ELECTRICITY GENERATION EXPANSION UNDER UNCERTAINTY AND RISK (IMPACT OF TRANSMISSION)

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(with help from Transpower)

EPOC Winter Workshop 2015

Department of Engineering Science
University of Auckland

INTRODUCTION

MOTIVATION

NZ coal power generation gone by 2018

By James Russell

9:43 AM Thursday Aug 6, 2015

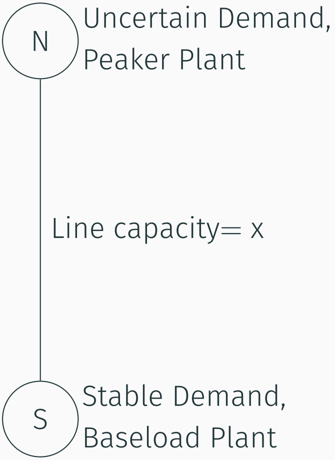
☆ 1.4k 57 22 0

Coal-fired generation at Huntly Power Station will cease by 2018. Photo: Christine Cornege

- Impact of CFDs vs VI
- Help justify transmission expansion.
- Current state of the art models are:
    - Deterministic.
    - System or plant focussed.
- Discrepancies between optimal and observed expansion.

COMPETITIVE AND SOCIAL WELFARE MODELS

- GEM minimises the social cost of construction and operation.
- Given investment decisions:
    - Perfect competition corresponds to minimising social cost.
- Perfect competition corresponds to GEM.
- Discrepancies caused by:
    - Imperfect competition/information.
    - Risk aversion.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Uncertain Demand,
Peaker Plant
Line capacity= x
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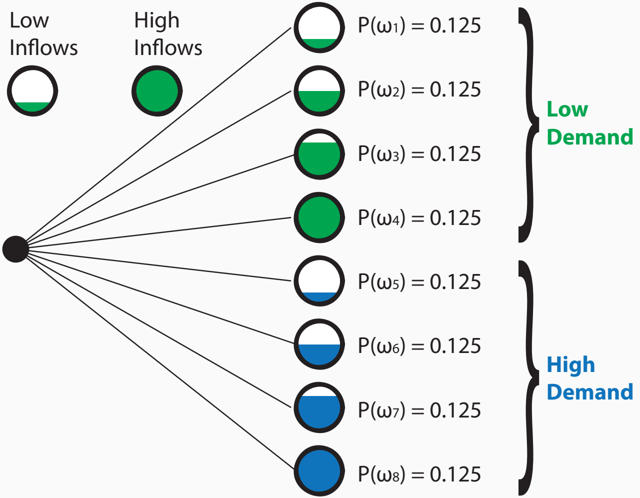
Stable Demand,
Baseload Plant

CASE STUDY: POTENTIAL OUTCOMES



GAMS MODEL

$$
\begin{aligned}
\text{SP}: \quad \min \quad & \text{Expansion Cost} + \sum_{\omega \in \Omega} \text{P}(\omega) \cdot \text{Operation Costs}(\omega) \\
\text{s.t.} \quad & \text{Operation Costs}(\omega) = \quad \text{Generation Cost}(\omega) \\
& \qquad\qquad - \text{Demand Revenue}(\omega) \\
& \qquad\qquad + \text{Curtailment Penalty}(\omega), \\
& \text{Generation}(\omega) \leq \text{Capacity}(\omega), \\
& \text{Curtailment}(\omega) \leq \text{Demand}(\omega), \\
& \text{Generation}(\omega) + \text{Curtailment}(\omega) = \text{Demand}(\omega), \\
& \text{Expansion}, \text{Generation}(\omega), \text{Curtailment}(\omega) \geq 0.
\end{aligned}
$$

COMPETITIVE GENERATION EXPANSION

- Profit-maximising agents that are a combination of:
  - Generators.
  - Retailers.
  - Industrial consumers.
- Each agent simultaneously solves a 2 stage stochastic optimisation problem.

Stage 0: Make generation expansion and contract decisions.

Stage 1: Offer available generation at marginal cost, earn/payout based on contract decisions and realised scenario.

