Capacity Equilibrium in Electricity Markets

Andy Philpott
Electric Power Optimization Centre
University of Auckland.
www.epoc.org.nz

(Joint work with Golbon Zakeri and Corey Kok)

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Reducing demand sees plant closures

Alternative energy sources have rendered a coal/gas unit at Huntly Power Station redundant. Picture / Christine Cornege

Flat demand sees Huntly unit retired

Paul McBeth

Genesis Energy, the country's biggest energy retailer, will permanently retire a coal/gas-fired unit at the Huntly Power Station which has been in storage as renewable and thermal generation provide more than enough electricity to meet customer demand.

The Auckland-based company decided to retire the 250 megaWatt Rankine unit because it wasn't needed by the wholesale market when a dry period kept hydro-lake levels low. The unit has been in long-term storage to be rolled out in the event of a shortage, something that hasn't eventuated.

"Supply growth over the past few years has been strong, while customer and industrial demand growth has been relatively flat," said chief executive Albert Brantley. "As a result, we have taken the decision to retire a second Rankine unit, delivering further operational efficiencies to Genesis Energy."

The power company will keep two coal/gas units available at the Huntly plant and two other gas-fired units.

Genesis shares closed down 1c yesterday at $1.74. — BusinessDesk

Gas fired plant are being mothballed in New Zealand (Source: New Zealand Herald, June 30, 2015)

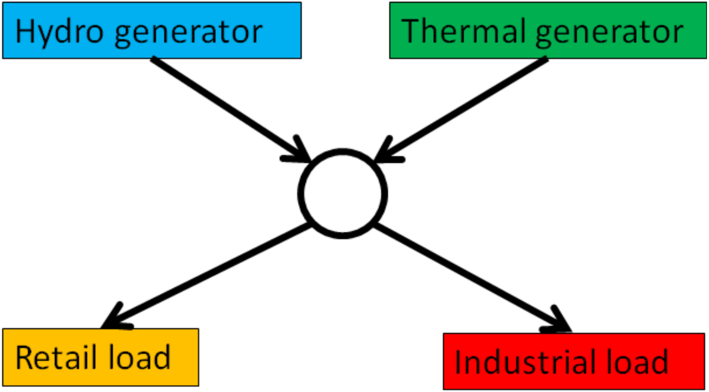
What is the impact of changes in load?

- Original motivation was investigating generation investment.
- Although lower demand leads to lower prices...
- ... if prices are too low then producers mothball underutilized plant.
- How do attitudes to risk alter the actions of the generators?
- How does ownership (vertical integration of generation and retail) affect these actions?
- We investigate incentives in incomplete competitive markets using coherent risk measures (as in Ehrenmann & Smeers, 2011).
- We restrict attention to toy models.

Summary

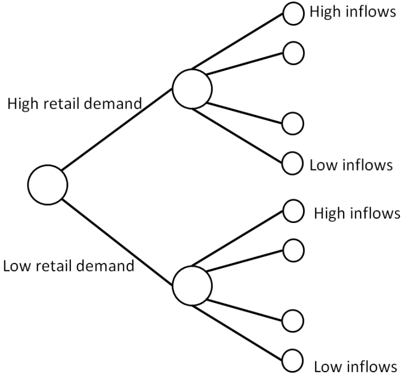
Summary

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.

We consider eight equally likely scenarios



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

Stochastic programming capacity expansion problem

Choose capacity x_g for each generator g, and sell generation $u_g(\omega)$ to retailers and industrial load to solve

$$
\begin{array}{llll}
\text{SP:} & \min & \sum_g K_g(x_g) & + \quad \mathbb{E}_\omega(Z(\omega)) \\
& \text{s.t.} & u_g(\omega) & \leq \quad x_g \phi_g(\omega), \\
& & r(\omega) & \leq \quad d(\omega), \\
& & s(\omega) & \leq \quad e(\omega), \\
& & \sum_g u_g(\omega) + r(\omega) + s(\omega) & = \quad d(\omega) + e(\omega), \\
& & Z(\omega) & = \quad \sum_g C_g(u_g(\omega)) \\
& & & \qquad -v(e(\omega) - s(\omega)) \\
& & & \qquad -\pi d(\omega) \\
& & & \qquad +\text{VOLL}\, r(\omega) \\
& & r(\omega), s(\omega), x_g, y_g, u_g(\omega) & \geq \quad 0.
\end{array}
$$

