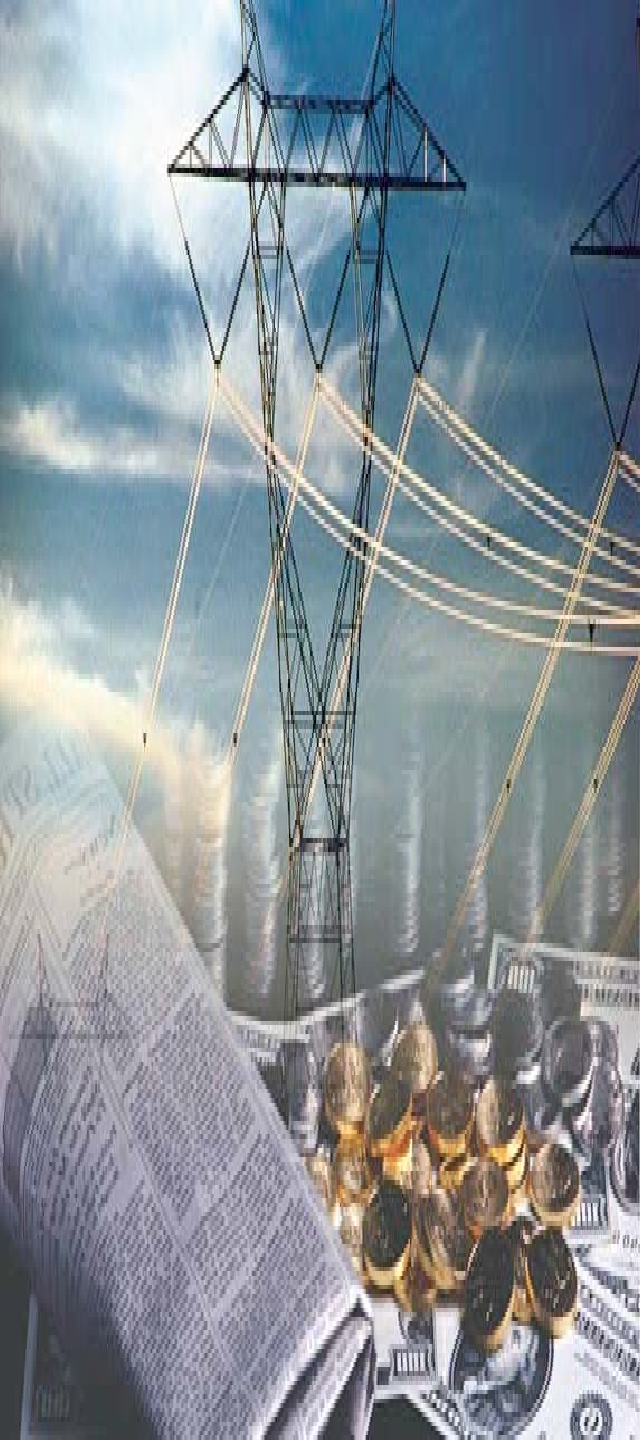

The Impact of Cap and Trade Regulation on Congested Electricity Market Equilibrium

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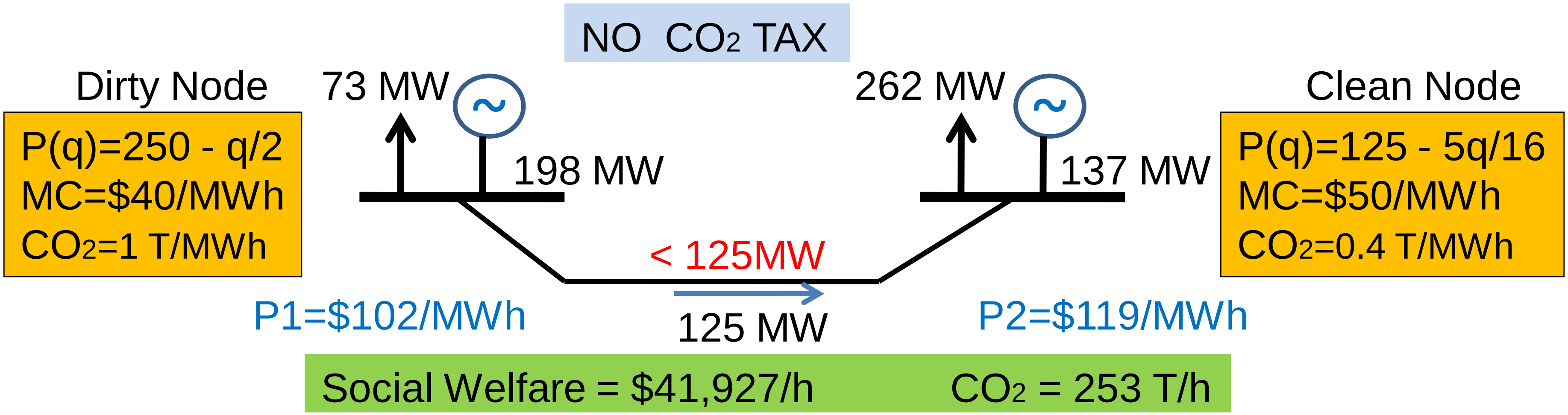
Research on Regional GHG Regulation

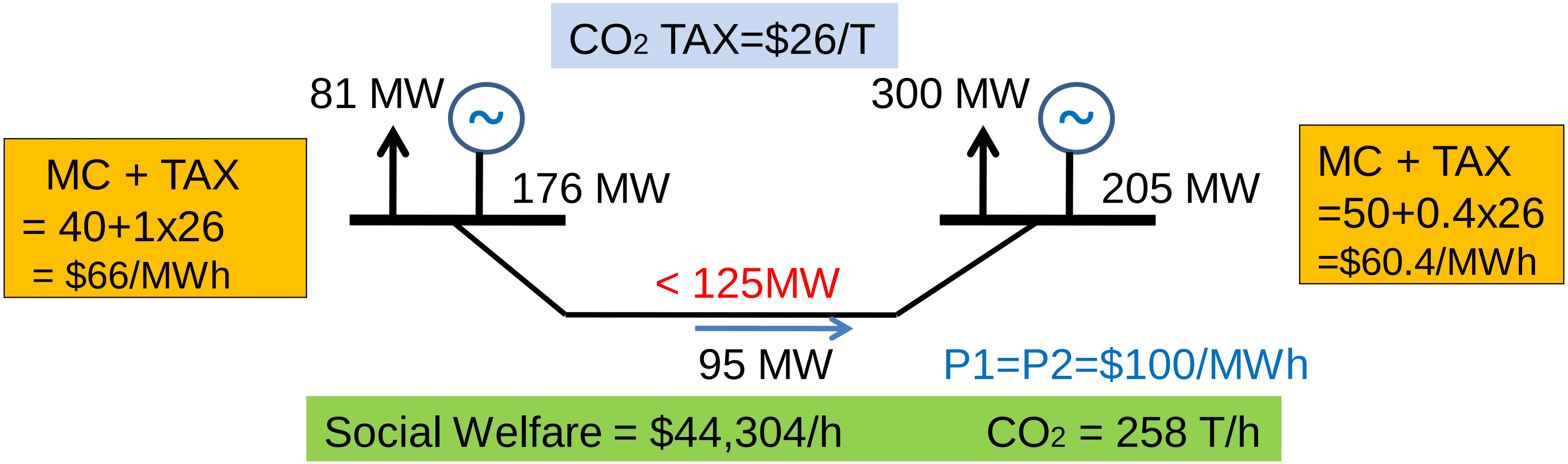
- **Study of Leakage (displacement of emissions to areas with less restrictive regulation) and on contract shuffling based on zonal models**
- **Study of enforcement strategies (Source based vs. Load based)**
- **Study of impact on local industry**
- **Study of impact on grid operations and power markets**

