Proactive Economic Assessment of Transmission Investments in Restructured Electricity Markets

Enzo E. Sauma and Shmuel S. Oren
IEOR Department, UC Berkeley

Presented at the 2nd CMU Conference in
Electric Power Systems
Pittsburgh, January 11-12, 2006

Motivation

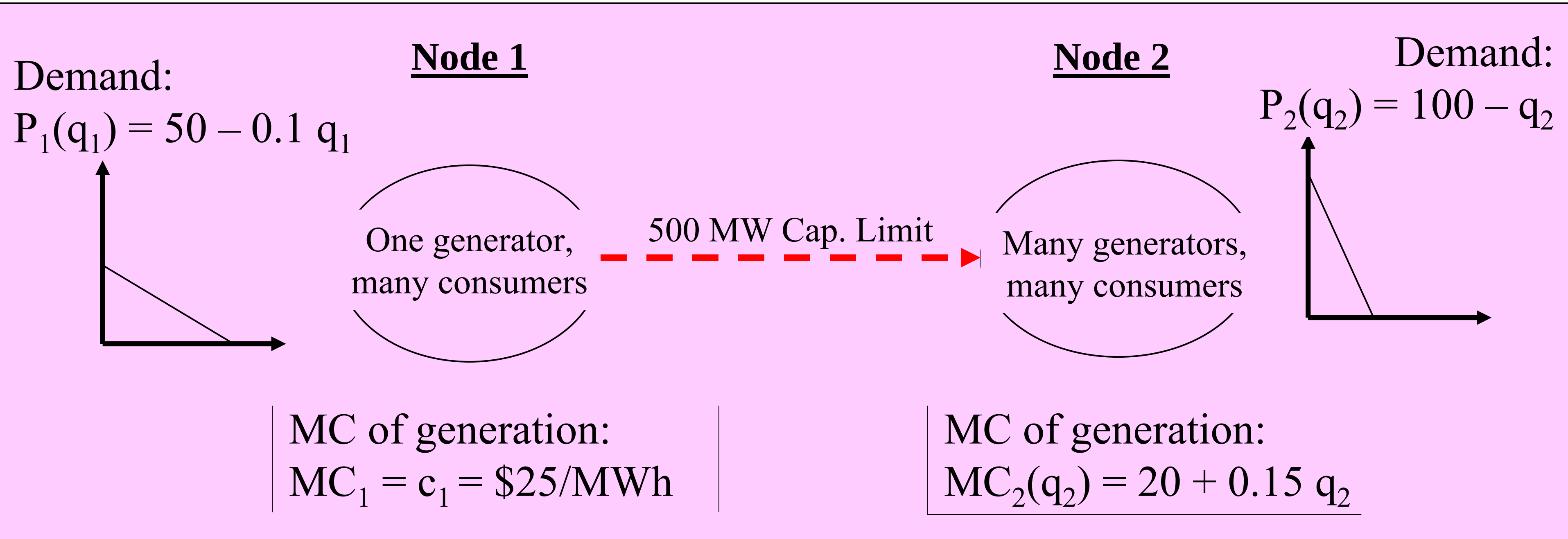
- Integrated resource planning is no longer viable in a restructured electricity industry
- Generation investment and operating decisions are driven by economic motives
- While most transmission investments are motivated by reliability considerations such investment impact the economic outcomes for market participants creating winners and losers
- The market outcomes of transmission investment are affected by market power which may circumvent intended gains from trade

Economic Objectives in Transmission Investment

- Maximize social welfare
- Minimize the local market power of the agents participating in the system
- Maximize consumer surplus
- Maximize producer surplus

These objective may conflict with each other

Illustrative Example



Node 1

Demand:

$P_1(q_1) = 50 - 0.1\, q_1$

One generator, many consumers

MC of generation:

$MC_1 = c_1 = \$25/MWh$

500 MW Cap. Limit

Node 2

Demand:

$P_2(q_2) = 100 - q_2$

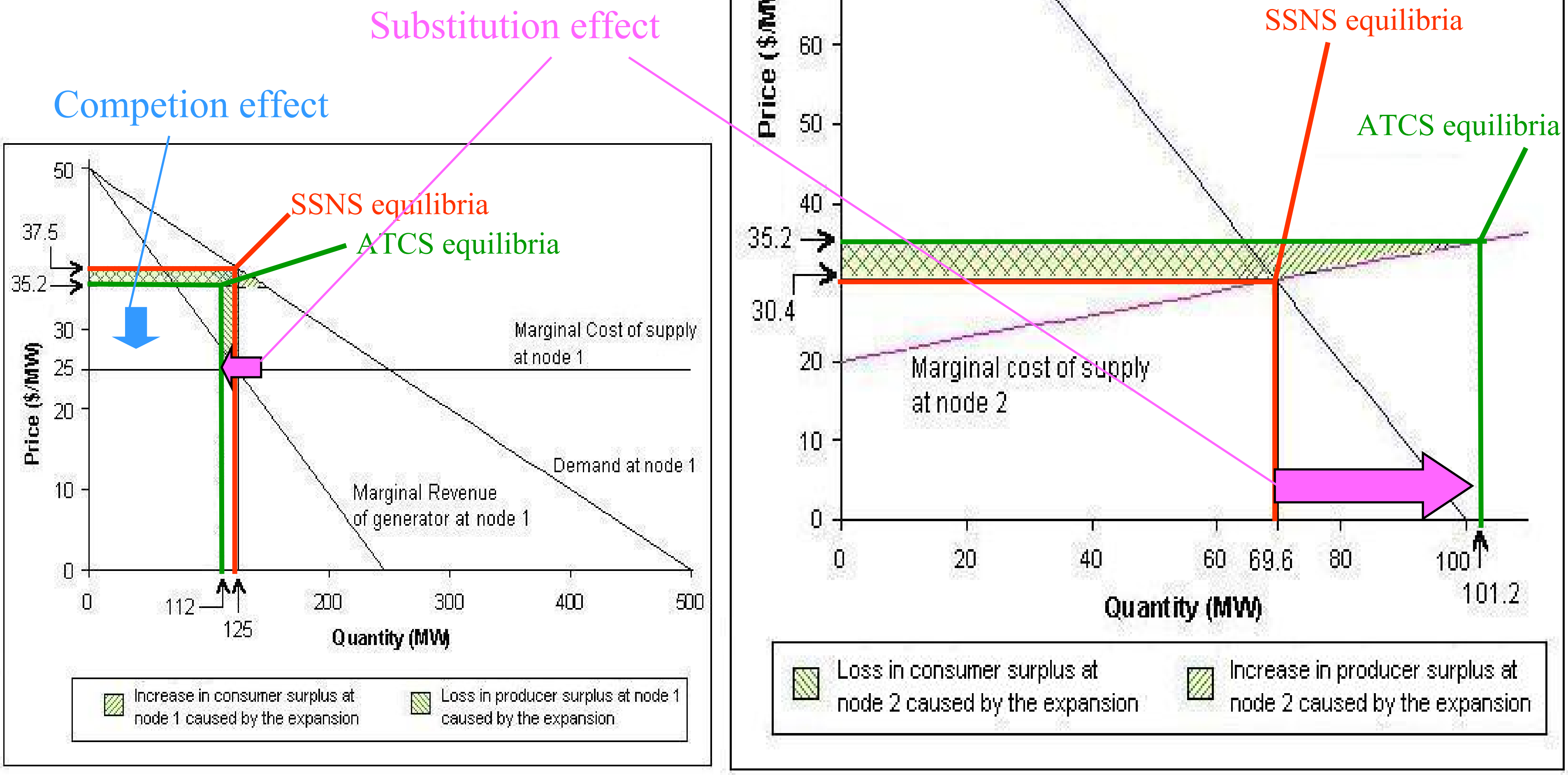
Many generators, many consumers

MC of generation:

