The Shale Revolution and the Dynamics of the Oil Market*

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Abstract

We build and estimate a dynamic, structural model of the world oil market in order to quantify the impact of the shale revolution. We model the shale revolution as a dramatic decrease in shale production costs and explore how the resultant increase in shale production affects the level and volatility of oil prices over our sample. We find that oil prices in 2020 would have been roughly 31% higher had the shale revolution not occurred and that the shale revolution implies a reduction in current oil price volatility around 20% and a decline in long-run volatility of over 30%.

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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, rose 7.9 million barrels per day (mb/d), more than doubling from 2007 to 2020 (Figure 1). This 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 dramatic 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 Bjornland et al., [10], Newell and Prest [41] and Smith and Lee [53]). The increase in shale production is likely to change how sensitive overall market supply is to oil price changes.

Shale's substantial growth has implications for the strategic calculus of OPEC. Figure 2 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 10 percent of the global oil market by 2018. Yet, despite shale's dramatic rise in market share, OPEC Core's market share is largely unchanged in this period. To the extent shale producers are more price sensitive than conventional producers, the increase in shale production has implications for the strategic calculus of OPEC. From the 1980s onward Saudi Arabia has 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]

[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 [43].

[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 rebalance 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 subsidize higher cost supplies only

Figure 3 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 are 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 may play an important (if not dominant) role in oil price and output fluctuations.

In particular, the emergence and expansion of shale production affects the global oil market by not only adding another and more elastic source of supply, but also altering how the global market, and especially OPEC Core, reacts to demand and supply shocks. Therefore, using reduced form econometric methods to evaluate the effect of the shale revolution is likely to understate shale's true contribution. We argue that understanding shale's effect on the global oil market requires a structural model that is capable of describing the changing behavior of global oil market participants as well as accounting for shale's direct effect on market supply.

In this paper, we build and estimate a dynamic structural model of the oil market in order to quantify how the emergence of shale production has impacted oil prices and production and to predict how the shale revolution will likely affect the oil market in the long-run. First, to capture the fact that shale could have altered OPEC's decision calculus, we model the dynamic supply decisions of conventional competitive fringe producers, shale fringe producers, and OPEC Core (Saudi Arabia, Kuwait, Qatar and the UAE).[3] Our structural model implies decision rules for utilization (short-run supply) and production capacity (long-run supply) for these three types of producers, which in turn, determine the short and long-run supply

delays an inevitable reckoning." (CERAWeek [31]. The trade press reported his views as "Naimi declares price war on U.S. shale." (Oil Daily [44]) Oil prices fell to $30 by February 2016.

[3]Among OPEC members, these four countries have 85% of OPEC' spare capacity and together are large enough to influence oil prices (see Pierru et al. [46]. The rest of OPEC members we include in the conventional competitive fringe as they appear to take the oil price as given when making their production decisions.

responses to changes in market conditions. We assume that OPEC Core acts strategically and takes into account how its production decision affects both market prices and how the competitive fringe's choices of utilization and capacity respond to changes in market prices. Second, as one may assume the oil market is currently in the midst of the shale revolution, 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. 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 various other sources of oil market fluctuates outside of the shale revolution.

Using oil market data over the period 1991-2020, we estimate the posterior distributions of key structural parameters in the model. We find that the estimated short-run supply elasticity of shale producers to be substantially higher than those of conventional fringe producers and OPEC core, We estimate that the long-run supply elasticities for shale producers are somewhat higher than those for the OPEC Core, which are, in turn, higher than those for conventional fringe produces. We estimate that cumulative effect of the Shale Revolution is to raise the price elasticity of market supply by nearly 30%.

Based on our structural model, 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 2014, we find that shale transition or shale 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 if the shale revolution had not happened, the price of oil would have been 36% higher and global output 5.8% lower by the end of 2020. In the long-run, once the shale transition is over, we estimate that the price of oil would be nearly 90% higher (and output 12% lower) if the shale revolution had not occurred. In addition, our analysis suggests that shale oil has lowered oil price volatility as of 2019 by nearly 20% and that eventually the variance of oil prices is expected to decline by more than 30% once the shale revolution is complete. While shale's market share has risen substantially over the sample, we find that OPEC Core's output share is little effected by the increase in shale output share; most of shale's growth is at the expense of conventional producers in the rest of the world.

The rest of the paper is organized as follows. Section 2 provides a brief review of the literature on OPEC market structure. Section 3 describes how shale oil production is different from conventional oil production. In Section 4, we present a simple, static version of our model in order to display the key mechanisms through which the shale revolution will impact the oil market. In section 5, we develop the dynamic model used to quantify the effects of the shale revolution. We describe the dynamic decision rules of the conventional and shale competitive fringe as well as that of OPEC Core who acts as a dominant producer. Section 6 discusses how the model is solved and estimated. Our solution method takes into account that the oil market is in the midst of a transition from one steady state to another. In section 7, we discuss our empirical results and assess shale's effect on the oil market. Section 8 concludes.

2 Related Literature

There are many studies that have extensively analyzed the oil market and OPEC market structure. The earliest papers modeling the oil industry as a dominant producer with a competitive fringe were Salant [48] and Pindyck [45]. Econometric models testing for OPEC market structure, began with Griffin [25], followed by Salehi-Isfahani [49], Jones [33], Dahl and Yucel [21],Spilimbergo [54] among others. There was little consensus among all these studies about the OPEC's market structure (see Smith) [52], ranging from a market-sharing cartel, revenue-targeting cartel, loose cooperation and non-collusive behavior. Alhajji and

Huettner [2] rejected the cartel models and suggested that Saudi Arabia was the dominant producer with the rest of OPEC behaving as a competitive fringe.

The spike in oil prices in 2008 and the subsequent decline brought forth a renewed interest in oil market structure. The new studies include regression models such as Lin [37], Almoguera et al. [1] and Golombek et al. [24]. Almoguera et al. [1] posited that OPEC was a cartel faced by a competitive fringe and tested for switching between collusive and non-cooperative behavior in the 1974-2004 time frame. Golombek et al. [24] showed empirically that OPEC was a dominant firm with the rest of the world a competitive fringe, and that OPEC exercised its market power during 1986-2009.

There are a couple of recent studies that find OPEC and/or Saudi Arabia acting as a Stackelberg leader with the rest of the world and/or rest of OPEC acting as a competitive fringe. Using a numerical, partial equilibrium, one-period model, Huppman and Holz [30] find that observed prices are very close to those from a Stackelberg model, with Saudi Arabia the Stackelberg leader, during 2005-2007, but were closer to competitive prices during 2008 and 2009. Nakov and Nuno [40] employ a dynamic general equilibrium model with Saudi Arabia as the dominant producer and the rest of the oil exporters as a competitive fringe plus an oil importing, manufacturing country. The dominant producer is a Stackelberg leader, internalizing the responses of consumers and the competitive fringe. Huppman [29] models the oil market as a two-level Stackelberg oligopoly. The fringe's output response to a change in prices depends on its capacity utilization. Similar to Huppmann and Holz, the model is computed as a one-shot game in each period. Huppman finds that the Stackelberg oligopoly market fits market prices well over 2003-2008. Jin [32] develops a dynamic model of a dominant producer who sets both capacity utilization and capacity to influence not only market prices but the behavior of the competitive fringe as well.

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 and the global economy. Papers studying the effects of the shale boom on the

U.S. economy and importer/exporter GDP and oil revenues include Kilian [34], Manescu and Nuno [38], Mohaddes and Raisi [39], and Melek et al. [17] among others. Newell and Prest [42] show that the price responsiveness of U.S. supply is 13 times that of the pre-shale era. Bjornland et al [10] find very high short-run elasticities of supply for shale wells, with no significant supply response from conventional wells. Behar and Ritz [14] maintain that OPEC strategy had a regime change in 2014, switching from an "accommodative" strategy to a "squeeze" strategy to improve its market share. Frondel and Horvath, [23], with a reduced form dynamic OLS model, show that WTI prices would have been $40 - $50 higher without the shale boom. Gundersen [27] shows that oil prices would be $10 higher in 2014-2015 without US shale.

There are two papers that take very similar approaches to the one that we take in this paper. Manescu and Nuno [38], utilize the model of Nakov and Nuno [40] to analyze the effect of the increase in shale production. The model is a calibrated general equilibrium model of the world economy that includes an oil sector. As in our model, producers choose utilization and capacity, however in their model Saudi Arabia takes into account how its production decisions affect the fringe's utilization, 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 (utilization) and long-run (capacity) strategic decisions of the dominant producer. Bornstein et al. [13] 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 oil price volatility is reduced 65% 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 dynamics and the underlying shock processes in the model. Our estimation, on the other hand, uses actual time series dynamics in the oil market to estimate key market parameters. Furthermore, our estimation and analysis explicitly takes the shale transition into account, i.e., that the shale revolution is a transition 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.

Overall, our paper contributes to the literature on shale's effect on the oil market in three ways. First, to our best knowledge, ours is the first paper that models the dynamics of the ongoing shale revolution in that we explicitly model and estimate the transition from the pre-shale oil market to one where shale oil is fully developed. This feature allows us to speak to the current contribution of shale to the global oil market while allowing the contribution of shale to be substantially larger in the future. Second, 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." Third, we use actual price and output dynamics in the oil market to estimate key parameters in our structural model.

3 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 12.8 mb/d by the end of 2019. This increase of 7.9 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). Tight oil is defined as being from very low permeability rock that requires hydraulic fracturing in order for oil to flow (Schlumberger [50]).[4]. The combination of hydraulic fracking with horizontal drilling has unlocked a vast oil resource in these formations that were not formerly

[4]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 Resources [47])

accessible.[5] 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 5000 to 10,000 feet.[6] 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 [22]). Horizontal drilling exposes the well to much greater length and surface of rock, increasing production levels.

Horizontal drilling and hydraulic fracturing are not new technologies. The first commercial application of hydraulic fracking was done in 1949 (Aogh [3]), 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 [35]). 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 short amount of time. This reduces nonproductive times for rigs and simplifies the infrastructure and supply chains (Kleinberg, [36]). 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, [51]). Other techniques such as zipper fracking and stacked laterals in multiple shale layer have all helped to increase production from shale fields (Badiali [7]). Figure 4 shows the dramatic increase in productivity for the three major U.S. shale basins. This increase in productivity translates into reduced costs and greater

[5] 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.

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

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 [51]). 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. [7] As noted in the Literature Survey section, there are recent academic studies showing the supply elasticities from shale are quite a bit higher than from conventional oil.[8] The market structure of the U.S. oil industry may be another factor in the quicker response of shale producers to oil price changes. US 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) [16]). These producers typically act independently and as price takers (Kleinberg [36]).

All this suggests that similar to non-OPEC conventional oil producers, shale producers behave as a competitive fringe. However, unlike conventional producers, they have higher supply elasticities, faster response times, and rapidly increasing productivity.

4 Simple Static Model

To help us understand the implications of the increase in shale oil production on the world oil market, we first build a simple static model of the oil market.[9] In this simple model, we consider three types of producers: a competitive fringe of conventional oil producers, a competitive fringe of shale oil producers, and a dominant producer that may exercise its market power when setting production. The competitive fringe producers take prices as given choose output so that price equal marginal cost. The dominant producer will choose output

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

[8] See for example, Newell and Prest [42] and Bjornland, et al., [10]

[9] Appendix A provides the details for the static model.

taking into account how its production affects not only demand but also the competitive fringe's production.

One can think of the shale revolution in the context of our simple model as an increase in shale productivity that results in a large increase in the market share of shale. To help us understand the implication of the shale revolution where the dominant producer has market power, we consider a few numerical examples of the static model. The parameters of the model were chosen so that the market price and output were 100 in the pre-shale period and that pre-shale output shares of shale, conventional, and OPEC Core are set at roughly their actual market share's over the 1991-2004 period, 0.5%, 79.5%, and 20.0%, respectively. In our benchmark model, we set the elasticity of oil demand to be fairly low ($\eta_d = .3$). Shale's elasticity of supply was set to be substantially higher than that of OPEC Core and conventional fringe ($\eta_s = 1$ versus $\eta_o = .3$ and $\eta_f = .1$).

In Table 1, we present the response of oil price and total production, as well as the shares of OPEC Core, conventional fringe producers, and shale fringe producers to a dramatic (100 fold) increase in shale productivity. Panel A presents the market outcomes for the benchmark model. Not surprisingly, the increase in shale production results in a substantial increase in output and even greater proportional decrease in prices. Conventional fringe producers and OPEC Core lose market share as shale producers gain market share. Panel B considers the same 100 fold increase in shale productivity for the case where shale elasticity of supply is low ($\eta_s = 0.3$). Here the impact of the shale revolution on market outcomes is even larger than in the benchmark case. The lower elasticity of shale supply relative to the benchmark case implies greater price and output changes as well as greater changes in the shares. Panel C considers the case where the elasticity of demand (in absolute value terms) is greater than the benchmark case. Here the effect of the shale revolution on prices is smaller and the effect on output is larger than in the benchmark case. Comparing the three scenarios, the magnitude of the effect of the dramatic increase in shale productivity depends, in part, on the elasticities of demand and the various supplies.

The increase in shale production also has implications for how the oil market responds to changes in demand and supply unrelated to shale production. Table 2 displays the percent change in market price and output in response to a 10% increase in oil demand and a 10% increase in conventional fringe supply, respectively, before and after the shale revolution. Panel A displays the benchmark case, while Panel B presents the low shale supply elasticity case. For both scenarios, the shale revolution implies a reduction in the price response and an increase in the output response to changes in demand. This is not too surprising given our assumption that the supply elasticity of shale fringe is greater than that of the conventional fringe. The change in responses is greater for the benchmark case where supply elasticity is relatively high. For both cases, prices and output respond less to conventional supply changes after the shale revolution than before. Again, the reduction in responses is greater in the benchmark case where shale supply elasticity is relatively large. Together, this suggests the shale revolution is likely to reduce price fluctuations in the face of demand and conventional supply shocks. The direction of the effect on oil output fluctuations depends on the source of the shocks and their relative magnitude: for net demand shocks, output responds more than before; for net supply shocks, output ends up responding less.

Finally, the increase of shale production also changes the strategic calculus of the OPEC core. OPEC Core when exercising its market power takes into account how its choice of production not only affects market prices, but also how conventional and shale producers respond to market prices. This is similar to a Stackleberg leader where the dominant producer takes into account how competitors will respond to the dominant producer's choices. It can be shown that the optimal choice production of OPEC Core results in a price as a mark-up over marginal cost:

$$P = \frac{(\eta_d + \eta_s S_s + \eta_f S_f)}{(\eta_d + \eta_s S_s + \eta_f S_f) - (1 - S_s - S_f)} MC_o \tag{1}$$

where $(1 - S_s - S_f) = S_o$ is the dominant producer's market share. η_j is the parameter in the marginal cost function relating to the supply elasticity for producer j, η_d is minus the elasticity of market demand. The term $(\eta_d + \eta_s S_s + \eta_f S_f)$ in equation (1) is (minus) the elasticity of residual demand for OPEC Core's output $(Q - Q_f - Q_s)$. This residual demand elasticity reflects not only how demand responds to changes in the market price but also how conventional and shale fringe supplies respond to changes in market prices.

