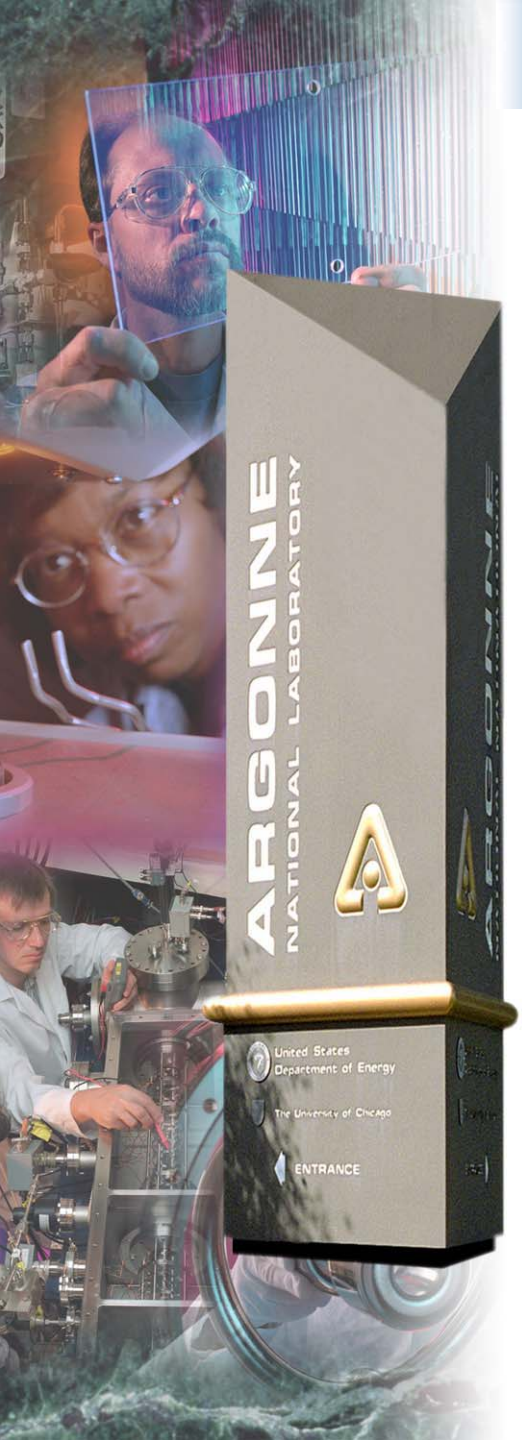

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Simulating GenCo Bidding Strategies in Electricity Markets with an Agent-Based Model

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Outline

- Background
  - Market Power Analysis in Restructured Electricity Markets
  - Agent-Based Modeling and Simulation (ABMS)
  - Pricing Mechanisms and Congestion Management
- Electricity Market Complex Adaptive Systems (EMCAS)
  - Agent Representation
  - GenCo Bidding Strategies
- 11-Node Case Study
  - Assumptions
  - Locational Marginal Pricing (LMP) vs. Counter-Trading (SMP)
  - Results
- Conclusions and Future Work

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Market Power Analysis in Electricity Markets

- Market Power Indicators
  - Herfindahl-Hirschman Index (HHI)
  - Lerner Index
  - Pivotal Supplier Index
- Equilibrium models
  - Cournot
  - Bertrand
  - Supply function
- Several simplifying assumptions often necessary
  - Physical laws (e.g. transmission network, inter-temporal constraints)
  - Market rules (bid format, multiple markets, congestion, settlements etc.)

Agent-Based Modeling and Simulation (ABMS)

- ABMS uses sets of agents and a framework for simulating their decisions and interactions

- An agent
  - is a software representation of a decision-making unit
  - is a self-directed (autonomous) object with specific individual traits
  - typically exhibits bounded rationality under limited information

- Agent framework allows agents to interact in complex, dynamic ways

- ABMS is well suited for analyzing decentralized decision-making in restructured electricity markets

Some Agent-Based Models of Electricity Markets

- In most applications of ABMS the electricity market is simulated as a repeated game
  - Emergent behavior and convergence
  - Nash equilibrium