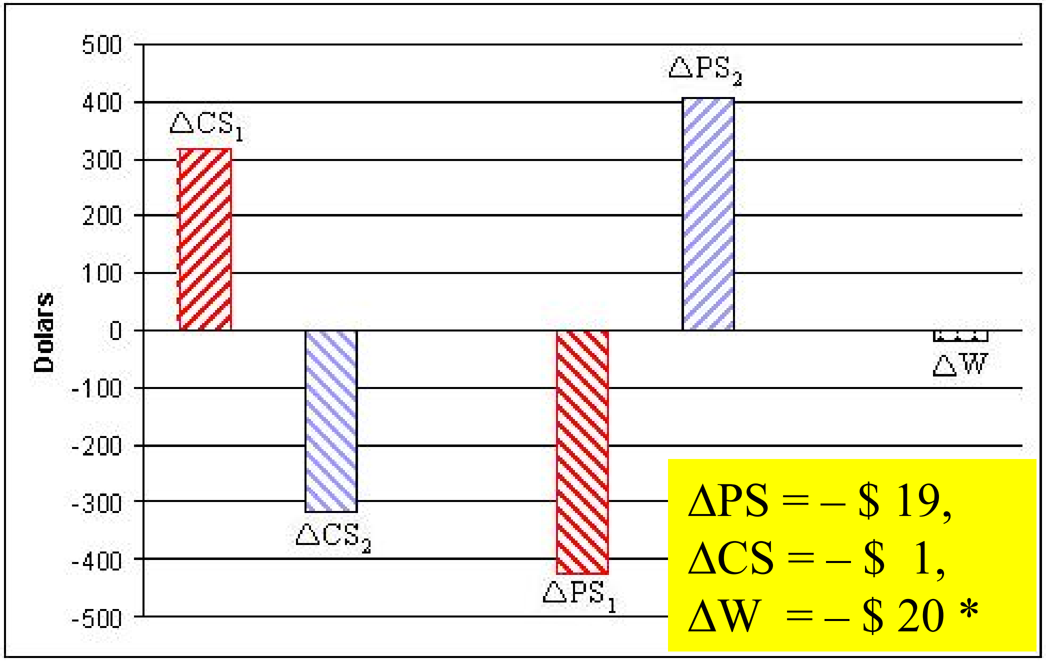
$MC_2(q_2) = 20 + 0.15\, q_2$

We want to evaluate the optimal network structure under different optimization objectives

Impact of Connectivity



Winners and Losers



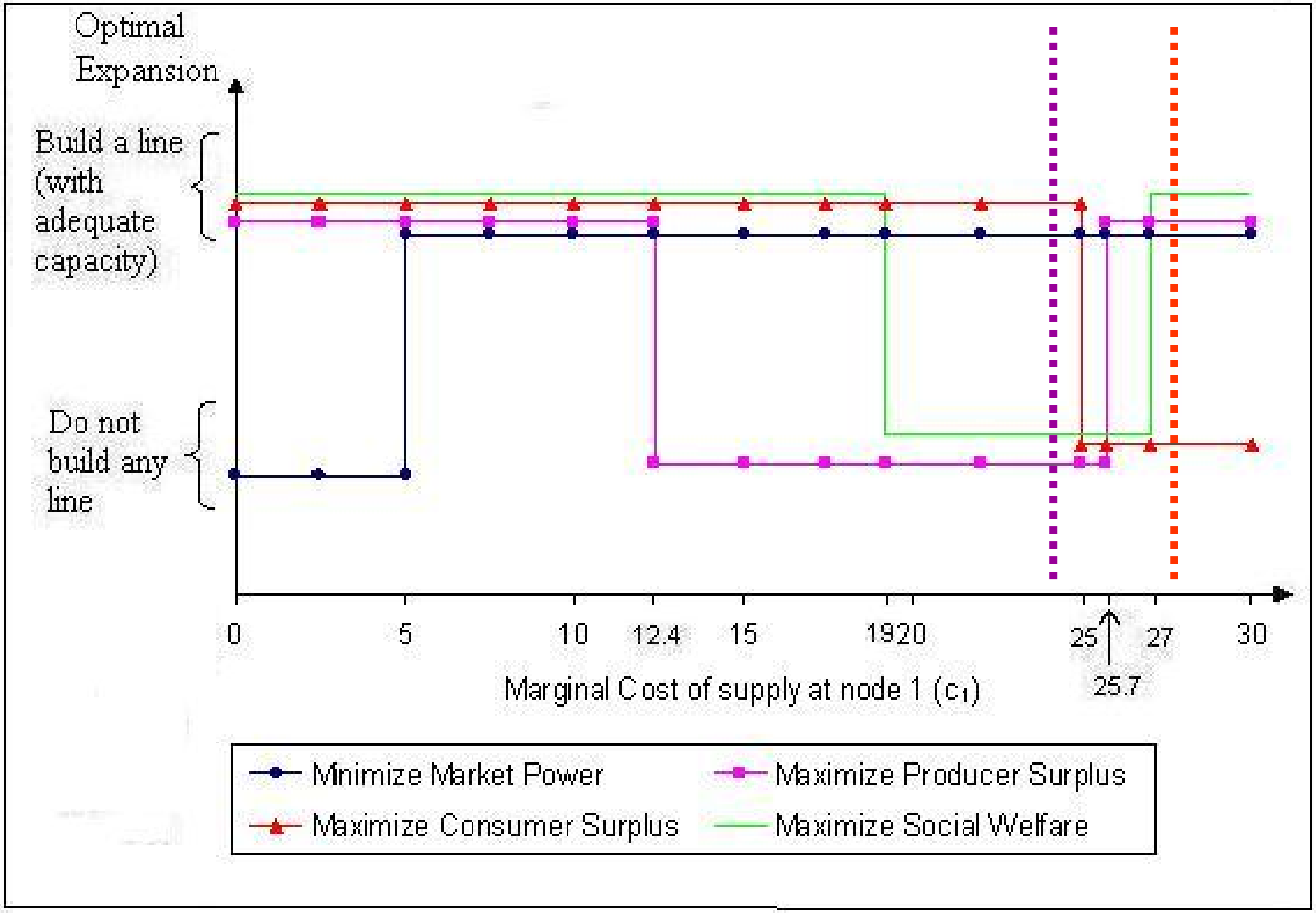
ΔPS = – $ 19,
ΔCS = – $ 1,
ΔW = – $ 20 *

- The expansion decision that minimizes local market power of generators may differ from the decisions that maximizes social welfare, maximizes consumer surplus, and maximizes producer surplus.
- The “winners” from the transmission investment (consumers at node 1 and generators at node 2) can be expected to expend up to the amount of rents that they stand gain on this expansion project to promote it although it reduces social welfare.

