Hotelling Under Pressure

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Presented by Matt Woerman

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Hotelling (1931)

Hotelling's Rule for non-renewable resource extraction

- Choose quantity in each time period to maximize the present value of the resource (or a "cake-eating problem")

$$\max_{q(t)} \int_0^T U\left[q(t)\right] e^{-rt} dt$$

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$$\max_{q(t)} \int_0^T U\left[q(t)\right] e^{-rt} dt$$

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- Empirical evidence generally does not support the Hotelling's Rule

Preview of Results

Texas oil industry over 1990-2007

- Observed patterns of oil production and prices are not consistent with Hotelling's Rule
- Constraints exist on well-level oil production

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Model of oil well drilling and oil production

- Hotelling model recast as a well-drilling investment problem ("keg-tapping problem," not a "cake-eating problem")
- Production from drilled wells is insensitive to oil prices
- Drilling of new wells and drilling rig rental prices respond strongly to oil price shocks

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Data

Oil production and well drilling

- Texas Railroad Commission, 1990-2007
- Date and location of every well drilled
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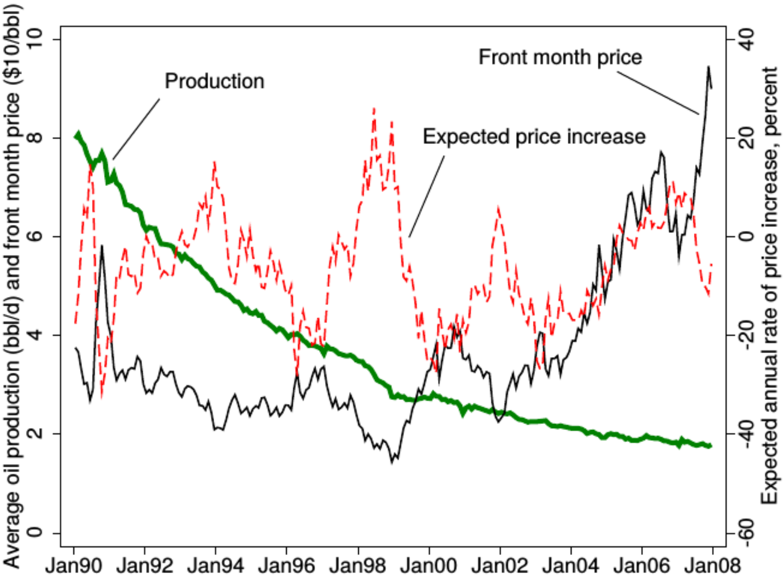
Oil prices

- New York Mercantile Exchange, 1990-2007
- West Texas Intermediate crude oil delivered in Cushing, Oklahoma
- Front-month futures price
- Longer-term futures prices

Oil Prices and Production from Existing Wells



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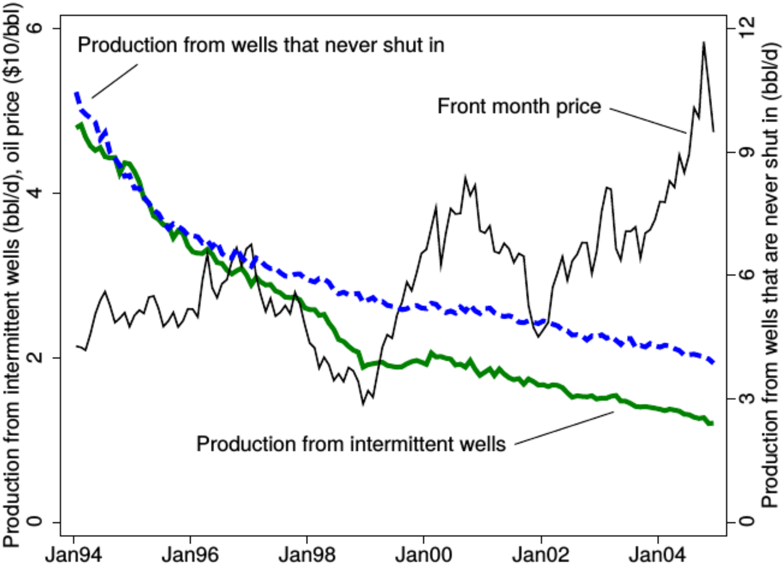
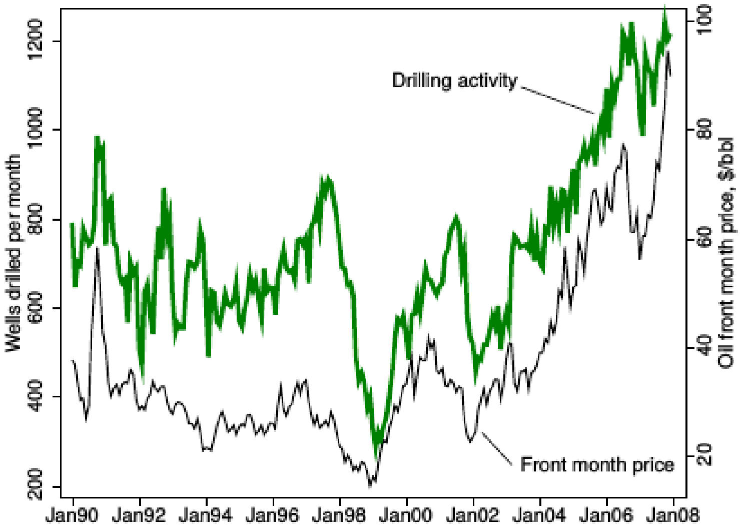


