Water Scarcity, Market Power and Reservoir Management in a Hydro Based Electricity Market Evidence from New Zealand

Oliver Browne¹

¹Department of Economics, The University of Chicago
obrowne@uchicago.edu
home.uchicago.edu/~obrowne

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Outline:

2 Parts:

1. Theory of hydro generator behaviour and water valuation
2. Estimate the implied value of water and risk of shortage from firm behaviour
Market Power in Hydro Markets

Features of Hydroelectric power

- Generation is flexible in short and medium term.
- Fuel free and storable, but arrival is uncertain and seasonal.
- Storage capacity is limited
- Local environmental costs which constrain operation of existing stations and investment new plants.
- Necessary for reliability in many countries.

These conditions make hydro operation both dynamic and susceptible to market power.
Static Model:

Monopolist’s (Oligopolist’s) Problem:

$$\max_{q_1,\ldots,q_T} \sum_{t=1}^{T} \beta^t p_t(q_t|Q_{-i,t}) q_t$$

s.t

$$\sum q_t = \sum f_t$$

$$q \leq q \leq \bar{q}$$

Social Planner’s Problem:

$$\max_{q_1,\ldots,q_T} \sum_{t=1}^{T} \beta^t \int_{q=0}^{Q_t} p_t(q) dq$$

s.t

$$\sum q_t = \sum f_t$$

$$q \leq q \leq \bar{q}$$
Static Model: Implications

1. Opportunity cost of water is constant across time and equal to the shadow value of additional inflows

\[ WV_t = \lambda \text{ for all } t \]

2. Monopolist attempts to equalize marginal revenue across periods

\[ MR^M_1(q_1|Q_{-i,1}) = MR^M_2(q_2|Q_{-i,2}) = \ldots = MR^M_T(q_T|Q_{-i,T}) = WV \]

3. Planner attempts to equalize price across periods

\[ p^P_1(Q_1) = p^P_2(Q_2) = \ldots = p^P_T(Q_T) = WV \]

4. Market Power is exercised by shifting generation from periods with more elastic demand to less elastic.

\[ \varepsilon_t \geq \varepsilon_T \iff \frac{q^M_t}{q^M_T} \geq \frac{q^P_t}{q^P_T} \]
Water Scarcity and Electricity Prices

Figure: Correlation between prices and lake levels
Stochastic Dynamic Model

- Future inflows uncertain and have distribution \( f \sim F(x, t) \)
- Constrained Lake Capacity \( L_{t+1} \leq \bar{L} \)

**Monopolist’s Problem:**

\[
V_t(L_t) = \max_{q_i, t} p(q_{i,t} | Q_{-i,t}) q_{i,t} + \beta \mathbb{E}_{f_{t+1}} V_t(L_{t+1})
\]

\[\text{s.t } 0 \leq L_{t+1} \leq \min(L_t - q + f_{t+1}, \bar{L})\]
\[q \leq q \leq \min(\bar{q}, \bar{L})\]

**Social Planner’s Problem**

\[
V_t(L_t) = \max_{q_i} \int_{q=0}^{Q_t} p(\sum q) dq + \beta \mathbb{E}_{f_t} V_t(L_{t+1})
\]

\[\text{s.t } 0 \leq L_{t+1} \leq \min(L_t - q + f_t, \bar{L})\]
\[q \leq q \leq \min(\bar{q}, \bar{L})\]
Model Predictions:

1. Opportunity Cost of Water reflects expected marginal benefits in the future

\[ WV_{t|L_t}(q_T) \equiv \frac{d}{dq_t} \beta \mathbb{E}_{f}(f) V_{t+1}(\min(L_t - q + f, \bar{L})) \]

2. Monopolist use Lerner’s Rule to mark-up above their opportunity cost (if interior solution)

\[ p_t(q) = \frac{1}{1 + \varepsilon^{RD}(q)} WV_t(q|L_t) \]

