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Edward J. Bloustein School
of Planning and Public Policy

Role of Governance in Independent Decision Making for Building Electric Infrastructure Resilience

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Center for Energy, Economic and Environmental Policy

Gene X. Shan and Frank A. Felder

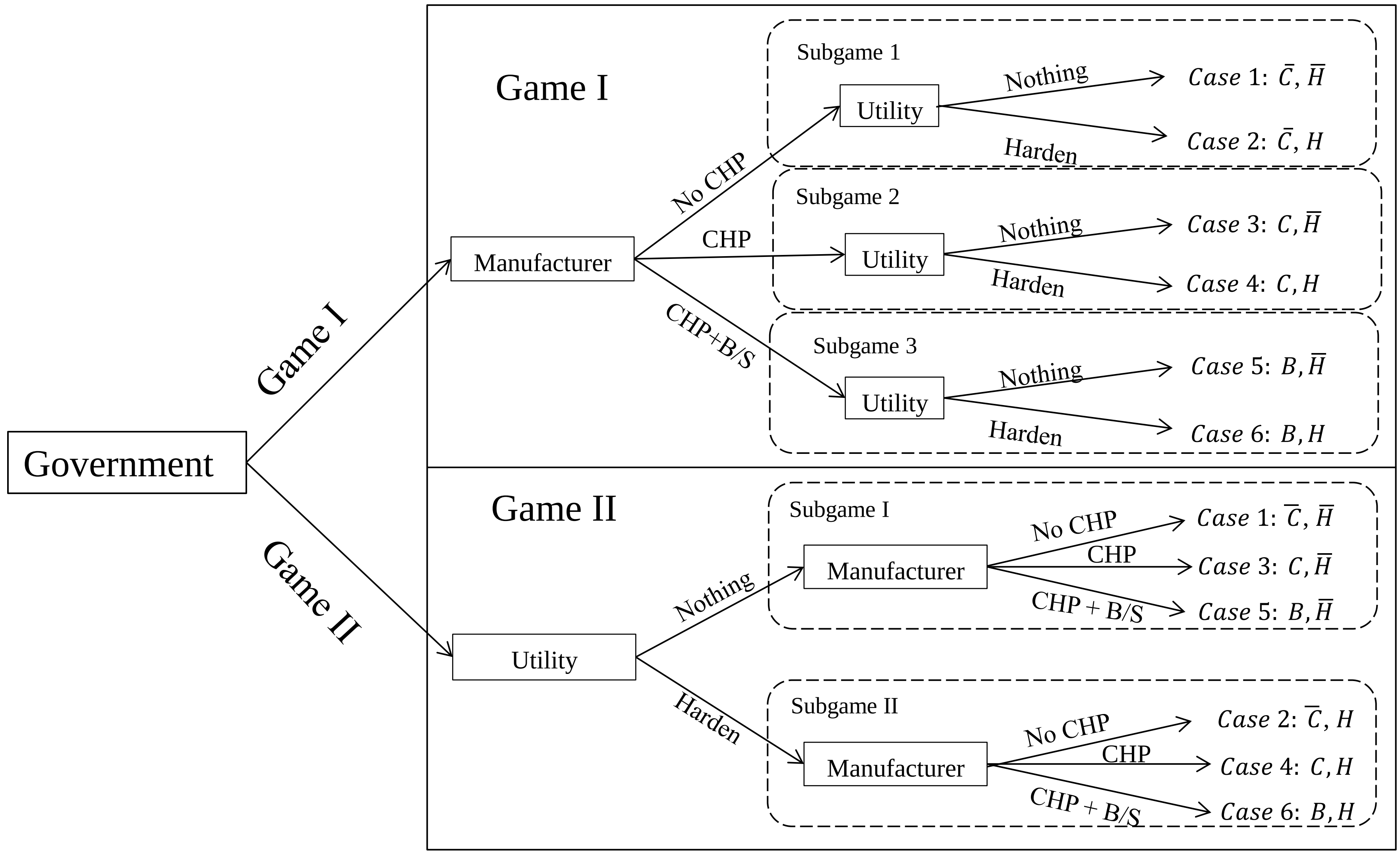
Department of Industrial and Systems Engineering

David W. Coit

Outline

- Introduction and background
- Sequential game-theoretic model of Government, Utility and Manufacturer
- 2 Key questions
  - Does order of decision-making between Utility and Manufacturer matter?
  - What might happen in reality?
- Conclusion

Game formulation when either manufacturer or utility moves first



Public vs. Private resiliency investments

Use alternate materials for stronger poles
http://www.fplenergyservices.com/storm/stormsecure/hardening.shtml

Flood walls
Photo: Brian A. Pounds
Source: http://www.ctpost.com/local/article/UI-hardens-substations-against-high-water-4682439.php

Combined Heat-Power Plant (CHP)
http://www.cospp.com/articles/print/volume-11/issue-2/Project_Profile/cogeneration-plant-to-boost-output-at-dubai-aluminium.html

Diesel backup generator
http://www.shutterstock.com/pic-88581673/stock-photo-high-voltage-industrial-standby-diesel-generator-at-a-power-generation-plant-in-a-textile-factory.html

