (ρ_{v_s})	0.97	0.97	0.95	0.98
8.	std. dev. for oil specific demand shock	0.023	0.023	0.020	0.026
9.	std. dev. for OPEC core cost shock	0.40	0.40	0.30	0.53
10.	std. dev. for conv. fringe cost shock	0.27	0.25	0.19	0.33
11.	std. dev. for shale cost shock	0.23	0.24	0.18	0.34
12.	std. dev. for world IP shock	0.014	0.014	0.012	0.016

Table 4. Implied supply elasticities
Mean, 5th and 95th percentiles of posterior distribution

Panel A: Pre-shale

horizon	market	conv.	shale	OPEC core
initial quarter	0.073	0.065	0.159	0.105
	(0.058, 0.087)	*(0.049, 0.079)*	*(0.115, 0.202)*	*(0.083, 0.128)*
1 year	0.127	0.113	0.270	0.176
	(0.085, 0.163)	*(0.071, 0.151)*	*(0.196, 0.349)*	*(0.132, 0.218)*
2 year	0.191	0.172	0.538	0.260
	(0.140, 0.243)	*(0.120, 0.224)*	*(0.382, 0.703)*	*(0.203, 0.320)*
5 year	0.269	0.249	0.847	0.334
	(0.181, 0.478)	*(0.158, 0.466)*	*(0.596, 1.092)*	*(0.242, 0.518)*
10 year	0.329	0.311	0.924	0.389
	(0.181, 0.730)	*(0.158, 0.725)*	*(0.620, 1.223)*	*(0.243, 0.748)*

Panel B: Transition period (2021Q3)

horizon	market	conv.	shale	OPEC core
initial quarter	0.083	0.065	0.159	0.117
	(0.068, 0.097)	*(0.049, 0.079)*	*(0.115, 0.202)*	*(0.091, 0.143)*
1 year	0.143	0.112	0.263	0.204
	(0.105, 0.176)	*(0.070, 0.150)*	*(0.192, 0.339)*	*(0.159, 0.249)*
2 year	0.234	0.173	0.528	0.330
	(0.186, 0.289)	*(0.119, 0.224)*	*(0.375, 0.691)*	*(0.265, 0.399)*
5 year	0.354	0.249	0.847	0.455
	(0.248, 0.549)	*(0.158, 0.469)*	*(0.594. 1.094)*	*(0.345, 0.616)*
10 year	0.454	0.309	0.937	0.556
	(0.295, 0.779)	*(0.158, 0.711)*	*(0.623, 1.251)*	*(0.409, 0.812)*

Panel C: Post-shale

horizon	market	conv.	shale	OPEC core
initial quarter	0.097	0.065	0.159	0.133
	(0.081, 0.112)	*(0.049, 0.079)*	*(0.115, 0.202)*	*(0.099, 0.167)*
1 year	0.167	0.112	0.258	0.244
	(0.129, 0.201)	*(0.069, 0.150)*	*(0.189, 0.339)*	*(0.185, 0.306)*
2 year	0.291	0.171	0.529	0.417
	(0.235, 0.349)	*(0.121, 0.226)*	*(0.375, 0.695)*	*(0.328, 0.500)*
5 year	0.429	0.250	0.855	0.551
	(0.322, 0.593)	*(0.158, 0.469)*	*(0.598, 1.094)*	*(0.445, 0.674)*
10 year	0.484	0.305	0.924	0.597
	(0.330, 0.774)	*(0.158, 0.694)*	*(0.620, 1.222)*	*(0.459, 0811)*

Table 5. Posterior distribution of post-shale steady states

Panel A: Steady state price, output, and market share

		pre-shale	**post-shale steady state**			
	variable	steady state	mode	mean	5th	95th
1.	real oil price	100.0	67.7	54.5	44.5	74.0
2.	market oil output	100.0	106.9	111.2	105.3	114.5
3.	OPEC Core share	20.0	20.4	19.3	17.8	20.9
4.	Shale share	0.5	20.0	20.0	20.0	20.0
5.	Conventional Fringe share	79.5	59.6	61.0	59.1	62.2

Panel B: Price to marginal cost ratio for OPEC Core

		mode	mean	5th	95th
1.	pre-shale steady state	11.5	10.7	6.9	15.4
2.	post-shale steady state	7.1	5.4	3.5	8.6

Table 6. Conditional forecast variance decompositions of log real oil price (mean of posterior distribution)

Panel A: pre-shale steady state

		Percent contribution of shocks to:				
horizon	variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
initial quarter	0.0196	46.7	33.2	17.6	0.0	2.5
1 year	0.1001	29.1	32.7	36.6	0.0	1.6
2 year	0.1614	27.2	26.2	44.4	0.0	1.2
5 year	0.2962	26.5	18.1	54.7	0.0	0.7
10 year	0.4502	27.8	13.5	58.1	0.0	0.5

Panel B: Transition period (2021Q3)

		Percent contribution of shocks to:				
horizon	variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
initial quarter	0.0178	47.5	33.7	14.2	1.2	3.4
1 year	0.0855	30.3	34.1	30.7	2.4	2.5
2 year	0.1334	28.3	28.7	37.3	3.8	1.9
5 year	0.2353	27.3	19.3	46.2	6.0	1.2
10 year	0.3520	28.1	14.4	49.5	7.1	0.9