Factors affecting the efficacy of GHG regulation and its impact on the electric power system

- **Transmission network** (Network congestion effects and congestion management approach)
- **Specific form of GHG regulation** (Carbon Tax, Cap & Trade, Renewable Portfolio Standard (RPS), RECs, GHG allowances)
- **Demand response** (Demand elasticity, Metering and load control technology, Rate regulation, Business models, PHEV/EV penetration & smart charging technology)
- **Market structure** (Resource ownership and market rules) and strategic behavior of participants
- **Renewables integration** (economic incentives and dispatch policies)

Example: Perverse Effect of Carbon Tax





Social Welfare = Consumer Surplus + Producers Profit + Congestion Rents + Tax

Downward, A. (2010). Carbon charges in electricity systems with strategic behavior and transmission. *The Energy Journal*, 31(4), 1–6.

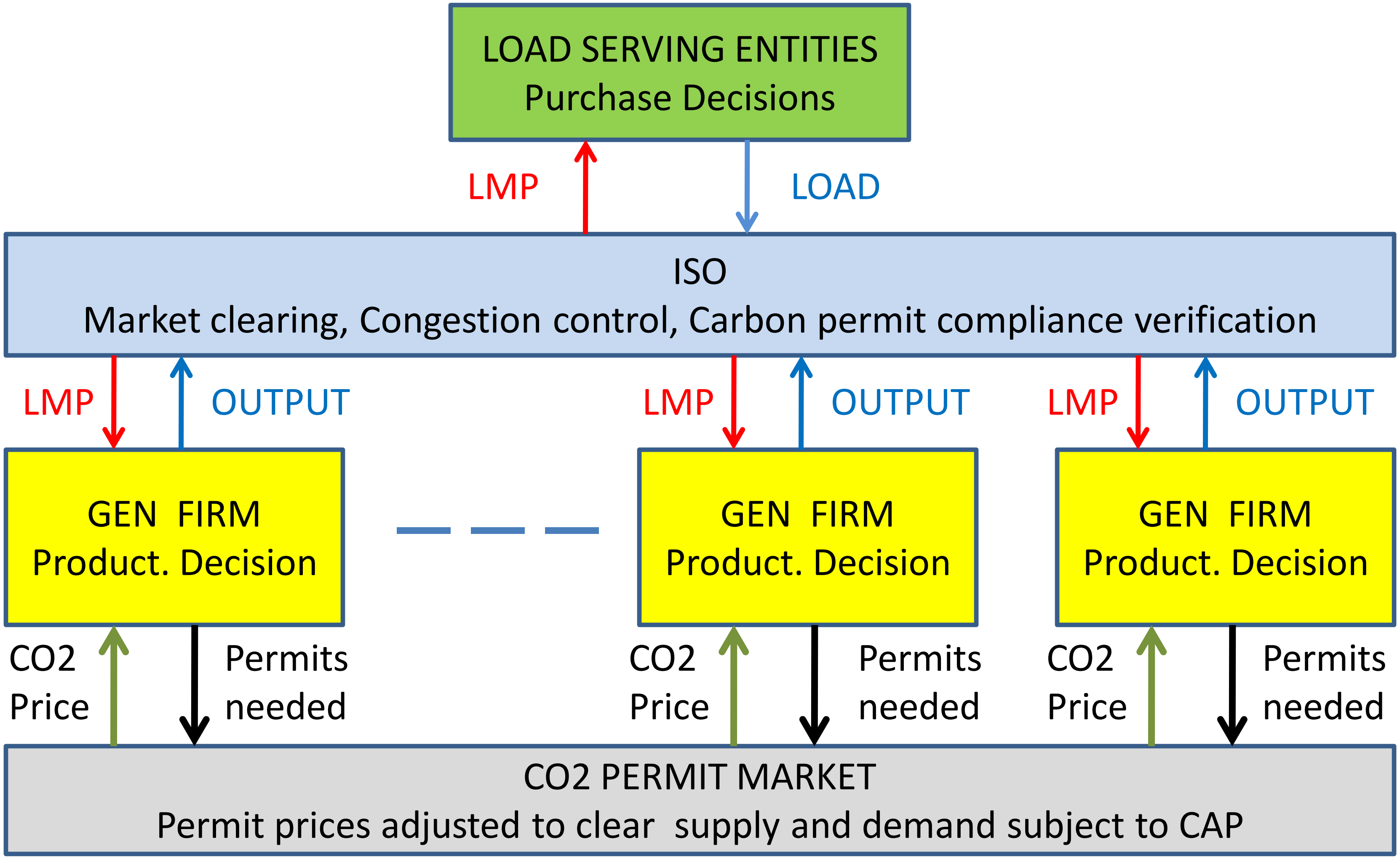
Scope of this talk

- Describe an equilibrium model of an oligopoly electricity market in conjunction with a cap-and-trade policy to study the impact of such interactions.
- Demonstrate the potential impacts on market and environmental outcomes, and on the performance of the transmission system
  - For an IEEE 24-bus test network
  - For a reduced WECC 225-bus model of the Western Interconnect

Equilibrium Model

- Transmission flows obey direct-current (DC) load flow model (Kirchhoff law) and are constrained by thermal limits (capacity of lines)
- Cournot producers with quadratic cost functions compete to sell energy at different locations in an LMP-based market and make output decisions so as to maximize profits.
- Demand is elastic and represented by nodal demand functions
- ISO clears the market and controls import/exports through locational congestion markups so as to maximize social welfare while satisfying security limits
- ISO monitors CO_2 permit compliance
- Endogenous CO_2 permit market sets carbon prices.