Stochastic programming capacity reduction problem

Given existing capacity $\bar{x}_g$ choose capacity reduction y_g for each generator g, and sell generation $u_g(\omega)$ to retailers and industrial load to solve

$$
\begin{array}{llll}
\text{SP:} & \min & \sum_g (K_g(\bar{x}_g) - F_g(y_g)) & + \quad \mathbb{E}_\omega(Z(\omega)) \\
& \text{s.t.} & u_g(\omega) & \leq \quad (\bar{x}_g - y_g)\phi_g(\omega), \\
& & r(\omega) & \leq \quad d(\omega), \\
& & s(\omega) & \leq \quad e(\omega), \\
& & \sum_g u_g(\omega) + r(\omega) + s(\omega) & = \quad d(\omega) + e(\omega), \\
& & Z(\omega) & = \quad \sum_g C_g(u_g(\omega)) \\
& & & \quad\; -v(e(\omega) - s(\omega)) \\
& & & \quad\; -\pi d(\omega) \\
& & & \quad\; +\text{VOLL}\, r(\omega), \\
& & r(\omega), s(\omega), x_g, y_g, u_g(\omega) & \geq \quad 0.
\end{array}
$$

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.

Our example: eight equally likely outcomes

All agents (except ISO) use a coherent risk measure ρ that is average of expected disbenefit and average value at risk at 25%. This has risk set

$$\begin{aligned}\mathcal{D} \quad = \quad & \text{conv}\{(\frac{5}{16},\frac{5}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16}),\\ & (\frac{5}{16},\frac{1}{16},\frac{5}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16}),\\ & (\frac{5}{16},\frac{1}{16},\frac{1}{16},\frac{5}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16}),\\ & \ldots,\\ & (\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{1}{16},\frac{5}{16},\frac{5}{16})\}.\end{aligned}$$

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

Risk-averse plan: 731 MW thermal, 600 MW hydro

Welfare ($M)	Low retail demand				High retail demand					
Inflows	50%	75%	125%	150%	50%	75%	125%	150%	Expected	Risk Adj
Thermal	-72.07	-72.76	-73.05	-73.08	393.52	392.02	-72.75	-72.90	43.62	-14.72
Hydro	21.44	-51.07	-104.35	-102.67	214.24	238.57	-98.97	-97.93	2.41	-50.55
Industry	164.38	211.49	230.61	230.65	158.46	205.35	229.16	229.35	207.43	184.43
Retailer	300.20	363.72	414.92	415.15	-314.84	-220.26	617.43	618.37	274.34	3.39
Total	413.95	451.37	468.13	470.04	451.37	615.67	674.87	676.89	527.79	480.22
Price	$ 59.06	$ 54.68	$ 9.42	$ 4.52	$128.82	$128.05	$ 50.31	$ 23.16	$ 57.25	

Benefits for each agent. This is not a competitive equilibrium. 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 122.54. The orange figure 480.22 is risk-adjusted total social welfare.

Sidebar: 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 scenario 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 load $d(\omega)$ (and no load shedding) has payoff

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

Agent problem (generator expanding)

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

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

Agent problem (generator mothballing)

Given existing capacity $\bar{x}_g$, contract price f and electricity wholesale price $p(\omega)$, choose capacity reduction y, purchase contract Q_g and sell generation $u(\omega)$ to solve

$$
\begin{aligned}
\text{GP:} \quad \min \quad & -F_g(y) && + && \rho(Z_g) \\
\text{s.t.} \quad & u(\omega) && \leq && (\bar{x}_g - y)\phi_g(\omega), \\
& Z_g(\omega) && = && -p(\omega)u(\omega) + C(u(\omega)) + (f - p(\omega))Q_g, \\
& x, u(\omega) && \geq && 0.
\end{aligned}
$$

Agent problem (retailer)

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

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

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

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

Sidebar: agent problem (gentailer expanding)

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

$$
\begin{array}{llcl}
\text{GP:} & \min & K_g(x) & + & \rho(Z_t) \\
& \text{s.t.} & u(\omega) & \leq & x\phi(\omega), \\
& & Z_t(\omega) & = & -p(\omega)u(\omega) + C(u(\omega)) \\
& & & & + (p(\omega) - \pi)(d(\omega) - r(\omega)) \\
& & & & + (\text{VOLL} - \pi) r(\omega), \\
& & r(\omega) & \leq & d(\omega), \\
& & & & x, r(\omega), u(\omega) \geq 0.
\end{array}
$$

