



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

Project M21 Part II

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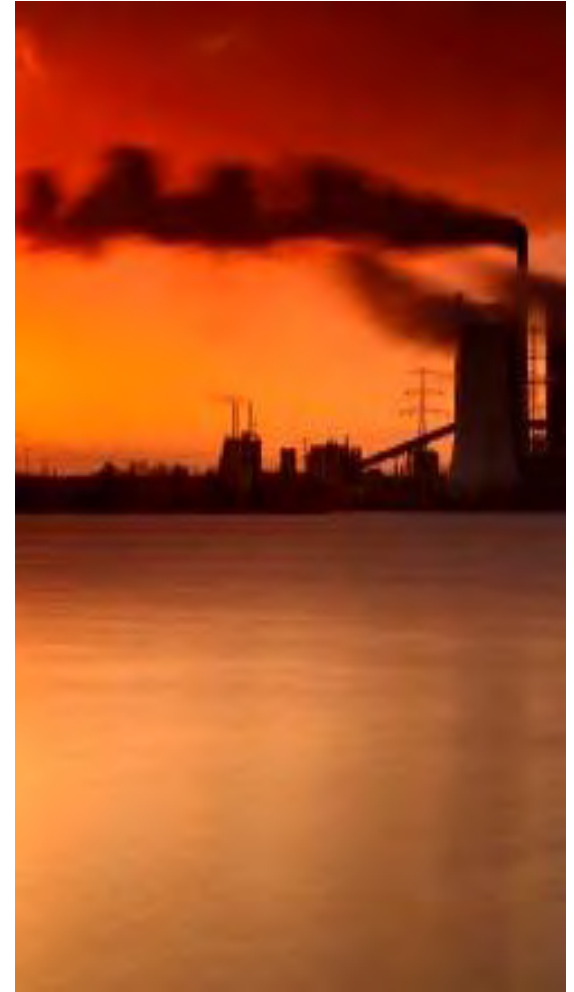
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Greenhouse Gas (GHG) Regulation in the US is Evolving on a Regional Basis

- Regional Greenhouse Gas Initiative (RGGI) continues to be a forum for trading emissions allowances in the north east of the US
- In California GHG regulation has taken the form of renewable portfolio standard (RPS) and AB 32, The California Global Warming Solution Act, which embraced the cap-and-trade (C&T) model
- The Western Renewable Energy Generation Information System (WREGIS) tracks and authenticates renewable energy generation certificates (RECs) in 14 western states and two Canadian provinces
- Recently the CPUC ruled that RECs can be used by California IOUs to meet up to 25% of their RPS obligation.



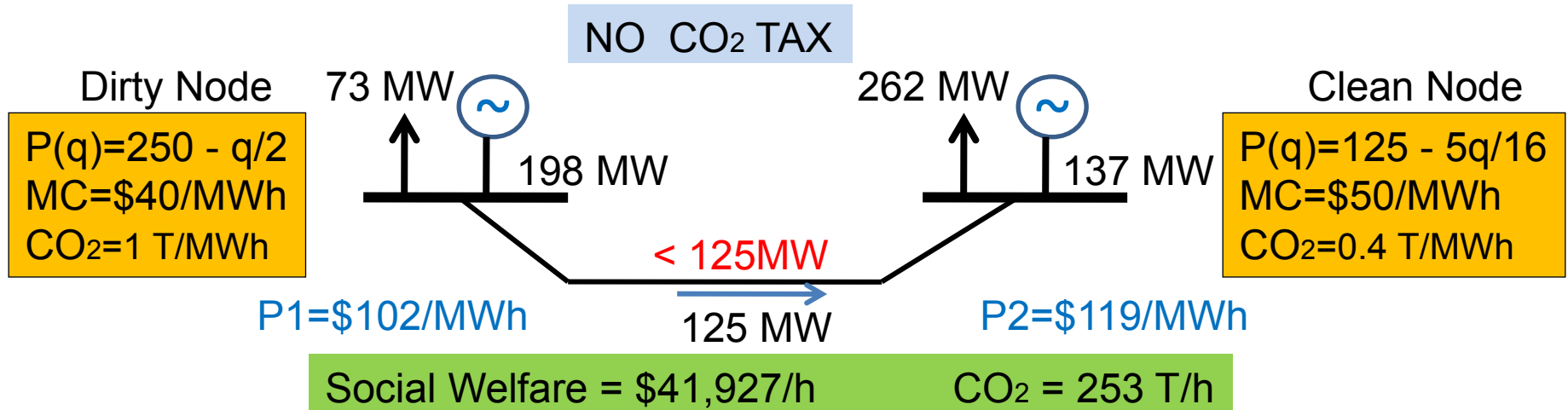
Research on Regional GHG Regulation

- 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)

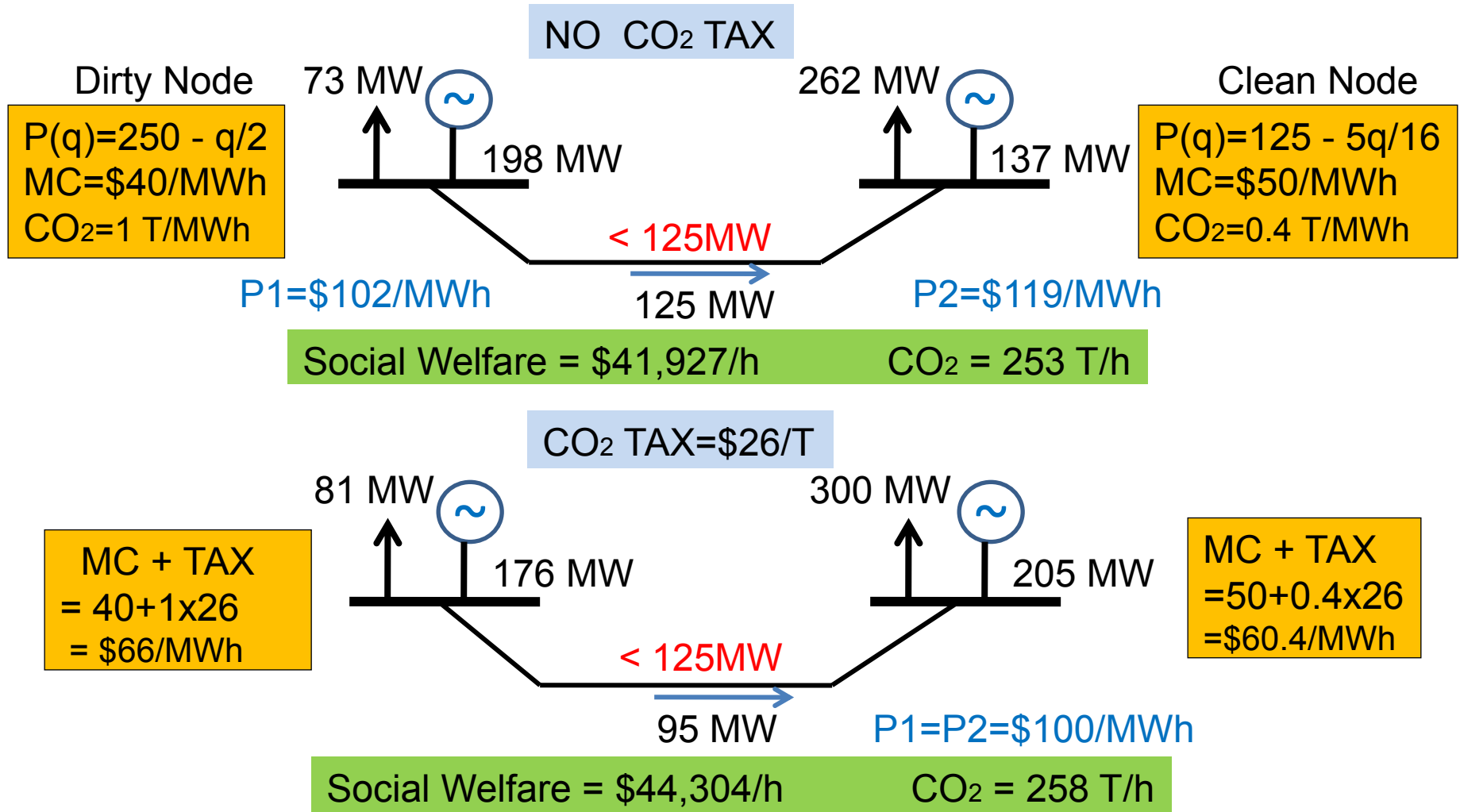
Example: Perverse Effect of Carbon Tax



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.