- Several theoretical applications on hypothetical test power systems/markets
  - Nicolaisen et al. (2001)
  - Krause et al. (2004)
  - Ernst et al. (2004)

- ABMS has been used to model the NETA electricity market in England and Wales
  - Bower and Bunn (2001)
  - Bunn and Oliveira (2001, 2003)

Congestion Management and Pricing Rules

- Several methods are used for congestion management
  - Locational Marginal Pricing (nodal pricing)
  - Zonal Pricing (market splitting)
  - System Marginal Price with Counter-Trading (re-dispatch)

- *To what extent do GenCos' ability to exercise market power depend on the market rules for congestion management and pricing?*

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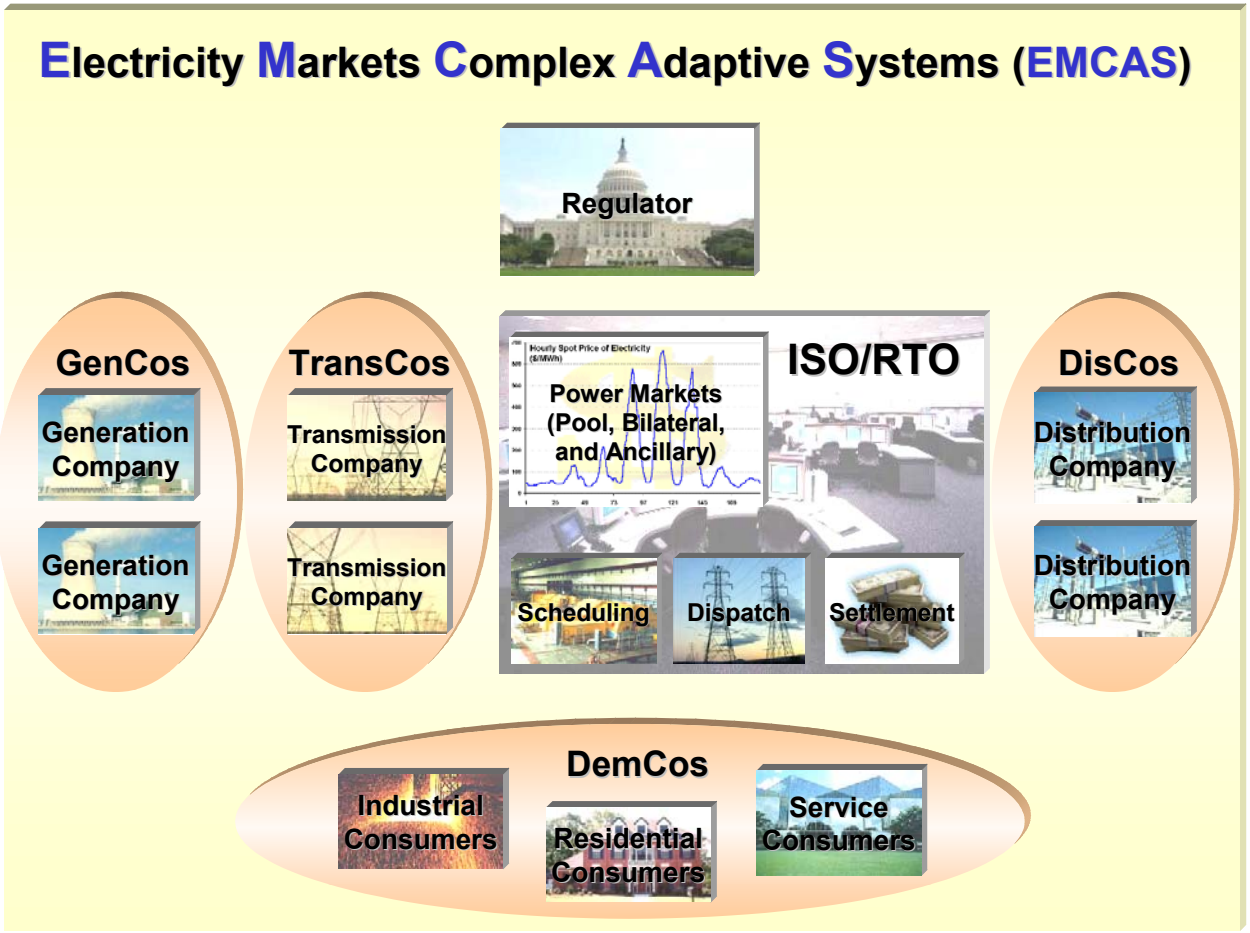
Electricity Market Complex Adaptive Systems (EMCAS)

