Default Risk Mitigation of Oil Hedging Producers (Working Paper)

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Abstract

This paper formalizes and estimates a model of oil & gas producers that face default risk under a stochastic price environment that features forward hedging instruments. First, the paper builds a basic model and a general framework of firm debt default under an exogenous default rule. Then second, it extends this framework by then allowing producers to access forward markets to hedge their next periods production, which endogenizes the firms default rule and lowers the firms risk of default. From the model, I then quantitatively estimate the oil producers hedging demand and then show that this demand is strongly related to the idiosyncratic cost efficiency, that is the cost per barrel of production, of each oil producer. I further confirm this fundamental effect by collecting a sample of the 23 largest independent oil & gas firms and then empirically estimating their cost efficiency and showing a strong negative relationship with the oil producers hedging ratio. The aim of this paper is to build a theoretical framework that helps understand the real dynamics of how oil producers insulate themselves to the price uncertainty they face with production and, most importantly, how they mitigate their exposure to unfavorable debt default valuation states.

1 Introduction

Fueled by the high volatility in oil prices over the last decade, the interest in understanding how oil producers mitigate their exposure to crude oil price fluctuation has become a topical research issue of study given the most recent high volatility episode. Demand by oil producers to hedge their forward production has gone up two fold over the last three years such that in 2017 hedged forward production represented an estimated 43% of total oil production[1]. Much of this excess demand stemmed from the high uncertainty about the future price of oil and the need for many oil producers to have a stable source of funds that allow them to be able to service their loan liabilities to banks and bondholders in spite of all possible future prices states.

The aim of this paper is help better understand the real empirical dynamics of how producers insulate themselves to the price uncertainty they experience in the oil market by attempting to solve for the optimal size and maturity structure of this operating insurance portfolio and to study how firm characteristics in operational efficiency influence this hedging decisions. In order to do so,

[1] Bloomberg Intelligence survey of 37 large publicly traded E&P companies producing 4.2 million barrels a day (46% of U.S. oil production). 32 out of the 37 responded to hedging their 2017 production, 43% percent of the samples expected oil output for 2017 was hedged at an average price of $50 a barrel. 21 out of the 37 reported hedging for the subsequent 2018FY.

I first build out a theoretical framework of risk neutral oil producers that borrow an initial upfront capital entry cost to enter into the oil production market and which face an exogenous oil price and risk of default each period. I then collect and analyze a sample of 23 large U.S. oil & gas firms producing a total of 4.9 million barrel of oil equivalent (BOE)/day to compare to the theoretical models implications [2]. The main motivating question that I will attempt to address in this paper is, what is the optimal hedging portfolio of a risk-neutral oil producer attempting to mitigate default risk? And secondarily, how do firm cost characteristics influence this hedging amount?

The need to investigate this topic has gained more relevance over the last decade as the United States has become a leading global energy producer and supplier, as the sector currently represents 14% of the U.S. economy's market capitalization ($25.6T) and 5.6% of total U.S. household employment. After crude oil prices dropped from $108 to $26 over the short span from June 2014 to Jan 2016, default rates on the loans of oil and gas producers rose from a historical average of 4% to highs of 14.2% [3]. While a 60% price drop over the span of 6 months (75% drop over the span of a 1.5 years) in the presence of unchanged demand may be regarded as an extraordinarily anamoly for any good, in the crude oil markets this could hardly be classified as a rare episode as it was not the first time to occur nor was witnessed by established oil producers ($1B+ in market capitalization) who have experienced a long history of short run and long run boom-bust cycles in oil and understand the necessity to hedge a percentage of their forward production (See Table I).

Although the empirical data clearly shows robust and active participation of oil producers in hedging their forward production, there has been an active debate in the economics literature as to the main motivating reasons as to why risk-neutral firms hedge in the first place. The three generally discussed motives given in the literature as to why firms hedge are (1) to reduce expected taxes, (2) to alleviate financial contracting costs, and (3) to reduce the manager's personal risk exposure.

Smith and Stulz (1985) argue that since the effective marginal tax rates is an increasing function of a corporations pre-tax earnings, i.e. corporations face a convex corporate tax schedule, firms strategically employ hedging strategies to intertemporally shift profits from year-to-year to reduce their overall tax expenses.

On the other hand, the literature's of Froot, Scharfstein, Stein (1993), Géczy, Minton, Schrand (1997), and Gay, Nam (1998) all view hedging from an external funding, contract theory perspective, and conclude that it adds value to the extent that it helps ensure that a corporation has a sufficient source of stable internal funds, which reduces the variability of the firms cashflow streams. This reduction in variability in-turn incentives potential outside equity investors to invest in the firm thereby enhancing the firms equity base which lenders/creditors base their initial lending decision on. This view was also further buttressed by Allayannis and Weston (2001) findings which show that large U.S. domiciled non-financial firms that have robust currency hedging programs have a statistically significant 4.87% equity premium over firms that do not actively hedge and that of Adam and Fernando (2005) whom find similar premiums to shareholder value and reduced cash-flow volatility for firms that actively hedge among a sample of gold mining companies they analayzed.

[2] BOE - Barrel of Oil Equivalent
[3] Fitch Ratings

A second line of the financial contracting costs theory literature considers the role of hedging in reducing the magnitude of a company's funding costs which it could face under financial distress. Mayers and Smith (1990) argue that hedging reduces expected default and bankruptcy costs by reducing the variability of a firms cash flows. Graham and Rodgers (1999) also argue firms hedge in order to reduce expected financial distress costs but to the contrary of Smith and Stulz's work find no evidence that firms hedge in response to tax convexity. Bessembinder (1991) demonstrates that by reducing the probability of default, hedging can reduce the incentives for equity holders to underinvest, improving contracting terms with creditors. Warner (1977) takes the view that firms hedge in order to reduce debt default costs which further decreases the firms value in unfavorable states, of which firm bankruptcy is a possibility. Warner lays out two major costs firms are trying to avoid in bankruptcy, first *direct costs* of which include equity dilution, asset seizures, costs of lawyers, accountants and the value of managerial time spent dealing with the bankruptcy. And second, *indirect costs* which include lost sales, lost profits, the inability to obtain credit and losses due to customers and employees abandoning the firm. It is also important to note that a firm does not have to be in bankruptcy for financial distress costs to occur, even before the firm goes into default there will likely be large indirect costs of bankruptcy. Ang, Chua, McConnell (1982) finds that a subset of the indirect costs, administrative costs, which include fees and compensation paid to third parties involved in the dissolution or reorganization of the bankrupt firm to be on average 7.5% of the firms value from a sample of 105 company bankruptcies.

And finally, the last line of literature views hedging from the perspective of managerial risk aversion. Stulz (1984) argues that managers are often unable to diversify firm-specific risks. For this reason, risk averse managers often choose to take actions that reduce the variability of the firm's returns. These arguments imply that, all else equal, managers with more wealth invested in a firm's equity will have greater incentives to manage the firm's risks. Additionally, survey analysis by Smithson and Simkins (2005) concludes that executives overall find corporate risk management as a value-adding activity.

Haushalter (2001) specifically studies the hedging behavior of oil & gas sector and empirically examines all of the three aforementioned reasons and finds that there is a strong association with an oil firms hedging policy and its financial leverage and ability to borrow new capital. Conducting a survey on the hedging activity of 92 oil & gas producer spanning over 3 years, Haushalter finds that the fraction of production hedged (hedge ratio) among the firms in the sample was increasing in their leverage and decreasing in their credit rating. He also finds that oil producers whose production is located primarily in regions where the producers nodal prices have a high correlation with the financially traded hub prices are more likely to manage risks, and vice verse for firms that have production located in regions where nodal oil and gas prices tend to have a low correlation to the hub price – this is consistent with notion that frictional hedging costs, basis risk being one of them, is an important cost factor influencing how much oil producers hedge (See also Ederington (1979)).