Oil Price and Well Drilling



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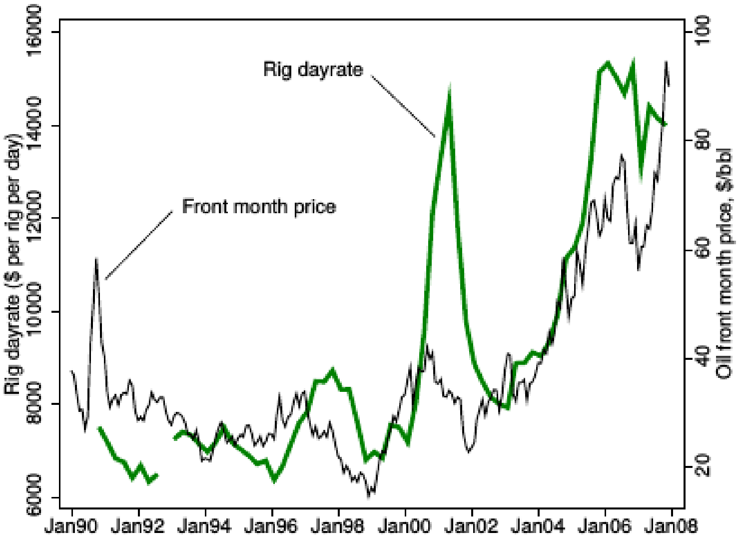

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- Rate of production from a well is physically constrained, and the constraint asymptotically declines to zero
- Marginal cost of production is small relative to oil prices
- Fixed costs of operating a producing well are non-zero; there may also be costs for restarting a shut-in well, but not too large to be overcome
- Drilling rigs are fixed in the short-run; higher prices are required to attract more rigs, leading to an upward-sloping supply curve

Ruling Out Possible Explanations

Leasing agreements require non-zero production

- Multiple-well leases show the same results

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Well-specific production quotas

- Production quotas are not binding

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Producer myopia or misaligned price expectations

- Producers respond to high futures prices by stockpiling drilled oil

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Planner's Problem

$$\max_{F(t),a(t)} \int_0^\infty e^{-rt}\left[U(F(t)) - D(a(t))\right] dt$$

$$\begin{aligned}
\text{subject to } 0 \leq F(t) &\leq K(t) \\
a(t) &\geq 0 \\
\dot{R}(t) &= -a(t), R_0 \text{ given} \\
\dot{K}(t) &= a(t)X - \lambda F(t), K_0 \text{ given}
\end{aligned}$$

$$\begin{aligned}
\text{where } F(t) &= \text{rate of oil flow} \\
a(t) &= \text{rate at which new wells are drilled} \\
K(t) &= \text{constraint on oil flow} \\
R(t) &= \text{measure of wells that remain untapped} \\
U(\cdot) &= \text{instantaneous utility function} \\
D(\cdot) &= \text{cost of drilling wells} \\
X &= \text{maximum flow from a new well} \\
\lambda &= \text{scaling constant}
\end{aligned}$$

