Agent-Based Modeling for Electric Power Markets

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Presentation Outline

- The complexity of electric power systems

- Can agent-based modeling (ABM) help?

- Adventures in ABM testbed development
  for U.S. restructured electric power markets:

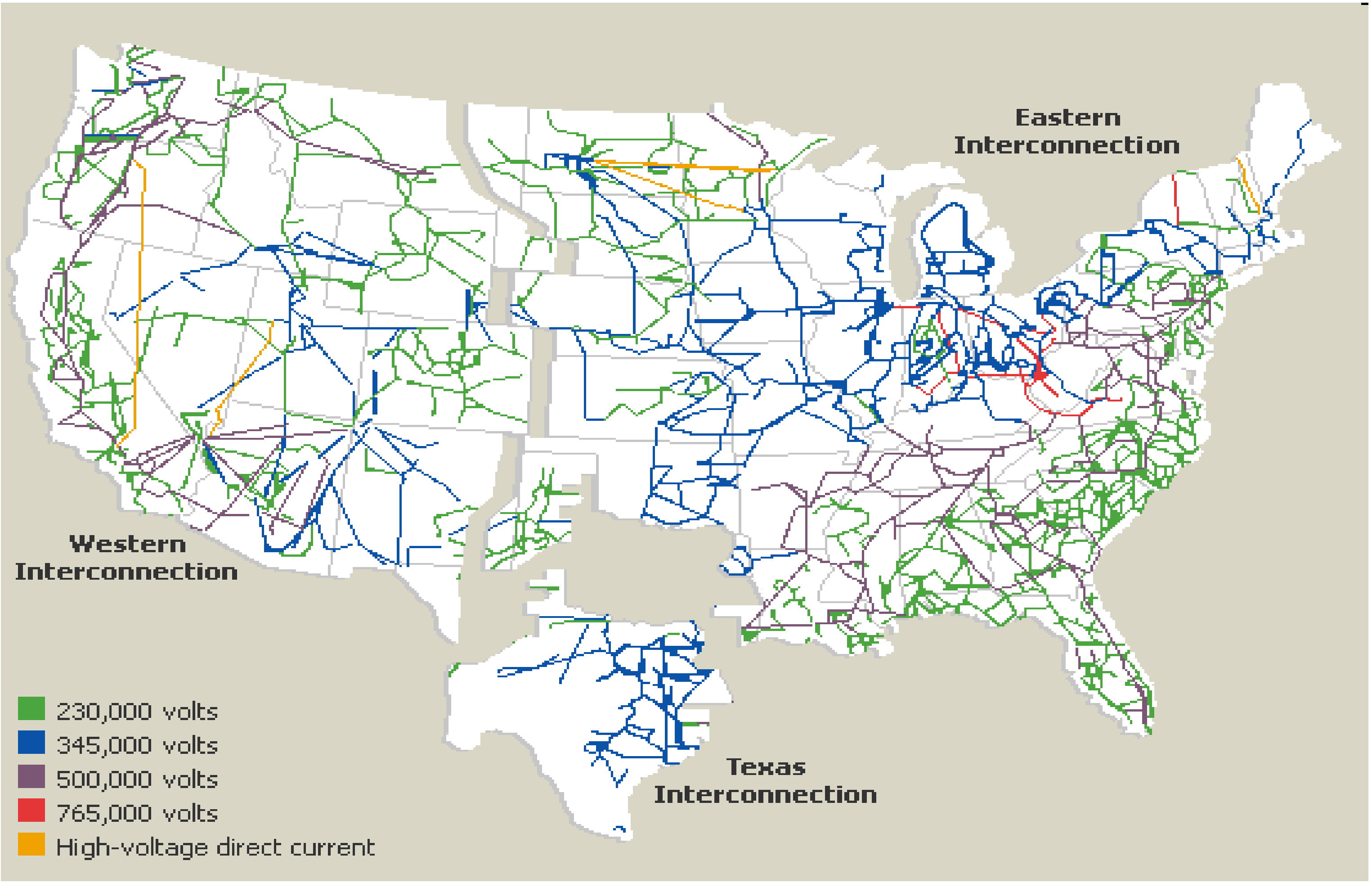
  AMES = Agent-based Modeling of Electricity Systems

- Illustrative experimental findings

The Complexity of Power Systems

- Many industrialized economies are in the process of restructuring the way power is produced & distributed
- These restructured power systems are immensely complicated, encompassing
  - Physical constraints
  - Institutional arrangements
  - Behavioral dispositions of human participants
- To be useful and informative, power system studies need to take proper account of all three elements.

U.S. Wholesale Electric Power Transmission Grid



North American Restructuring of Wholesale Power Markets

- In April 2003 the U.S. Federal Energy Regulatory Commission (FERC) proposed adoption of a wholesale power market design with particular core features.

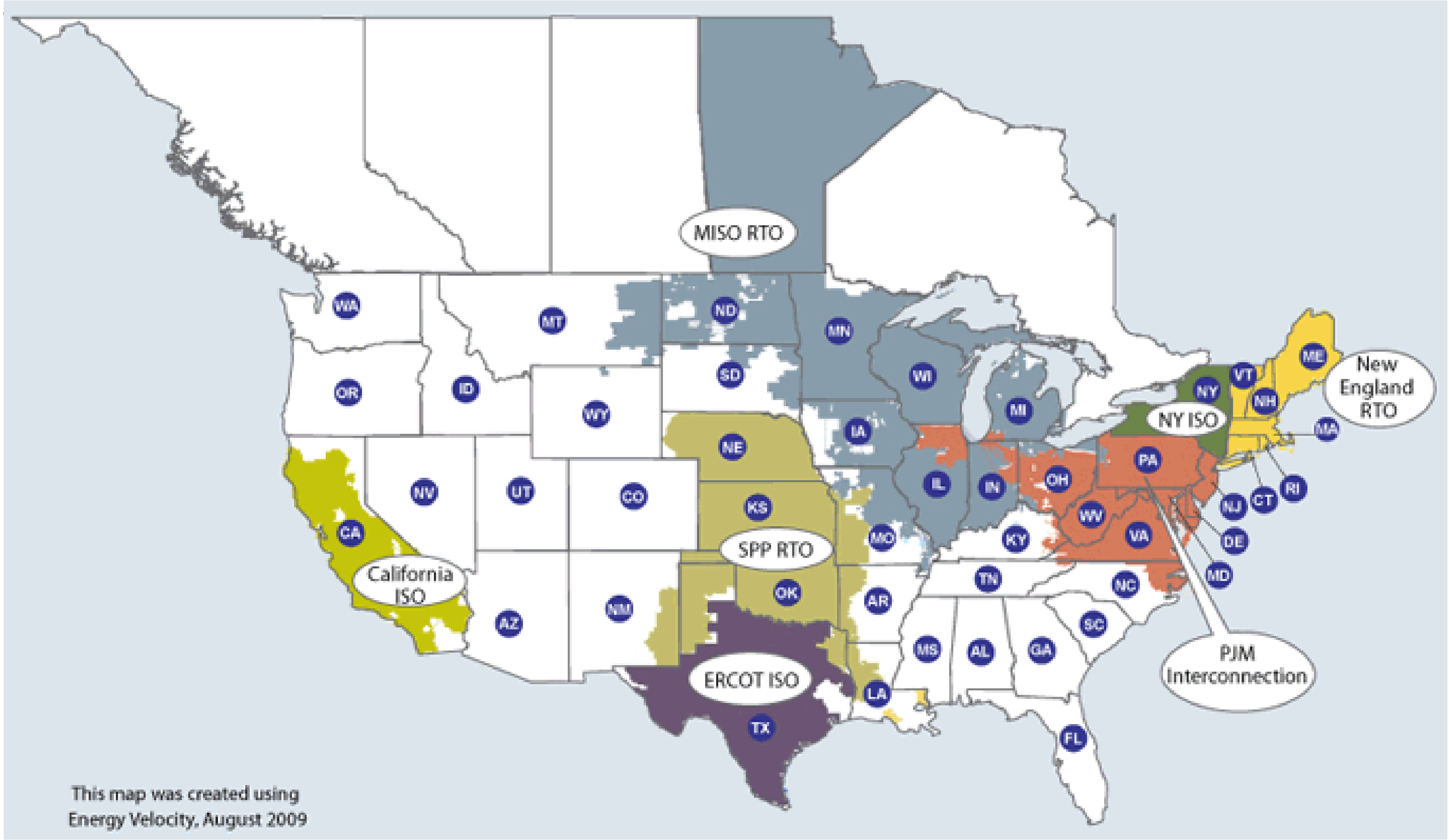
- Over 50% of North American generation now operates under some variant of the FERC design.

- **FERC Design Adopters to Date:**

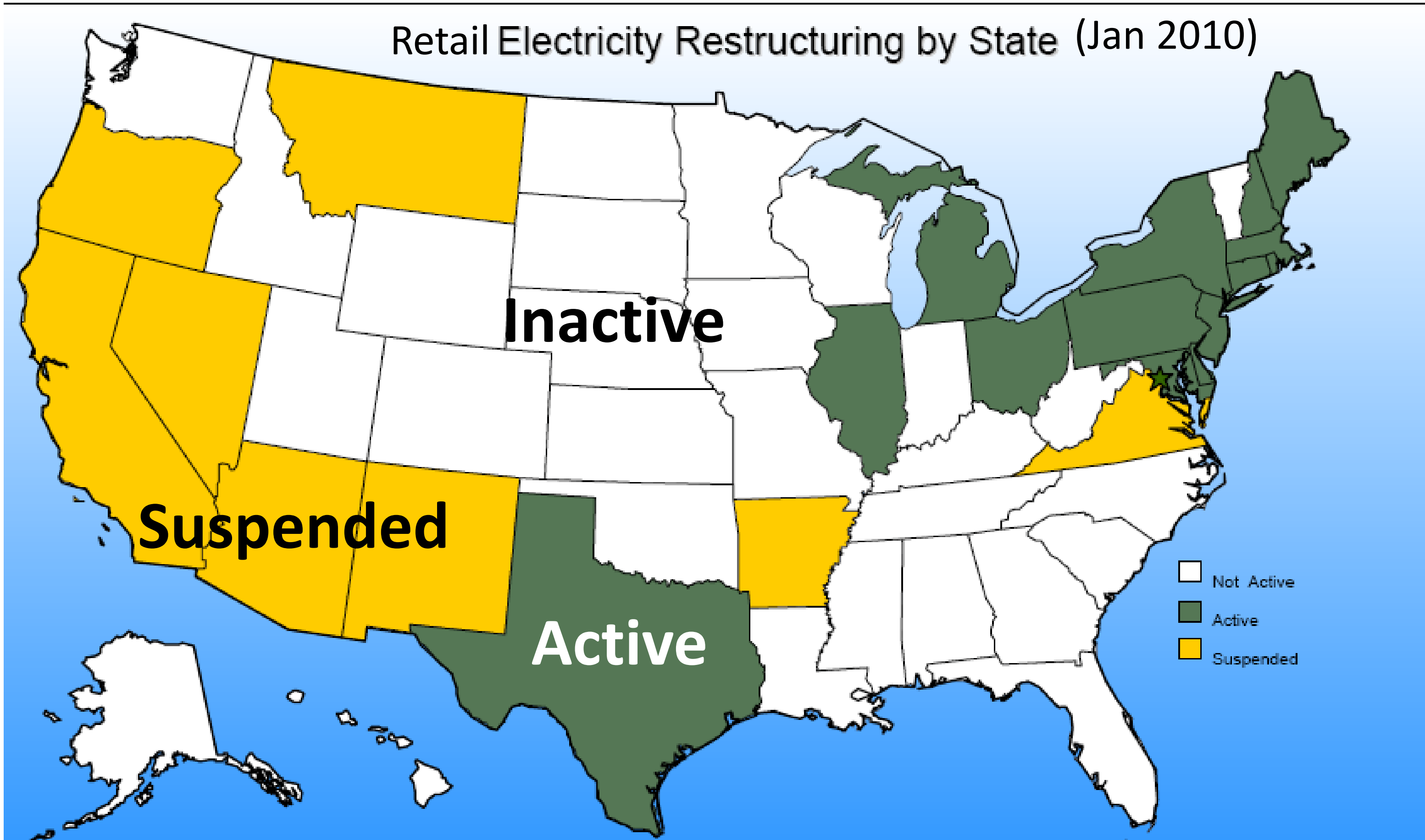
New York (NY-ISO), **mid-Atlantic states** (PJM), **New England** (ISO-NE), **Midwest/Manitoba** (MISO), **Texas** (ERCOT), **Southwest** (SPP), and **California** (CAISO)