Example: Perverse Effect of Carbon Tax

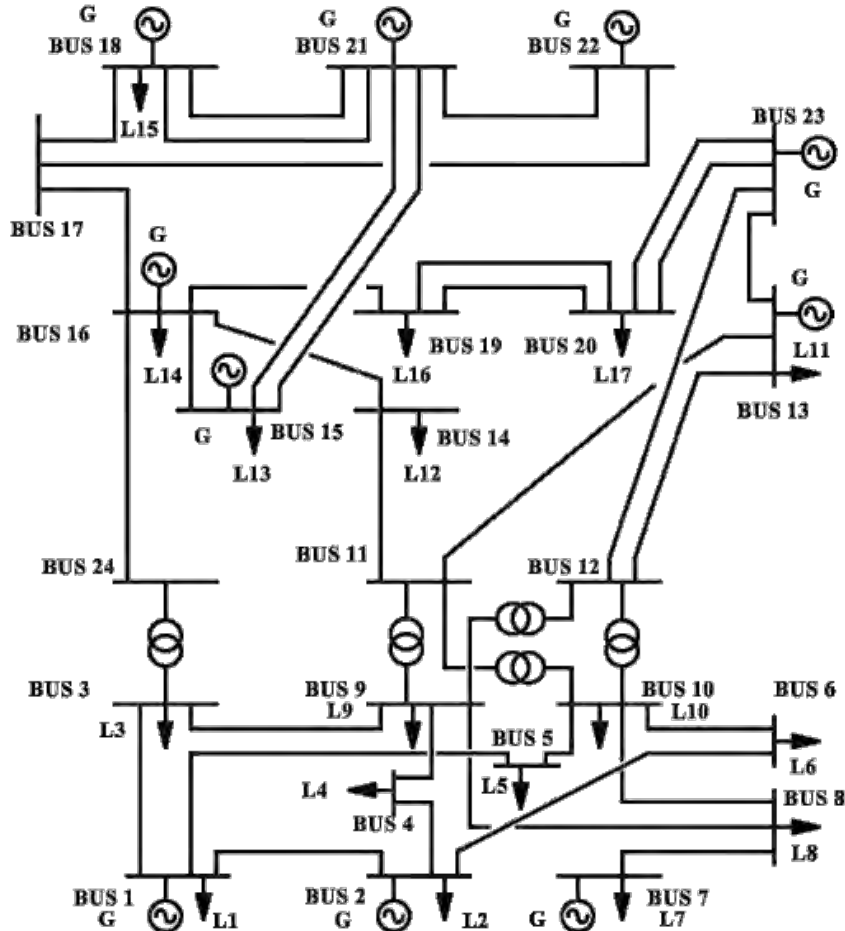


Social Welfare = Consumer Surplus + Producers Profit + Congestion Rents + Tax

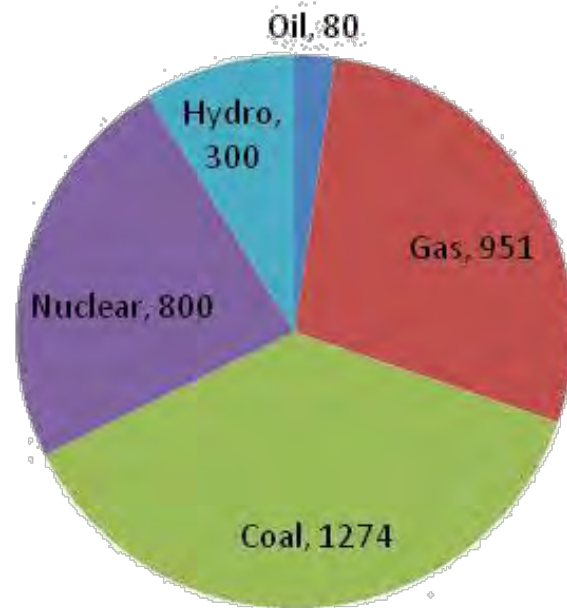
Scope of this talk

- 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

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

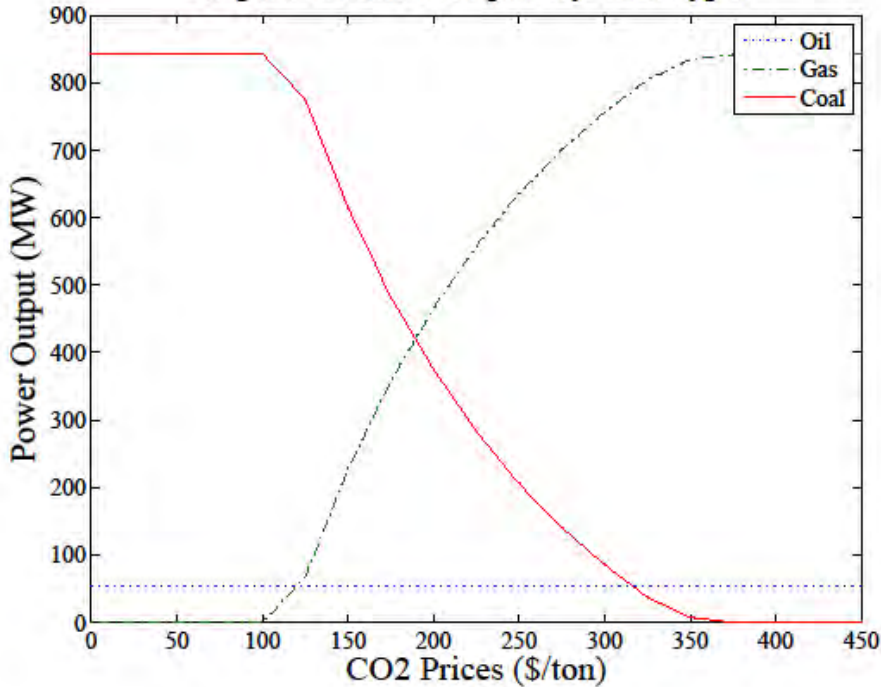


Fuel Type	\$/Mbtu	CO ₂ (lbs/Mbtu)	# of units	Total MW
Oil	12	160	4	80
Gas	9.09	116	11	951
Coal	1.88	210	9	2174
Hydro	0	0	6	300
Nuclear	0	0	2	800



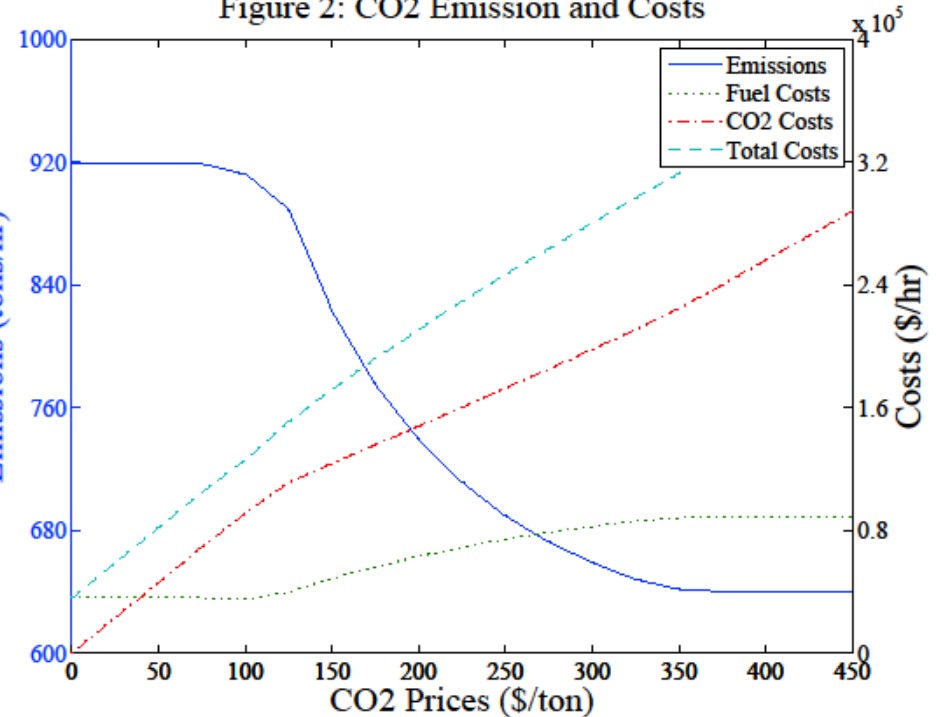
Benchmark Analysis for Perfect Competition

Figure 1: Power Outputs by Fuel Types



The total power outputs of all fuel types. At CO₂ price about \$100, Gas begins to replace Coal, and as CO₂ price increases, total coal-fueled output is falling.