- If no agent can improve their situation and all markets clear, then equilibrium found.

$$
\begin{aligned}
\text{GP}: \quad & \min \text{Expansion Cost} + \sum_{\omega \in \Omega} \text{P}(\omega) \cdot \text{Operation Costs}(\omega) \\
& \text{s.t.} \quad \text{Operation Costs}(\omega) = \quad \text{Generation Cost}(\omega) \\
& \qquad\qquad\qquad\qquad\qquad\quad - \text{Generation Revenue}(\omega), \\
& \qquad\quad \text{Generation}(\omega) \leq \text{Capacity}(\omega), \\
& \qquad\quad \text{Expansion}, \text{Generation}(\omega) \geq 0.
\end{aligned}
$$

$$
\begin{aligned}
\text{RP}: \quad & \min \sum_{\omega \in \Omega} \text{P}(\omega) \cdot \text{Operation Costs}(\omega) \\
\text{s.t.} \quad & \text{Operation Costs}(\omega) = \quad \text{Cost Meeting Demand}(\omega) \\
& \qquad\qquad\qquad\qquad\quad - \text{Demand Revenue}(\omega) \\
& \qquad\qquad\qquad\qquad\quad + \text{Curtailment Penalty}(\omega), \\
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\text{IP}: \quad & \min \sum_{\omega \in \Omega} \text{P}(\omega) \cdot \text{Operation Costs}(\omega) \\
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\text{AP}: \quad & \min \text{Expansion Cost} + \sum_{\omega \in \Omega} \text{P}(\omega) \cdot \text{Operation Costs}(\omega) \\
& \text{s.t.} \quad \text{Operation Costs}(\omega) = \quad \text{Generation Cost}(\omega) \\
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& \qquad\qquad\qquad\qquad\qquad\quad + \text{Cost Meeting Demand}(\omega) \\
& \qquad\qquad\qquad\qquad\qquad\quad - \text{Demand Revenue}(\omega) \\
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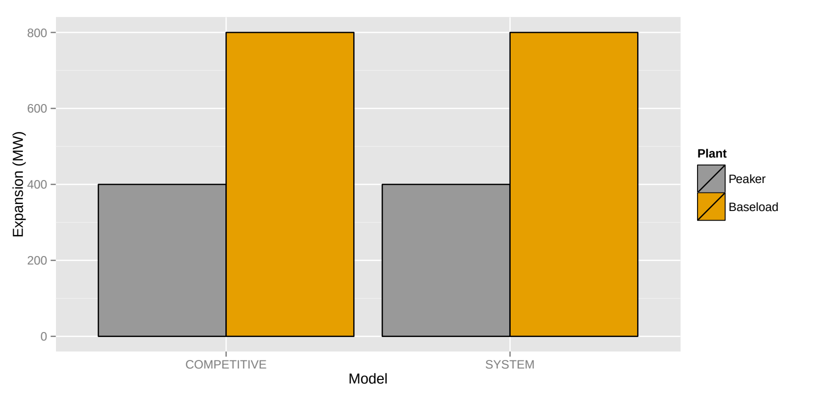
\end{aligned}
$$

- Formulated in GAMS
- EMP framework used to set up the KKT conditions
- Solved using PATH

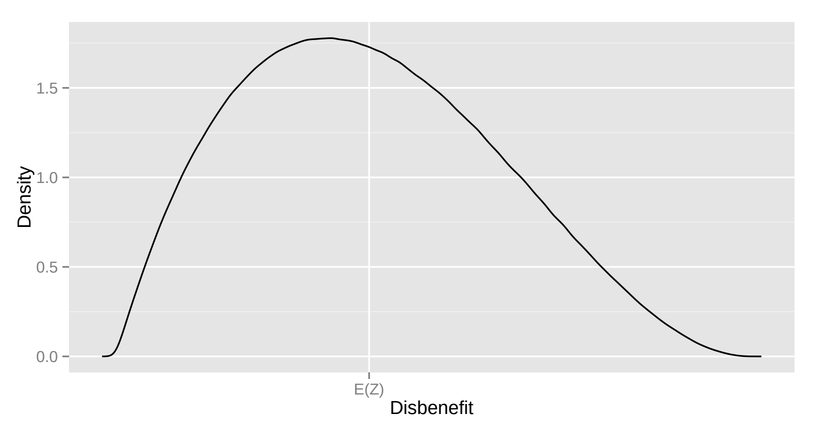
SYSTEM OPTIMAL VS COMPETITIVE MODEL EXPANSION

Simple example with risk neutral agents gives same expansion decisions



RISK AVERSION

Conditional Value at Risk (CVaR) is a coherent risk measure.



