Dynamic Competition in Electricity Markets

Hydropower and Thermal Generation

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Introduction

- Competition between hydro and thermal electricity generators.
- Examples:
  - Ontario
  - Norway (98%), New Zealand (80%), Brazil (97%)
  - Quebec, Manitoba ?
- Hydro:
  - Low marginal production cost.
  - Dynamics: water use across periods.
  - Difficult to increase capacity.
- Thermal:
  - Higher marginal production cost.
  - Capacity constraint.

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This paper

- Dynamic game between hydro and thermal power generators facing stochastic demand.
- Questions:
    - How does asymmetric nature of technologies affect competition?
    - Distribution of price?
    - Thermal producer's incentives to increase capacity?
- Two variations on model:
    - Infinite horizon game.
    - Two-period game.

Previous work

Papers with mixed hydro – thermal generation:

- Crampes and Moreaux (IJIO 2001)
- Bushnell (OR 2003)
- Scott and Reid (ITOR 1996)
- Ambec and Doucet (CJE 2003) — hydro duopoly.

Results

- Duopoly outcome can be “nearly efficient” in terms of average levels of outcomes — depending on capacities.
- Duopoly prices are “too smooth”.
- Incentive for hydro producer to strategically withold water.
- Thermal capacity choice: incentive to overinvest relative to open-loop.

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Model (Infinite Horizon)

- Inverse demand:

$$P_t = D_t - \beta(h_t + q_t), \qquad D_t \sim N(\mu, \sigma^2)$$

- Water dynamics:

$$W_{t+1} = (1-\gamma)(W_t - h_t) + \omega.$$

- Hydro production: Zero production costs and

$$0 \leq h_t \leq W_t$$

- Hydro payoff:

$$E_0 \sum_{t=0}^{\infty} \delta^t \left[(D_t - \beta(h_t + q_t))h_t\right]$$

- Thermal production: $C(q_t) = c_1 q_t + (c_2/2)q_t^2$

$$0 \leq q_t \leq K$$

- Thermal payoff:

$$E_0 \sum_{t=0}^{\infty} \delta^t \left[(D_t - \beta(h_t + q_t))q_t - c_1 q_t - (c_2/2){q_t}^2 \right]$$

Feedback Equilibrium

- Feedback strategies:

$$h_t = \sigma^H(D_t, W_t)$$

$$q_t = \sigma^T(D_t, W_t)$$

- Thermal producer faces “static” problem ⇒

$$\sigma^T(D_t, W_t) = \max\left[0, \min\left[\frac{D_t - c_1 - \beta\sigma^H(D_t, W_t)}{2\beta + c_2}, K\right]\right]$$

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Hydro producer's problem

- Bellman equation:

$$V(D_t, W_t) = \max_{h_t \in [0, W_t]} \Big\{ (D_t - \beta(h_t + \sigma^T(D_t, W_t)))h_t \\ + \delta E_t V(D_{t+1}, W_{t+1}) \Big\}$$

subject to $W_{t+1} = (1-\gamma)(W_t - h_t) + \omega$.

- Optimal h_t:

$$\psi(h_t) + b_{0t} - b_{Wt} = 0$$

where

$$\psi(h_t) = D_t - 2\beta h_t - \beta\sigma^T(D_t, W_t) \\ - \delta(1-\gamma)E_t V_W(D_{t+1}, (1-\gamma)(W_t - h_t) + w).$$

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Strategic water usage:

- We show

$$E_t V_W(D_{t+1}, W_{t+1}) = E_t\Bigg[-\beta \sum_{s=t+1}^{\infty} \delta^s (1-\gamma)^s h_s \sigma_W^T(D_s, W_s) + \sum_{s=t+1}^{\infty} \delta^s (1-\gamma)^s b_{Ws}\Bigg]$$

- Strategic witholding of water if $\sigma_W^T < 0$.

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Numerical algorithm

- Solve via collocation method.
- Approximate $E_t V(.,.)$:

$$E_t V(D_{t+1}, W_{t+1}) \approx \sum_{i=1}^{n} d_i \phi_i(W_{t+1}) \equiv \tilde{V}(W_{t+1})$$

- $\phi_i()$ are Chebyshev polynomials.