Figure 2: CO2 Emission and Costs



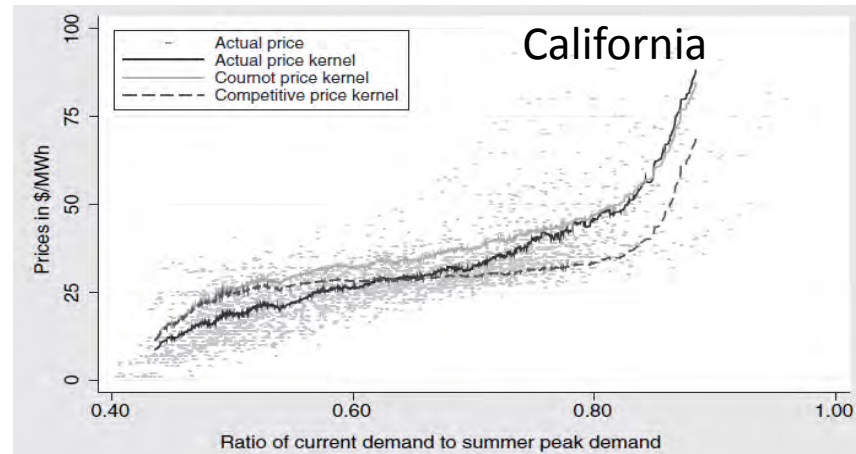
As CO₂ price increases, costs are rising and total CO₂ emissions are decreasing

Equilibrium Model

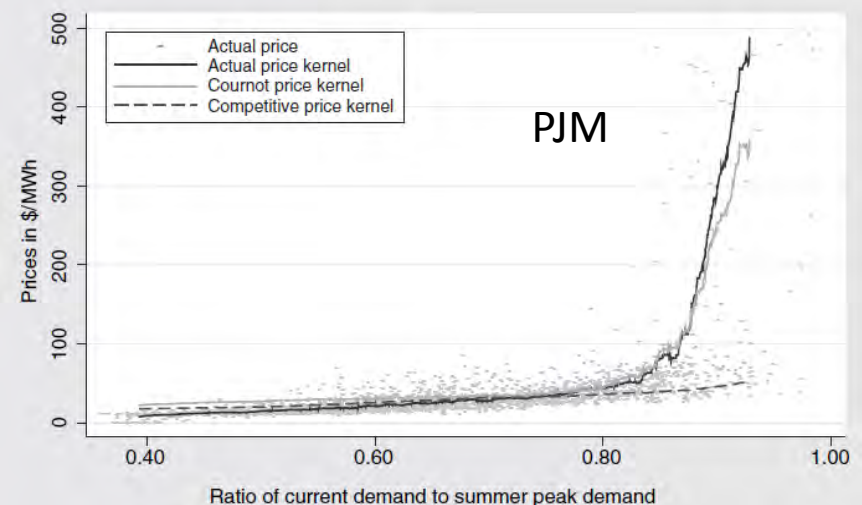
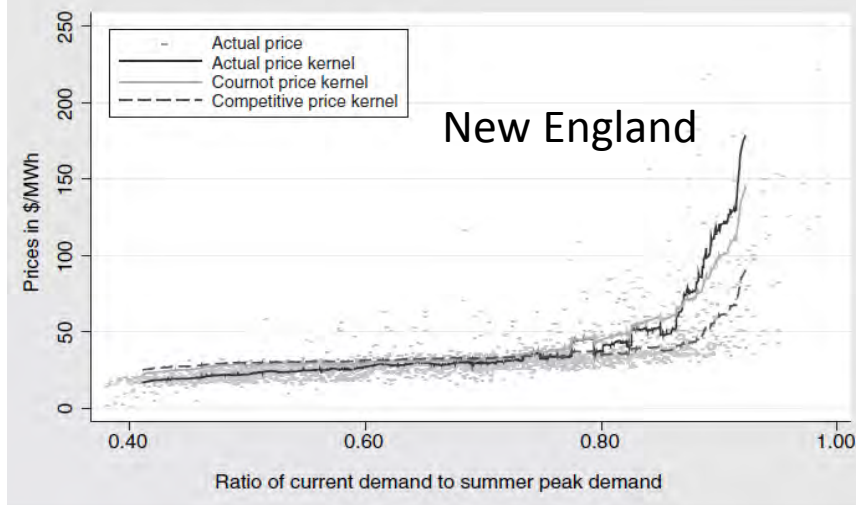
- Transmission flows obey direct-current (DC) load flow model (Kirchhoff law) and are constrained by thermal limits (capacity of lines)
- Cournot producers with quadratic cost functions compete to sell energy at different locations in an LMP-based market and make output decisions so as to maximize profits.
- 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 CO₂ permit compliance
- Endogenous CO₂ permit market sets carbon prices.

Empirical Validity of Cournot Models

(Based on 1999 data in CA, NE and PJM and accounting for vertical arrangements)



Source: Bushnell, James; Mansur, Erin T.; Saravia, Celeste, Vertical Arrangements, Market Structure and Competition Electricity An Analysis of Restructured U.S., Markets., *American Economic Review* Vol. 98 no. 1 (March 2008): 237-266.