Table 3 provides some insight into how OPEC Core as the dominant producer in the oil market might be affected by the shale revolution. Table 3 presents the mark-up of price over OPEC Core's marginal cost implied by the model. Table 3 also presents the pseudo elasticity of supply for OPEC Core and the overall oil market before and after the shale revolution. Since OPEC Core sets its output taking into account of its affect on the market price and the fringes' outputs, it's elasticity of supply is not given by the reciprocal of the elasticity of its marginal cost. We define pseudo supply elasticity as

$$\frac{\frac{dQ_o}{dx_d}}{\frac{dP}{dx_d}} \frac{P}{Q_o} \tag{2}$$

or the percent change in output relative to the percent change in price as a result of a change in oil demand (x_d). From Table 3, one observes that an increase in shale productivity in our static model lowers OPEC Core's mark-up and dramatically increases its pseudo supply elasticity. It also increases the pseudo supply elasticity of the overall market. These effects are substantially larger when shale supply elasticity is relatively high. This suggests that the shale revolution is likely to increase the responsiveness of OPEC Core to oil demand shocks and also increase the responsiveness of market supply as a whole.

5 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. Let $Q_{o,t}$ denote the dominant producer which we take as OPEC Core, $Q_{f,t}$ is the conventional fringe production, and $Q_{s,t}$ is the shale fringe production. 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 utilization provides the short run margin. We also allow the dominant producer (here OPEC Core) to take into account how the competitive fringe (both shale and conventional) will respond to market prices.

5.1 Dynamic demand

We consider a simple dynamic demand function which incorporates long-term and short-term demand:[10]

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

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

$$P_t = P(Q_t, Q_{t-1}, x_{d,t}) \tag{3}$$

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

$$Q_t = Q_{o,t} + Q_{f,t} + Q_{s,t}. \tag{4}$$

Substituting (4) into (3), yields the market clearing equation:

$$P(Q_{o,t} + Q_{f,t} + Q_{s,t}, Q_{o,t-1} + Q_{f,t-1} + Q_{s,t-1}, x_{d,t}) = P_t. \tag{5}$$

[10] Atkeson and Kehoe's (1999) [5] Putty-Clay technology suggests a demand for oil whose short-term and long-term price elasticities are different.

5.2 Dynamic supply

Conventional oil production typically has a lengthy initial development phase. This results in producers' limited ability to adjust production in the short-run in response to market changes. Over the long run, producers can explore, appraise and develop more fields. Shale technology may shorten the development phase, and different types of producers differ in their 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: output capacity and capacity utilization. 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 output capacity available in t which is predetermined in time period t and $u_{j,t}$ is the current utilization rate of capacity. In each period, producers choose their current utilization rate, $u_{j,t}$, and next-period's capacity $k_{j,t}$. This "time-build-to" feature of capacity reflects that substantial resources must be spent before production is realized.

Oil producers incur two types of costs. The first is the direct operating cost or "production cost", $C_j(u_{j,t}, k_{j,t-1})$. This cost reflects the cost of current production given current production capacity. The second is the cost of changing capacity, $\phi_j(k_{j,t}, k_{j,t-1})$. This second cost reflects the costs of exploration and developing new oil fields. Shale and conventional producers will differ both in their production costs, $C_j(u_{j,t}, k_{j,t-1})$, and their costs of changing capacity, $\phi_j(k_{j,t-1}, k_{k,t})$.

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

$$\underset{t}{E} \sum_{i=0}^{\infty} \beta^i \pi_{j,t+i} \tag{6}$$

where β is the discount factor and

$$\pi_{j,t} = P_t u_{j,t} k_{j,t-1} - C_j(u_{j,t}, k_{j,t-1}) - \phi_j(k_{j,t-1}, k_{j,t}). \tag{7}$$

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, $k_{j,t-1}$ and utilization, $u_{j,t}$ and next-period capacity, $k_{j,t}$.

5.2.1 Competitive fringe

Both traditional and shale fringe producers ($j = f, s$) are competitive price takers and choose $u_{j,t}$ and $k_{j,t}$ to maximize the present value of profits. Their choice can be described by the following first order conditions:

$$\frac{\partial \pi_{j,t}}{\partial u_{j,t}} = 0 \tag{8}$$

$$\frac{\partial \pi_{j,t}}{\partial k_{j,t}} + \underset{t}{E}\left[\beta \frac{\partial \pi_{j,t+1}}{\partial k_{j,t}}\right] = 0 \tag{9}$$

Given $\frac{\partial \pi_{j,t}}{\partial u_{j,t}} = P_t k_{j,t-1} - \frac{\partial C_j(u_{j,t}, k_{j,t-1})}{\partial u_{j,t}}$, equation (8) sets marginal revenue equal to marginal cost of increasing current utilization. The term in equation (9) $\frac{\partial \pi_{j,t}}{\partial k_{j,t}} = -\frac{\partial \phi_j(k_{j,t-1}, k_{j,t})}{\partial k_j,t}$ represents the cost of adding an extra unit of capacity, and $\frac{\partial \pi_{j,t+1}}{\partial k_{j,t}} = P_{t+1} u_{j,t+1} - \frac{\partial C_j(u_{j,t+1}, k_{j,t})}{\partial k_{j,t}} - \frac{\partial \phi_j(k_{j,t}, k_{j,t+1})}{\partial k_{j,t}}$, which represents the future net revenue of adding an extra unit of capacity. Thus, the fringe production is trading off the current cost of additions to $k_{f,t}$ against its affect on $t + 1$ revenue.

5.2.2 OPEC Core

We distinguish between the OPEC Core and the competitive fringe by allowing OPEC Core to take into account of its market power when making its production decision. Here we assume that OPEC Core is acting strategically as a Stackelberg leader.[11] We assume that

[11] Appendix E presents alternative assumptions about the behavior of OPEC Core.

OPEC Core chooses $u_{o,t}$ and $k_{o,t}$ to maximize the present value of profits but takes into account how prices and the competitive fringe (both conventional and shale) will respond to its production decisions. Specifically, the dominant producer takes into account that price is determined by equation (5) and that the competitive fringe production decisions will be governed by equations (8) and (9). In each period the OPEC Core anticipates that its choice of current utilization and next-period's capacity will affect current and next period's price and, hence, influence the competitive fringe's decisions about its current utilization and next-period capacity. Essentially, one can think of OPEC core as picking capacity and utilization in order to achieve a desired price for oil. In choosing this price, the OPEC Core takes into account how this price will affect the competitive fringe's production decisions.

Formally, we set the OPEC Core's problem up as a constrained optimization problem where the market clearing conditions and the fringe's optimality conditions enter as constraints.[12] 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' utilization 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:

$$\max_{u_{o,t},\ k_{o,t},\ P_t,\ u_{j,t},\ k_{j,t},\ j=f,s} \underset{t}{E} \sum_{i=0}^{\infty} \beta^i \pi_{o,t+i} \tag{10}$$

subject to constraints given by equation (5) and equations (8), and (9) for $j = f, s$. We denote λ_t^p as the Lagrange multiplier on constraint (5) and $\lambda_{j,t}^u$ and $\lambda_{j,t}^k$ for j = f,s as the Lagrange multipliers on constraints (8) and (9). The Lagrange multiplier λ_t^p reflects the value of an incremental increase in price while $\lambda_{j,t}^u$ and $\lambda_{j,t}^k$ for j = f,s reflect the value of influencing the fringes' utilization and capacity decisions. We consider time consistent choices on the part of the dominant producer, so that the first order conditions that characterize time t decisions will also characterize future decisions.[13]

[12]This model uses a very similar structure to that in the Ph.D. dissertation of Jin [32]. The most recent version of Bornstein, Krusell, and Rebelo [13] also approaches the dominant producer's optimization problem in similar way as we do. See Appendix C for fuller description of OPEC Core's optimization problem.

[13]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

The first-order conditions for the dominant producer's utilization rate, $u_{o,t}$, and capacity, $k_{o,t}$, are:

$$(u_{o,t}) : \frac{\partial \pi_{o,t}}{\partial u_{o,t}} + \lambda_t^p \frac{\partial P_t}{\partial Q_t} k_{o,t-1} + \underset{t}{E}[\lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_t} k_{o,t-1}] = 0 \tag{11}$$

$$(k_{o,t}) : \frac{\partial \pi_{o,t}}{\partial k_{o,t}} + \underset{t}{E}[\beta \frac{\partial \pi_{o,t+1}}{\partial k_{o,t}} + \lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_{t+1}} u_{o,t+1} + \lambda_{t+2}^p \frac{\partial P_{t+2}}{\partial Q_{t+1}} u_{o,t+1}] = 0 \tag{12}$$

The term, $\frac{\partial \pi_{o,t}}{\partial u_{o,t}}$, in equation (11) reflects the effect of utilization on current profits while the terms $\lambda_t^p \frac{\partial p_t}{\partial Q_t} k_{o,t-1} + \underset{t}{E}[\lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_t} k_{o,t-1}]$ reflects the value of increasing current production by influencing the current and future prices. Similarly, the dominant producer's choice of capacity ($k_{o,t}$) takes into account not just the effect on current and future profits but also the effect on the market price.

The first-order condition for P_t reflects the dominant producer's ability to affect market prices and, hence, its profits as well as how price affects fringes' production decisions:

$$(P_t) : \frac{\partial \pi_{o,t}}{\partial P_t} - \lambda_t^p - \lambda_t^{u,s} \frac{\partial^2 \pi_{s,t}}{\partial u_{s,t} \partial P_t} - \lambda_t^{u,f} \frac{\partial^2 \pi_{f,t}}{\partial u_{f,t} \partial P_t} = 0. \tag{13}$$

The optimal choice of price takes into account how the price will affect the first order conditions of the shale and conventional fringe. The Lagrange multipliers $\lambda_t^{u,s}$ and $\lambda_t^{u,f}$ capture the value of influencing the fringes' choice of current production (through capacity utilization).

The first order conditions for $u_{j,t}$ and $k_{j,t}$ for $j = f, s$ are given by:

$$(u_{j,t}) : \quad \lambda_t^p \frac{\partial P_t}{\partial Q_t} k_{j,t-1} + \underset{t}{E}[\beta \lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_t} k_{j,t-1}] - \lambda_t^{u,j} \frac{\partial^2 \pi_{j,t}}{\partial {u_{j,t}}^2} = 0. \tag{14}$$

---

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 [32] considered commitment case but preliminary analysis found little empirical difference between the commitment and the time consistent model in our application.

$$(k_{j,t}): \quad \mathop{E}_{t}[\beta\lambda^{p}_{t+1}\frac{\partial P_{t+1}}{\partial Q_{t+1}}u_{j,t+1} + \beta^2\lambda^{p}_{t+2}\frac{\partial P_{t+2}}{\partial Q_{t+1}}u_{j,t+1}] - \mathop{E}_{t}\left[\beta\lambda^{u}_{j,t+1}\frac{\partial^2 \pi_{j,t+1}}{\partial u_{j,t+1}\partial k_{j,t}}\right]$$

$$-\lambda^{k}_{j,t}\left[\frac{\partial^2 \pi_{j,t}}{\partial {k_{j,t}}^2} + \mathop{E}_{t}\left[\beta\frac{\partial^2 \pi_{j,t+1}}{\partial {k_{j,t}}^2}\right]\right] - \mathop{E}_{t}\left[\beta\lambda^{k}_{j,t+1}\frac{\partial^2 \pi_{j,t+1}}{\partial k_{j,t+1}\partial k_{j,t}}\right] = 0. \tag{15}$$

The first two terms in (14) and (15) reflect the value of influencing current and future prices by influencing the fringes' choice of utilization and capacity, respectively. The remaining terms in (14) and (15) reflect how this affects the fringe producers' optimality conditions.

To summarize Section 5.1 and 5.2, the model's first order conditions and market clearing condition include 8, 9, 11, 12, 13, 14, 15, 5.

5.3 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.

5.3.1 Oil Demand

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

$$Q_t = x_{d,t}\left(\frac{Q_{t-1}}{x_{d,t-1}}\right)^{\rho_d} P_t^{-\eta_d(1-\rho_d)} \tag{16}$$

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 changing demand in response to price changes in the short-run.

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

$$x_{d,t} = x_{b,t} x_{c,t} x_{i,t} \tag{17}$$

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 steady trend is discernible in oil prices. To capture this feature of the data, we, as in Bornstein, Krusell and Rebelo (2019) [13], introduce the balance growth trend component that 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 0.8% per year absent the shale revolution.

For the cyclical component of oil demand, in our empirical analysis below we set

$$log(x_{c,t}) = \eta_y log(WEA_t) \tag{18}$$

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.[14]

5.3.2 Cost Functions for Oil Production

We specify the cost functions in order to capture the different responsiveness oil supply in the short and long runs. In particular, we specify the cost function so that the short and long-run elasticities of supply are different. More generally, this reflects differences in the direct production cost for field operation and investment costs of development new fields.

[14] See Appendix C for a fuller description of the demand processes.

With those goals in mind, we model production costs as:

$$C_j(u_{j,t}, k_{j,t-1}) = c_j(u_{j,t})\ z_{j,t} \frac{k_{j,t-1}^{(1+\frac{1}{\eta_{k,j}})}}{(1+\frac{1}{\eta_{k,j}})} \tag{19}$$

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

$$c_j(u_{j,t}) = c_{0,j} + c_{1,j} u_{j,t}^{(1+\frac{1}{\eta_{u,j}})}. \tag{20}$$

The parameter $\eta_{u,j}$ is the short-run (within a period) elasticity of supply. The parameters $c_{0,j}$ and $c_{1,j}$ are chosen to normalize utilization and the cost function $c_j(u_{j,t})$ to be one in the steady state ($u_{j,ss} = 1$ and $c_j(1) = 1$).[15] The level of capacity determines long-run productions costs. These are given by $z_{j,t} \frac{k_{j,t-1}^{(1+\frac{1}{\eta_{k,j}})}}{(1+\frac{1}{\eta_{k,j}})}$. The long-run (balance growth steady state) elasticity of supply is given by $\eta_{k,j}$.

While costs and output are determined by utilization in the very short run and by capacity in the very long run, in the intermediate term there are costs of adjusting capacity, $\phi_j(k_{j,t-1}, k_{j,t})$. Here we assume these are quadratic and given by:

$$\phi_j(k_{j,t-1}, k_{j,t}) = \kappa_{j,0} \left(\frac{k_{j,t}/x_{b,t}}{k_{j,t-1}/x_{b,t-1}} - 1 \right)^2 \ k_{j,t-1} \tag{21}$$

We normalize 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 $z_{j,t} \frac{k_{j,t-1}^{(1+\frac{1}{\eta_{k,j}})}}{(1+\frac{1}{\eta_{k,j}})}$.[16]

All three producers are periodically hit with cost shocks that change the costs of produc-

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

[16] We do not model the extraction and depletion of oil as the steady growth of world oil production and oil reserves suggests that not modeling these elements is unlikely to be an important oversight when modeling oil market dynamics over our sample period.

tion. We assume that this cost shock consists of two components:

$$z_{j,t} = \frac{v_{j,t}}{x_{b,t}^{(1+\frac{1}{\eta_{k,j}})}} \tag{22}$$

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 a 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 balance growth trend will not affect the relative market share of producers in the long run.

