A Dynamic Oligopolistic Electricity Market Model with Interdependent Segments

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Background

- Traditional electricity sectors: vertically integrated $\Longrightarrow$ overcapacity
- Deregulation: competition between generators (i.e. profit maximization)
- Each generator
  - has two types of decision: production (short-run), investment (long-run);
  - can invest in different types of technology: base-load capacity, peak-load capacity;
  - faces interdependent demand segments: base-load demand, peak-load demand.

Review of selected papers

References	Market model	Information structure	Main feature	Solution method	Intended market
Lise and Krusemann (2008)	Stackelberg	Feedback	Model with a static part (trade, capacity and environmental constraints) and a dynamic part (investment decisions).	Recursive dynamic formualtion	EU8
Genc and Sen (2008)	Cournot equilibrium	S-adapted open loop	Capacity investments dynamic and pricing behavior of suppliers as uncertain demand evolves over time.	Games with probabilistic scenarios formulation	Ontario
Genc et al. (2007)	Cournot equilibrium	S-adapted open loop	Several stochastic programming formulations of dynamic oligopolistic games under uncertainty.	Stochastic programming	Ontario
Pineau and Zaccour (2007)	Cournot equilibrium	Complete information	Two-load-period electricity market model with interdependent demand, where oligopolistic generators make investments in peak- and base-load capacities.	Analytic with numerical illustration	Ontario

Review of selected papers

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Murphy and Smeers (2005)	Cournot equilibrium	Open loop; closed loop	Conversion of the inverse of the load duration curve to a probability density function (a way to cope with overall uncertainty about the future demand for electricity).	Variational inequality; Equilibrium subject to equilibrium constraints	
Pineau and Murto (2003)	Cournot equilibrium	S-adapted Open loop	Dynamic stochastic oligopoly model to describe the production and investment in deregulated electricity markets, where the demand growth rate is modeled as a stochastic variable.	Variational inequality; Non-linear programming	Finland
Ventosa et al. (2002)	Cournot equilibrium; Stackelberg	Open loop; closed loop	Cournot-based model: mixed linear complementarity structure; Stackelberg-based model: mathematical program with equilibrium constraints structure.	Cournot-based model: directly solved taking advantage of its complementarity structure; Stackelberg-based model: solved by general-purpose non-linear solvers.	
Chuang and Varaiya (2001)	Cournot equilibrium	Open loop	Generation expansion planning model that may characterize expansion planning in pool-dominated generation supply industries, where separate markets for energy and capacity reserves are modeled.	Iterative search procedure	California ISO/PX system

Our contribution:

1. Investment in both base- and peak-load capacity;
2. Dynamic framework;
3. Interdependent segments;
4. Numerical analysis with Ontario data;
5. More realistic costs function.

Model

Inverse demand laws:

$$P_b^t\left(Q_b^t, Q_p^t\right) = A_b^t - B_b.Q_b^t - C_b.Q_p^t \qquad t = 0, ..., T \tag{1}$$

$$P_p^t\left(Q_b^t, Q_p^t\right) = A_p^t - B_p.Q_p^t - C_p.Q_b^t \qquad t = 0, ..., T \tag{2}$$

Investment cost functions:

$$\Gamma_b\left(I_{ib}, k_{ib}\right) = \kappa_i.I_{ib}.k_{ib} + \frac{1}{2}\psi_i.I_{ib}^2 \tag{3}$$

$$\Gamma_p\left(I_{ip}\right) = \frac{1}{2}\varphi.I_{ip}^2 \tag{4}$$

Production cost functions:

$$G_{ib}\left(q_{ib}, k_{ib}\right) \triangleq G_{ib}\left(q_{ib}\right) = \alpha_b.q_{ib} \tag{5}$$

$$G_{ip}\left(q_{ip}, k_{ip}\right) = \alpha_p.q_{ip} + \nu_p\left(\frac{h_p.k_{ip}}{\phi + 1}\right)\left(\frac{q_{ip}}{h_p.k_{ip}}\right)^{\phi+1} \tag{6}$$

