Modeling incentives with vertical integration in electricity markets

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Competition and investment

- Continued debate about investment and competition.
- Deterministic incompleteness: missing money removes the incentive to invest. Different remedies and debates over capacity payments versus energy only markets.
- Stochastic incompleteness: Stoft (2002) showed how missing money can be provided by VOLL pricing in a risk neutral setting,
- (National) New Zealand approach: Workable competition with tolerated exercise of market power provides the missing risk premium for investing. "Perfectly competitive prices would chill investment."
- (Labour) New Zealand approach: Regulate all market power from the spot market to reduce spot prices and reimburse consumers.
- What is effect on investment when agents are risk averse?

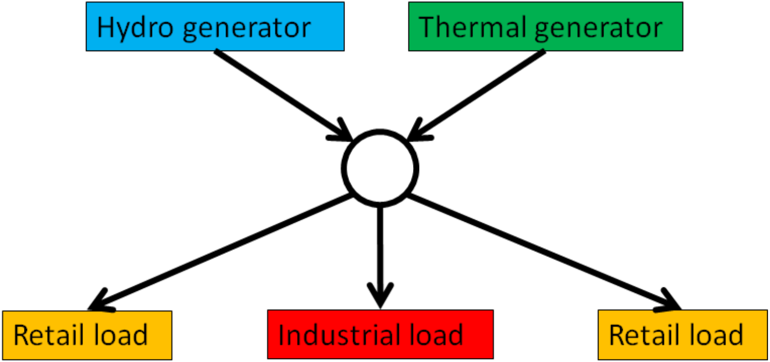
Vertical integration of retailers and generators

- Vertical Integration means some generators and retailers have common ownership and operation.
- The combined entity is called a gentailer.
- There is a long history of research on incentives for integration in supply chains (see e.g. Joskow, 2005).
- "..almost any market imperfection becomes a candidate for creating private incentives for integration".
- Like futures contracts (Allaz and Vila, 1993), integration decreases market power rents in equilibrium.
- So we investigate incentives from competitive models using risk (Ehrenmann & Smeers, 2011).

Summary

Summary

Example toy problem



In state of the world ω, industrial load buys all power at the wholesale price $p(\omega)$. A retailer buys electricity at $p(\omega)$ and sells it at a fixed price π.

Futures contracts

Industrial and retail purchasers can hedge the risk of high future prices by buying a contract for differences of Q from a generator at contract price f. In state of the world ω, a generator generating $q(\omega)$ at cost $C(\cdot)$ has payoff

$$\Pi_G(Q,\omega) = p(\omega)q(\omega) - C(q(\omega)) + Q(f - p(\omega)).$$

A retailer with fixed load Q has payoff

$$\Pi_R(Q,\omega) = Q\pi - Qp(\omega) + Q(p(\omega) - f) = Q(\pi - f).$$

Vertical integration

Vertical integration combines the agent's profits Π_R and Π_G to give a gentailer agent. Gentailer might also trade energy and contracts on the wholesale market. The gentailer power produced $u(\omega)$ need not match its retail consumption $r(\omega)$. The gentailer's profit is

$$\begin{aligned}\Pi_T(0.\omega) &= \Pi_G(Q,\omega) + \Pi_R(0.\omega) \\ &= u(\omega)p(\omega) - C(u(\omega)) + Q(f - p(\omega)) \\ &\quad + r(\omega)(\pi - p(\omega)).\end{aligned}$$

The gentailer's profit has less risk than generator alone because it is exposed to variation in $(u(\omega) - r(\omega))\, p(\omega)$ rather than $q(\omega)p(\omega)$.

Vertical integration reduces risk

- Risk reduction incentives for integration in wholesale markets demonstrated under perfect competition and mean-variance risk measures (Aid et al, 2011).
- We use coherent risk measures, and look at incentives for investments in new generation in perfect competition.
- Does vertical integration incentivize investment in capacity, or does it reduce investment?