In this paper I take many of the viewpoints presented in the financial contracting cost literature and assume that risk-neural oil producers hedge because of the the high associated costs of defaulting and the need to have a stable source of internal funding. I do this by restricting the ability of the firms to borrow additional capital after entry (i.e. infinite refinancing cost in debt default states) and by introducing absorbing state default risk each period. However, unlike much of the empirically focused literature, I examine how idiosyncratic fundamental factors, primarily, cost efficiency, as the underlying reason why some oil & gas firms hedge more than others. The wide range of idiosyncratic cost structure among oil & gas firms is largely attributable to difference in human capital (geologists, engineers, executive management, etc), patents in innovative drilling technology, and ease of oil production among different geologic formations that separate lower marginal cost producers from higher ones. It is also topical to note that this paper deals with a specific type of hedging that is unique to only energy firms. Unlike other firms and industries, banks and financials for example, which cash settle all their financial hedging on paper, the hedging of oil producers translates to *actual* physical production and is meant to insure and insulate the firms day-to-day business operations, and is not meant for speculative nor profit making means.

The aim of this paper is to better understand how oil company's mitigate their exposure to the price of oil and to understand if cost efficiency factors influence their hedging quantity decisions. In the sections of this paper, I first build a general framework of firm debt default under and use an exogenous default rule. Then second, I extend this framework by then allowing producers to hedge their forward production in order to mitigate their default risk. I then analyze the hedging, production, and financial data of 23 large U.S. oil & gas sampled firms to compare to the theoretical models implications and find that cost efficiency factors play a significant role in *how much* oil producers hedge.

2 Basic Model

In order to model oil producers under the presence of default risk, I construct a model that values a debt burdened producer over its entire liability schedule: from the initial time period the debt was incurred and the firm enters the market to the time period the debt is either (a) fully paid-off at the normal maturity of its schedule or (b) the unscheduled default and liquidation of the firm.

At $t = 0$, an oil producer borrows B in nominal debt, at an interest rate r, that is due T periods later, in order to finance the purchase of capital equipment which will allow the firm to enter the oil drilling business. The amount borrowed B is an upfront lump-sum entry cost to enter.

Since I am only concerned with firms that can potentially default, that is firms that have debts, I assume the game ends at time period T. However, this horizon can be easily extended to infinity, $T \to \infty$, in which the debt essentially becoming a perpetuity bond.

I assume the oil producer is a price taker whom observes the price p_t each period and then chooses its optimal quantity q_t^* that maximize its profit function:

$$\pi_t = p_t q_t - \frac{\alpha}{2} q_t^2 - rB$$

Therefore the producers optimal quantity, for any period, and for any price state under which the firm normally operates, will *always* be,

$$q_t^* = \frac{p_t}{\alpha}.$$

To formulate a Bellman equation for the firms problem, I introduce two value functions that correspond to default and no-default (normal operation) states which depend on profitability price threshold,

$$V(p_t) = \begin{cases} V^N(p_t) & \text{if } p_t \geq \bar{p} \quad \leftarrow \text{Normal operation} \\ V^D(p_t) & \text{if } p_t < \bar{p} \quad \leftarrow \text{Default} \end{cases}$$

where $\bar{p}$ is the break-even spot price such that $\pi_t(q^*(\bar{p})) = 0$. This threshold value will always be the same each period and must exist because the profit function is negative $\pi_t(0) = -rB$ at zero production. For price draws below the threshold, the peak profit function is always negative for all quantities. The threshold value at which the firm normally operates can then be easily calculated by substituting the optimal quantity in the profit function,

$$\bar{p} = \left(2\alpha rB\right)^{1/2}.$$

Note that this exogenous threshold will then vary in the model where the oil producer can hedge and is decreasing in the firm hedging decision.

The first value function I specify is that of a firm current on its debt payments and is in a normal operating state, i.e. $p_t \geq \bar{p}$. A firm in the normal state has the following value function,

$$V^N(p_t) = \max_{q_t} \pi_t + \beta E_t\big[V(p_{t+1}, B)|p_t\big].$$

Therefore a firm that is successful in servicing its debts throughout its entire schedule and which never defaults, drawing a history path $\Omega_T = \{p_2, ..., p_T\}$ where all the prices are above the threshold $\bar{p}$, has the following realized value in period $t = 1$,

$$V^N(p_1, \Omega_T) = \underbrace{\sum_{t=1}^{T} \beta^t \pi_t}_{Asset} + \beta^T \underbrace{\left(\frac{\pi(P_T)}{1-\beta} - B\right)}_{V_T(P_T,B)}.$$

In converse to being in a normal operating state, If the firm draws a price under which it runs a negative profit, i.e. when the current market price is below the threshold value $p_t < \bar{p}$, then the firm defaults and enters into an absorbing default state. To insure price monotonicity in the value function and to model the high direct/indirect costs associated with default and bankruptcy, I specify the default value K as being greater than the initial debt incurred. I specify the default state value function as,

$$V^D(p_t) = -K, \quad \text{where} \quad K > B.$$

Some important properties about the firms value function after entry $V(p_t, t)$ is that it is strictly monotonically decreasing with respect to time $\frac{\partial V(p_t,t)}{\partial t} < 0$ for prices far from the threshold where the firm has little default risk as future profits are realized and the debt owed $-B$ nears and conversely is strictly monotonically increasing in time for prices near the threshold $\frac{\partial V(p_t,t)}{\partial t} > 0$, since the remaining time for which the firm could potentially default gets smaller and smaller (appreciation to avoiding a high K). Avoiding the pitfall drop in value causes the firm to appreciate as the debt matures as the firm avoid the "disaster" type valuation $-K$, (see Figure 1). Moreover, the value function is always monotonically increasing in the price $\frac{\partial V(p_t,t)}{\partial p} \geq 0$ for prices below and above the default threshold $\bar{p}$. And finally that V is also continuous, though it obviously has a kink at the default threshold.

In order to solve the dynamic problem, I make a distributional assumption that the oil price price is log-normally distributed and evolves according to the following law of motion,

$$p_{t+1} = \exp(p_t + \sigma z_{t+1}) \quad \text{where} \quad z \sim N(0,1).$$

The mean-variance parameters about next periods oil price p_{t+1} are time varying and therefore depend on the current price state, p_t, ther conditional mean variance are,

$$p_{t+1}|p_t \sim \ln N(\mu_{p_t}, \sigma^2_{p_t}),$$

where,

$$\mu_{p_t} = E[p_{t+1}|p_t] = \exp\Big(p_t + \frac{1}{2}\sigma^2\Big),$$

$$\sigma^2_{p_t} = \text{Var}[p_{t+1}|p_t] = [\exp(\sigma^2) - 1]\exp(2p_t + \sigma^2).$$

Though I employ backward induction in order to compute the value of the firm in this basic debt default setting, by using recursion and classical survival analysis, the Bellman equation can be simplified to a closed form expression. This closed form solution can be derived by substituting the optimal profit of the firm each period,

$$\pi(q^*_t(p_t)) = p_t\Big(\frac{p_t}{\alpha}\Big) - \alpha\Big(\frac{p_t}{\alpha}\Big)^2 - rB,$$

into the Bellman objective function and by re-expressing next periods expected value of the firm over the conditional expectation of the two possible event state value functions (see Appendix). The Bellman can then be recursively solved to derive the following closed form expression of the firms value function at time t,

$$V^N(p_t) = \sum_{j=1}^{T} \beta^j S(t+j) E[\pi^*_{t+j}|p_{t+j} \geq \bar{p}] + (-K)\sum_{j=1}^{T} \beta^j [S(t+j) - S(t+j-1)] - S(T)B.$$

Where S is the survival function, which is the probability that a firm currently in a normal state at time t survives to time period $t+k$ in the future,

$$S(t+k) = \text{P}\Big(\bigcap_{j=1}^{k}\{p_{t+j} \geq \bar{p}\}\Big) = 1 - \text{P}(\tau \leq t+k)$$

and τ is the (random) time event of default between t and $t+k$. The value function of the firm in the normal state can be intuitively thought of as a price weighted convex combination between the value of the firm remaining in the normal state and possible default.