Model

$$\max \pi_i = \sum_{t=0}^{T} \beta^t \left\{ \sum_{l\in\{b,p\}} \left[q_{il}^t P_l^t \left(Q_b^t, Q_p^t \right) - G_l \left(q_{il}^t, k_{il}^t \right) - \Gamma_l \left(I_{il}^t, k_{il}^t \right) \right] \right\} + \beta^T \sum_{l\in\{b,p\}} V_l \left(k_{il}^T \right)$$

subject to :

Expansion of capacity :

$$k_{il}^{t+1} = (1-\delta)\, k_{il}^t + I_{il}^t, l \in \{b, p\}, k_{il}^0 given, \quad t = 0, ..., T-1$$

Capacity of base load :

$$q_{ib}^t \leq h_b.k_{ib}^t , \quad t = 0, ..., T$$

Capacity of peak load :

$$q_{ip}^t \leq h_p.k_{ip}^t , \quad t = 0, ..., T$$

Non-negativity constraints :

$$I_{il}^t \geq 0, \quad q_{il}^t \geq 0, \;\; l \in \{b, p\}, \quad t = 0, ..., T$$

Ontario electricity market

Table 1. Generation Capacities in Ontario, by Fuel type

Ownership	Fuel Type	Capacity (MW)
OPG	Nuclear	6,600.0
Bruce Power	Nuclear	4,223.0
OPG & affiliates	Hydro	7,894.9
OPG	Coal	7,205.0
NUGA	Natural Gas	2,674.4
OPG	Oil/Gas	2,100.0
NUGA	Wood Waste	224.6
Total		**30,921.9**

Table 2. Generation Capacities in Ontario, by Fuel type and by Ownership

Technology	Player	Capacity (MW)	Capacity for Residential and Commercial consumers (MW)
Base	OPG	21,699.9	9,208.8
	Bruce	4,223.0	2,156.2
	NUGA	0	0
	Total	**25,922.9**	**11,365.0**
Peak	OPG	2,100.0	1,333.3
	Bruce	0	0
	NUGA	2,899.0	1,840.7
	Total	**4,999.0**	**3,174.0**

Costs parameters

Table 3. Production Costs

Technology	Marginal production cost ($/MWh)	Duration of use
Base-load	20	8,760 hours
Peak-load (α_p)	60	3,845 hours
Peak-load ($\alpha_p + \upsilon_p$)	110	3,845 hours

Table 4. Investment Costs

Technology	Investment cost ($/MW)	Duration of use
Base-load	4,000,000	8,760 hours
Peak-load	800,000	3,845 hours

Demand parameters

- **Table 5. Direct- and Cross-Price Elasticities**

	Short-run		Long-run	
Period	**Elasticity**	**Cross elasticity**	**Elasticity**	**Cross elasticity**
Base	-0.3	0.02	-0.6	0.04
Peak	-0.1	0.01	-0.8	0.02

- To determine the parameters of the demand laws in (1) and (2), we use the above elasticity values, the quantities purchased in Ontario in 2005 during peak- and base- load periods, and the uniform price of \$92.20/MWh paid by residential and commercial customers in both periods.
- Finally, we assume that energy demand is increasing at a constant growth rate $g = 0.013$ each year. This value corresponds to the highest growth rate that IMO expects for the future per year (see Genc and Sen (2008)).

Results

- Here, our goal is to predict investment and production equilibrium strategies over a ten-year period for the three players forming the Ontario electricity industry, i.e., OPG, Bruce and NUGA.

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- Here, our goal is to predict investment and production equilibrium strategies over a ten-year period for the three players forming the Ontario electricity industry, i.e., OPG, Bruce and NUGA.
- We also investigate the impact on these strategies of varying three key parameters of our model, namely, the number of players, the salvage value of production capacities, and price elasticities.