FERC Wholesale Power Market Design Adopters to Date

https://www.ferc.gov/industries/electric/indus-act/rto/rto-map.asp



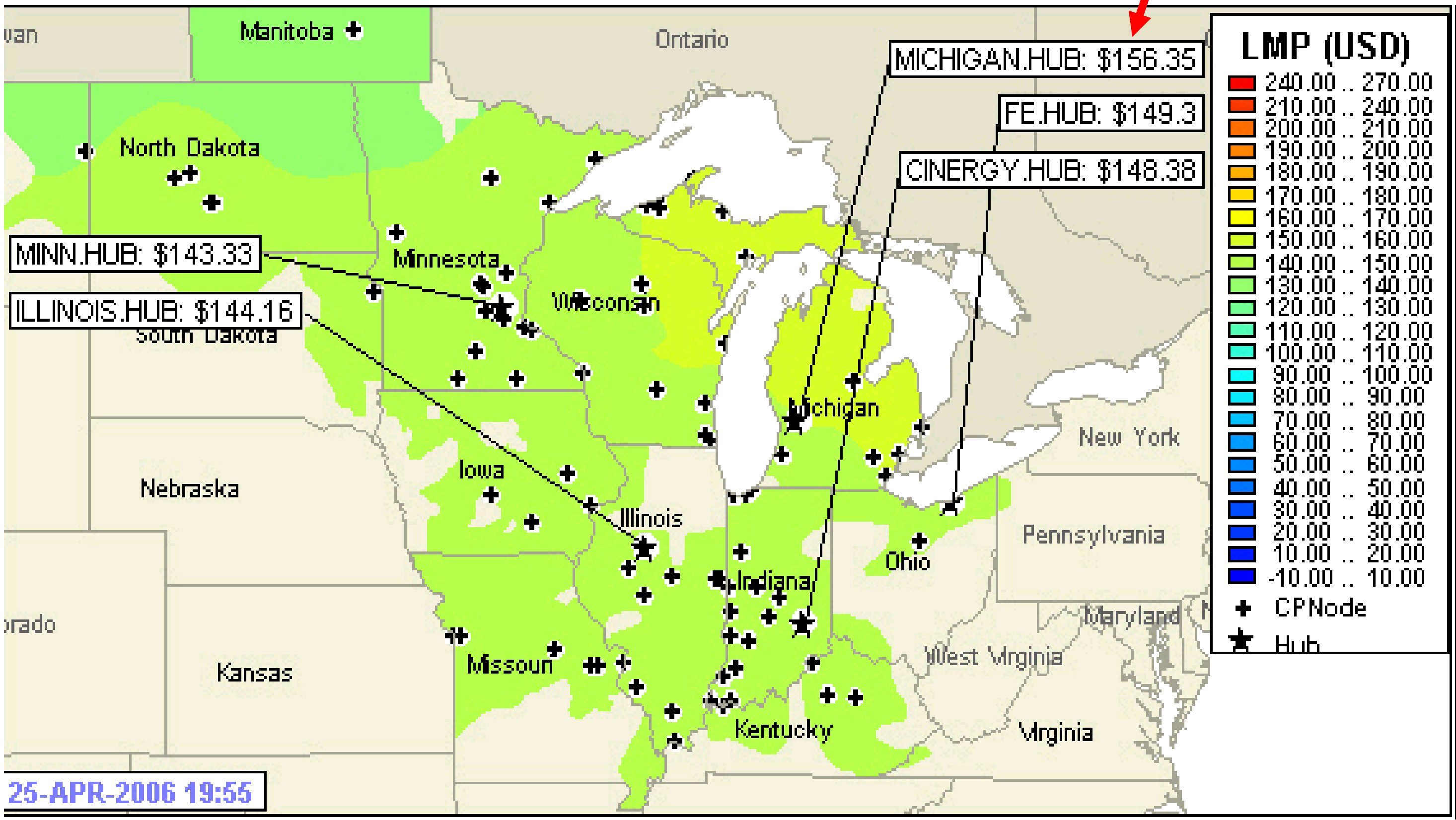
Since 2000 Cal/Enron scandal, retail restructuring has slowed/stopped



Source: https://www.eia.doe.gov/cneaf/electricity/page/restructuring/restructure_elect.html

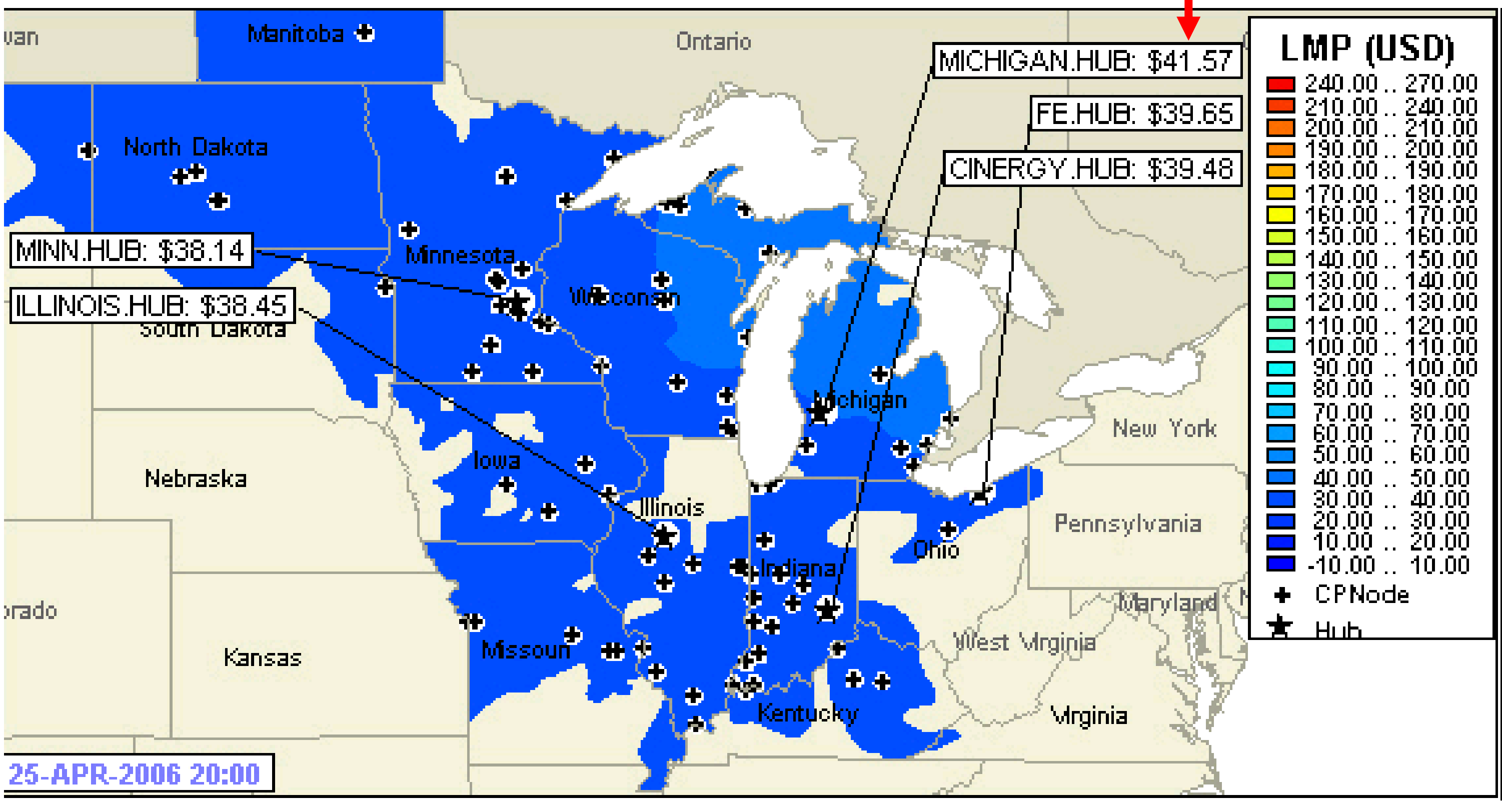
Actual Electricity Prices in Midwest ISO (MISO)
April 25, 2006, at 19:55

Note this price,$156.35



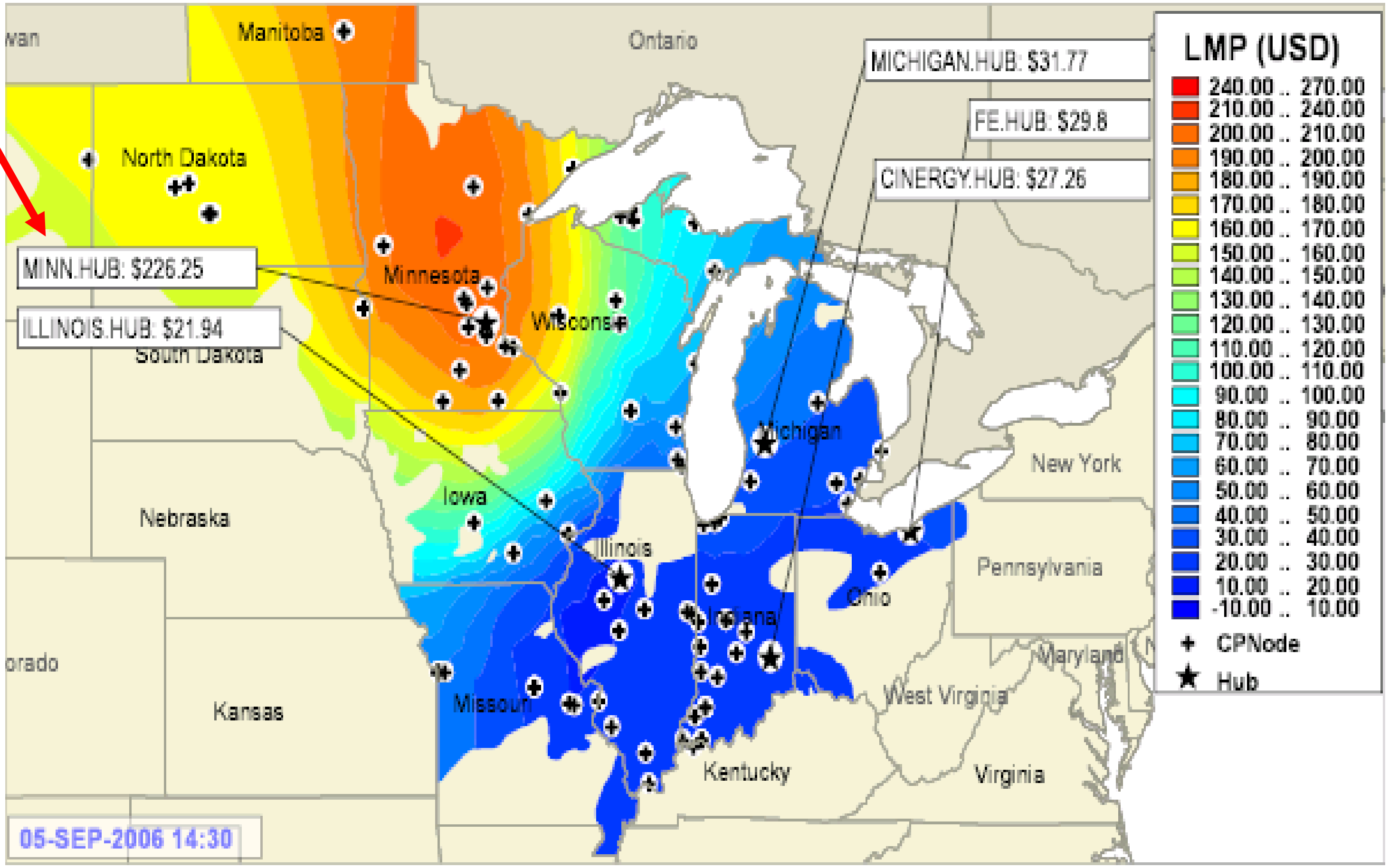
Five Minutes Later…

73% drop in price in 5 minutes!



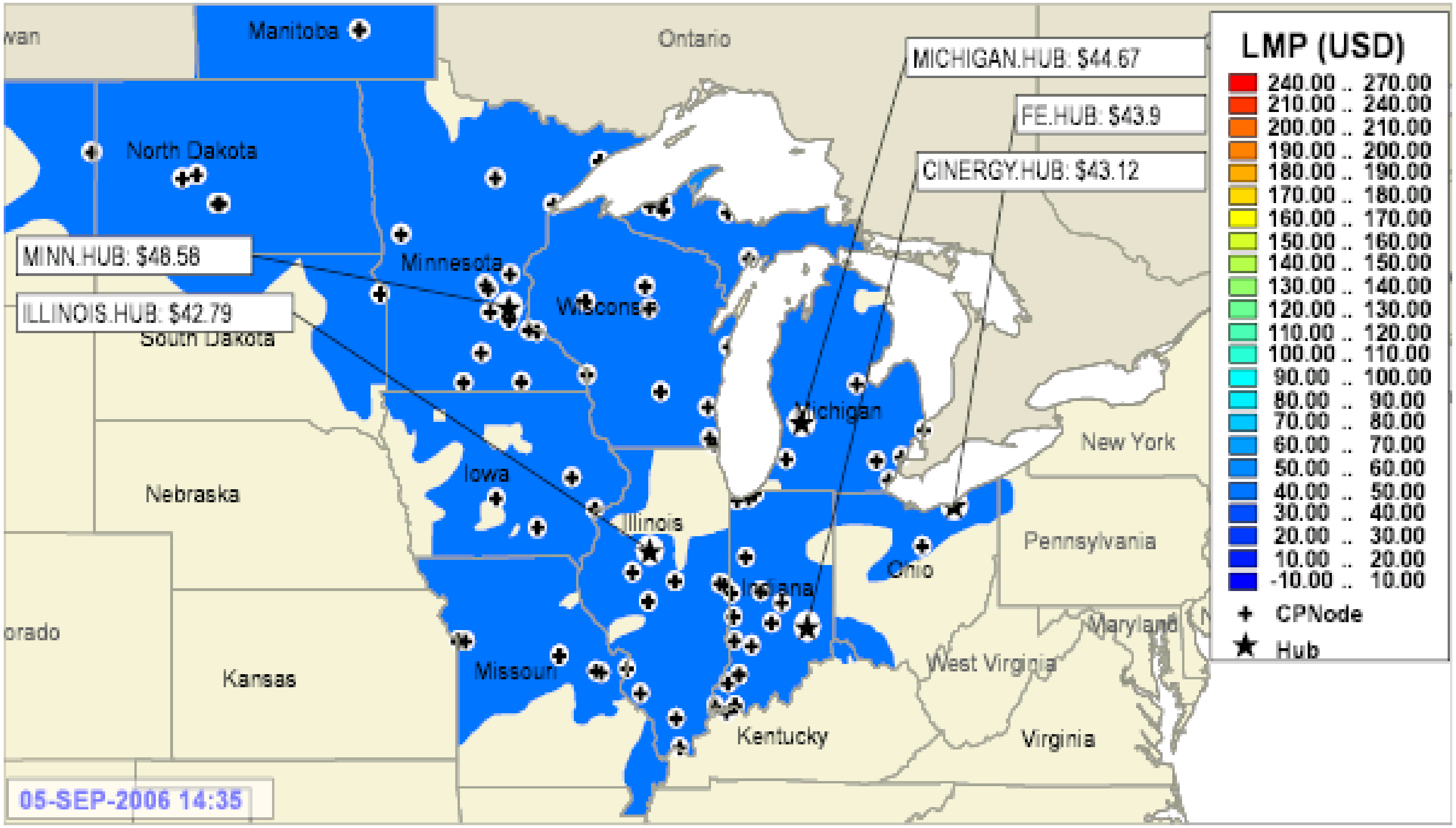
Actual Electricity Prices in Midwest ISO (MISO)
September 5, 2006, 14:30

Note this price, $226.25



Five Minutes Later…

79% drop in price in 5 minutes!