3 Basic Model With Hedging

I now extend the basic model by allowing the producer to access a forward contract at time t trading at a price $\mathcal{F}_t$ that guarantees the producer fixed revenue of $\mathcal{F}_t h_t$ in period $t+1$, where h_t is the amount of contracts the producer sells at time t. Therefore each period the producer has access to two different markets, a spot market and forward market, and two different types of revenue streams that allows the producer to sell its production forward.

By committing a portion of its production in the prior period by means of hedging, the producers optimal spot production is therefore net of the hedged decision amount,

$$q_t^* = \max\{0, \frac{p_t}{\alpha} - h_{t-1}\}.$$

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The profit function now includes two sources of revenue: stochastic revenue from spot product and deterministic revenue from hedged production that was optimally determined in period $t-1$,

$$\pi_t = p_t q_t + \underbrace{\mathcal{F}_{t-1} h_{t-1}}_{\text{static}} + \frac{\alpha}{2}(q_t + h_{t-1})^2 - rB.$$

For this paper, I assume the forward price is fully deterministic given that periods spot price p_t. I do this by pegging next periods expectation of the spot price, $E_t[p_{t+1}|p_t] = \mathcal{F}_t$ to the forward price. This satisfies a no-arbitrage condition that the firm is not hedging simply because of mispricing in the contract.

As with the basic model, I specify for a given state space $S_t = (h_{t-1}, \mathcal{F}_{t-1}, \mathcal{F}_t)$ the normal state value of the firm as,

$$V^N(p_t, \mathcal{F}_t, h_{t-1}, \mathcal{F}_{t-1}) = \max_{q_t, h_t} \pi_t - c(h_t) + \beta\left[\int_0^{\bar{p}(h_t)} V^D(p_{t+1}, S_{t+1}) f(p_{t+1}|p_t)dp + \int_{\bar{p}(h_t)}^{\infty} V^N(p_{t+1}, S_{t+1}) f(p_{t+1}|p_t)dp\right].$$

Where $c(h_t) = \gamma h_t^\eta/\eta$ is a strictly convex hedging cost and $\bar{p}(h_t)$ is the default threshold for $t+1$. This convex hedging cost can be intuitively thought of as a frictions, margin/collateral costs, banking fees, trading fees, etc, incurred at time t for hedging profits in $t+1$.

However, unlike the basic model, allowing the producer to hedge forward gives the firm the ability to alter which states of nature constitute a default by means of its hedging activity h_t thereby influencing the threshold value $\bar{p}(h_t)$. This in effect endogenizes the default threshold which was was static and unalterable and fixed at $\bar{p}$ in the basic model. The debt default threshold value for each period t is,

$$\bar{p}(h_{t-1}, \mathcal{F}_{t-1}) = \alpha h_{t-1} + \Big((\alpha h_{t-1})^2 + 2\alpha(rB - \mathcal{F}_{t-1}h_{t-1})\Big)^{1/2}.$$

To simplify notation, I drop the forward price notation in the threshold function. Prices below this debt default threshold constitutes a default in which the firm enters into an absorbing state. Some noteworthy remarks about the threshold function arise from analyzing the sensitivity of the threshold to hedging quantities to better understand how hedging influences default risk. By differentiating the threshold with respect to h_t,

$$\frac{\partial \bar{p}(h_t)}{\partial h_t} = \alpha + \frac{\alpha(\alpha h_t - \mathcal{F}_t)}{\Big((\alpha h_t)^2 + 2\alpha(rB - \mathcal{F}_t h_t)\Big)^{1/2}} = \alpha + \frac{\alpha(\alpha h_t - \mathcal{F}_t)}{\bar{p}(h_t) - \alpha h_t},$$

we find that the threshold can only be decreasing in the firms hedging quantity decision, i.e. $\frac{\partial \bar{p}(h_t)}{\partial h_t} < 0$, if and only if (1) the forward price is above the unaltered default threshold $\mathcal{F}_t > (2\alpha r B)^{1/2} = \bar{p}$ and (2) the firm does not optimally over-hedge such that $h_t^* \leq \frac{\mathcal{F}_t}{\alpha}$

In converse to a firm in a normal operating state of the business where it can meet its debt service obligation, If the firm enters a state in which it defaults, I specify that the firms default value is K plus the operating profit of the hedging commitment it made in the prior period.

$$V^D(p_t, S_t) = \mathcal{F}_t h_t - \frac{\alpha}{2}(h_t)^2 - K, \quad \text{where} \quad K > B.$$

This avoids the scenario of the firm defaulting on its promise to deliver forward production, which would generate a second source of default in the model, I insure that even in the absorbing default state, production occurs for one time only to meet its forward production obligation made the prior period.

From the FOC with respect to h_t, I find the following optimality condition for the firms hedging demand h^*,

$$\gamma h_t^{\eta-1} + \beta\alpha h_t + \beta\alpha\Big(\frac{E_t[p_{t+1}|p_{t+1} \geq \alpha h_t]}{\alpha} - h_t\Big)(1 - F[\alpha h_t]) = \beta\Big[\mathcal{F}_t - \Big(V^N(\bar{p}(h_t), S_{t+1}) - V^D(\bar{p}(h_t), S_{t+1})\Big)\frac{\partial F[\bar{p}(h_t)]}{\partial h_t}\Big]$$

However unlike the basic model, the only way to calculate h^* in the hedging model is numerically. Though, an obvious and noteworthy result that can be implied from the optimality condition is that the firms hedging demand is decreasing in the default probability.

Considering a price scenerio where the initial probability of default was 0, $F[\bar{p}] = \mathrm{P}(p_{t+1} < \bar{p}) \approx 0$, which occurs for very high price states, the firms optimal hedge quantity is not to hedge, or $h^* = 0$

Which can be seen from the FOC, since $F[\bar{p}(h_t)] \leq F[\bar{p}] = 0$, this implies that hedging activity cannot reduce the default threshold any further, therefore the change in the probability of default due to hedging is always 0, $\frac{\partial}{\partial h_t} F[\bar{p}(h_t)] = 0$. This reduces the FOC as such

$$\gamma h_t^{\eta-1} + \beta\alpha h_t + \beta\alpha\Big(\frac{E_t[p_{t+1}|p_{t+1} \geq \alpha h_t]}{\alpha} - h_t\Big)(1 - F[\alpha h_t]) - \beta\mathcal{F}_t = 0,$$

and since the optimal h^* will always satisfy $\alpha h^* \leq \mathcal{F}_t$

$$\gamma h_t^{\eta-1} + \beta\alpha\Big(\frac{E_t[p_{t+1}|p_{t+1} \geq \alpha h_t]}{\alpha} - h_t\Big)(1 - F[\alpha h_t]) \leq 0,$$

this leads to the only possible solution for the firm when no default risk present at very high price states which is $h^* = 0$ which occurs when $F[\bar{p}] \to 0$ as $\bar{p}$ becomes larger. Moreover, setting $h^* = 0$ in the optimality condition yields our classic assumption that the forward price is equal to tomorrows expected price,

$$E_t[p_{t+1}|p_{t+1} \geq 0] = E_t[p_{t+1}|p_t] = \mathcal{F}_t.$$

4 Model Simulation

In order to solve the Bellman equations for the firms value over the entire game I use backward induction and make a simplifying assumption by discretizing the continuous state space for each period $\mathcal{S}_t = (p_t, h_{t-1}, \mathcal{F}_{t-1}, \mathcal{F}_t)$ into s finite grid of discrete points. I set the redundant state variable, $\mathcal{F}_t$, to the expectation of tomorrows price at each state node, $\mathcal{F}_t = E_t[p_{t+1}]$. I discretize the price state space over \$1 increments ranging from $\mathcal{F}, p \in [0, \$150]$, as such $\mathcal{F}, p \in \{0, 1, ..., 150\}$.