NUGA's capacity trajectories

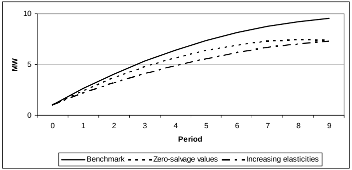

Fig.9 NUGA's base-load capacity $(n = 3)$

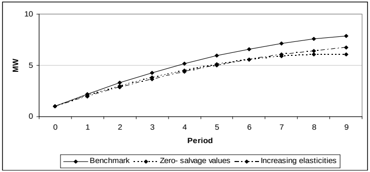

Fig.10 NUGA's base-load capacity $(n = 5)$

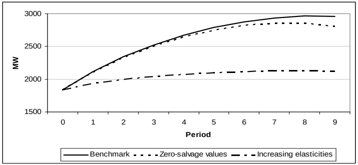

Fig.11 NUGA's peak-load capacity $(n = 3)$

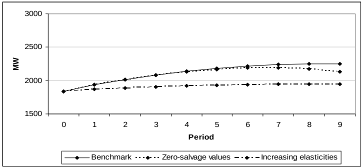

Fig.12 NUGA's peak-load capacity $(n = 5)$

Bruce's capacity trajectories

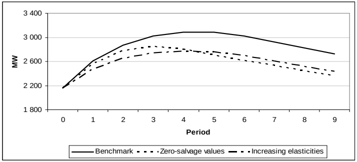

Fig.13 Bruce's base-load capacity $(n = 3)$

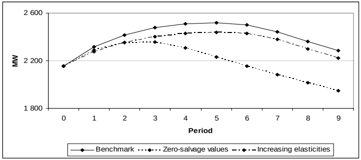

Fig.14 Bruce's base-load capacity $(n = 5)$

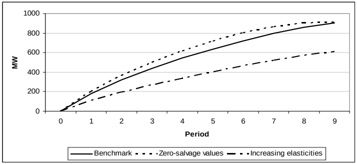

Fig.15 Bruce's peak-load capacity $(n = 3)$

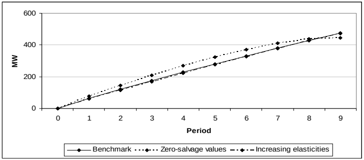

Fig.16 Bruce's peak-load capacity $(n = 5)$

OPG's capacity trajectories

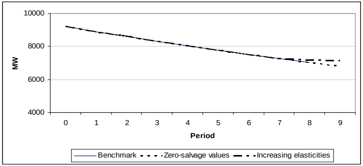

Fig.17 OPG's base-load capacity $(n = 3)$

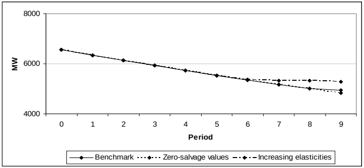

Fig.18 OPG's base-load capacity $(n = 5)$

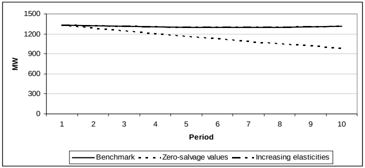

Fig.19 OPG's peak-load capacity $(n = 3)$

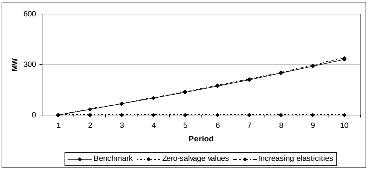

Fig.20 OPG's peak-load capacity $(n = 5)$

Conclusion

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- Our numerical results show that when elasticity changes overtime, then prices decrease more in the peak-load market segment than in the base-load one, especially toward the end of the planning horizon.
- The numerical results also suggest that the distribution of initial capacity is generally determinant.

Limitations

- As in any modeling effort, we made here some simplifying assumptions. The two main ones being that demand is known with certainty and that the players adopt an open-loop information structure to determine their strategies. It is clearly of interest to relax both assumptions in future investigations.

Thank you for your attention!