5.4 The shale revolution

We model the shale revolution as 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.[17] We assume an "S" shaped transition curve from the low shale steady state to the high shale steady state. Specifically, we set

$$log(v_{s,t}) = log(v_{s,t}^{temp}) + log(v_{t}^{perm}) \tag{23}$$

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

[17]The consulting firm Rystad predicts that shale's share of global production will be 20 percent in 2050.

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

$$log(v_t^{perm}) = log(v_{new\ ss}^{perm}) + 2\rho_{v_s}(log(v_{t-1}^{perm}) - log(v_{new\ ss}^{perm})) - \rho_{v_s}^2(log(v_{t-2}^{perm}) - log(v_{new\ ss}^{perm})) \quad (24)$$

The values of $v_{old\ ss}^{perm}$ and $v_{new\ ss}^{perm}$ are chosen so that the 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 as "S" shaped transition in (log) shale's share of world production. We estimate the value of ρ_{v_s} in our empirical analysis below.[18]

6 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 into account of the transitional nature of the dynamics, both in terms of dynamic evolution of shale costs but also in the solution of the model. Appendix D contains a detailed description of our solution technique.

6.1 Model solution and approximation

The model outlined in Section 5 can be written as a system of nonlinear difference equations:

$$\underset{t}{E}\left[g(X_t, X_{t+1}, X_{t-1}, e_t, v_{old\ ss}^{perm}, \Theta)\right] = 0, \qquad t < 2005Q1 \quad (25)$$

and

$$\underset{t}{E}\left[g(X_t, X_{t+1}, X_{t-1}, e_t, v_{new\ ss}^{perm}, \Theta)\right] = 0, \qquad t \geq 2005Q1 \quad (26)$$

[18] S-shaped diffusion curves have been used widely in the literature to model technology adoption. See Comin and Mestieri [20].

where X_t is $n \times 1$ vector of endogenous variables, e_t is $p \times 1$ vector of exogenous, i.i.d. N(0,1) shocks, and Θ are structural parameters of the model. X_t includes variables such as market price, P_t, 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 system of equations given by (25) and (26) is the steady state of shale's production cost.

Typically, a model such as implied by equation (25) or equation (26) 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 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^{perm}_t. Recall that we set the original steady state value, $v^{perm}_{old\ ss}$ so that shale's share of world oil market is 0.5% while the new steady state value results in shale share of world oil market 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 first order approximation multiple times as shale costs transition toward the new steady state. That is, we employ a sequence of linear approximations that depend on the value of the transition variable, v^{perm}_t. As a result, rather than approximate around a single steady state, we allow the approximation point to change over time as the shale costs (v^{perm}_t) change over time. From the perspective of time periods before 2005, the success of the shale revolution has been almost certainly been 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 (24).

For time periods before the shale revolution, we linearly approximate the model around the pre-shale steady state:

$$X_t = G^{[0]} + P^{[0]} X_{t-1} + Q^{[0]} e_t \tag{27}$$

where where $G^{[0]}$ is a $n \times 1$ vector, $P^{[0]}$ is $n \times n$ matrix, and $Q^{[0]}$ is a $n \times p$ matrix. The matrices $G^{[0]}$, $P^{[0]}$, and $Q^{[0]}$ depend on the steady state values of the endogenous variables when shale production costs are equal $v^{perm}_{old\ ss}$ (and the other structural parameters θ):

$$\begin{aligned} G^{[0]} &= G(X_{ss|v^{perm}_{old\ ss}}) \\ P^{[0]} &= P(X_{ss|v^{perm}_{old\ ss}}) \\ Q^{[0]} &= Q(X_{ss|v^{perm}_{old\ ss}}) \end{aligned} \tag{28}$$

These matrices depend on the steady state values of X_t when the steady-state value of shale production cost is equal to $v^{perm}_{old\ ss}$ or $X_{ss|v^{perm}_{old\ ss}}$. Equation 27 holds in all the time periods before 2005Q1 and reflects the fact that the "shale revolution" was a surprise from the point of view of time periods before 2005Q1.

For the time periods after the shale revolution begins, our approach is similar to the piecewise linear approximation of Guerrieri and Iacoviello [26].[19] For a time period sufficiently far in the future, t_N, we linearly approximate the model around the new steady state.[20] That is, for $t \geq t_N$:

$$X_t = G^{[N]} + P^{[N]} X_{t-1} + Q^{[N]} e_t \tag{29}$$

[19]See supplementary appendix D for details of solution method.

[20]We take $t_N = 2045Q1$.

where

$$
\begin{aligned}
G^{[N]} &= G(X_{ss|v^{perm}_{new\ ss}}) \\
P^{[N]} &= P(X_{ss|v^{perm}_{new\ ss}}) \\
Q^{[N]} &= Q(X_{ss|v^{perm}_{new\ ss}})
\end{aligned}
\tag{30}
$$

$G^{[N]}$ is a $n \times 1$ vector, $P^{[N]}$ is $n \times n$ matrix, and $Q^{[N]}$ is a $n \times p$ matrix. For periods before t_N, the new steady state is not good approximation, so we approximate around different values of v_t^{perm} along its transition path from the pre-shale to post-shale steady state. We start at post-shale steady state and work backwards in time to solve the model, periodically changing the approximation point. The resulting first order approximation for time periods, $2005Q1 \leq t < t_N$, is given by:

$$
X_t = G^{[t]} + P^{[t]} X_{t-1} + Q^{[t]} e_t. \tag{31}
$$

The matrices $G^{[t]}$, $P^{[t]}$, and $Q^{[t]}$ reflect both changing approximation points and the fact that agents in the model know the transition path to the post-shale steady state. For time periods before 2005Q1, $G^{[t]} = G^{[0]}$, $P^{[t]} = P^{[0]}$, and $Q^{[t]} = Q^{[0]}$.

6.2 Estimation equations

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

$$
Y_t^{obs} = H X_t \tag{32}
$$

where Y_t^{obs} is the vector of observable variables and H is a selector matrix that pulls the observable variables from the variables in the model. The state equation is given by equation (31). 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.

We assume that these structural shocks are normally distributed with mean zero. The matrices $G^{[t]}$, $P^{[t]}$, and $Q^{[t]}$ in the state equation depend on the deep model parameters (Θ) such as elasticities of supply and demand and adjustment cost parameters along with the values of $log(v_t^{perm})$ used to the approximate the model along the transition path. One way to think about our model is it allows for the parameters in a first order approximation to change as shale production costs change during the transition from pre-shale steady state to the post-shale steady state. Since we assume that 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 with time varying parameter in the state equation to evaluate the model likelihood.

Table 4. lists the observable variables in our empirical analysis. Along with real oil price and world oil production, we include the share of OPEC Core in world oil production and US shale's share of world oil production as well. As an indicator of cyclical oil demand, we include detrended log world industrial production from Baumeister and Hamilton [8].[21] Our data are quarterly and the sample period runs from 1991Q1 to 2020Q. As shale production data start in 2001, we treat shale share observations before 2001 as missing when estimating the model.

We estimate the model using Bayesian methods similar to An and Schorfeide [4]. We use a Metropolis-Hasting MCMC to simulate the posterior distribution of the parameters. Here we take 500k draws from the Markov Chain, discard the first 200K draws and take the last 300k to form an estimate of the posterior distribution of the parameters using every 10th draw.[22] From this posterior distribution, we calculate the posterior distribution of various functions of the parameters and the model such as unconditional moments implied by the model, impulse responses, variance decomposition, and historical decomposition.

[21] We use a linear time trend to detrend log world industrial production.

[22] Standard diagnostics suggest that the Markov chain has converged. These are available upon request.

6.3 Prior distribution of parameters

To implement Bayesian estimation, we specify prior distributions over model parameters. Table 5 displays the structural parameters along with their specified values or prior distributions. The discount factor is not estimated but is set a priori. For many of the parameters, such as the autoregressive parameters and the variances of the shock processes, the prior distribution is relatively uninformed. However, for several structural parameters the prior distribution is informative. In particular, the mode of the prior distribution for the long-run elasticity of supply for shale oil is twice that implied for conventional fringe and OPEC Core. For the short-run elasticity of supply, we assume prior distributions across the three types of producer are the same with a mode of 0.1. We set the mode of prior distribution for the long run elasticity of demand to be 0.5 while the short-run elasticity of demand is set at 0.1. We set a fairly large range for the interior 90% range of the prior distributions to reflect the uncertainty about these parameters present in the literature. Herrera and Sangaraju (forthcoming) [28] document the wide distribution of short-run demand and supply elasticities in the literature from structural VAR models: demand elasticities range from -0.087 to -1.72, while supply elasticities range from 0.017 to 0.447. Newell and Prest [42] note that the price responsiveness of post-shale U.S. supply is 13 times that of pre-shale supply.

7 Empirical results

In this section, we examine the impact of the shale revolution on the oil market and the behavior of OPEC. We first briefly discuss the posterior distribution of the structural parameters. We then examine the effect of the shale revolution on global and OPEC Core supply and the volatility of oil price and output. Finally, we present historical decompositions of oil price and quantities to assess the importance of the various shocks in our model.

7.1 Posterior distribution of parameters

Table 6 displays features of the posterior distribution of estimated structural parameters in the demand function and the cost functions and the parameters of the shock processes.

The demand function parameters correspond to the long-term and short-term elasticities of demand, and the elasticity of oil demand with respect to world economic activity. The mean of the posterior distribution for the long-run elasticity of demand was estimated to be -0.19 and the posterior distribution 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. The low estimated values for the short- and long-run elasticities of demand arise, in part, because oil prices fluctuate much more over our sample than does oil quantity and a low elasticity of demand helps reconcile the model with the data. The mean of the posterior distribution of the elasticity of oil demand with respect to economic activity is around 1.5 which is higher than the mode of the prior distribution and higher than in the literature.[23]

While the structural parameters in the cost functions of different producers ($\eta_{k,j} and \eta_{u,j}, j = f, s, o$) are related to the supply elasticities, for OPEC core they are not identical to the to price elasticity of supply. We will discuss the cost parameter estimates for OPEC core below and present the implied pseudo supply elasticity in the later section.

The mean of the posterior distribution for OPEC Core's long-run cost parameter was 0.29 while that for conventional fringe suppliers was 0.18. These are lower than values implied by the prior distribution, but not too out of line with the literature.[24] The estimated long-run cost parameter for shale producers was estimated to be around 0.45 (posterior mean equal to 0.46 and posterior mode of 0.45). These are in line with our priors that the long-run elasticity of supply is greater for shale than for other producers. For all producers, the posterior distribution is less dispersed than the prior, suggesting that the data is informative

[23] Brown [14], in a survey of elasticities across different models, has income elasticites ranging from 0.55 to 0.8.

[24] See Brown [14]

about these parameters.

The posterior distribution of the short-run cost parameters are estimated to be substantially lower than the long-run ones. In fact, most of the mass of the posterior distribution for the producers other than shale was on values less than 0.10. Somewhat surprisingly given the same priors for all three types of producers, we estimate shale cost parameter to be the highest, followed by conventional fringe, indicating a flatter, with respect to output, short-run marginal cost for the shale than the others. The value of $\eta_{u,o}$ is lower than those of the conventional and shale fringes.[25] The low estimated value for OPEC Core short-run parameter is in part a result OPEC Cores relatively stable market share and output level despite volatile price movements. A low short-run cost parameter or a steep marginal cost would help reconcile the model which assumes profit-maximizing OPEC Core with the data. In particular, shale producers appeared much more responsive to the drastic drop in price in 2020, while OPEC Core even briefly increased its output in April 2020, before cutting back and maintaining a lower new constant output level.

7.2 Shale revolution and the oil market

In this section, we examine the pseudo-supply elasticities implied by our estimates. We show how the supply elasticities change as a result of the shale revolution, both for OPEC Core and for the overall market. We also consider the effect that the shale revolution might have on the volatility of oil price and output.

The static model suggested that the elasticity of market supply with respect to price might be affected as the share of shale production became larger. Not only can the increase in shale production change shale's share of market output, but it may also change how OPEC Core production responds to market forces. In order to measure supply's responsiveness to price changes from our dynamic model, we calculate pseudo-supply elasticities similar to those derived from the static model. Specifically, we take the response of log output to

[25] Recall that the parameter $\eta_{u,o}$ is the elasticity of supply if OPEC Core behaved as a competitive producer.

an oil-specific demand shock relative to the response of log market price to an oil-specific demand shock:

$$\frac{E[log(Q_{t+k})|e_{i,t}, Y_{t-1}] - E[log(Q_{t+k})|Y_{t-1}]}{E[log(p_{t+k})|e_{i,t}, Y_{t-1}] - E[log(p_{t+k})|Y_{t-1}]}. \tag{33}$$

where $e_{i,t}$ is the oil specific demand shock. We do this at various horizons to account for the dynamic behavior 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 (33) is well defined.

Table 7 displays the mean 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 the supply elasticities in the post-steady state, and Panel C displays supply elasticities in 2019Q4 which is roughly halfway through the transition from the pre-shale to post-shale steady state. 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; the supply elasticities are very similar across the three panels. On the other hand, the implied supply elasticity of OPEC Core changes somewhat across the three panels, especially at longer horizons, getting larger as shale's share increases.

At the five-year horizon, OPEC Core's pseudo supply elasticity is 20% higher in the post-shale steady state than in the pre-shale steady state. This suggests that OPEC Core's strategic calculus changes as shale's share gets larger, resulting in greater sensitivity to demand shocks. Finally, 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 an increase in the market supply elasticity at the 5 - year horizon of around 30%, from 0.194 to 0.254. The transition period (Panel C) suggests increased elasticities in supply roughly halfway between the pre-shale and post-shale elasticities, suggesting that even now shale production is changing the responsiveness of market supply.

Changes in supply elasticities have implications for price and output volatility as well. Increased shale production and the increased elasticity of market supply implies it 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 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 price and output, we calculate the unconditional variance of these variables implied by the model. Table 8 displays the variance and variance decompositions of (log) oil prices and (log) total oil production in the pre-shale steady state, in the transition period and in the post-shale steady state.[26] Comparing pre- and post-shale variance decompositions reveals a 30% decline in the variance of (log) prices in the pre-shale versus the post-shale periods. The variances in the transition period also suggests that the shale revolution has already lessened the potential price volatility in the oil market. On the other hand, the variance of (log) oil output does not vary between the pre and post-shale steady states, suggesting the greater responsiveness of output to demand shocks is offset by the lessened response of output to conventional supply shocks.

Indeed, we find that conventional supply shocks become less important as a source oil price and output volatility with the advent of the shale revolution. Shale's role as a buffer to conventional and OPEC Core 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., 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 Hill [15] state, "the costs to the United States to exercise market power in the oil market, the costs of maintaining a strong military presence

[26]We present the variance decompositions for the parameter vector evaluated at the posterior mode.

in the Middle East and various other foreign policy factors".[27] Shale's rise may lessen the strategic considerations oil plays in future international relations.

7.3 Sources of oil market fluctuations

Our model has insights about the sources of oil price and quantity movements over the 1991-2020 time horizon. 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}) from the old steady state towards the new steady state. Figures 5-8 display historical decompositions for the oil market variables.[28] The shaded regions show the contributions of the various shocks while the black line in the figures is the actual observations. With the except of OPEC Core, the contributions of the various shocks nearly add up to the actual time series by construction except for early in the sample.[29]

Figure 5 displays the historical decomposition of (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 and to 2015. In the context of our model, the decline in conventional fringe supply relative to trend shows up as conventional fringe cost shocks.[30] Some of the dramatic increase 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

[27]See Brown and Hill [15] for a summary of the literature on the costs of oil import dependence.