Since the state space, $\mathcal{S}_t$ is quite large (3 variables + 1 time), I vectorize (in other words "flatten") the state space for each time period and solve the dynamic finite-horizon optimization problem via backward induction from the last period for the optimal hedging quantity, $h(\mathcal{F}_t)$ for a producer with the empircal data's mean cost efficiency $\alpha = 1.1$ (see Figure 5). Given the fact the statespace is 4 dimensional for the hedging model it is almost impossible to visualize the value function. However, I do compute and plot the value function for the basic model only since there are only two variables (1 variable (price) + time) (see Figure 1).

In order to better understand how idiosyncratic cost efficiencies, driven by fundamental factors such as human capital, geologic formations of the oil basin, drilling patents and proprietary exploration technology, influence how much a firms hedge, I conduct a computational comparative statistics excersize estimating the models hedging demand for two different firms, a low type $\alpha_L = 1.1$ and a high type $\alpha_H = .75$, with respective default thresholds $\bar{p}_L = \$57$ and $\bar{p}_H = \$48$. I estimate each types hedging insurance demand curve (See Figure 4) and then run a price simulation for comparison and compute the spot production and hedging ratios for both types (See Figure 2 & Figure 3).

Clearly from the firms optimal hedging curve, oil producers hedge as a form of insurance to protect the firm from default. Though technically another form of production supply output by the firm, however under the presence of default risk, convex hedging costs, and no arbitrage, hedging behavior by the oil producer is more akin to that of insurance demand. This demand to hedge is decreasing in the default probability as predicted by the theory of the model. For very high price state, when the probability of default is approximately 0, both firms simply do not hedge. However the low type clearly hedges almost 1.5x more than the high type for most price greater than the low types default threshold. As can be seen from the price simulation, hedging helps low type firms avoid debt default by reducing the overall volatility in their earnings avoiding default scenarios and therefore the theoretical model implies their hedging demand should be higher than highly efficient producers.

Empirical data on hedging also supports this downward sloping hedging demand curve. There were two recent exogenous oil demand shocks that caused a leftward shift in oil demand – in 2008 at during the financial crisis and in 2015 during a global industrial slow down. In both events the movement in the price of oil was demand influenced causing the price of oil to plummet from very high prices to very low prices over the span of a few months. Assuming supply is slow to adjust in this short time period of only a few months this helps with the identification of the forward supply curve of hedgers, without the need for structural modeling. Figure 5 plots the hedging demand for those two exogenous oil episodes from data collected from the CFTC's Commitment of Traders report on the positioning of total futures and options contracts of commercial oil & gas hedgers on the WTI crude contract. In both episodes, the forward supply curve exhibits the same downward sloping hedging behavior with respect to the forward price implied by the theoretical model. This suggests the increase in hedging behavior as the price of oil reaches the default thresholds of many of the oil businesses.

5 Empirical Data

I collect the financial costs, hedging and production volume data of a sample of 23 large publically traded oil & gas firms producing a total of 4.9 million BOE/day from Bloomberg which derive their data from the direct SEC form 10-K filings.

I calculate the hedge ratios for all the firms over the last 4 fiscal years (2014-2017)

$$\text{Hedge Ratio} = \hat{h} = \frac{\text{Volume BOE hedged}}{\text{Total Volume Production BOE}}$$

Because there is a maturity dimension to the portfolio which will vary from firm-to-firm of how much was hedged for what future time period, that is some firms may have short duration maturity profile and others a longer duration, I average the firms hedge ratio over all 4 years in the available sample to calculate an average hedge ratio. This removes any potential maturity differences among firms hedging portfolio over different horizon and produces a more robust characteristic measure of the firm that is largely attributable to its idiosyncratic factors, such as cost efficiency for example.

Using the reported gross operating cost of production the firms report in their traditional income statement, I calculate each firms idiosyncratic cost efficiency parameter, $\hat{\alpha}$ as such, [4]

$$\text{Cost Efficienty (Alpha)} = \hat{\alpha} = \frac{\text{Nominal Cost}}{\frac{1}{2}(\text{Total Production BOE})^2}.$$

Likewise, I average the estimated alpha over 4 years of data for each firm to get a more robust measure of the firms idiosyncratic cost efficiency. The mean alpha across the entire sample of 23 firms is 1.12 with a median of 0.59.

Table II, reports the descriptive statistics for both the hedge ratio and cost efficiency parameter. Table III reports the distribution of the cost efficiency parameter across the firms. 65% of the sample has an $\hat{\alpha} < 1$ and 35% $\hat{\alpha} > 1$ with a range from [0.05, 4.16]. Though it is hard to determine for certain what is driving the wide range of idiosyncratic cost efficiency differences among the oil producers, it seems size differences (Big vs Small) among the firms seems to be a *potential* explanatory factor. The firms with cost efficiency factors $\hat{\alpha} > 1$ have an average market capitalization of \$2.5B while the firms with cost efficiency factors $\hat{\alpha} < 1$ have an average market capitalization of \$18.3B. Likewise for the firms above and below the median, \$21B vs \$2.9B. However suggesting that size factors are influencing firm cost efficiency could raise endogeniety problems. Are larger firms cost efficient due to their size, scale, access to capital etc. or are fundamental cost efficiency drivers (such better patents or proprietary drilling & exploration technology, etc) the reason why those firms become large firm in the place? With the exception of only two firms (average of \$300M), 21 out-of 23 of the firms in the sample are a \$1B+ in market capitalization.

Regressing the hedge ratio on the cost efficiency parameter, the empirical data shows a strong statistically significant casual relationship between a firms cost efficiency and it hedge ratio.

$$E[\hat{h}] = 0.24 + 0.10\hat{\alpha}$$

with a t-stat of 4.49 (See Figure 5). This statistically significant relationship holds for any subset of the sample, even for firms with $\hat{\alpha}$ above and below 1.

6 Conclusion

This paper attempts to understand the real dynamics of how oil producers insulate themselves to price uncertainty faced with production and how to mitigate their exposure to unfavorable debt

[4]as opposed to net cost which includes non-cash expenses such as depreciation & amortization and investment impairments and which also include non-related costs to oil production such as, general administrative, etc. Both measures produce the exact same exact figures, relationships, etc.

default valuation states. It builds a general framework of firm debt default under an exogenous default rule and then extends this framework by allowing producers to access forward markets to hedge their forward production, thus endogenizing the default rule and lowering the risk of default. It then quantitatively estimates the oil producers hedging demand and conduct a comparative statistics exercise and simulation to show that this hedging demand is strongly related to the idiosyncratic cost efficiency factors of the firm. I further confirm this computational result by collecting a sample of 23 oil & gas firms and then empirically estimating the firms cost efficiency and showing its strong negative relationship with oil producers hedging ratios.

