

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

C. Kok A. Philpott G. Zakeri
(with help from Transpower)

EPOC 2016

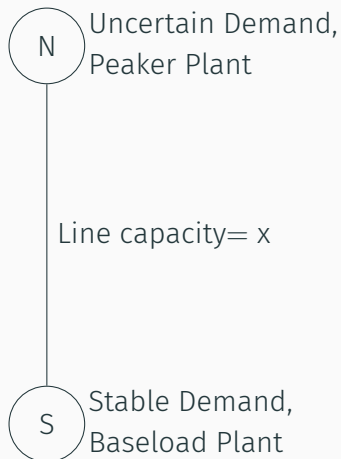
Department of Engineering Science
University of Auckland

INTRODUCTION

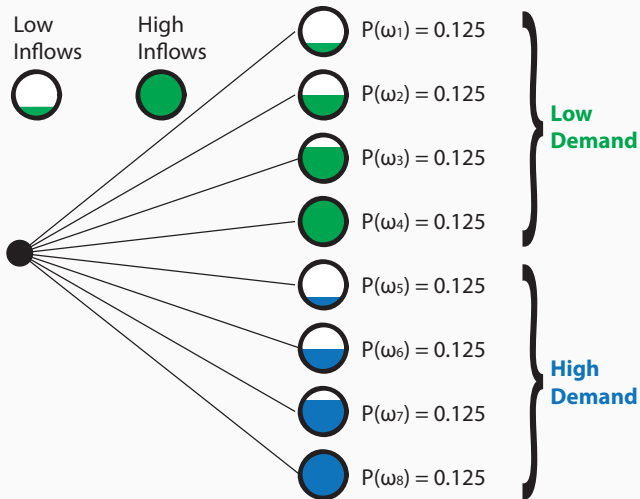
- Impact of CFDs vs VI
- Help justify transmission expansion.
- Current state of the art models are:
 - Deterministic.
 - System or plant focussed.
- Discrepancies between optimal and observed expansion.

- 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.

CASE STUDY: NETWORK LAYOUT



CASE STUDY: POTENTIAL OUTCOMES



GAMS MODEL

$$\text{SP : } \min \quad \text{Expansion Cost} + \sum_{\omega \in \Omega} P(\omega) \cdot \text{Operation Costs}(\omega)$$

$$\begin{aligned} \text{s.t.} \quad \text{Operation Costs}(\omega) = & \quad \text{Generation Cost}(\omega) \\ & \quad - \text{Demand Revenue}(\omega) \\ & \quad + \text{Curtailment Penalty}(\omega), \\ \text{Generation}(\omega) \leq & \quad \text{Capacity}(\omega), \\ \text{Curtailment}(\omega) \leq & \quad \text{Demand}(\omega), \\ \text{Generation}(\omega) + & \quad \text{Curtailment}(\omega) = \text{Demand}(\omega), \\ \text{Expansion, Generation}(\omega), & \quad \text{Curtailment}(\omega) \geq 0. \end{aligned}$$

- 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.

$$\text{GP : } \min \text{ Expansion Cost} + \sum_{\omega \in \Omega} P(\omega) \cdot \text{Operation Costs}(\omega)$$

$$\begin{aligned} \text{s.t. } \text{Operation Costs}(\omega) &= \text{Generation Cost}(\omega) \\ &\quad - \text{Generation Revenue}(\omega), \\ \text{Generation}(\omega) &\leq \text{Capacity}(\omega), \\ \text{Expansion, Generation}(\omega) &\geq 0. \end{aligned}$$

$$\text{RP : } \min \sum_{\omega \in \Omega} P(\omega) \cdot \text{Operation Costs}(\omega)$$

$$\begin{aligned} \text{s.t. } \text{Operation Costs}(\omega) = & \text{Cost Meeting Demand}(\omega) \\ & - \text{Demand Revenue}(\omega) \\ & + \text{Curtailment Penalty}(\omega), \\ \text{Curtailment}(\omega) \leq & \text{Demand}(\omega), \\ \text{Curtailment}(\omega) \geq & 0. \end{aligned}$$