Notation	Description
$l = 24$	Outage length (Hrs)
$p_H^l = 0.1$	Probability of l-hour outage in a year given grid is hardened (%)
$p_N^l = 0.8$	Probability of l-hour outage in a year given grid is not hardened (%)
$K = 1$	Cost of grid hardening ($million) to Utility
$c_H = 0.1$	Cost of grid hardening ($million) to Manufacturer
$V^M(l) = 5{,}000$ $V^W(l) = 50{,}000$	Value of lost load (VOLL) from an l-hour outage for Manufacturer and the other customer ($/kWh)
$h_O = 8{,}322$	Hours of CHP operation in a year (Hrs) implying Capacity Factor=95%
$e^W(t) = 15.7$ [a]	Cost of annual electricity consumption ($million) for the other customer
$i = 0.59$	Incentive given to Manufacturer for installing a CHP ($million) regardless of blackstart capability
$e^M(t) = 1.57$ [a]	Cost of annual electricity consumption ($million) to Manufacturer
$e_c^M(t) = 0.42$ [a]	Cost of annual electricity consumption with a CHP ($million) to Manufacturer

Notation	Description
$M = 8{,}760$	Hours in a year (Hrs)
t	Time period (y), from 0 to 20 years
$k = 1{,}070$	CHP electric capacity (kW)
$c = 3.82$	Cost of buying a CHP ($million)
$b = 3.958$	Cost of buying a CHP with black-start capability ($million)
$c_O(h_O) = 0.1$ [a]	Annual operation and maintenance cost of a CHP ($million)
$D = 1{,}200$, $D^W = 12{,}000$	Manufacturer's and the other customer's average hourly demands (kW)
$S(h_O, D) = 0.11$ [a]	Annual standby charge ($million)
$g = 0.62$ [a]	Cost of annual gas consumption ($million) to Manufacturer
$g_c = 1.09$ [a]	Cost of annual gas consumption with a CHP ($million) to Manufacturer
$r^e = 1.98$	Electric tariff escalation (% per year)
$r^g = 3.20$	Gas tariff escalation (% per year)
$d = 8$	Discount rate (% per year)

Manufacturer: CHP+B/S, Utility: Harden

Manufacturer payoff:

Year 0

$$\underbrace{\left(\frac{\sum_l p_H^l * (M-1) + (1-\sum_l p_H^l) * M}{M}\right)}_{\text{(Prob. of Normal Operation)}} * \underbrace{(e^M + g)}_{\text{(Energy Use without CHP)}} + \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} \underbrace{* l * D * v^H(l)}_{\text{(VOLL)}} + \underbrace{b - i + c_H}_{\text{(Capital Costs)}}$$

Year 1-20

$$+\sum_{t=1}^{20} \underbrace{\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right)}_{\text{(Prob. of Normal Operation)}} * \underbrace{\left(e_c^M + g_c + S(h_o, D) + c_o(h_o)\right)}_{\text{(Energy\& OM Costs with CHP)}} * \underbrace{(1-d)^t}_{\text{(Discount)}} + \sum_{t=1}^{20} \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} * \underbrace{(g_c^b(l) + c_o(h_o))}_{\text{(Energy\& OM Costs with CHP at outage)}} * \underbrace{(1-d)^t}_{\text{(Discount)}}$$

Utility payoff:

Year 0 / Year 1-20

$$\underbrace{K - \sum_t fK(1-d)^t}_{\text{(Capital Costs with Overtime Return)}} - \underbrace{\left(\frac{\sum_l p_H^l * (M-1) + (1-\sum_l p_H^l) * M}{M}\right)}_{\text{(Prob. of Normal Operation)}} * \underbrace{(e^M + e^W)}_{\text{(Electricity Tariff)}} + \sum_{t=1}^{20} \underbrace{\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right)}_{\text{(Prob. of Outage)}} * \underbrace{(e_c^M + e^W)}_{\text{(Electricity Tariff)}} * \underbrace{(1-d)^t}_{\text{(Discount)}}$$

Society payoff:

Year 0

$$\underbrace{\left(\frac{\sum_l p_H^l * (M-1) + (1-\sum_l p_H^l) * M}{M}\right)}_{\text{(Prob. of Normal Operation)}} * \underbrace{(e^M + g)}_{\text{(Energy Use without CHP)}} + \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} \underbrace{* l * D * \left(v^H(l) + v^W(l)\right)}_{\text{(VOLL)}} + \underbrace{b + c_H}_{\text{(Capital Costs)}}$$

Year 1-20

$$+\sum_{t=1}^{20} \underbrace{\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right)}_{\text{(Prob. of Normal Operation)}} * \underbrace{\left(g_c + S(h_o, D) + c_o(h_o) - u * n(h_o)\right)}_{\text{(Gas\& OM Costs with CHP – Emission Reduction)}} * \underbrace{(1-d)^t}_{\text{(Discount)}} + \sum_{t=1}^{20} \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} * \underbrace{(g_c^b(l) + c_o(h_o) + D * v^W(l))}_{\text{(Gas\& OM Costs with CHP \& VOLL at outage)}} * \underbrace{(1-d)^t}_{\text{(Discount)}}$$

