Demand Effects and Speculation in Oil Markets: Theory and Evidence

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Introduction

- Is there a long-run stable relationship between the price of crude oil and inventories? Should there be?
- Currently there is no agreement on either question (Fattouh et al. 2012, Hamilton 2009, Murphy and Kilian 2012, Singleton 2012)
- Our extension of the canonical commodity storage model predicts a stable relationship between price, inventories, supply and demand
- Our results in this paper show that U.S. oil market monthly data are consistent with the model’s predictions
Theoretical Results (Existing Model, New Application)

- A dynamic, rational expectations model of commodity storage: stable relationships among variables
- The key is demand for oil and its interaction with the supply regime:
  - When supply is unrestricted, demand growth will cause price to rise only temporarily, and inventories should drop
  - When supply is restricted, demand growth will cause a persistent rise in price, and inventories should rise
Empirical Results (This Paper)

- Monthly series of crude oil supply, demand, inventories, and price; cannot reject a unit root for any of them
- Therefore the model’s predicted stable relationship translate empirically to predicted cointegrating vectors among these variables
- We show that these vectors exist in the data, and that the signs of coefficients in the estimated cointegrating equations are consistent with the model’s predictions
We write a theoretical model of the oil market:

- Extension of canonical commodity storage model à la Deaton and Laroque (1992, 1996)
- We introduce growth dynamics into the canonical model
- Model accommodate both stationary and non-stationary stochastic processes
- Focus on intermediaries: how does their behavior change?

Important features:

- Supply of oil is either restricted (increases with technology development) or flexible (accommodates demand shocks fully)
- Cost of storage is positive and fixed
An Extended Commodity Storage Model

- Oil availability $A_t$: amount of oil that can potentially be consumed at time $t$

$$A_t = X_{t-1} + Z_t,$$

- Where $X_{t-1}$ is oil stored from last period, $Z_t$ oil extracted this period (supply)

- Inverse demand function for oil:

$$P_t = P(Q_t, Y_t)$$

- Where $Q_t = A_t - X_t$ is consumption, $Y_t$ is an income variable

- Assume only ratio of consumption to income matters:

$$P_t = P(Q_t, Y_t) = P\left(\frac{Q_t}{Y_t}, 1\right) = p(q_t)$$

- Where lowercase letters denote variables normalized by $Y_t$ ("effective" variables)
Demand: Two Alternative Income Processes

- A simple AR(1) process:

\[
\frac{Y_{t+1}}{Y_t} = \left(\frac{Y_t}{Y_t}\right)^\rho e^{\varepsilon_{t+1}},
\]

where \(\varepsilon_{t+1} \sim N(0, \sigma_{\varepsilon}^2)\) is an iid shock, and \(\overline{Y}_t\) is trend income, increasing over time at rate \(\overline{\mu} > 0\)

- Alternative assumption: income is subject to growth shocks

\[
Y_{t+1} = e^{\mu_{t+1}} Y_t,
\]

such that

\[
\mu_{t+1} = (1 - \phi)\overline{\mu} + \phi \mu_t + \nu_{t+1},
\]

where \(\phi \in (0, 1)\) is a persistence parameter and \(\nu_{t+1} \sim N(0, \sigma_{\nu}^2)\) is an iid shock.
Supply: Two Alternative Regimes

- Supply in our model is non-stochastic.
- Under a "restricted" regime, it grows at the trend income rate $\mu$:
  \[ Z_{t+1} = \tilde{Z} \bar{Y}_t \]
  where $\tilde{Z}$ is a capacity parameter.
- Trend income $\bar{Y}_t$ captures the effects of technological progress:
  - Global ratio of oil production to known reserves has been actually dropping since 1980, currently below 2%.
- Under a "flexible" regime supply fully accommodates demand shocks:
  - AR(1) shocks:
    \[ Z_{t+1} = \tilde{Z} \bar{Y}_t \left( \frac{Y_t}{\bar{Y}_t} \right)^\rho \]
  - Growth shocks:
    \[ Z_{t+1} = \tilde{Z} e^{(1-\phi)\mu + \phi \mu_t} Y_t \]
Determination of Storage

- Storage $X_t$ and equilibrium price $P_t$ are determined together in equilibrium:

$$X_t \geq 0 \iff P_t = \beta E_t[P_{t+1}] - C$$

where $\beta = 1 / (1 + r)$ is the discount factor, $r > 0$ is the exogenously given interest rate, and $C > 0$ denotes per barrel cost of storage.

- Equilibrium price $P_t$ must be such that there is no incentive to increase or decrease $X_t$.