Summary

Dual representation of coherent risk measures
(Artzner et al, 1999, Shapiro & Ruszczynski, 2006)

A coherent risk measure ρ of a random disbenefit Z can be expressed as

$$\rho(Z) = \max_{\mu \in \mathcal{D}} \mathbb{E}_{\mu}[Z]$$

where D is a convex set of probability measures called the risk set.

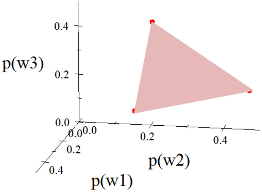
Example: three outcomes

Consider possible disbenefit outcomes $Z(\omega_1) < Z(\omega_2) < Z(\omega_3)$ with equal probability. The coherent risk measure

$$\rho(Z) = \frac{3}{4}\mathbb{E}[Z] + \frac{1}{4}\max[Z]$$

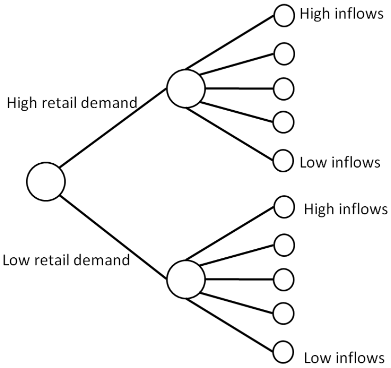
has risk set

$$\mathcal{D}=\text{conv}\{(\frac{1}{2},\frac{1}{4},\frac{1}{4}),(\frac{1}{4},\frac{1}{2},\frac{1}{4}),(\frac{1}{4},\frac{1}{4},\frac{1}{2})\}.$$



$$\rho(Z) = \max_{\mu\in\mathcal{D}} \mathbb{E}_\mu[Z] = \frac{1}{4}Z(\omega_1) + \frac{1}{4}Z(\omega_2) + \frac{1}{2}Z(\omega_3).$$

Our example: ten scenarios



In our example there are ten equally likely scenarios. Demand is either high or low, and varying inflow levels influence hydro generation capacity for that outcome.

Our example: ten outcomes

We use a coherent risk measure ρ that averages expected disbenefit and 20% conditional value at risk. This has risk set

$$\begin{aligned} \mathcal{D} \;=\; & \operatorname{conv}\{(\frac{6}{20},\frac{6}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20}), \\ & (\frac{6}{20},\frac{1}{20},\frac{6}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20}), \\ & (\frac{6}{20},\frac{1}{20},\frac{1}{20},\frac{6}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20}), \\ & \ldots, \\ & (\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{1}{20},\frac{6}{20},\frac{6}{20})\}. \end{aligned}$$

$$\rho(Z) = \max_{\mu \in \mathcal{D}} \sum_{i=1}^{10} \mu_i Z(\omega_i).$$

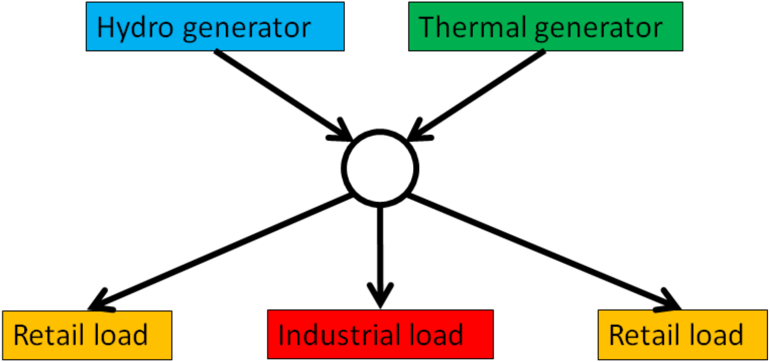
Risked equilibrium and social planning

(Heath and Ku 2004, Ralph and Smeers, 2011, Ehrenmann and Smeers, 2011)

Model assumptions	Perfect competition (complete risk market)	Perfect competition (incomplete risk market)	Imperfect competition
Risk neutral agents	Competitive equilibrium gives socially efficient solution.	Competitive equilibrium gives socially efficient solution.	Nash equilibrium can result in social inefficiency.
Risk averse coherent agents	Competitive equilibrium gives socially efficient solution with social risk measure.	Competitive equilibrium is not always socially efficient.	The most realistic model.