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Appendices

Basic Model

$$V^N(p_t) = \max_{q_t} \pi_t + \beta\Big(\mathrm{P}(p_{t+1} < \bar{p})E_t[V^D(p_{t+1})|p_{t+1} < \bar{p}] + \mathrm{P}(p_{t+1} \geq \bar{p})E_t[V^N(p_{t+1})|p_{t+1} \geq \bar{p})]\Big)$$

$$= \pi_t^* + \beta\Big(\mathrm{P}(p_{t+1} < \bar{p})E_t[-K|p_{t+1} < \bar{p}] + \mathrm{P}(p_{t+1} \geq \bar{p})E_t[V^N(p_{t+1})|p_{t+1} \geq \bar{p})]\Big)$$

$$= \pi_t^* + \beta\Big(\mathrm{P}(p_{t+1} < \bar{p})(-K) + \mathrm{P}(p_{t+1} \geq \bar{p})(E_t[\pi_{t+1}^*|p_{t+1} \geq \bar{p}]) + \beta E_t[V(p_{t+2})|p_{t+1} \geq \bar{p})]\Big)$$

If we continue this process of forward recursion we will find that the profit expectation k periods out, $E[\pi_{t+k}^*| \bigcap_{j=1}^{k} \{p_{t+j} \geq \bar{p}\}]$, is conditioned on having survived in all prior periods from t to $t+k$. Since the event of having survived to period $t+k-1$, the event date the expectation is formed for $t+k$, implies having survived all periods prior, we can simply condition on the most recent, and random event as such, $E_t[\pi_{t+k}^*|p_{t+k} \geq \bar{p}]$. The posterior probabilities on each expectation can be rewritten as a survival probability,

$$\prod_{j=1}^{k} \mathrm{P}\big(p_{t+j} > \bar{p}| \bigcap_{i=1}^{j-1}\{p_{t+i} \geq \bar{p}\}\big) = \mathrm{P}\big(\bigcap_{j=1}^{k}\{p_{t+j} \geq \bar{p}\}\big) = 1 - \mathrm{P}(\tau \leq t+k) = S(t+k)$$

Likewise, the posterior probabilities on each of the defaulted value K in recursion can be rewritten as a survival probability of having made it to period $t+k-1$ but then defaulting in period k

$$\mathrm{P}\big(p_{t+k} < \bar{p}| \bigcap_{i=1}^{k-1}\{p_{t+i} \geq \bar{p}\}\big) \prod_{j=1}^{k-1} \mathrm{P}\big(p_{t+j} > \bar{p}| \bigcap_{i=1}^{j-1}\{p_{t+i} \geq \bar{p}\}\big) = S(t+k) - S(t+k-1)$$

Continuing this recusion you finally end up with the following expression,

$$V^N(p_t) = \sum_{j=1}^{T} \beta^j S(t+j)E_t[\pi_{t+j}^*|p_{t+j} \geq \bar{p}] + (-K)\sum_{j=1}^{T} \beta^j[S(t+j) - S(t+j-1)] - S(T)B$$

Hedging Model

For a firm in a normal state, the F.O.C with respect to h_t is,

$$0 = -\gamma h_t^{\eta-1} + \beta\Big[\frac{\partial}{\partial h_t}\int_0^{\bar{p}(h_t)} V^D(p_{t+1}, S_{t+1})f(p_{t+1})dp + \frac{\partial}{\partial h_t}\int_{\bar{p}(h_t)}^{\infty} V^N(p_{t+1}, S_{t+1})f(p_{t+1})dp\Big]$$

With the following two envelope conditions,

$$\frac{\partial}{\partial h_t}V^N(p_{t+1}, S_{t+1}) = \mathcal{F}_t - \alpha(q_{t+1} + h_t)$$

$$\frac{\partial}{\partial h_t}V^D(p_{t+1}, S_{t+1}) = \mathcal{F}_t - \alpha(h_t).$$

Note, Because the firms hedging influences the bankruptcy threshold $\bar{p}(h_t)$, therefore altering which states of nature constitute a default, I must use Leibeniz rule to differentiate the two integrals in the F.O.C.

I differentiate the first integraled term with respect to h_t

$$\frac{\partial}{\partial h_t}\int_0^{\bar{p}(h_t)} V^D(p_{t+1}, S_{t+1})f(p_{t+1})dp = \int_0^{\bar{p}(h_t)} \frac{\partial}{\partial h_t}V^D(p_{t+1}, S_{t+1})f(p_{t+1}) + V^D(\bar{p}(h_t), S_{t+1})f(\bar{p}(h_t))\frac{\partial \bar{p}(h_t)}{\partial h_t}$$

$$= \int_0^{\bar{p}(h_t)} [\mathcal{F}_t - \alpha(h_t)]f(p_{t+1}) + [\mathcal{F}_t h_t - \frac{\alpha}{2}(h_t)^2 - K]f(\bar{p}(h_t))\frac{\partial \bar{p}(h_t)}{\partial h_t}$$

$$= [\mathcal{F}_t - \alpha h_t]F[\bar{p}(h_t)] + [\mathcal{F}_t h_t - \frac{\alpha}{2}(h_t)^2 - K]f(\bar{p}(h_t))\frac{\partial \bar{p}(h_t)}{\partial h_t}$$

and differentiate the second integraled term with respect to h_t.

$$\frac{\partial}{\partial h_t}\int_{\bar{p}(h_t)}^{\infty} V^N(p_{t+1}, S_{t+1}) = \int_{\bar{p}(h_t)}^{\infty} \frac{\partial}{\partial h_t}V^N(p_{t+1}, S_{t+1})f(p_{t+1}) - V^N(\bar{p}(h_t), S_{t+1})f(\bar{p}(h_t))\frac{\partial \bar{p}(h_t)}{\partial h_t}$$

$$= \int_{\bar{p}(h_t)}^{\infty} [\mathcal{F}_t - \alpha(q_{t+1} + h_t)]f(p_{t+1}) - V^N(\bar{p}(h_t), S_{t+1})f(\bar{p}(h_t))\frac{\partial \bar{p}(h_t)}{\partial h_t}$$

$$= [\mathcal{F}_t - \alpha h_t](1 - F[\bar{p}(h_t)]) - \alpha \int_{\bar{p}(h_t)}^{\infty} \max\{0, \frac{p_{t+1}}{\alpha} - h_t\} f(p_{t+1}) - V^N(\bar{p}(h_t), S_{t+1}) f(\bar{p}(h_t)) \frac{\partial \bar{p}(h_t)}{\partial h_t}$$

Whether the firm produces on the spot next period, $q_{t+1} = \max\{0, \frac{p_{t+1}}{\alpha} - h_t\}$, depends on how much it hedged the prior period, h_t. The breakeven price at which the firm begins producing on the spot is $\frac{\bar{p}_{t+1}}{\alpha} - h_t = 0 \rightarrow \bar{p}_{t+1} = \alpha h_t$.

$$= [\mathcal{F}_t - \alpha h_t](1 - F[\bar{p}(h_t)]) - \alpha \int_{\bar{p}(h_t)}^{\alpha h_t} 0 \cdot f(p_{t+1}) - \alpha \int_{\alpha h_t}^{\infty} \Big(\frac{p_{t+1}}{\alpha} - h_t\Big) f(p_{t+1}) - V^N(\bar{p}(h_t), S_{t+1}) f(\bar{p}(h_t)) \frac{\partial \bar{p}(h_t)}{\partial h_t}$$

$$= [\mathcal{F}_t - \alpha h_t](1 - F[\bar{p}(h_t)]) - E_t[p_{t+1} | p_{t+1} \geq \alpha h_t](1 - F[\alpha h_t]) - \alpha h_t (1 - F[\alpha h_t]) - V^N(\bar{p}(h_t), S_{t+1}) f(\bar{p}(h_t)) \frac{\partial \bar{p}(h_t)}{\partial h_t}$$

Combine the two differentiated integral terms above to derive the optimal hedging quantity, h_t^*, which must satisfy the following F.O.C. equation under the conditions (1) $\mathcal{F}_t > (2\alpha r B)^{1/2} = \bar{p}$ and (2) $p_t^* = \alpha h_t^* < \mathcal{F}_t$.