$$\text{IP : } \min \sum_{\omega \in \Omega} P(\omega) \cdot \text{Operation Costs}(\omega)$$

$$\begin{aligned} \text{s.t. } \text{Operation Costs}(\omega) &= \text{Cost Meeting Demand}(\omega) \\ &\quad - \text{Demand Revenue}(\omega), \\ \text{Curtailment}(\omega) &\leq \text{Demand}(\omega), \\ \text{Curtailment}(\omega) &\geq 0. \end{aligned}$$

$$\text{AP : } \min \text{ Expansion Cost} + \sum_{\omega \in \Omega} P(\omega) \cdot \text{Operation Costs}(\omega)$$

$$\begin{aligned} \text{s.t. } \text{Operation Costs}(\omega) = & \text{Generation Cost}(\omega) \\ & - \text{Generation Revenue}(\omega) \\ & + \text{Cost Meeting Demand}(\omega) \\ & - \text{Demand Revenue}(\omega) \\ & + \text{Curtailment Penalty}(\omega), \end{aligned}$$

$$\text{Generation}(\omega) \leq \text{Capacity}(\omega),$$

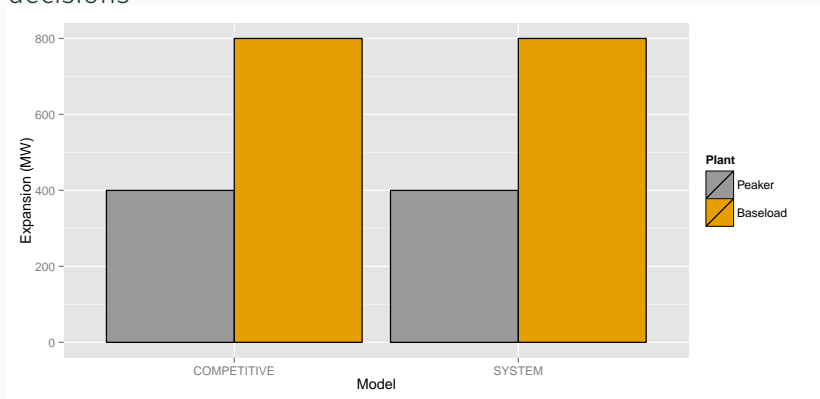
$$\text{Curtailment}(\omega) \leq \text{Demand}(\omega),$$

$$\text{Expansion, Generation}(\omega), \text{Curtailment}(\omega) \geq 0.$$

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

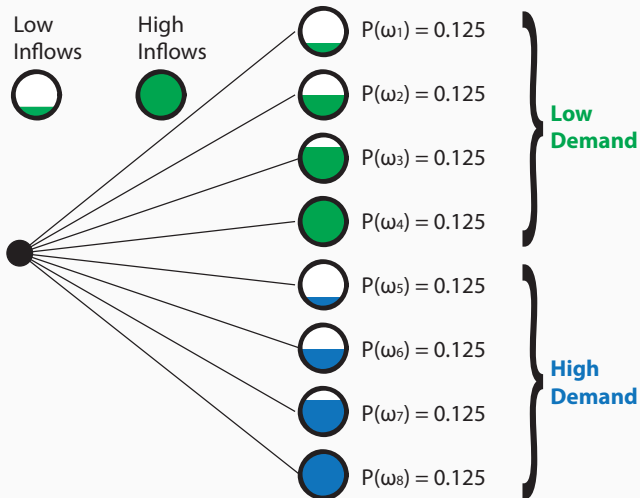
SYSTEM OPTIMAL VS COMPETITIVE MODEL EXPANSION