Numerical application

- $c_1 = 0, c_2 = 1.0,\ \delta = 0.9,\ \gamma = 0.3,\ \mu = 10.0,\ \beta = 1.0,\ \sigma = 1.0.$
- "large" thermal capacity: $K = 4.0$.
- Three levels of water inflow:
  - Low: $\omega = 1.0$
  - Medium: $\omega = 4.0$ — hydro's "static" Cournot output.
  - High: $\omega = 5.0$ — 2.5 s.d. above "static" hydro output.
- Note: "static" Cournot output: $h = 4.0,\ q = 2.0$.

Simulation Statistics

	Low inflow		Medium inflow		High Inflow	
	Duopoly	Efficient	Duopoly	Efficient	Duopoly	Efficient
$E(h)$	1.00	1.00	3.78	4.00	4.00	5.00
$E(q)$	3.00	3.96	2.07	2.99	2.00	2.50
$E(p)$	6.00	5.04	4.14	3.00	4.00	2.50
st.dev.(p)	0.67	0.92	0.44	0.51	0.40	0.49
skew(p)	0.02	0.34	0.23	0.25	0.00	0.13
$\%\ h = W$	0.994	0.997	0.039	0.988	0.000	0.969
$\%\ q = K$	0.001	0.840	0.000	0.022	0.000	0.001
$E\Pi^T$	137.0	122.1	65.3	46.6	60.7	32.7
$E\Pi^H$	60.1	50.5	158.6	120.5	162.0	125.4
E(Welfare)	277.8	295.7	397.4	413.3	405.0	440.9

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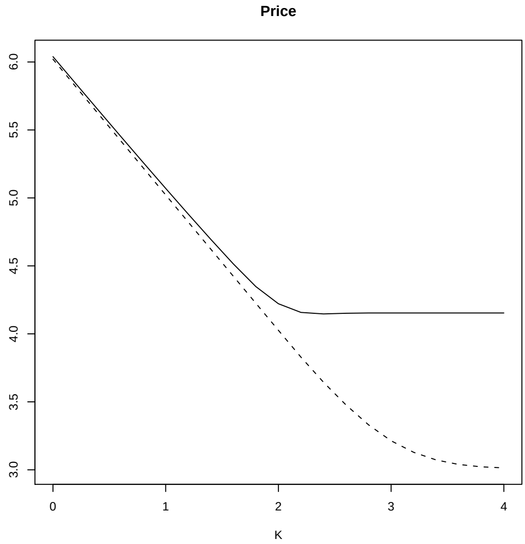
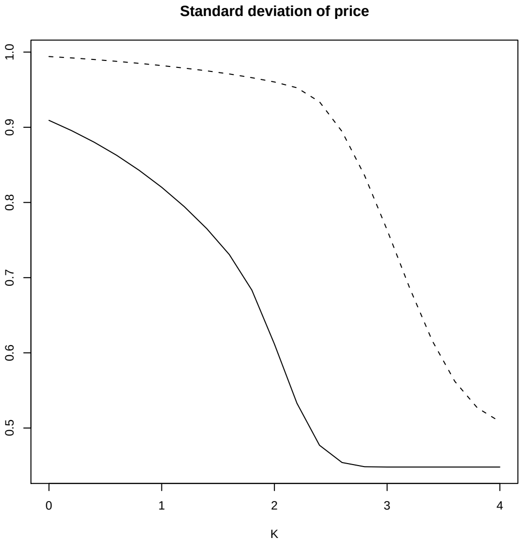
Effects of Thermal Capacity

- Vary K from 0.1 to 4.0.
- Water inflow at medium level: $\omega = 4.0$.
- Plot averages from 100 runs of 1,000 period simulations.