Can Agent-Based Modeling (ABM) Help?

ABM = Computational modeling of systems as collections of autonomous interacting "agents"

Agent = Encapsulated bundle of data and methods that represents physical, bio., institutional or social entity

- ABM is designed to handle complex systems.
- ABM tools permits researchers to construct testbeds in the form of **computational virtual worlds**
- Starting from user-specified initial conditions, world events are **driven entirely by agent interactions**.

Meaning of “Agent” in ABM … Continued

Decision-making agents are capable (in various degrees) of

- Behavioral adaptation
- Goal-directed learning
- Social communication (talking with each other!)
- Endogenous formation of interaction networks
- **Autonomy:**

  Self-activation and self-determination based on encapsulated (hidden) internal data and methods

Importance of Agent Encapsulation

- In the real world, all calculations must be done by entities actually residing in the world.

- Encapsulation forces ABM modelers to respect this constraint:
  - Each procedure must be encapsulated in method of some agent
  - Any procedure encapsulated in a method of a particular agent can only be implemented using the resources of that agent

- **Encapsulation** → more realistic modeling of real-world systems composed of interacting distributed entities with limited information and computational capabilities.

ABM via Iterative Participatory Modeling

- Stakeholders and researchers from multiple disciplines engage together in a **repeated looping through four stages of analysis**:

  1) Field work and data collection
  2) Role-playing games/human-subject experiments
  3) Incorporate findings into agent-based test bed
  4) Generate hypotheses through intensive computational experiments.

ABM and Institutional Design

Key Issues:

- Will a proposed or actual design promote **efficient, robust (resilient), & fair social outcomes over time**?
- Will the design give rise to **unintended consequences**?

ABM Culture-Dish Approach:

- **Develop a computational world** embodying the design, physical constraints, strategic participants, …
- Set initial world conditions (agent states).
- **Let the world evolve** with no further intervention, and observe and evaluate the resulting outcomes.

Example ABM Project: Integrated Wholesale/Retail Power System Operation with Smart-Grid Functionality

Project Directors: **Leigh Tesfatsion** (Prof. of Econ, Courtesy Prof of Math & ECpE, ISU)
Dionysios Aliprantis (Ass't Prof. of ECpE, ISU)
David Chassin (Staff Scientist, PNNL/DOE)

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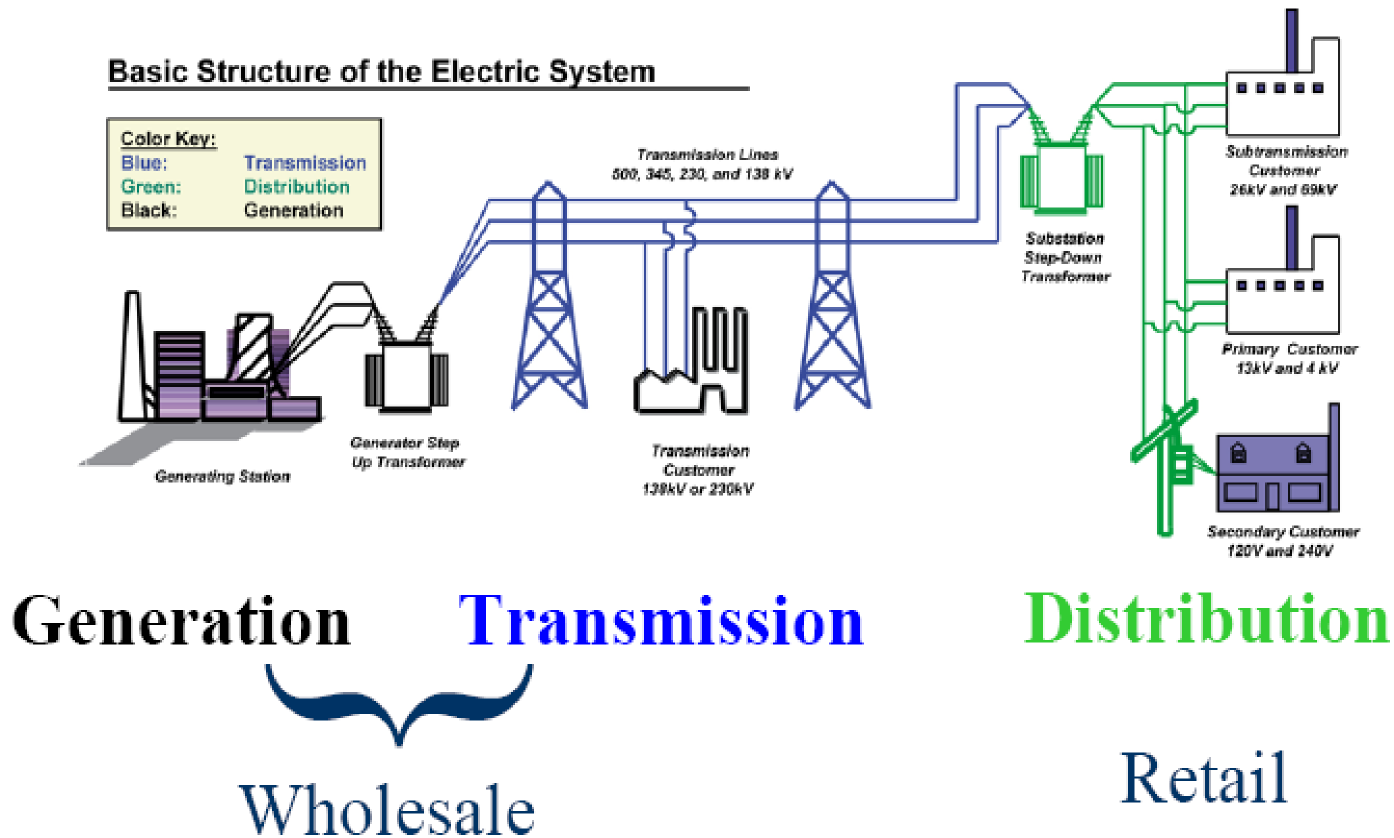
Pedram Jahangiri (ECpE grad student, ISU)

Auswin Thomas (ECpE grad student, ISU)

Retail & Wholesale Power System Operations

Source: https://www.nerc.com/page.php?cid=1|15



Meaning of "Smart Grid Functionality"?

- For our project purposes:

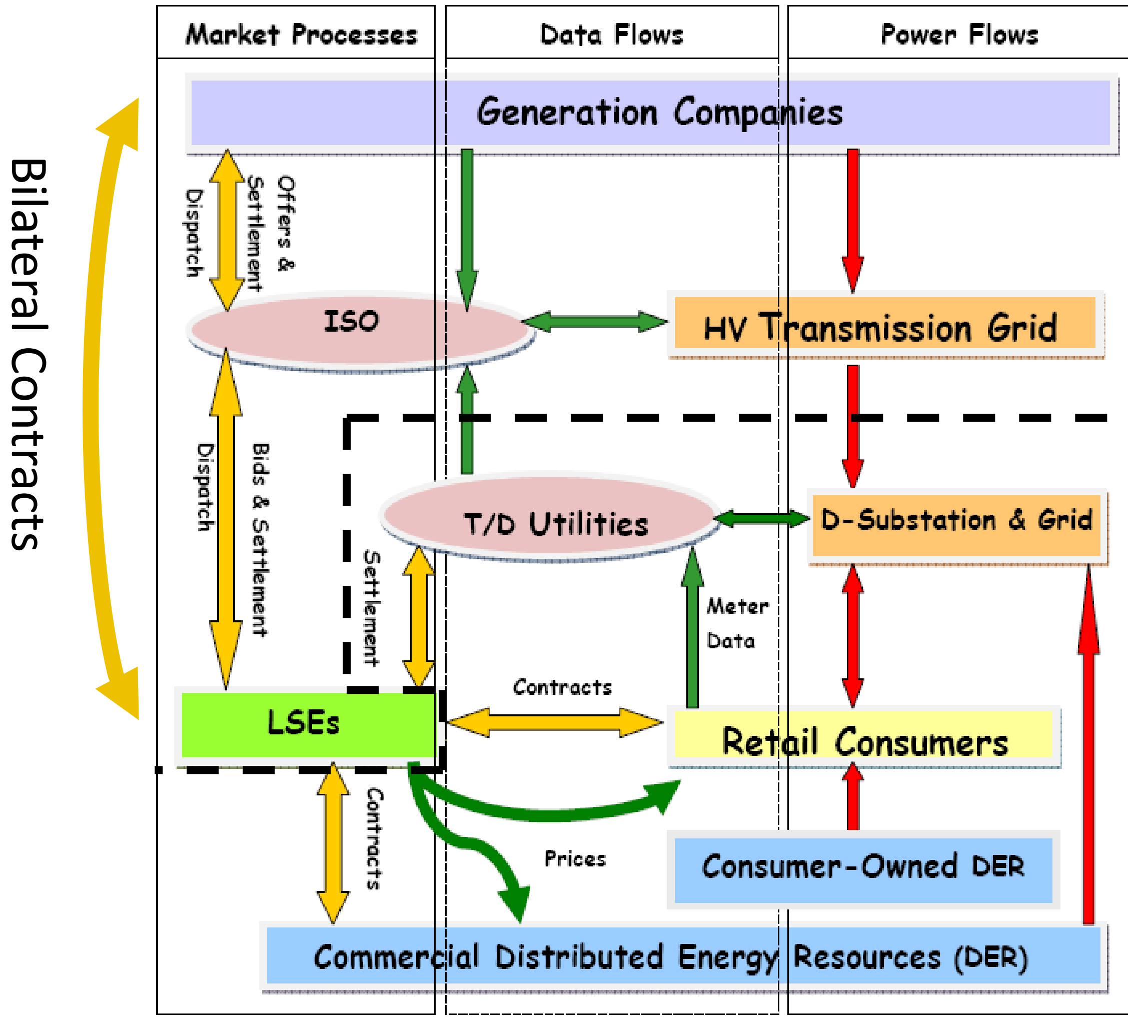
Smart-grid functionality =
Service-oriented grid enhancements permitting more responsiveness to needs and preferences of retail customers.

Examples: Introduction of advanced metering and other technologies to support

– flexible retail contracting between "load-serving entities" (retail suppliers) and retail consumers
– embedding and use of distributed energy resources

Integrated Retail/Wholesale Testbed Platform

Based on Texas (ERCOT) Retail/Wholesale Structure



Wholesale

AMES Testbed

developed by ISU Team

Seamed

Retail

GridLAB-D Testbed

developed by DOE/PNNL

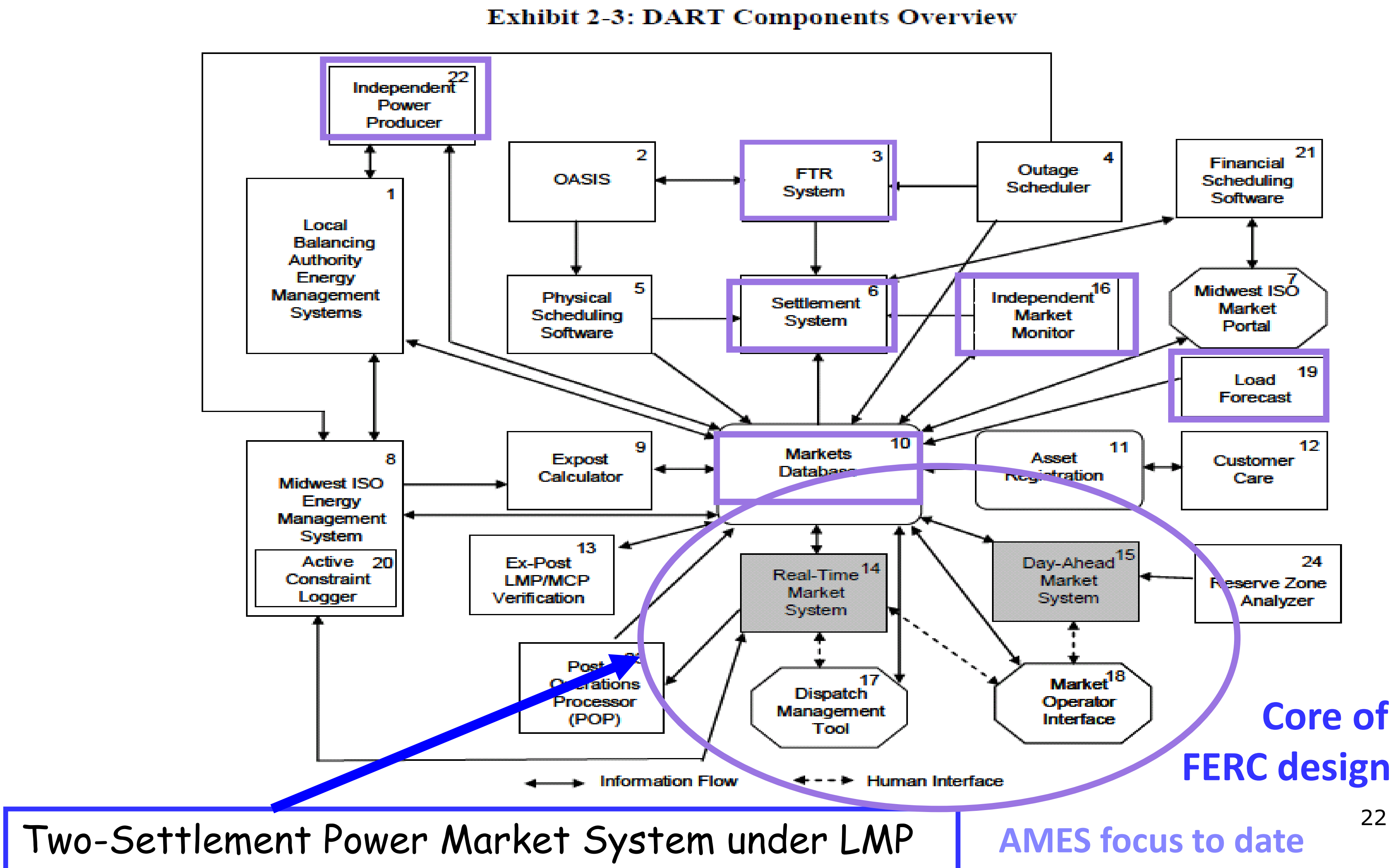
Core of FERC's 2003
Wholesale Power Market Design