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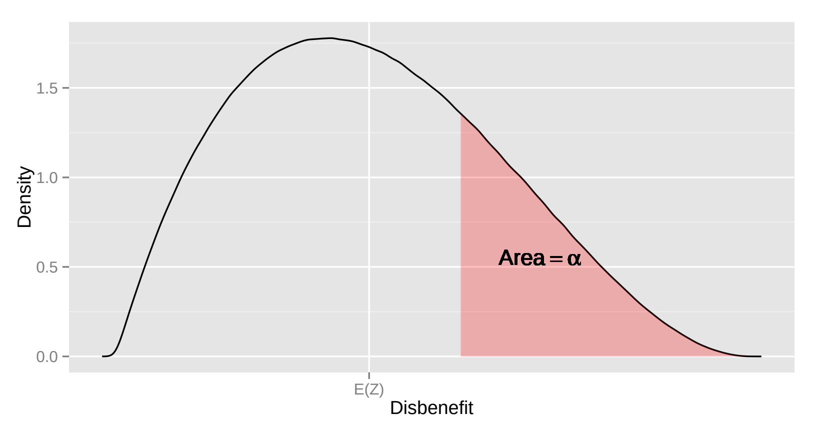

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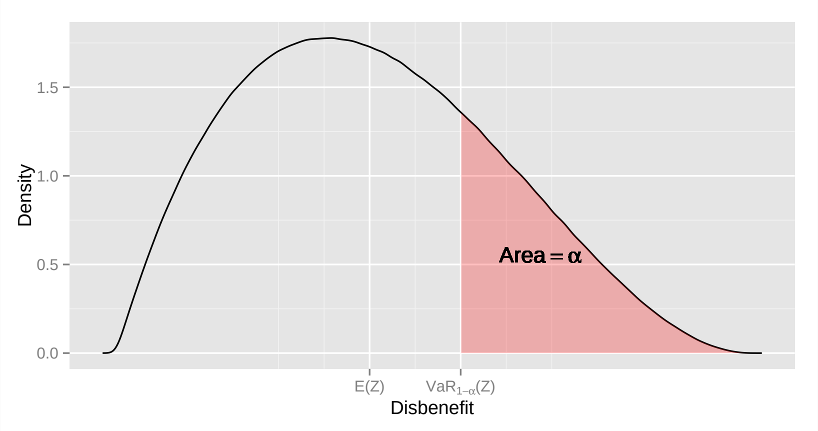