$$\gamma h_t^{\eta-1} = \beta \Big[\mathcal{F}_t - \alpha h_t - \big(E_t[p_{t+1} | p_{t+1} \geq \alpha h_t] - \alpha h_t\big)(1 - F[\alpha h_t]) - \Big(V^N(\bar{p}(h_t), S_{t+1}) - V^D(\bar{p}(h_t), S_{t+1})\Big) f\big(\bar{p}(h_t)\big) \frac{\partial \bar{p}(h_t)}{\partial h_t}\Big],$$

$$\gamma h_t^{\eta-1} + \beta \alpha h_t + \beta \alpha \Big(\frac{E_t[p_{t+1} | p_{t+1} \geq \alpha h_t]}{\alpha} - h_t\Big)(1 - F[\alpha h_t]) = \beta \Big[\mathcal{F}_t - \Big(V^N(\bar{p}(h_t), S_{t+1}) - V^D(\bar{p}(h_t), S_{t+1})\Big) f\big(\bar{p}(h_t)\big) \frac{\partial \bar{p}(h_t)}{\partial h_t}\Big],$$

Where the reduction in the probability of default due to the hedging position,

$$\Delta \mathrm{P(default)} = \frac{\partial F[\bar{p}(h_t)]}{\partial h_t} = f(\bar{p}(h_t)) \frac{\partial \bar{p}(h_t)}{\partial h_t}$$

Rearranging the costs of hedging to the LHS and the marginal gain to the R.H.S we can better interpret the F.O.C for h^*,

$$\underbrace{\gamma h_t^{\eta-1} + \beta \Big[\alpha h_t + \alpha \underbrace{\Big(\frac{E_t[p_{t+1} | p_{t+1} \geq \alpha h_t]}{\alpha} - h_t\Big)}_{(+)/\text{spot prod.}} \underbrace{(1 - F[\alpha h_t])}_{\text{P(spot prod.)}}\Big]}_{\text{marginal cost}} = \underbrace{\beta \Big[\mathcal{F}_t - \underbrace{\Big(V^N(\bar{p}(h_t), S_{t+1}) - V^D(\bar{p}(h_t), S_{t+1})\Big)}_{(+)/\text{cost of defaulting}} \underbrace{\frac{\partial F[\bar{p}(h_t)]}{\partial h_t}}_{(-)}\Big]}_{\text{marginal gain}}.$$

There are two positive effects that occur when a firm hedges observed within the FOC. First, from the envelope conditions we see that the difference, or "gap", between the normal state value and the default state value is decreasing in the firms hedging quantity decision, this effect reduces nominal cost,

$$\frac{\partial}{\partial h_t}\big(V^N(p_{t+1}, S_{t+1}) - V^D(p_{t+1}, S_{t+1})\big) = \alpha q_{t+1} = p_{t+1} - \alpha h_t$$

And the second effect is that hedging reduces the probability of default,

$$\frac{\partial F[\bar{p}(h_t)]}{\partial h_t} = f(\bar{p}(h_t))\frac{\partial \bar{p}(h_t)}{\partial h_t} < 0.$$

Table 1: Historical Episodes in Oil

Episode	Duration (months)	Percentage Drop	Avg. Ann. Volatility	Production Drop
1990-1991	10	57%	38%	9%
1997-1998	23	60%	21%	7%
2001-2002	16	43%	25%	3%
2008-2009	10	76%	32%	17%
2014-2015	18	75%	31%	9%

