Exploration Activity, Long Run Decisions, and the Risk Premium in Energy Futures

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Recent years have seen the development of increasingly sophisticated technologies for the extraction of natural resources such as hydraulic fracturing through large scale investment.

At the same time, futures curve has turned from being predominantly being downward sloping (backwardation) to predominantly positive sloping (contango).

**Question of Paper:** Is investment activity related to futures slope? Does it affect risk premiums?
Two Economic Variables That Might Explain Oil Futures

E&D Capital Raised Share of GDP

Oil Inventories as a Share of GDP

Oil Inventories as a Share of GDP (Detrended)
What Explains the Futures Relative Basis?

<table>
<thead>
<tr>
<th>No.</th>
<th>$\alpha$</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>-6.36</td>
<td>0.209</td>
<td></td>
<td>0.103</td>
</tr>
<tr>
<td></td>
<td>[-4.382]*</td>
<td>[1.986]*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>-11.203</td>
<td></td>
<td>0.106</td>
<td>0.179</td>
</tr>
<tr>
<td></td>
<td>[-6.095]*</td>
<td></td>
<td>[4.673]*</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>-10.483</td>
<td>0.147</td>
<td>0.912</td>
<td>0.228</td>
</tr>
<tr>
<td></td>
<td>[7.885]*</td>
<td>[2.405]*</td>
<td>[3.859]*</td>
<td></td>
</tr>
</tbody>
</table>

Rel.Basis($t$) = $\alpha + \beta_1(t)$ Inv./GDP($t-1$) + $\beta_2$ New Capital/GDP($t-1$) + $\epsilon(t)$

- Both short-run (inventory) and long-run (E&D) affect the basis
- **Surprisingly** Latter is more important.
- Storage models: Kaldor (1939), Working (1948), Deaton and Laroque (1982), Routledge, Seppi and Spatt (2000) focus on former
- Also obtain similar results for natural gas futures
Futures Relative Basis, Inventory and New Capital for E&D

- E&D helps to explain the upward spikes more than the downward spikes
Roll Return\( (t) \) = \( \alpha + \beta_1(t) \) Inventory\( (t-1) \) + \( \beta_2 \) New Capital Share\( (t-1) \)+\( \epsilon(t) \)

The roll return is defined as:

\[
\text{Roll Return}(t) = \begin{cases} 
- \left( \frac{S(t+4) - F(t)}{F(t)} \right) & \text{if } F(t) > S(t) \\
\left( \frac{S(t+4) - F(t)}{F(t)} \right) & \text{if } F(t) < S(t), 
\end{cases}
\]

where \( F(t) \) is the 1-year futures prices and \( S(t) \) is the spot price of WTI oil in Cushing, Oklahoma.
Statistics of Excess Returns on Alternative Rolling Strategies on Oil Futures

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Mean</th>
<th>Sharpe Ratio</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Futures</td>
<td>0.022</td>
<td>0.362</td>
<td>-0.982</td>
</tr>
<tr>
<td>Unconditional Roll</td>
<td>0.021</td>
<td>0.061</td>
<td>0.067</td>
</tr>
<tr>
<td>Roll Conditioned on Inventory</td>
<td>0.042</td>
<td>0.318</td>
<td>0.059</td>
</tr>
<tr>
<td>Roll Conditioned on E&amp;D Capital</td>
<td>0.109</td>
<td>0.333</td>
<td>0.460</td>
</tr>
</tbody>
</table>

The roll return conditioned on a variable $x$ is defined as:

\[
\text{Roll Return}(t) = \begin{cases} 
- \left( \frac{S(t + 4) - F(t)}{F(t)} \right) & \text{if } x > \bar{x} \\
\left( \frac{S(t + 4) - F(t)}{F(t)} \right) & \text{if } x < \bar{x}
\end{cases}
\]
Returns of Roll Strategies

Long Futures Return

Roll Futures Return

Roll Futures Return Conditioned on Inventory

Roll Futures Return Conditioned on E&D
Distribution of Returns on Roll Strategies
What’s surprising?