Case	Manufacturer Payoff	Utility payoff	Society payoff
1. $\bar{C}, \bar{H}$	$\sum_t \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e^M + g) * (1-d)^t + \sum_t \sum_l p_N^l * l * D * V^M(l) * (1-d)^t$	$-\sum_t \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e^M + e^W) * (1-d)^t$	$\sum_t \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e^M + g) * (1-d)^t + \sum_t \sum_l p_N^l * l * (D * V^M(l) + D^W * V^W(l)) * (1-d)^t$
2. $\bar{C}, H$	$c_H + \sum_{t=1} \left(\frac{\sum_l p_H^l * (M-l) + \left(1-\sum_l p_H^l\right) * M}{M}\right) * (e^M + g) * (1-d)^t + \sum_t \sum_l p_H^l * l * D * V^M(l) * (1-d)^t$	$K - \sum_t fK(1-d)^t - \sum_t \left(\frac{\sum_l p_H^l * (M-l) + \left(1-\sum_l p_H^l\right) * M}{M}\right) * (e^M + e^W) * (1-d)^t$	$K - \sum_t fK(1-d)^t + c_H + \sum_t \left(\frac{\sum_l p_H^l * (M-l) + \left(1-\sum_l p_H^l\right) * M}{M}\right) * (e^M + g) * (1-d)^t + \sum_t \sum_l p_H^l * l * (D * V^M(l) + D^W * V^W(l)) * (1-d)^t$
3. $C, \bar{H}$	$c - i + \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e^M + g) + \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e_c^M + g_c + S(h_o, D) + c_o(h_o)) * (1-d)^t + \sum_t \sum_l p_N^l * l * k * V^M(l) * (1-d)^t$	$-\left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e^M + e^W) - \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e_c^M + e^W) * (1-d)^t$	$c + \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e^M + g) * (1-d)^t + \sum_t \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e_c^M + g_c + S(h_o, D) + c_o(h_o) - u * n(h_o)) * (1-d)^t + \sum_t \sum_l p_H^l * l * (D * V^M(l) + D^W * V^W(l)) * (1-d)^t$

Case	Manufacturer Payoff	Utility payoff	Society payoff
4. C, H	$c - i + c_H + \left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * (e^M + g) + \sum_{t=1}^{20}\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * \left(e_c^M + g_c + S(h_o, D) + c_o(h_o)\right) * (1-d)^t + \sum_t \sum_l p_H^l * l * k * V^M(l) * (1-d)^t$	$K - \sum_t fK(1-d)^t - \left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * (e^M + e^W) - \sum_{t=1}^{20}\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * \left(e_c^M + e^W\right) * (1-d)^t$	$c + c_H + K - \sum_t fK(1-d)^t + \left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * (e^M + g) + \sum_{t=1}^{20}\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * \left(e_c^M + g_c + S(h_o, D) + c_o(h_o) - u * n(h_o)\right) * (1-d)^t + \sum_t \sum_l p_H^l * l * (D * V^M(l) + D^W * V^W(l)) * (1-d)^t$
5. $B, \bar{H}$	$b - i + \left(\frac{\sum_l p_N^l * (M-l) + (1-\sum_l p_N^l) * M}{M}\right) * (e^M + g) + \sum_l p_N^l * l * k * V^M(l) + \sum_{t=1}^{20}\left(\frac{\sum_l p_N^l * (M-l) + (1-\sum_l p_N^l) * M}{M}\right) * \left(e_c^M + g_c + S(h_o, D) + c_o(h_o)\right) * (1-d)^t + \sum_{t=1}^{20}\sum_l p_N^l * (g_c^b(l) + c_o(h_o)) * (1-d)^t$	$-\left(\frac{\sum_l p_N^l * (M-l) + (1-\sum_l p_N^l) * M}{M}\right) * (e^M + e^W) - \sum_{t=1}^{20}\left(\frac{\sum_l p_N^l * (M-l) + (1-\sum_l p_N^l) * M}{M}\right) * \left(e_c^M + e^W\right) * (1-d)^t$	$b + \left(\frac{\sum_l p_N^l * (M-l) + (1-\sum_l p_N^l) * M}{M}\right) * (e^M + g) + \sum_l p_N^l * l * k * (V^M(l) + V^W(l)) + \sum_{t=1}^{20}\left(\frac{\sum_l p_N^l * (M-l) + (1-\sum_l p_N^l) * M}{M}\right) * \left(e_c^M + g_c + S(h_o, D) + c_o(h_o) - u * n(h_o)\right) * (1-d)^t + \sum_{t=1}^{20}\sum_l p_N^l * (g_c^b(l) + c_o(h_o) + l * D^W * V^W(l)) * (1-d)^t$
6. B, H	$b - i + c_H + \left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * (e^M + g) + \sum_l p_H^l * l * k * V^M(l) + \sum_{t=1}^{20}\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * \left(e_c^M + g_c + S(h_o, D) + c_o(h_o)\right) * (1-d)^t + \sum_{t=1}^{20}\sum_l p_H^l * (g_c^b(l) + c_o(h_o)) * (1-d)^t$	$K - \sum_t fK(1-d)^t - \left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * (e^M + e^W) - \sum_{t=1}^{20}\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * \left(e_c^M + e^W\right) * (1-d)^t$	$b + c_H + K - \sum_t fK(1-d)^t + \left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * (e^M + g) + \sum_l p_H^l * l * k * (V^M(l) + V^W(l)) + \sum_{t=1}^{20}\left(\frac{\sum_l p_H^l * (M-l) + (1-\sum_l p_H^l) * M}{M}\right) * \left(e_c^M + g_c + S(h_o, D) + c_o(h_o) - u * n(h_o)\right) * (1-d)^t + \sum_{t=1}^{20}\sum_l p_H^l * (g_c^b(l) + c_o(h_o) + l * D^W * V^W(l)) * (1$

Assumptions:

1. $e^M + g - e_c^M - g_c - S(h_o, D) - c_o(h_o) > 0$ (running CHP is cheaper than relying on the grid)
2. $l * D * V^M(l) - (g_c^b(l) + S(h_o, D) + c_o(h_o)) > 0$ (during outage, running CHP with Blackstart is cheaper than the Value Of Lost Load)
3. $e^M > e_c^M$(annual consumption of electricity is lower with CHP than that without CHP)
4. $p_N^l > p_H^l$ (probability of outage with a hardened grid would be lower than with an unhardened grid)
5. $b > c$ (cost of CHP with Blackstart capability is higher than cost of CHP)

Key Question 1

DOES ORDER MATTER?