Sensitivity to Cost at Node 1

Different objectives could lead to different network expansion Decisions

Optimal network expansion depends on cost structures of generators

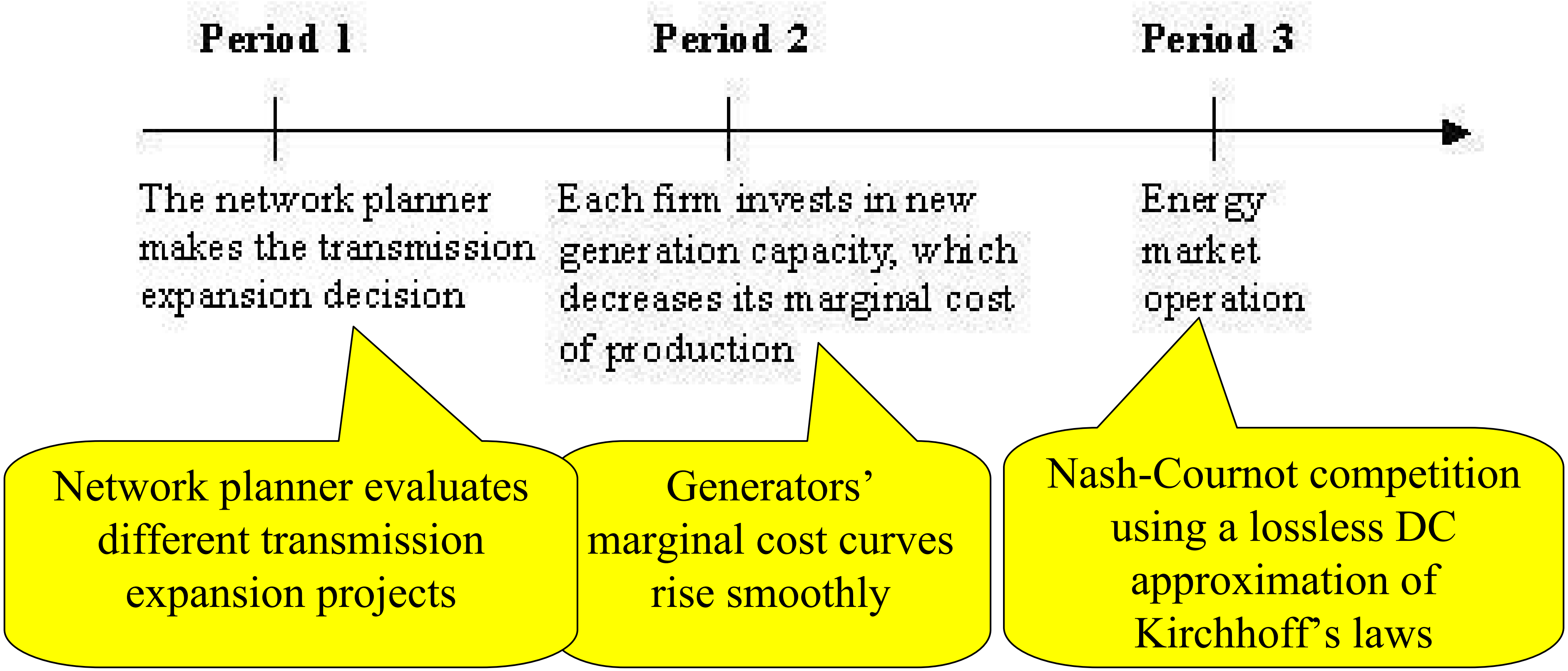


Implications for Economic Assessment of Transmission Upgrades

- Transmission upgrades may create winners and looser
- Valuation of an upgrade may be different for different stakeholders
- Value of an upgrade is sensitive to generation cost
- Value of an upgrade is affected by market outcomes and may be preempted by exercise of market power
- Value of an upgrade will be affected by generation investment response
- Transmission planning can influence generation investment

Proactive Transmission Investment Model

Model Assumptions:



Period 1

The network planner makes the transmission expansion decision

Period 2

Each firm invests in new generation capacity, which decreases its marginal cost of production

Period 3

Energy market operation

Network planner evaluates different transmission expansion projects

Generators' marginal cost curves rise smoothly

Nash-Cournot competition using a lossless DC approximation of Kirchhoff's laws

Model Formulation

Period 3: Spot Market - LCP

Firm G

$$\underset{\{q_i^c,\, i \in N_G\}}{Max} \quad \pi_G^{\,c} = \sum_{i \in N_G} \{P_i^c(q_i^c + r_i^c) \cdot q_i^c \; - CP_i^c\,(q_i^c, g_i^c)\}$$

$$s.t. \qquad q_i^c \ge 0 \;,\; i \in N_G$$

System Operator

$$\underset{\{r_i^c,\, i \in N\}}{Max} \quad \Delta W^c = \sum_{i \in N} \left(\int_0^{r_i^c} P_i^c(q_i^c + x_i)\, dx_i \right)$$

$$s.t. \qquad \sum_{i \in N} r_i^c = 0$$

$$-f_l^c \le \sum_{i \in N} \phi_{l,i}^{\;c} \cdot r_i^c \le f_l^c \;, \forall\, l \in L$$

$$q_i^c + r_i^c \ge 0 \;,\; \forall\, i \in N$$

Jointly

solving

KKT

conditions

Model Formulation

Period 2: Strategic generation investment - EPEC

Firm G

$$\underset{\{g_i,\ i \in N_G\}}{Max} \quad E_c[\pi_G{}^c] - \sum_{i \in N_G} \{ CIG_i(g_i, g_i^0) \}$$

$$s.t. \quad \text{KKT conditions of period-3 problem}$$

Model Formulation

Period 1: Transmission investment - MP EPEC

Proactive Network Planner (PNP)

$$\mathit{Max}_{\,l,\, f_l} \quad \sum_{i \in N} \left\{ \mathrm{E}_c \left[\int_0^{q_i^c + r_i^c} P_i^c(q)\,\mathrm{d}q - CP_i^c(q_i^c, g_i^c) \right] \right\}$$

$$- \sum_{i \in N} \{CIG_i(g_i, g_i^0)\} - CI_l(f_l, f_l^0)$$

s.t. KKT conditions of period-3 problem

and all optimality conditions of period-2 problem

Models Comparison

- Proactive Network Planner (PNP) model: The network planner proactively plans transmission investments to induce a more socially-efficient equilibrium of generation investments.
- Reactive Network Planner (RNP) model: The network planner plans transmission investments only considering the currently installed generation capacities.
- Integrated-Resources Planner (IRP) model: The network planner jointly plans generation and transmission expansions, although the energy market operation is still decentralized.
- Fully-Vertically-Integrated Social Planner (FVISP) model: The social planner jointly plans and operates both the generation and the transmission sectors.

Models Comparison

Integrated-Resources Planner (IRP) model

Period B $\equiv$ period 3 of PSO model

Period A:

$$\mathit{Max}_{\{g_i\},\ell,\,f_\ell} \quad \sum_{i\in N}\left\{E_c\left[\int_0^{q_i^c+r_i^c} P_i^c(q)\,dq - CP_i^c(q_i^c,\,g_i^c)\right]\right\} - \sum_{i\in N}\left\{CIG_i(g_i,g_i^0)\right\} - CI_\ell(f_\ell,f_\ell^0)$$

$s.t.$ KKT conditions of period B problem

Reactive System Operator (RSO) model

Periods b and c $\equiv$ periods 2 and 3 of PSO model

Period a:

$$\mathit{Max}_{\ell,\,f_\ell} \quad \sum_{i\in N}\left\{E_c\left[\int_0^{q_i^c+r_i^c} P_i^c(q)\,dq - CP_i^c(q_i^c,\,g_i^c)\right]\right\} - \sum_{i\in N}\left\{CIG_i(g_i,g_i^0)\right\} - CI_\ell(f_\ell,f_\ell^0)$$

s.t. KKT conditions of period c problem

$$g_i = g_i^0 \quad , \quad \forall\, i\in N$$

Models Comparison

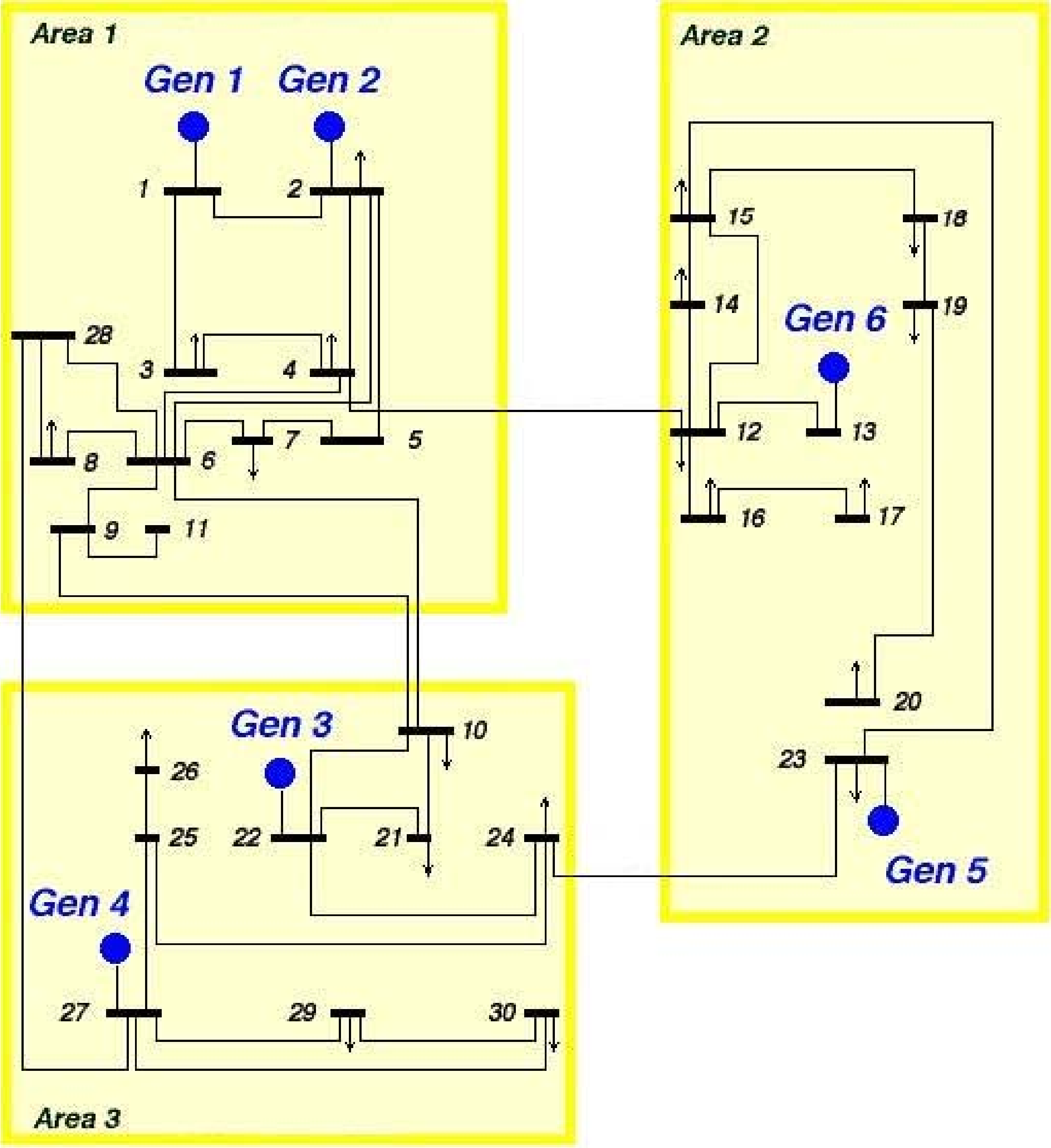
<u>Proposition:</u> The optimal expected social welfares obtained from the PNP, RNP, IRP and FVISP models have always the following order:

$$SW_{RNP} \leq SW_{PNP} \leq SW_{IRP} \leq SW_{FVISP}$$

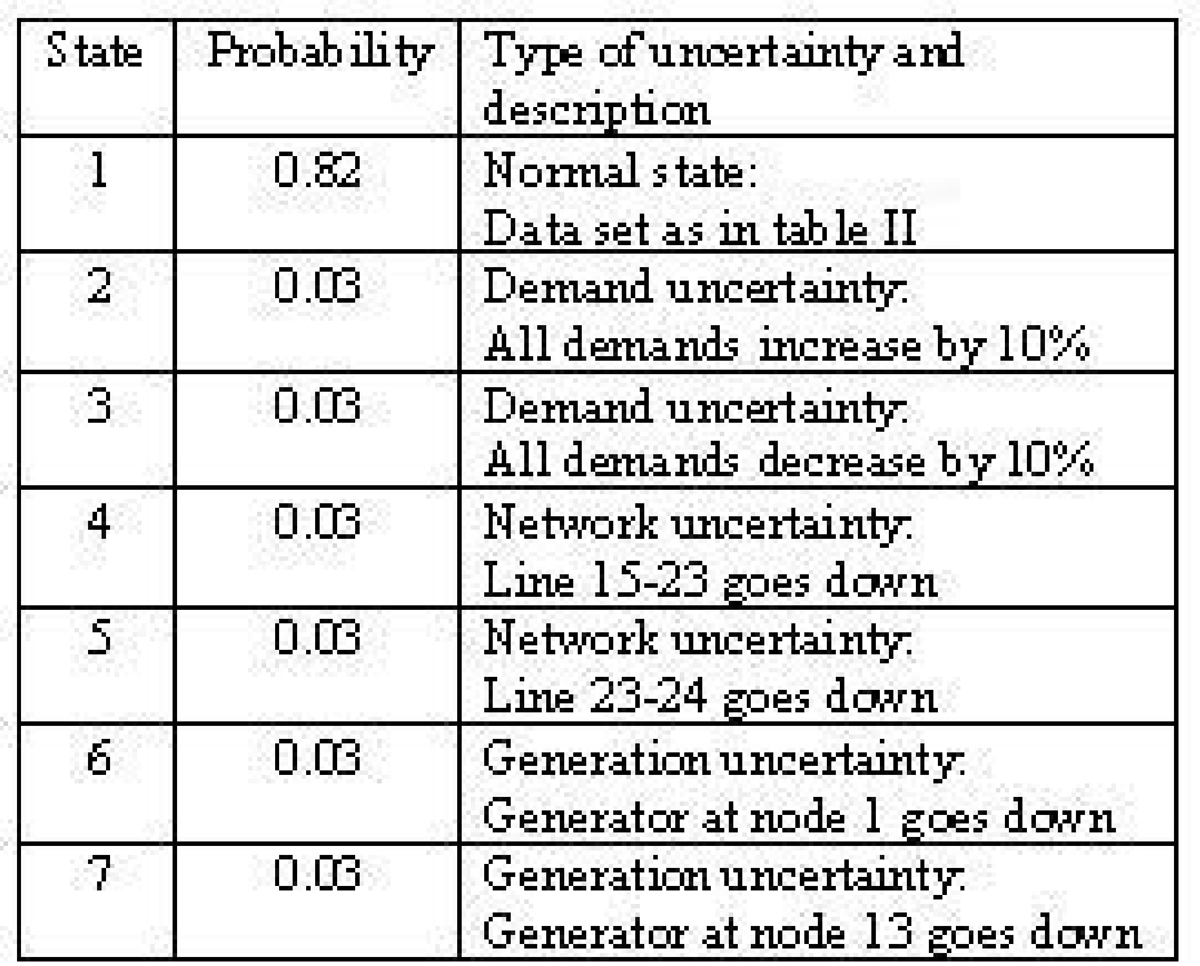
Case Study:

30-bus Cornell Network

- Six Generation firms (each owning generation capacity at a single node)
- 39 Transmission lines

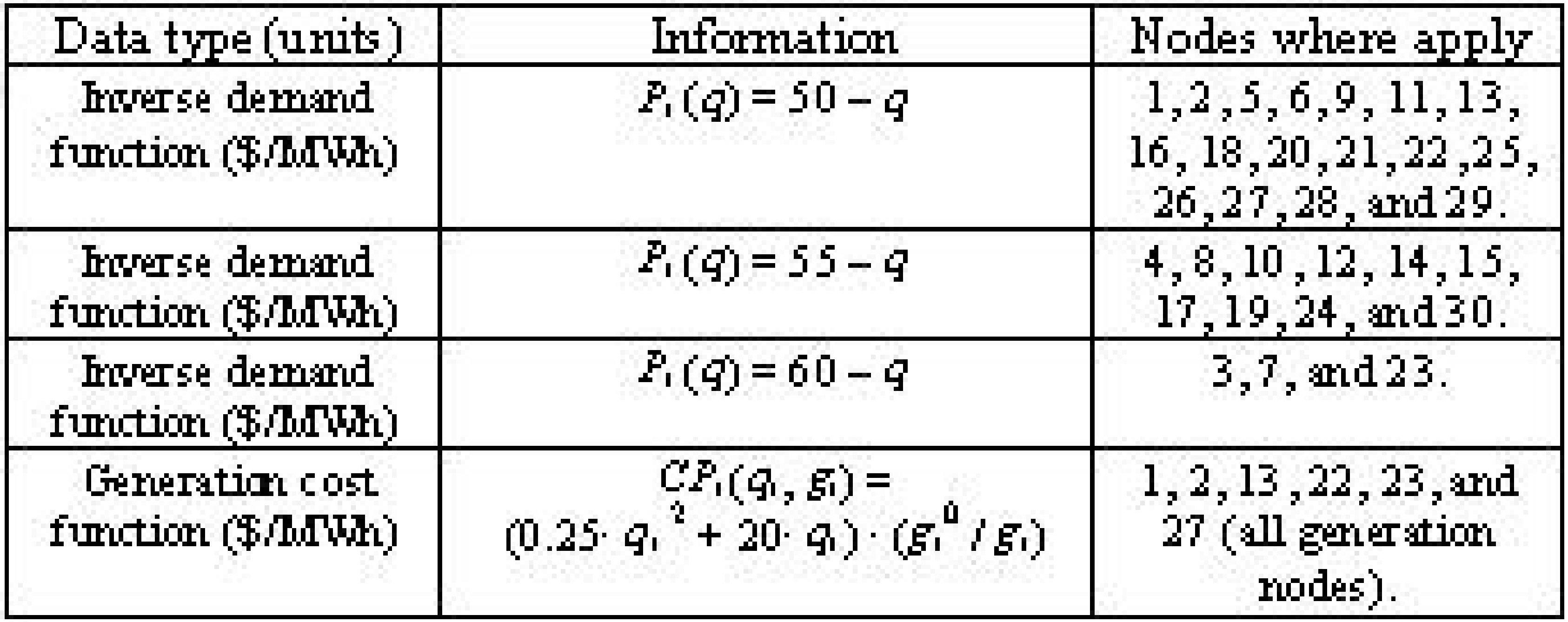


Case Study



State	Probability	Type of uncertainty and description
1	0.82	Normal state: Data set as in table II
2	0.03	Demand uncertainty: All demands increase by 10%
3	0.03	Demand uncertainty: All demands decrease by 10%
4	0.03	Network uncertainty: Line 15-23 goes down
5	0.03	Network uncertainty: Line 23-24 goes down
6	0.03	Generation uncertainty: Generator at node 1 goes down
7	0.03	Generation uncertainty: Generator at node 13 goes down