- The main participants in the electricity market are represented in EMCAS



Simulated Market Operation in EMCAS

- Daily bidding into a pool market
- Hourly chronological simulations
  - Bid-based scheduling (day-ahead) and dispatch (real-time) based on DC-OPF (stochastic forced generator outages)
- Calculation of prices and profits based on “two-settlement system” for all agents in the system
  - Day-ahead (DA) schedule at DA price
  - Deviations from DA at real-time (RT) price
- EMCAS can simulate the electricity market under different assumptions about agent behavior and market rules, e.g.:
  - Locational marginal prices (LMP)
  - Unconstrained system marginal price (SMP) and counter trading

GenCo Bidding Strategies

- Production cost bidding (Base)
  - Base case representing competitive bidding
  - Bidding according to marginal cost (incremental heat rate)

- Physical Withholding based on System Reserve (PWSR)
  - GenCo withholds capacity in hours when the expected SR is below a specified limit
  - GenCo tries to reduce SR with a target amount in those hours by withholding units
  - GenCo bids production cost for remaining units

- Fixed Increment Price Probing (FIPP)
  - GenCo increases its bid w/fixed percentage for the accepted hours
  - GenCo decreases its bid w/fixed percentage for the rejected hours
  - A lower limit on bid price is also specified

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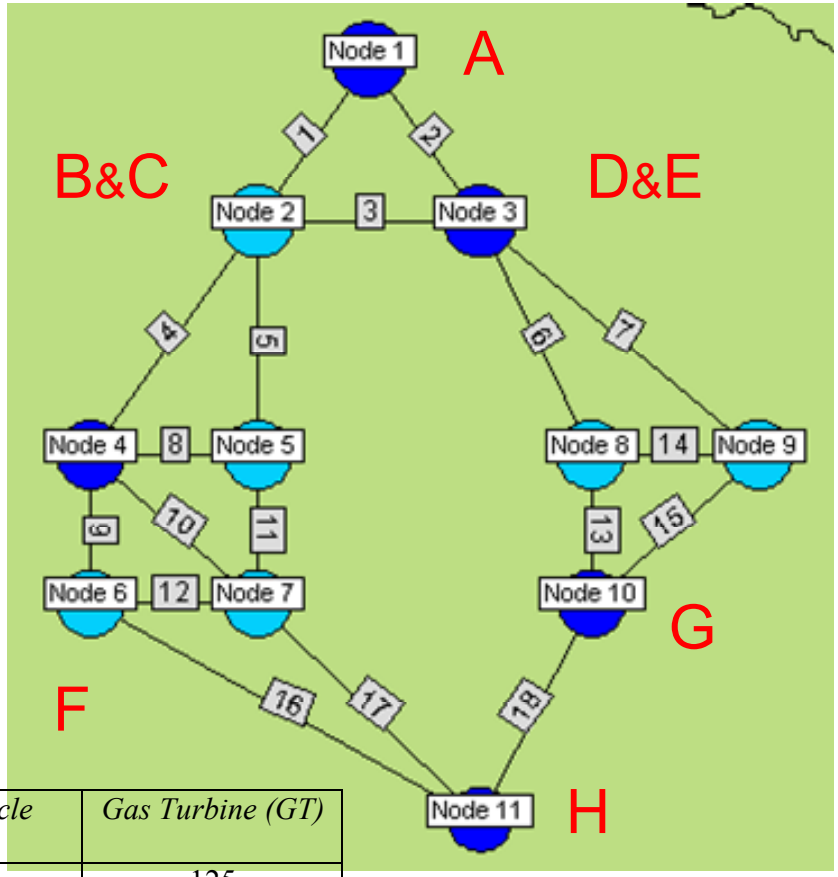
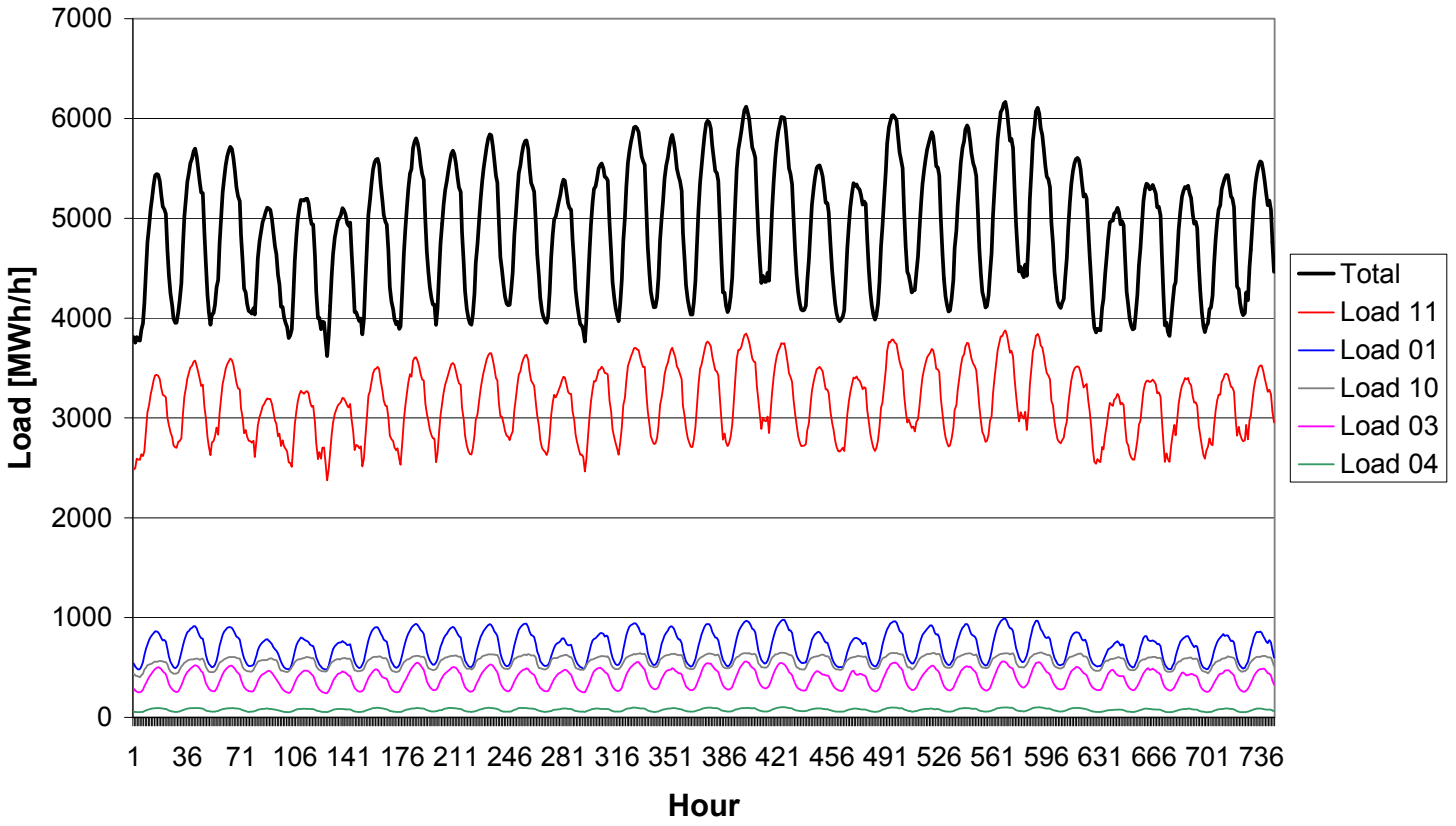
Assumptions: Network and Plants

- 11-node network (Christie et al. 2000)
  - Capacities and reactances
- 8 GenCos (A-H) with 3 plants each
  - Base Coal (CO), Combined Cycle (CC), and Gas Turbine (GT)
  - Marginal costs from heat rate curves
  - Forced outages