Simple example with risk neutral agents gives same expansion decisions

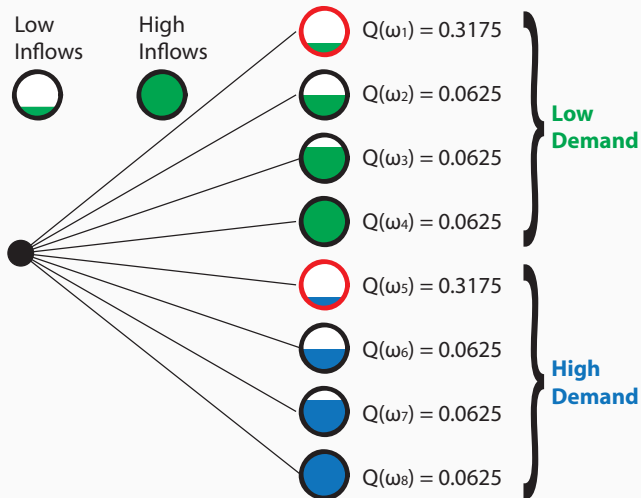


RISK AVERSION

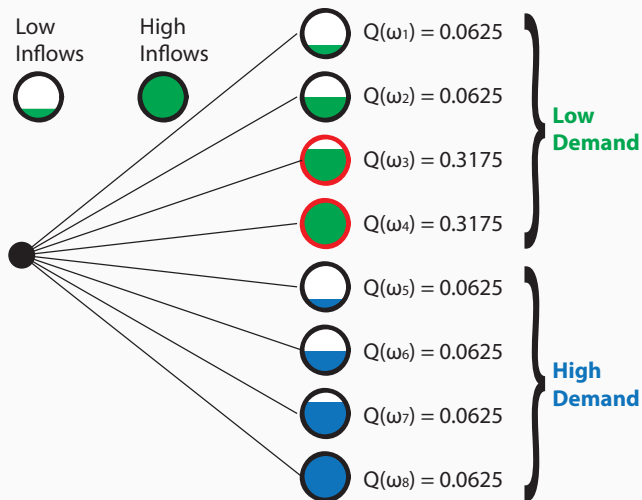
CASE STUDY: POTENTIAL OUTCOMES



WORST SCENARIOS FOR SYSTEM



WORST SCENARIOS FOR GENERATOR



$$\text{SP : } \min \quad \text{Expansion Cost} + \sum_{\omega \in \Omega} Q(\omega) \cdot \text{Operation Costs}(\omega)$$

$$\begin{aligned} \text{s.t.} \quad \text{Operation Costs}(\omega) = & \text{Generation Cost}(\omega) \\ & - \text{Demand Revenue}(\omega) \\ & + \text{Curtailment Penalty}(\omega), \\ \text{Generation}(\omega) \leq & \text{Capacity}(\omega), \\ \text{Curtailment}(\omega) \leq & \text{Demand}(\omega), \\ \text{Generation}(\omega) + \text{Curtailment}(\omega) = & \text{Demand}(\omega), \\ \text{Expansion, Generation}(\omega), \text{Curtailment}(\omega) \geq & 0. \end{aligned}$$

$$\text{AP : } \min \text{ Expansion Cost} + \sum_{\omega \in \Omega} Q(\omega) \cdot \text{Operation Costs}(\omega)$$

$$\begin{aligned} \text{s.t. } \text{Operation Costs}(\omega) = & \text{Generation Cost}(\omega) \\ & - \text{Generation Revenue}(\omega) \\ & + \text{Cost Meeting Demand}(\omega) \\ & - \text{Demand Revenue}(\omega) \\ & + \text{Curtailment Penalty}(\omega), \end{aligned}$$

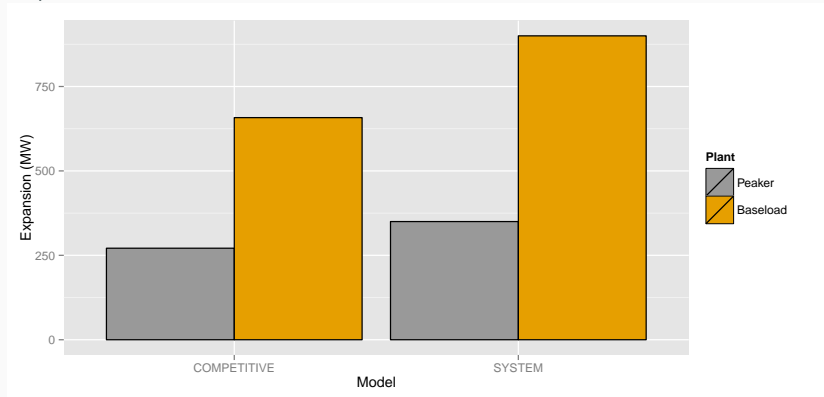
$$\text{Generation}(\omega) \leq \text{Capacity}(\omega),$$