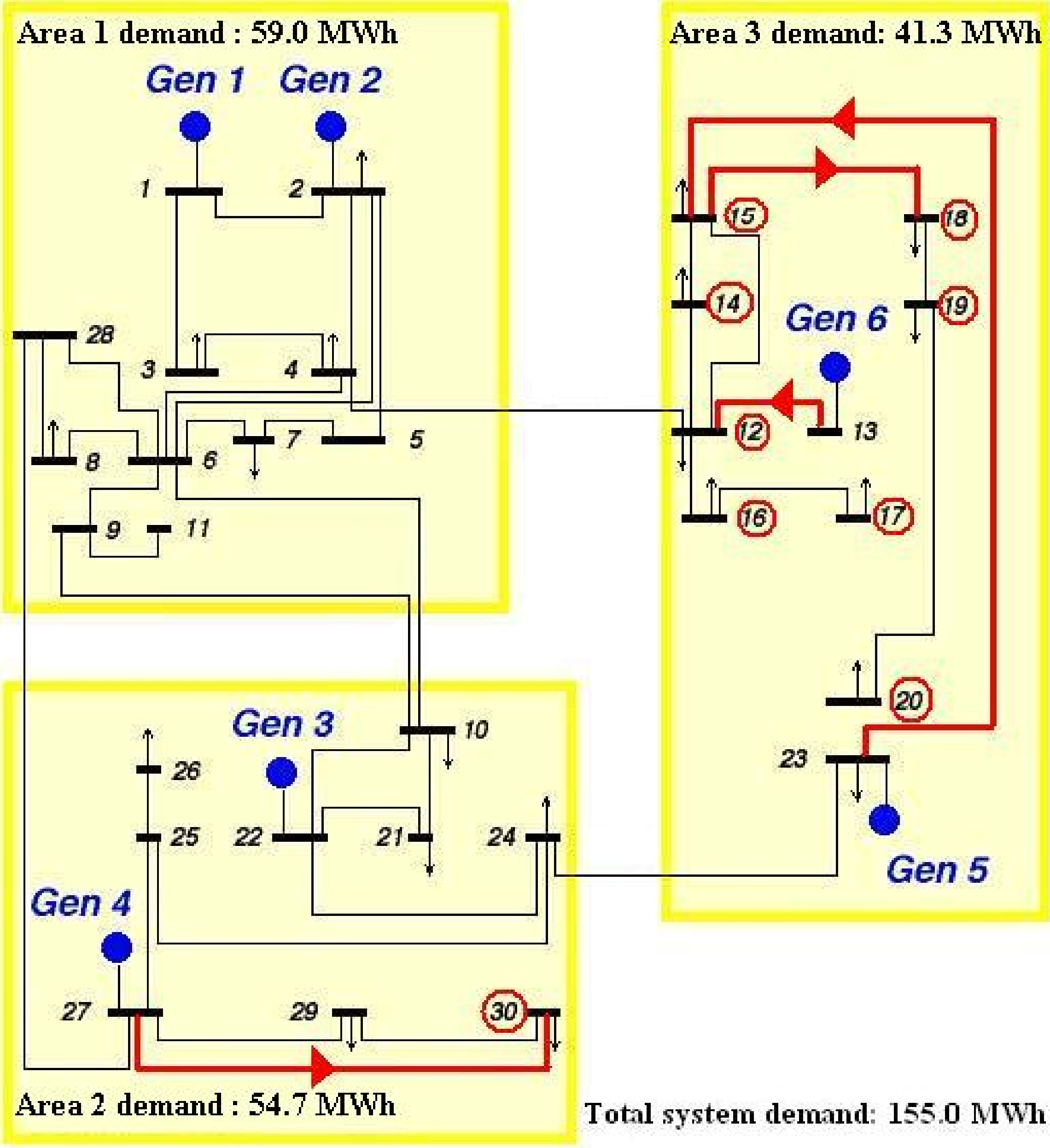
Case Study

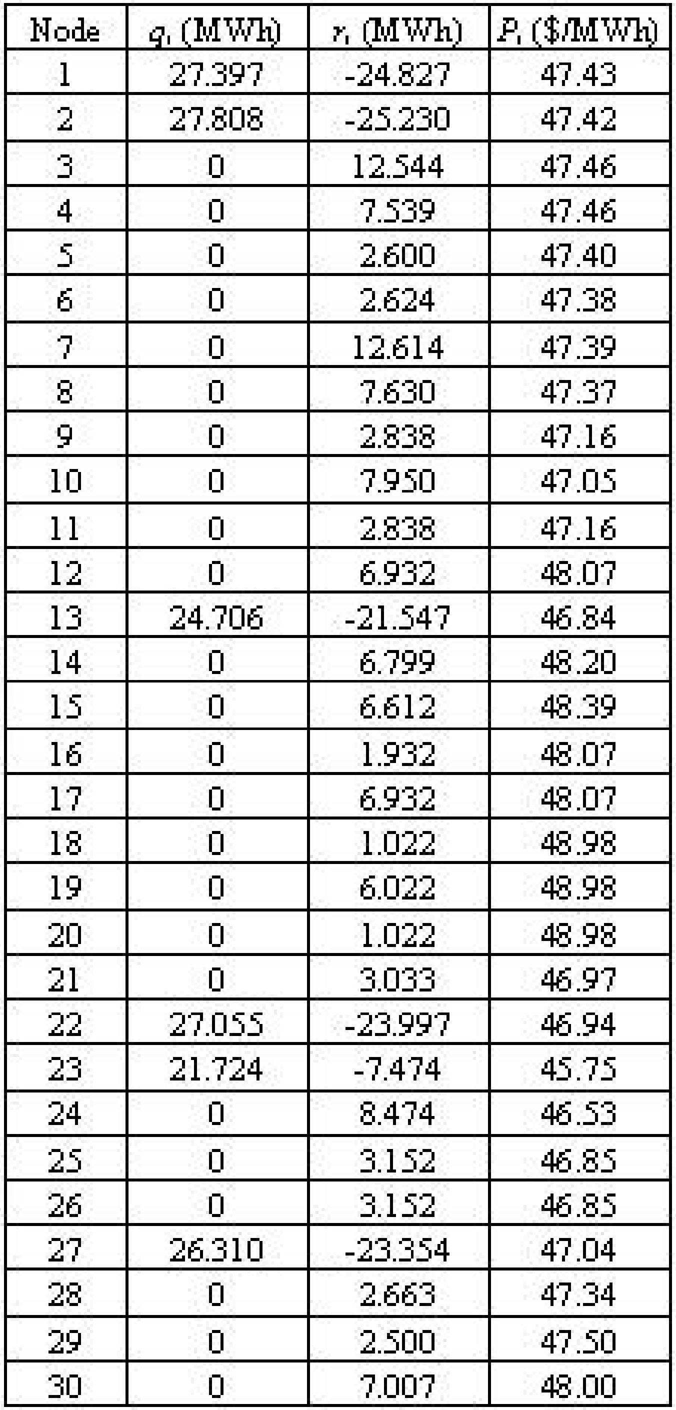


Data type (units)	Information	Nodes where apply
Inverse demand function ($/MWh)	$P_i(q) = 50 - q$	1, 2, 5, 6, 9, 11, 13, 16, 18, 20, 21, 22, 25, 26, 27, 28, and 29.
Inverse demand function ($/MWh)	$P_i(q) = 55 - q$	4, 8, 10, 12, 14, 15, 17, 19, 24, and 30.
Inverse demand function ($/MWh)	$P_i(q) = 60 - q$	3, 7, and 23.
Generation cost function ($/MWh)	$CP_i(q_i, g_i) =$ $(0.25 \cdot q_i^2 + 20 \cdot q_i) \cdot (g_i^0 / g_i)$	1, 2, 13, 22, 23, and 27 (all generation nodes).