3. Planner Sells at their opportunity cost \( p_t(q) = WV_t(q|L_t) \)

4. Opportunity Cost of Water increases with current lake level and expected future inflows

\[ \frac{\partial WV_t(q|L)}{\partial L} \leq 0 \text{ and } \frac{\partial WV_t(q|L)}{\partial L} \leq 0 \]

5. As the storage capacity becomes arbitrarily large, the probability of capacity constraints binding goes to zero and the opportunity cost of water is constant across time and states.
Estimating the Opportunity Cost of Water

- Construct Residual Demand Curves using half hourly bid and offer data.
- Smoothed residual demand curve reflects ex-ante uncertainty over electricity demand / rival offers.
- Within each week, isolate all periods when generator capacity constraint and environmental constraints do not bind.
- Use elasticity of residual demand curve and Lerner’s rule to infer implied Opportunity Cost of Water

\[
WV_t(q|L_t) = (1 + \varepsilon^{RD}(q))p_t(q)
\]

- Average over all hours in week
Figure: Example of bid and offer curves
Constructing Residual Demand

Figure: Example Residual Demand Curve and Smoothing
How does the opportunity cost of water vary?

Figure: Storage Difference vs Implied Water Value
Figure: Series of Market Price and Hydro Cost
Empirical Regression Model of Opportunity Cost:

\[ y_{i,w,y} = \alpha + \beta_1 l_{i,t} + \beta_2 l_{-i,t} + \beta_3 E_{f_i,t+1} + \beta_4 E_{-i,t+1} - f_{-i,t+1} + \gamma w + \gamma y + \epsilon_{i,w,y} \]

<table>
<thead>
<tr>
<th></th>
<th>p</th>
<th>cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Meridian Water Stock</td>
<td>-237.745***</td>
<td>-233.869***</td>
</tr>
<tr>
<td>Other Water Stock</td>
<td>-235.244***</td>
<td>-237.185***</td>
</tr>
<tr>
<td></td>
<td>(43.431)</td>
<td>(41.947)</td>
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<tr>
<td>Meridian Inflows</td>
<td>0.031</td>
<td>0.027</td>
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<tr>
<td></td>
<td>(0.070)</td>
<td>(0.030)</td>
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<tr>
<td>Other Inflows</td>
<td>0.172</td>
<td>-0.012</td>
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<tr>
<td></td>
<td>(0.142)</td>
<td>(0.061)</td>
</tr>
<tr>
<td>Meridian Forecast Inflows</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>(0.011)</td>
<td>(0.005)</td>
</tr>
<tr>
<td>Other Forecast Inflows</td>
<td>0.048*</td>
<td>-0.004</td>
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<tr>
<td></td>
<td>(0.029)</td>
<td>(0.012)</td>
</tr>
<tr>
<td>Observations</td>
<td>219</td>
<td>219</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.552</td>
<td>0.554</td>
</tr>
<tr>
<td>Residual Std. Error (df = 162)</td>
<td>42.867</td>
<td>42.740</td>
</tr>
<tr>
<td>F Statistic (df = 56; 162)</td>
<td>5.793***</td>
<td>5.844***</td>
</tr>
</tbody>
</table>

Note: *p<0.1; **p<0.05; ***p<0.01
Empirically Observed Policy Function

- Optimal policy function inferred using Lerner’s rule and opportunity cost of water

\[ q_i^*(WV_t, Q_{-i}^*) : p_t^*(q) = \frac{1}{1 + \varepsilon^{RD}(q)} WV_t(q|L_t) \]

- Simulate the lake levels in each period using the optimal policy function and

\[ I_{t=1,\ldots,52} \sim F_l(q_i^*(WV_t), Q_{-i}^*, F_f) \]

- Estimate expected frequency of electricity shortage
Equilibrium Lake Levels: First Week of Jan

Figure: Example Residual Demand Curve and Smoothing
Equilibrium Lake Levels: Winter Minimum

Figure: Example Residual Demand Curve and Smoothing
Conclusions

- Dispatch decisions of hydrogenerator governed by opportunity cost of water.
- Variations in opportunity cost of water are governed by changes in the risk that reservoirs become full or empty.
- Reservoir Capacity is determined by environmental and regulatory constraints.
- Firm’s implied valuations of their water can be inferred from their bidding behaviour.
- This can be used to calculate the risk of water shortage.
- Counterfactual analysis requires more detailed structural model.
Questions / Comments?