[28]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.

[29]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 die out. We leave out the contribution of the initial conditions to lessen the clutter in the figures.

[30]The relative decline in conventional fringe supply during this period coincided with much discussion by commentators at the time about "peak oil". See for example, Campbell and Laherrere, [19]

to a decrease in oil specific demand and an increase in conventional fringe supply.[31] 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. The direct contribution of shale cost changes to oil price movements over our sample, either by the shale revolution transition or temporary shale cost shocks, are relatively modest. For example, in 2020Q3, the direct effect of the shale revolution transition variable is to lower the oil price approximately 10%.

Figure 6 displays the decomposition of oil output over the 1991-2020 period. Unlike oil prices, the balanced growth trend has an important effect on oil output movements, contributing to the steady upward trend in world oil production. Oil specific demand shocks and conventional fringe cost shocks are also large contributors to oil output fluctuations, although their contributions tend to offset one another. Specifically, oil specific demand shocks in the 2000s contributed to higher oil output while conventional fringe cost shocks contributed to lower oil output (and higher prices). Once more the effect of the decline in economic activity as a result of the coronavirus pandemic largely contributes 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 is relatively modest; in 2020Q3 the direct effect of the shale transition variable on world oil production is roughly 2%.

Figures 7 and 8 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. In fact, it is the variable that is largely responsible for increase in shale's share over our sample. However, shale share also responds to other shocks as shale oil production has a different cost structure than either conventional fringe or OPEC Core production. In fact, Figure 7 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 the estimated parameters suggest

[31] 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.

that shale output is more sensitive to prices than the conventional fringe. OPEC Core's share (see Figure 8) 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 behavior does not capture. on the other hand, the impact of the shale transition becomes more important for OPEC Core's share, especially after 2015.

7.4 The effect of the shale revolution on oil price and quantities

As we saw above, the direct effect of the shale transition variable on market price and output is relatively modest. 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) change 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 Figures 5-8, display the variables' paths over the sample for the counterfactual experiment.

From the counterfactual, we observe in Figure 5 that the overall effect of the shale revolution begins to manifest itself around 2010 and gradually gets larger. If the shale revolution had not happened, by 2020Q3 oil prices would have been 31% higher (see Figure 5) and output would have been 5% lower (see Figure 6). Note that, shale's output share is higher at the end of the sample than the beginning of the sample but is still small in the counterfactual, 1% ($exp(-4.5)$) in the counterfactual versus 10% ($exp(-2.5)$) in the benchmark model. OPEC Core has roughly the same share, with and without shale, 21% in both cases. This suggests that shale's growth has been at the expense of conventional producers in the ROW and not OPEC Core.

That we find the effect of the shale revolution on the world oil market becomes substantial in the early 2010s is consistent with the emergence of shale into the public's collective consciousness at about that time. Figure 9 displays a count of articles from the Wall Street Journal and the Financial Times that contain references to "shale oil" over our sample 1991-2020. From the article count it is clear that shale oil began to garner much greater attention starting in 2010 right around when our counterfactual analysis suggests that the shale revolution began to make a substantial difference on the world oil market.

Table 9 displays the posterior distribution of the post-shale steady states for oil price, output, and output shares. In the long-run, the model implies that the shale revolution lowers real oil price by about 48% and increases market output by roughly 13% (relative to the balanced growth trend).[32] By construction, shale's share is constrained to be 20% in the post-shale steady state. OPEC Core's share falls slightly in the new steady state while conventional fringe producers' market share falls from around 80% of the market to 63% of the market. This implies that OPEC Core is adjusting its production to keep its market share from falling very much. On the other hand, the conventional fringe responds to the decrease in prices by cutting its production relative to the entire market, resulting in a dramatic fall in the conventional fringe's market share.

7.5 The role of OPEC Core behavior

We modeled OPEC Core as if they behaved strategically when setting their production decisions. In this section, we consider two additional counterfactuals where we consider alternative ways of modeling OPEC Core behavior. The first is to model OPEC Core as a non-strategic price setter that takes into account how its production decision affects the market price but takes the fringe production decisions as given (similar to the Cournot model of oligopoly). The second is to assume OPEC Core takes prices as given as in a competitive

[32]From Table 9, comparing post-shale with pre-shale steady state, the pre-shale steady state price is roughly 90% higher (100/52.5-1) and pre-shale output is 12% lower (100/112.9-1)

market structure. We use the estimated parameters and shocks from the benchmark model but use the decision rules implied by competitive or cournot market structure to model the behavior of OPEC Core. Figure 10 displays (log) real oil price and (log) market output for the benchmark model as well as the competitive and Cournot counterfactuals. From the figure, we observe that the real oil price would have been slightly higher (roughly 4.8% higher in 2020Q3) and market oil output would have been slighly lower (3% lower) assuming Cournot behavior compared to the benchmark model.

Under a competitive market structure, market prices would have been substantially lower (30% lower) and output higher (5% higher). Under a competitive market structure the model suggests that OPEC Core's market share would also have been substantially higher (30% versus 21%) than the actual market share in 2020Q3. Viewing the fluctuations in the figure, it appears that the price volatility (in logarithms) would have been slightly smaller and output volatility (in logarithms) would have been slightly larger with a competitive market than either the Cournot and benchmark (Stackelberg) structure. This suggests that by exercising its market power, OPEC Core somewhat moderates price fluctuations in the oil market than if it acted as a price taker.[33]

8 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

[33] In Appendix F, we consider additional robustness exercises by examining the effect of alternative assumptions about expectations of future shale production costs and the long-run share of shale in world oil production. For the most part, these alternative assumptions do not change the substance of model's results.

in the model and then use these to identify the source of fluctuations in the oil prices and production.

We find that the advent of shale lowered oil prices substantially – prices would have been approximately 31% higher in 2020Q3 had the shale revolution not occurred. We also show that shale production acts as a buffer to demand and non-shale supply shocks, lowering the volatility of oil prices and output. Despite the entry of shale into the market, OPEC Core producers, by acting strategically, have maintained their market share, suggesting the 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 U.S., 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.

A Static Model

We assume oil demand is given by:

$$Q = x_d P^{-\eta_d} \tag{A.1}$$

where $-\eta_d$ is the elasticity of demand and x_d is a demand shifter. Total quantity produced is equal to sum of the production from the conventional fringe (Q_f), shale fringe (Q_s), and OPEC Core (Q_o):

$$Q = Q_f + Q_s + Q_o \tag{A.2}$$

We assume that competitive fringe conventional and shale producers are price takers and their behavior is characterized by the supply functions:

$$Q_f = x_f P^{\eta_f} \tag{A.3}$$

and

$$Q_s = x_s P^{\eta_s} \tag{A.4}$$

where η_f is the elasticity of supply for the conventional fringe and η_s is the elasticity of supply for the shale fringe. The terms x_f and x_s reflect supply shifters and help determine the relative share of conventional and shale fringe production.

We assume OPEC Core has the following cost function

$$C(Q_o) = x_o \frac{(Q_o/x_o)^{(1+\frac{1}{\eta_o})}}{(1+\frac{1}{\eta_o})}. \tag{A.5}$$

This implies a marginal cost curve of:

$$MC_o = (Q_o/x_o)^{\frac{1}{\eta_o}}. \tag{A.6}$$

We assume that OPEC core chooses production to maximize profits.

We can think of the dominant producer's problem as maximizing profits subject to the constraint that competitive fringe are choosing their outputs' optimally (taking prices as given) and that the oil market clears. Formally we can write this as:

$$\max_{Q_o,P} P\ Q_o - x_o \frac{(Q_o/x_o)^{(1+\frac{1}{\eta_o})}}{(1+\frac{1}{\eta_o})} \tag{A.7}$$

subject to the following constraints:

$$(\text{market clearing}) : Q = Q_o + Q_s + Q_f \tag{A.8}$$

$$(\text{market demand}) : Q = x_d P^{-\eta_d} \tag{A.9}$$

$$(\text{conventional fringe supply}) : Q_f = x_f P^{\eta_f} \tag{A.10}$$

$$(\text{shale fringe supply}) : Q_s = x_s P^{\eta_s} \tag{A.11}$$

Substituting the market demand and fringe supplies into the market clearing constraint, the dominant producer's problem simplifies to:

$$\max_{Q_o,P} P\ Q_o - x_o \frac{(Q_o/x_o)^{(1+\frac{1}{\eta_o})}}{(1+\frac{1}{\eta_o})} \tag{A.12}$$

subject to

$$x_d P^{-\eta_d} = Q_o + x_f P^{\eta_f} + x_s P^{\eta_s}. \tag{A.13}$$

The first order conditions from this problem are:

$$(Q_o): \quad P - \left(\frac{Q_o}{x_o}\right)^{\frac{1}{\eta_o}} - \lambda^p = 0 \tag{A.14}$$

$$(P): \quad Q_o + \lambda^p \left(-\eta_d x_d P^{\eta_d} + \eta_f x_f P^{\eta_f} + \eta_s x_s P^{\eta_s}\right) P = 0 \tag{A.15}$$

$$(\lambda^p) : x_d P^{-\eta_d} - Q_o - x_f P^{\eta_f} - x_s P^{\eta_s} = 0. \tag{A.16}$$

where λ^p is the Lagrange multiplier on the constraint (A.13). From these, one can derive the mark-up and solve for equilibrium P and Q_o as well as equilibrium values of Q_f and Q_s. The optimal choice production can be described as choosing production so that price is a mark-up over marginal cost:[34]

$$P = \frac{(\eta_d + \eta_s S_s + \eta_f S_f)}{(\eta_d + \eta_s S_s + \eta_f S_f) - (1 - S_s - S_f)} MC_o \tag{A.17}$$

where S_f and S_s are the share of conventional fringe and shale in total production and $(1 - S_s - S_f) = S_o$ is the dominant producer's market share.

[34] If the dominant producer acts as a price taker, it sets quantity so that $P = MC_o$ and its supply is given by: $Q_o = x_o P^{\eta_o}$.

B Derivation of structural dynamic model

We proceed to solve the dominant producer's optimization problem in the dynamic model in a similar fashion as the static model. The dominant producer in time period t can be described as:

$$
\begin{aligned}
&\max_{u_{o,t},\ k_{o,t},\ P_t,\ u_{j,t},\ k_{j,t},\ j=f,s} \quad \underset{t}{E} \sum_{i=0}^{\infty} [\beta^i \pi_{o,t+i} \\
&+ \lambda^p_{t+i} \left(P \left(u_{o,t+i} k_{o,t-1+i} + u_{f,t+i} k_{f,t-1+i} + u_{s,t+i} k_{s,t-1+i},\right.\right. \\
&\left.\left. u_{o,t-1+i} k_{o,t-2+i} + u_{f,t-1+i} k_{f,t-2+i} + u_{s,t-1+i} k_{s,t-2+i}, x_{d,t}\right) - P_t\right) \\
&+ \lambda^u_{f,t+i} \left(-\frac{\partial \pi_{f,t+i}}{\partial u_{f,t+i}}\right) \\
&+ \lambda^k_{f,t+i} \left(-\left[\frac{\partial \pi_{f,t+i}}{\partial k_{f,t+i}} + \beta \frac{\partial \pi_{f,t+i+1}}{\partial k_{f,t+i}}\right]\right) \\
&+ \lambda^u_{s,t+i} \left(-\frac{\partial \pi_{s,t+i}}{\partial u_{s,t+i}}\right) \\
&+ \lambda^k_{s,t+i} \left(-\left[\frac{\partial \pi_{s,t+i}}{\partial k_{s,t+i}} + \beta \frac{\partial \pi_{s,t+Ii+1}}{\partial k_{s,t+i}}\right]\right)].
\end{aligned}
$$

The terms $\lambda^p_{t+i}, \lambda^u_{f,t+i}, \lambda^k_{f,t+i}, \lambda^u_{s,t+i}, \lambda^k_{s,t+i}$ are Lagrange multipliers on the market clearing constraint, and the first order conditions of fringe production decisions. We consider time consistent choices on the part of the dominant producer in that first order conditions for time t decision variables take future decision variable as given.

The first order conditions are given by:

$$(u_{o,t}): \frac{\partial \pi_{o,t}}{\partial u_{o,t}} + \lambda_t^p \frac{\partial P_t}{\partial Q_t} k_{o,t-1} + \underset{t}{E}[\lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_t} k_{o,t-1}] = 0 \tag{B.1}$$

$$(k_{o,t}): \frac{\partial \pi_{o,t}}{\partial k_{o,t}} + \underset{t}{E}[\beta \frac{\partial \pi_{o,t+1}}{\partial k_{o,t}} + \lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_{t+1}} u_{o,t+1} + \lambda_{t+2}^p \frac{\partial P_{t+2}}{\partial Q_{t+1}} u_{o,t+1}] = 0 \tag{B.2}$$

$$(p_t): \frac{\partial \pi_{d,t}}{\partial p_t} - \lambda_t^p - \lambda_t^{u,s} \frac{\partial^2 \pi_{s,t}}{\partial u_{s,t} \partial P_t} - \lambda_t^{u,f} \frac{\partial^2 \pi_{f,t}}{\partial u_{f,t} \partial P_t} = 0. \tag{B.3}$$

$$(u_{f,t}): \quad \lambda_t^p \frac{\partial P_t}{\partial Q_t} k_{f,t-1} + \underset{t}{E}[\beta \lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_t} k_{f,t-1}] - \lambda_{f,t}^u \frac{\partial^2 \pi_{f,t}}{\partial {u_{f,t}}^2} = 0. \tag{B.4}$$

$$(k_{f,t}): \quad \underset{t}{E}[\beta \lambda_{t+1}^p \frac{\partial p_{t+1}}{\partial Q_{t+1}} u_{f,t+1} + \beta^2 \lambda_{t+2}^p \frac{\partial P_{t+2}}{\partial Q_{t+1}} u_{f,t+1}] - \underset{t}{E}\left[\beta \lambda_{f,t+1}^u \frac{\partial^2 \pi_{f,t+1}}{\partial u_{f,t+1} \partial k_{f,t}}\right]$$

$$- \lambda_{f,t}^k \left[\frac{\partial^2 \pi_{f,t}}{\partial {k_{f,t}}^2} + \underset{t}{E}\left[\beta \frac{\partial^2 \pi_{f,t+1}}{\partial {k_{f,t}}^2}\right]\right] - \underset{t}{E}\left[\beta \lambda_{f,t+1}^k \frac{\partial^2 \pi_{f,t+1}}{\partial k_{f,t+1} \partial k_{f,t}}\right] = 0. \tag{B.5}$$

$$(u_{s,t}): \quad \lambda_t^p \frac{\partial P_t}{\partial Q_t} k_{s,t-1} + \underset{t}{E}[\beta \lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_t} k_{s,t-1}] - \lambda_{s,t}^u \frac{\partial^2 \pi_{s,t}}{\partial {u_{s,t}}^2} = 0. \tag{B.6}$$

$$(k_{s,t}): \quad \underset{t}{E}[\beta \lambda_{t+1}^p \frac{\partial P_{t+1}}{\partial Q_{t+1}} u_{s,t+1} + \beta^2 \lambda_{t+2}^p \frac{\partial P_{t+2}}{\partial Q_{t+1}} u_{s,t+1}] - \underset{t}{E}\left[\beta \lambda_{s,t+1}^u \frac{\partial^2 \pi_{s,t+1}}{\partial u_{s,t+1} \partial k_{s,t}}\right]$$

$$- \lambda_{s,t}^k \left[\frac{\partial^2 \pi_{s,t}}{\partial {k_{s,t}}^2} + \underset{t}{E}\left[\beta \frac{\partial^2 \pi_{s,t+1}}{\partial {k_{s,t}}^2}\right]\right] - \underset{t}{E}\left[\beta \lambda_{s,t+1}^k \frac{\partial^2 \pi_{s,t+1}}{\partial k_{s,t+1} \partial k_{s,t}}\right] = 0. \tag{B.7}$$

$$(\lambda_t^p): \quad P(Q_{o,t} + Q_{f,t} + Q_{s,t}, Q_{o,t-1} + Q_{f,t-1} + Q_{s,t-1}, x_{d,t}) - P_t \tag{B.8}$$

where $Q_{j,t} = u_{j,t} k_{j,t-1}$ for $j = o, f, s$.