$$\text{Curtailment}(\omega) \leq \text{Demand}(\omega),$$

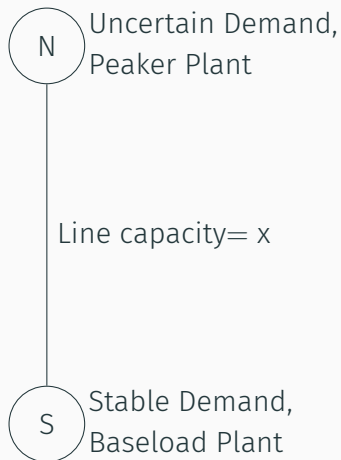
$$\text{Expansion, Generation}(\omega), \text{ Curtailment}(\omega) \geq 0.$$

RISK AVERSE SYSTEM VS RISK AVERSE COMPETITION

Simple example with risk averse agents now gives different expansion decisions



CASE STUDY: NETWORK LAYOUT



EXPANSION AND RISK ADJUSTED WELFARE

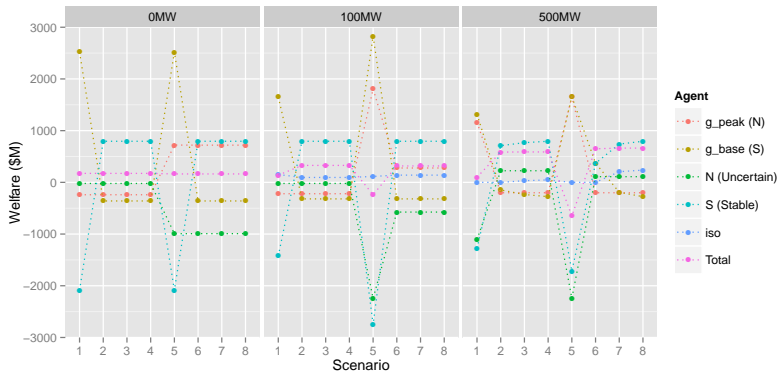
Line Cap	Expansion		Risk Adjusted Welfare (\$M)					
	PEAK (N)	BASE (S)	G_{peak} (N)	G_{base} (S)	N	S	ISO	Total
0MW	1200	1800	0	0	-750	-1005	0	165
100MW	1100	1600	0	0	-958	-1005	108	89.1
500MW	1007	1386	0	0	-984	-675	32.6	61.5

EXPANSION AND RISK ADJUSTED WELFARE WITH CFDS

Line Cap	Expansion		Risk Adjusted Welfare (\$M)					
	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