If the market for hedging instruments is sufficiently rich, and agents use coherent risk measures, then there is a social risk measure that is optimized by a competitive equilibrium.

Toy example revisited



Basic model. In stage 0 we invest in hydro and thermal capacity and then in stage 1 generate to meet industrial and retail demand in each scenario.

Benefits of investing in 1500 hydro and 600 thermal.

Welfare ($M)	Low retail demand					High retail demand						
Inflows	40%	55%	70%	85%	100%	40%	55%	70%	85%	100%	Expected	Risk Adj
Thermal	48.61	-33.47	-35.60	-35.82	-35.82	204.19	47.51	-30.56	-34.10	-34.38	6.06	-14.88
Hydro	235.05	78.50	73.54	71.69	71.69	478.92	282.10	154.31	147.12	145.98	173.89	122.79
Retail 1	331.46	407.77	411.01	411.73	411.73	324.41	501.54	588.38	593.24	593.78	457.50	392.72
Retail 2	331.46	407.77	411.01	411.73	411.73	324.41	501.54	588.38	593.24	593.78	457.50	392.72
Hydro gentailer	380.07	374.30	375.41	375.91	375.91	528.60	549.06	557.83	559.15	559.40	463.56	419.21
Thermal gentailer	566.51	486.26	484.54	483.42	483.42	803.33	783.64	742.69	740.36	739.76	631.39	557.40
Industry	969.05	1080.13	1083.37	1084.09	1084.09	899.60	978.32	1044.43	1047.67	1048.03	1031.88	983.10
Total	1915.63	1940.69	1943.32	1943.41	1943.41	2231.52	2311.02	2344.95	2347.18	2347.20	2126.83	2,027.50
Price	$83.44	$51.74	$50.82	$50.61	$50.61	$129.84	$80.80	$61.93	$61.01	$60.90		

Benefits $\Pi(\omega)$ for agents. Yellow cells identify the two worst scenarios. The right-hand column shows the result of evaluating the policy of each agent using its risk set. Each agent's risk adjusted welfare sums to 1876. The orange figure 2027.5 is risk-adjusted total social welfare.

Summary

Competitive Risk-Averse Generation Expansion
(Kok, 2013)

- A GAMS MOPEC model coded under the EMP system (Ferris.et al 2009)
- It has risk averse agents: generators, retailers, gentailers, industrial load all with known coherent risk measures.
- Ownership (i.e. vertical integration) is exogeneous.
- An auctioneer announces contract price and wholesale spot prices in each scenario.
- Each agent then solves a two-stage risk-averse stochastic programming problem:
  - Stage 0: choose increase in generation capacity and purchase contract positions at contract price.
  - Stage 1: Offer all generation capacity at short-run marginal cost in the spot market and earn market rents minus contract payments.
- If contracts and generation quantities clear their markets then we have a competitive equilibrium.

Agent problem (generator)

Given contract price f and electricity wholesale price $p(\omega)$, choose capacity expansion x, purchase contract Q_g and sell generation $u(\omega)$ to solve

$$
\begin{aligned}
\text{GP:} \quad \min \quad & K(x) && + \quad \rho_g(Z_g) \\
\text{s.t.} \quad & u(\omega) && \leq \quad x\phi(\omega), \\
& Z_g(\omega) && = \quad -p(\omega)u(\omega) + C(u(\omega)) + (f - p(\omega))Q_g, \\
& x, u(\omega) && \geq \quad 0.
\end{aligned}
$$