$$\left(\lambda_{f,t}^u\right): \quad \frac{\partial \pi_{f,t}}{\partial u_{f,t}} = 0 \tag{B.9}$$

$$\left(\lambda_{f,t}^k\right): \quad \frac{\partial \pi_{f,t}}{\partial k_{f,t}} + \underset{t}{E}\left[\beta \frac{\partial \pi_{f,t+1}}{\partial k_{f,t}}\right] = 0 \tag{B.10}$$

$$\left(\lambda_{s,t}^u\right): \quad \frac{\partial \pi_{s,t}}{\partial u_{s,t}} = 0 \tag{B.11}$$

$$\left(\lambda_{s,t}^k\right): \quad \frac{\partial \pi_{s,t}}{\partial k_{s,t}} + \underset{t}{E}\left[\beta \frac{\partial \pi_{s,t+1}}{\partial k_{s,t}}\right] = 0 \tag{B.12}$$

In addition to equations (B.1) through (B.12), the model includes equations that describe the dynamic process of the exogenous variables.

$$\text{(demand shifter)}: \quad log(x_{d,t}) = log(x_{b,t}) + log(x_{c,t}) + log(x_{i,t}) \tag{B.13}$$

$$\text{(balance growth)}: \quad log(x_{b,t}) = log(x_{b,t-1}) + 0.0022 \tag{B.14}$$

$$\text{(cyclical demand)}: \quad log(x_{c,t}) = \eta_y log(WEA_t) \tag{B.15}$$

$$\text{(world IP)}: \quad log(WEA_t) = \theta_{w,1} log(WEA_{t-1}) + \theta_{w,2} log(WEA_{t-2}) \tag{B.16}$$

$$+ \sigma_w e_{w,t}, \quad \text{where } e_{w,t} \sim \mathrm{N}(0,1)$$

$$\text{(shale cost)}: \quad log(z_{s,t}) = log(v_{s,t}^{temp}) + log(v_t^{perm}) + \left(1 + \frac{1}{\eta_{k,s}}\right) log(x_{b,t}) \tag{B.17}$$

$$\text{(temp shale cost)}: \quad log(v_{s,t}^{temp}) = \theta_s log(v_{s,t-1}^{temp}) + \sigma_s e_{s,t}, \quad \text{where } e_{s,t} \sim \mathrm{N}(0,1) \tag{B.18}$$

(perm shale cost) :

$$log(v_t^{perm}) = log(v_{old\ ss}^{perm}), \quad t < 2005Q1 \tag{B.19}$$

$$log(v_t^{perm}) = log(v_{new\ ss}^{perm}) + 2\rho_{v_s}(log(v_{t-1}^{perm}) - log(v_{new\ ss}^{perm})) \tag{B.20}$$

$$- \rho_{v_s}^2 (log(v_{t-2}^{perm}) - log(v_{new\ ss}^{perm})), \quad t \geq 2005Q1$$

$$\text{(OPEC core cost)}: \quad log(z_{o,t}) = log(v_{o,t}^{temp}) + \left(1 + \frac{1}{\eta_{k,o}}\right) log(x_{b,t}) \tag{B.21}$$

$$\text{(temp OPEC Core cost)}: \quad log(v_{o,t}^{temp}) = \theta_o log(v_{o,t-1}^{temp}) + \sigma_o e_{o,t}, \quad \text{where } e_{o,t} \sim \mathrm{N}(0,1) \tag{B.22}$$

$$\text{(conventional cost)}: \quad log(z_{f,t}) = log(v_{f,t}^{temp}) + \left(1 + \frac{1}{\eta_{k,f}}\right) log(x_{b,t}) \tag{B.23}$$

$$\text{(temp conventional cost)}: \quad log(v_{f,t}^{temp}) = \theta_f log(v_{f,t-1}^{temp}) + \sigma_f e_{f,t}, \quad \text{where } e_{f,t} \sim \mathrm{N}(0,1) \tag{B.24}$$

C Model solution

The model outlined in equations (B.1)-(B.24) can be written as:

$$\underset{t}{E}\left[g(X_t, X_{t+1}, X_{t-1}, e_t, v^{perm}_{old\ ss}, \theta)\right] = 0, \quad t < 2005Q1 \tag{C.1}$$

and

$$\underset{t}{E}\left[g(X_t, X_{t+1}, X_{t-1}, e_t, v^{perm}_{new\ ss}, \theta)\right] = 0, \quad t \geq 2005Q1 \tag{C.2}$$

where X_t are the endogenous variables in the system, e_t a vector of exogenous shocks, $v^{perm}_{old\ ss}$ is the steady state of shale producers production cost before the shale revolution, and $v^{perm}_{new\ ss}$ is the steady state of shale producers production cost variable after the shale revolution. A first order approximation around a steady state yields the difference equation system of the form:

$$\begin{aligned} A(X_{ss|v^{perm}_{ss}})\underset{t}{E}(X_{t+1} - X_{ss|v^{perm}_{ss}}) + B(X_{ss|v^{perm}_{ss}})(X_t - X_{ss|v^{perm}_{ss}}) \\ + C(X_{ss|v^{perm}_{ss}})(X_{t-1} - X_{ss|v^{perm}_{ss}}) + D(X_{ss|v^{perm}_{ss}})e_t = 0 \end{aligned} \tag{C.3}$$

$X_{ss|v^{perm}_{ss}}$ is the steady state value of the variables in the model which is, in turn, a function of the structural parameters of the model (θ) and the steady state value of shale producer's costs. The rational expectations solution to this difference equation system will have the form:

$$X_t = G(X_{ss|v^{perm}_{ss}}) + P(X_{ss|v^{perm}_{ss}})X_{t-1} + Q(X_{ss|v^{perm}_{ss}})e_t \tag{C.4}$$

where

$$G(X_{ss|v^{perm}_{ss}}) = X_{ss|v^{perm}_{ss}} - P(X_{ss|v^{perm}_{ss}})X_{ss|v^{perm}_{ss}}.$$

For time periods, where v^{perm}_t is not close to either the pre-shale or post-shale steady states, we will use a piecewise linear method of approximation similar to Guerrieri and Iacoviello (2015) [26]. We start at the post-shale steady state and work backwards in time.

For a time period sufficiently far in the future, we approximate the model around the new steady state. That is, for $t \geq t_N$:

$$X_t = G^{[N]} + P^{[N]} X_{t-1} + Q^{[N]} e_t \tag{C.5}$$

where

$$\begin{aligned} G^{[N]} &= G(X_{ss|v^{perm}_{new\ ss}}) \\ P^{[N]} &= P(X_{ss|v^{perm}_{new\ ss}}) \\ Q^{[N]} &= Q(X_{ss|v^{perm}_{new\ ss}}) \end{aligned} \tag{C.6}$$

For periods before t_N, the new steady state is not good approximation, we approximate around a different value, $v^{perm}_{t_N}$, where $v^{perm}_{t_N}$ is value of the transition variable in time period t_N. The resulting first order approximation for time periods, $t_{N-1} \leq t < t_N$, is given by:

$$\begin{aligned} A^{[t_N]} \underset{t}{E}(X_{t+1} - X_{ss|v^{perm}_{t_N}}) + B^{[t_N]}(X_t - X_{ss|v^{perm}_{t_N,\theta}}) \\ + C^{[t_N]}(X_{t-1} - X_{ss|v^{perm}_{t_N}}) + D^{[t_N]} e_t + E^{[t_N]} = 0 \end{aligned} \tag{C.7}$$

where

$$\begin{aligned} A^{[t_N]} &= A(X_{ss|v^{perm}_{t_N}}) \\ B^{[t_N]} &= B(X_{ss|v^{perm}_{t_N}}) \\ C^{[t_N]} &= C(X_{ss|v^{perm}_{t_N}}) \\ D^{[t_N]} &= D(X_{ss|v^{perm}_{t_N}}) \\ E^{[t_N]} &= E(X_{ss|v^{perm}_{t_N}}) \end{aligned} \tag{C.8}$$

The value $X_{ss|v^{perm}_{t_N}}$ represents the steady state value of X_t for the model where the steady state value of $v^{perm}_t = v^{perm}_{t_N}$. Given the actual model implies a steady state value of $v^{perm}_t =$

$v^{perm}_{new\ ss}$, the constant term in equation (C.7), $E^{[t_N]]} = E(X_{ss|v^{perm}_{t_N}})$, reflects the fact that $v^{perm}_{t_N} \neq v^{perm}_{new\ ss}$. Recall that given equation (C.2), $g(X_{ss|v^{perm}_{new\ ss}}, X_{ss|v^{perm}_{new\ ss}}, X_{ss|v^{perm}_{new\ ss}}, 0, v^{perm}_{new\ ss}, \theta) = 0$ in the new steady state. When not evaluating the function at the new steady state, the term $E^{[t_N]} = E(X_{ss|v^{perm}_{t_N}}) = g(X_{ss|v^{perm}_{t_N}}, X_{ss|v^{perm}_{s,t_N}}, X_{ss|v^{perm}_{t_N}}, 0, \check{}perm_{new\ ss}, \theta) \neq 0$.

Combining equations (C.5) and (C.7), we get for $t_{N-1} \leq t < t_N$:

$$X_t = G^{[t]} + P^{[t]} X_{t-1} + Q^{[t]} e_t \tag{C.9}$$

where

$$\begin{aligned} G^{[t]} = &- \left(A^{[t_N]} P^{[t+1]} + B^{[t_n]}\right)^{-1} \\ &\left(E^{[t_N]} + A^{[t_N]} G^{[t+1]} - \left(A^{[t_N]} + B^{[t_N]} + C^{[t_N]}\right) X_{ss|v^{perm}_{t_N}}\right) \end{aligned} \tag{C.10}$$

$$P^{[t]} = - \left(A^{[t_N]} P^{[t+1]} + B^{[t_N]}\right)^{-1} C^{[t_N]} \tag{C.11}$$

$$Q^{[t]} = - \left(A^{[t_N]} P^{[t+1]} + B^{t_N]}\right)^{-1} D^{[t_N]} \tag{C.12}$$

One can iterate equations (C.9)-(C.12) backwards allowing for the approximation point on the transition path, v^{perm}_{s,t_i} to change. In our application, we set $t_N = 2045Q1$, $t_{N-1} = 2035Q1$, and $t_{N-2} = 2030Q1$. From 2030Q1 until 2005Q3, we work backwards taking every second quarter of $v^{perm}_{t_i}$ as the approximation point. Before 2005Q1, we approximate the model around the pre-Shale steady state:

$$X_t = G^{[0]} + P^{[0]} X_{t-1} + Q^{[0]} e_t \tag{C.13}$$

where

$$
\begin{aligned}
G^{[0]} &= G(X_{ss|v^{perm}_{old\ ss}}) \\
P^{[0]} &= P(X_{ss|v^{perm}_{old\ ss}}) \\
Q^{[0]} &= Q(X_{ss|v^{perm}_{old\ ss}})
\end{aligned}
\tag{C.14}
$$

Equation 27 holds in all the time periods before 2005Q1 and reflects the fact that the ”shale revolution” was a surprise from the point of view of time periods before 2005Q1.

D Alternative market structures

D.1 Price-taking Dominant Firm: Competitive Case

When the dominant firm is a price taker, the market is essentially competitive. Similarly, the price-taking dominant firm would choose $u_{o,t}$ and $k_{o,t}$ similar to the competitive fringe 8 and 9:

$$(k_{o,t}) : \frac{\partial \pi_{o,t}}{\partial k_{o,t}} + \underset{t}{E}\left[\beta \frac{\partial \pi_{o,t+1}}{\partial k_{o,t}}\right] = 0 \tag{D.1}$$

$$(u_{o,t}) : \frac{\partial \pi_{o,t}}{\partial u_{o,t}} = 0 \tag{D.2}$$

Combining the decision rules of the dominant producer with those of the of the competitive fringe the competitive market structure would be completed by the market-clearing condition equation (5).

D.2 Non-strategic exercise of market power

For the Cournot-style dominant firm, it chooses $u_{o,t}$ and $k_{o,t}$ to maximize the present value of profits taking into account of its effect on market prices but taking the production decisions of the competitive fringe as given. We can think of the Dominant producers problem as maximizing profits subject to the market clearing constraint where one of its choice variables is the market price, P_t:

$$\max_{u_{o,t},k_{o,t},p_t} \underset{t}{E} \sum_{i=0}^{\infty} \beta^i \pi_{o,t+i} \tag{D.3}$$

subject to constraint given by equation (5).

The first-order condition for the dominant firm's utilization rate, $u_{o,t}$, and capacity, $k_{o,t}$, and price, p_t, are:

$$(u_{o,t}) : \frac{\partial \pi_{o,t}}{\partial u_{o,t}} + \lambda_t^p \frac{\partial p_t}{\partial Q_t} k_{o,t-1} + \underset{t}{E}[\lambda_{t+1}^p \frac{\partial p_{t+1}}{\partial Q_t} k_{o,t-1}] = 0 \tag{D.4}$$

$$(k_{o,t}) : \frac{\partial \pi_{o,t}}{\partial k_{o,t}} + \underset{t}{E}[\beta \frac{\partial \pi_{o,t+1}}{\partial k_{o,t}} + \lambda_{t+1}^p \frac{\partial p_{t+1}}{\partial Q_{t+1}} u_{o,t+1} + \lambda_{t+2}^p \frac{\partial p_{t+2}}{\partial Q_{t+1}} u_{o,t+1}] = 0 \tag{D.5}$$

$$(p_t) : \frac{\partial \pi_{d,t}}{\partial p_t} - \lambda_t^p = 0 \tag{D.6}$$

E Robustness

In this section we explore several alternative modeling assumptions. In particular, we examine alternative assumptions about expectations of future shale production costs and alternative assumptions about the size of future shale production.

E.1 Expectations about future shale costs

In the benchmark model, we assume that the market had perfect foresight about the deterministic component of shale production costs. In this section, we consider two alternatives to perfect foresight. In one case, we assume that the increased shale output is a continual surprise once the shale revolution starts in 2005Q1. That is, we take the shale transition path for the benchmark model, but assume the market expects shale costs in the future to remain at current levels. We refer to this the "naive expectations model". The second alternative assumption is that the ongoing shale revolution was initially a surprise as in the "naive expectations model" but that by 2014Q4, the market began to expect shale output growth in the future, in which case the market now has perfect foresight about the transition of shale. We refer to this model as "mixed expectations model".[35] Again, we take the estimated parameters from the benchmark model and solve the alternative models for this set of parameters. Figure F1 displays (log) real oil price and (log) market output implied by the benchmark, naive, and switching model. The differences between the three model are relatively small, suggesting that the results over our sample period are not particularly sensitive to assumptions about expectations of the future of the shale sector.