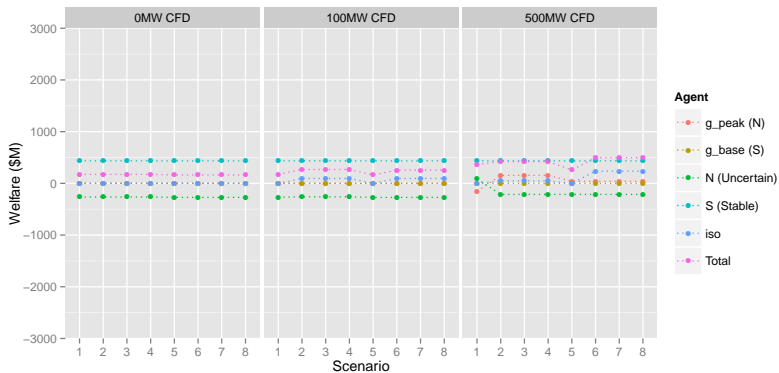
WELFARE ACROSS SCENARIOS

Welfare in each model for each scenario



WELFARE ACROSS SCENARIOS

Welfare in each model for each scenario with CFDs



- 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

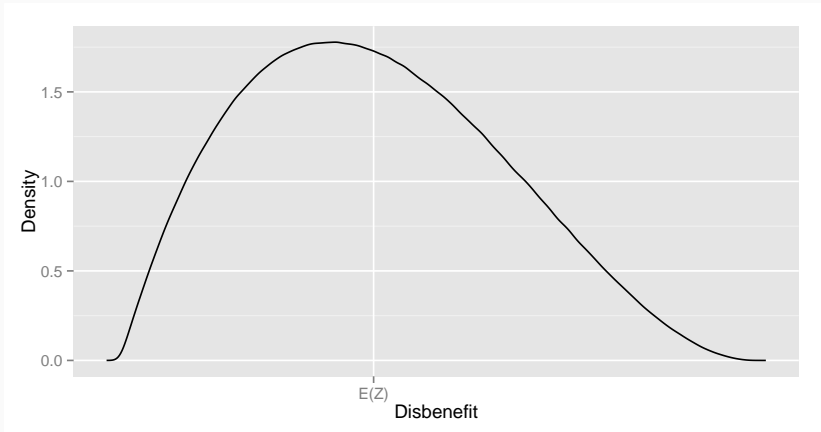
CONCLUSIONS

- 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.

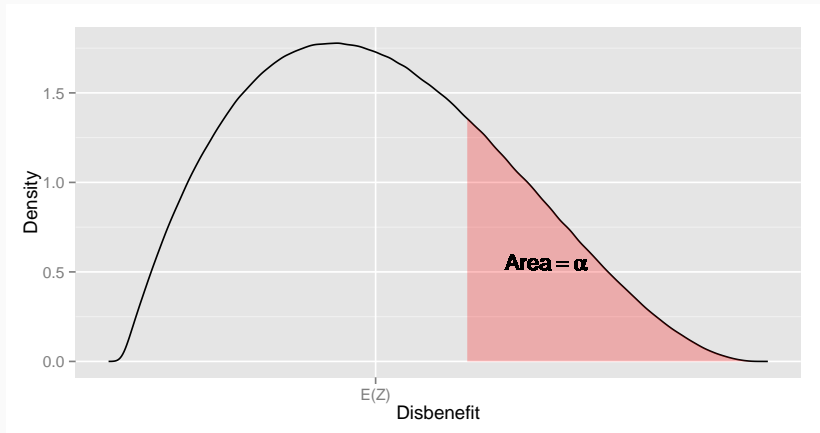
QUESTIONS?

APPENDIX

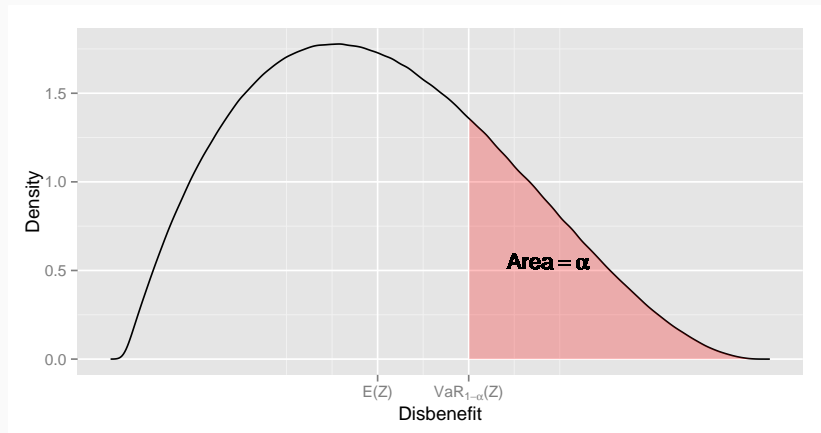
Conditional Value at Risk (CVaR) is a coherent risk measure.