‘

Figure 1: Estimated Value Function

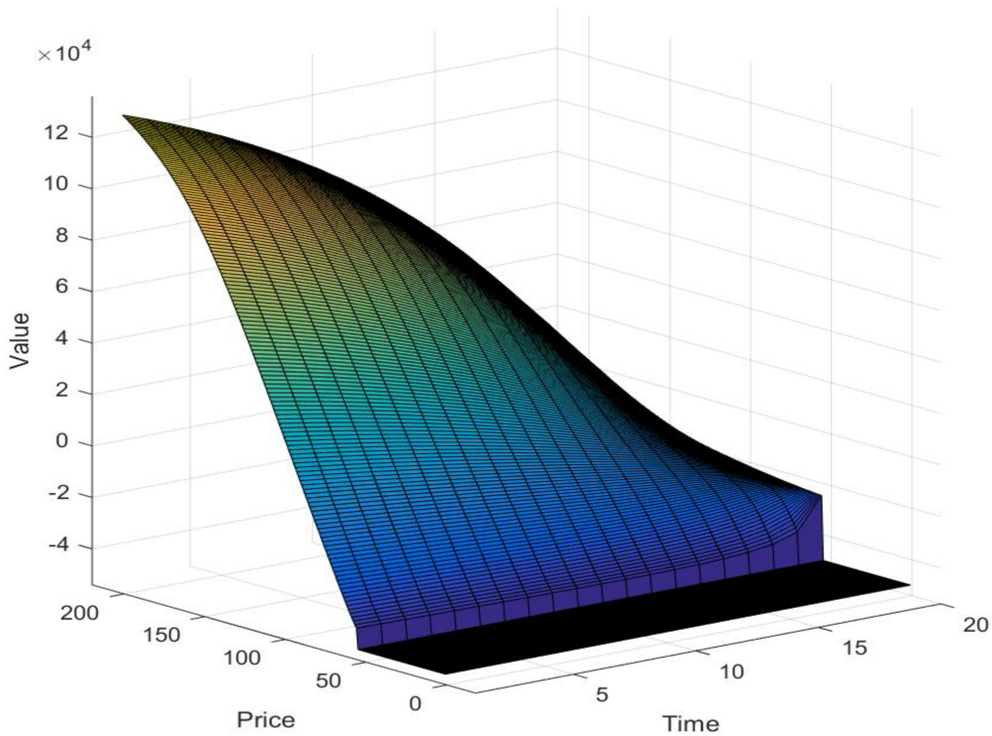


Figure 2: Comparative Statistics Simulation

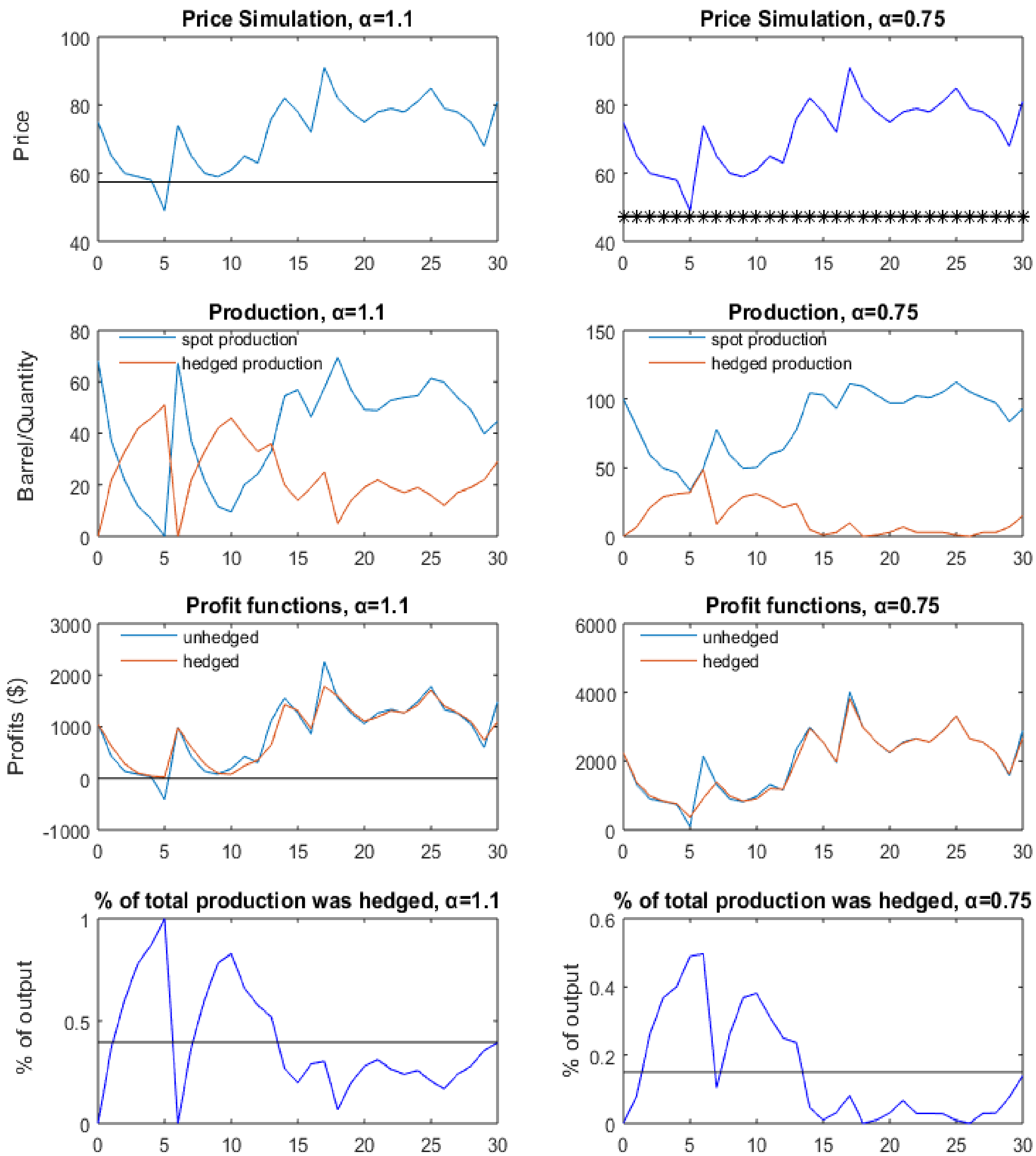
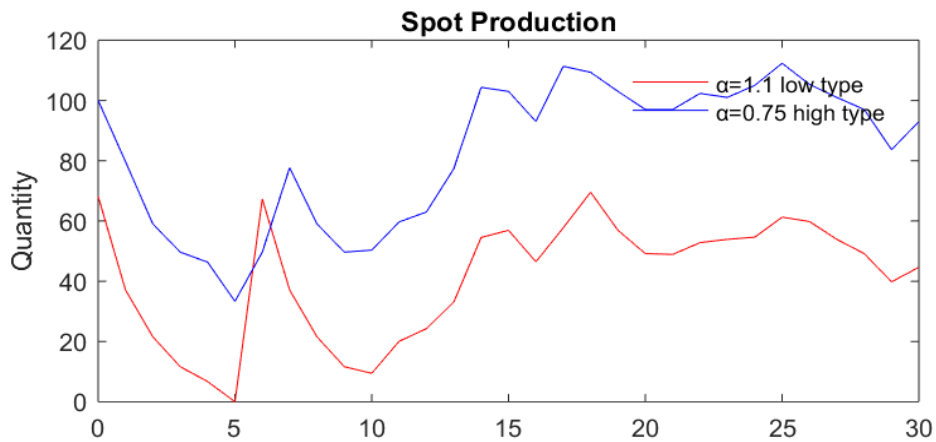


Figure 3: Comparative Statistics Simulation: Production and Hedge Quantities



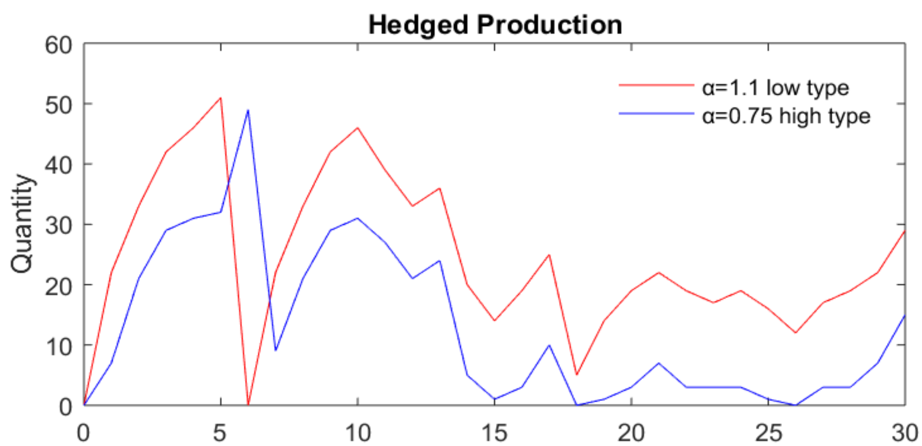


Figure 4: Hedging Demand

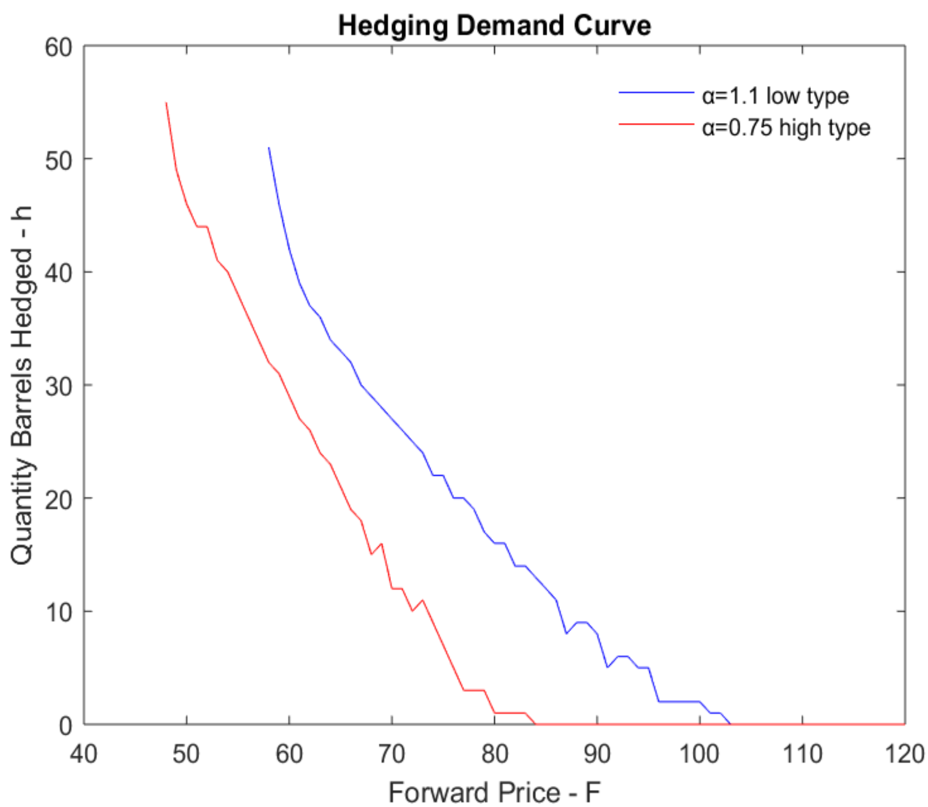


Figure 5: Negative oil demand shock: Hedging positions reported by the CFTC from commercial large oil & gas producers