Panel C: post-shale steady state

		Percent contribution of shocks to:				
horizon	variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
initial quarter	0.0162	46.3	32.9	9.2	6.2	4.8
1 year	0.0733	29.8	33.7	19.5	12..2	4.3
2 year	0.1125	27.0	28.0	22.9	18.2	3.4
5 year	0.1948	24.6	18.7	27.5	26.4	2.2
10 year	0.2851	24.9	14.1	30.1	28.8	1.6

Table 7. Posterior distribution of post-Shale steady states

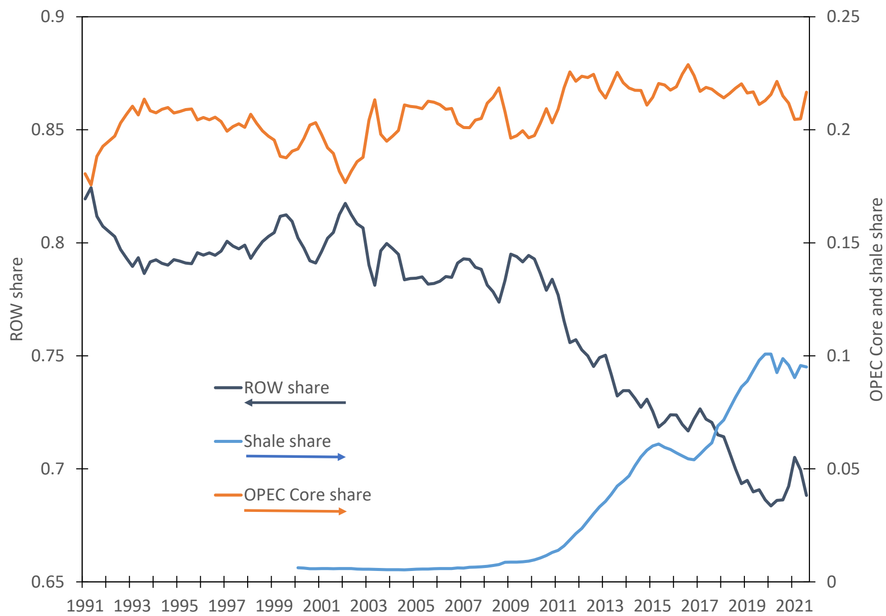
Model with shale share = 15%

	variable	pre-shale steady state	**post-Shale steady state** mode	mean	5th	95th
1.	real oil price	100.0	75.5	64.1	55.3	80.5
2.	market oil output	100.0	104.9	108.0	103.8	110.4
3.	OPEC Core share	20.0	20.4	19.6	18.6	20.8
4.	Shale share	0.5	15.0	15.0	15.0	15.0
5.	Conventional Fringe share	79.5	64.6	65.4	64.2	66.4

Model with shale share = 25%

	variable	pre-shale steady state	**post-Shale steady state** mode	mean	5th	95th
1.	real oil price	100.0	60.2	46.2	35.7	67.5
2.	market oil output	100.0	109.1	114.5	106.9	118.8
3.	OPEC Core share	20.0	20.4	18.7	16.9	21.0
4.	Shale share	0.5	25.0	25.0	25.0	25.0
5.	Conventional Fringe share	79.5	54.6	56.3	54.0	58.1

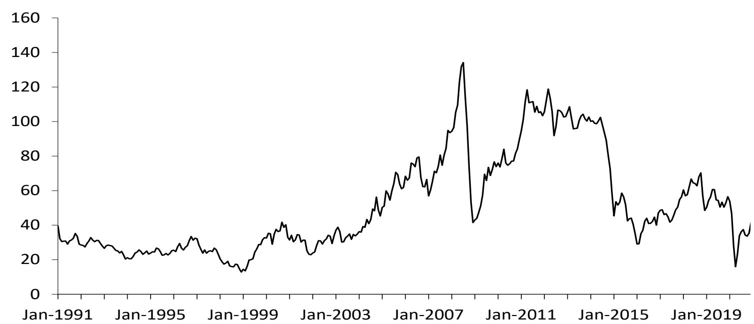
Figure 1. *World Crude Oil Production shares*



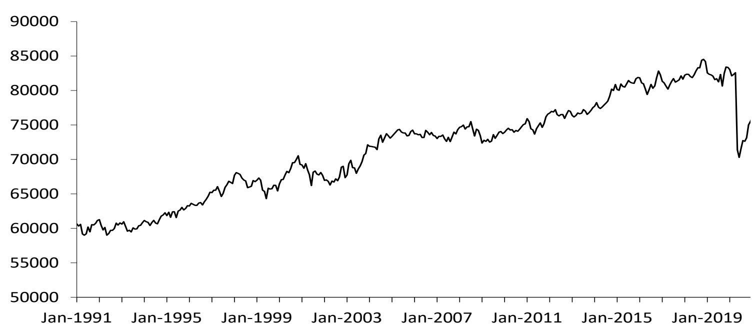
Note: SOURCE: EIA;OGJ.