Solution to Planner's Problem

Current-value Hamiltonian

$$H = U(F(t)) - D(a(t)) + \theta(t)[a(t)X - \lambda F(t)] + \gamma(t)[-a(t)] + \phi(t)[K(t) - F(t)]$$

where $\theta(t)$ = co-state variable on $K(t)$

$\gamma(t)$ = co-state variable on $R(t)$

$\phi(t)$ = shadow value of the oil flow constraint

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where $\theta(t) =$ co-state variable on $K(t)$

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Selected necessary conditions

$$F(t) \geq 0, U'(F(t)) - \lambda\theta(t) - \phi(t) \leq 0, \text{c.s.}$$

$$a(t) \geq 0, \theta(t)X - d(a(t)) - \gamma(t) \leq 0, \text{c.s.}$$

$$\dot{\theta}(t) = -\phi(t) + r\theta(t)$$

$$\dot{\gamma}(t) = r\gamma(t)$$

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$$\dot{\theta}(t) = -\phi(t) + r\theta(t)$$

$$\dot{\gamma}(t) = r\gamma(t)$$

Also a competitive equilibrium outcome

- $U'(F(t)) = p(t)$

Implications for Oil Production

$$F(t) \geq 0, U'(F(t)) - \lambda\theta(t) - \phi(t) \leq 0, \text{c.s.}$$

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Interpretation of terms

- $\theta(t)$ is the present discounted shadow value of capacity

$$\theta(t) \geq \int_t^{\infty} U'(F(\tau))e^{-(r+\lambda)(\tau-t)}d\tau$$

- $\lambda\theta(t)$ is the opportunity cost of increased production

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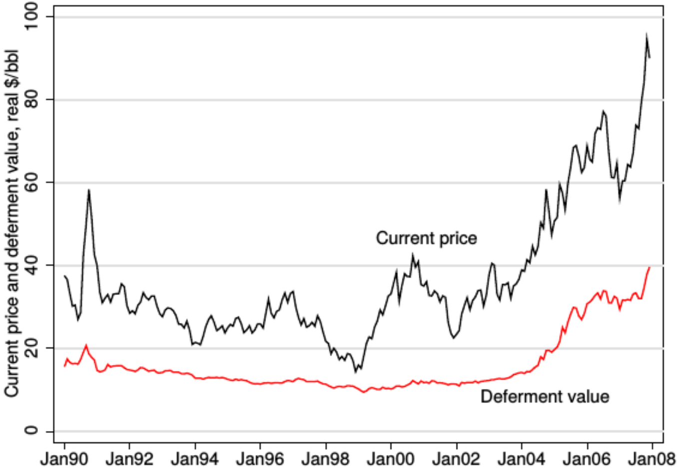
Implications

- If oil prices are expected to rise slower than r, $U'(F(t)) > \lambda\theta(t)$
- If oil prices are expected to rise faster than r forever, $U'(F(t)) = \lambda\theta(t)$
- If oil prices are expected to temporarily rise faster than r, firms want to defer production but cannot due to capacity constraint

Implications for Oil Production



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If oil flow constraint is not binding

$$U'(F(t)) = \lambda\theta(t)$$
$$\dot{\theta}(t) = r\theta(t)$$

- $\theta(t)$ and $U'(F(t))$ both increase at r
- Oil price increases at r

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When production is unconstrained, this model gives Hotelling's Rule

Implications for Oil Well Drilling

$$a(t) \geq 0, \theta(t)X - d(a(t)) - \gamma(t) \leq 0, \text{c.s.}$$
$$\dot{\gamma}(t) = r\gamma(t)$$

Implications for Oil Well Drilling

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Interpretation of terms

- $\gamma(t)$ is the shadow value of the marginal undrilled well
- $\theta(t)X$ is the value of capacity created by drilling a new well
- $d(a(t))$ is the marginal cost of drilling a new well

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Implications

- When well drilling occurs

$$\theta(t)X - d(a(t)) = \gamma(t) = \gamma_0 e^{rt}$$

- Returns to well drilling increase at r

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When drilling occurs, oil well drilling (but not necessarily oil production) is governed by Hotelling's Rule

Implications for Oil Production and Well Drilling

If drilling occurs and production is constrained

$$U'(F(t)) - \left[\frac{(r+\lambda)d(a(t))}{X} - \frac{d'(a(t))\dot{a}(t)}{X}\right] = \frac{\lambda\gamma_0}{X}e^{rt}$$