Competitive risked equilibrium conditions

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

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

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

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

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

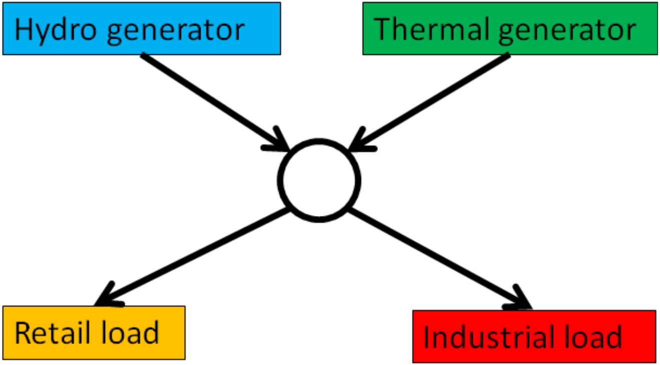
Summary

Competitive Risk-Averse Generation Expansion (CRAGE)

(Kok, 2013)

- A GAMS MOPEC model coded under the EMP system (Ferris et al 2009)
- Given prices f and $p(\omega)$, each agent 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.
- In practice, we obtain a solution to CRAGE in GAMS by iteratively solving the MOPEC with all but one investment fixed to yield good starting points for PATH.

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.

Summary

Capacity expansion equilibria with vertical integration

		Risk Neutral	Risk averse	VI thermal	VI hydro	CFD	Complete
Expansion decisions	Thermal	821.54	650.00	967.14	50.00	750.00	730.86
	Hydro	504.61	440.00	366.67	1500.00	600.00	600.00
Risk adjusted welfare ($M)	Thermal	-40.50	0.70		0.00	0.81	0.79
	Hydro	-40.31	5.20	4.54		5.04	4.87
	Retail	178.90	173.28			194.33	195.14
	Industry	145.13	-64.97	172.67	222.45	203.51	279.43
	Thermal gentailer			253.33			
	Hydro gentailer				142.77		
	Total	477.73	447.81	462.18	377.57	479.83	480.22

Risk-adjusted benefits for each agent for different solutions.

Capacity reduction equilibria with vertical integration

		Risk Neutral	Risk averse	VI thermal	VI hydro	CFD	Complete
Expansion decisions	Thermal	300.00	150.00	366.67	150.00	250.00	250.00
	Hydro	600.00	600.00	466.67	600.00	600.00	600.00
Risk adjusted welfare ($M)	Thermal	-7.47	0.02		0.02	0.06	0.05
	Hydro	-8.91	3.44	2.80		25.97	11.19
	Retail	209.94	203.27			213.89	221.38
	Industry	163.04	98.55	186.06	215.87	176.69	194.37
	Thermal gentailer			181.91			
	Hydro gentailer				179.22		
	Total	453.23	422.42	421.75	422.42	426.99	426.99

Retail demand is 50% of previous forecast. Each plant reduces capacity from $\bar{x}_g = (731, 600)$ the optimal risk-averse social level of investment. Risk-adjusted benefits for each agent are shown.

Summary

Agent problem (ISO)

Given reactance X_{ij} of line (i,j) electricity wholesale price $p_i(\omega)$ at node i, choose branch flow $q_{ij}(\omega)$ and voltage angles $\theta_i(\omega)$ to solve

$$\begin{array}{llll} \text{ISO}(\omega): & \min & \sum_i \sum_{j>i} \left(p_i(\omega) - p_j(\omega)\right) q_{ij}(\omega) & \\ & \text{s.t.} & X_{ij} q_{ij}(\omega) - (\theta_i(\omega) - \theta_j(\omega)) & = & 0, \\ & & q_{ij}(\omega) & \leq & L_{ij}, \\ & & q_{ij}(\omega) & \geq & -L_{ij}. \end{array}$$