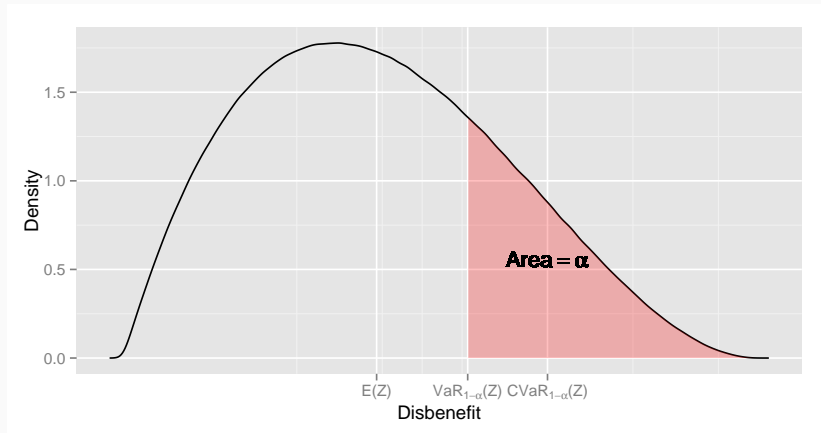
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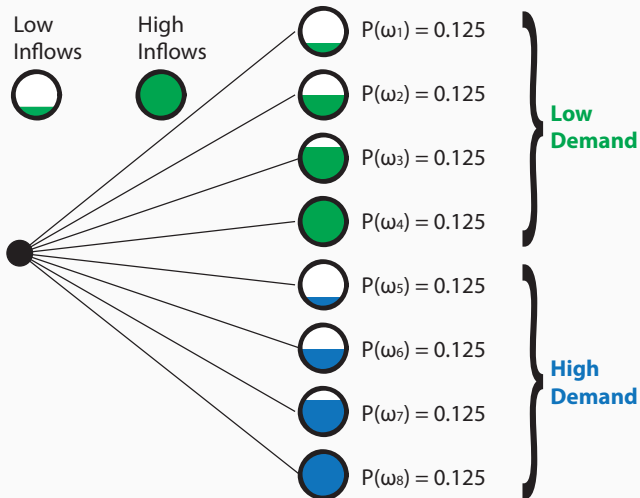
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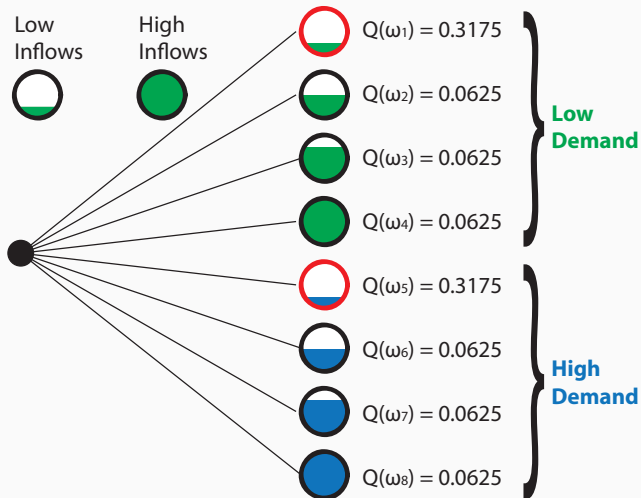
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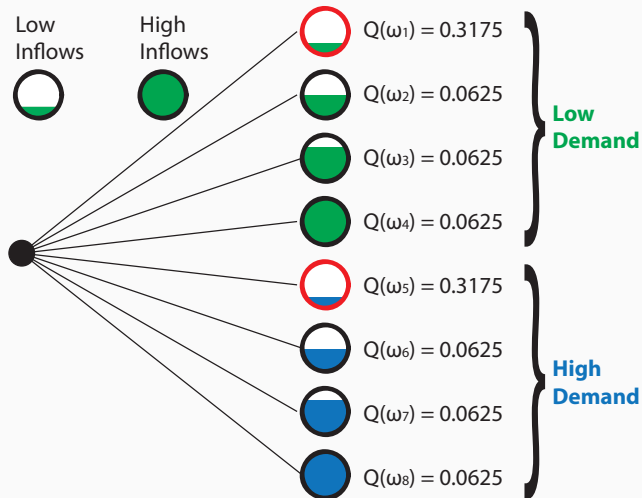
CASE STUDY: POTENTIAL OUTCOMES