$$CIG_i\,(g_i\,,\, g_i^0) = 8 \cdot (g_i - g_i^0)$$

Case Study Results

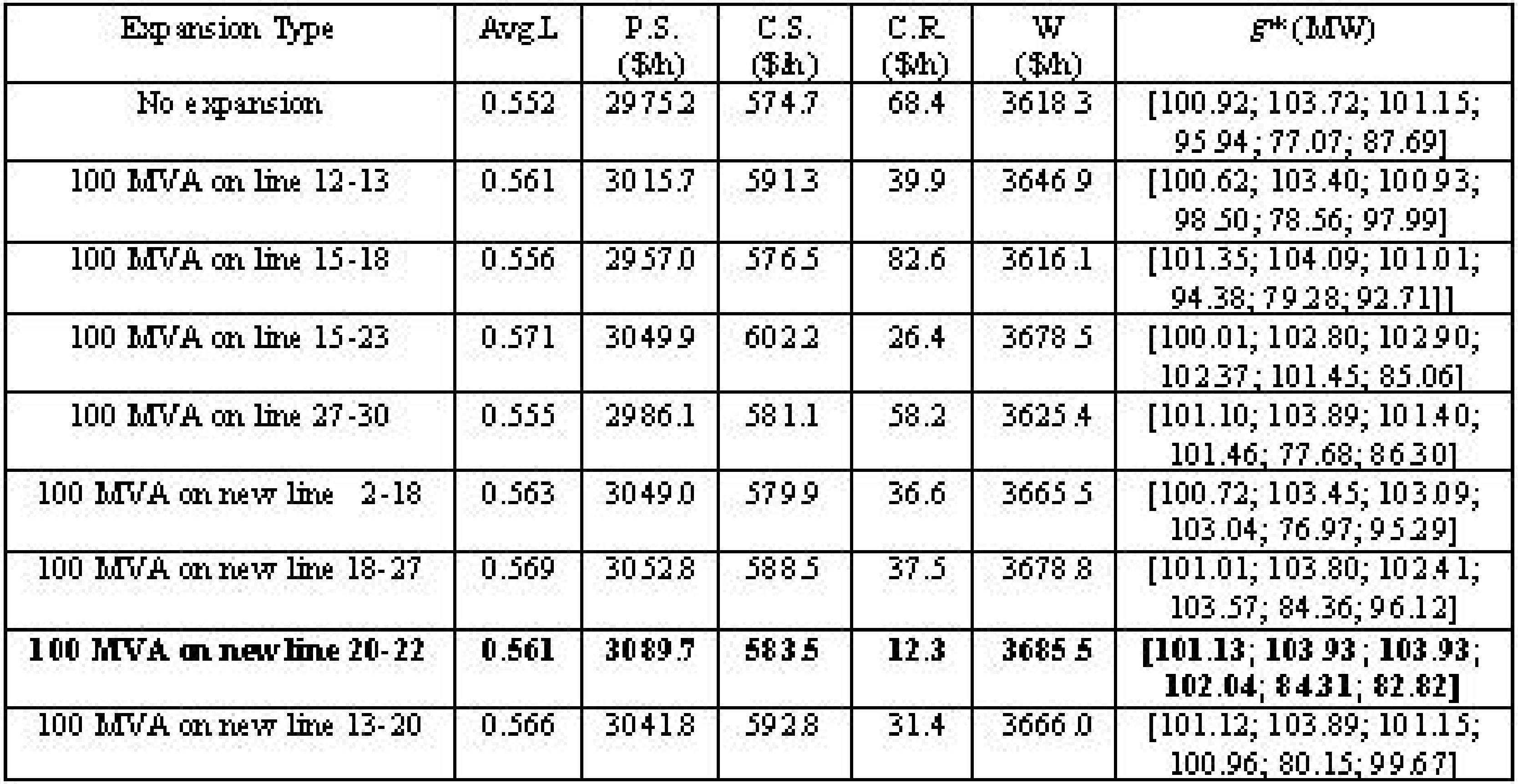




Node	q_i (MWh)	r_i (MWh)	P_i ($/MWh)
1	27.397	-24.827	47.43
2	27.808	-25.230	47.42
3	0	12.544	47.46
4	0	7.539	47.46
5	0	2.600	47.40
6	0	2.624	47.38
7	0	12.614	47.39
8	0	7.630	47.37
9	0	2.838	47.16
10	0	7.950	47.05
11	0	2.838	47.16
12	0	6.932	48.07
13	24.706	-21.547	46.84
14	0	6.799	48.20
15	0	6.612	48.39
16	0	1.932	48.07
17	0	6.932	48.07
18	0	1.022	48.98
19	0	6.022	48.98
20	0	1.022	48.98
21	0	3.033	46.97
22	27.055	-23.997	46.94
23	21.724	-7.474	45.75
24	0	8.474	46.53
25	0	3.152	46.85
26	0	3.152	46.85
27	26.310	-23.354	47.04
28	0	2.663	47.34
29	0	2.500	47.50
30	0	7.007	48.00

Case Study Results

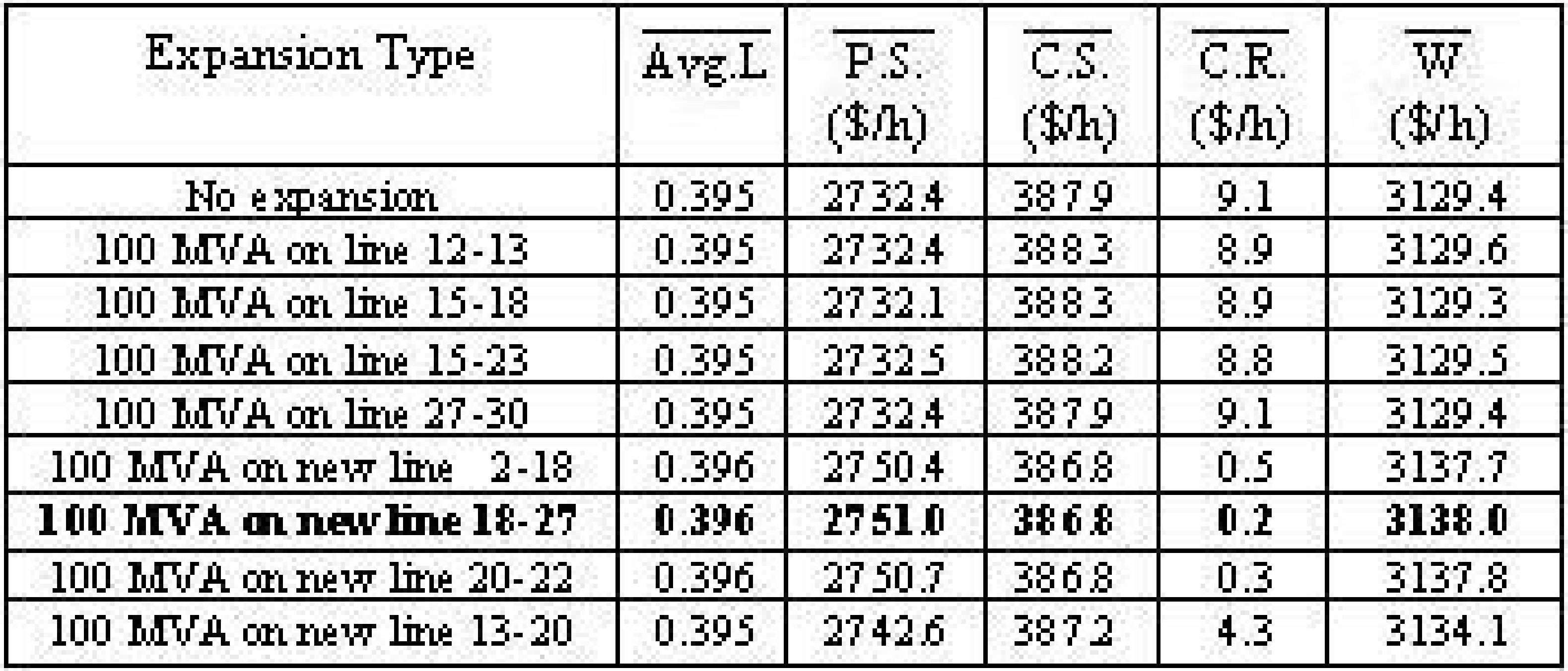
PNP model:



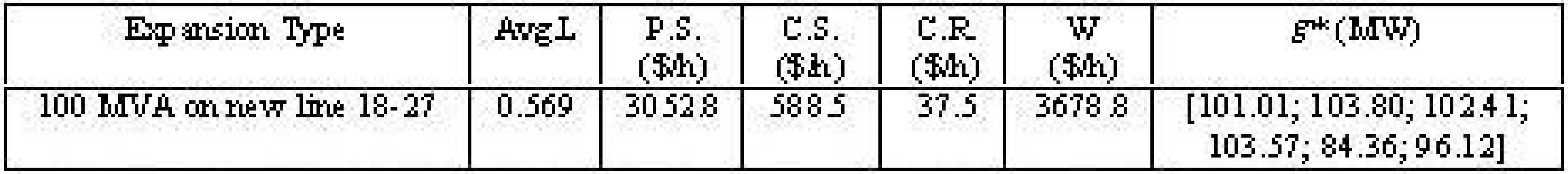
Expansion Type	Avg L	P.S. ($/h)	C.S. ($/h)	C.R. ($/h)	W ($/h)	g* (MW)
No expansion	0.552	2975.2	574.7	68.4	3618.3	[100.92; 103.72; 101.15; 95.94; 77.07; 87.69]
100 MVA on line 12-13	0.561	3015.7	591.3	39.9	3646.9	[100.62; 103.40; 100.93; 98.50; 78.56; 97.99]
100 MVA on line 15-18	0.556	2957.0	576.5	82.6	3616.1	[101.35; 104.09; 101.01; 94.38; 79.28; 92.71]]
100 MVA on line 15-23	0.571	3049.9	602.2	26.4	3678.5	[100.01; 102.80; 102.90; 102.37; 101.45; 85.06]
100 MVA on line 27-30	0.555	2986.1	581.1	58.2	3625.4	[101.10; 103.89; 101.40; 101.46; 77.68; 86.30]
100 MVA on new line 2-18	0.563	3049.0	579.9	36.6	3665.5	[100.72; 103.45; 103.09; 103.04; 76.97; 95.29]
100 MVA on new line 18-27	0.569	3052.8	588.5	37.5	3678.8	[101.01; 103.80; 102.41; 103.57; 84.36; 96.12]
100 MVA on new line 20-22	**0.561**	**3089.7**	**583.5**	**12.3**	**3685.5**	**[101.13; 103.93; 103.93; 102.04; 84.31; 82.82]**
100 MVA on new line 13-20	0.566	3041.8	592.8	31.4	3666.0	[101.12; 103.89; 101.15; 100.96; 80.15; 99.67]

Case Study Results

RNP model:



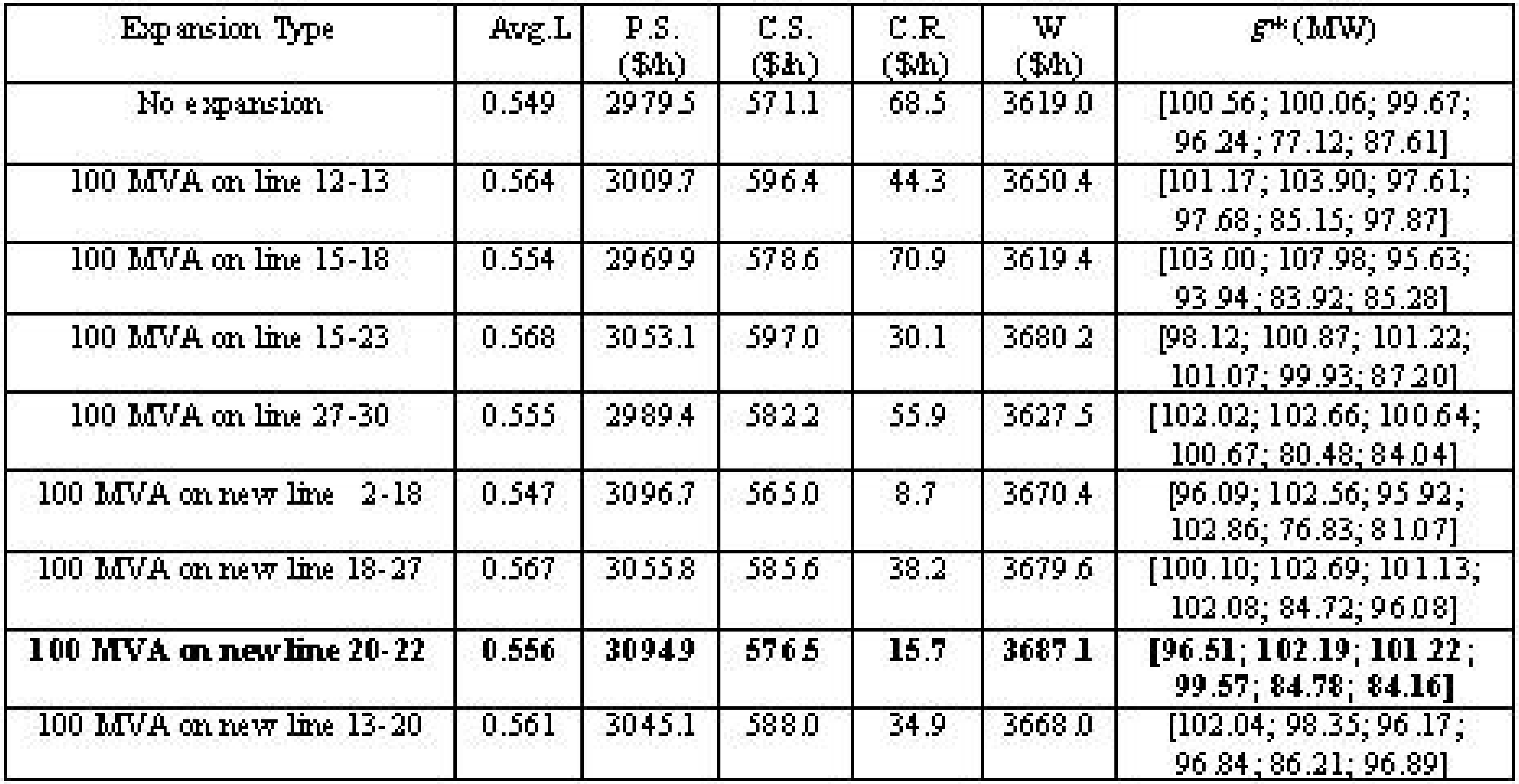
Expansion Type	$\overline{\text{Avg.L}}$	$\overline{\text{P.S.}}$ (\$/h)	$\overline{\text{C.S.}}$ (\$/h)	$\overline{\text{C.R.}}$ (\$/h)	$\overline{\text{W}}$ (\$/h)
No expansion	0.395	2732.4	387.9	9.1	3129.4
100 MVA on line 12-13	0.395	2732.4	388.3	8.9	3129.6
100 MVA on line 15-18	0.395	2732.1	388.3	8.9	3129.3
100 MVA on line 15-23	0.395	2732.5	388.2	8.8	3129.5
100 MVA on line 27-30	0.395	2732.4	387.9	9.1	3129.4
100 MVA on new line 2-18	0.396	2750.4	386.8	0.5	3137.7
100 MVA on new line 18-27	**0.396**	**2751.0**	**386.8**	**0.2**	**3138.0**
100 MVA on new line 20-22	0.396	2750.7	386.8	0.3	3137.8
100 MVA on new line 13-20	0.395	2742.6	387.2	4.3	3134.1