Oliver Browne
obrowne@uchicago.edu
home.uchicago.edu/~obrowne
## Installed Generation Capacity by firm (2008)

Table: 2008 Capacity by Firm (MW)

<table>
<thead>
<tr>
<th>Firm</th>
<th>Hydro</th>
<th>Gas</th>
<th>Coal</th>
<th>Geothermal</th>
<th>Wind</th>
<th>Oil</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MERI</td>
<td>2282</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>150</td>
<td>0</td>
<td>31%</td>
</tr>
<tr>
<td>CTCT</td>
<td>752</td>
<td>724</td>
<td>0</td>
<td>104</td>
<td>0</td>
<td>155</td>
<td>23%</td>
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<tr>
<td>MRPL</td>
<td>1090</td>
<td>320</td>
<td>0</td>
<td>195</td>
<td>0</td>
<td>0</td>
<td>21%</td>
</tr>
<tr>
<td>GENE</td>
<td>501</td>
<td>40</td>
<td>960</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20%</td>
</tr>
<tr>
<td>TRST</td>
<td>384</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>68</td>
<td>0</td>
<td>6%</td>
</tr>
<tr>
<td>Total</td>
<td>66%</td>
<td>14%</td>
<td>12%</td>
<td>4%</td>
<td>3%</td>
<td>2%</td>
<td>100%</td>
</tr>
</tbody>
</table>
### Lake Reservoir capacity by firm

#### Table: Lake Storage by Firm

<table>
<thead>
<tr>
<th>Firm</th>
<th>Hydro (MW)</th>
<th>Lake Storage GWh</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meridian</td>
<td>2282</td>
<td>3990</td>
<td>69%</td>
</tr>
<tr>
<td>Contact</td>
<td>752</td>
<td>909</td>
<td>16%</td>
</tr>
<tr>
<td>Mighty River Power</td>
<td>1090</td>
<td>677</td>
<td>12%</td>
</tr>
<tr>
<td>Genesis</td>
<td>501</td>
<td>178</td>
<td>3%</td>
</tr>
<tr>
<td>Trustpower</td>
<td>384</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>
How the Waitaki system works
FACTS ABOUT ELECTRICITY GENERATION FROM MT COOK THROUGH THE WAITAKI SYSTEM.

Lake Tekapo
Max Storage: 318.55GWh

Tekapo A
Commissioned: 1951
Capacity: 25.2 MW
*Annual Generation: 160GWh

Tekapo B
Commissioned: 1977
Capacity: 160 MW
*Annual Generation: 833GWh

Tekapo canal
Length: 25.5 km

Lake Pukaki
Max Storage: 1144.95GWh

Ohau A
Commissioned: 1979
Capacity: 264 MW
*Annual Generation: 1140GWh

Pukaki canal
Length: 12 km

Lake Ohau
Storage: 42.62GWh

Ohau B
Commissioned: 1984
Capacity: 212 MW
*Annual Generation: 958GWh

Lake Ruataniwha
Storage: 1.05GWh

Ohau C canal
Length: 2.4 km

Lake Benmore
Storage: 24.45GWh

Ohau C canal
Length: 8 km

Lake Aviemore
Storage: 4.04GWh

Ohau C
Commissioned: 1985
Capacity: 212 MW
*Annual Generation: 958GWh

Ohau C to Benmore
Canal length: 0.5 km

Lake Waitaki
Storage: 0.54GWh

Ohau C to Benmore
Canal length: 0.5 km

Figure: Waitaki System (Source: Meridian Energy)
Average Storage

![Average Storage Graph](image)

**Figure:** Average Storage
**Figure:** Inflows between 2000-2010