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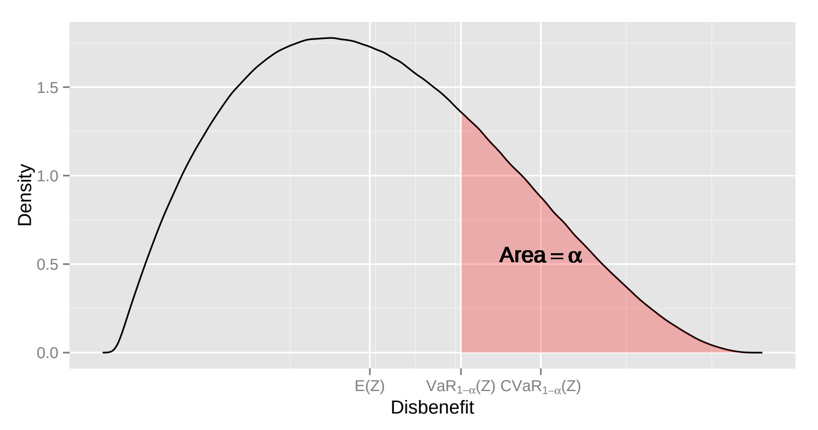
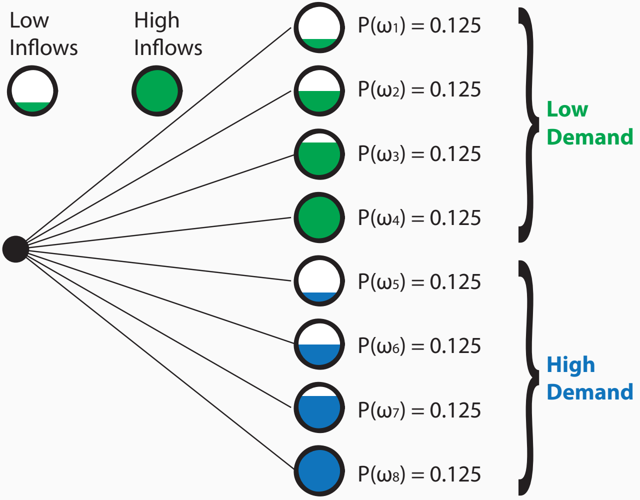
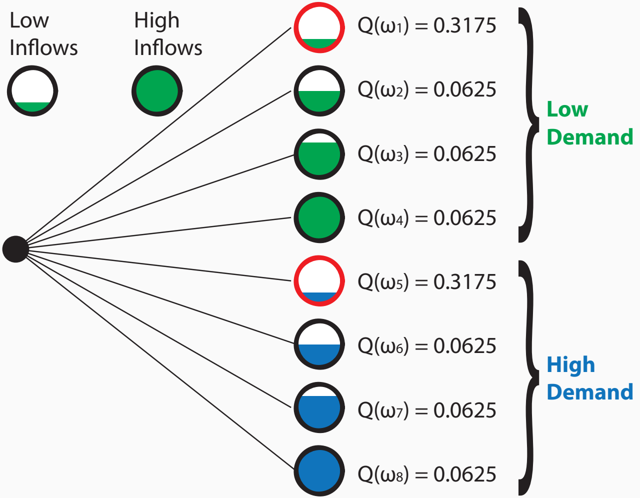
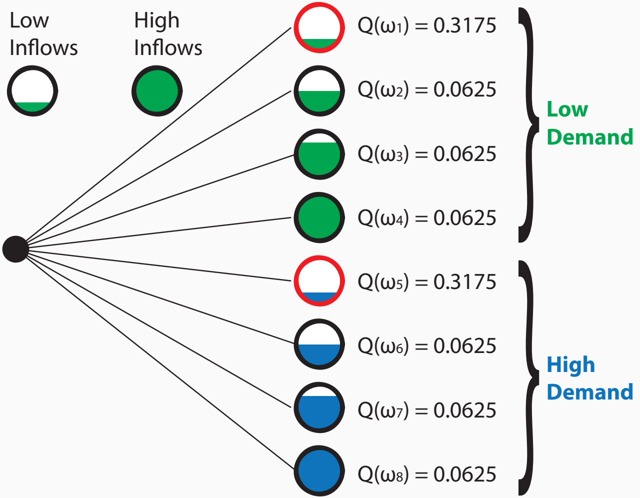


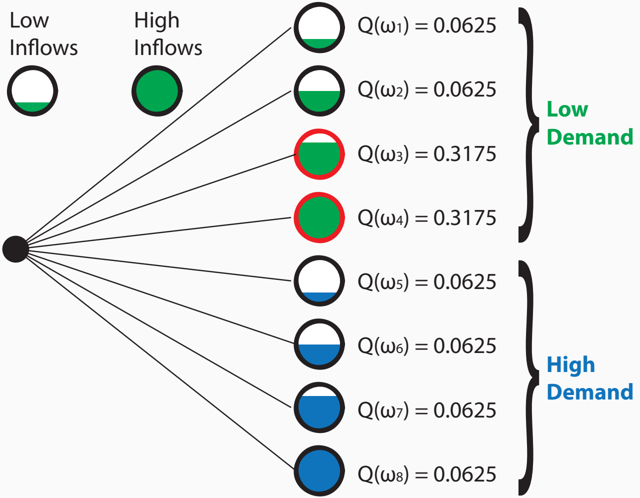

Low Inflows
High Inflows
P(ω1) = 0.125
P(ω2) = 0.125
P(ω3) = 0.125
P(ω4) = 0.125
P(ω5) = 0.125
P(ω6) = 0.125
P(ω7) = 0.125
P(ω8) = 0.125
Low Demand
High Demand