Under some conditions, order matters

- If costs of grid hardening, CHP & CHP+B/S are medium ($T_K^{34} < K < T_K^{12}$, $T_c^{23} < c < T_c^{24}, \max\{T_b^{46}, T_b^{25}\} < b < \min\{T_b^{15}, T_b^{35}\}$),
  - $\bar{C}, H$ (Case 2) is optimal to Game I, where M moves first
  - $B, \bar{H}$ (Case 5) is optimal to Game II, where U moves first
- How are thresholds defined?
  - T_K^{34} = U Payoff in Case 3 – U Payoff in Case 4 $+K$ (benefit of Harden for U given CHP)
  - T_c^{24} = M Payoff in Case 2 – M Payoff in Case 4 $-c$ (benefit of CHP for M given Harden)
  - T_b^{46} = M Payoff in Case 4 – M Payoff in Case 6 $-b$ (benefit of B/S for M given CHP & Harden)
- Both Manufacturer & Utility prefers Manufacturer to move first ($\bar{C}, H$ is better than $B, \bar{H}$)

Society preference depends on benefit/cost of Harden and CHP with B/S

- Difference in society payoff $(C, H - B, \overline{H})$:

$$\underbrace{K-b}_{\text{Costs}} + \underbrace{\left(\frac{\sum_l p_H^l * (M-l) + \left(1-\sum_l p_H^l\right) * M}{M}\right) * (e^M + g) - \left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * (e^M + g)}_{\text{Impact of Harden on normal energy consumption}}$$

$$+\underbrace{\sum_{t=1}\left(\frac{\sum_l p_H^l * (M-l) + \left(1-\sum_l p_H^l\right) * M}{M}\right) * (e^M + g) * (1-d)^t - \sum_{t=1}^{20}\left(\frac{\sum_l p_N^l * (M-l) + \left(1-\sum_l p_N^l\right) * M}{M}\right) * \left(e_c^M + g_c + S(h_o, D) + c_o(h_o) - u * n(h_o)\right) * (1-d)^t}_{\text{Benefit (impact) of \& CHP+B/S (Harden) on normal energy consumption}}$$

$$+\underbrace{\sum_l p_H^l * l * (D * V^M(l) + D^W * V^W(l)) - \sum_l p_N^l * l * (D * V^M(l) + D^W * V^W(l))}_{\text{Benefit of Harden on VOLL}}$$

$$+\underbrace{\sum_{t=1}\sum_l p_H^l * l * (D * V^M(l) + D^W * V^W(l)) * (1-d)^t - \sum_{t=1}^{20}\sum_l p_N^l * (g_c^b(l) + c_o(h_o) + l * D^W * V^W(l)) * (1-d)^t}_{\text{Benefit of CHP+B/S (Harden) on VOLL}}$$

Requirements for existence

- $T_K^{34} < T_K^{12}$: benefit of Harden greater without CHP than with CHP due to assumptions 1 and 4 (cost is irrelevant) to Utility;
- **$T_c^{23} < T_c^{24}$: benefit of Harden greater than cost given CHP ($T_c^{24} - T_c^{23} = Case\ 2 - Case\ 4 + c - \text{Case } 2 + \text{Case } 3 - c = \text{Case } 3 - \text{Case } 4$) to Manufacturer**
- $T_b^{25} < T_b^{15}$: benefit of Harden greater than cost given no CHP ($T_c^{15} - T_c^{25} = \text{Case } 1 - \text{Case } 5 + b - \text{Case } 2 + \text{Case } 5 - b = \text{Case } 1 - \text{Case } 2$) to Manufacturer
- $T_b^{25} < T_b^{35}$: net benefit of CHP less than net benefit of Harden ($T_c^{35} - T_c^{25} = \text{Case } 3 - \text{Case } 5 + b - \text{Case } 2 + \text{Case } 5 - b = \text{Case } 3 - \text{Case } 2$) to Manufacturer
- $T_b^{46} < T_b^{15}$: benefit of CHP+B/S greater than benefit of B/S given CHP & Harden
- $T_b^{46} < T_b^{35}$: benefit of B/S greater without than with Harden

What if existence conditions fail?