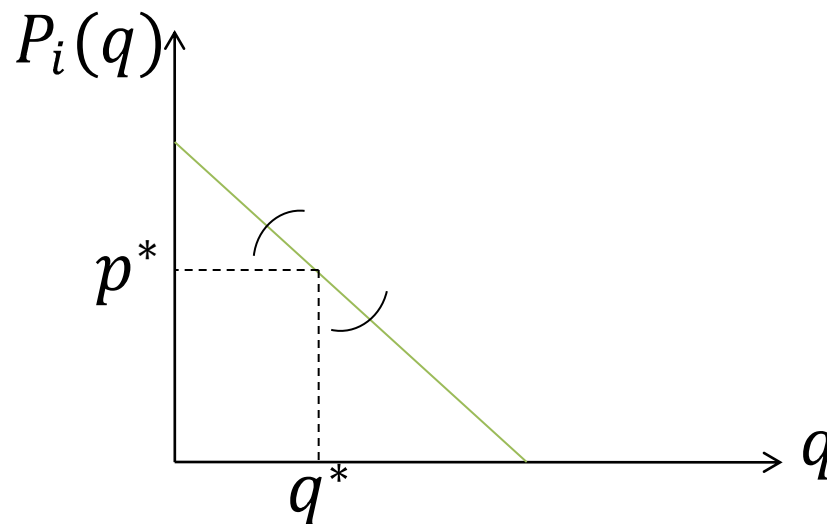


Price-responsive demand

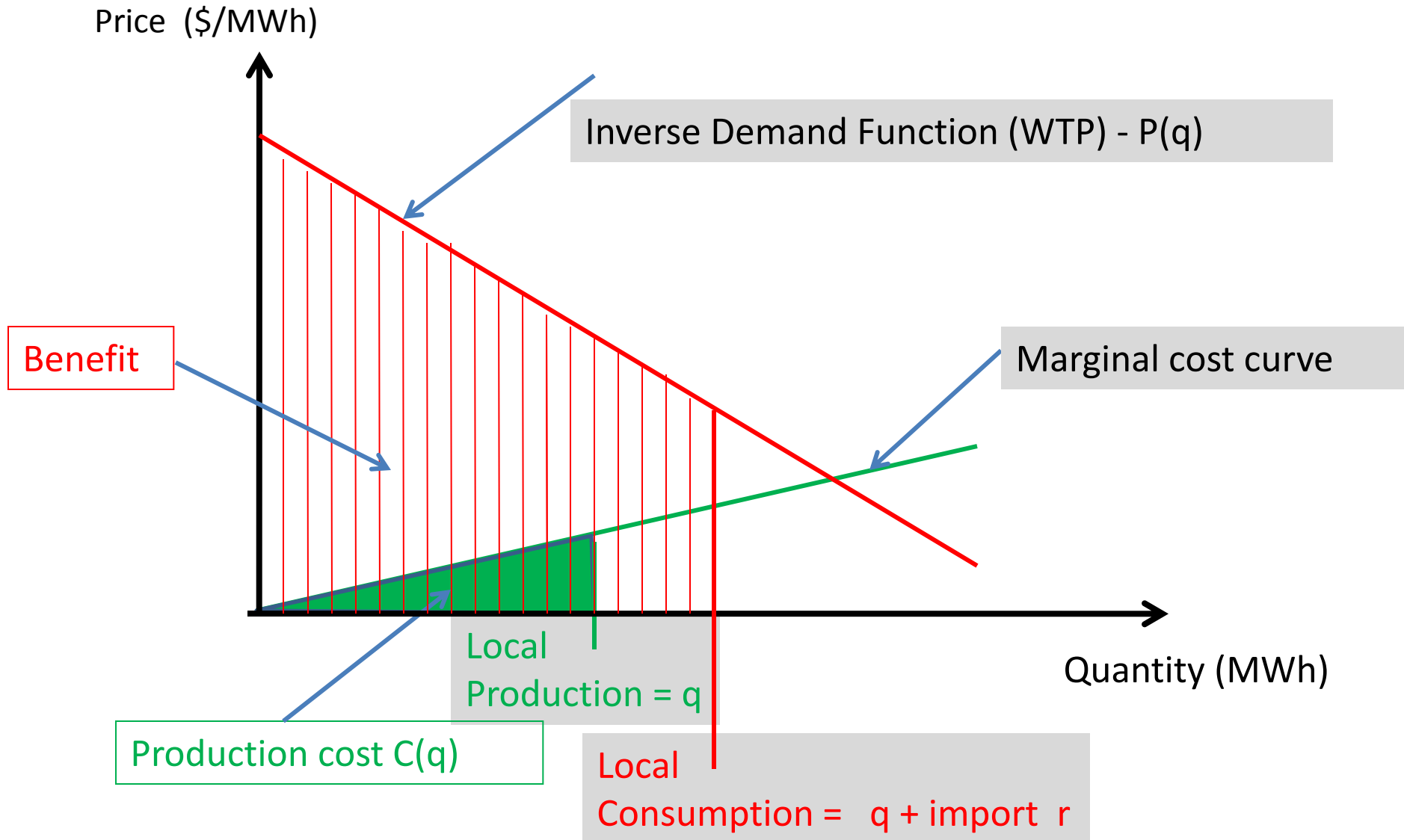
Consumers in each location i are represented by a linear inverse demand function:

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

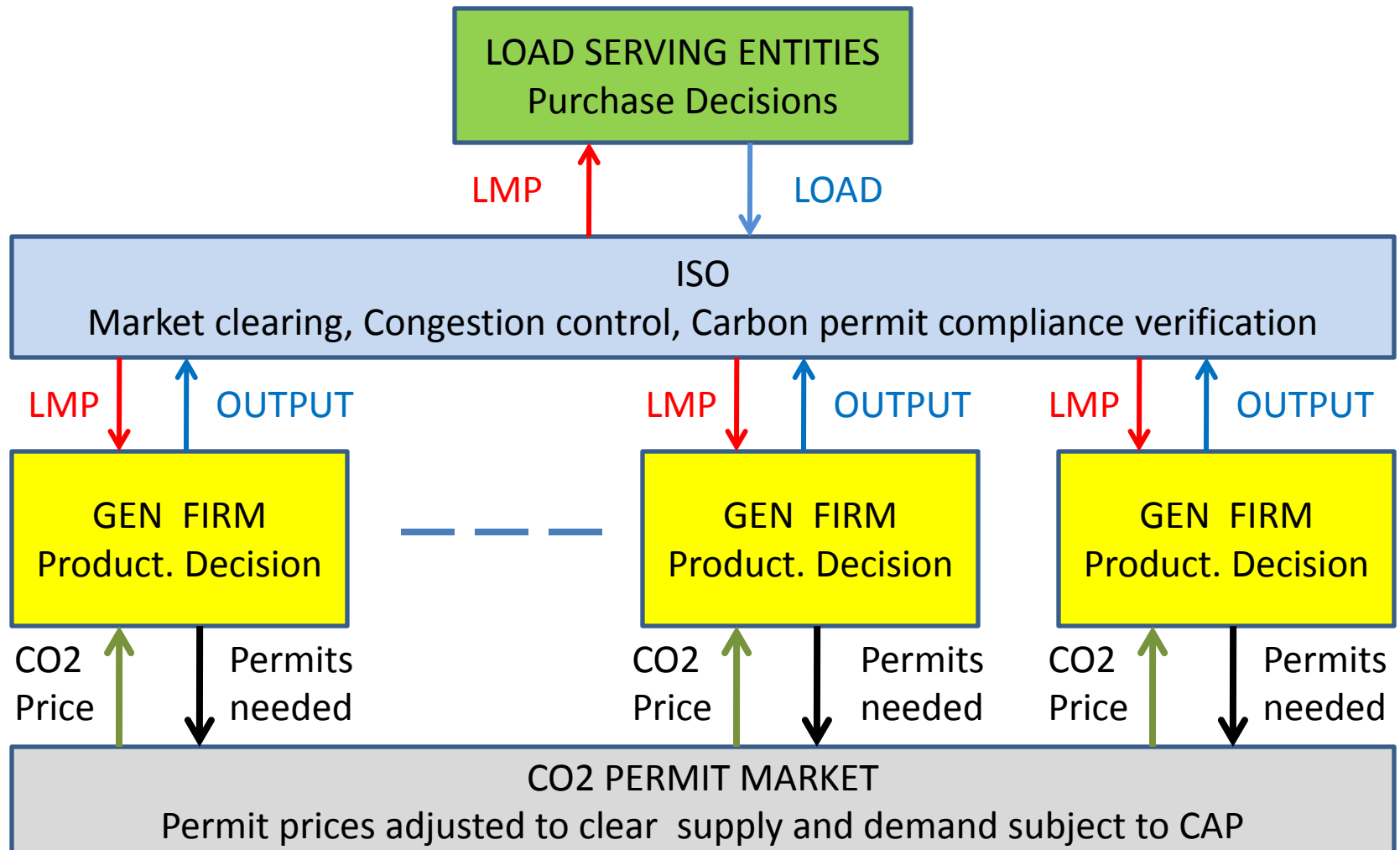
- The inverse demand function at each bus is obtained from the results of a cost-minimizing power flow model.
- The price elasticity of demand is assumed to be -0.1 (Espey and Espey, 2004)



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



Equilibrium Model with CO2 C&T



Equilibrium Model Mathematical Formulation (Linear Complementarity Problem)

ISO solves (redispatch problem)

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

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

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

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

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

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)

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

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

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

CO₂ Market equilibrium

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

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

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.