WORST SCENARIOS FOR SYSTEM




Low Inflows
High Inflows
Q(ω1) = 0.3175
Q(ω2) = 0.0625
Q(ω3) = 0.0625
Q(ω4) = 0.0625
Q(ω5) = 0.3175
Q(ω6) = 0.0625
Q(ω7) = 0.0625
Q(ω8) = 0.0625
Low Demand
High Demand

WORST SCENARIOS FOR GENERATOR



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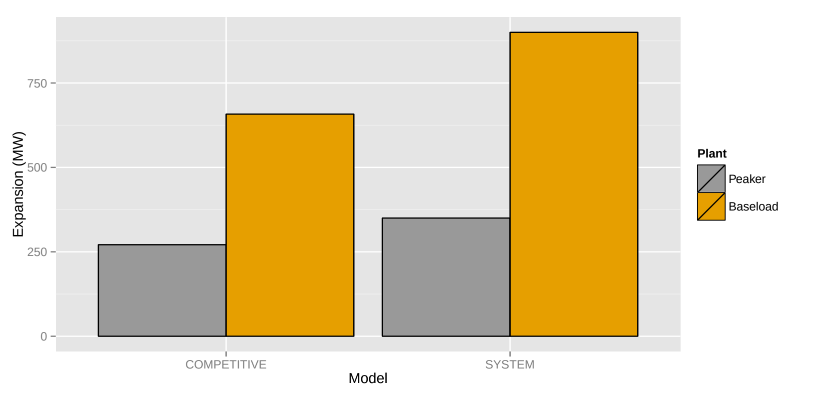
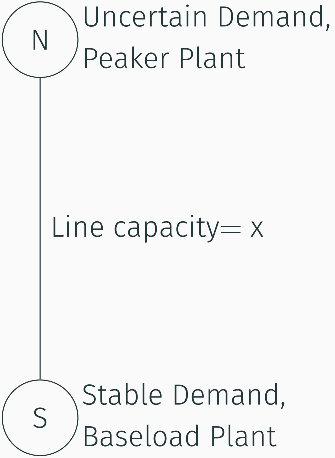
\end{aligned}$$

RISK AVERSE SYSTEM VS RISK AVERSE COMPETITION

Simple example with risk averse agents now gives different expansion decisions




N
Uncertain Demand,
Peaker Plant
Line capacity= x
S
Stable Demand,
Baseload Plant

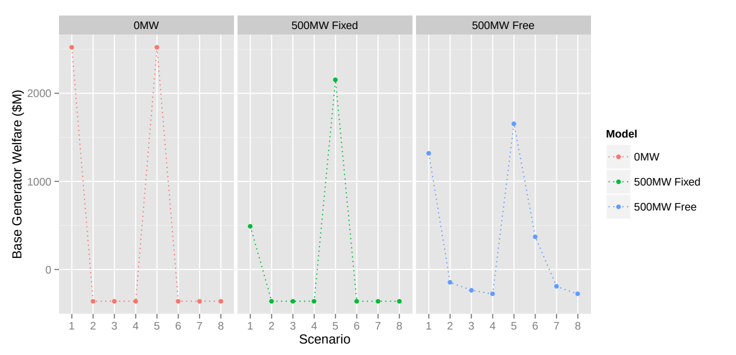
	Expansion		Risk Adjusted Welfare ($M)					
Line Cap	PEAK (N)	BASE (S)	G_{peak} (N)	G_{base} (S)	N	S	ISO	Total
0MW	1200	1800	0	0	-750	-1005	0	165
100MW	1100	1600	0	0	-958	-1005	108	89.1
500MW	1007	1386	0	0	-984	-675	32.6	61.5

EXPANSION AND RISK ADJUSTED WELFARE WITH CFDS

	Expansion		Risk Adjusted Welfare ($M)					
Line Cap	PEAK (N)	BASE (S)	G_{peak} (N)	G_{base} (S)	N	S	ISO	Total
0MW	1200	1800	0	0	-269	435	0	165
100MW	1100	2000	0	0	-269	435	35.5	203
500MW	874	2200	0	0	-195	435	53.2	367