Equilibrium Model with CO_2 C&T



Electric Power Network

N = the set of buses
L = the set of transmission lines

(MW = Megawatt)

q_i MW output of the plant at bus i
r_i MW import/export at bus i (import = +)

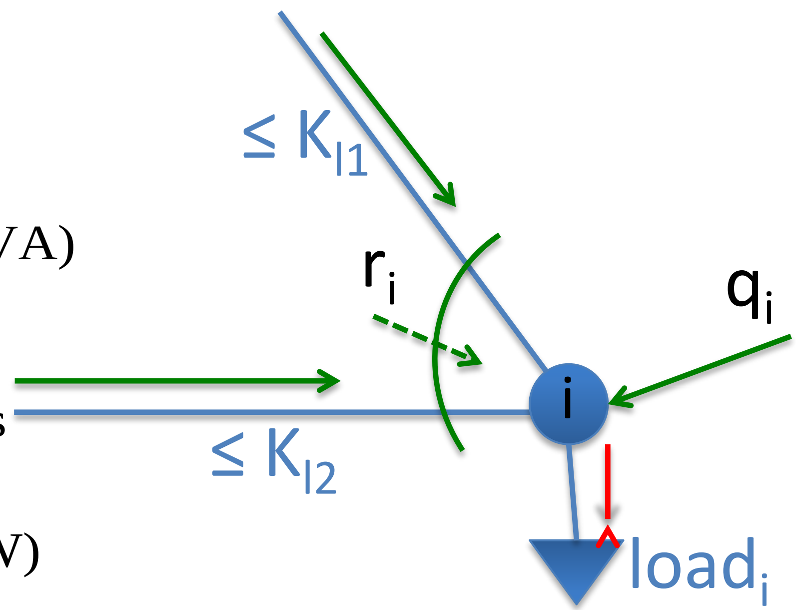
$load_i$ MW fixed load at bus i
K_l Rating of transmission line l (MVA)
$D_{l,i}$ $PTDF_{l,i}$ of line l with respect to a unit injection at bus i and a unit withdrawal at the slack bus
$\underline{q}_i$ Plant i's must-run limit (MW)
$\bar{q}_i$ Plant i's maximum capacity (MW)

$$q_i + r_i = load_i, \quad \forall i \in N$$

$$\textstyle\sum_{i \in N} r_i + \ Losses = 0$$

$$-K_l \leq \textstyle\sum_{i \in N} D_{l,i} r_i \leq K_l, \ \forall l \in L$$

$$\underline{q}_i \leq q_i \leq \bar{q}_i, \quad \forall i \in N$$

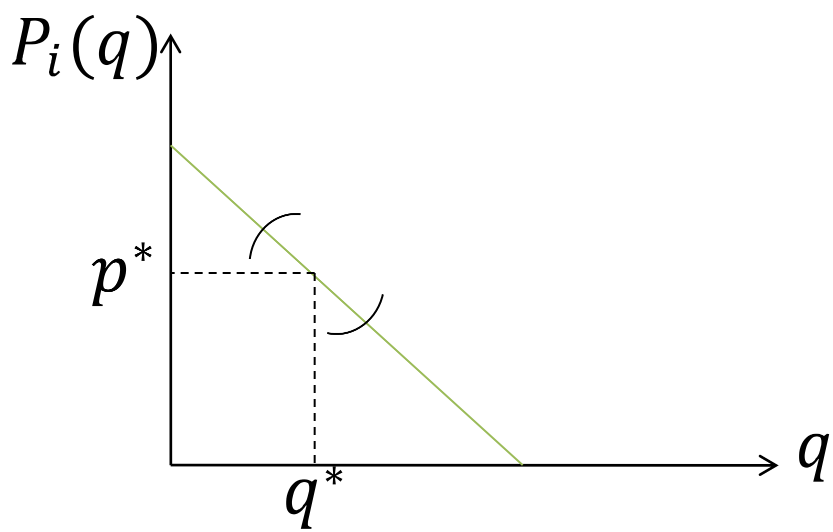


Price-responsive demand

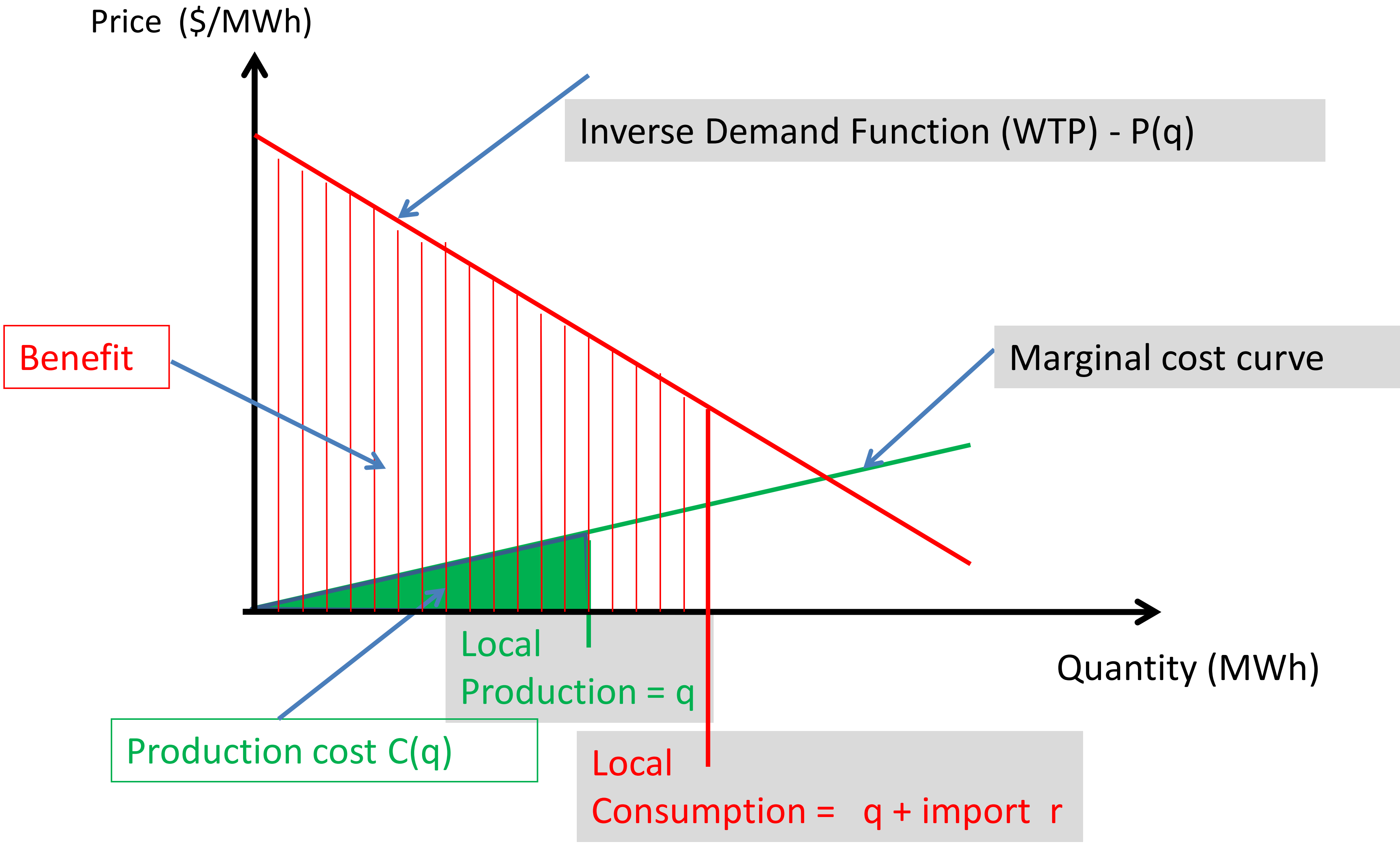
Consumers in each location *i* are represented by a linear inverse demand function:

$$P_i(q) = a_i - b_i q \;, \forall i \in N$$

- The inverse demand function at each bus is obtained from the results of a cost-minimizing power flow model.
- The price elasticity of demand is assumed to be -0.1 (Espey and Espey, 2004)



ISO Maximizes Social Welfare subject to Transmission Constraints and Enforces CO2 Cap



Equilibrium Model Mathematical Formulation (Linear Complementarity Problem)

ISO solves (redispatch problem)

$$\max_{r_i : i \in N} W = \sum_{i \in N} \int_0^{r_i + q_i} P_i(\tau_i) d\tau_i - C_i(q_i)$$

$$P_i(x) = a_i - b_i x, \forall i \in N$$

s.t. $\sum_{i \in N} r_i = 0 \qquad (p)$

$$\sum_{i \in N} D_{l,i} r_i \leq K_l, \forall l \in L \qquad (\lambda_l^+)$$

$$-K_l \leq \sum_{i \in N} D_{l,i} r_i, \quad \forall l \in L \qquad (\lambda_l^-)$$

KKT ISO:

$$P_i(q_i + r_i) = p + \varphi_i, \forall i \in N$$

$$\varphi_i = \sum_{l \in L} \lambda_l^+ D_{l,i} - \lambda_l^- D_{l,i}, \forall i \in N$$

$$\sum_{i \in N} r_i = 0$$

$$0 \leq \lambda_l^- \perp \sum_{i \in N} D_{l,i} r_i + K_l \geq 0, \quad \forall l \in L$$

$$0 \leq \lambda_l^+ \perp -\sum_{i \in N} D_{l,i} r_i + K_l \geq 0, \quad \forall l \in L$$

Each Firm g solves (profit maximization)

$$\max_{q_i : i \in N_g, p} \sum_{i \in N_g} (p + \varphi_i) q_i - C_i(q_i) - \mu e_i q_i$$

s.t. $\underline{q}_i \leq q_i \leq \bar{q}_i, \ \forall i \in N_g$

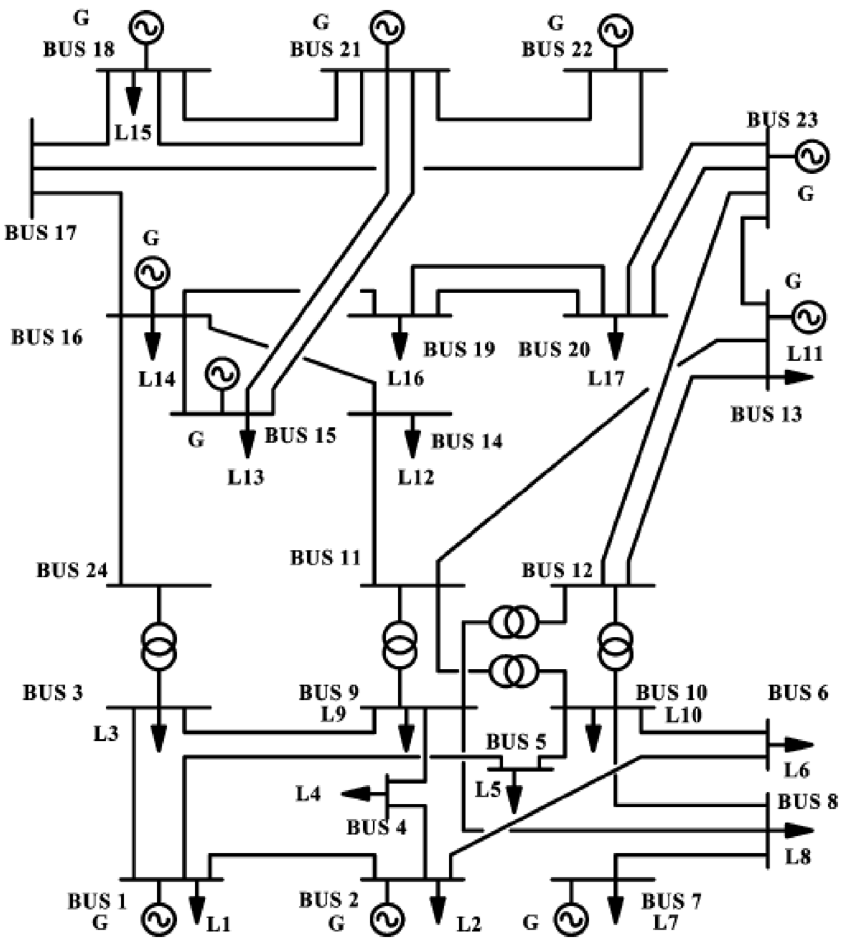
$$\sum_{i \in N} q_i = \sum_{i \in N} (P_i)^{-1} (p + \varphi_i)$$