Equilibrium Results for IEEE 24 Bus Case

Ownership Structure

		PC	N+H+24	N+H+2	NH+G+CO	NHG+CO	MP	
CO2 CAP	1205 Tons/h	Total CO2 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
		CO2 Price [\$/ton]	0	66	0	0	0	0
		CO2 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
		Total CO2 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
		CO2 Price [\$/ton]	444	432	238	405	317	0
		CO2 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

IEEE 24 Bus: Perfect Competition VS Oligopoly

Ownership Structure

		PC N+H+24		N+H+2	NH+G+CO	NHG+CO	MP	
CO2 CAP	1205 Tons/h	Total CO2 Emission [tons]	1,060	1,205	942	833	765	370
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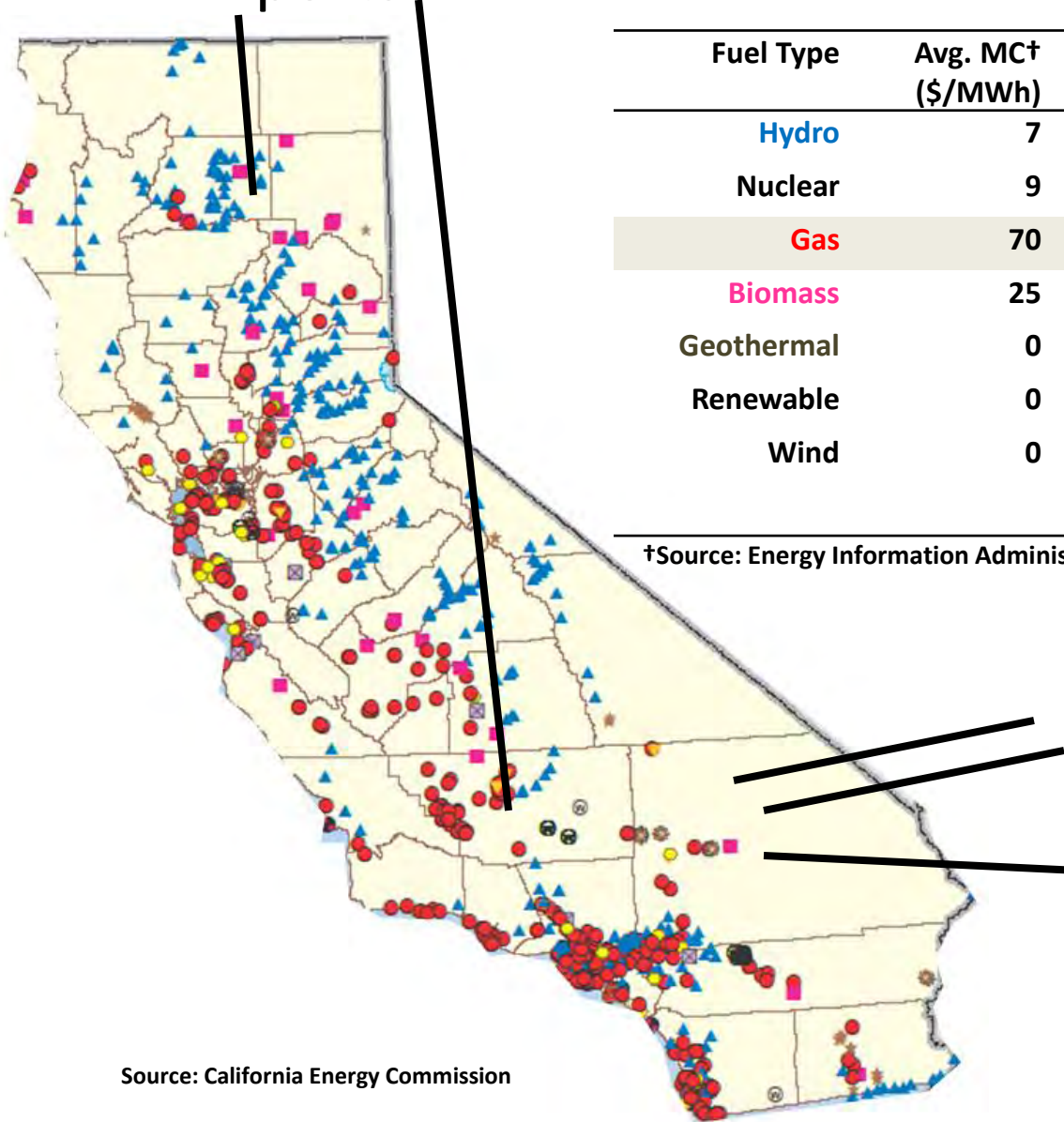
IEEE 24 Bus: Electricity Price

Ownership Structure

		PC	N+H+24	N+H+2	NH+G+CO	NHG+CO	MP	
CO2 CAP	1205 Tons/h	Total CO2 Emission [tons]	1,060	1,205	942	833	765	370
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Resource Mix

Imports



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%

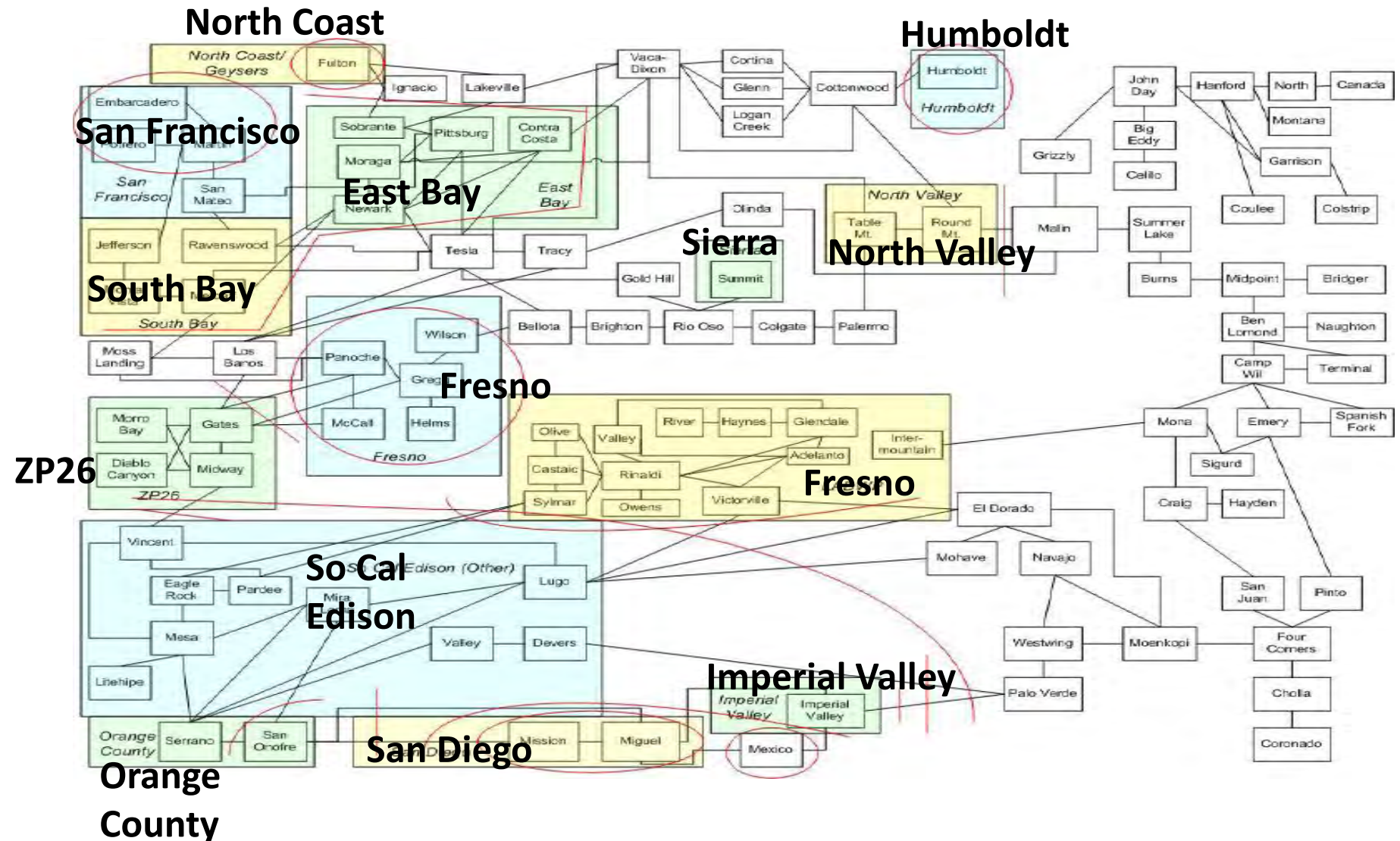
†Source: Energy Information Administration, Annual Energy Outlook 2010, DOE/EIA-0383(2009)