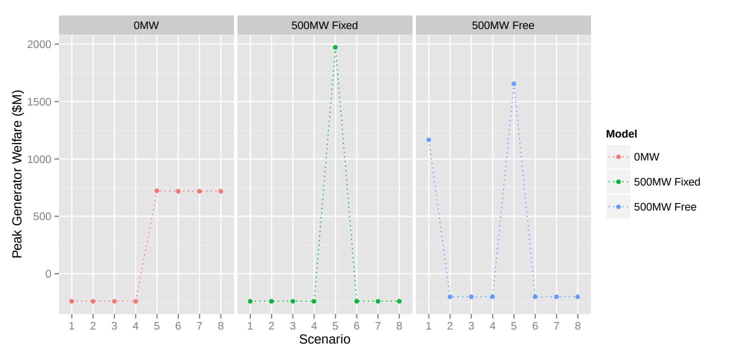
FIX 'BASE' EXPANSION TO 1800MW

		Expansion		Risk Adjusted Welfare ($M)					
	Line Cap	PEAK (N)	BASE (S)	G_{peak} (N)	G_{base} (S)	N	S	ISO	Total
No Contract	0MW	1200	1800	0	0	-750	-1005	0	165
	500MW Fixed	1007	1800	-85.4	-150	-645	-256	53.2	221
	500MW Free	1007	1386	0	0	-984	-675	32.6	61.5

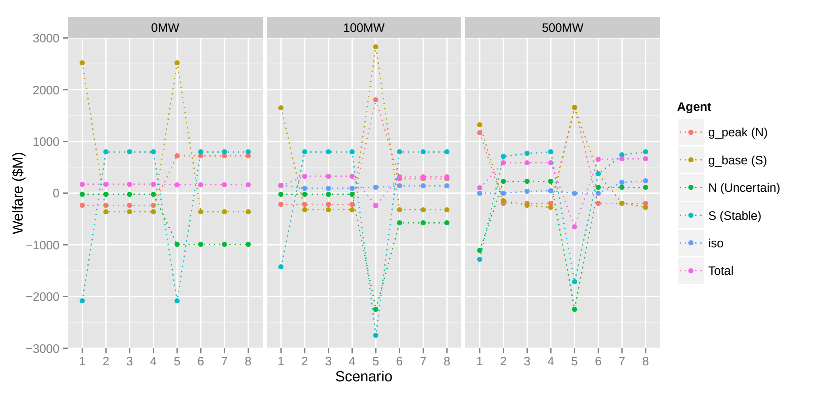


FIX 'PEAK' EXPANSION TO 1200MW

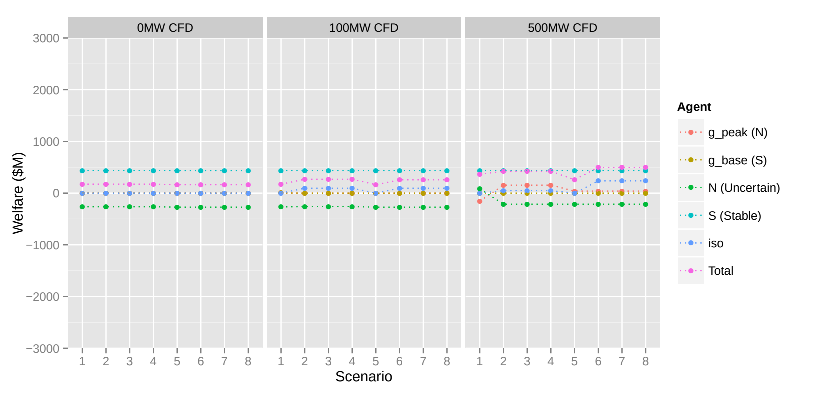
		Expansion		Risk Adjusted Welfare ($M)					
	Line Cap	PEAK (N)	BASE (S)	G_{peak} (N)	G_{base} (S)	N	S	ISO	Total
No Contract	0MW	1200	1800	0	0	-750	-1005	0	165
	500MW Fixed	1200	1386	-102	-66.7	-645	-288	35.5	134
	500MW Free	1007	1386	0	0	-984	-675	32.6	61.5



Welfare in each model for each scenario



Welfare in each model for each scenario with CFDs



OBSERVATIONS

- Increasing the capacity of the transmission line drives down the average price of generation due to less curtailment.
- Generation agents decide to expand less to compensate the fact they would receive less.
- Including the CFD greatly reduces the uncertainty in payoff and partially aligns generator payoff with system welfare.
- With the CFD, system welfare is higher with a larger transmission line.