CO_2 Market equilibrium

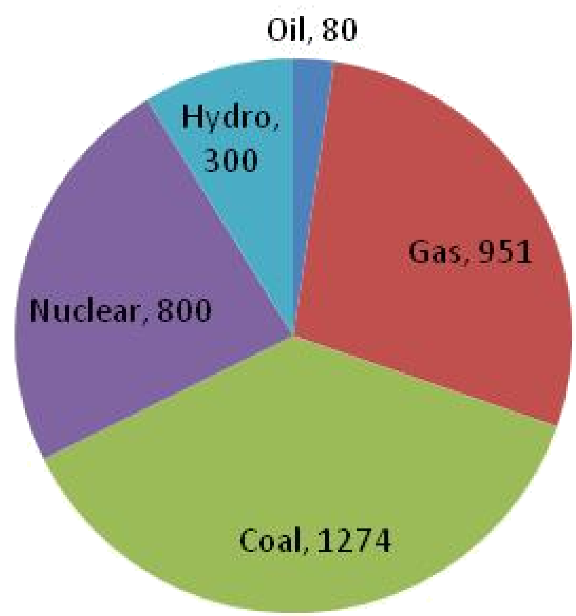
$$0 \leq \mu \perp \boldsymbol{M} - \sum_{i \in N} F_i(q_i) \leq 0$$

$$F_i(q) = e_i q \qquad \forall i \in N$$

IEEE 24-Bus Test System – 3,405 MW Load



Fuel Type	$/Mbtu	CO_2 (lbs/Mbtu)	# of units	Total MW
Oil	12	160	4	80
Gas	9.09	116	11	951
Coal	1.88	210	9	2174
Hydro	0	0	6	300
Nuclear	0	0	2	800



IEEE 24 Bus: Market Scenario

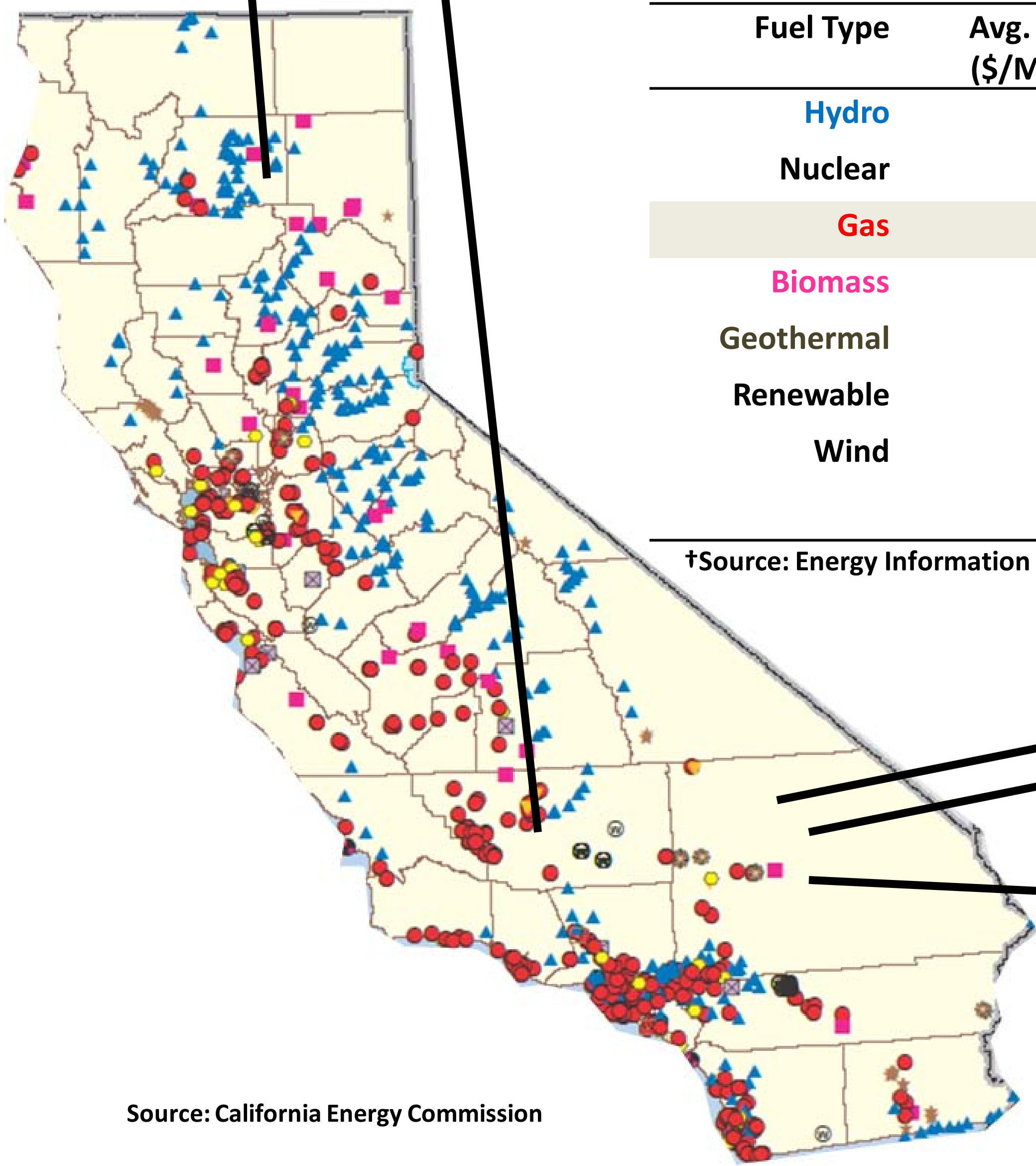
Scenario	Description
PC	Perfect competition
N+H+24T	Oligopolistic competition with 26 firms in total: Nuclear firm, Hydro firm + 24 thermal firms
N+H+2T	Oligopolistic competition with 4 firms in total: Nuclear firm, Hydro firm +2 thermal firms
NH+G+CO	Oligopolistic competition with 3 firms in total: one firm owns all nuclear and hydro facilities, second firm owns all gas facilities, third firm owns all coal and oil facilities.
NHG+CO	Duopoly: one firm owns nuclear, hydro, and gas Second firm owns all coal and oil facilities.
MP	Monopoly: all facilities belong to only one firm.