- Low frequency component (long-run risk) and high frequency component are both important.
- Business cycle frequency (2-4 years is not). Suggests that commodities pricing cycle is different from business cycle.
Optimal Extraction Models and Storage Models

- Existing models of resource extraction have no storage [e.g. Pindyck (1980), Litzenberger and Rabinowitz (1995), Carlson, Khokker and Titman (2007), Cassasus, Collin-Dufresne, and Routledge (2008), Kogan, Livdan and Yaron (2008)]

- Models with inventory do not have optimal resource extraction [e.g. Deaton and Laroque (1992) and Routledge, Seppi and Spatt (2000)]. Storage model: owner of resource can sell it at strategic points of time, in particular in periods of shortages

- None of these models have exploration activity.

- Here we provide the analysis of a model with production, storage and exploration.
Elements of the Model

- The demand function for the resource at time $t$ is $q_t = f(S_t, \varepsilon_t)$. We set $\varepsilon_0 = 0$, and $\varepsilon_1 = \varepsilon$. The inverse demand function is $s = f^{-1}(q_t; \varepsilon_t)$.

- Pricing kernel of economy is related to energy shocks

$$M_1 = M_0 \cdot \exp(-r - \sigma_M \varepsilon).$$

- Resource is of varying quality. Extraction costs across grades of resources are uniformly distributed $x \in [0, \bar{x}]$.

- Resource that is not extracted in period 0 is available for extraction in period 1.

- Extraction costs are related to amount of capital in industry by function $g(K) = \gamma_0 / (\gamma_1 K)$. In periods where there is low capital production becomes uneconomical.

- New Capital: $K_1 = (1 - \delta) K_0 + l_0$

- Timing: The investment choice is made before any extraction decisions are made.
The Plant’s Optimal Extraction Decision

- **Firm’s objective**

\[
\pi_0 = \max_{l_0>0} \max_{x_0^e \in [0, \bar{x}]} \max_{z_1 \in [0, \frac{x_0^e}{\bar{x}}]} R_0 + Z_0 - Z_1
\]

\[
= \max_{l_0>0} \max_{x_0^e \in [0, \bar{x}]} \max_{z_1 \in [0, \frac{x_0^e}{\bar{x}}]} \frac{x_0^e}{\bar{x}} R_0 + Z_0 - Z_1
\]

\[
- 0.5 \frac{(x_0^e)^2}{\bar{x}} g(K_0) R_0 - P_0 l_0
\]

\[
+ E^Q \left[ e^{-(r+u) \tilde{S}_1} Z_1 \right] + \left( \int_{x_0^e}^{\bar{x}} C(x, g(K_1)|Y_0) \, dx \right) \frac{R_0}{\bar{x}},
\]

- **Optimal extraction choice of firm** \( x \) satisfies:

\[
S_0 - x_0^e g(K_0) = C(x_0^e e^{g(K_1)}|Y_0), \text{ if } 0 < x_0^e < \bar{x},
\]

\[
x_0^e = 0 \text{ if } s(0) g(K_0) < C(0|Y_0),
\]

\[
x_0^e = \bar{x} \text{ if } s(\bar{x}) g(K_0) - \bar{x} > C(\bar{x}|Y_0),
\]

- **The call option is American with an endogenous stock price, which depends on firm level decision on investment and the optimal choices of all plants on extraction**
The Firm’s Optimal Inventory Decision

- Inventory can be used to take advantage of price spikes
- Optimal inventory satisfies:

\[-S_0 + e^{-(r+u)} E^Q[S_1] = 0 \text{ if } 0 < Z_1 < \frac{x^e}{\bar{x}} R_0 + Z_0,\]

\[- < 0 \text{ if } Z_1 = 0,\]

\[- > 0 \text{ if } Z_1 = \frac{x^e}{\bar{x}} R_0 + Z_0.\]
Specializing to the linear demand case: \( q_0 = a - b S_0 \), and \( q_1 = a \cdot e^{m+\sigma \epsilon} - b S_1 \).

Equilibrium at date 1 now requires:

\[
\frac{1}{\bar{X}} (S_1/g(K_1) - x_0^e) R_0 + Z_1 e^{-u} = a e^{\mu+\sigma \epsilon} - b S_1.
\]

Solving for prices

\[
S_0 = \frac{1}{b} \left( a + Z_1 - Z_0 - \frac{x_0^e}{\bar{X}} R_0 \right),
\]

\[
S_1 = \frac{a e^{\mu+\sigma \epsilon} + \frac{x_0^e}{\bar{X}} R_0 - Z_1 e^{-u}}{b + \frac{R_0}{\bar{X} g(K_1)}}.
\]
Model Basis, Firm’s Decision, and Expected Returns

- Futures Price:

\[
F_0 = E^Q[s(Q_1; \epsilon)] = \frac{ae^{\mu - \sigma_M \sigma + 0.5\sigma^2} + \frac{x_0^e}{\bar{x}} R_0 - Z_1 e^{-u}}{b + \frac{R_0}{\bar{x}} g(K_1)}.
\]

- Comparative statics make sense: lower capital, higher extraction costs, less future supply, imply higher future price.