CONCLUSIONS

CONCLUSIONS

- We have developed competitive models that incorporate risk aversion.
- Without contracts, risk aversion leads to underinvestment.
- In some circumstances, without these contracts, underinvestment can be exacerbated with a larger transmission line.
- CFDs are extremely useful in improving agent and system welfare.
- By aligning worst case scenarios towards that of the system, CFDs help ensure that having a larger transmission line is beneficial to the system.

QUESTIONS?

$$
\begin{aligned}
\text{SP}: \quad \min \quad & K(x_i) \quad + \quad \rho(Z) \\
\text{s.t.} \quad & Z(\omega) = G(y_i(\omega)) - r \cdot d_i(\omega) + v \cdot \delta_i(\omega), \\
& y_i(\omega) \leq x_i \cdot \phi(\omega), \\
& \delta_i(\omega) \leq d_i(\omega), \\
& 0 \leq y_i(\omega) + \delta_i(\omega) + f_{j,i}(\omega) - d_i(\omega) - f_{i,j}(\omega) - L_i(\omega) \\
& L_i(\omega) = \sum_{(i,j)\in\mathcal{L}} \frac{c_{i,j}(\omega)}{2} \cdot (f_{i,j}(\omega))^2 + \sum_{(j,i)\in\mathcal{L}} \frac{c_{j,i}(\omega)}{2} \cdot (f_{j,i}(\omega))^2 \\
& f_{i,j}(\omega) \leq f^{+}_{i,j}(\omega), \\
& f_{i,j}(\omega) \geq f^{-}_{i,j}(\omega), \\
& f_{i,j}(\omega) = \frac{1}{c_{j,i}(\omega)} \cdot (\theta_i(\omega) - \theta_j(\omega)) \\
& \theta_0(\omega) = 0, \quad x_i, y_i(\omega), \delta_i(\omega) \geq 0.
\end{aligned}
$$

$$\begin{aligned}
\text{AP}: \quad \min \quad & K(x) && + \quad \rho^a(Z^a) \\
Z^a(\omega) \quad = \quad & G(y_i(\omega)) - \pi(\omega) \cdot y_i(\omega) && \\
& && +(\pi_i(\omega) - p_i^a) \cdot d_i(\omega) \\
& && +(v_i^a - \pi_i(\omega)) \cdot \delta_i(\omega), \\
& y_i(\omega) && \leq \quad x_i \cdot \phi_i(\omega), \\
& \delta_i(\omega) && \leq \quad d_i(\omega), \\
& x_i, y_i(\omega), \delta_i(\omega) \quad \geq \quad 0. &&
\end{aligned}$$

INDEPENDENT SYSTEM OPERATOR PROBLEM

$$\mathrm{IP}(\omega): \quad \min \quad \sum_{(i,j)\in\mathcal{L}} (\pi_i(\omega) - \pi_j(\omega)) \cdot f_{i,j}(\omega) + \sum_{i\in\mathcal{I}} L_i(\omega) \cdot \pi_i(\omega)$$

$$\begin{aligned}
\text{s.t.} \quad L_i(\omega) &= \sum_{(i,j)\in\mathcal{L}} \frac{c_{i,j}(\omega)}{2} \cdot (f_{i,j}(\omega))^2 + \sum_{(j,i)\in\mathcal{L}} \frac{c_{j,i}(\omega)}{2} \cdot (f_{j,i}(\omega))^2 \\
f_{i,j}(\omega) &\leq f^+_{i,j}(\omega), \\
f_{i,j}(\omega) &\geq f^-_{i,j}(\omega), \\
f_{i,j}(\omega) &= \frac{1}{c_{j,i}(\omega)} \cdot (\theta_i(\omega) - \theta_j(\omega)) \\
\theta_0(\omega) &= 0.
\end{aligned}$$

COMPETITIVE EQUILIBRIUM CONDITIONS

$$(x, y, \delta) \in \arg\min AP,$$
$$(f, \theta, L) \in \arg\min IP,$$
$$0 \leq y_i(\omega) + \delta_i(\omega) + f_{j,i}(\omega) - d_i(\omega) - f_{i,j}(\omega) - L_i(\omega) \perp \pi_i(\omega) \geq 0.$$