- Wholesale power market to be managed by ***independent system operator (ISO)*** having no ownership stake
- ***Two-settlement system:*** Concurrent operation of day-ahead (forward) & real-time (spot) markets
- Transmission grid congestion managed via ***Locational Marginal Prices (LMPs),*** where LMP at bus k = least cost of servicing 1 additional MW of power at bus k
- Oversight & market power mitigation by outside agency

➔ **Has led in practice to complicated systems difficult to analyze by means of standard analytical & statistical tools !**

Example: Complex MISO Market Organization
Business Practices Manual 001-r1 (1/6/09)

Exhibit 2-3: DART Components Overview



Project Work to Date: Wholesale Level

- Development and open-source release of **AMES = A**gent-based **M**odeling of **E**lectricity **S**ystems

- AMES = ABM testbed with core FERC design features

- Used to test performance under FERC design

- Used to test performance under modifications of design

✸ **AMES Homepage (code/manual/publications):**

http://www.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

AMES (V2.05) Architecture
(based on business practices manuals for MISO/ISO-NE)

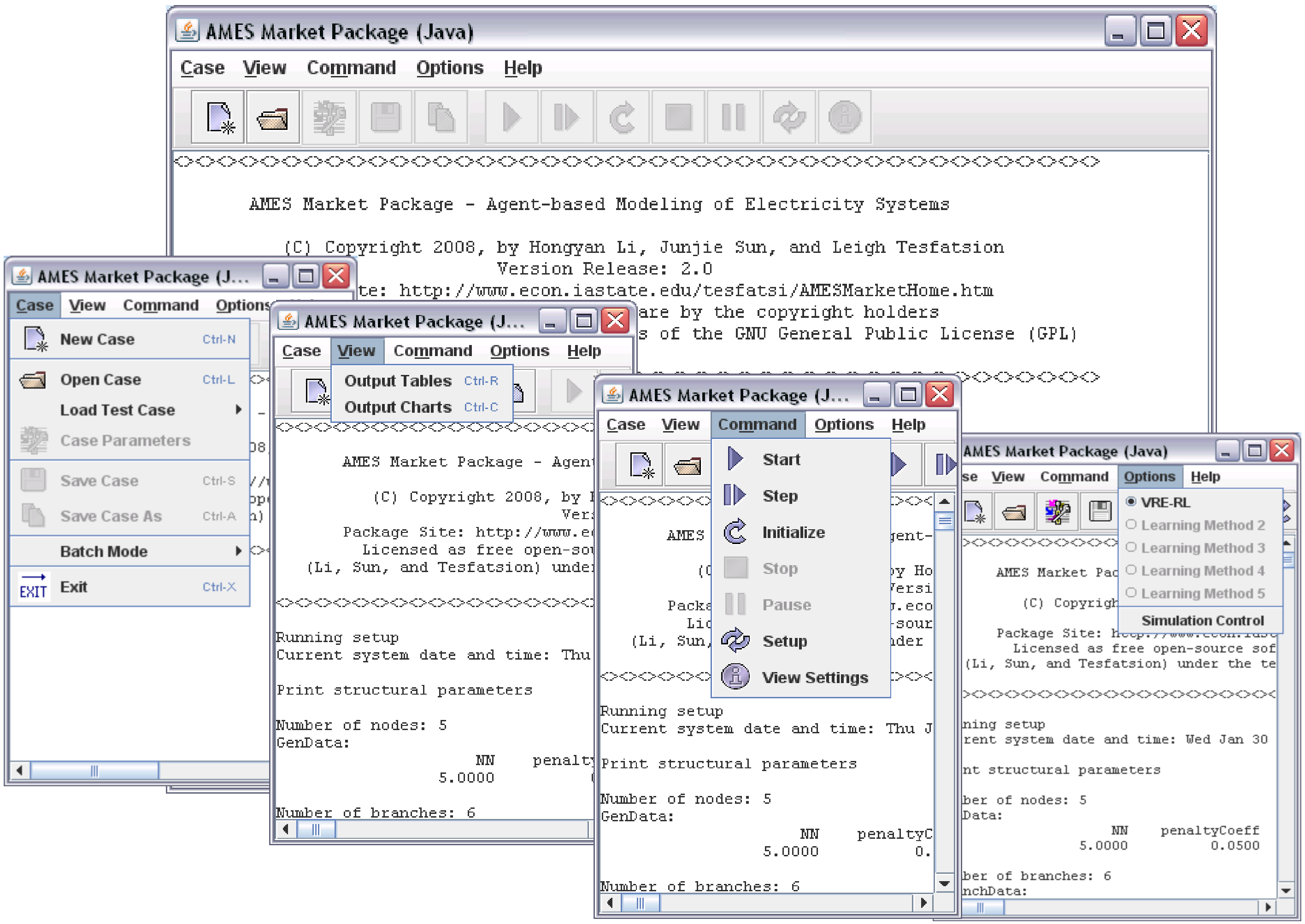
- **Traders**
  - GenCos (sellers)
  - LSEs (buyers)
  - **Learning** capabilities
- **Independent System Operator (ISO)**
  - System reliability assessments
  - Day-ahead scheduling via **bid/offer based optimal power flow (OPF)**
  - Real-time dispatch
- **Two-settlement system**
  - Day-ahead market (double auction, financial contracts)
  - Real-time market (settlement of differences)
- **AC transmission grid**
  - **Generation Companies (GenCos)** & **Load-Serving Entities (LSEs)** located at user-specified transmission buses
  - Grid congestion managed via **Locational Marginal Prices (LMPs)**
  - **LMP at bus k** = Least cost of servicing one additional MW of power at bus k.

AMES Modular & Extensible Architecture (Java)

- **Market protocols & AC transmission grid structure**
  - **Graphical user interface (GUI) & modularized class structure** permit easy experimentation with alternative parameter settings and alternative institutional/grid constraints
- **Learning representations for traders**
  - **Java Reinforcement Learning Module (JReLM)**
  - "Toolbox" permitting experimentation with a wide variety of learning methods (Roth-Erev, Temp Diff/Q-learning,…)
- **Bid/offer-based optimal power flow formulation**
  - **Java DC Optimal Power Flow Module (DCOPFJ)**
  - Permits experimentation with various DC OPF formulations
- **Output displays and dynamic test cases**
  - Customizable chart/table displays & 5-bus/30-bus test cases

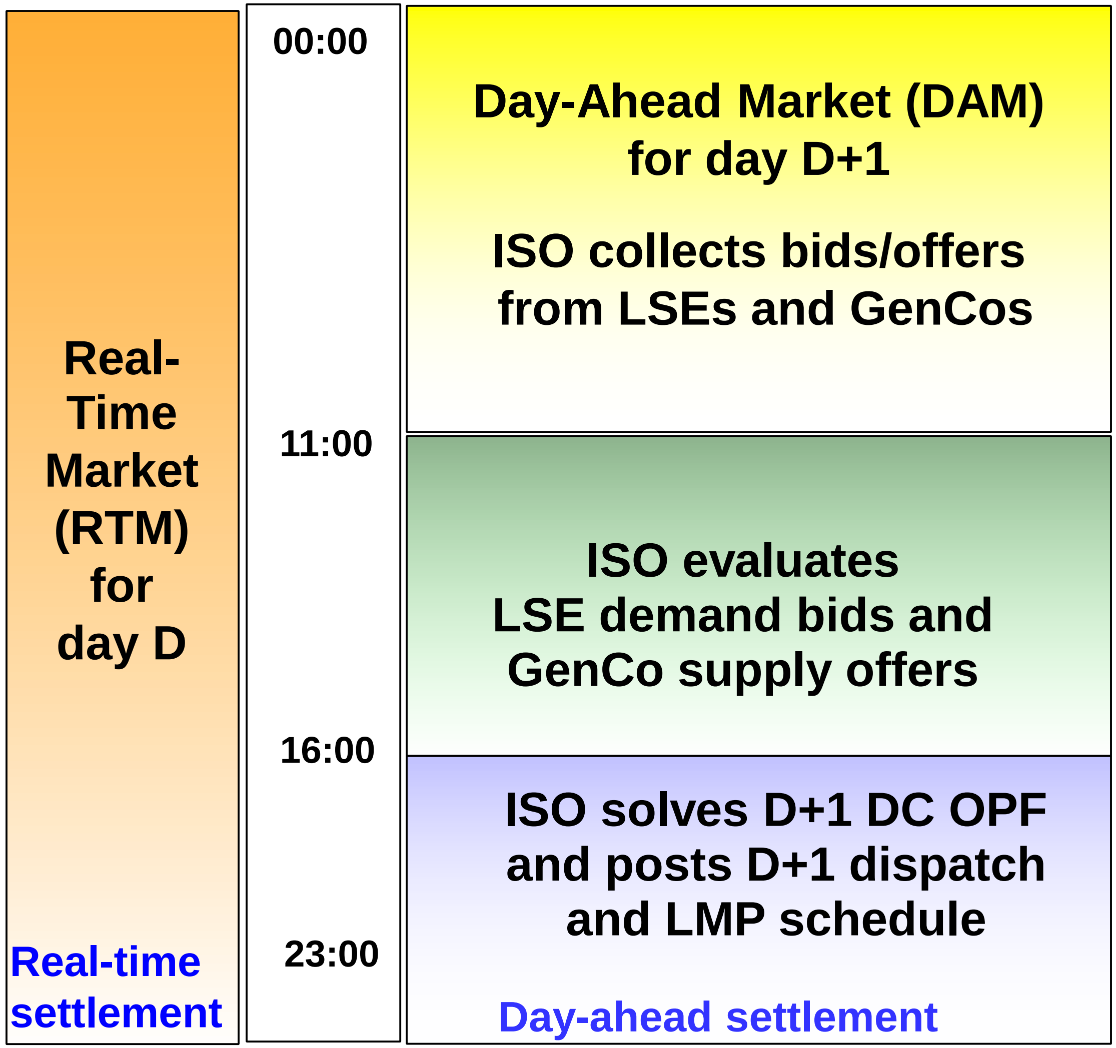
AMES Graphical User Interface (GUI)

Tool Bar and Menus for Data Input and Output Displays



Activities of AMES ISO During Each Operating Day D:

Timing Adopted from Midwest ISO (MISO)



AMES LSE Hourly Demand-Bid Formulation

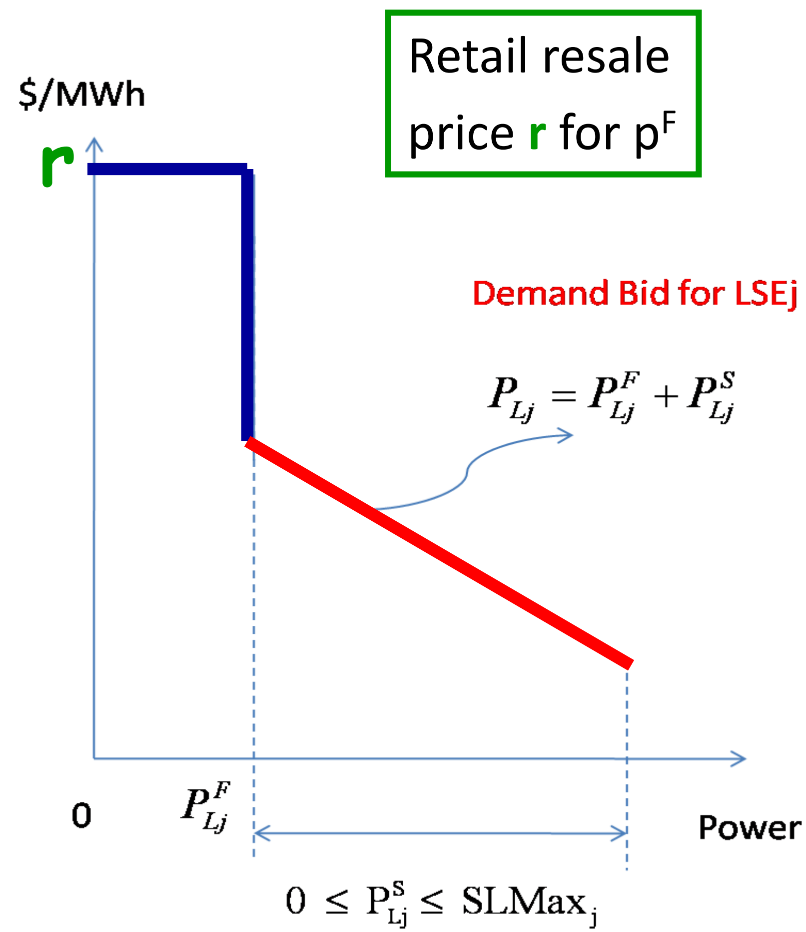
- Hourly demand bid for each LSE j

Fixed** + **Price-Sensitive Demand Bid

- **Fixed** demand bid = p^F_{Lj} (MWs)
- **Price-sensitive** demand bid
  = Inverse demand function for real power p^S_{Lj} (MWs) over a purchase capacity interval:

$$F_j(p^S_{Lj}) = c_j - 2d_j\, p^S_{Lj}$$

$$0 \le p^S_{Lj} \le SLMax_j$$



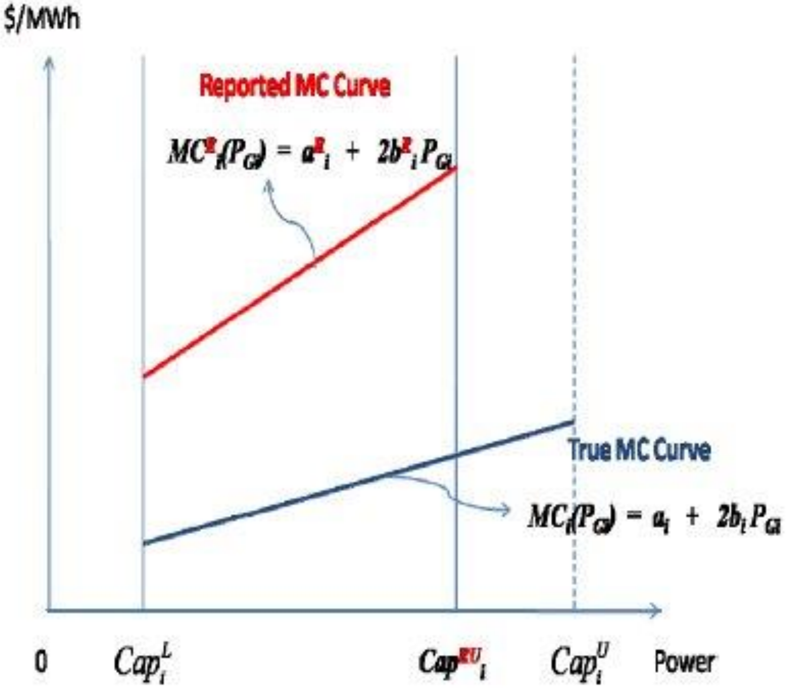
AMES GenCos are learners who report strategic supply offers to ISO for DAM

Hourly supply offer for each GenCo i = ***Reported*** linear marginal cost function over a ***reported*** operating capacity interval for real power p_{Gi} (in MWs):

$$MC^R_i(p_{Gi}) = a^R_i + 2b^R_i\, p_{Gi}$$

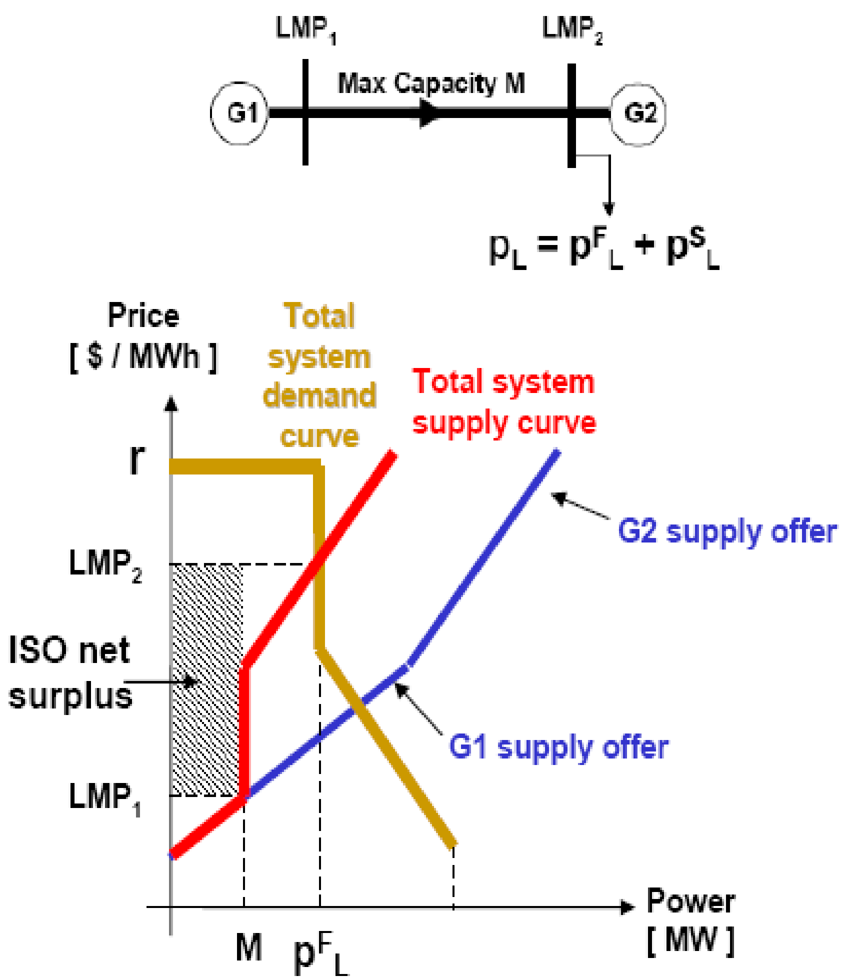
$$Cap_i^L \leq p_{Gi} \leq Cap_i^{RU}$$

GenCos can learn to report ***higher-than-true*** marginal costs and/or to report ***lower-than-true*** maximum capacity.



ISO Goal is Max[Total Net Surplus] subject to trans & gen constraints: 2-bus example

(Adapted from H. Salazar, M.S. Thesis, 2008)



Cleared load = p^F_L. LSE at bus 2 pays $LMP_2 > LMP_1$ for each unit of p^F_L. M units of p^F_L are supplied by cheaper G1 at bus 1 who receives only LMP_1 per unit.

ISO collects difference:

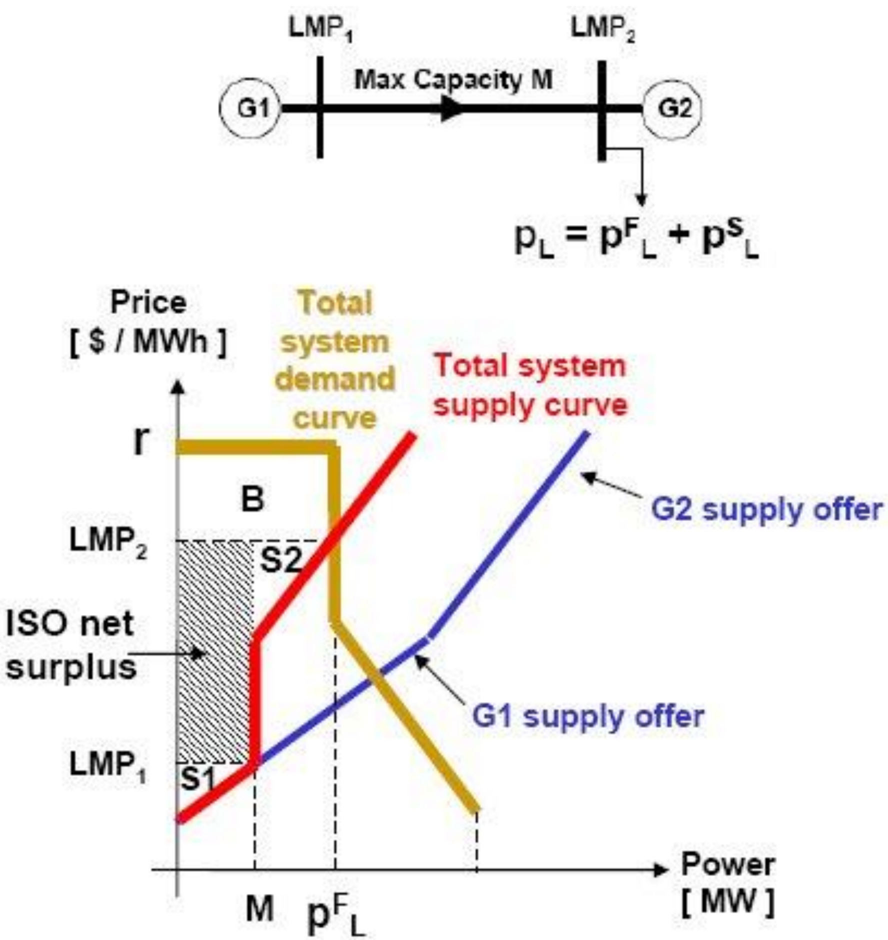
ISO Net Surplus

= [LSE Payments

– GenCo Revenues]

= $M \times [LMP_2 - LMP_1]$

Calculation of TNS: 2-Bus Example … Cont'd



ISO Net Surplus:

INS=M x [LMP_2 – LMP_1]

GenCo Net Surplus:

Area S1 + Area S2

LSE Net Surplus:

Area B

Total Net Surplus:

TNS = [INS+S1+S2+B]

ISO Objective (DC-OPF):

maximize **TNS** subject to

trans/gen constraints.

AMES ISO Solves Hourly DC-OPF for Day-Ahead Market†:

SI unit representation for AMES ISO's DC-OPF problem for hour H of the day-ahead market on day D+1, solved on day D.

DC-OPF formulation is derived from AC-OPF under three assumptions:

(a) Resistance on each branch km = 0

(b) Voltage magnitude at each bus k= base voltage V_o

(c)Voltage angle difference d_{km} = [delta_k - delta_m] across each branch km is small so that $\cos(d_{km}) \cong 1$ and $\sin(d_{km}) \cong d_{km}$

$$\max \quad \text{TNS}^R \tag{15}$$

with respect to LSE real-power price-sensitive demands, GenCo real-power generation levels, and voltage angles

$$p^S_{Lj},\ j = 1, ..., J;\ p_{Gi},\ i = 1, ..., I;\ \delta_k,\ k = 1, ..., K \tag{16}$$

subject to

(i) a real-power balance constraint for each bus k=1,...,K:

$$\sum_{i \in I_k} p_{Gi} - \sum_{j \in J_k} p^S_{Lj} - \sum_{km} P_{km} = \sum_{j \in J_k} p^F_{Lj} \tag{17}$$

where, letting x_{km} (ohms) denote reactance for branch km, and V_o denote the base voltage (in line-to-line kV),

$$P_{km} = [V_o]^2 \cdot [1/x_{km}] \cdot [\delta_k - \delta_m]$$

(ii) a limit on real-power flow for each branch km:

$$|P_{km}| \leq P^U_{km} \tag{18}$$

(iii) a real-power operating capacity interval for each GenCo i = 1,...,I:

$$\text{Cap}^L_i \leq p_{Gi} \leq \text{Cap}^U_i \tag{19}$$

(iv) a real-power purchase capacity interval for price-sensitive demand for each LSE j = 1,...,J:

$$0 \leq p^S_{Lj} \leq \text{SLMax}_j \tag{20}$$

(v) and a voltage angle setting at angle reference bus 1:

$$\delta_1 = 0 \tag{21}$$

TNS^R = Total Net Surplus based on *reported* GenCo marginal cost functions rather than *true* GenCo marginal cost functions.

Lagrange multiplier (or "shadow price") solution for the bus-k balance constraint (17) gives the LMP_k at bus k

Illustrative AMES Experimental Findings for a 5-Bus Test Case

Definition: ***Incentive misalignment*** → Institutional design fails to align incentives of market participants with efficiency (non-wastage of resources), robustness (resilience), and/or social welfare (socially desirable distribution of total net surplus)