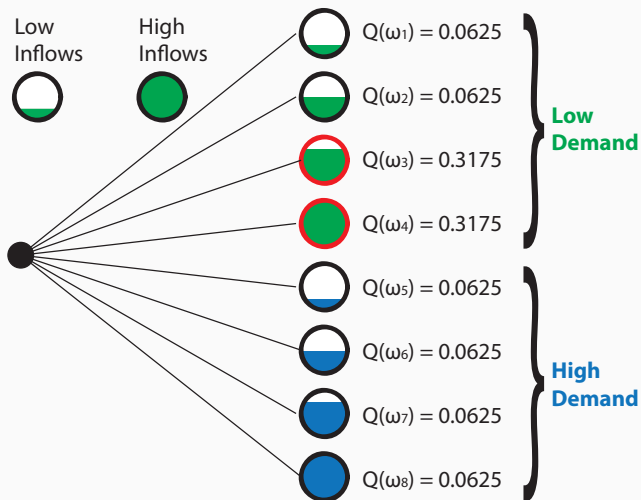
WORST SCENARIOS FOR SYSTEM



WORST SCENARIOS FOR RETAILER AND INDUSTRIAL



WORST SCENARIOS FOR GENERATOR



$$\text{SP : } \min \quad K(x_i) \quad + \quad \rho(Z)$$

$$\text{s.t. } Z(\omega) = G(y_i(\omega)) - r \cdot d_i(\omega) + v \cdot \delta_i(\omega),$$

$$y_i(\omega) \leq x_i \cdot \phi(\omega),$$

$$\delta_i(\omega) \leq d_i(\omega),$$

$$0 \leq y_i(\omega) + \delta_i(\omega) + f_{j,i}(\omega) - d_i(\omega) - f_{i,j}(\omega) - L_i(\omega)$$

$$L_i(\omega) = \sum_{(i,j) \in \mathcal{L}} \frac{c_{i,j}(\omega)}{2} \cdot (f_{i,j}(\omega))^2 + \sum_{(j,i) \in \mathcal{L}} \frac{c_{j,i}(\omega)}{2} \cdot (f_{j,i}(\omega))^2$$

$$f_{i,j}(\omega) \leq f_{i,j}^+(\omega),$$

$$f_{i,j}(\omega) \geq f_{i,j}^-(\omega),$$

$$f_{i,j}(\omega) = \frac{1}{c_{j,i}(\omega)} \cdot (\theta_i(\omega) - \theta_j(\omega))$$

$$\theta_0(\omega) = 0, \quad x_i, y_i(\omega), \delta_i(\omega) \geq 0.$$

$$\text{AP : } \min \quad K(x) + \rho^a(Z^a)$$

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

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

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

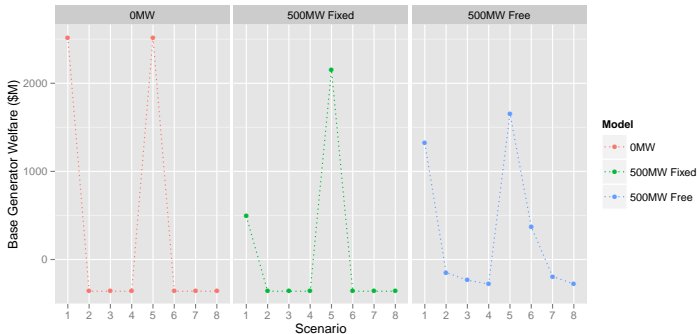
$$(x, y, \delta) \in \arg \min AP,$$

$$(f, \theta, L) \in \arg \min IP,$$

$$0 \leq y_i(\omega) + \delta_i(\omega) + f_{j,i}(\omega) - d_i(\omega) - f_{i,j}(\omega) - L_i(\omega) \perp \pi_i(\omega) \geq 0.$$

FIX 'BASE' EXPANSION TO 1800MW

	Line Cap	Expansion		Risk Adjusted Welfare (\$M)					
		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

	Line Cap	Expansion		Risk Adjusted Welfare (\$M)					
		PEAK (N)	BASE (S)	$G_{\text{peak}} (N)$	$G_{\text{base}} (S)$	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