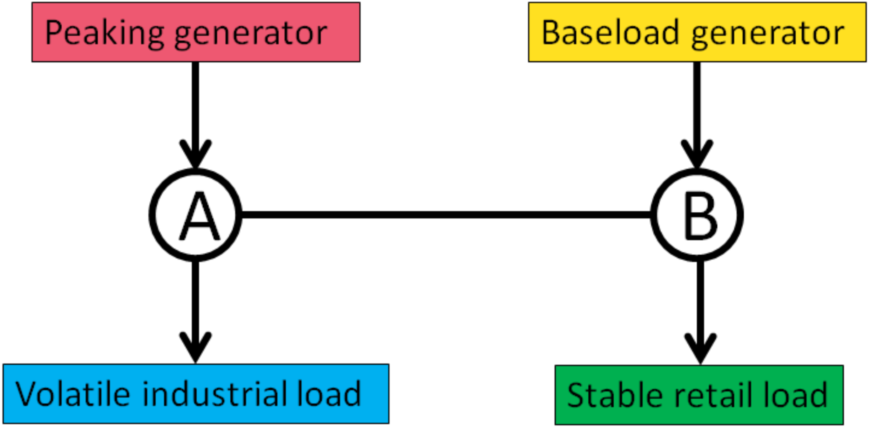
Competitive risked equilibrium conditions

We denote excess supply at each node i by

$$E_i(\omega) = u_i(\omega) + r_i(\omega) + s_i(\omega) - d_i(\omega) - e_i(\omega) + \sum_{j>i} (q_{ji}(\omega) - q_{ij}(\omega)) .$$

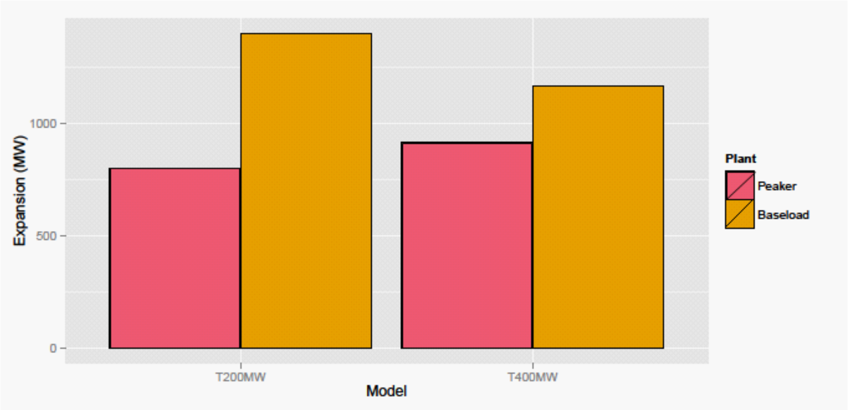
$$\begin{aligned}
(Q_g, x, u) &\in \arg\min \text{GP}, \\
(Q_r, r) &\in \arg\min \text{RP}, \\
(Q_i, s) &\in \arg\min \text{IP}, \\
0 \leq Q_g + Q_r + Q_i &\perp f \geq 0, \\
(q(\omega), \theta(\omega)) &\in \arg\min \text{ISO}(\omega) \\
0 \leq E_i(\omega) &\perp p_i(\omega) \geq 0.
\end{aligned}$$

Transmission examples



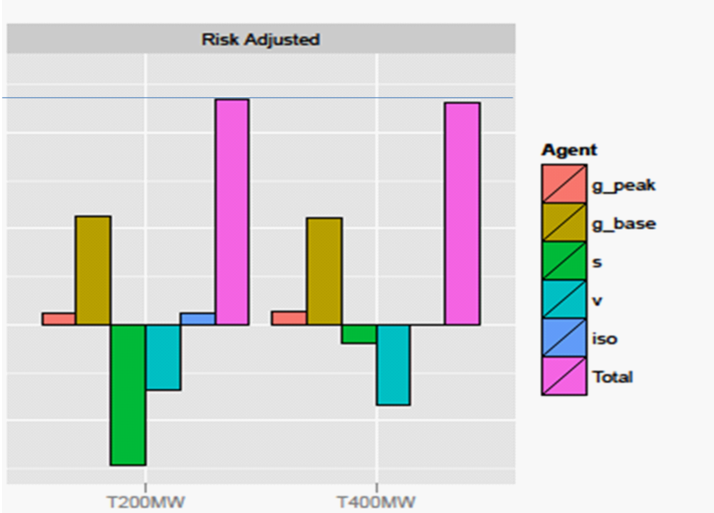
Transmission line increased from 200MW to 400 MW. This example uses (four) different inflow scenarios from previous example.