Figure 2. *World Crude Oil Price and Output*

[Real Brent Price]

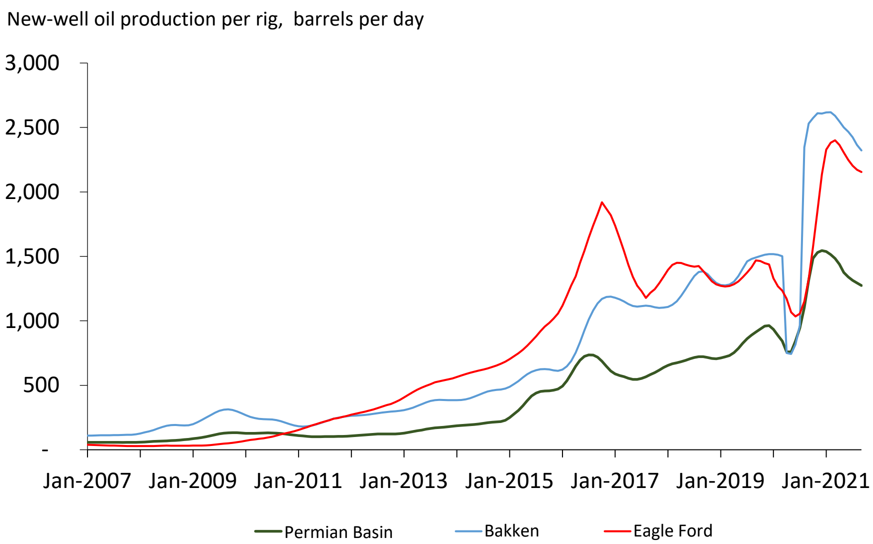


[World Oil output]



Note: (a) SOURCE: BLS;OGJ; (b) Brent oil price deflated by CPI (1982-1984=100).

Figure 3. *U.S. Shale Productivity*



Note: SOURCE: EIA, Drilling Productivity Report.