IEEE 24 Bus: Electricity Price

CO_2 CAP		Ownership Structure					
		PC	N+H+24	N+H+2	NH+G+CO	NHG+CO	MP
1205 Tons/h	Total CO_2 Emission [tons]	1,060	1,205	942	833	765	370
	Energy Consumption [MWh]	2,160	1,924	1,702	1,599	1,452	1,086
	Avg. LMP [$/MWh]	18	137	249	301	376	564
	CO_2 Price [$/ton]	0	66	0	0	0	0
	CO_2 Emissions Rate [tons/MWh]	0.491	0.626	0.553	0.521	0.527	0.341
	Congestion Rents [$]	0	0	0	0	0	10,020
	System Fuel Costs [$]	38,750	67,401	36,379	62,991	32,834	24,906
515 Tons/h	Total CO_2 Emission [tons]	515	515	515	515	515	370
	Energy Consumption [MWh]	1,734	1,556	1,537	1,367	1,294	1,086
	Avg. LMP [$/MWh]	249	323	333	419	456	564
	CO_2 Price [$/ton]	444	432	238	405	317	0
	CO_2 Emissions Rate [tons/MWh]	0.297	0.331	0.335	0.377	0.398	0.341
	Congestion Rents [$]	170,959	0	0	0	0	10,020
	System Fuel Costs [$]	66,649	63,629	56,158	49,113	27,877	24,906

Resource Mix

Imports



Source: California Energy Commission

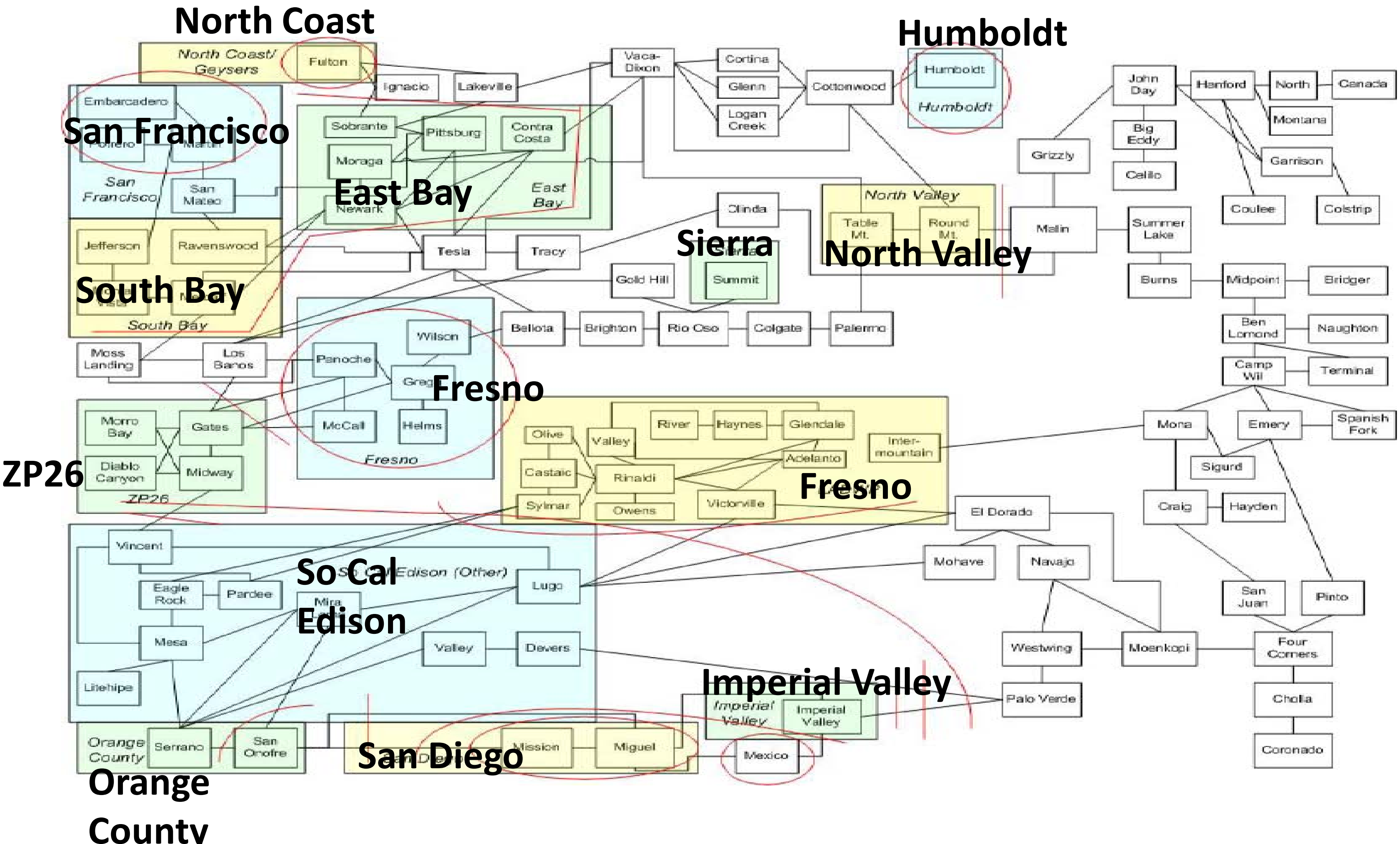
Fuel Type	Avg. MC† ($/MWh)	Avg. CO_2 rate (lb/MWh)	Total MW	Percent
Hydro	7	0	10,842	23%
Nuclear	9	0	4,499	10%
Gas	70	1,281	26,979	57%
Biomass	25	0	558	1%
Geothermal	0	0	1,193	3%
Renewable	0	0	946	2%
Wind	0	0	2,256	5%
			47,273	100%

†Source: Energy Information Administration, Annual Energy Outlook 2010, DOE/EIA-0383(2009)