Expansion Type	Avg.L	P.S. (\$/h)	C.S. (\$/h)	C.R. (\$/h)	W (\$/h)	g^* (MW)
100 MVA on new line 18-27	0.569	3052.8	588.5	37.5	3678.8	[101.01; 103.80; 102.41; 103.57; 84.36; 96.12]

Case Study Results

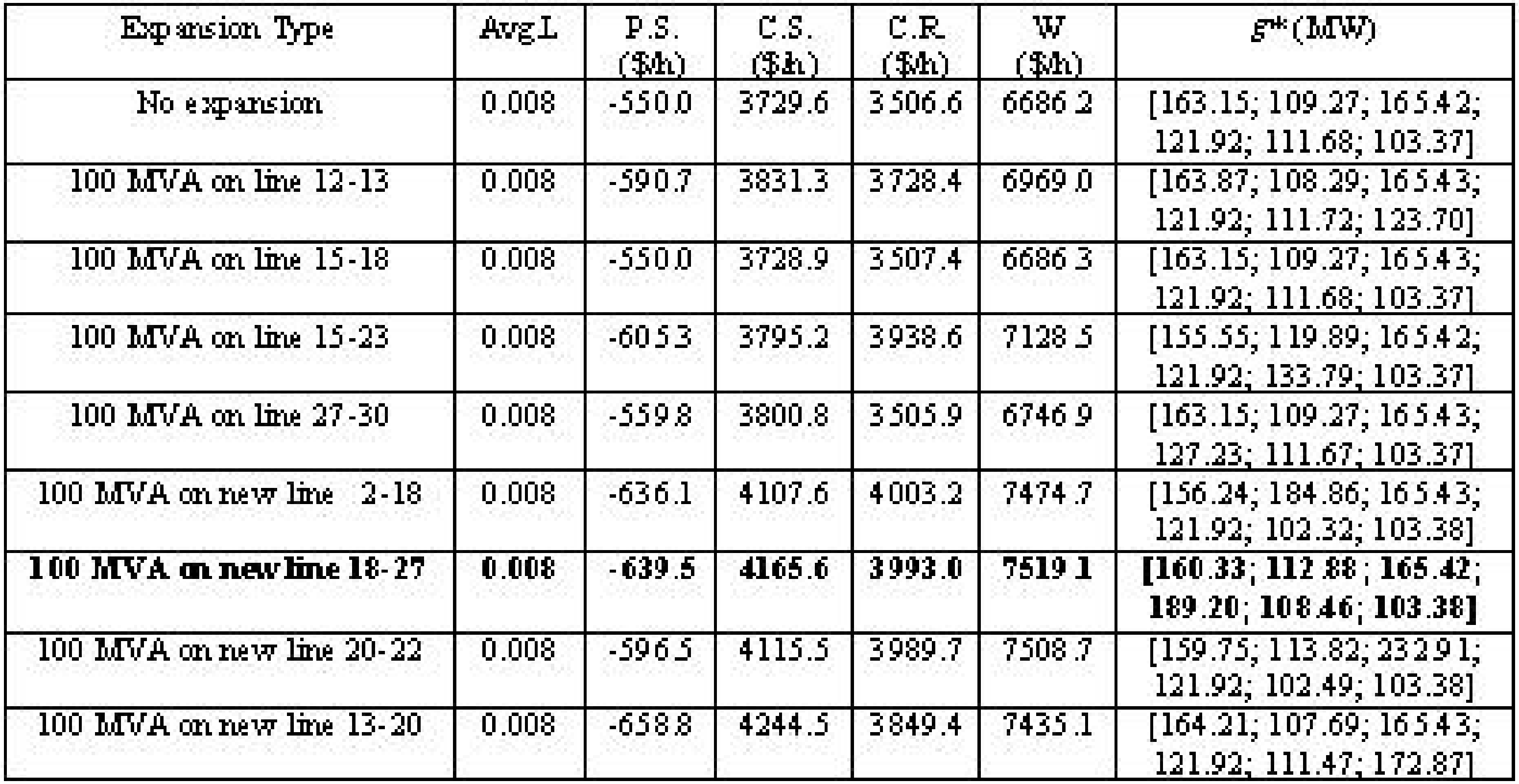
IRP model:



Expansion Type	Avg.L	P.S. ($/h)	C.S. ($/h)	C.R. ($/h)	W ($/h)	g^* (MW)
No expansion	0.549	2979.5	571.1	68.5	3619.0	[100.56; 100.06; 99.67; 96.24; 77.12; 87.61]
100 MVA on line 12-13	0.564	3009.7	596.4	44.3	3650.4	[101.17; 103.90; 97.61; 97.68; 85.15; 97.87]
100 MVA on line 15-18	0.554	2969.9	578.6	70.9	3619.4	[103.00; 107.98; 95.63; 93.94; 83.92; 85.28]
100 MVA on line 15-23	0.568	3053.1	597.0	30.1	3680.2	[98.12; 100.87; 101.22; 101.07; 99.93; 87.20]
100 MVA on line 27-30	0.555	2989.4	582.2	55.9	3627.5	[102.02; 102.66; 100.64; 100.67; 80.48; 84.04]
100 MVA on new line 2-18	0.547	3096.7	565.0	8.7	3670.4	[96.09; 102.56; 95.92; 102.86; 76.83; 81.07]
100 MVA on new line 18-27	0.567	3055.8	585.6	38.2	3679.6	[100.10; 102.69; 101.13; 102.08; 84.72; 96.08]
100 MVA on new line 20-22	**0.556**	**3094.9**	**576.5**	**15.7**	**3687.1**	**[96.51; 102.19; 101.22; 99.57; 84.78; 84.16]**
100 MVA on new line 13-20	0.561	3045.1	588.0	34.9	3668.0	[102.04; 98.35; 96.17; 96.84; 86.21; 96.89]

Case Study Results

FVISP model:



Expansion Type	Avg.L	P.S. ($/h)	C.S. ($/h)	C.R. ($/h)	W ($/h)	g^* (MW)
No expansion	0.008	-550.0	3729.6	3506.6	6686.2	[163.15; 109.27; 165.42; 121.92; 111.68; 103.37]
100 MVA on line 12-13	0.008	-590.7	3831.3	3728.4	6969.0	[163.87; 108.29; 165.43; 121.92; 111.72; 123.70]
100 MVA on line 15-18	0.008	-550.0	3728.9	3507.4	6686.3	[163.15; 109.27; 165.43; 121.92; 111.68; 103.37]
100 MVA on line 15-23	0.008	-605.3	3795.2	3938.6	7128.5	[155.55; 119.89; 165.42; 121.92; 133.79; 103.37]
100 MVA on line 27-30	0.008	-559.8	3800.8	3505.9	6746.9	[163.15; 109.27; 165.43; 127.23; 111.67; 103.37]
100 MVA on new line 2-18	0.008	-636.1	4107.6	4003.2	7474.7	[156.24; 184.86; 165.43; 121.92; 102.32; 103.38]
100 MVA on new line 18-27	**0.008**	**-639.5**	**4165.6**	**3993.0**	**7519.1**	**[160.33; 112.88; 165.42; 189.20; 108.46; 103.38]**
100 MVA on new line 20-22	0.008	-596.5	4115.5	3989.7	7508.7	[159.75; 113.82; 232.91; 121.92; 102.49; 103.38]
100 MVA on new line 13-20	0.008	-658.8	4244.5	3849.4	7435.1	[164.21; 107.69; 165.43; 121.92; 111.47; 172.87]

Conclusions

- We evaluated the social welfare implications of transmission investments based on equilibrium models characterizing the competitive interaction among oligopolistic generation firms.
- We illustrated that, although a PNP cannot do better (in terms of expected social welfare) than an IRP, it can recoup some of the lost welfare by proactively expanding transmission capacity.

Conclusions

- We also illustrated that the valuations of transmission expansion projects made by a PNP can differ from the valuations made by a RNP.

- We illustrated that, when valuations of transmission expansion projects are different under the PNP and the RNP models, a PNP could make more socially efficient transmission expansion decisions than its reactive counterpart.

Questions?