Transmission example



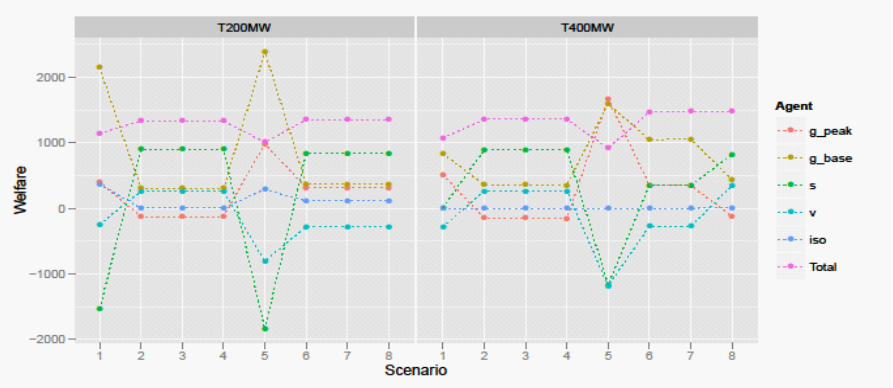
Generation capacities in equilibrium for a 200MW line and for a 400MW line. Baseload generator at node B faces increased competition from peaker, so decreases capacity.

Risk-adjusted welfare



Risk-adjusted welfare of each agent. Increased line capacity has reduced overall welfare.

Risk-adjusted welfare



Increasing line capacity has reduced profit of baseload generator in (dry) scenarios 1 and 5, as peaker can compete more at node B. System welfare is worse in (dry) scenarios 1 and 5, but better in others. Risk-adjusted welfare weights 1 and 5 more highly.

Summary

Conclusions from toy problems

- Risk aversion in equilibrium can lead to underinvestment.
- Vertical integration can exacerbate this effect if no contracting.
- Contracts appear to enable investments close to optimal social investment.
- Incompleteness and risk might lead to too much mothballing. Contracts help.
- Incompleteness and risk can make transmission expansion welfare decreasing. Contracts help.
- Next challenge for us is to move beyond toy problems.

References

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This is the end

THE END

SP capacity expansion: 822 MW thermal, 505 MW hydro

Welfare ($M)	Low retail demand				High retail demand				
Inflows	50%	75%	125%	150%	50%	75%	125%	150%	Expected
Thermal	-80.69	-81.58	-82.06	-82.12	442.76	55.86	-81.54	-81.83	1.10
Hydro	19.17	-41.72	-86.69	-85.19	181.29	140.53	-4.29	-80.55	5.32
Industry	163.93	211.27	230.57	230.61	158.03	159.18	210.72	229.31	199.20
Retailer	299.38	363.09	414.75	414.94	-315.98	249.63	543.58	618.05	323.43
Total	401.78	451.06	476.57	478.23	466.10	605.21	668.47	684.97	529.05
Price	$ 55.24	$ 19.21	$ 4.53	$ 4.50	$128.60	$ 74.19	$ 19.63	$ 5.49	$ 38.92

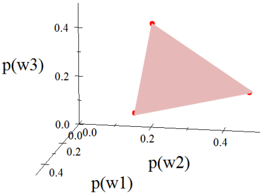
Benefits for each agent under a solution of a risk-neutral stochastic program.

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



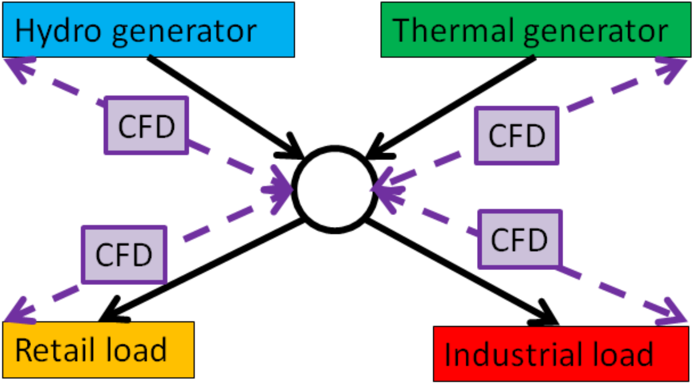
$$\rho(Z) = \max_{\mu\in\mathcal{D}} \mathbb{E}_{\mu}[Z] = \frac{1}{4}Z(\omega_1) + \frac{1}{4}Z(\omega_2) + \frac{1}{2}Z(\omega_3).$$

Risked equilibrium and social planning
(Heath and Ku 2004, Ralph and Smeers, 2011, Ehrenmann and Smeers, 2011)