Import	Avg. CO_2 rate (lbs/MWh)
Arizona	1,219
Nevada	1,573
Oregon	456

Source: eGRID2006 V2.1, April 2007

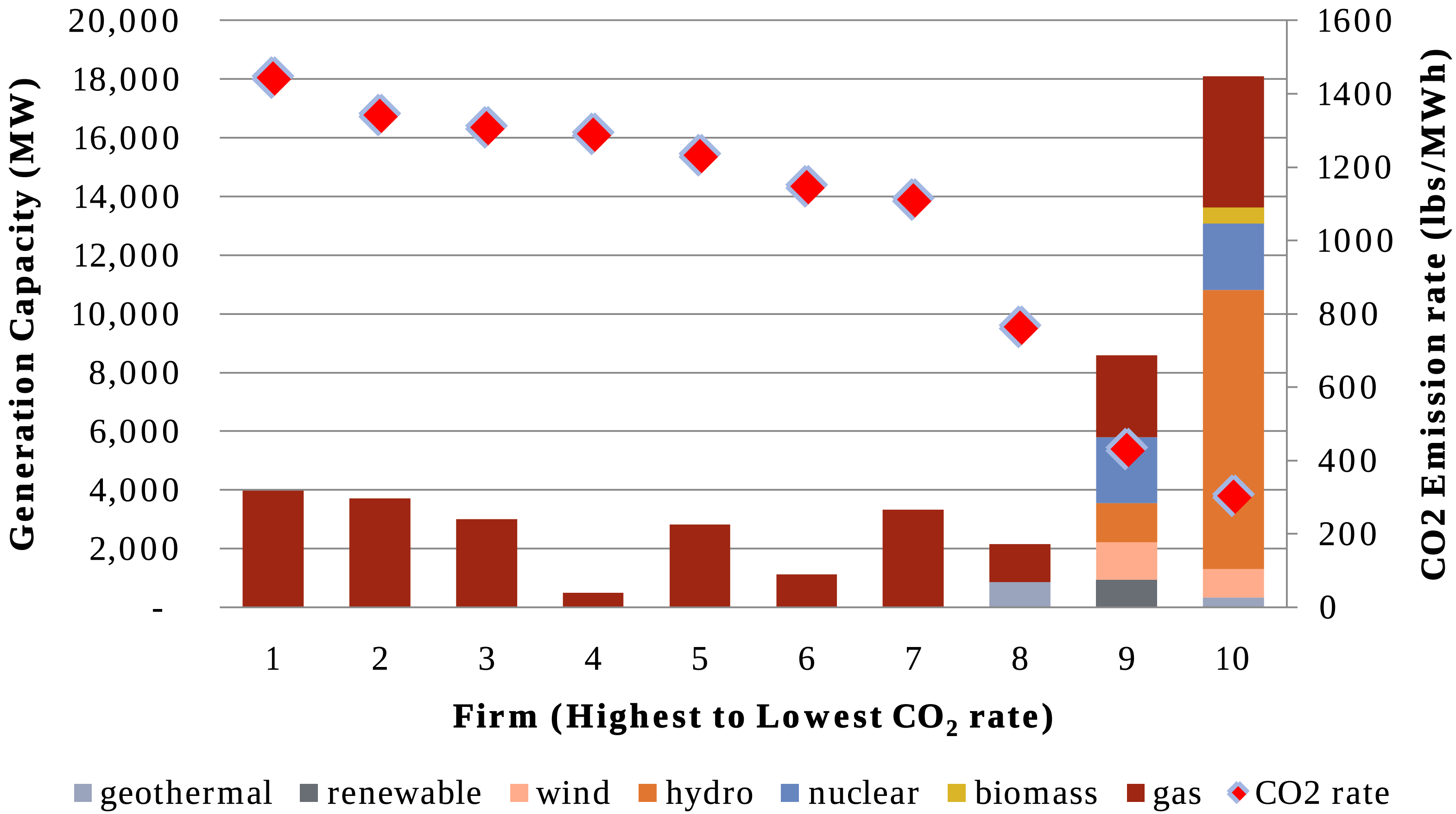
WECC 225 Bus System



Source: Power Systems Engineering Research Center

Resource Mix by Firm

HHI Index by capacity = 2,100
(Moderate Concentration)



Test Case Scenarios and Assumptions

- Scenarios:
  - Perfect Competition vs Oligopoly Competition
    - 10 firms with 1 competitive fringe
  - No CO_2 cap and CO_2 cap (20% reduction below Perfect Competition with No Cap and Transmission Constraints)
  - With/without transmission constraints
- Assumptions:
  - Price-responsive linear demand function
    - with demand elasticity of -0.1 (Espey and Espey, 2004)
  - Price-responsive linear supply function for imports
    - with supply elasticity of 0.005 (Tsao et. al., *Energy Policy [2011]*)
  - Simulated hour: the median load (Summer 2004)

Economic Results 225 Bus Case (**With**/**Without** Tr. Constr.)

	Perfect Competition				Oligopoly			
	No Cap		Cap		No Cap		Cap	
Total CO_2 Emission [tons]	6,111	4,977	4,889	4,889	9,766	9,611	4,889	4,889
Energy Consumption [MWh]	30,362	30,471	28,576	30,286	28,060	28,184	25,040	25,170
Avg. LMP [$/MWh]	59	53	94	56	97	95	154	151
CO_2 Price [$/ton]	0	0	74	8	0	0	155	151
CO_2 rate [ton/MWh]	0.201	0.163	0.171	0.161	0.348	0.341	0.195	0.194
Import CO_2 rate [ton/MWh]	0.465	0.464	0.465	0.464	0.464	0.464	0.464	0.464
In-State Fuel Costs (K$)	347	235	245	225	663	651	215	216
Social Surplus (K$)	10,386	10,511	10,348	10,510	9,899	9,923	9,968	9,988
Consumer Surplus (K$)	8,945	9,135	7,905	9,033	7,839	7,906	6,320	6,400
Producer Surplus (K$)	1,243	1,376	1,701	1,437	2,038	2,017	2,804	2,849
Congestion Revenues (K$)	198	0	379	0	22	0	84	0

Congestion VS No Congestion (**With**/**Without** Tr. Constr.)