Agent problem (retailer)

Given retail demand $d(\omega)$, retail price π, contract price f and electricity wholesale price $p(\omega)$, purchase contract Q_r and purchase $d(\omega) - s(\omega)$ to solve

$$
\begin{aligned}
\text{RP:} \quad \min \quad & \rho_r(Z_r) \\
\text{s.t.} \quad Z_r(\omega) &= (p(\omega) - \pi)(d(\omega) - s(\omega)) \\
&\quad + (f - p(\omega))Q_r + (\text{VOLL} - \pi)s(\omega), \\
s(\omega) &\leq d(\omega), \\
s(\omega) &\geq 0.
\end{aligned}
$$

Agent problem (industrial)

Given industrial demand $e(\omega)$, value of electricity $v <$VOLL, contract price f and electricity wholesale price $p(\omega)$, purchase contract Q_i and purchase $e(\omega) - r(\omega)$ to solve

$$
\begin{aligned}
\text{IP:} \quad \min \quad & \rho_i(Z_i) \\
\text{s.t.} \quad Z_i(\omega) &= (p(\omega) - v)(e(\omega) - r(\omega)) \\
&\quad + (f - p(\omega))Q_i, \\
r(\omega) &\leq e(\omega), \\
r(\omega) &\geq 0.
\end{aligned}
$$

Competitive equilibrium conditions

$$(Q_g, x, u) \in \arg\min \text{GP},$$

$$(Q_r, s) \in \arg\min \text{RP},$$

$$(Q_i, r) \in \arg\min \text{IP},$$

$$0 \leq Q_g + Q_r + Q_i \perp f \geq 0,$$

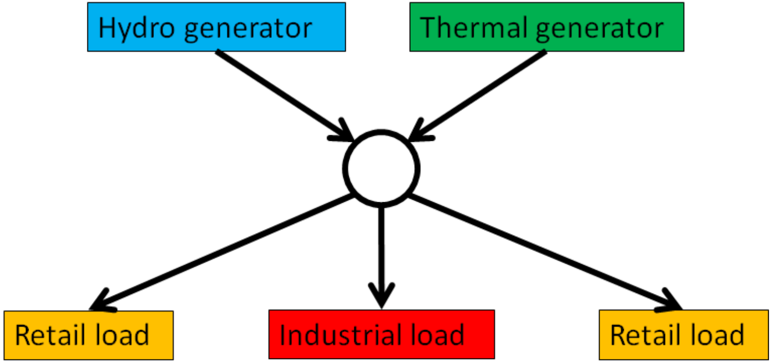
$$0 \leq u + s + r - d - e \perp p \geq 0.$$

Agent problem (gentailer)

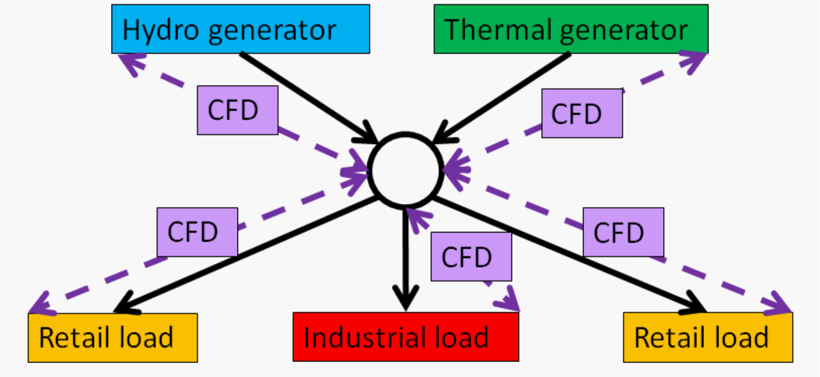
Given contract price f and electricity wholesale price $p(\omega)$, choose capacity expansion x, purchase contract Q_t and sell generation $u(\omega)$ to solve