- Alternatively, there could be a stockout:

$$X_t = 0 \iff P_t > \beta E_t[P_{t+1}] - C$$

- In a stockout the storage non-negativity constraint is binding.
- The model therefore has to be solved numerically.
Model Equations

\[ a_{t+1} = \frac{(x_t + z_{t+1})}{e^{\mu_{t+1}}}, \]
\[ \frac{Y_{t+1}}{Y_{t+1}} = e^{\mu_{t+1} - \bar{\mu}} \frac{Y_t}{Y_t}, \]
\[ \mu_{t+1} = (1 - \phi)\bar{\mu} + \phi \mu_t + \nu_t, \]
\[ (a_t - x_t)^{-\gamma} = \beta E_t[P_{t+1}] - C. \]
The Rational Expectations Equilibrium

- Under all four sets of assumptions, equilibrium maintains classic features:
  - Storage rises with effective availability
  - Price declines with effective availability
- We can also see the effect of income growth on storage
- Where supply is unrestricted:
  - Agents calculate that supply will quickly catch up with demand $\Rightarrow P > E[P]$
  - Storage will decrease, flooding the market with extra oil, mitigating price increase
- Where supply is restricted:
  - There is no prospect for supply to accommodate $\Rightarrow P < E[P]$
  - Storage will increase, withdrawing oil from the market, exacerbating price rise
Effect of Availability on Storage Choice and Price

- Storage Rule
- Equilibrium Price
Effect of Income and Availability on Storage Choice

Flexible Supply: Storage by Income

Restricted Supply: Storage by Income
Predictions of the Model:

- The model solution provides a description of a stable equilibrium, even in the presence of growth shocks.
- This implies that a stable relationship between supply, demand, stocks, and price should be present in the data.
- If these series are I(1), then we should be able to find a stationary cointegrating vector.
- Moreover, there should be different cointegrating vectors for periods with restricted vs. unrestricted supply.
Data Description

- All series are monthly (1931/1 - 2011/12) and pertain to the U.S.
- Oil supply: crude oil production (EIA)
- Oil demand: index of overall industrial production (Federal Reserve)
- Oil stocks: commercial inventories of crude oil (EIA)
- Oil price: composite price series of Texas and Oklahoma oil
- We split the series at 1972/12, since our previous work shows a break in both persistence and volatility in either 1972 or 1973.
- We test all series, and cannot reject a unit root in any of them (DF-GLS, at 5%)
Figure 3: 1920/1 - 1972/12

Log Stocks

Log Oil Production

Log Industrial Production

Log Real Price
Figure 4: 1973/1 - 2011/12

Log Stocks

Log Oil Production

Log Industrial Production

Log Real Price
## Johansen Tests for the Existence of Cointegration Vectors

<table>
<thead>
<tr>
<th></th>
<th>Column I</th>
<th>Column II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>1931/5 - 1972/12</td>
<td>1975/1 - 2011/12</td>
</tr>
<tr>
<td><strong>Cointegrating Rank</strong></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td><strong>Trace Statistic</strong></td>
<td>98.89***</td>
<td>28.86</td>
</tr>
<tr>
<td><strong>5% Critical Value</strong></td>
<td>47.21</td>
<td>29.68</td>
</tr>
<tr>
<td><strong>1% Critical Value</strong></td>
<td>54.46</td>
<td>35.65</td>
</tr>
<tr>
<td><strong>Obs.</strong></td>
<td>500</td>
<td>444</td>
</tr>
<tr>
<td><strong>Differenced Lags</strong></td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Tests include a constant and seasonal dummies. Number of lags chosen by HQ information criterion. (***) denotes that the trace statistic for the applicable rank is larger than the 1% critical value. (**) denotes that the trace statistic for the applicable rank is larger than the 5% critical value.
## Long-Run Relationships of Stocks, Production, Demand, and Price

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<td><strong>Period</strong></td>
<td>1931/5 - 1972/12</td>
<td>1975/1 - 2011/12</td>
</tr>
<tr>
<td><strong>ln Stocks(_t)</strong></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>ln Oil_Production(_t)</strong></td>
<td>-6.80*** (1.12)</td>
<td>-1.02*** (0.27)</td>
</tr>
<tr>
<td><strong>ln Industrial_Production(_t)</strong></td>
<td>3.58*** (0.68)</td>
<td>-0.65*** (0.20)</td>
</tr>
<tr>
<td><strong>ln Price(_t)</strong></td>
<td>3.98*** (0.47)</td>
<td>-0.10** (0.04)</td>
</tr>
<tr>
<td><strong>Obs.</strong></td>
<td>500</td>
<td>444</td>
</tr>
<tr>
<td><strong>Differenced Lags</strong></td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>χ(^2)(p-value)</strong></td>
<td>75.54 (&lt;0.0001)</td>
<td>18.27 (0.0004)</td>
</tr>
</tbody>
</table>