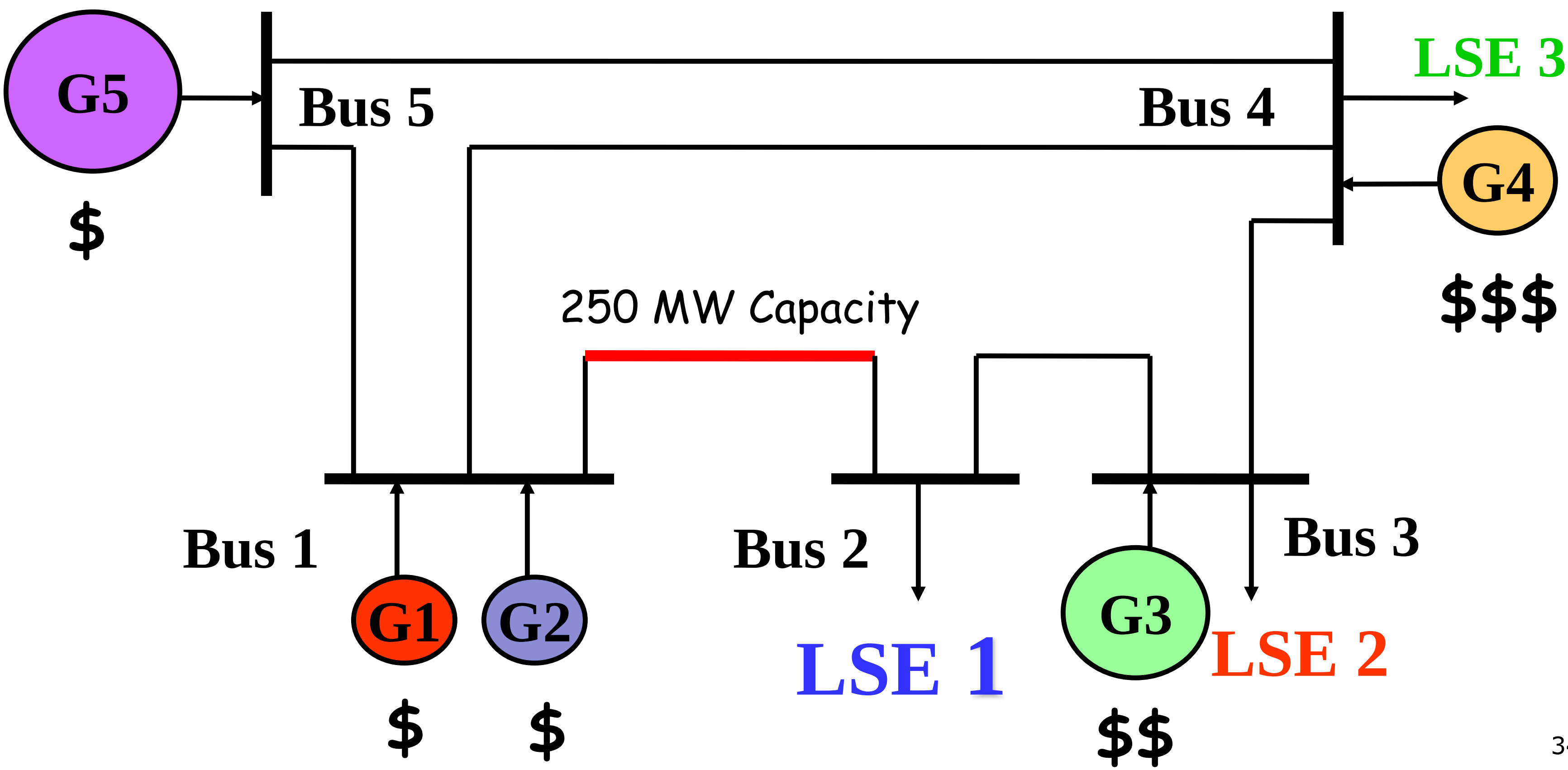
Experiments Reported Below: Incentive misalignment problems under FERC wholesale power market design for a range of experimental treatments:

- **Generator learning** [intensive parameter sweep]
- **Sensitivity of wholesale demand to price** [0 to 100%]

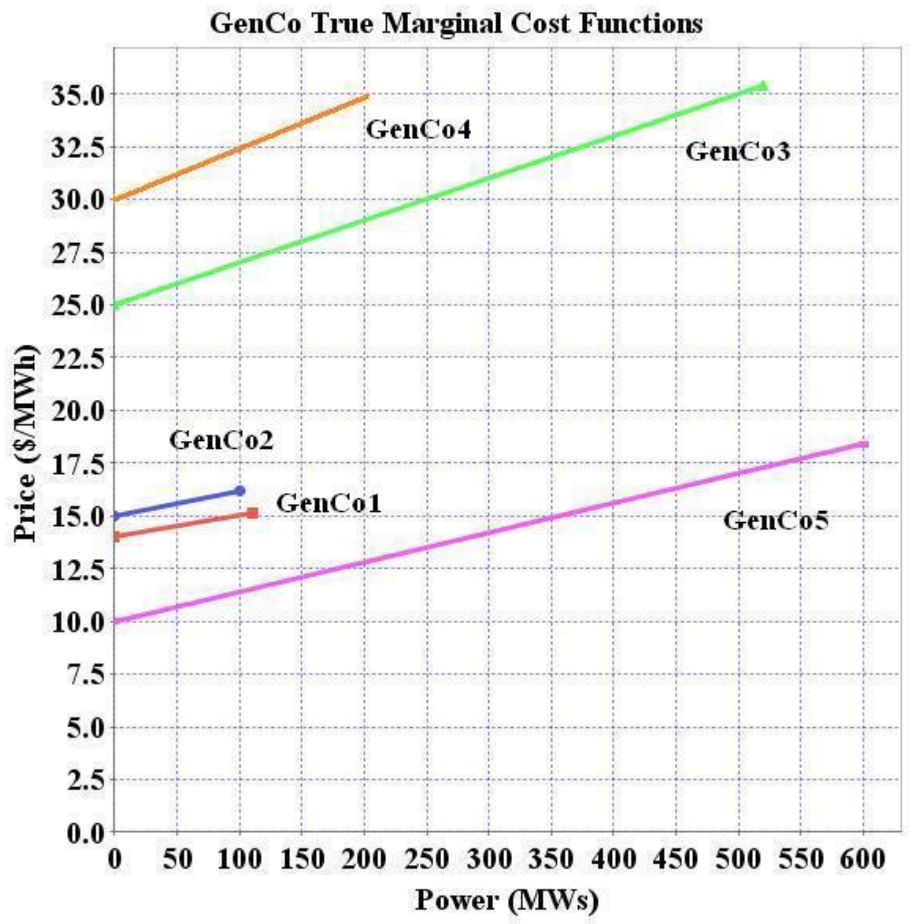
5-Bus Transmission Grid

(Used in many ISO business practice/training manuals)

Five GenCo sellers G1,…,G5 and three LSE buyers LSE 1, LSE 2, LSE 3

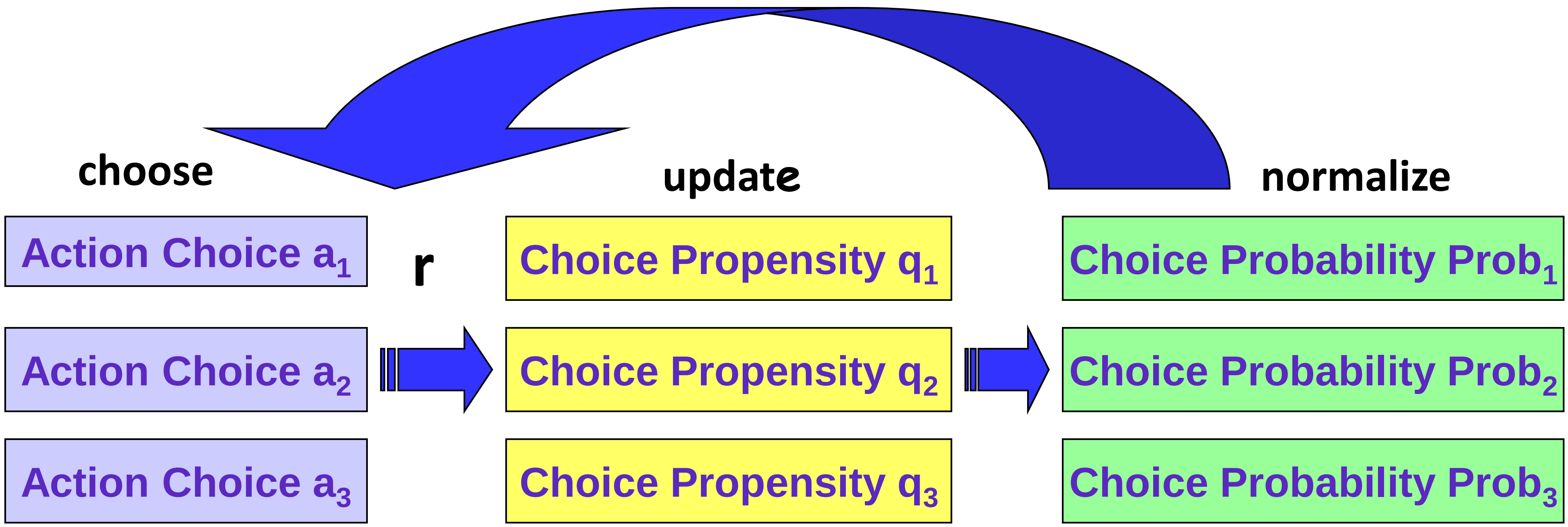


GenCo True Cost & Capacity Attributes



In 5-bus study, AMES GenCos use VRE learning

(version of Roth-Erev stochastic reinforcement learning)



- Each GenCo maintains action choice propensities q, normalized to choice probabilities Prob, to choose actions (supply offers). A good (bad) reward r_k resulting from an action a_k results in an increase (decrease) in both q_k and $Prob_k$.

R Measure for Demand-Bid Price Sensitivity

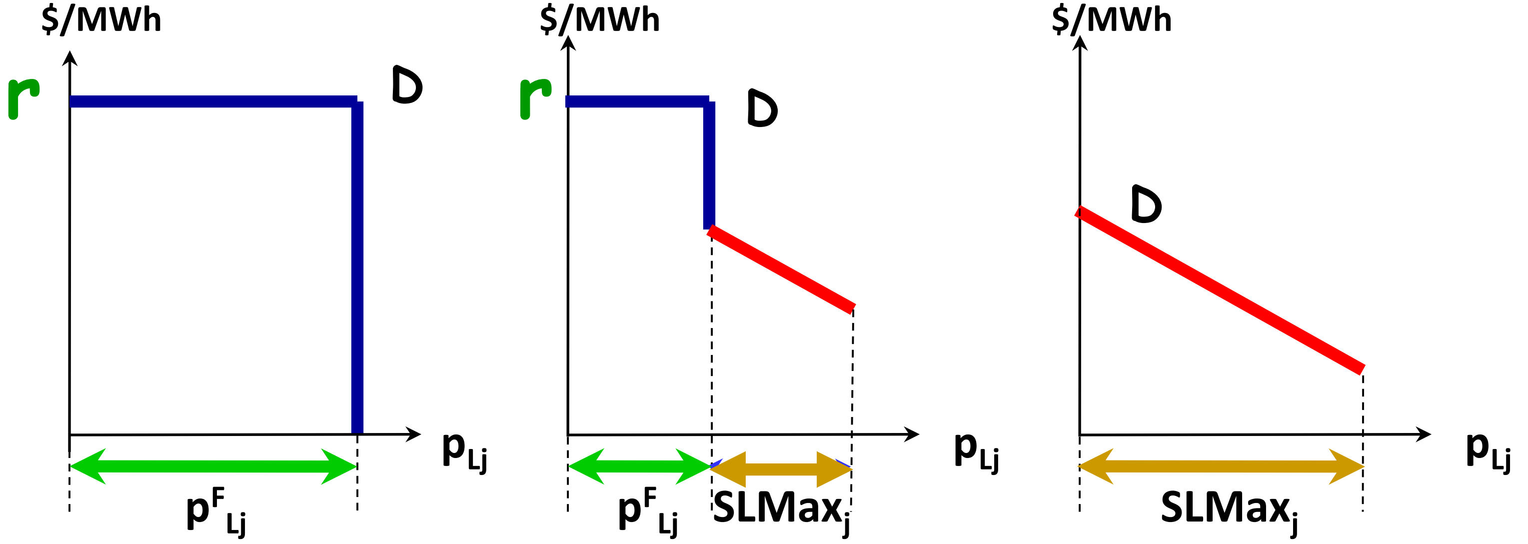
Note: In actual U.S. ISO energy regions, R ≅ 0.01

For LSE j in Hour H:

pF_{Lj} = Fixed demand for real power (MWs)

$SLMax_j$ = Maximum potential price-sensitive demand (MWs)

$$R = SLMax_j / [\, p^F_{Lj} + SLMax_j \,]$$

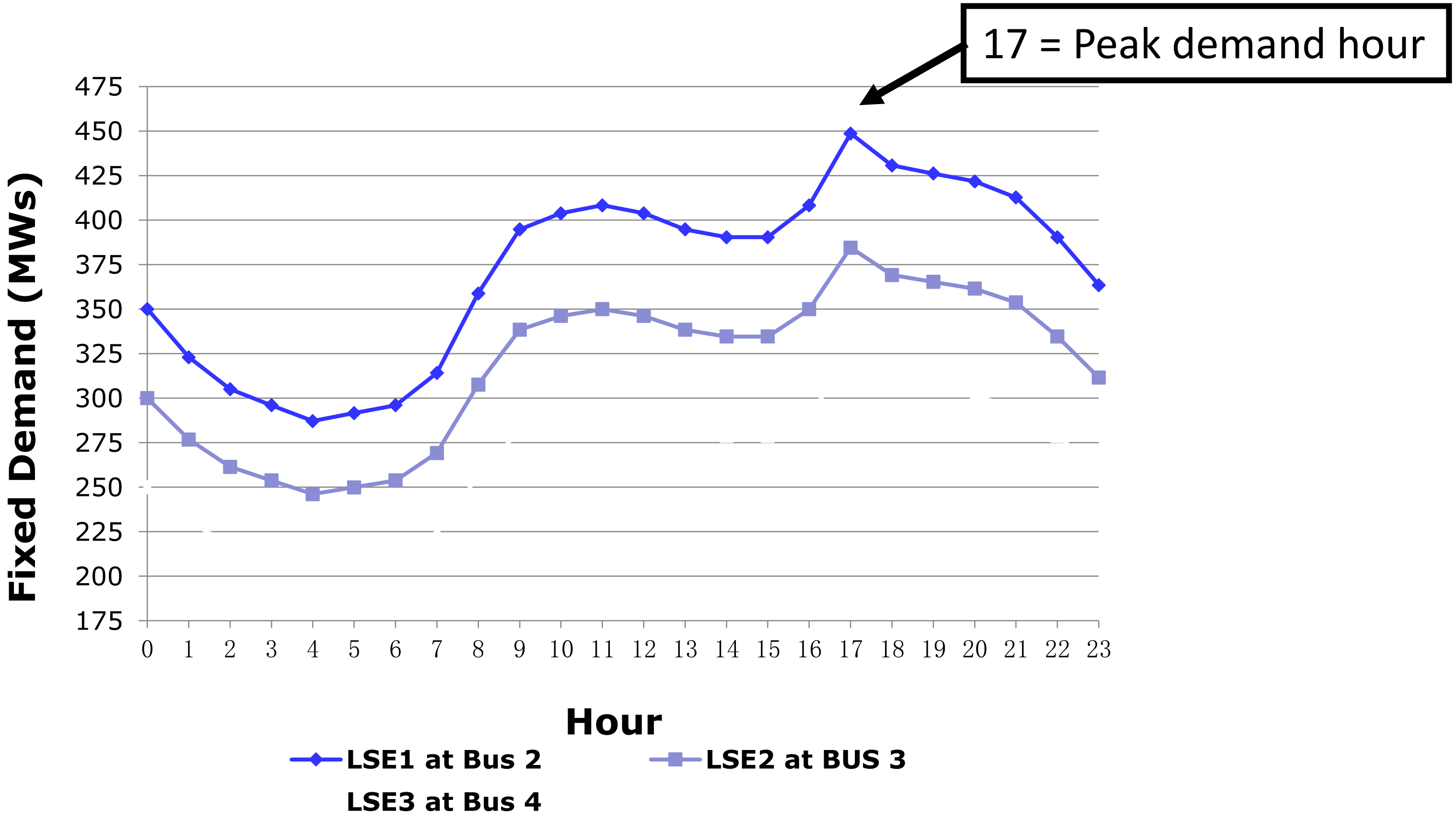


R=0.0 (100% Fixed Demand)