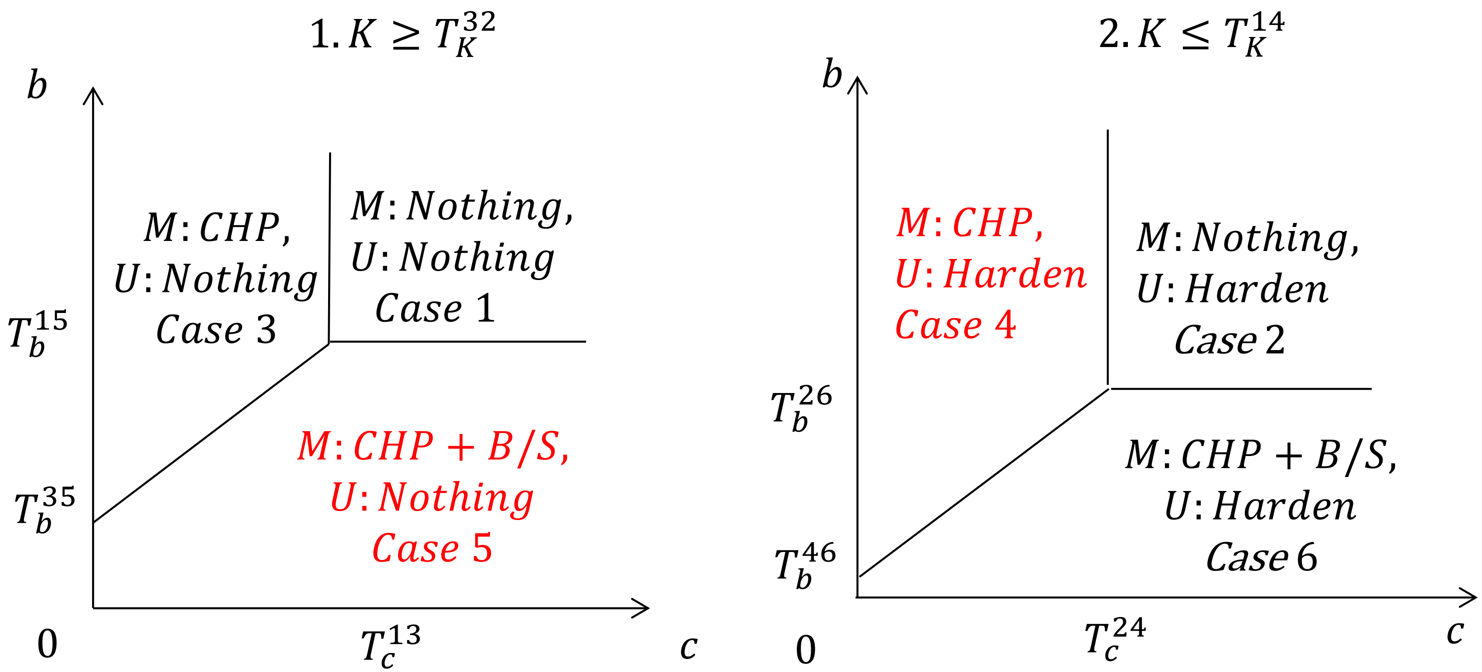
- $T_c^{23} > T_c^{24}$:
  benefit of Harden *less* than cost given CHP
  ($T_c^{24} - T_c^{23} = \text{Case } 2 - \text{Case } 4 + c - \text{Case } 2 + \text{Case } 3 - c = \text{Case } 3 - \text{Case } 4$) to Manufacturer

- $\bar{C}, H$(Case 2) is optimal to both games

- Order does not matter

- Society can not induce $B, \bar{H}$ (Case 5)

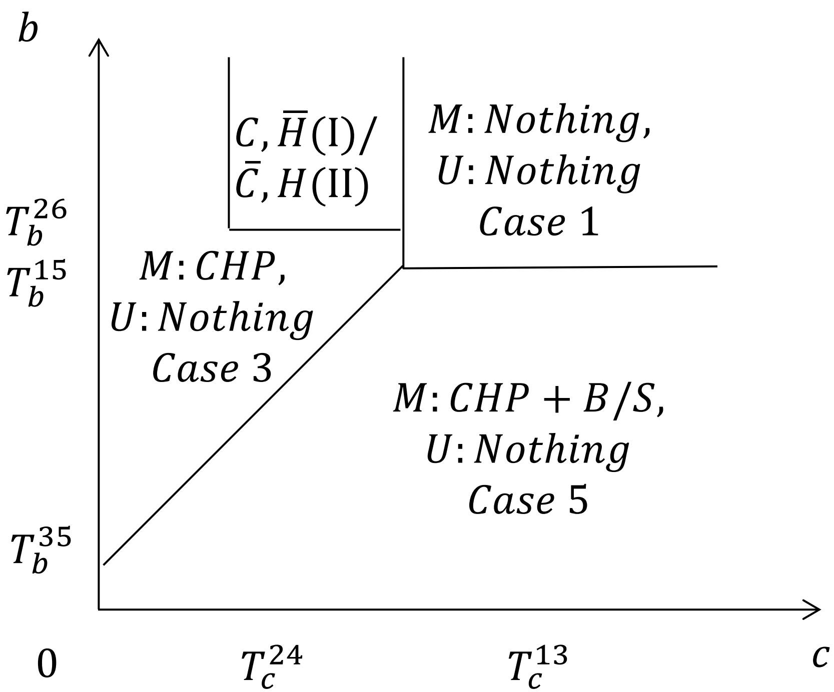
Large or small cost of Harden, then order does not matter



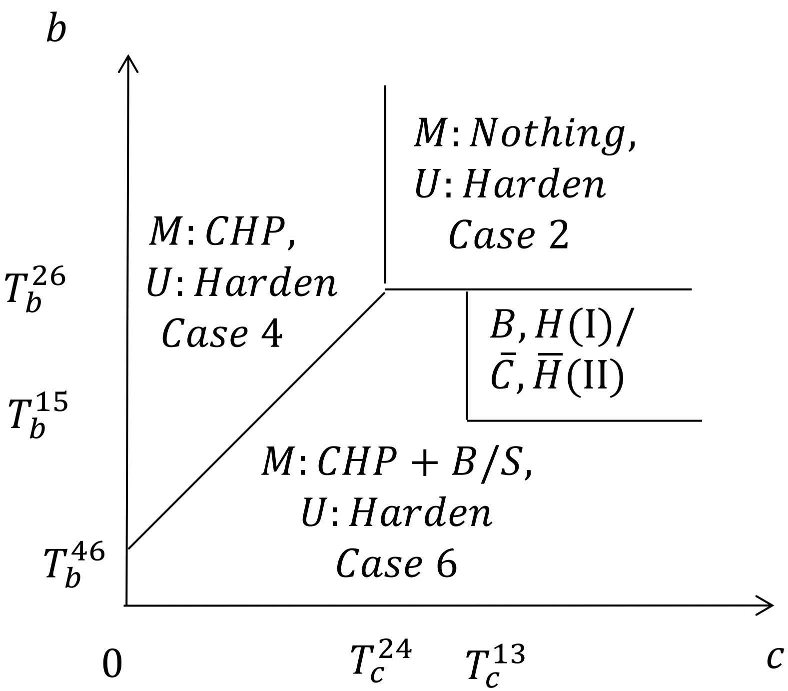
- Equilibriums are indicated (assuming M: CHP > Nothing regardless of Harden)
- Red could be socially desired outcomes
- Subsidizing CHP with/without Blackstart cannot prefer CHP to CHP+B/S