- Risk Premium:

\[
\frac{E[S_T] - F_0}{F_0} = \frac{ae^{\mu + 0.5 \sigma^2} - e^{\mu - \sigma_m \sigma + 0.5 \sigma^2}}{ae^{\mu - \sigma_m \sigma + 0.5 \sigma^2} + \frac{x_0^e}{\bar{x}} R_0 - Z_1 e^{-u}}
\]

- In addition to \(-\sigma_M \sigma\), risk premium depends on firm’s investment policy through its effect on the firm’s production and inventories

- These variables are endogenous and in equilibrium are related to the firm’s investment policy
Call option value:

\[
C(x \, g(K_1)|Y_0) = \frac{a \, e^{-r}}{D} \left[ e^{(\mu - \sigma M \sigma + 0.5 \sigma^2)} N(-d_1) - kN(-d_2) \right],
\]

\[
d_1 = \frac{\log(k^s) - m - \sigma M \sigma - \sigma^2}{\sigma}; \quad d_2 = \frac{\log(k^s) - m - \sigma M \sigma}{\sigma},
\]

\[
k^s = \frac{1}{a} \left( D \times g(K_1) - \frac{x_0^e}{\bar{x}} R_0 + Z_1 e^{-u} \right); \quad D^s = b + \frac{R_0}{\bar{x} \, g(K_1)}.
\]

Inventory:

\[
Z_1(x_0^e) = \frac{e^{r+u}(-a + \frac{x_0^e}{\bar{x}} R_0 + Z_0)(b \, g(K_1) \bar{x} + R_0) + b \, g(K_1) \bar{x}(a \, e^{\mu - \sigma M \sigma + 0.5 \sigma^2} e^{r+u}(b \, g(K_1) \bar{x} + R_0) + e^{-u} b \, g(K_1) \bar{x})}{e^{r+u}(b \, g(K_1) \bar{x} + R_0) + e^{-u} b \, g(K_1) \bar{x}}.
\]

\[
= 0 \text{ if } s(x_0^e|Z_1 = 0) > e^{-(r+u)} F(x_0^e|Z_1 = 0)
\]

\[
= \frac{x}{\bar{x}} R_0 \text{ if } s(x_0^e|Z_1 = \frac{x_0^e}{\bar{x}} R_0 + Z_0) < e^{-(r+u)} F(x_0^e|Z_1 = \frac{x_0^e}{\bar{x}} R_0 + Z_0),
\]
Optimal Decisions, Basis, and Risk Premium
Model Relative Basis, Capital and Investment (2 Regime Model for Demand Shocks)

![Model Relative Basis (\%)](image1)

![Model Capital](image2)

![Model Investment (E&I)](image3)
Roll Returns in Model (2 Regimes)

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<td>0.001</td>
<td>0.000</td>
<td>-0.55</td>
</tr>
<tr>
<td>Unconditional Roll</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.67</td>
</tr>
<tr>
<td>Roll Conditioned on Investment</td>
<td>0.065</td>
<td>0.213</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Roll Return\( (t) \) = \(- \left( \frac{S(t+4) - F(t)}{F(t)} \right) \) \quad \text{If} \ x > \bar{x} \)

\(= \left( \frac{S(t+4) - F(t)}{F(t)} \right) \) \quad \text{If} \ x < \bar{x},\)

where \( x \) is the level of investment in the model.

- Long futures return is close to 0. Not surprising, since we have assumed risk neutrality.
- We get a 6.5 percent return when the roll is conditioned on investment. Why? The model investment predicts the futures basis.
Model Short and Long Run Risk Decomposition

Variance At Alternative Frequencies
We build a model of optimal choice of inventory, extraction, and exploration of resources by energy firms.

Decisions are driven by demand shocks.

Since these are unobservable by the econometrician, she can use optimal decisions to back out firm’s risk premiums.

Model helps to understand relation in data between investment, futures basis, and risk premium.