Stress-Testing Institutional Arrangements via Agent-Based Modeling

Illustrative Results for U.S. Electric Power Markets

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Presentation Outline

- Complexity of large-scale institutions
- How might agent-based modeling enable pre-testing of institutional arrangements prior to implementation?
- Adventures in agent-based test-bed development for U.S. electric power markets

  ***AMES = A*gent-based *M*odeling of *E*lectricity *S*ystems**

- Illustrative findings

Complexity of Large-Scale Institutions

- Modern societies depend strongly on large-scale institutions for the production and distribution of critical goods and services such as energy, health care, education, and financial credit

- Institutional outcomes depend in complicated ways on
  - **Rules** governing participation, operation and oversight
  - **Structural restrictions** on feasible actions
  - **Behavioral dispositions** of human participants

- To be useful and informative, institutional studies need to take proper account of all three elements.

Can Agent-Based Modeling (ABM) Help?

- ABM tools are designed to handle complex systems.
- ABM tools permits researchers to construct ***test beds*** in the form of ***computational virtual worlds***
- Starting from user-specified initial conditions, ***world events are driven entirely by agent interactions***.
- ***Agents*** can range from structural and institutional entities with no cognitive function (e.g., transmission grids and market protocols) to sophisticated decision makers capable of communication and learning (e.g., electricity traders).

ABM and Institutional Design

Key Issue: Does a proposed or actual design ensure **efficient, fair, and orderly social outcomes over time** despite possible attempts by participants to “game” the design in accordance with their own objectives?

ABM Approach:

- Construct an ***agent-based test bed*** capturing salient aspects of the institutional design.
- ***Introduce self-interested cognitive agents with learning capabilities.*** Let the world evolve. Observe and evaluate the resulting outcomes.

Concrete Example: The AMES Project

AMES Wholesale Power Market Test Bed

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Project Homepage: AMES Market Package Homepage (Code/Manuals/Pubs)
https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

Project Context

- In April 2003 the U.S. Federal Energy Regulatory Commission (FERC) proposed that all U.S. wholesale power markets adopt a market design with specific types of core features.

- As of 2009, over 50% of U.S. generation capacity operates under some variant of FERC's wholesale power market design.

Core Features of FERC's Market Design

- Market to be managed by an ***independent system operator*** (no ownership or financial stake in market operations)

- ***Two-settlement system:*** Concurrent daily operation of day-ahead and real-time markets

- Grid congestion managed via ***Locational Marginal Pricing (LMP),*** the determination of a separate per-unit price ($/MWh) for energy (MWh) at designated grid locations where power is injected or withdrawn

- Oversight & market power mitigation by outside agency

➔ Has led in practice to complicated market operations difficult to analyze by means of standard analytical and statistical tools !

Our Project Goals

- Develop an ***agent-based test bed*** that captures core features of the FERC wholesale power market design