$$
\begin{aligned}
\text{GP:} \quad \min \quad & K(x) + \rho_t(Z_t) \\
\text{s.t.} \quad & u(\omega) \le x\phi(\omega), \\
& Z_t(\omega) = -p(\omega)u(\omega) + C(u(\omega)) + (f - p(\omega))Q_t \\
& \qquad + (p(\omega) - \pi)(d(\omega) - s(\omega)) \\
& \qquad + (\text{VOLL} - \pi)s(\omega), \\
& s(\omega) \le d(\omega), \\
& x, s(\omega), u(\omega) \ge 0.
\end{aligned}
$$

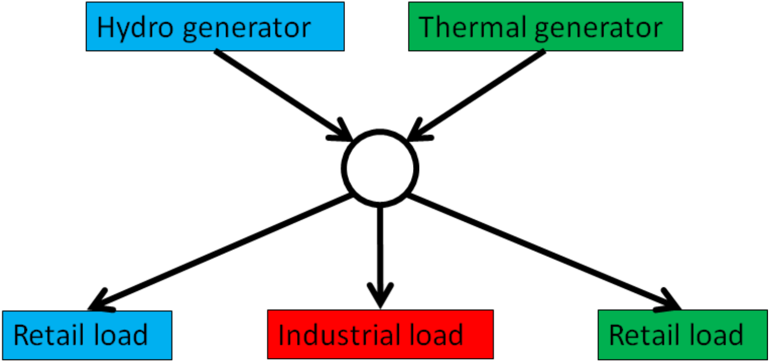
Toy example revisited



With contracts



With vertical integration



With vertical integration there are three agents.

Stochastic risk-neutral social planning model

Welfare ($M)	Low retail demand					High retail demand						
Inflows	40%	55%	70%	85%	100%	40%	55%	70%	85%	100%	Expected	Risk Adj
Thermal	48.61	-33.47	-35.60	-35.82	-35.82	204.19	47.51	-30.56	-34.10	-34.38	6.06	-14.88
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Total	1915.63	1940.69	1943.32	1943.41	1943.41	2231.52	2311.02	2344.95	2347.18	2347.20	2126.83	2,027.50
Price	$83.44	$51.74	$50.82	$50.61	$50.61	$129.84	$80.80	$61.93	$61.01	$60.90		

Candidate solution from previous slide is optimal under risk neutrality. The hydro plant expands by 1500 and thermal plant expands by 600. Thermal plant makes losses in some high inflow years. Agents' risk-adjusted welfare is 1876.

Competitive risk-averse equilibrium

		RN	RA	VI	CFD	CFD_VI	AD
Expansion decisions	Thermal	600.00	690.91	697.45	535.53	600.00	590.55
	Hydro	1500.00	1272.73	1256.36	1661.16	1500.00	1523.63
Risk adjusted welfare ($M)	Thermal	-14.88	5.47		3.33		6.07
	Hydro	122.79	159.81		162.13		154.38
	Retail 1	392.72	289.02		402.30		411.20
	Retail 2	392.72	289.02		402.30		411.20
	Hydro gentailer	419.21	413.71	412.45	410.12	417.48	417.27
	Thermal gentailer	557.40	571.96	574.40	564.52	566.90	565.58
	Industry	983.10	954.44	953.63	1041.66	1043.11	1044.66
	Total	2027.50	2018.55	2017.52	2027.00	2027.50	2027.52

Risk-adjusted profits $\max_{\mu \in D} \mathbb{E}_{\mu}[\Pi(\omega)]$ for each agent for a competitive equilibrium with risk.

Vertical integration of retailers and generators

		RN	RA	VI	CFD	CFD_VI	AD
Expansion decisions	Thermal	600.00	690.91	697.45	535.53	600.00	590.55
	Hydro	1500.00	1272.73	1256.36	1661.16	1500.00	1523.63
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	Hydro	122.79	159.81		162.13		154.38
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	Industry	983.10	954.44	953.63	1041.66	1043.11	1044.66
	Total	2027.50	2018.55	2017.52	2027.00	2027.50	2027.52

Risk-adjusted profits $\max_{\mu \in D} \mathbb{E}_\mu [\Pi(\omega)]$ for gentailers and industrial for a vertically integrated competitive equilibrium with risk.