Import	Avg.CO ₂ rate (lbs/MWh)
Arizona	1,219
Nevada	1,573
Oregon	456

Source: eGRID2006 V2.1, April 2007

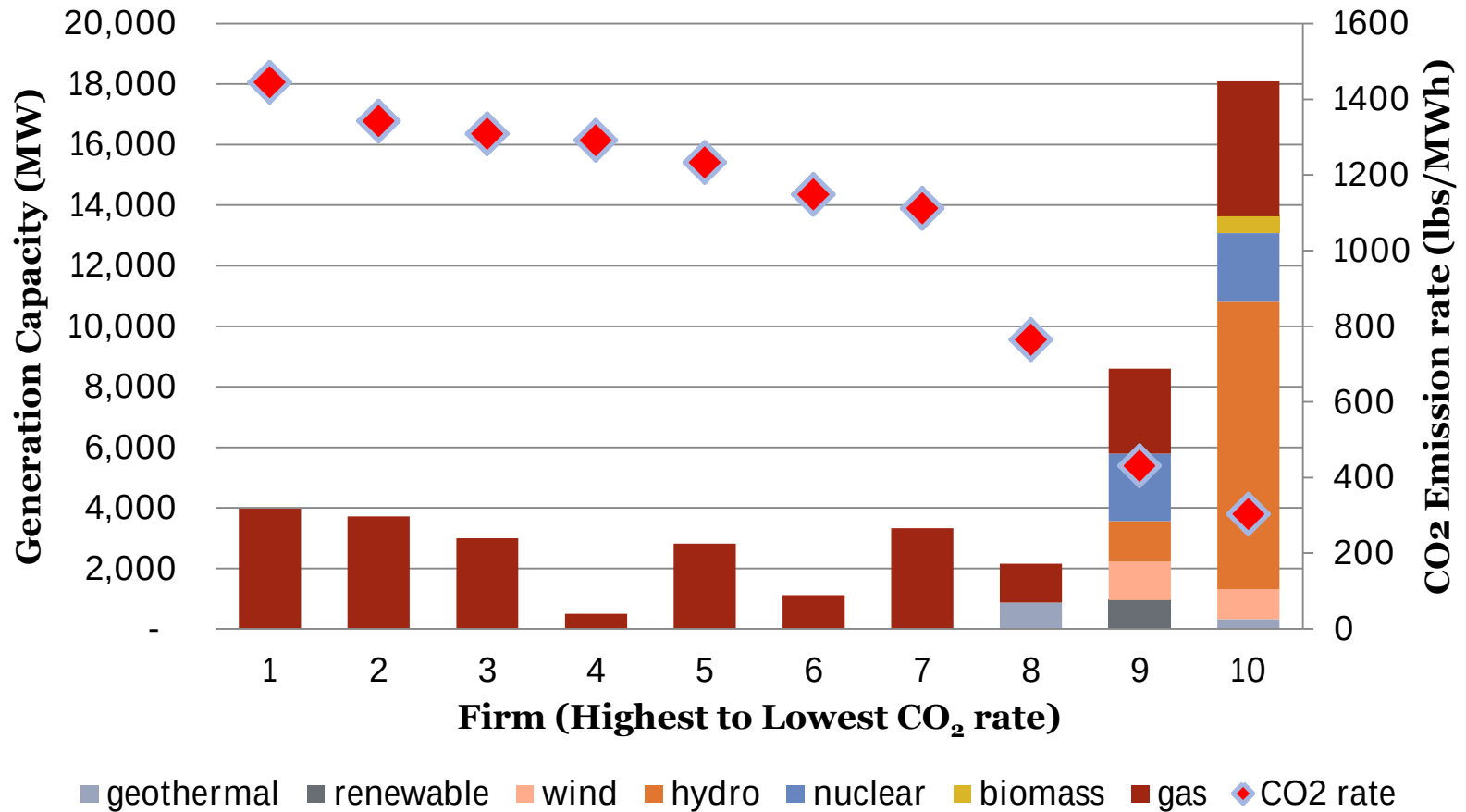
Source: California Energy Commission

WECC 225 Bus System



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 CO₂ cap and CO₂ cap (20% reduction below Oligopoly's No Cap)
- 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., *working paper*)
- Simulated hour: the median load (Summer 2004)

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

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	Perfect Competition				Oligopoly			
	No Cap		Cap		No Cap		Cap	
Total CO ₂ Emission [tons]	6,227	4,927	4,593	4,593	5,741	9,396	4,593	4,593
Energy Consumption [MWh]	30,362	30,362	27,766	29,864	28,994	28,032	27,368	24,780
Avg. LMP [\$ /MWh]	52	52	98	61	66	93	99	149
CO ₂ Price [\$ /ton]	0	0	96	17	0	0	95	155
CO ₂ rate [ton/MWh]	0.205	0.162	0.165	0.154	0.198	0.335	0.168	0.185
Import CO ₂ rate [ton/MWh]	0.465	0.465	0.464	0.465	0.465	0.465	0.464	0.464
In-State Fuel Costs (K\$)	348	229	219	204	319	627	218	181
Social Surplus (K\$)	8,814	8,878	8,405	8,804	8,686	7,980	8,383	7575
Consumer Surplus (K\$)	7,957	7,946	6,636	7,687	7,594	6,773	6,631	5,293
Producer Surplus (K\$)	681	932	1,412	1,104	962	1,207	1,460	2,160
Congestion Revenues (K\$)	175	0	280	0	129	0	216	0
Import Costs (K\$)	387	428	725	498	501	759	746	1,218