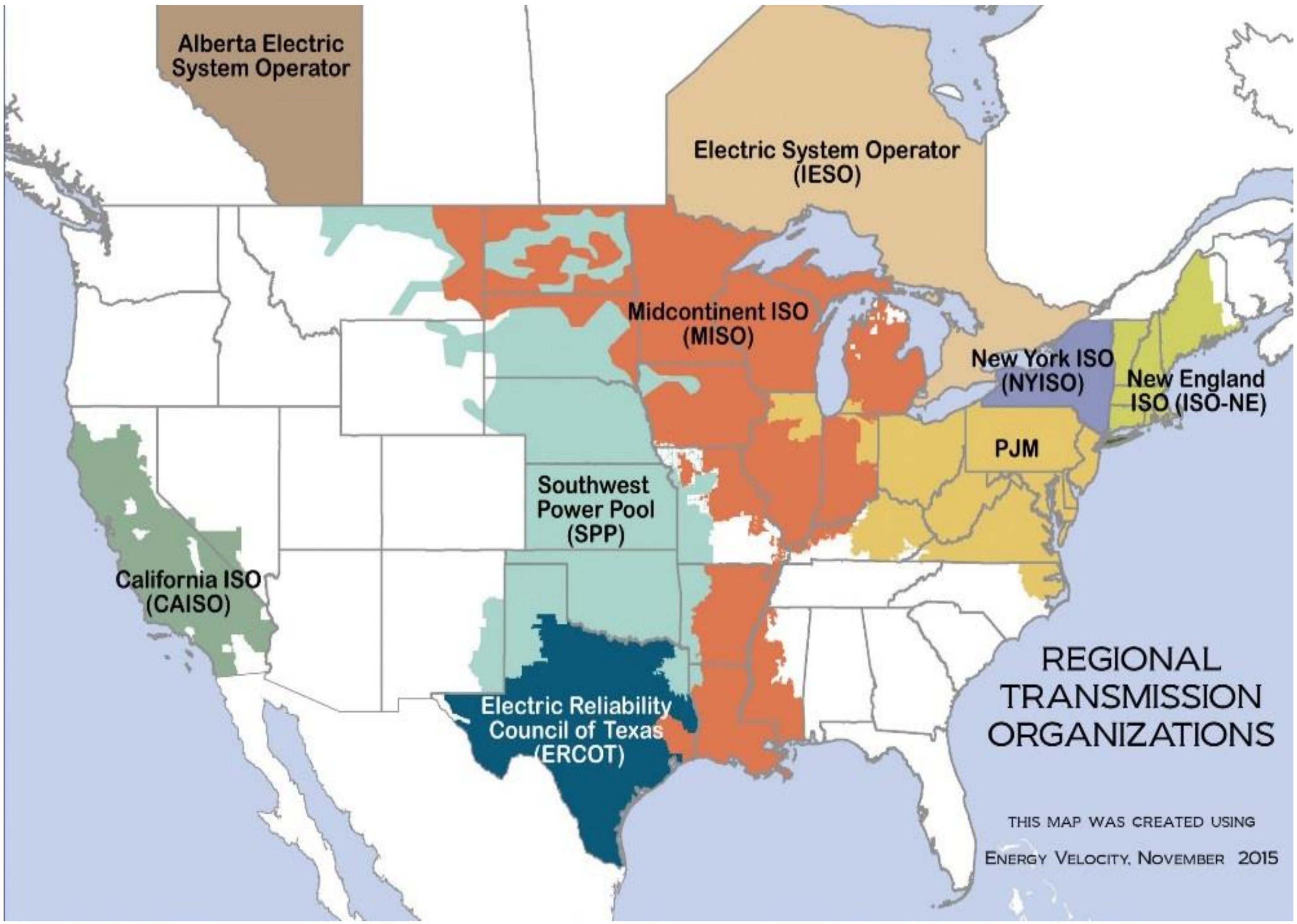
- Use this test bed to systematically explore dynamic performance under the FERC market design, using Midwest (MISO) and New England (ISO-NE) energy regions as main case studies.

- Use this test bed to systematically explore new and/or modified market design features

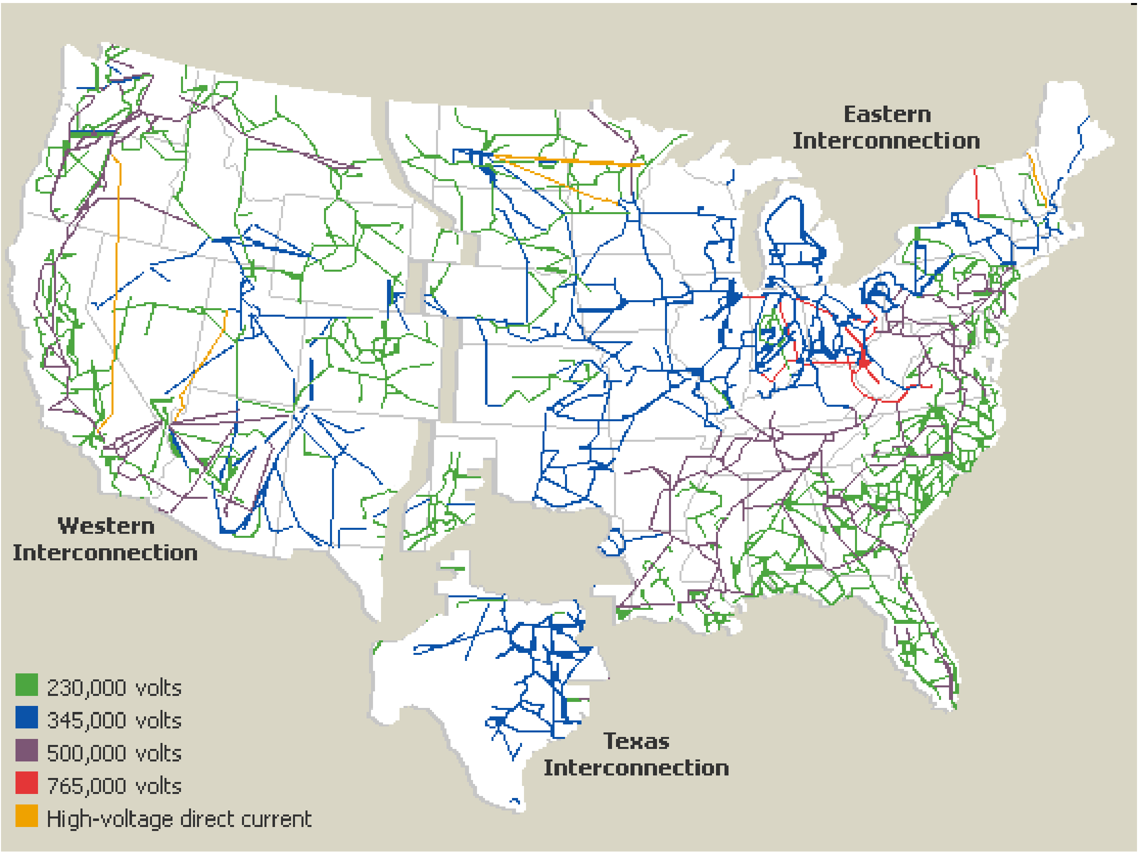
- Use this test bed to encourage ongoing communication among researchers and power industry stakeholders