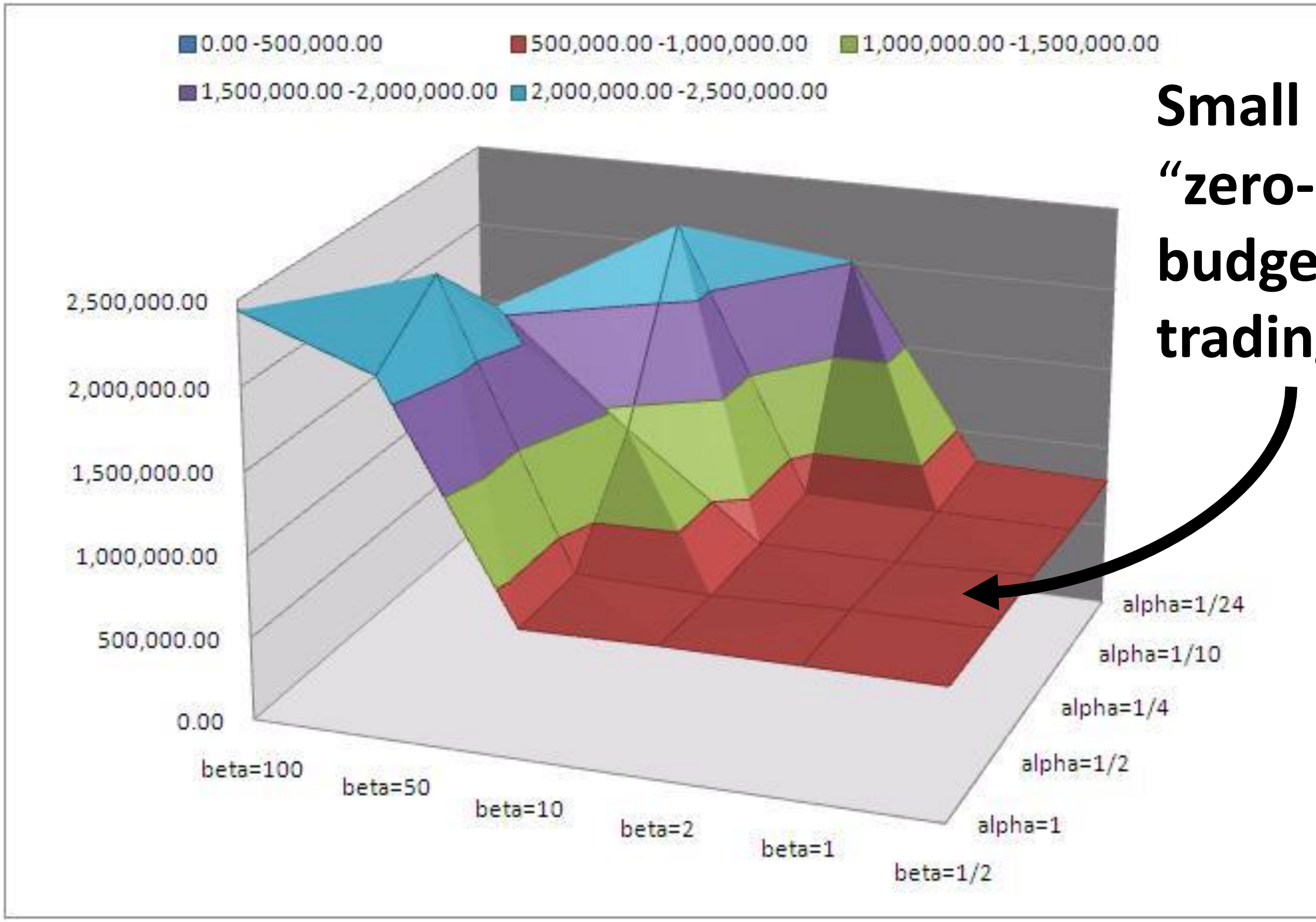
R=0.5

R=1.0 (100% Price-Sensitive Demand)

LSE Hourly Fixed Demands for R=0.0



First Experiments: Avg GenCo net earnings (Day 1000) for R=0 under varied learning parameter settings



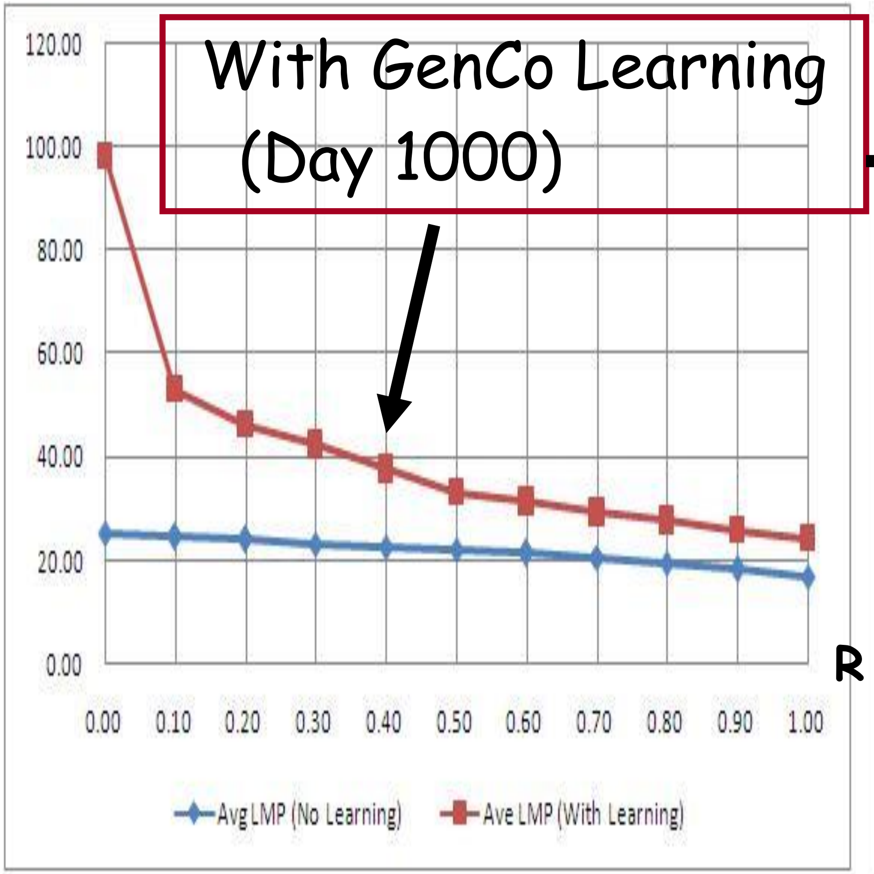
Small beta ≅ "zero-intelligence" budget-constrained trading.

Implication: Learning matters !

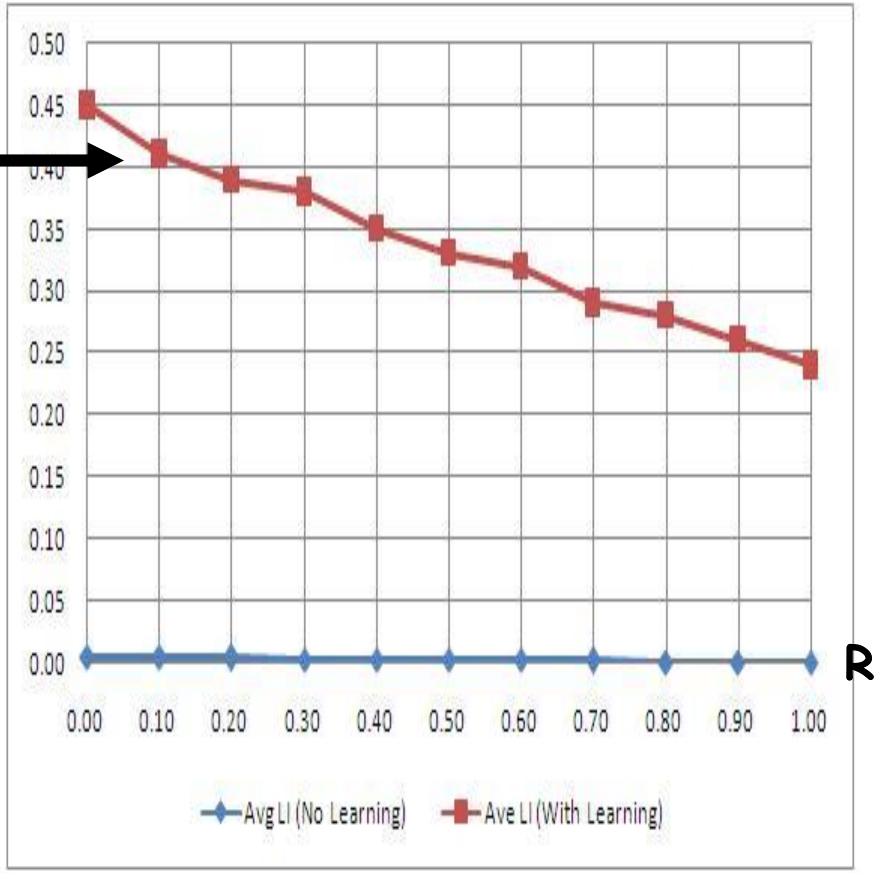
= Sweet spot region

Second Experiments: Avg LMP with/without GenCo learning as demand varies from R=0 (100% fixed) to R=1 (100% price sensitive)

Avg LMP (locational marginal price)



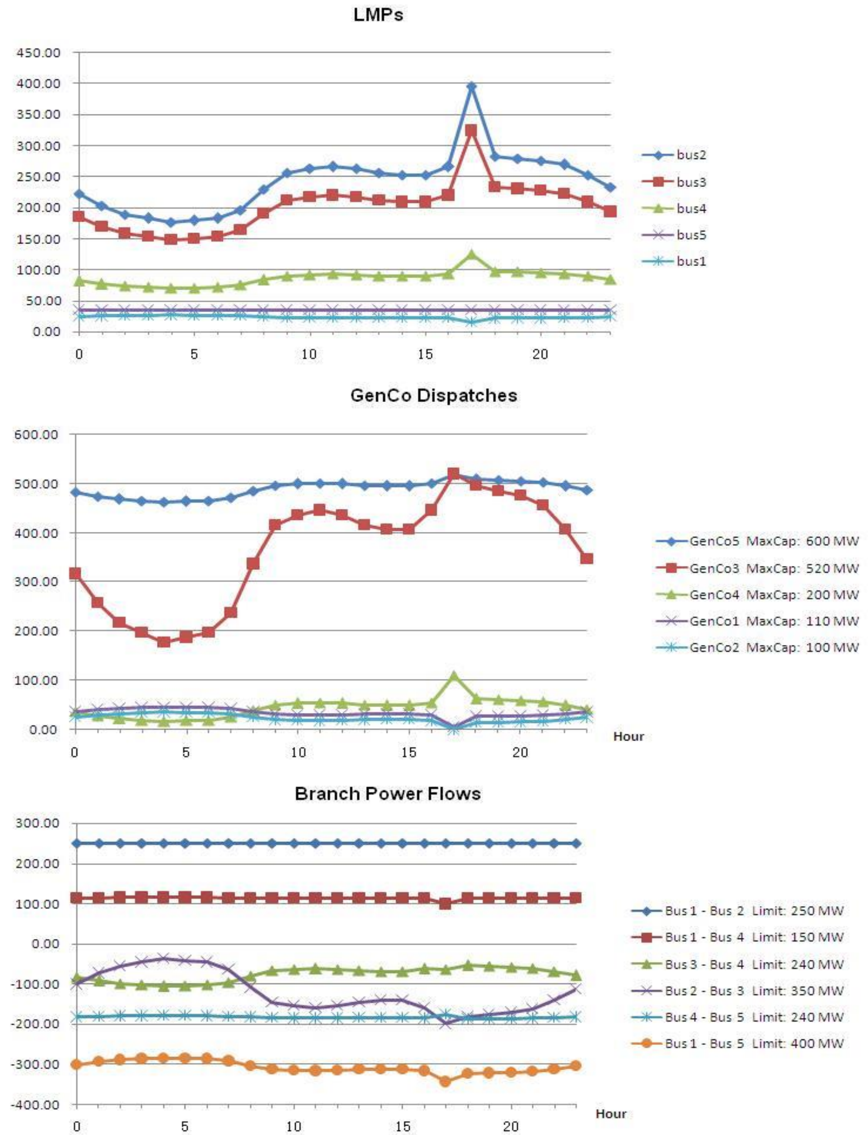
Avg LI (Lerner Market Power Index)



Single-Run Illustration of Findings for R=0.0 (100% Fixed Demand)

W/O Gen Learning (Day 1000)

With Gen Learning (Day 1000)