Contracts traded in an exchange at single price

		RN	RA	VI	CFD	CFD_VI	AD
Expansion decisions	Thermal	600.00	690.91	697.45	535.53	600.00	590.55
	Hydro	1500.00	1272.73	1256.36	1661.16	1500.00	1523.63
Risk adjusted welfare ($M)	Thermal	-14.88	5.47		3.33		6.07
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	Industry	983.10	954.44	953.63	1041.66	1043.11	1044.66
	Total	2027.50	2018.55	2017.52	2027.00	2027.50	2027.52

Risk-adjusted profits $\max_{\mu \in D} \mathbb{E}_{\mu}[\Pi(\omega)]$ for agents for competitive equilibrium with risk and futures contracts.

Contracts and vertical integration

		RN	RA	VI	CFD	CFD_VI	AD
Expansion decisions	Thermal	600.00	690.91	697.45	535.53	600.00	590.55
	Hydro	1500.00	1272.73	1256.36	1661.16	1500.00	1523.63
Risk adjusted welfare ($M)	Thermal	-14.88	5.47		3.33		6.07
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	Hydro gentailer	419.21	413.71	412.45	410.12	417.48	417.27
	Thermal gentailer	557.40	571.96	574.40	564.52	566.90	565.58
	Industry	983.10	954.44	953.63	1041.66	1043.11	1044.66
	Total	2027.50	2018.55	2017.52	2027.00	2027.50	2027.52

Industry's risk-adjusted profit increases when gentailers are broken up, and everyone contracts instead.

Arrow-Debreu securities complete the risk market
(Heath and Ku 2004, Ralph and Smeers, 2011)

Arrow-Debreu securities are contracts that charge a price $\mu(\omega)$ at time 0, to receive a payment of 1 in scenario time ω at time 1. These form a complete market for risk (i.e. contracts traded at time 0 span the $|\omega|$ payoff outcomes).

Let $\{x_a \mid a \in H \cup T\}$ be a solution to the risk-averse social planning problem with risk set $D_0 \neq \emptyset$. Suppose this gives prices $\{p(\omega)\}$. These prices and quantities form a risked equilibrium in which agents trade risk i.e. agent a minimizes $\rho_a(Z_a)$ with a solution defined by x_a together with a policy of trading Arrow-Debreu securities.

Risk-averse social plan

		RN	RA	VI	CFD	CFD_VI	AD
Expansion decisions	Thermal	600.00	690.91	697.45	535.53	600.00	590.55
	Hydro	1500.00	1272.73	1256.36	1661.16	1500.00	1523.63
Risk adjusted welfare ($M)	Thermal	-14.88	5.47		3.33		6.07
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	Total	2027.50	2018.55	2017.52	2027.00	2027.50	2027.52

Risk-adjusted profits $\max_{\mu \in D} \mathbb{E}_\mu[\Pi(\omega)]$ for agents for a social plan (or trading Arrow-Debreu securities).

Features of example problem

- Risk aversion in equilibrium leads to underinvestment in risky production (hydro).
- Vertical integration exacerbates this effect.
- Industrial plant object to integration if they cannot contract.
- Contracts alone give underinvestment in thermal.
- Contracts and vertical integration together get close to optimal social investment.

Conclusions

- Market power has been the focus of attention in electricity markets.
- Also it is important to see how risk affects outcomes - ownership matters.
- Risk can be removed by trading - instruments matter.
- Models with complete risk markets and coherent risk measures can be solved by optimization.
- A need remains for robust solution methods for models with incomplete risk markets (decomposition will be key).

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Summary

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