Figure 4. *Decomposition of log real oil price posterior mean contribution*

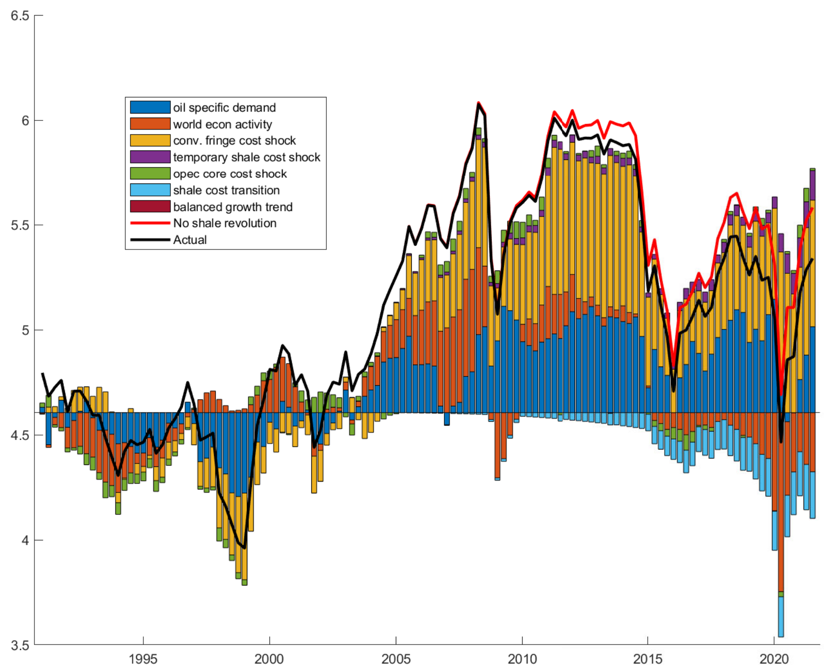


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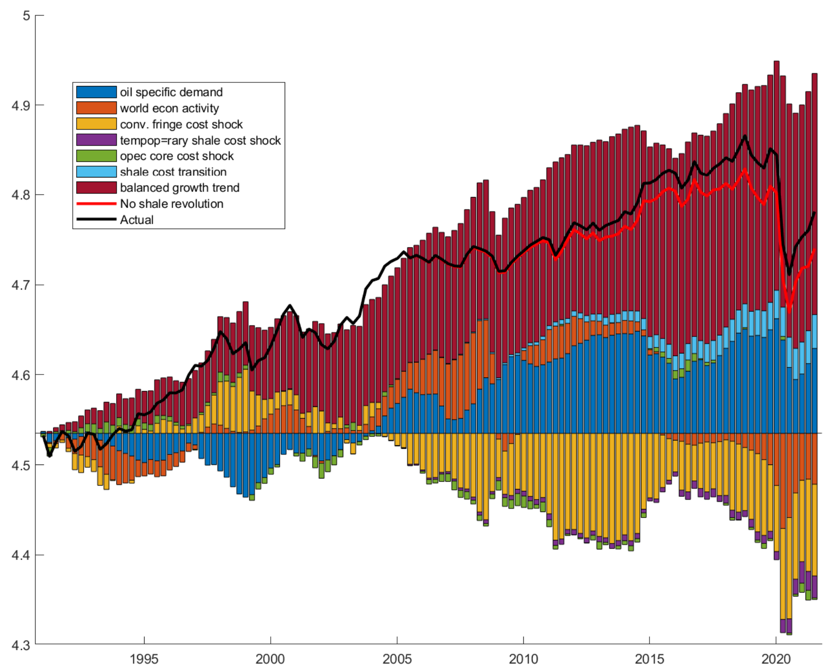
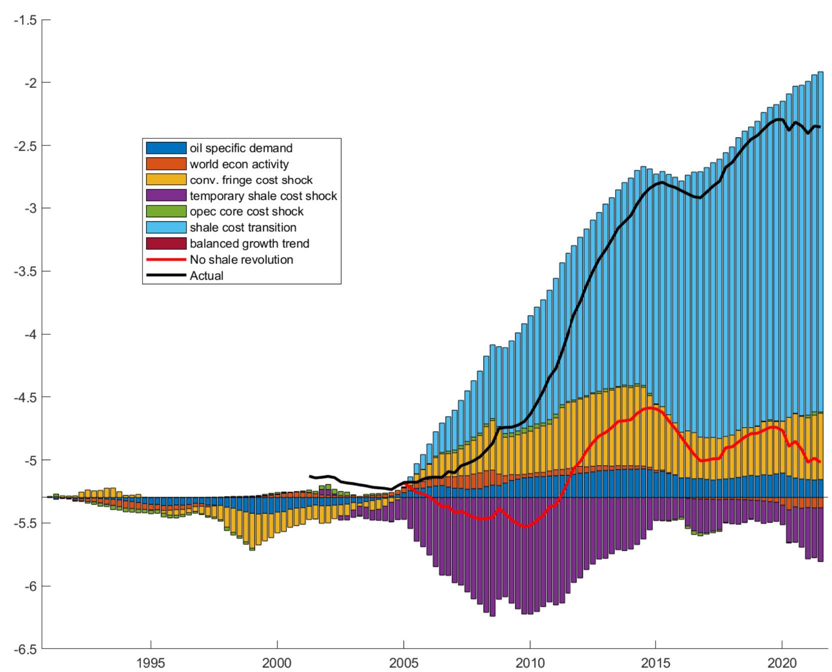
Figure 5. *Decomposition of log world oil production posterior mean contribution*



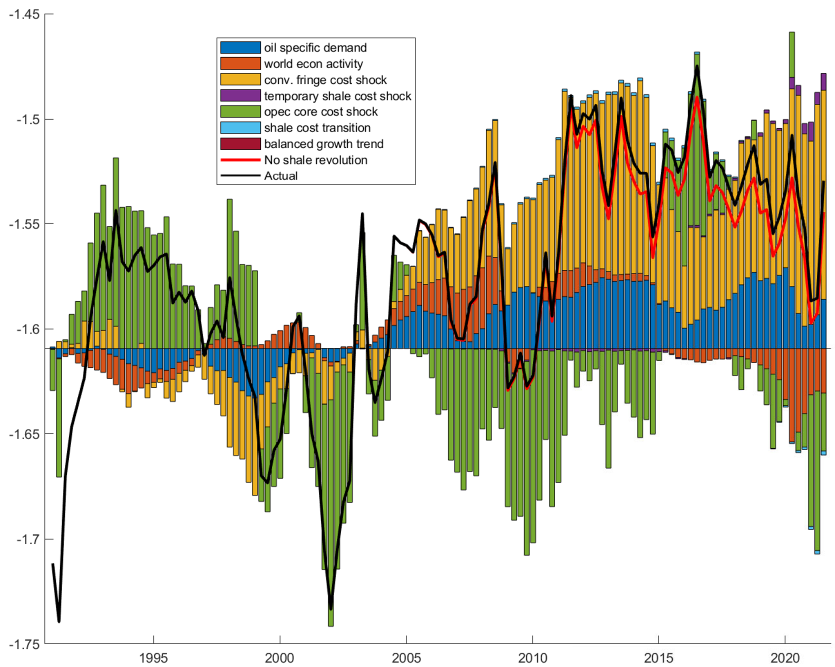
$5_2022.pdf$

Figure 6. *Decomposition of log shale share of world oil output posterior mean contribution*



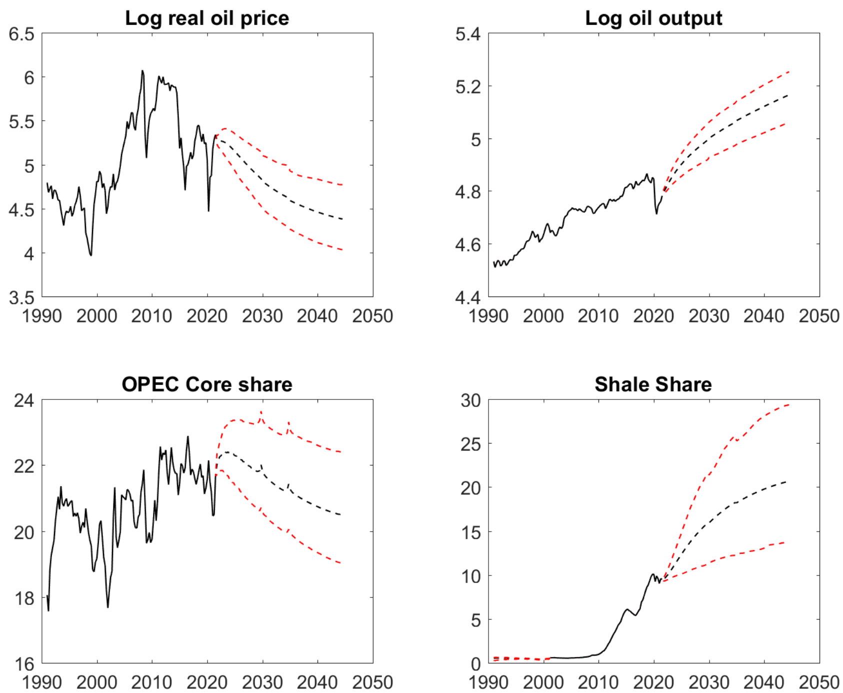
$6_2022.pdf$

Figure 7. *Decomposition of log OPEC core share of world oil output posterior mean contribution*