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

25

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

26

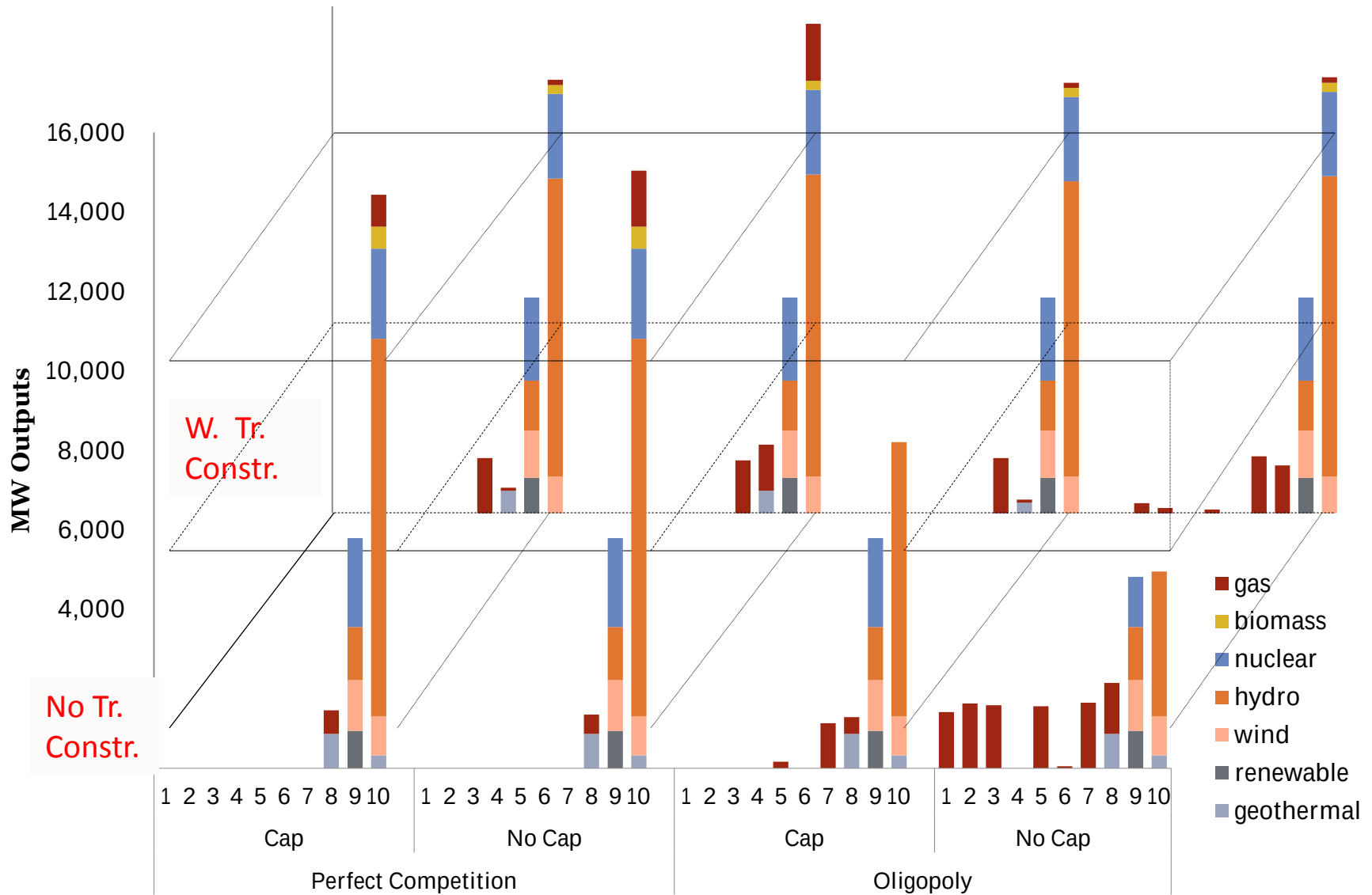
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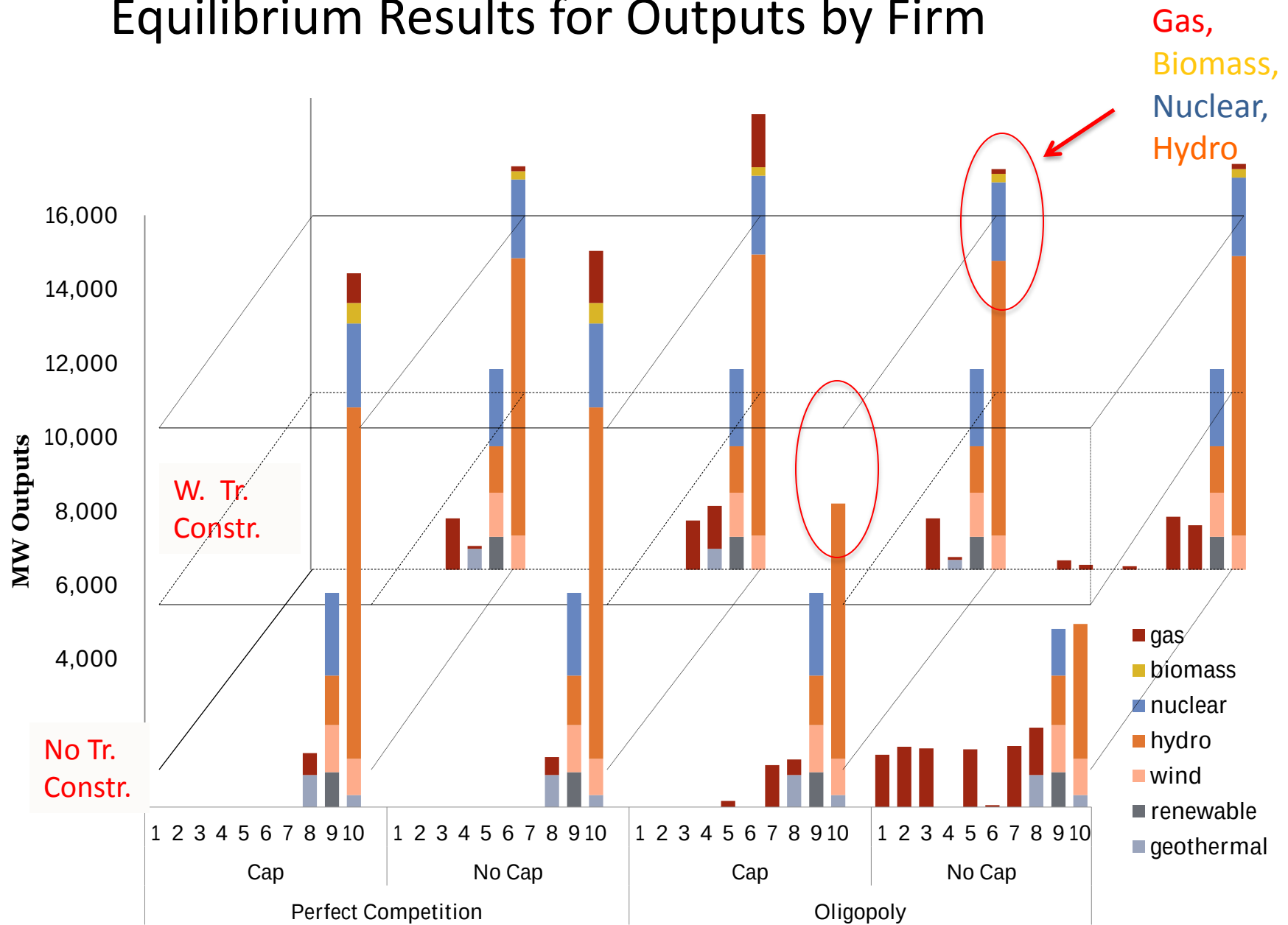
27

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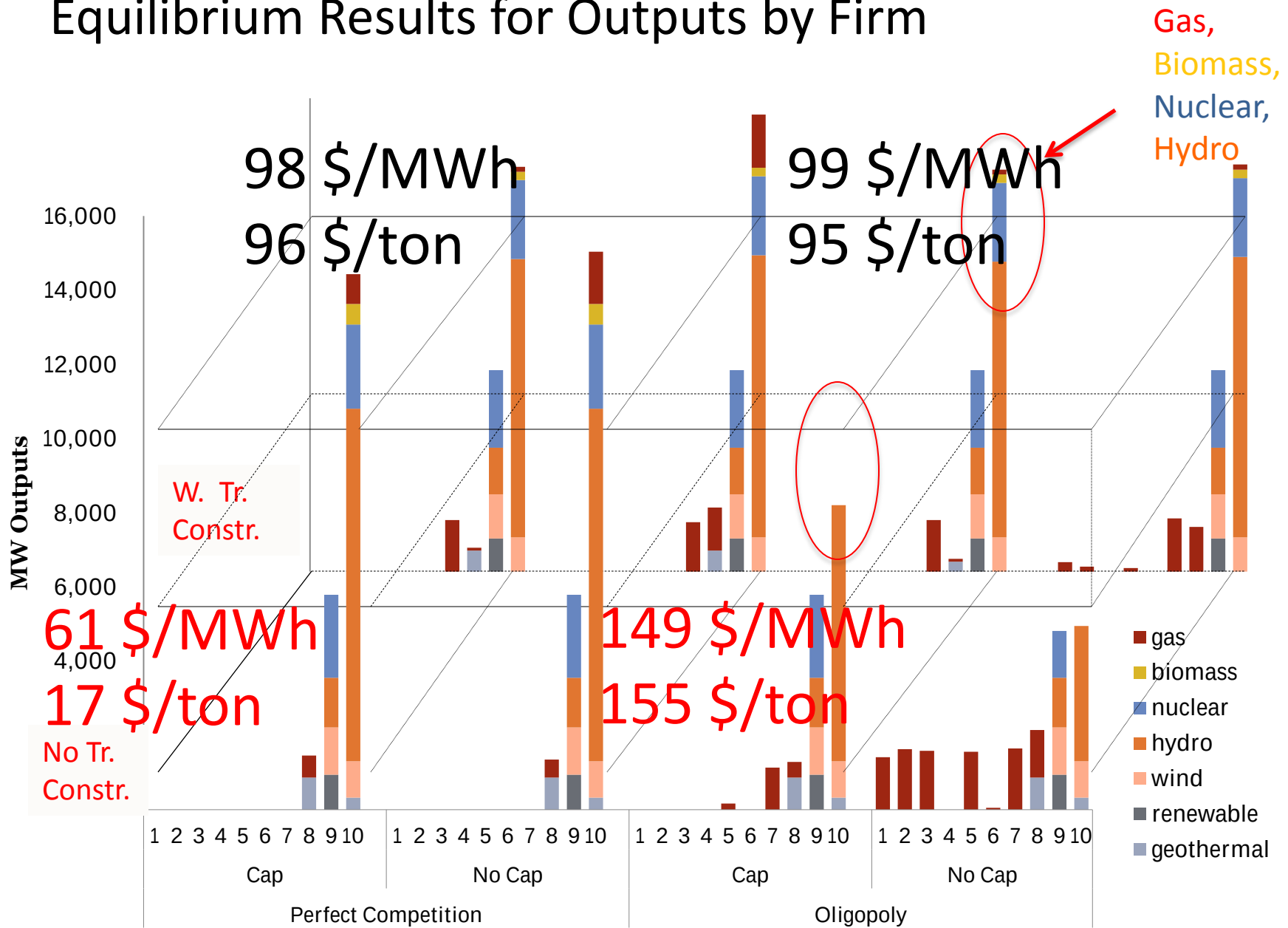
Equilibrium Results for Outputs by Firm