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If drilling costs are affine rather than convex

$$U'(F(t)) - \frac{(r+\lambda)d(a(t))}{X} = \frac{\lambda\gamma_0}{X}e^{rt}$$

- Standard Hotelling's Rule for barrel-by-barrel extraction
- Assumptions required to get this result are unrealistic

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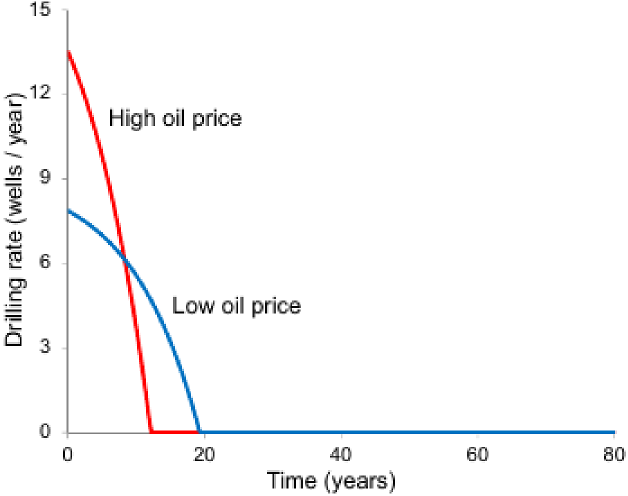
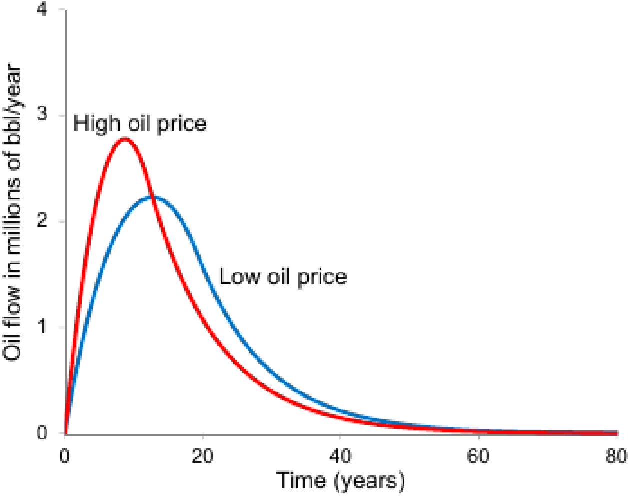
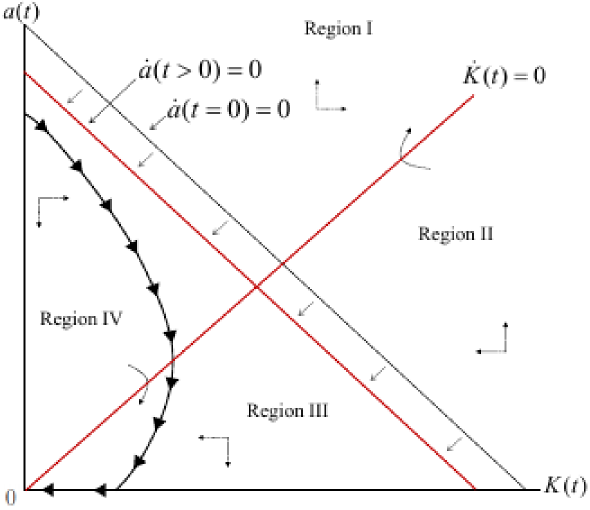
Oil Well Drilling with Exogenous Oil Prices