Implications of Second Experiments

(Li/Sun/Tesfatsion in *Comp Methods in Economic Dynamics*, 2010)

- **BOTTOM LINE:**

For all R, prices (LMPs) much higher under GenCo learning due to strategic GenCo supply offers

- **NEEDED:**

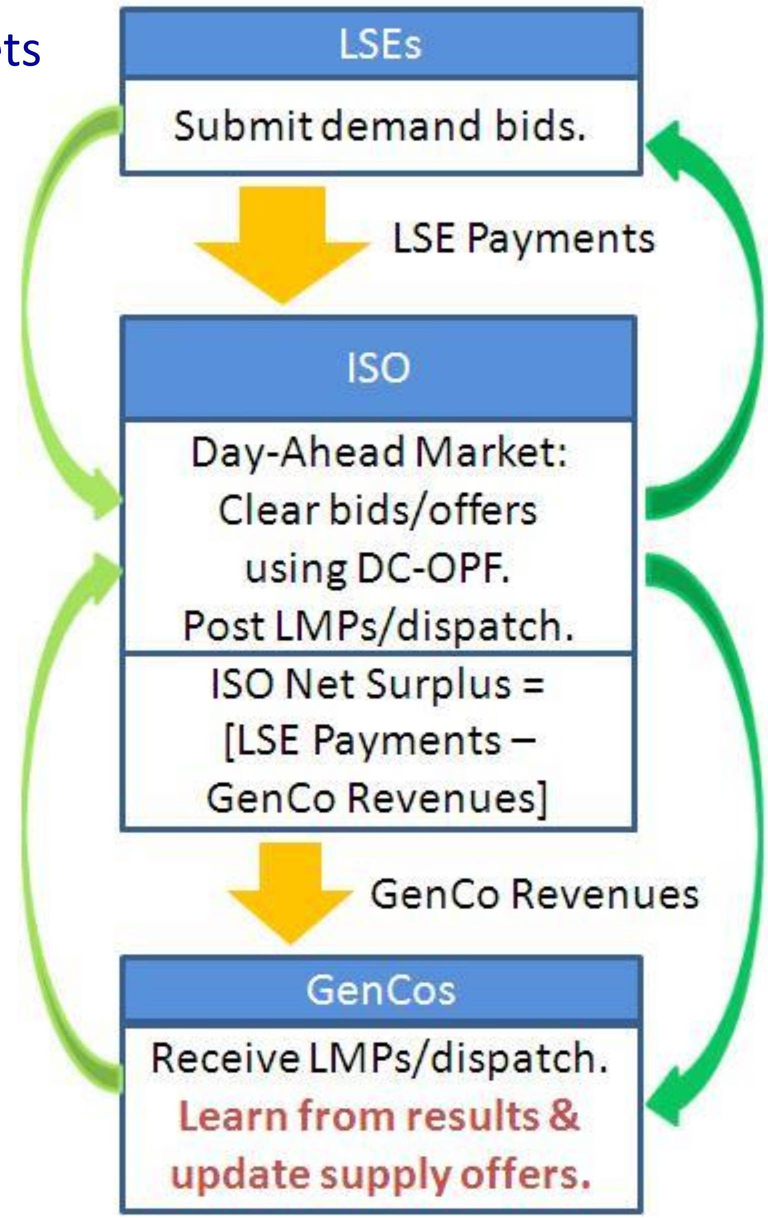
Active price-sensitive LSE demand bidding to offset power of strategic GenCos (well-working double auction)

- **POSSIBLE MEANS:**

Integrated wholesale/retail restructuring providing array of price-sensitive retail contracts and permitting retail consumers to select their LSE suppliers

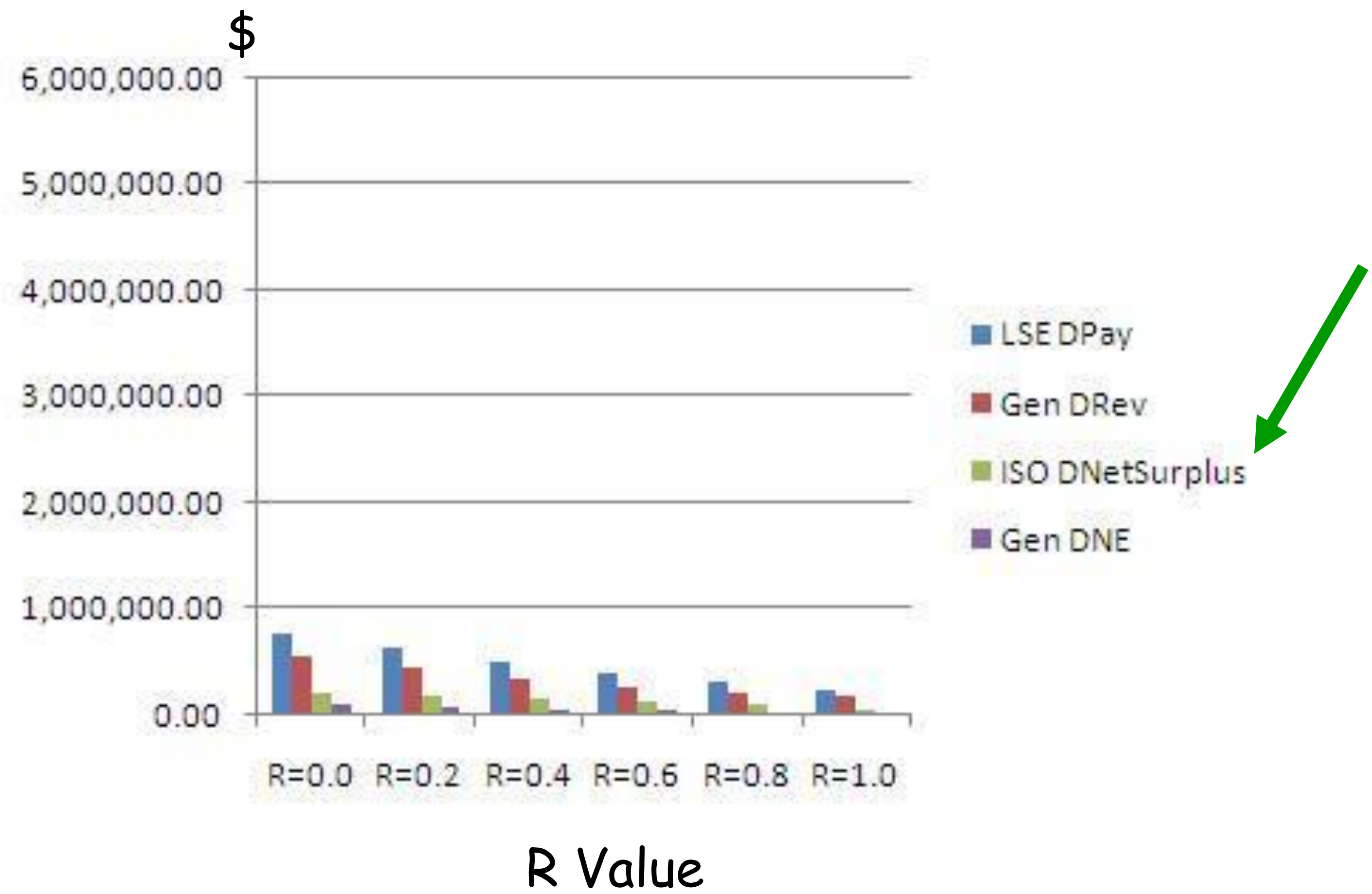
Third Experiments: Extraction of net surplus by ISOs in day-ahead energy markets under Locational Marginal Pricing (LMP):

Day-ahead market activities on a typical operating day D:



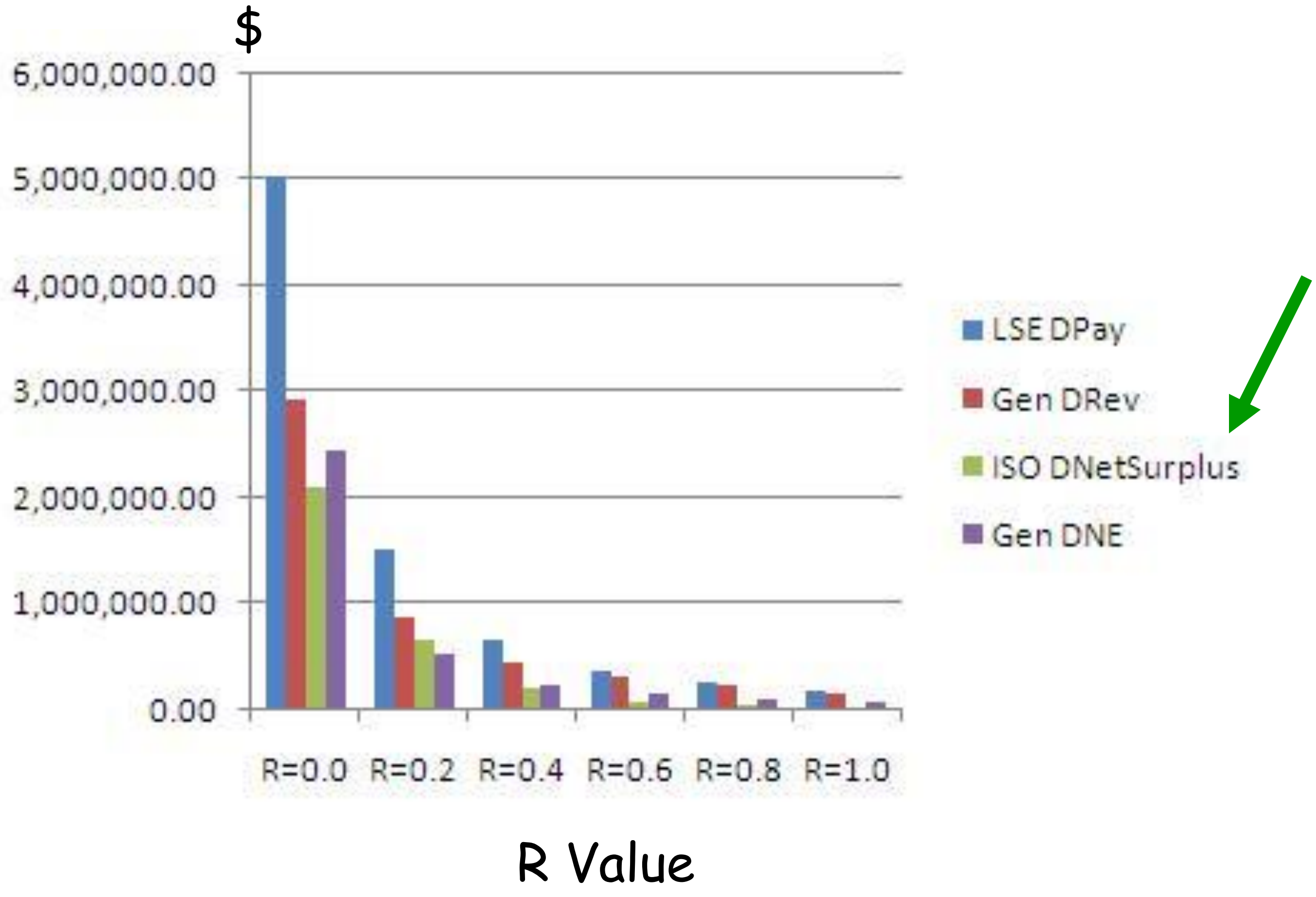
5-Bus Test Case Results ****Without**** GenCo Learning:

ISO net surplus on Day 1000 as LSE demand varies from R=0.0 (100% fixed) to R=1.0 (100% price sensitive)



5-Bus Test Case Results ***With*** GenCo VRE Learning:

Mean ISO net surplus on Day 1000 as LSE demand varies from R=0.0 (100% fixed) to R=1.0 (100% price sensitive)



Empirical Comparisons

- **From PJM 2008 report:**
  ISO net surplus from day-ahead market: **$2.66 billion**
- **From MISO 2008 report:**
  ISO net surplus from day-ahead market: **$500 million**
- **From CAISO 2008 report:**
  ISO net surplus from day-ahead inter-zonal congestion charges: **$176 million**.
- **From ISO-NE 2008 report:**
  Combined ISO net surplus for real-time and day-ahead markets: **$121 million**.

Implications of ISO Net Surplus Findings

(Li/Tesfatsion, *IEEE Transactions on Power Systems*, 2010, to appear)

- ISO net surplus extractions ***not well aligned with market efficiency***
- Treatments resulting in ***greater*** GenCo economic capacity withholding (hence higher & more volatile LMPs) also result in ***greater*** ISO & GenCo net surplus
- ISO net surplus collections should be allocated for ***ex ante*** remedy of structural/behavioral problems that encourage GenCo economic capacity withholding.
- Should not be used ***ex post*** for LMP payment offsets and LMP risk hedge support (current norm)

Conclusions

- **Restructured wholesale power markets** are complex large-scale systems encompassing physical constraints, institutional rules of operation, and strategic human participants.

- **Agent-based testbeds** permit the systematic dynamic study of such systems through intensive computational experiments.

- For increased empirical validity, testbeds should be **iteratively developed** with ongoing input from actual market participants.

- To increase usefulness for research/teaching/training and to aid knowledge accumulation, testbeds should be **open source**.

On-Line Resources

Presentation Slides

https://www2.econ.iastate.edu/tesfatsi/DARPAISATJuly2010.LTTalk.pdf

AMES Test Bed Homepage (Code/Manual/Publications)

https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

Agent-Based Electricity Market Research

https://www2.econ.iastate.edu/tesfatsi/aelect.htm

Agent-Based Computational Economics Homepage

https://www2.econ.iastate.edu/tesfatsi/ace.htm

ISU Electric Energy Economics (E3) Group

https://www2.econ.iastate.edu/tesfatsi/E3GroupISU.htm