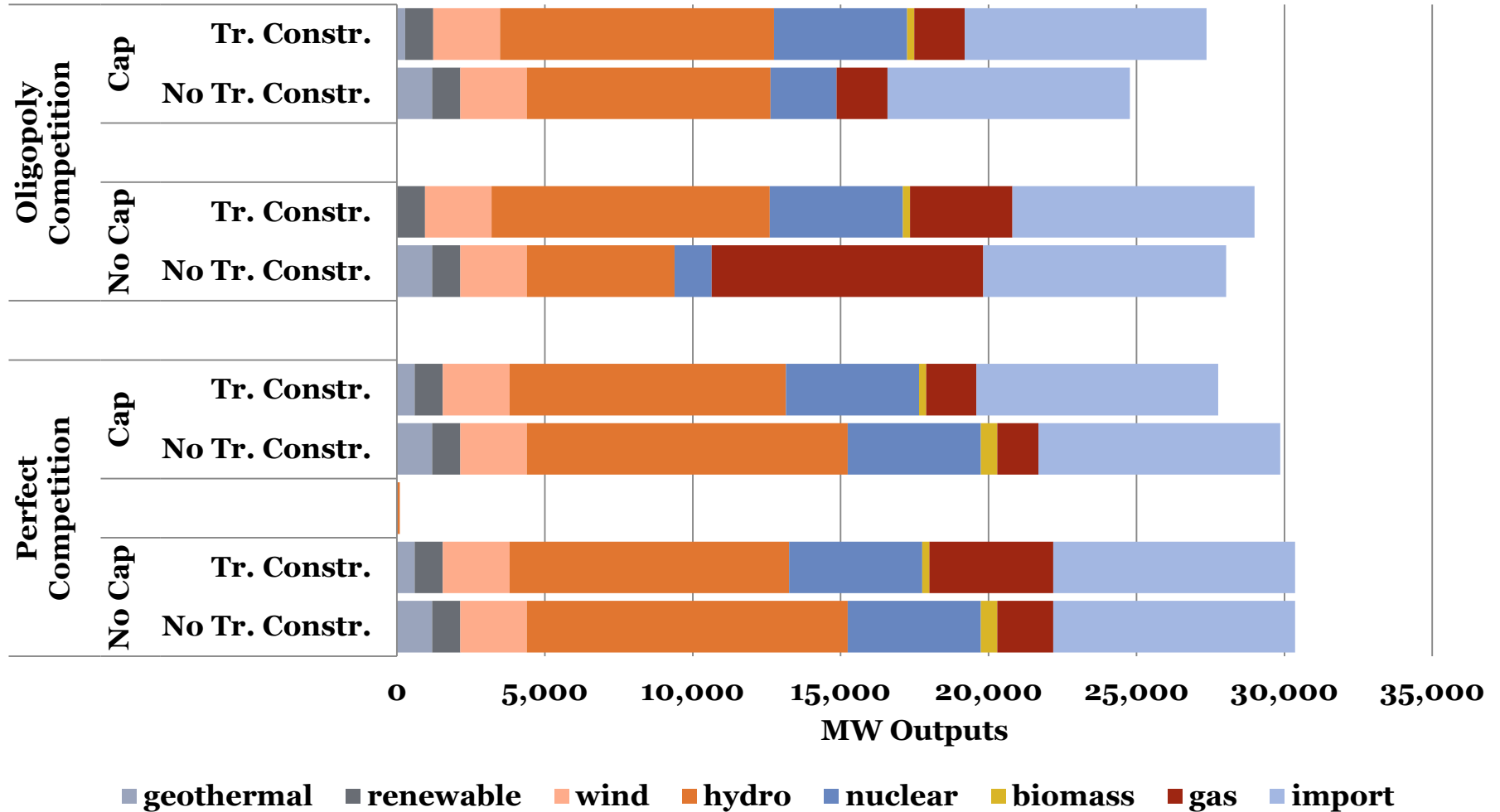
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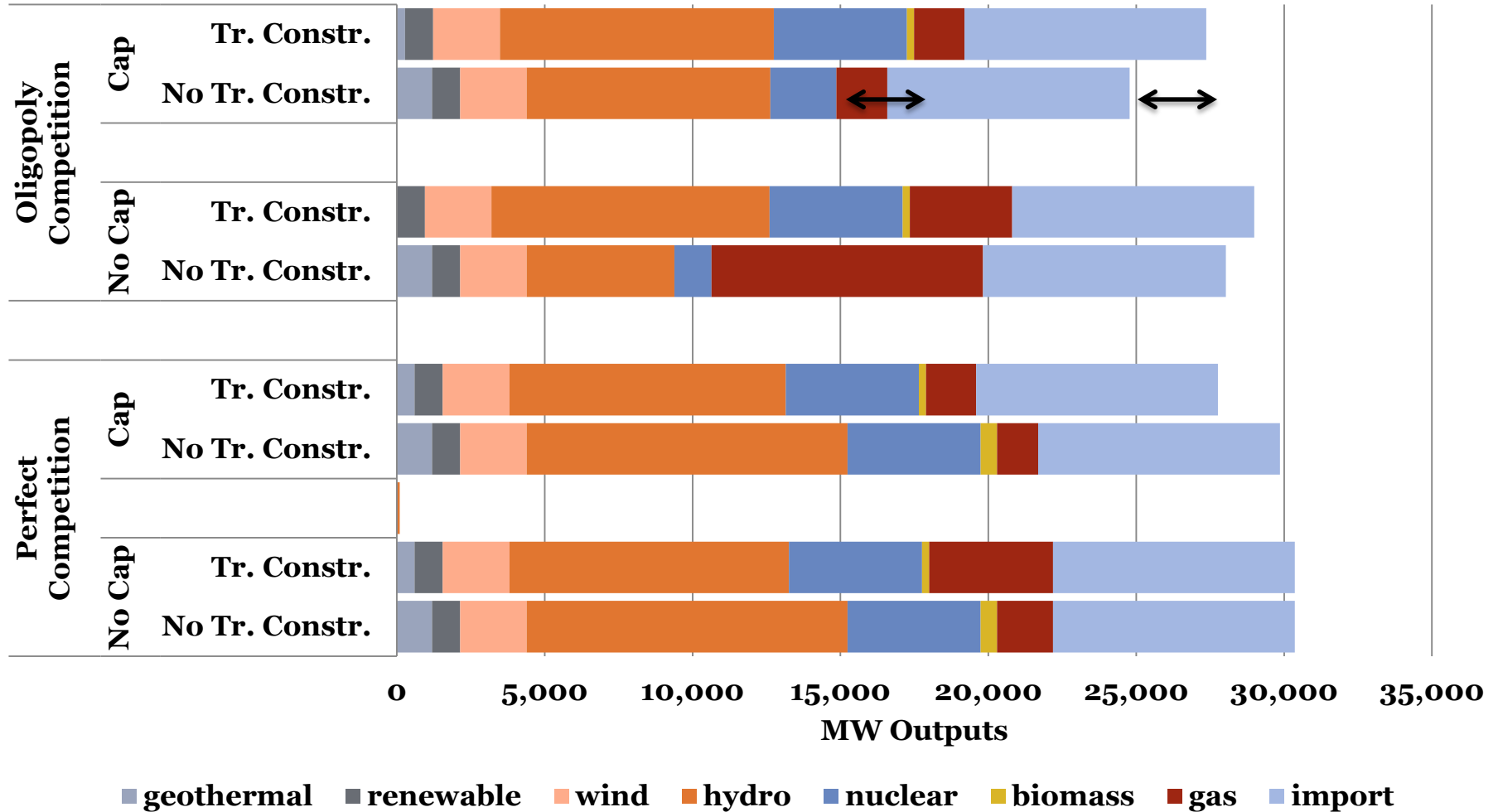
Equilibrium Results for Outputs by Firm



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



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.

Questions?