E.2 Alternative future Shale steady states

In our benchmark model, we assume that the future steady state shale market share was 20%. Here we consider two alternative steady states, one where shale's share is 15% and the

[35] We considered alternative dates such as 2010Q1 or 2012Q4 and the results are not substantially different when setting the switch date to 2014Q4.

other where shale's share is 25%. Because changing shale's steady state market share will alter the transition dynamics for a given parameter vector, we re-estimate the model taking into account the alternative assumptions about the shale's future steady state.

Tables E1 and E2 display posterior distributions for model with shale market share of 15% and a shale market share of 20%. Comparing the benchmark model with these two alternative assumptions about the long-run size of shale, the posterior distributions of many of the parameters are very similar regardless of shale sector's future size. In particular, our estimate of the posterior distribution of the elasticities of supply and demand are nearly identical across the three models. The historical decompositions across alternative steady states also suggest that the contribution of shale revolution to in-sample movements in oil price and output are nearly identical across the three alternative steady state models. That the in-sample implications of the three models are nearly identical is not too surprising. For each model, the parameter ρ_{v_s} that controls the transition dynamics is "chosen" to match the actual transition in shale production share over the sample. This implies that while the future steady states are quite different across models, the "in-sample fit" of the alternative models is nearly identical to the benchmark model.

Table E3 displays the posterior distribution of the steady states and Table E4 displays the variances and variance decomposition for the two alternative assumptions about shale's long-run share. From Table E3, not surprisingly, the larger the shale revolution, the greater effect it has on oil price and output in the steady state. Interestingly, OPEC Core's share is relatively stable across the alternative assumptions about shale's share. From Table E4, the shale revolution results in the reduction of volatility in oil prices and output across the three alternative assumptions about the future of size of the shale sector. Although the reduction in volatility in the long-run is larger in the model with the larger shale sector, the reduction in volatility during the transition period (2019Q4) is of similar magnitude across the three models.

Table 1. Pre and post-shale market outcomes for static model

Panel A: Benchmark model ($\eta_d = 0.3, \eta_s = 1.0$)

			market share of:		
period	price	output	conv. fringe	OPEC core	shale fringe
pre-shale	100.0	100.0	79.5	20.0	0.5
post-shale	53.8	120.4	62.0	15.6	22.3

Panel B: Low shale elasticity ($\eta_d = 0.3, \eta_s = 0.3$)

			market share of:		
period	price	output	conv. fringe	OPEC core	shale fringe
pre-shale	100.0	100.0	79.5	20.0	0.5
post-shale	42.7	129.1	56.5	13.5	30.0

Panel C: High demand elasticity ($\eta_d = 1.0, \eta_s = 1.0$)

			market share of:		
period	price	output	conv. fringe	OPEC core	shale fringe
pre-shale	100.0	100.0	79.5	20.0	0.5
post-shale	74.9	133.5	57.8	14.1	28.0

Note: For all three models, $\eta_f = 0.1, \eta_o = 0.3$.

Table 2. Percent change in market price and output in response to 10% increase in demand and conventional fringe supply

Panel A: Benchmark model ($\eta_d = 0.3, \eta_s = 1.0$)

	demand		conv. supply	
period	price	output	price	output
pre-shale	24.3	3.0	-16.8	5.7
post-shale	15.9	5.2	-9.4	3.0

Panel B: Low shale elasticity ($\eta_d = 0.3, \eta_s = 0.3$)

	demand		conv. supply	
period	price	output	price	output
pre-shale	24.6	3.0	-17.0	5.7
post-shale	21.7	3.7	-11.0	3.5

Table 3. Pre and post-shale mark-ups and pseudo-elasticities

Panel A: Benchmark model ($\eta_d = 0.3, \eta_s = 1.0$)

	OPEC Core	pseudo-supply	
period	mark-up	OPEC Core	Overall market
pre-shale	2.08	0.26	0.14
post-shale	1.37	0.37	0.34

Panel B: Low shale elasticity ($\eta_d = 0.3, \eta_s = 0.3$)

	OPEC Core	pseudo-supply	
period	mark-up	OPEC Core	Overall market
pre-shale	2.11	0.29	0.13
post-shale	1.43	0.29	0.19

Note: for all three models in Table 1 and 2, $\eta_f = 0.1$, $\eta_o = 0.3$.

Table 4. 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.	$log\left(\frac{Q_{o,t}}{Q_t}\right)$	log of: US shale production as a share of world oil production
5.	$log\left(WIP_t\right)$	log of: World industrial production

Table 5. 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 supply elasticities ($\eta_{k,o}, \eta_{k,f}$)	$beta(3.86, 10, .15, 1.6)$	0.50	0.31	0.86
2.	long-run supply elasticity, shale ($\eta_{k,s}$)	$beta(11.5, 10, 0.3, 1.6)$	1.00	0.5	1.22
3.	short-run supply elasticities ($\eta_{u,o}, \eta_{u,f}, \eta_{u,s}$)	$beta(5.5, 10, 0, 0.3)$	0.10	0.05	0.17
5.	long-run demand elasticity (-η_d)	$beta(3.86, 10, 0, 1.6)$	0.50	0.31	0.86
6.	short-run demand elasticity (-(1$-_d$)η_d)	$beta(5.5, 10, 0, 0.3)$	0.10	0.05	0.17
7.	oil demand elast. wrt world econ. activ. (η_y)	$N(1, (.5)^2)$	1.0	0.18	1.82
8.	adjustment costs ($\kappa_{o,2}, \kappa_{f,2}, \kappa_{s,2}$)	$\Gamma(2, 10)$	10.0	3.55	47.44
	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 less than one in absolute value.

Table 6. Posterior distribution of parameters

	structural parameters	mode	mean	5th	95th
	long-run supply elasticities:				
1.	OPEC Core ($\eta_{k,o}$)	0.28	0.29	0.20	0.43
2.	Conventional fringe ($\eta_{k,f}$)	0.17	0.18	0.16	0.22
3.	Shale fringe ($\eta_{k,s}$)	0.45	0.46	0.39	0.55
	short-run supply elasticities:				
4.	OPEC Core ($\eta_{u,o}$)	0.03	0.03	0.02	0.05
5.	Conventional fringe ($\eta_{u,f}$)	0.07	0.08	0.06	0.09
6.	Shale fringe ($\eta_{u,s}$)	0.15	0.17	0.12	0.20
	demand elasticities:				
7.	long-run demand elasticity (-η_d)	-0.19	-0.19	-0.21	-0.17
8.	short-run demand elasticity (-$(1-\rho_d)\eta_d$)	-0.18	-0.19	-0.21	-0.17
9.	oil demand elast. wrt world econ. activ. (η_y)	1.51	1.50	1.22	1.78
	adjustment costs:				
10.	OPEC Core ($\kappa_{o,2}$)	8.01	5.08	0.19	14.92
11.	Conventional fringe ($\kappa_{f,2}$)	20.87	12.11	0.73	34.92
12.	Shale fringe ($\kappa_{s,2}$)	40.06	55.85	16.67	109.33

	shock parameters	mode	mean	5th	95th
13.	AR(1) coeff. for oil specific demand shock	0.99	0.99	0.966	0.999
14.	AR(1) coeff. for OPEC core cost shock	0.88	0.88	0.77	0.99
15.	AR(1) coeff. for conv. fringe cost shock	0.98	0.98	0.94	0.999
16.	AR(1) coeff. for shale cost shock	0.96	0.96	0.90	0.999
17.	AR(1) coeff. for world IP shock	1.36	1.27	1.12	1.43
18.	AR(2) coeff. for world IP shock	-0.44	-0.37	-0.53	-0.20
19.	shale cost transition parameter (ρ_{v_s})	0.96	0.96	0.96	0.97
20.	std. dev. for oil specific demand shock	0.025	0.025	0.021	0.029
21.	std. dev. for OPEC core cost shock	0.29	0.31	0.23	0.41
22.	std. dev. for conv. fringe cost shock	0.19	0.19	0.16	0.22
23.	std. dev. for shale cost shock	0.20	0.21	0.17	0.25
24.	std. dev. for world IP shock	0.01	0.01	0.01	0.02

Table 7. Implied supply elasticities
mean of posterior distribution

Panel A: pre-shale steady state

horizon	conv. fringe	OPEC core	shale fringe	market
initial quarter	0.077	0.038	0.166	0.069
1 year	0.146	0.163	0.339	0.150
2 year	0.183	0.230	0.458	0.194
5 year	0.183	0.230	0.458	0.194

Panel B: post-shale steady state

horizon	conv. fringe	OPEC core	shale fringe	market
initial quarter	0.077	0.037	0.166	0.088
1 year	0.144	0.184	0.323	0.187
2 year	0.183	0.274	0.458	0.254
5 year	0.183	0.274	0.458	0.254

Panel C: transition period (2019Q4)

horizon	conv. fringe	OPEC core	shale fringe	market
initial quarter	0.077	0.037	0.166	0.075
1 year	0.145	0.173	0.334	0.162
2 year	0.183	0.251	0.457	0.212
5 year	0.183	0.251	0.457	0.212

Table 8. Variance decomposition pre- and post-Shale evaluated at posterior mode

Panel A: Variance decomposition of price (log)

		percent contribution of shocks to:				
period	total variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
pre-shale	0.324	52.8	10.8	35.9	0.0	0.5
transition	0.283	55.2	11.4	31.8	1.0	0.6
post-shale	0.230	56.5	12.0	21.2	9.5	0.8

Panel B: Variance decomposition of market output (log)

		percent contribution of shocks to:				
period	total variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
pre-shale	0.011	51.3	9.0	39.1	0.0	0.6
transition	0.011	57.5	10.1	30.9	0.9	0.6
post-shale	0.011	65.0	11.3	16.0	7.2	0.6

Table 9. Posterior distribution of post-Shale steady states

	variable	pre-shale steady state	post-Shale steady state mode	mean	5th	95th
1.	real oil price	100.0	52.1	52.5	49.0	56.1
2.	market oil output	100.0	113.3	112.9	111.6	113.9
3.	Conventional Fringe share	79.5	62.7	62.6	62.0	63.1
4.	OPEC Core share	20.0	17.3	16.9	17.0	17.9
5.	Shale share	0.5	20.0	20.0	20.0	20.0

Table E1. Posterior distribution of parameters for model with shale share = 15%

	structural parameters	mode	mean	5th	95th
	long-run supply elasticities:				
1.	OPEC Core ($\eta_{k,o}$)	0.24	0.29	0.19	0.46
2.	Conventional fringe ($\eta_{k,f}$)	0.17	0.18	0.16	0.22
3.	Shale fringe ($\eta_{k,s}$)	0.48	0.46	0.39	0.55
	short-run supply elasticities:				
4.	OPEC Core ($\eta_{u,o}$)	0.03	0.04	0.02	0.05
5.	Conventional fringe ($\eta_{u,f}$)	0.07	0.08	0.06	0.09
6.	Shale fringe ($\eta_{u,s}$)	0.16	0.17	0.13	0.20
7.	long-run demand elasticity (-η_d)	-0.19	-0.19	-0.21	-0.17
8.	short-run demand elasticity (-$(1-\rho_d)\eta_d$)	-0.17	-0.19	-0.21	-0.17
9.	oil demand elast. wrt world econ. activ. (η_y)	1.45	1.49	1.21	1.78
	adjustment costs:				
10.	OPEC Core ($\kappa_{o,2}$)	7.52	5.12	0.23	15.31
11.	Conventional fringe ($\kappa_{f,2}$)	8.06	11.68	0.89	33.91
12.	Shale fringe ($\kappa_{s,2}$)	47.19	56.97	16.15	110.18

	shock parameters	mode	mean	5th	95th
13.	AR(1) coeff. for oil specific demand shock	0.99	0.99	0.96	0.999
14.	AR(1) coeff. for OPEC core cost shock	0.83	0.88	0.77	0.97
15.	AR(1) coeff. for conv. fringe cost shock	0.96	0.98	0.94	0.999
16.	AR(1) coeff. for shale cost shock	0.95	0.96	0.90	0.999
17.	AR(1) coeff. for world IP shock	1.36	1.27	1.11	1.43
18.	AR(2) coeff. for world IP shock	-0.45	-0.36	-0.53	-0.20
19.	shale cost transition parameter (ρ_{v_s})	0.96	0.96	0.95	0.97
20.	std. dev. for oil specific demand shock	0.024	0.025	0.022	0.029
21.	std. dev. for OPEC core cost shock	0.34	0.31	0.23	0.42
22.	std. dev. for conv. fringe cost shock	0.18	0.19	0.16	0.22
23.	std. dev. for shale cost shock	0.20	0.21	0.17	0.25
24.	std. dev. for world IP shock	0.01	0.01	0.01	0.02

Table E2. Posterior distribution of parameters for model with shale share = 25%

	structural parameters	mode	mean	5th	95th
	long-run supply elasticities:				
1.	OPEC Core ($\eta_{k,o}$)	0.35	0.35	0.21	0.60
2.	Conventional fringe ($\eta_{k,f}$)	0.18	0.18	0.16	0.22
3.	Shale fringe ($\eta_{k,s}$)	0.44	0.45	0.38	0.54
	short-run supply elasticities:				
4.	OPEC Core ($\eta_{u,o}$)	0.11	0.11	0.08	0.15
5.	Conventional fringe ($\eta_{u,f}$)	0.07	0.08	0.06	0.09
6.	Shale fringe ($\eta_{u,s}$)	0.17	0.17	0.13	0.20
7.	long-run demand elasticity (-η_d)	-0.19	-0.19	-0.22	-0.17
8.	short-run demand elasticity (-$(1-\rho_d)\eta_d$)	-0.17	-0.17	-0.19	-0.16
9.	oil demand elast. wrt world econ. activ. (η_y)	1.40	1.41	1.16	1.66
	adjustment costs:				
10.	OPEC Core ($\kappa_{o,2}$)	17.43	18.96	3.51	43.34
11.	Conventional fringe ($\kappa_{f,2}$)	11.62	10.71	0.56	31.83
12.	Shale fringe ($\kappa_{s,2}$)	77.85	63.86	18.10	121.96

	shock parameters	mode	mean	5th	95th
13.	AR(1) coeff. for oil specific demand shock	0.98	0.98	0.97	0.999
14.	AR(1) coeff. for OPEC core cost shock	0.77	0.78	0.68	0.89
15.	AR(1) coeff. for conv. fringe cost shock	0.97	0.98	0.94	0.999
16.	AR(1) coeff. for shale cost shock	0.91	0.95	0.88	0.997
17.	AR(1) coeff. for world IP shock	1.30	1.29	1.13	1.44
18.	AR(2) coeff. for world IP shock	-0.38	-0.37	-0.54	-0.21
19.	shale cost transition parameter (ρ_{v_s})	0.97	0.97	0.96	0.97
20.	std. dev. for oil specific demand shock	0.022	0.023	0.020	0.027
21.	std. dev. for OPEC core cost shock	0.39	0.39	0.29	0.52
22.	std. dev. for conv. fringe cost shock	0.20	0.20	0.17	0.23
23.	std. dev. for shale cost shock	0.23	0.22	0.18	0.26
24.	std. dev. for world IP shock	0.013	0.014	0.012	0.015