Oil Production with Exogenous Oil Prices



Phase Diagram with Endogenous Oil Prices



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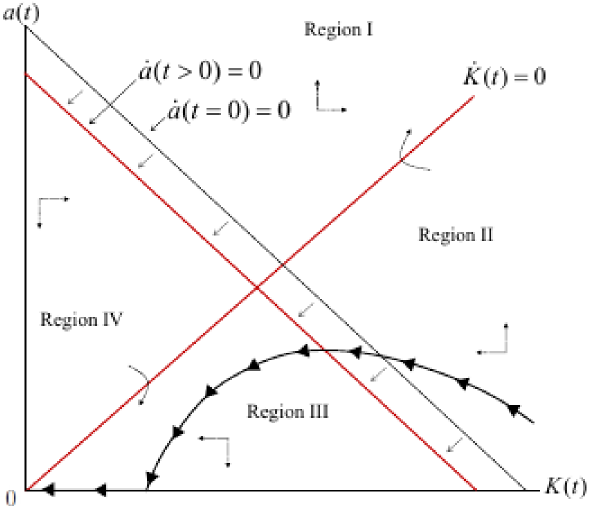
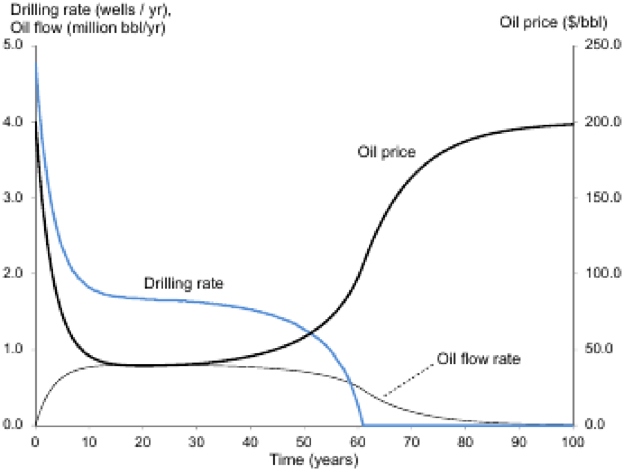


Equilibrium Paths



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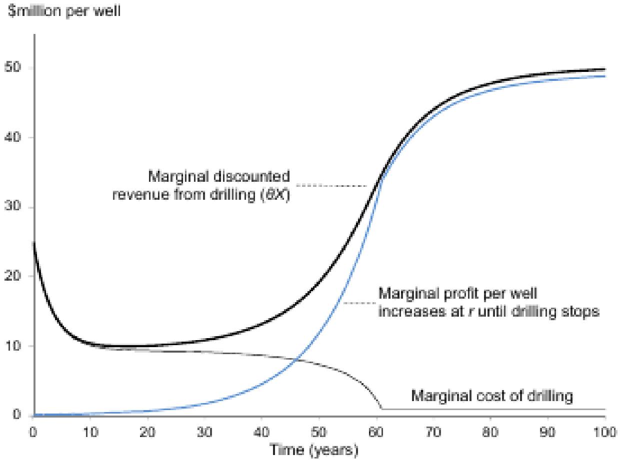
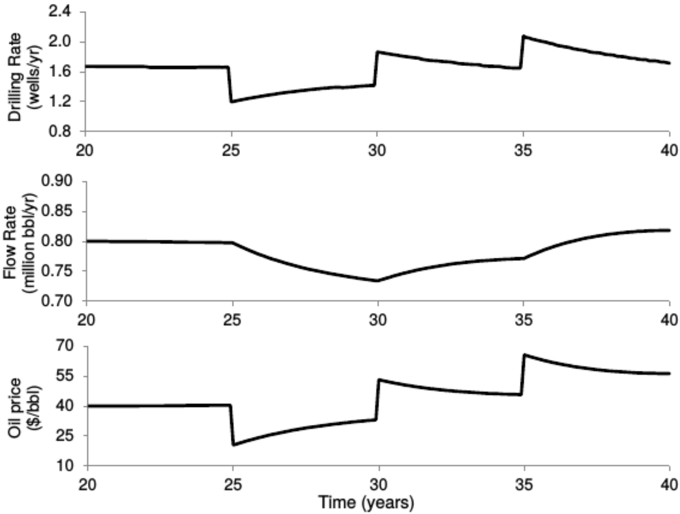


Equilibrium Model with Demand Shocks



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Conclusions

Empirical evidence from the Texas oil industry does not support Hotelling's Rule

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- Oil production always occurs at capacity and does not respond to oil prices
- Oil well drilling responds to oil prices

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New model of exhaustible resource extraction

- Production from existing wells declines asymptotically and does not respond to oil prices
- Drilling of new wells and drilling rig rental rates strongly co-vary with oil prices
- Local oil-producing regions exhibit production peaks
- Expected future oil prices can be backwardated after positive demand shocks and can rise faster than the interest rate after negative demand shocks