Relatively large or small K, order could matter

$3. T_K^{12} < K < T_K^{32}$

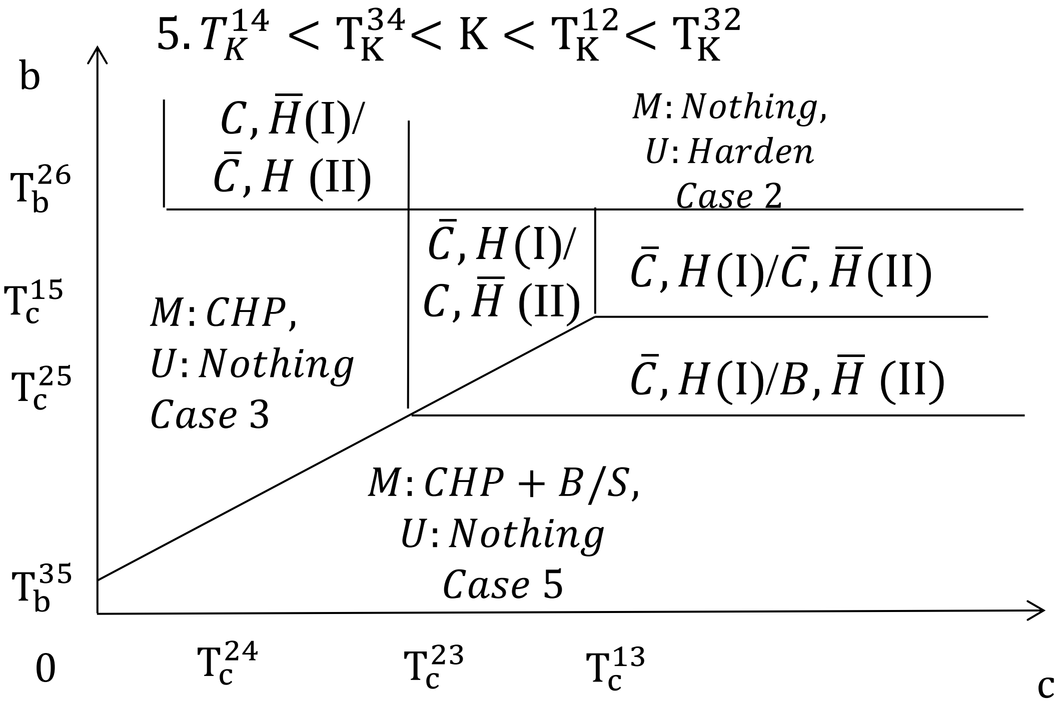


$4. T_K^{14} < K < T_K^{34}$



- If K relatively large, let M OR U move first depending on Society preferences over emission reduction & electricity reliability
- If K relatively small, let M move first to encourage B, H over $\bar{C}, \bar{H}$

Medium K, order more likely matters



- $\bar{C}, \bar{H}$ is less likely to occur
- let M move first if both c & b are medium
- Let U move first if c is relatively small & b is large

Key question 2

WHAT IN REALITY?

Case	Manufacturer Payoff ($million)	Utility Payoff ($million)	Society Payoff ($million)
1.$\bar{c},\bar{H}$	27.44 = **26.11**(energy cost) + 1.33(VOLL)	-200.61 = -18.24(M)-182.37(W)	37.72 = 26.11(energy cost) + 1.33(F VOLL) + 10.28(O VOLL)
2.$\bar{c},H$	26.39 = 26.16(energy cost) + 0.13(VOLL) + 0.1(c_H)	-199.99 = -18.27(M)-182.72(W)+1(K)	28.82 = 26.16(energy cost) + 0.17(F VOLL) + 1.29(O VOLL) +1(K) + 0.1(c_H)
3.$c,\bar{H}$	25.47 = 18.97(energy cost) + 1.03(VOLL) + 3.82(CHP cost) – 0.59(CHP incentive)	-188.25 = -5.88(M)-182.37(W)	32.97 = 18.97(energy cost) + 1.03(F VOLL) + 3.82(CHP cost) + 10.28(O VOLL) **-1.13(emission reduction)**
4.$c,\bar{H}$	24.67 = 18.98(energy cost)+0.13(VOLL) + 3.82(CHP cost) – 0.59(CHP incentive) + 0.1(c_H)	-187.61 = -5.89(M)-182.72(W)+1(K)	24.19 = 18.98(energy cost) + 0.13(F VOLL) + 3.82(CHP cost) + 1.29(O VOLL) +1(K) + 0.1(c_H) -1.13(emission reduction)
5.$b,\bar{H}$	22.34 = 18.97(energy cost) + 3.96(CHP cost) – 0.59(CHP incentive)	-188.25 = -5.88(M)-182.37(W)	24.79 = 18.97(energy cost) + 3.96(CHP cost) + 13.09(O VOLL)-1.13(emission reduction)
6.b,H	24.69 = 18.98(energy cost) + 3.96(CHP cost) – 0.59(CHP incentive) + 0.1(c_H)	-187.61 = -5.89(M)-182.72(W) +1(K)	25.33= 18.98(energy cost) +3.96(CHP cost) + 1.29(O VOLL) +1(K) + 0.1(c_H)-1.13(emission reduction)