Table E3. 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	62.0	62.5	59.2	65.6
2.	market oil output	100.0	109.6	109.3	108.4	110.0
3.	Conventional Fringe share	79.5	66.9	66.8	66.2	67.2
4.	OPEC Core share	20.0	18.1	18.2	17.8	18.8
5.	Shale share	0.5	15.0	15.0	15.0	15.0

Model with shale share = 25%

	variable	pre-shale steady state	**post-Shale steady state** mode	mean	5th	95th
1.	real oil price	100.0	39.4	40.5	37.1	44.2
2.	market oil output	100.0	116.9	116.7	115.1	118.0
3.	Conventional Fringe share	79.5	57.7	57.7	56.9	58.5
4.	OPEC Core share	20.0	17.3	17.3	16.5	18.1
5.	Shale share	0.5	25.0	25.0	25.0	25.0

Table E4. Variance decomposition pre- and post-Shale evaluated at posterior mode

Model with shale share = 15%

Panel A: Variance decomposition of price (log)

		percent contribution of shocks to:				
period	total variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
pre-shale	0.411	33.9	5.6	60.1	0.0	0.5
transition	0.308	38.5	7.1	53.1	0.5	0.8
post-shale	0.190	47.2	10.7	35.5	5.0	1.6

Panel B: Variance decomposition of market output (log)

		percent contribution of shocks to:				
period	total variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
pre-shale	0.012	24.8	0.6	74.0	0.0	0.6
transition	0.010	37.6	0.9	60.0	0.6	0.9
post-shale	0.008	62.2	1.4	30.7	4.3	1.4

Model with shale share = 25%

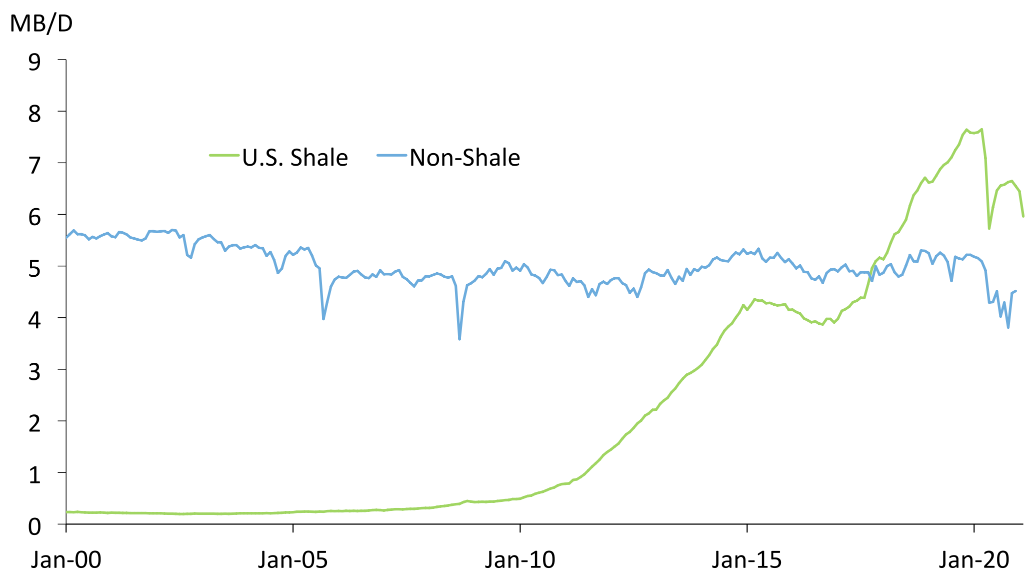
Panel C: Variance decomposition of price (log)

		percent contribution of shocks to:				
period	total variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
pre-shale	0.270	43.6	11.2	44.8	0.0	0.4
transition	0.225	46.7	12.2	39.6	0.9	0.6
post-shale	0.161	50.3	13.8	22.8	11.8	1.2

Panel D: Variance decomposition of market output (log)

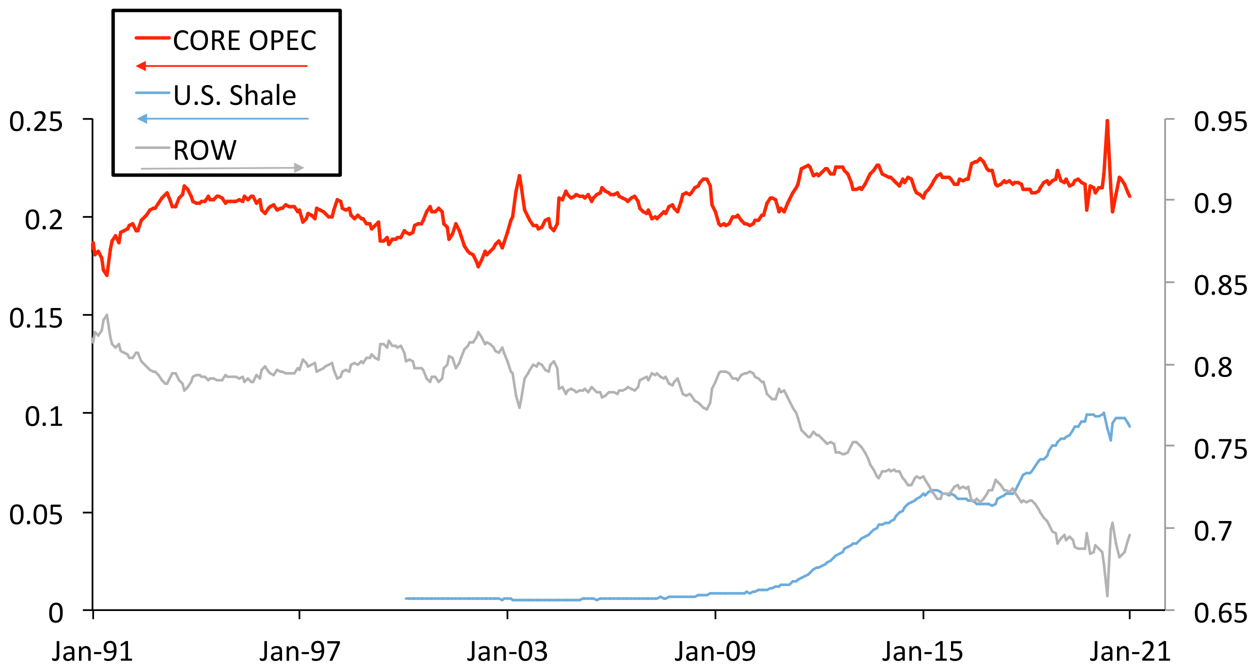
		percent contribution of shocks to:				
period	total variance	oil specific demand	world demand	Conv. supply	shale supply	OPEC core supply
pre-shale	0.008	47.7	10.8	41.1	0.0	0.4
transition	0.008	54.9	12.4	31.5	0.7	0.5
post-shale	0.008	65.4	14.4	12.8	6.6	0.7

Figure 1: US shale and nonshale production



Note: Source: EIA.

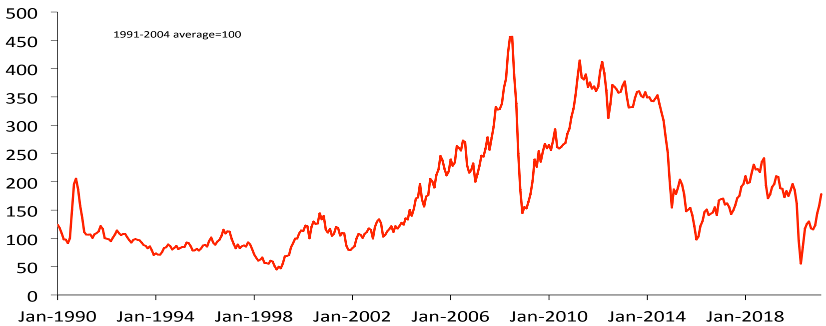
Figure 2: World Crude Oil Production shares



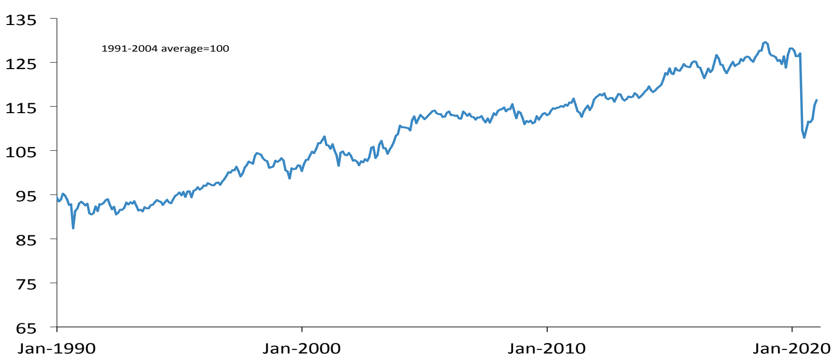
Note: SOURCE: EIA;OGJ.

Figure 3: World Crude Oil Price and Output

(a) Normalized Real Brent Price

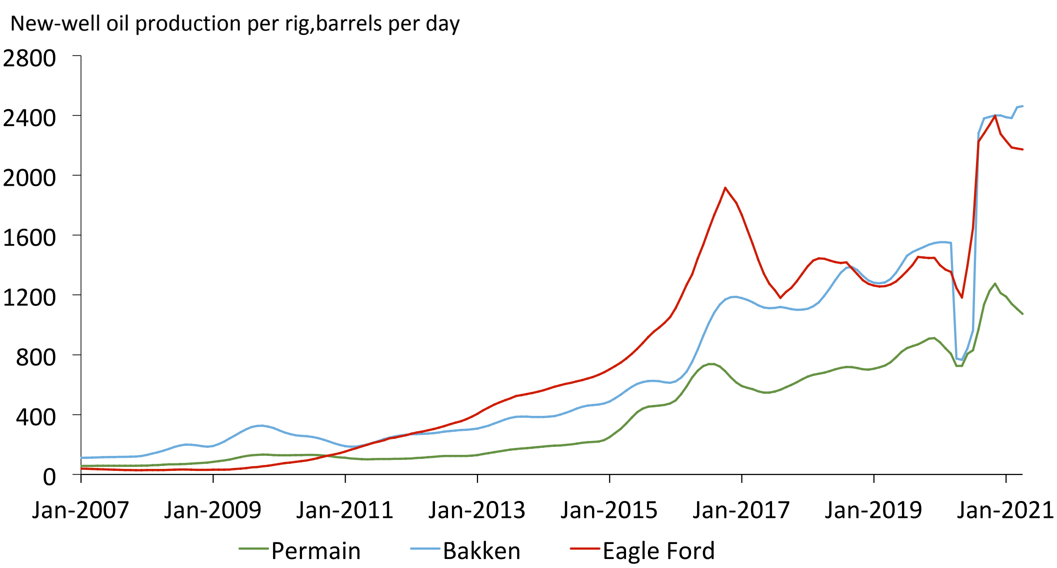


(b) Normalized World Oil output



Note: (a) SOURCE: BLS;OGJ; (b) the real Brent price and the world output have been normalized so that in the pre-shale period (1991-2004) both have averages of 100.

Figure 4: U.S. Shale Productivity



Note: SOURCE: EIA.

Figure 5: Decomposition of log real oil price posterior mean contribution

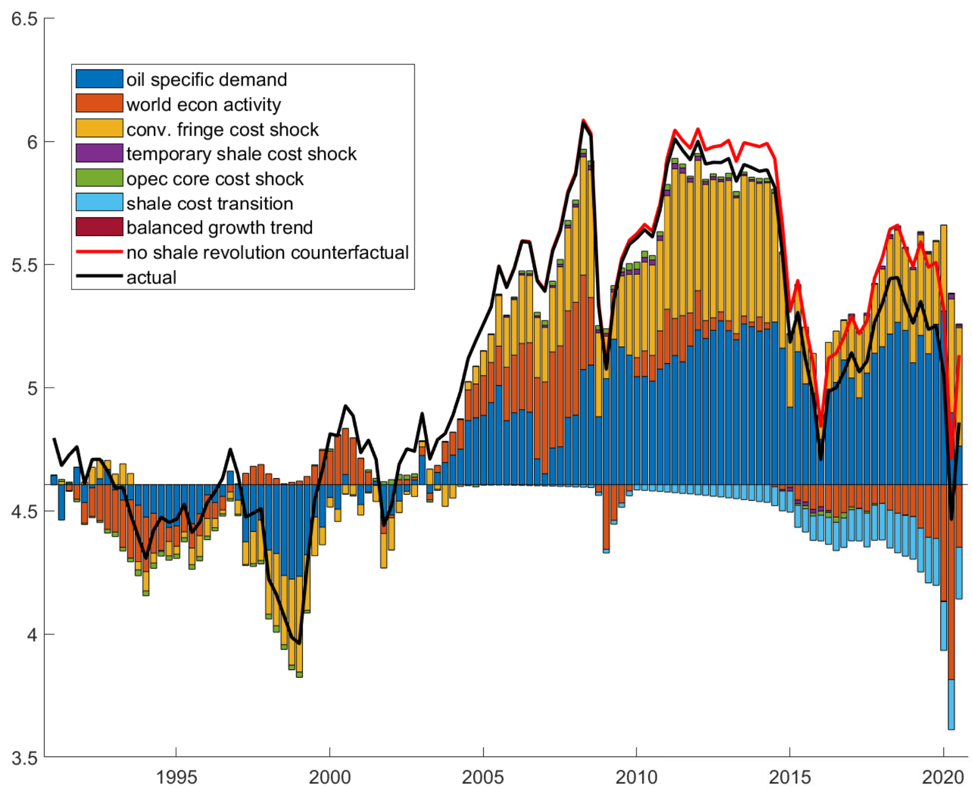


Figure 6: Decomposition of log world oil production posterior mean contribution

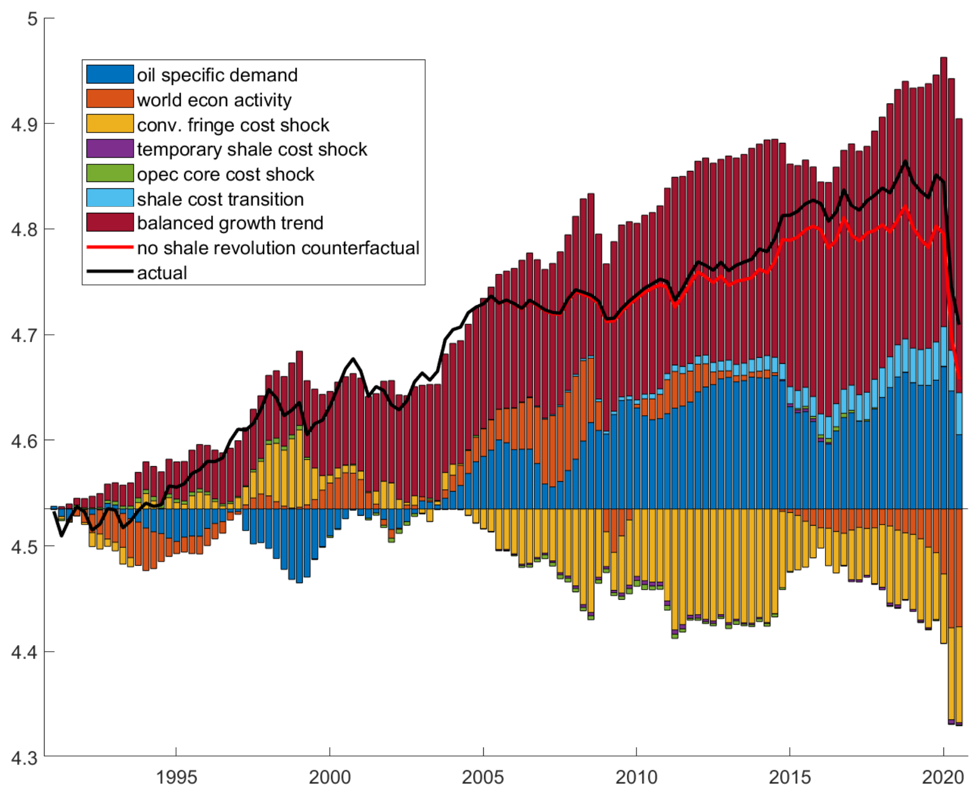


Figure 7: Decomposition of log shale share of world oil output posterior mean contribution