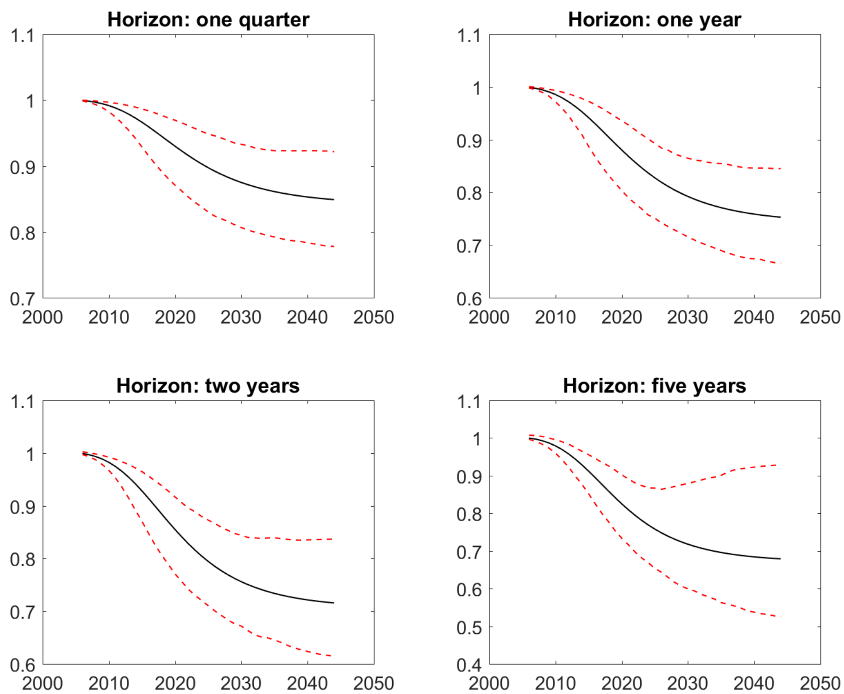
$7_2022.pdf$

Figure 8. *Oil market and shale transition*
Mean, 5th and 95th percentiles of posterior distribution



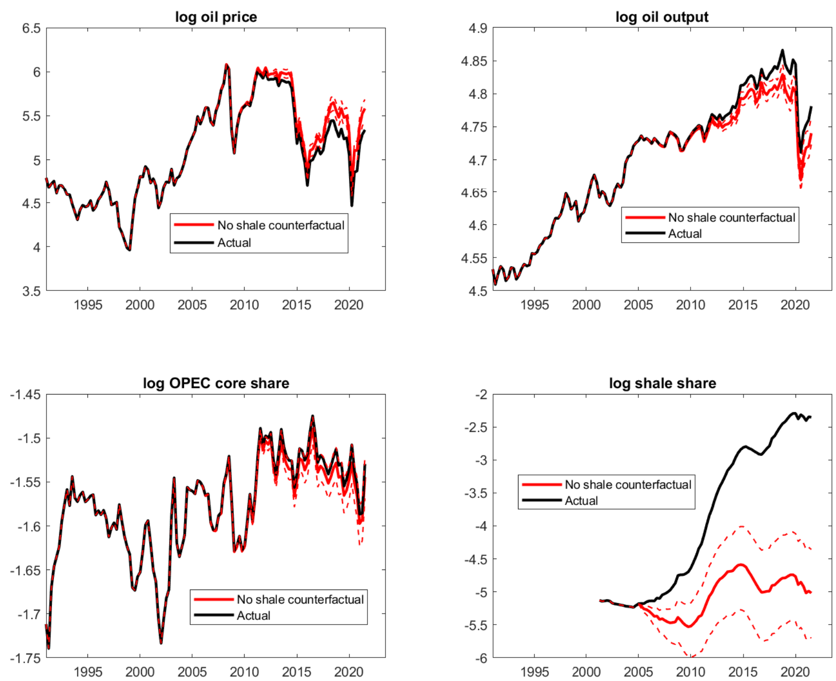
Note: The solid black line is the actual, the black dashed line is the mean of the posterior distribution for the expected transition path, and the red dashed lines are the 5th and 95th percentiles of the expected transition path.