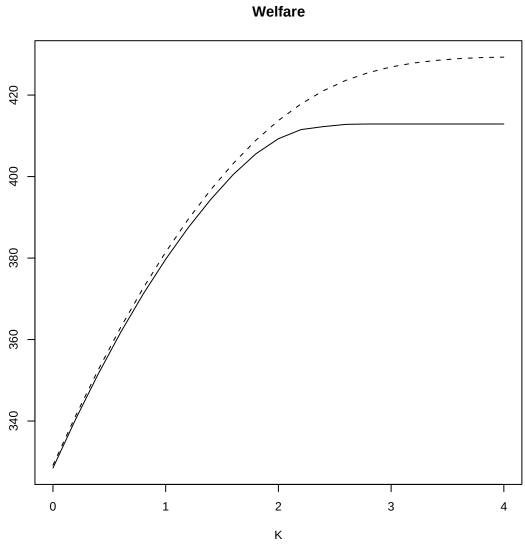
Average Price



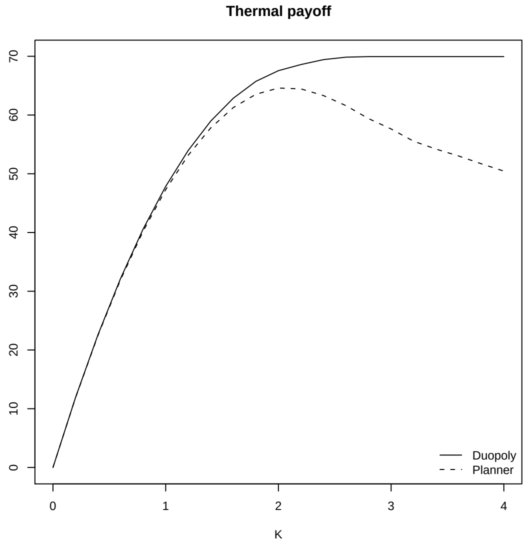
Price Volatility



Welfare



Thermal Payoff



Two-period game with thermal investment

- Uncertain demand in second period.
- Thermal producer can invest to increase capacity in first period.
- Sufficient water that hydro producer is unconstrained.
- Sufficient thermal capacity that thermal producer is not always constrained.
- Compare S-adapted Open-Loop equilibrium with Closed-Loop equilibrium.

Two-period game: results

- Strategic incentive to increase thermal capacity results in higher level of capacity than in open-loop.
- Equilibrium investment may be higher or lower than efficient.
  - $W \to 0$: underinvestment (thermal monopoly).
  - $W \to \infty$: overinvestment.
  - Suggests a point where investment is efficient?

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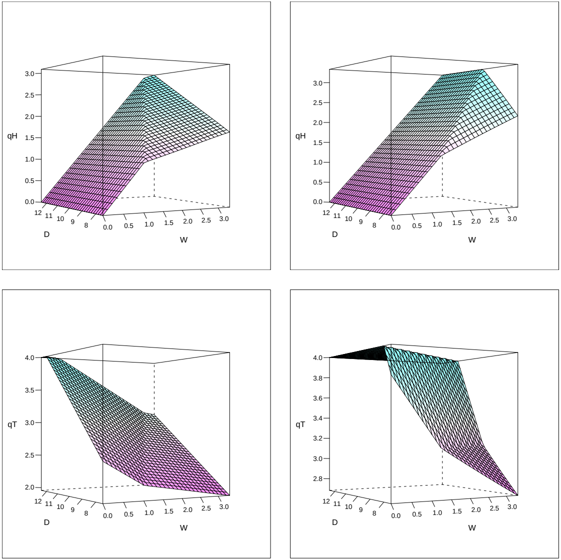
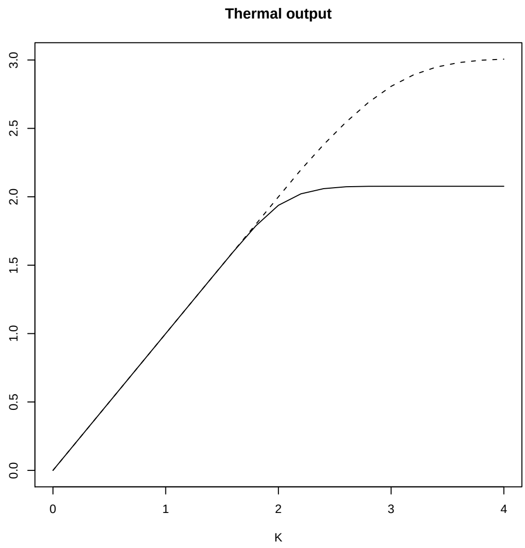
Thank You

Strategies: Duopoly (left), Planner (right)



Averge Thermal Production



Average Hydro Production