Data sources: see text. Three asterisks (***) denote significance at the 1% level, two asterisks (**) denote significance at the 5% level. Standard errors are shown in parentheses. See text for definition of variables. All regressions include a constant and seasonal dummies (not shown).
Discussion of Results

- The existence of a stationary framework for the U.S. oil market seems consistent with the data:
  - Stable long-run relationships between the main variables do appear in monthly data
  - Signs of coefficients in estimated cointegration equations consistent with model’s predictions
    - Before 1973/1 stocks *decrease* as income and price increase
    - After 1975/1 stocks *increase* as income and price increase
    - In both periods stocks decrease as supply increases.

- We can reject the null of I(1) for both cointegrating vectors
- These results are robust to changing lag length, beginning and end months
Estimated Cointegrating Relationship 1931/1 - 1972/12

Predicted cointegrated equation

Date

1930m1 1940m1 1950m1 1960m1 1970m1
Estimated Cointegrating Relationship 1973/1 - 2011/12
## Robustness Check: Long-Run Relationships of Stocks, Production, Demand (Excluding Price)

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<tr>
<td>Period</td>
<td>1931/5 - 1972/12</td>
<td>1975/1 - 2011/12</td>
</tr>
<tr>
<td>$\ln Stocks_t$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\ln Oil_Production_t$</td>
<td>-2.22*** (0.60)</td>
<td>-1.35*** (0.33)</td>
</tr>
<tr>
<td>$\ln Industrial_Production_t$</td>
<td>1.47*** (0.40)</td>
<td>-0.86*** (0.25)</td>
</tr>
<tr>
<td>Obs.</td>
<td>500</td>
<td>444</td>
</tr>
<tr>
<td>Differenced Lags</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$\chi^2$(p-value)</td>
<td>13.86 (0.001)</td>
<td>16.93 (0.0002)</td>
</tr>
</tbody>
</table>

Data sources: see text. Three asterisks (*** ) denote significance at the 1% level, two asterisks (**) denote significance at the 5% level. Standard errors are shown in parentheses. See text for definition of variables. All regressions include a constant and seasonal dummies (not shown).
Robustness Check: Global Long-Run Relationships

<table>
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<th>Period</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975/4 - 2011/12</td>
<td>1975/1 - 2011/12</td>
</tr>
<tr>
<td>In OECD_Stocks&lt;sub&gt;t&lt;/sub&gt;</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>In World_Oil_Prod&lt;sub&gt;t&lt;/sub&gt;</td>
<td>0.56*** (0.18)</td>
<td>-</td>
</tr>
<tr>
<td>In Non_Opec_Oil_Prod&lt;sub&gt;t&lt;/sub&gt;</td>
<td>-</td>
<td>0.02 (0.15)</td>
</tr>
<tr>
<td>In OECD_Ind_Prod&lt;sub&gt;t&lt;/sub&gt;</td>
<td>-0.65*** (0.08)</td>
<td>-0.34*** (0.07)</td>
</tr>
<tr>
<td>In Price&lt;sub&gt;t&lt;/sub&gt;</td>
<td>-0.02 (0.02)</td>
<td>-0.01 (0.02)</td>
</tr>
<tr>
<td>Obs.</td>
<td>441</td>
<td>441</td>
</tr>
<tr>
<td>Differenced Lags</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\chi^2$ (p-value)</td>
<td>196.80 ($&lt;0.0001$)</td>
<td>87.76 ($&lt;0.0001$)</td>
</tr>
</tbody>
</table>

Data sources: see text. Three asterisks (***') denote significance at the 1% level, two asterisks (**) denote significance at the 5% level. Standard errors are shown in parentheses. See text for definition of variables. All regressions include a constant and seasonal dummies (not shown).
Conclusion

- We build on our extended storage model which features non-stationary processes and supply regime changes.
- The model predicts the existence of stable long-run relationships among oil market variables: production, inventories, and demand, with price co-determined.
- An application to the U.S. oil market: stable long-run relationships show up in monthly data.
- Relationship changes with the 1973 crisis, in a way that is consistent with the model:
  - Before 1973/1 crude oil inventories decrease as income (and price) increase.
  - After 1975/1 crude oil inventories increase as income (and price) increase.
- Results are robust to changes in specification (changes in lag order, start and end dates, exclusion of price variable).
- OECD stocks and industrial production also exhibit a long-run relationship with the expected signs.