Equilibria

- Optimal: Manufacturer buys CHP+B/S & Utility Nothing regardless of order of moves
- Nothing is dominant strategy for Utility
  - $T_K^{14} = -200.61 + 188.61 + 1 = -11$
  - $T_K^{34} = -188.25 + 187.61 + 1 = 0.36$
  - $T_K^{12} = -200.61 + 199.99 + 1 = 0.38$ (vs 1, go to Fig. 3)
  - $T_K^{32} = -188.25 + 199.99 + 1 = 12.74$
  - $T_b^{15} = 27.44 - 22.34 + 3.37 = 8.47$ (vs 3.37)
  - $T_b^{25} = 26.39 - 22.34 + 3.37 = 7.42$
  - $T_b^{35} = 25.47 - 22.34 + 3.37 = 6.50$
- Socially desired outcomes

$$(C, H) > (B, \bar{H}) > (B, H) > (\bar{C}, H) > (C, \bar{H}) > (\bar{C}, \bar{H})$$

Sensitivity analyses

- If decrease Harden cost (K) below \$0.36 M, Harden becomes Utility's dominant strategy & (C, H) is Equilibrium (Fig. 4)

Why not (B, H)?

- $T_b^{46} = 24.67 - 24.69 + 3.37 = 3.35\ (< 3.37)$
- Therefore, (C, H) is preferred to (B, H).
- However, if VOLL increases more than 15%, (B, H) is preferred since $\mathrm{CHP} + B/S$ provide more reliability improvement than $Harden$.

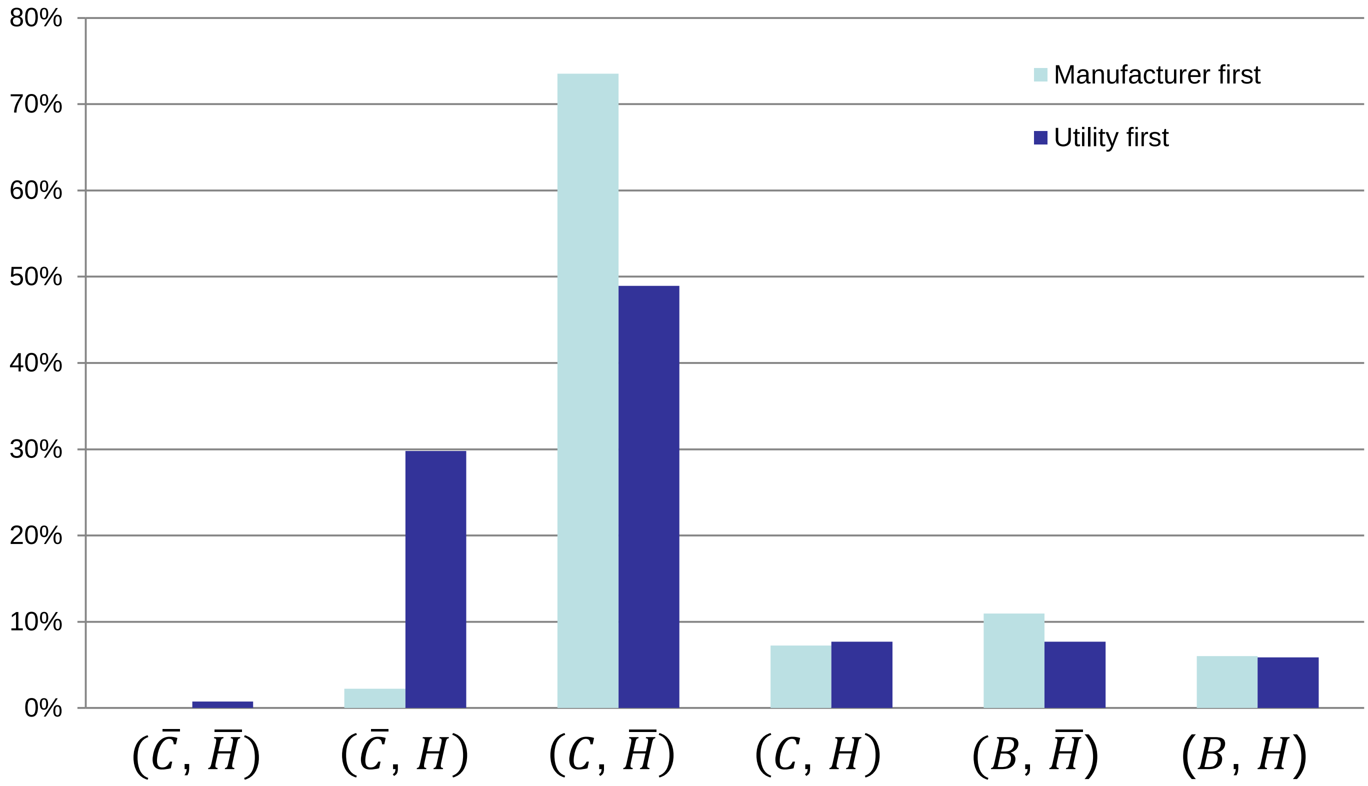
- What if outage duration is 12 hours instead of 24 hours?