Figure 9. *Conditional variance of log real oil price along transition path relative to pre-share variance*
Mean, 5th and 95th percentiles of posterior distribution



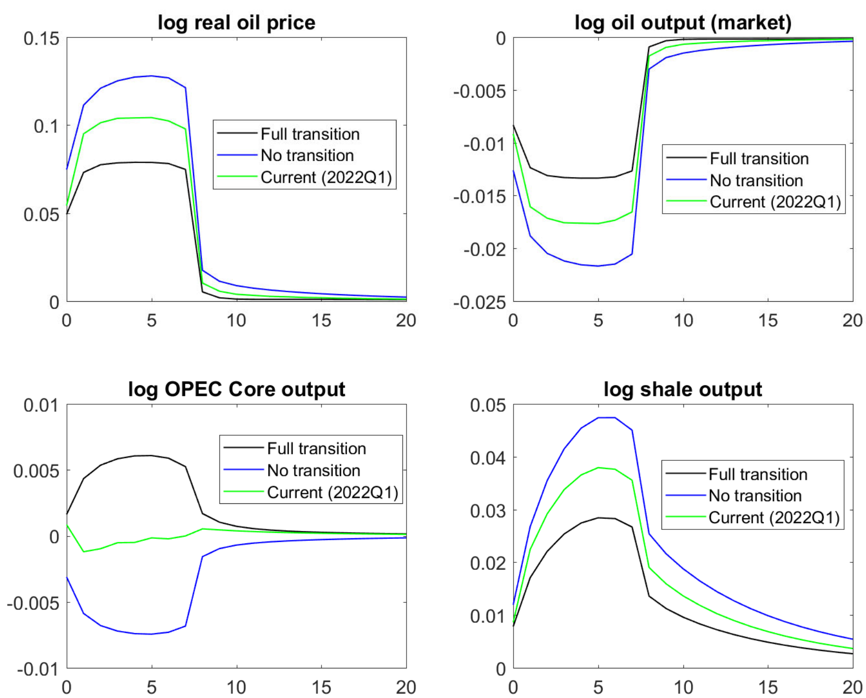
Note: The solid black line is the ratio of conditional forecast error variance at that time period relative to the conditional forecast error variance at the pre-shale steady state. The dashed red lines are the 5th and 95th percentiles of the posterior distribution.

Figure 10. *Shale Revolution vs No Shale Revolution Counterfactual*



Note: The solid black line in the actual data. The solid red line is mean of the posterior distribution for the no shale revolution counterfactual. The red dashed lines are the 5th and 95th percentiles of the posterior distribution.

Figure 11. *Response to shock in conventional fringe supply of 2%*



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References

Alhajji, A. Huettner, D. (2000), 'Opec and world crude oil markets from 1973 to 1994: cartel, oligopoly or competitive?' *Energy Journal*, 21, 31–60. doi:10.5547/ISSN0195-6574-EJ-Vol21-No3-2.

An, S. and Schorfheide, F. (2007). 'Bayesian analysis of dsge models. *Econometric Reviews*, 26, 113–172. doi:10.1080/07474930701220071.

Asker, J., Collard-Wexler, A. and De Loecker, J. (2019). '(Mis)Allocation, Market Power, and Global Oil Extraction', *American Economic Review*, vol. 109(4), pp. 1568-1615. doi:10.1257/aer.20171438.

Atkeson, A. and Kehoe, P.J. (1999). 'Models of Energy Use: Putty-Putty versus Putty-Clay', *American Economic Review*, vol. 89(4), pp. 1028-1043. doi:10.1257/aer.89.4.1028.

Agerton, M. and Upton, G.B. (2019). 'Decomposing crude price differentials: Domestic shipping constraints or the crude oil export ban?', *The Energy Journal*, vol. 40, pp. 155-172. doi:10.5547/01956574.38.1.mage.

Aoghs Editors. (2007). 'Shooters-A Fracking History', *https://aoghs.org/technology/hydraulic-fracturing*. September 1.

Badiali, M. (2014). '2 New Drilling Techniques that Will Shatter US Oil Expectations', *St. Paul Research*.

Baumeister, C. and Hamilton, J. (2019). 'Structural Interpretation of Vector Autoregressions with Incomplete Identification: Revisiting the Role of Oil Supply and Demand Shocks', *American Economic Review*, vol. 109, pp. 1873-1910. doi:10.1257/aer.20151569.

Bjornland, H., Nordvik, F. and Rohrer, M. (2021). 'Supply Flexibility in the Shale Patch: Evidence from North Dakota', *Journal of Applied Econometrics*, vol. 6, pp. 273-292.

Bjornland, H. and Zhulanova, J. (2019). 'The Shale Boom and the US Economy: Spillovers and Time-Varying Effects', *CAMA Working Paper 59/2019*.

Borenstein, S. and Kellogg, R. (2014). 'The incidence of an oil glut: Who benefits from cheap crude oil in the Midwest' *The Energy Journal*, vol. 35, pp. 15-33. doi:10.5547/01956574.35.1.2.

Bornstein, G., Krusell, P. and Rebelo, R. (2022). 'A World Equilibrium Model of the Oil Market', *Review of Economic Studies*, vol 90, pp. 132-164.

Brown, S.P.A. and Huntington, H. (2015). 'Evaluating U.S. Oil Security and Import Reliance', *Energy Policy*, vol.79, pp.9-22. doi:10.1016/j.enpol.2015.01.001.

Bureau of Labor Statistics (2022). *Consumer Price Index- All Urban Consumerss*, Top Picks (Most Requested Statistics) : U.S. Bureau of Labor Statistics (bls.gov).