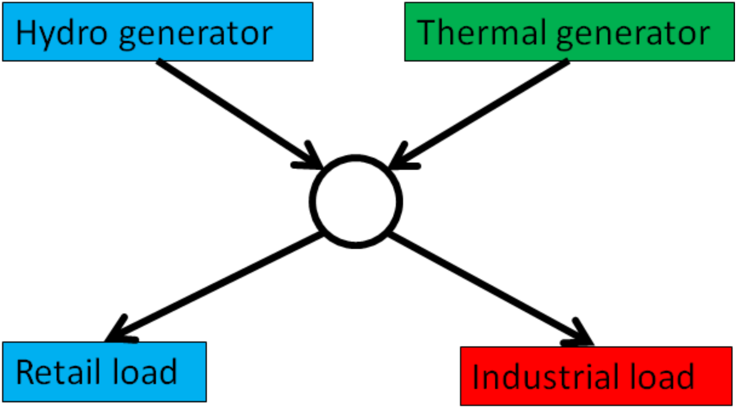
Model assumptions	Perfect competition (complete risk market)	Perfect competition (incomplete risk market)	Imperfect competition
Risk neutral agents	Competitive equilibrium gives socially efficient solution.	Competitive equilibrium gives socially efficient solution.	Nash equilibrium can result in social 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 with contracts

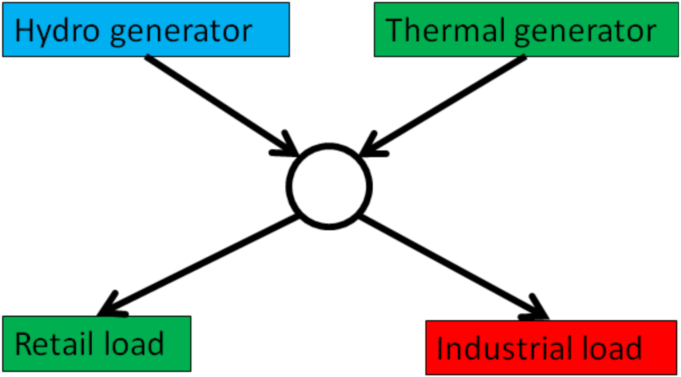


Vertically integrated hydro agent



With vertical integration there are three agents.

Vertically integrated thermal agent



With vertical integration there are three agents.

Risk-averse equilibrium: 650 MW thermal, 440 MW hydro

Welfare ($M)	Low retail demand				High retail demand					
Inflows	50%	75%	125%	150%	50%	75%	125%	150%	Expected	Risk Adj
Thermal	-42.76	-64.20	-64.85	-64.92	351.65	349.88	109.58	-44.03	66.29	0.70
Hydro	24.29	66.64	-51.28	-73.41	158.74	278.74	145.08	33.10	72.74	5.20
Industry	158.92	164.67	224.14	230.58	157.73	158.74	205.79	206.09	188.33	173.28
Retailer	273.70	300.72	397.53	414.79	-316.74	-314.13	221.95	506.20	185.50	-64.97
Total	414.15	467.84	505.54	507.03	351.37	473.22	682.40	701.36	512.87	447.81
Price	$ 59.06	$ 54.68	$ 9.42	$ 4.52	$128.82	$128.05	$ 50.31	$ 23.16	$ 57.25	

Benefits for each agent for the competitive equilibrium without vertical integration or contracts. 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 114.22. The orange figure 447.81 is risk-adjusted total social welfare. Complete market social welfare is 480.22.

With contracts: 750 MW thermal, 600 MW hydro

Welfare ($M)	Low retail demand				High retail demand					
Inflows	50%	75%	125%	150%	50%	75%	125%	150%	Expected	Risk Adj
Thermal	-126.55	30.25	93.88	93.99	28.90	164.40	28.90	89.83	50.45	0.81
Hydro	-9.36	10.41	-5.41	-3.65	-5.41	102.58	52.09	-1.46	17.47	5.04
Industry	170.16	199.95	212.04	212.06	199.69	225.10	199.69	211.24	203.74	194.33
Retailer	377.78	208.85	165.72	165.73	238.43	133.83	392.27	375.37	257.25	203.51
Total	412.03	449.46	466.22	468.13	461.61	625.91	672.96	674.98	528.91	479.83
Price	$ 54.90	$ 19.05	$ 4.50	$ 4.47	$128.26	$ 86.59	$ 19.36	$ 5.46	$ 40.32	

Benefits for each agent for the competitive equilibrium with contracts. There is more investment. Yellow cells identify the two worst scenarios. The orange figure 479.83 is risk-adjusted total social welfare. Complete market social welfare is 480.22.