Monte Carlo Simulation

- Above illustration is based on one set of parameters
- To account for uncertainty in the set of parameters, we use simulation to study ranges for certain parameters
- Simulation runs: 10,000
- Randomly varied parameters: CF of CHP: U(0%, 95%), Outage length l: U(0h, 48h), Prob. of outage given hardened grid p_H^l :U(0,0.2), Prob. of outage given unhardened grid p_N^l :U(0.7,0.9), Cost of grid hardening to utility and factory K:U($0, $2M), c_H:U($0, $0.2M), Electric consumption and hourly demand of the other user e^W (t):U($0, $31.40M) & U($0, $12,000), VOLL of the other user V^W: U($1.4, $69,284)
- Varied decision variable: CHP incentive $\mathrm{i} \in \{0, 5\%, 10\%, 15\%, 20\%, 25\%, 30\%\}$ of CHP cost

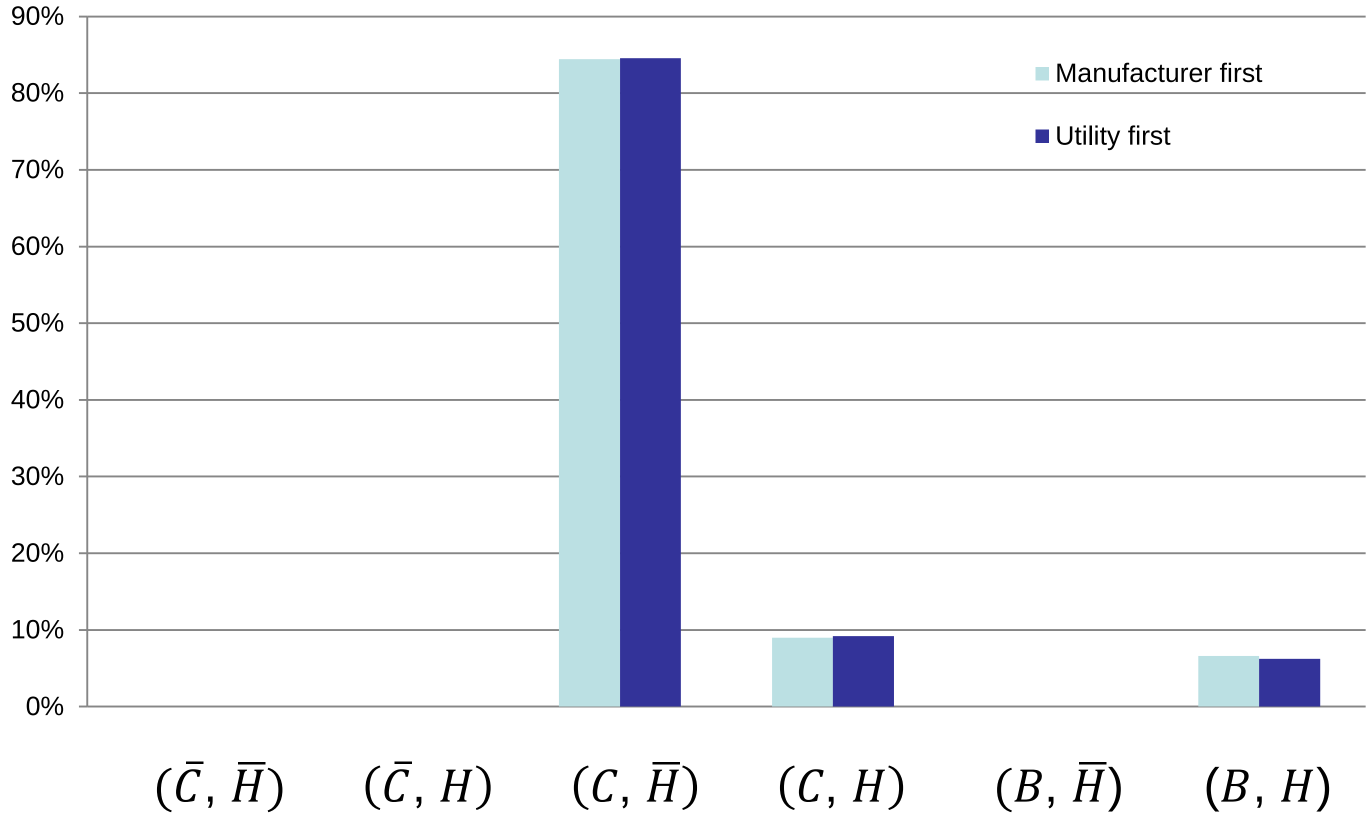
Simulation Result – Gas Turbine CHP

Order matters 53% of 10,000 runs



Simulation Result – Reciprocating Engine CHP

Order matters 17% of 10,000 runs



Conclusion

- Government might incentivize grid hardening & CHP (either with or without Blackstart capability but not both)
- If desired set of parameters are reached (perhaps after incentives), government could induce socially desirable outcomes
- In practice, with Gas Turbine (GT) CHP, socially desirable outcomes could be reached ((C, H) or $(B, \overline{H})$)
- Monte Carlo simulation shows
  - More outcomes could happen with GT CHP
  - With reciprocating engine CHP, only (C, H) can be reached
  - Regardless of CHP type, socially desirable outcomes could not be easily reached ((C, H) or $(B, \overline{H})$) suggesting investment in reducing the uncertainty of key parameters

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Professor Honggang Wang (Rutgers University)

Rasika Athawale (Rutgers University)

Q&A?

Contact information

Gene X. Shan

Xiaojun.shan@ejb.rutgers.edu

Frank A. Felder

ffelder@rutgers.edu

David W. Coit

coit@rci.rutgers.edu