Buyuksahin, B., Lee, T.K., Moser, J.T. and Robe, M.A. (2013). 'Physical markets, paper markets and the WTI-Brent spread', *The Energy Journal*, vol. 34, pp. 129-151. doi:10.5547/01956574.34.3.7.

Cakir Melek, N., Plante, M. and Yucel, M. (2021). 'Resource Booms and the Macroeconomy: The Case of U.S. Shale Oil', *Review of Economic Dynamics*, vol. 42, pp. 307-332.

Caldara, D., Cavallo, M. and Iocoviello, M. (2018). 'Oil Price Elasticities and Oil Price Fluctuations', *Journal of Monetary Economics*, vol.103, pp.1-20. doi:10.1016/j.jmoneco.2018.08.004.

Canadian Society for Unconventional Resources (2019). 'Understanding Tight Oil', *https://www.mpgpetroleum.com/home/docs/Understanding*$_T$*ightOil*$_F$*INAL.pdf : Web.*

Comin, D. and Mestieri, M. (2014). 'Technology Diffusion: Measurement, Causes and Consequences', in (P. Aghion and S. Durlauf, eds), *Handbook of Economic Growth*, Vol 2, New York: Elsevier Publishing Co. doi:10.1016/B978-0-444-53540-5.00002-1.

Dahl, C. and Yucel, M. (1991). 'Testing alternative hypotheses of oil producer behavior', *The Energy Journal*, vol. 12(4), pp. 117-138. doi:10.5547/ISSN0195-6574-EJ-Vol12-No4-8.

Dunn, S. (2016). 'Fracking 101: Breaking down the most important part of today's oil, gas drilling', *Greeleytribune.com*, October 14.

Eckhouse, G. (2021). 'United States hydraulic fracturing short-cycle revolution and the global industry's uncertain future', *Geoforum*, vol. 127 pp. 246-256. doi:10.1016/j.geoforum.2021.07.010.

Energy Information Administration. (2022). 'What drives crude oil prices: Supply OPEC', *EIA Website*, https://www.eia.gov/finance/markets/crudeoil/supply-opec.php.

Energy Information Administration (2022a). 'Petroleum and Other Liquids Production', *EIA Website*, https://www.eia.gov/international/data/world/petroleum-and-other-liquids/quarterly-petroleum-and-other-liquids-production?pd=5p=0000000000000000000000000000000000vgu=0f=Qv=mapbubblea=-i=nonevo=valuet=Cg=0000000000000000000000000000000000000000000000001l=249-ruvvvvvfvtvnvv1vrvvvvfvvvvvvfvvvou20evvvvvvvvvvvnvvvs0008s=94694400000e=1656633600000, September.

Energy Information Administration (2022b). 'Petroleum and Other Liquids Production', *EIA Drilling Productivity Report, EIA Website*, https://www.eia.gov/petroleum/drilling/, September.

Energy Information Administration (2022c). ‘Petroleum and other Liquids, Spot Price-Brent’, *EIA website*, https://www.eia.gov/dnav/pet/pet_pri_spt_s1_m.htm

Frondel, M. and Horvath, M. (2019). ‘The U.S. Fracking Boom: Impact on U.S. Oil Prices’, *Energy Journal*, vol. 40(4), pp. 191-205. doi:10.5547/01956574.40.4.mfro.

Golombek, R., Irarrazabal, A. and Ma, L. (2018). ‘OPEC’s market power: An empirical dominant firm model for the oil market’, *Energy Economics*, vol. 70, pp. 98-115. doi:10.1016/j.eneco.2017.11.009.

Griffin, J.M. (1985). ‘OPEC Behavior: A Test of Alternative Hypotheses’, *American Economic Review*, vol. 75(5), pp. 954-63.

Guerrieri, L. and Iacoviello, M. (2015). ‘OccBin: A Toolkit for Solving Dynamic Models with Occasionally Binding Constraints Easily’, *Journal of Monetary Economics*, vol. 70, pp. 22-38. doi:10.1016/j.jmoneco.2014.08.005.

Gundersen, S.T. (2020). ‘The Impact of U.S. Supply Shocks on the Global Oil Price’, *Energy Journal* vol. 41(1). doi:10.5547/01956574.41.1.tgun.

Herrera, A.M. and Rangaraju, S.K. (2020). ‘The Effect of Oil Supply Shocks on U.S. Economic Activity: What Have We Learned?’ *Journal of Applied Econometrics*, vol. 35(2), pp. 141-159. doi:10.1002/jae.2735.

Huppmann, D. and Holz, F. (2012). ‘Crude Oil Market Power – Shift in Recent Years?’ *The Energy Journal*, vol. 33(4). doi:10.5547/01956574.33.4.1.

IHS CERAWeek. (2016). *IHS CERAWeek*, February 23.

Jin, X. (2013). ‘Crude Oil Price Dynamics: A Study on the Effects of Market Expectations and Strategic Supply on Price Movements’, Ph.D. Dissertation, Southern Methodist University.

Jones, C.T. (1990). ‘OPEC Behavior Under Falling Prices: Implications for Cartel Stability,’, *The Energy Journal* vol. 11(3), pp. 117-129. doi:10.5547/ISSN0195-6574-EJ-Vol11-No3-6.