	Perfect Competition				Oligopoly			
	No Cap		Cap		No Cap		Cap	
Total CO_2 Emission [tons]	6,111	4,977	4,889	4,889	9,766	9,611	4,889	4,889
Energy Consumption [MWh]	30,362	30,471	28,576	30,286	28,060	28,184	25,040	25,170
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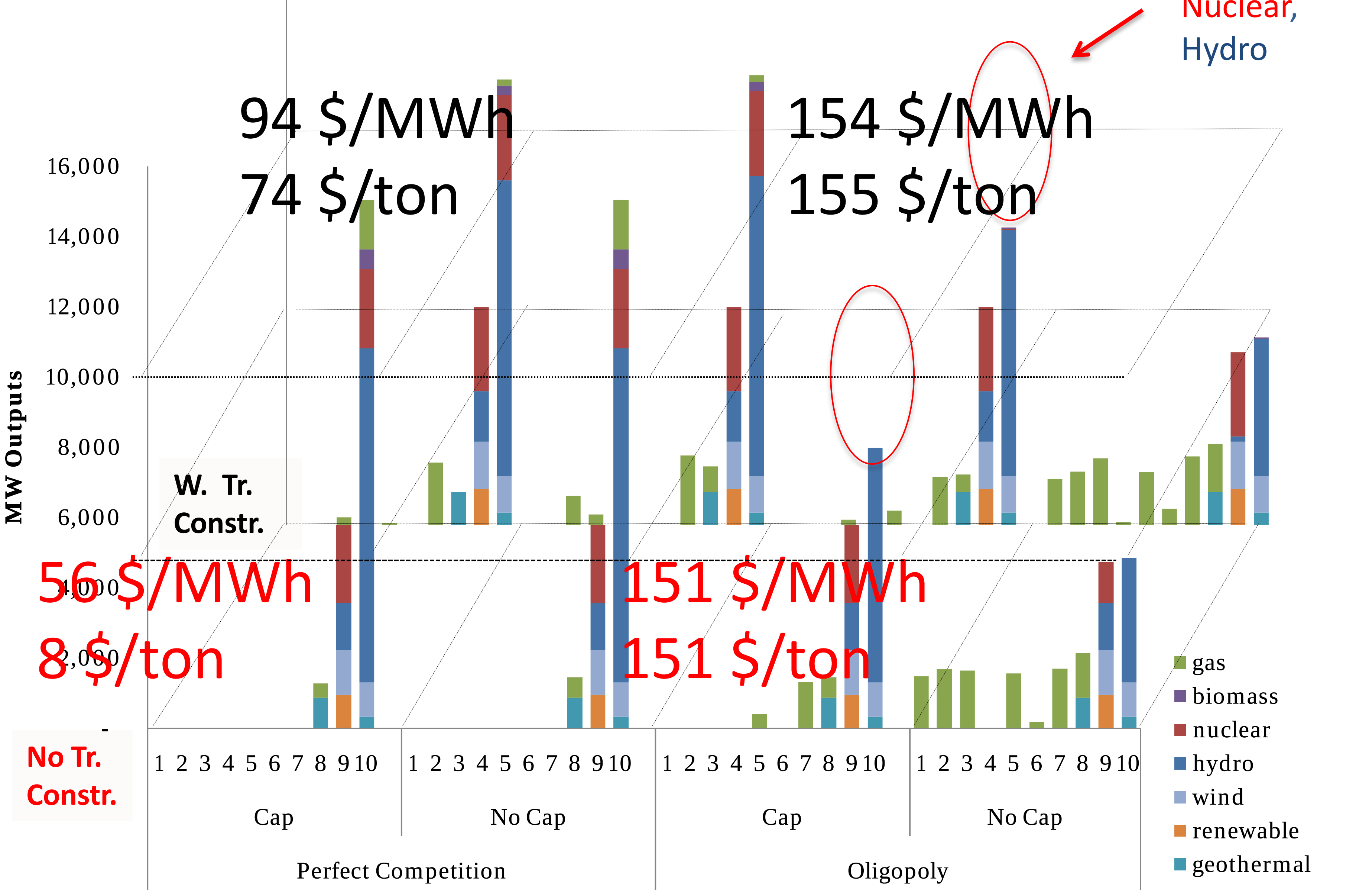
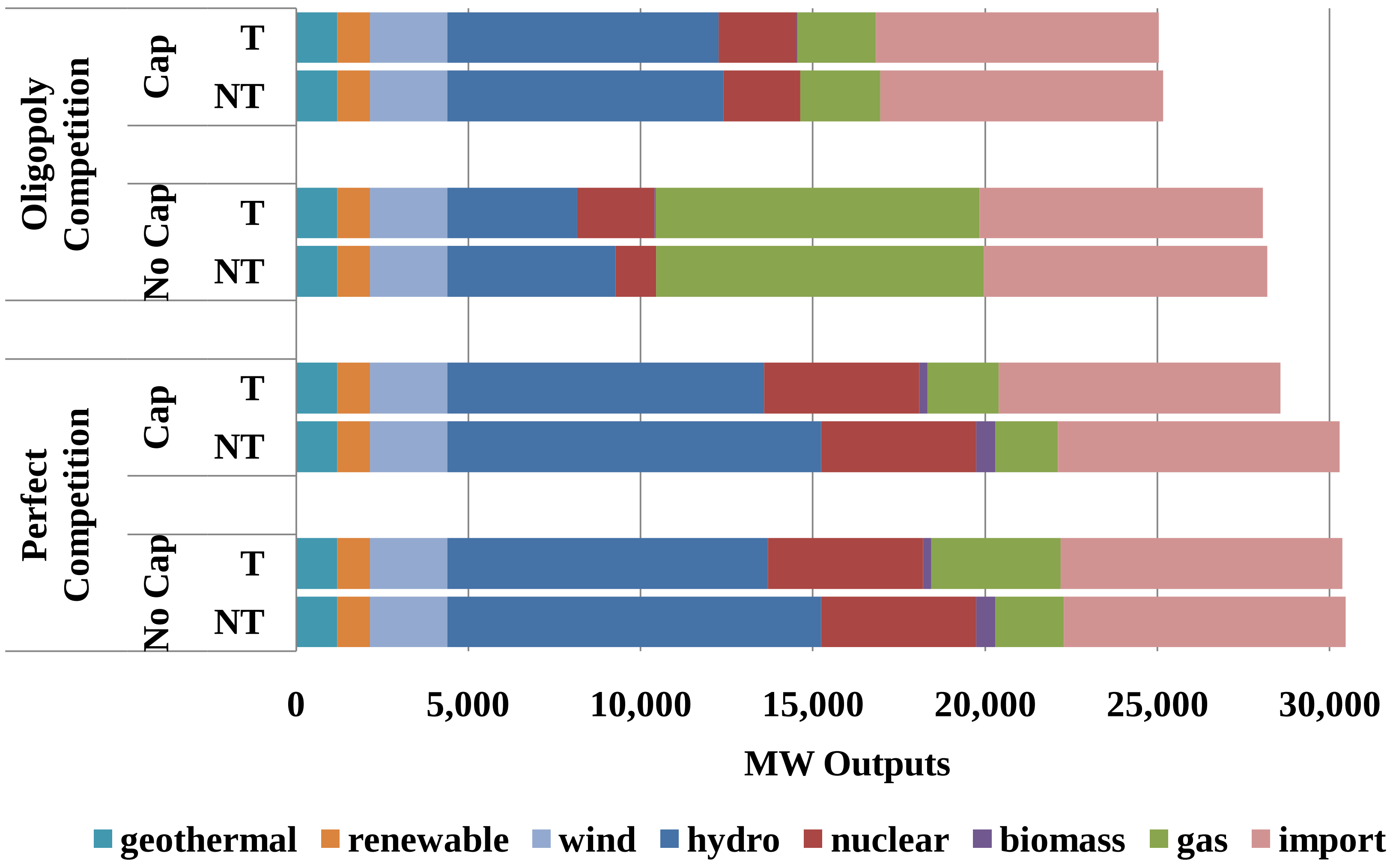
Equilibrium Results for Outputs by Firm



Comparison of Equilibrium Outputs between Transmission-Constrained and Unconstrained Electricity Markets



Implications of Simulation Studies

- We have demonstrated the need to consider the interaction of congestion and ownership structure (market power) in evaluating the impact of environmental policies on performance of the power system.
- Complex interaction may lead to unintended consequences that would not be revealed by simplified models.
  - A tight emission cap and ownership concentration of clean resources amplify market power effects.
  - In a transmission-constrained market, geographical concentration of clean resources can indirectly amplify market power via the permit market.
- Major Limitation of the Analysis:
  - One hour snapshot ignores intertemporal price smoothing in carbon market
  - Our carbon permit market targets only electricity and ignores the impact of other industry sectors participating in C&T on permit prices.

Questions?