Parameter/Plant	*Unit*	*Base Coal (CO)*	*Comb. Cycle (CC)*	*Gas Turbine (GT)*
Capacity	*MW*	500	250	125
Fuel		Coal (BIT)	Natural Gas	Natural Gas
Fuel price	*$/MMBtu*	1.5	5	5
Variable O&M	*$/MWh*	1.75	2.8	8
Fixed O&M	*$/kWmonth*	2.1	0.6	0.7
Start-up time	*min*	720	180	0
Minimum down time	*min*	480	120	0
Warm start-up cost	*$*	7000	2000	50
Cold start-up cost	*$*	20000	5000	150

Assumptions: Loads



- One month simulation period with hourly loads (inelastic)
- Majority of load in node 11

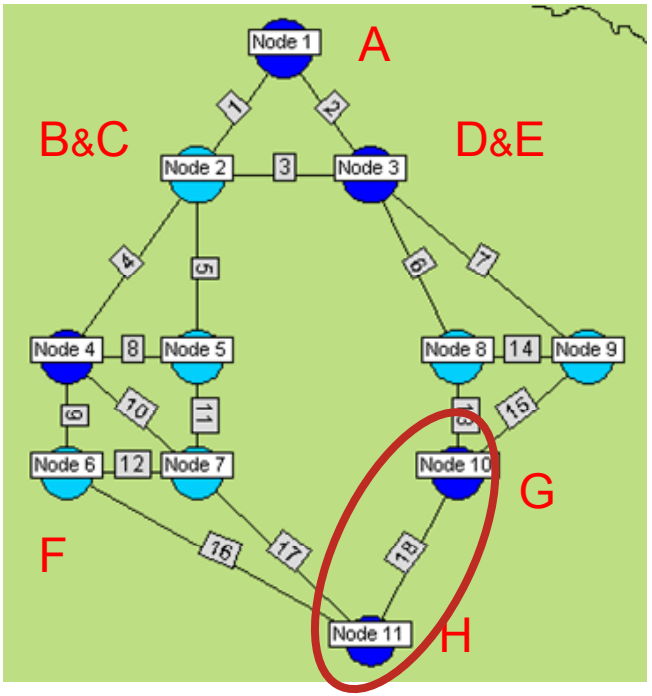
Simulated Scenarios

- Two sets of market rules simulated
  - Locational Marginal Prices (LMP)
  - System Marginal Price (SMP)
    - *Generators dispatched out of order to relieve congestion receive bid price*
    - *Congestion costs socialised*
  - Two settlement system under both rules

- Seven scenarios for each market rule
  - Base case: all GenCos bid marginal production cost
  - PWSR: One GenCo (A, G, or H) applies Physical Withholding System Reserve with CC and GT (30% trigger point, 6% target reduction)
  - FIPP: One GenCo (A, G, or H) applies Fixed Increment Price Probing with 10% adjustment and lower limit equal to production cost