Kilian, L. (2017). ‘The Impact of the Fracking Boom on Arab Oil Producers’, *The Energy Journal*, Vol. 38(6), pp. 137-160. doi:10.5547/01956574.38.6.lkil.

Kleinberg, R. and Fagan, M. (2019). ‘Business Cycles and Innovation Cycles in the U.S.Upstream Oil and Gas Industry’, *USAEE Working Paper no. 19-423*.

Kleinberg, R.S., Paltsev, S., Ebinger, C.K.E., Hobbs, D.A. and Boersma, T. (2018). 'Tight Oil Market Dynamics: Benchmarks, breakeven points and inelasticities', *Energy Economics*, Vol. 70, pp. 70-83. doi:10.1016/j.eneco.2017.11.018.

Langer, A. and Lemoine, D. (2020). 'What Were the Odds? Estimating the Market's Probability of Uncertain Events', *NBER Working Paper 28265*.

Manescu, C.B. and Nuno, G. (2015). 'Quantitative effects of the shale oil revolution', *Energy Policy* vol. 86, pp. 855-66. doi:10.1016/j.enpol.2015.05.015.

Mohaddes, K. and Raissi, M. (2019). 'The U.S. oil supply revolution and the global economy', *Empirical Economics* vol. 57, pp. 1515-1546. doi:10.1007/s00181-018-1505-9.

Motley Fool Transcripts. (2021). 'FANG Earnings Call for period ending October 31, 2021', *Motley Fool Transcripts*, November 5, 2021.

Nakov, A. and Nuno, G. (2013). 'Saudi Arabia and the oil market', *Economic Journal*, vol. 123(573), pp. 1333-62. doi:10.1111/ecoj.12031.

Nakov, A. and Pescatori, A. (2010). 'Monetary policy tradeoffs with a dominant oil producer', *Journal of Money, Credit and Banking*, vol. 42 (1), pp. 1-32. doi:10.1111/j.1538-4616.2009.00276.x.

New York Times. (1983). 'Communique by OPEC', *New York Times*, March.

New York Times. (2002). 'Saudi oil output down 2.6% in 2002', *New York Times*, August.

New York Times. (2008). 'OPEC says it will cut oil output', *New York Times*, October.

Newell, R.G. and Prest, B. (2019). 'The Unconventional Oil Supply Boom: Aggregate Price Response', *Energy Journal*, Vol. 40(3). doi:10.5547/01956574.40.3.rnew.

Newell, R.G., Prest, B. and Vissing, A.B. (2019). 'Trophy Hunting versus Manufacturing Energy: The Price Responsiveness of Shale Gas', *Journal of the Association of Environmental and Resource Economics*,vol. 6(2). doi:10.1086/701531.

Oil Daily. (2016). 'Naimi Declares Price War on U.S. shale', *Oil Daily*.

Pindyck, R.S. (1978). 'Gains to Producers From the Cartelization of Exhaustible Resources,' *Review of Economics and Statistics*, vol. 60(2), pp. 238-251. doi:10.2307/1924977.

Plante, M. and Strickler, G. (2021). 'Closer to One Great Pool? Evidence from Structural Breaks in Oil Price Differentials', *The Energy Journal*, vol. 42(2).

Pierru, A., Smith, J.L. and Zamrik, T. (2017). 'OPEC's Impact on Oil Price Volatility: The Role of Spare Capacity', *The Energy Journal*, Vol. 39(2). doi:10.5547/01956574.39.2.apieie.

Rystad Energy, (2022). UCube August 2022.

Salant, S.S. (1976). 'Exhaustible Resources and Industrial Structure: A Nash-Cournot Approach to the World Oil Market', *Journal of Political Economy*, vol. 84, pp. 1079-94. doi:10.1086/260497.

Salehi-Isfahani, D. (1987). 'Testing OPEC Behavior: A Comment', *VPI Department of Economics Working Paper no.E87-01-02*.

Schlumberger. nd. 'Tight Oil', *Schlumberger Energy Glossary*, https://glossary.slb.com/en/.

Siegel, H. (2013). *Bakken 5-Year Drilling and Completion Trends*, October 13, https://dtcenergygroup.com/.

Smith, J.L. (2005). 'Inscrutable OPEC? Behavioral Tests of the Cartel Hypothesis', *The Energy Journal*, vol. 26(1). doi:10.5547/ISSN0195-6574-EJ-Vol26-No1-3.

Smith, J.L. and Lee, T.K.(2017). 'The Price Elasticity of U.S. Shale Oil Reserves', *Energy Economics*, vol. 67.

Spilimbergo, A. (2001). 'Testing the hypothesis of collusive behavior among OPEC members', *Energy Economics* vol. 23, pp. 339-353. doi:10.1016/S0140-9883(00)00064-5.

Walls, W.D. and Zheng, X. (2022). 'Fracking and Structural Shifts in Oil Supply', *The Energy Journal*, vol. 43(3).

Vatter, M. (2017). 'OPEC's Kinked Demand Curve', *Energy Economics*, vol. 63, pp. 272-287.

Vatter, M.H., Van Vactor, S.A. and Coburn, T.C. (2022). 'Price Responsiveness of Shale Oil: A Bakken Case Study', *Natural Resources Research,* vol. 31(1). doi:10.1007/s11053-021-09972-9.