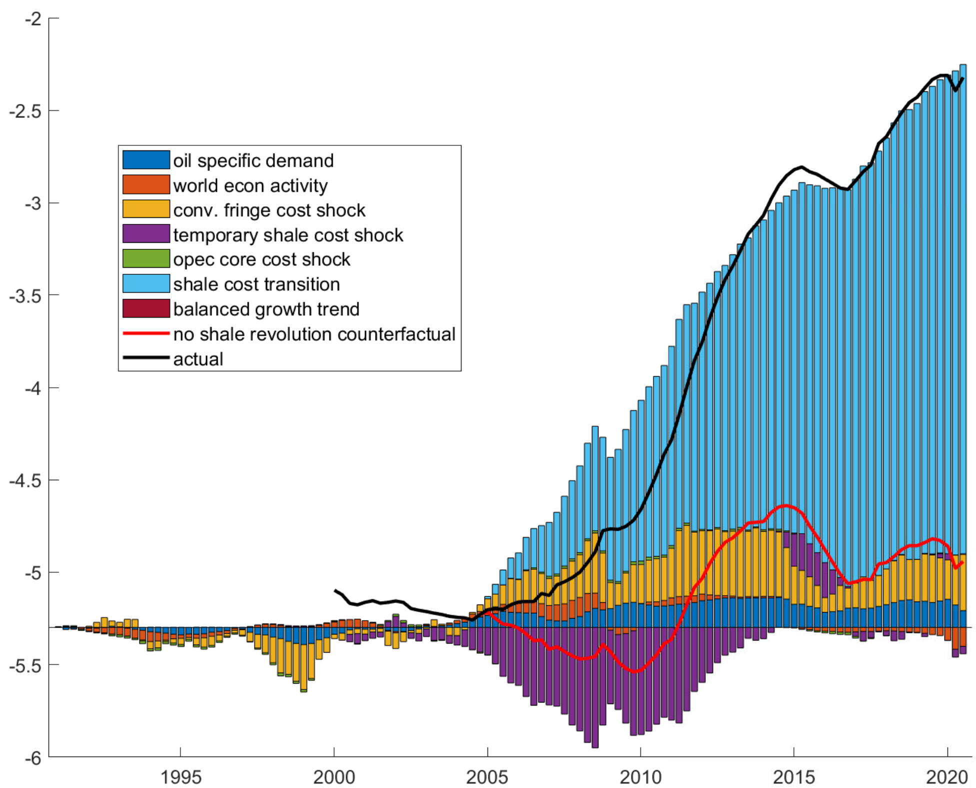


Figure 8: Decomposition of log OPEC core share of world oil output posterior mean contribution

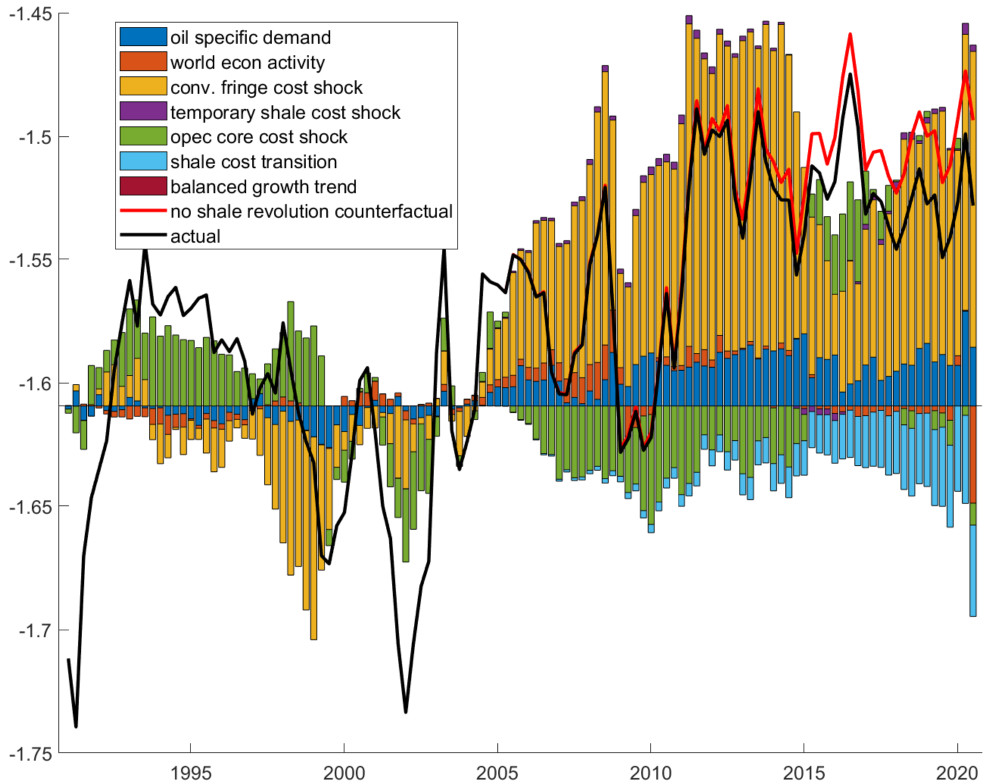


Figure 9: Shale article count in financial press

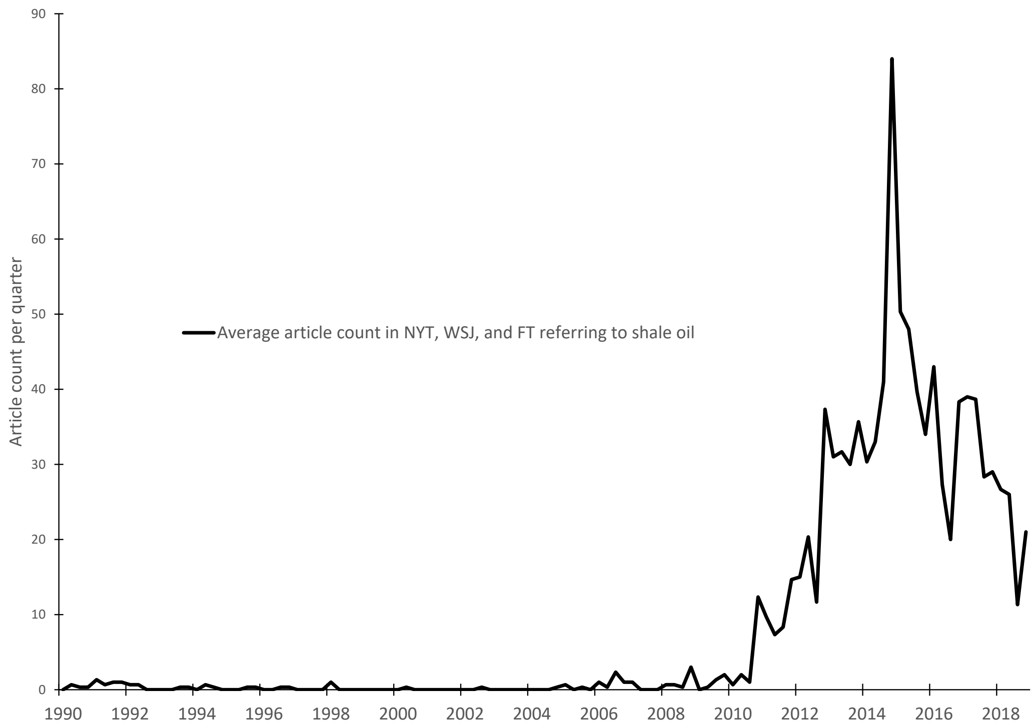


Figure 10: Market structure counterfactuals

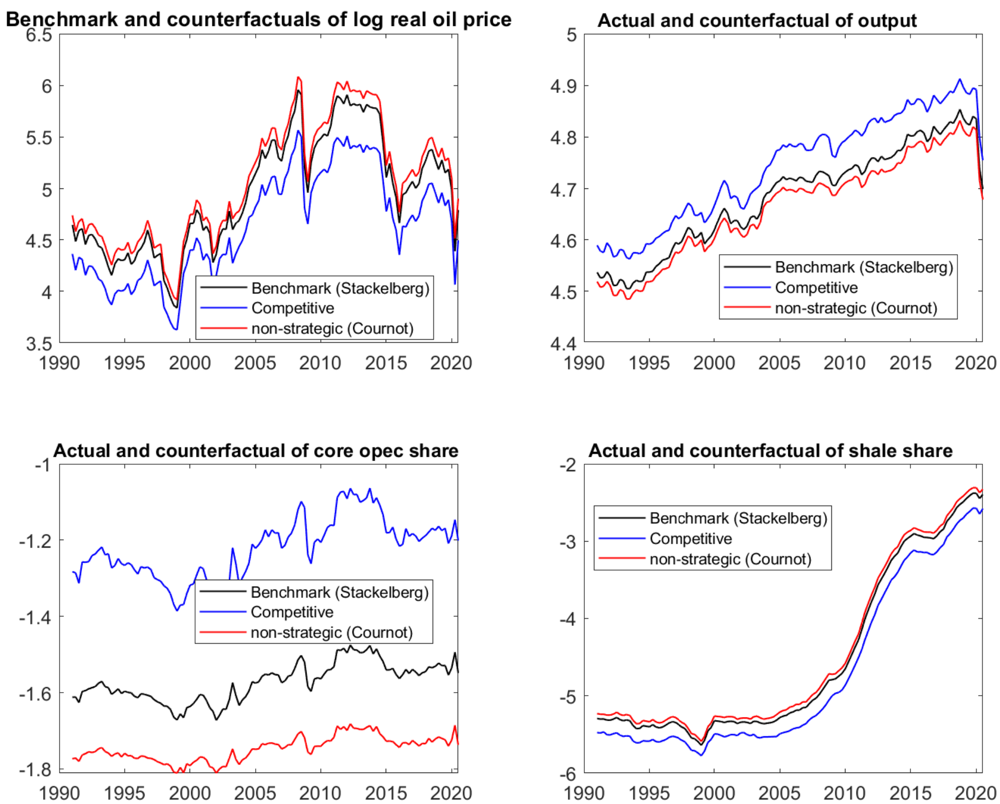
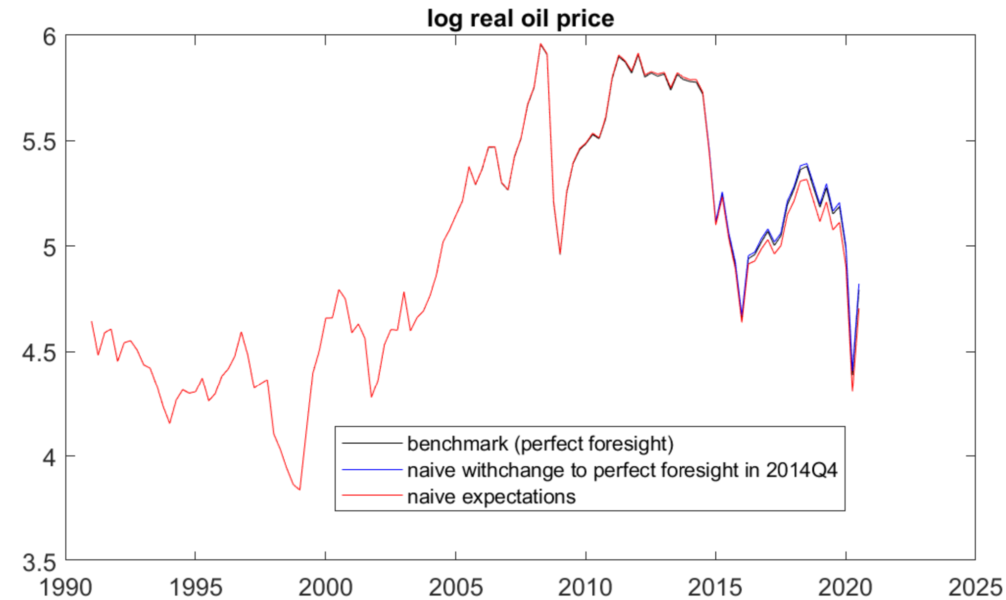
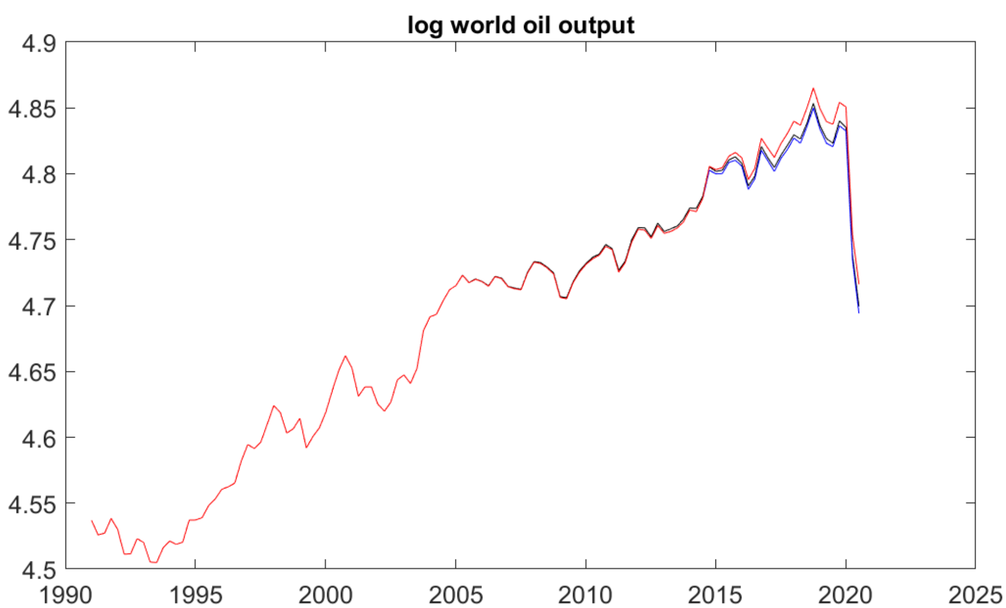


Figure E1. Real oil price and world output
for alternative expectations about shale future





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