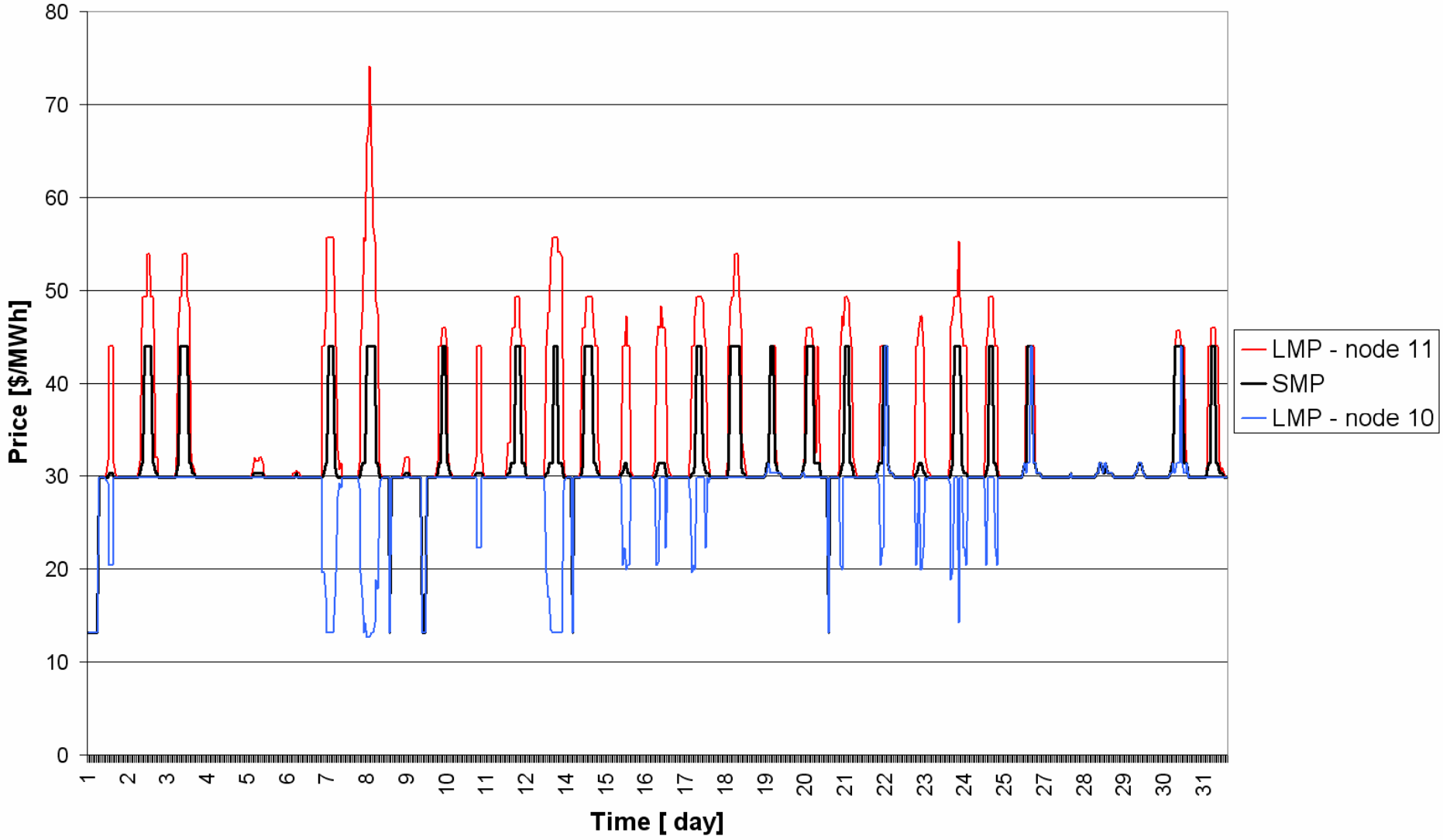
Results: Average Monthly Prices in Base Case

- Same price in all nodes under SMP
- LMP gives highest price in node 11 and lowest in node 10
  - Congestion on the connecting line 18 (50.8 % of the time)



	Node 1	Node 2	Node 3	Node 4	Node 6	Node 10	Node 11
SMP (DA)	29.9	29.9	29.9	29.9	29.9	29.9	29.9
SMP (RT)	31.3	31.3	31.3	31.3	31.3	31.3	31.3
LMP (DA)	30.5	31.0	29.8	31.4	31.7	28.1	32.2
LMP (RT)	31.9	32.6	30.9	33.1	33.5	28.5	34.2

Results: Hourly Real-Time Prices in Base Case



Results: Total GenCo Profits and Consumer Costs (LMP vs SMP)

Total GenCo Profits (10^6)

Scenario	*SMP*	*LMP*	*% Change*
Base	19.6	22.6	15.0
PWSR A	23.2	53.4	130.2
PWSR G	23.5	23.7	0.9
PWSR H	22.3	86.1	285.3
FIPP A	23.6	25.9	10.2
FIPP G	21.7	23.5	8.5
FIPP H	25.1	28.1	11.7

Total Consumer Costs (10^6)

Scenario	*SMP*	*LMP*	*% Change*
Base	110.2	115.7	5.0
PWSR A	114.4	154.1	34.8
PWSR G	114.3	116.7	2.1
PWSR H	114.5	224.6	96.2
FIPP A	114.3	119.7	4.7
FIPP G	112.2	116.2	3.6
FIPP H	116.4	126.4	8.6