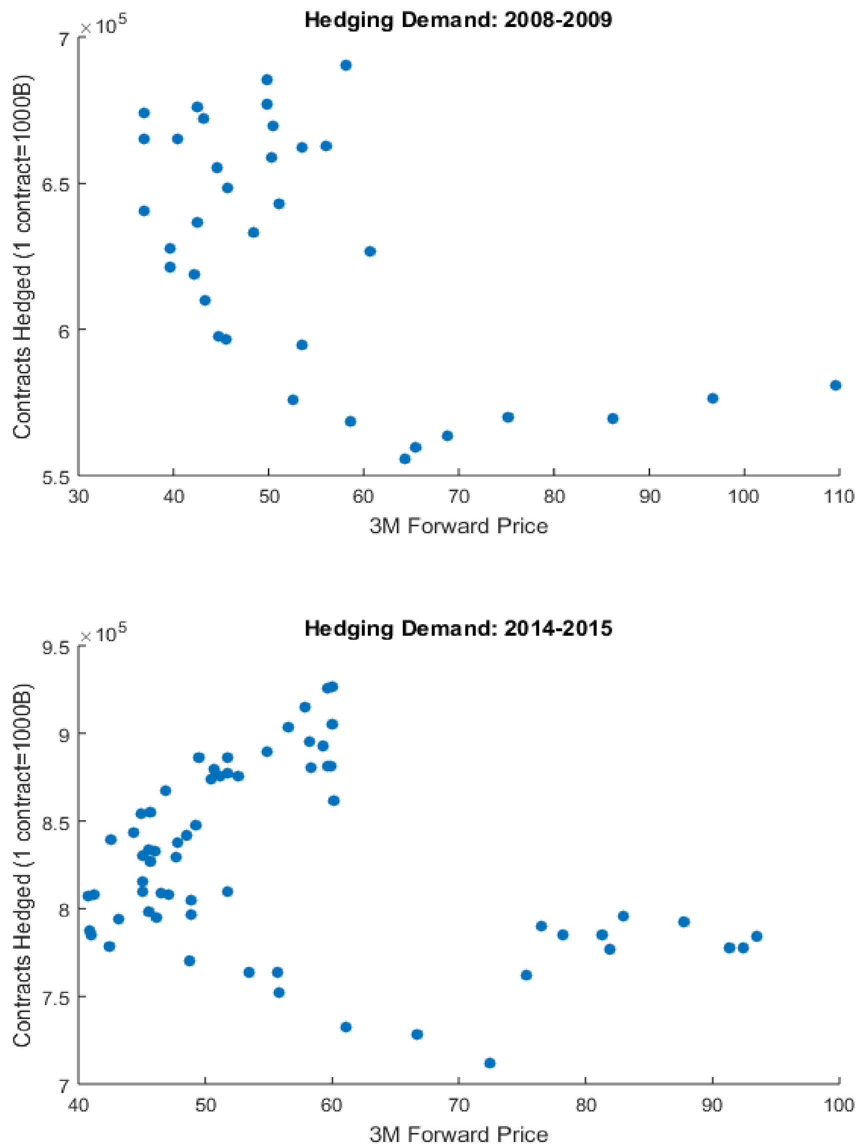


Table 2: Hedge Ratio and Firm Cost Efficiency Statistics

	Sample	Min	Max	Mean	Median	Std. Dev	Mean 95% C.I
Alpha ($\hat{\alpha}$)	23	0.05	4.16	1.12	0.59	1.21	[0.60 , 1.65]
Hedge Ratio ($\hat{h}$)	23	0.06	0.9	0.36	0.36	0.22	[0.26 , 0.49]

Table 3: Cost Efficiency Frequency

Bin	[0,.5]	[.5,1]	[1,1.5]	[1.5,2]	[2,2.5]	[2.5,3]	[3,3.5]	[3.5, 4]	[4. 4.5]
Frequency	34.7%	30%	8.7%	4.3%	4.3%	4.3%	4.3%	4.3%	4.3%

Figure 6: Idiosyncratic cost efficiency and firms hedge ratios

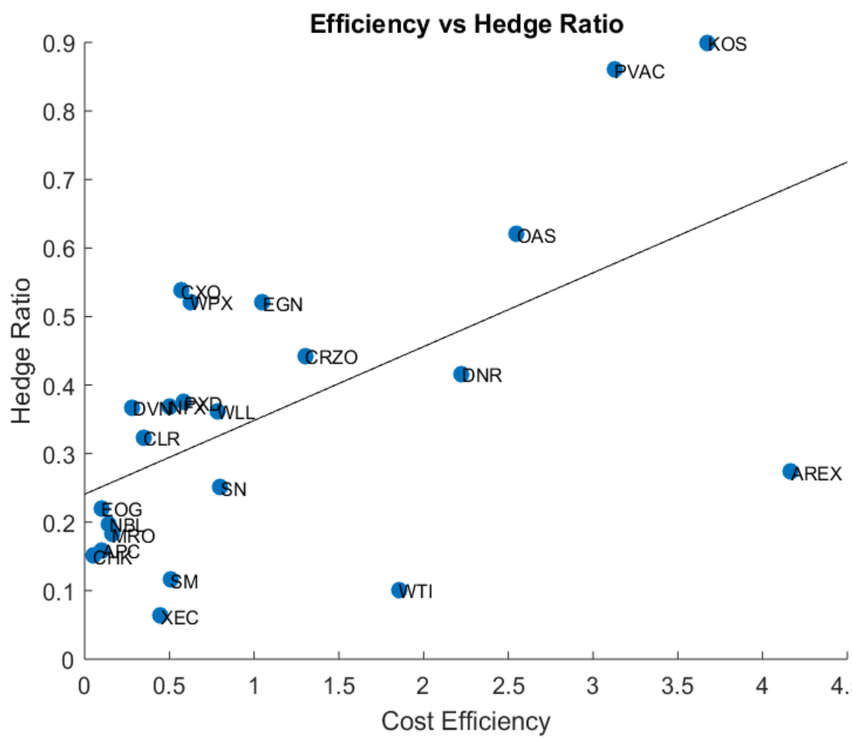


Table 4: Firm Statistics and Production Hedge Ratio

Firm Name	**Symbol**	**Market Cap.** ($B)	**Oper. Mgn.**	**Profit Mgn.**	**Debt/Assets**	**Hedge Ratio** (3 yr avg)
EOG Resources	EOG	$68.5	18%	12%	0.50	22%
Anadarko Petroleum	APC	$36.6	2%	-11%	0.67	29%
Pioneer Natural Resources	PXD	$32.9	17%	9%	0.34	81%
Continental Resources	CLR	$25.63	23%	13%	0.64	61%
Concho Resources	CXO	19.26	25%	32%	0.35	87%
Marathon Oil	MRO	18.36	1%	2%	0.47	27%
Noble Energy	NBL	17.29	9%	-40%	0.51	20%
Cimarex Energy	XEC	8.87	39%	35%	0.49	10%
WPX Energy	WPX	7.2	6%	-21%	0.50	98%
Newfield Exploration	NFX	6.84	32%	17%	0.72	33%
Energen Corporation	EGN	6.24	25%	18%	0.32	89%
Whiting Petroleum Corporation	WLL	4.47	1%	-97%	0.53	52%
Oasis Petroleum	OAS	4.31	17%	-8%	0.47	63%
Chesapeake Energy	CHK	4.13	14%	12%	1.03	18%
Kosmos Energy	KOS	3.15	-4%	-42%	0.72	83%
SM Energy	SM	2.93	5%	-4%	0.61	14%
Carrizo Oil & Gas	CRZO	2.04	35%	10%	0.79	84%
Denbury Resources	DNR	1.88	24%	5%	0.86	67%
Penn Virginia Corporation	PVAC	1.04	40%	5%	0.65	77%
Sanchez Energy Corp	SN	0.335	24%	-8%	1.02	32%
Approach Resources	AREX	0.272	-15%	-40%	0.45	15%