- GenCo profits and consumer costs are higher under LMP
  - Especially in PWSR A+H, where curtailment occurs
- A higher transmission charge might be necessary under SMP
  - No congestion rent to transmission owner
  - This is not considered in this analysis

Results: Changes (%) in GenCo Profits Compared to Base Case

SMP

Scenario	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
PWSR A	19.6	17.5	20.1	18.2	17.1	**20.2**	14.2	19.7
PWSR G	19.9	19.2	22.4	19.6	18.3	**24.6**	13.8	22.1
PWSR H	14.9	12	14.4	17	15.6	13.1	-1.3	**25.8**
FIPP A	**32.2**	17.9	20.3	18	16.7	26.2	13.5	20.4
FIPP G	9.8	8.1	9.7	8.5	7.9	14.5	**15.9**	11
FIPP H	27.8	20.6	24.8	26.6	24.3	28.4	20.2	**54.1**

LMP

Scenario	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
PWSR A	51.1	162.1	180.7	126.0	124.3	179.4	12.4	**181.3**
PWSR G	3.3	3.9	4.5	8.8	6.8	2.1	**15.0**	1.0
PWSR H	315.8	340.8	**361.3**	235.3	229.7	301.6	-53.8	361.0
FIPP A	**22.1**	13.8	15.2	13.5	12.0	19.8	6.8	15.5
FIPP G	3.0	1.3	1.7	6.2	5.4	0.7	**25.8**	-0.7
FIPP H	22.2	30.9	35.6	0.5	-1.4	69.1	-54.3	**55.2**

- Locational differences under both rules, but more pronounced for LMP
- *Unilateral market power* occurs under both SMP and LMP
  - Most frequent under FIPP strategies

Results: Changes (%) in Consumer Costs Compared to Base Case

SMP

Scenario	*Load 1*	*Load 3*	*Load 4*	*Load 10*	*Load 11*
PWSR A	4.0	4.1	3.9	3.7	3.7
PWSR G	3.9	4.0	3.8	3.6	3.7
PWSR H	4.3	4.3	4.1	3.9	3.8
FIPP A	3.9	4.0	3.8	3.6	3.7
FIPP G	1.9	1.9	1.8	1.7	1.8
FIPP H	6.0	6.1	5.8	5.4	5.6

LMP

Scenario	*Load 1*	*Load 3*	*Load 4*	*Load 10*	*Load 11*
PWSR A	26.7	27.8	36.2	2.8	39.8
PWSR G	1.5	1.5	0.8	2.7	0.4
PWSR H	49.1	50.8	75.1	-10.9	125.3
FIPP A	3.1	3.2	3.6	1.8	3.8
FIPP G	1.1	1.2	0.3	2.5	-0.1
FIPP H	3.2	3.3	10.5	-11.4	14.4

- Cost increase dependent on location under LMP
- Large difference between SMP and LMP in cases with curtailment

Discussion of Case Study Results

- Market power can be exercised under both SMP and LMP
  - All three GenCos are able to manipulate prices and increase profits
  - Unilateral market power occurs more frequently with the simulated price probing strategy (FIPP)
  - Higher impact on consumer costs of market power under LMP scheme, locational price signals amplified
  - SMP and counter-trading reduce impact of market power, but do not have correct locational price signals

- Location is important, especially under LMP scheme
  - GenCo H has the best location (load pocket)
  - GenCo G benefits the least

- Traditional market power indices are inadequate for electricity markets
  - HHI is 1250 in the simulated market

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Conclusions and Future Work

- Advantages of using ABMS for market power analysis
  - Detailed representation of physical system
  - Detailed representation of market rules and settlements
  - More realistic market behavior than equilibrium models
- Some challenges with ABMS
  - Difficult to draw general conclusions
  - Complex results (often necessary to run a high number of simulations)
- Possible extensions
  - Other congestion management mechanisms
  - Demand-side response/bidding
  - Bilateral contracts
  - Investments
  - Other strategies (learning and adaptation)
  - Simulate market as a repeated game
  - Real-world applications (US, Europe, Asia, Latin America, etc)