Seven North-American Regions Operate Under Variants of the FERC Market Design

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

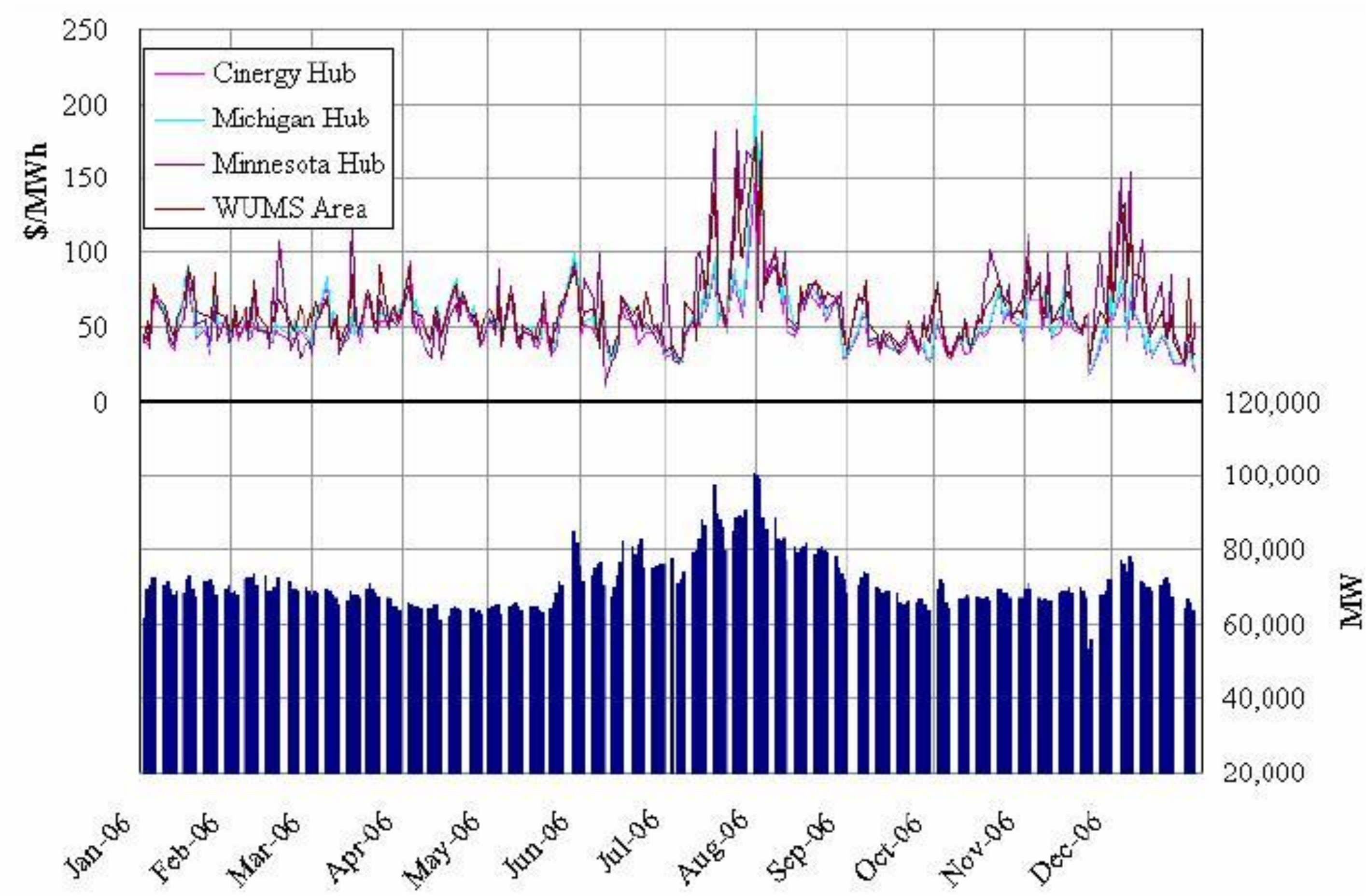


U.S. High-Voltage AC Transmission Grid for Electric Power



The U.S. high-voltage AC transmission grid consists of three separately-synchronized parts.

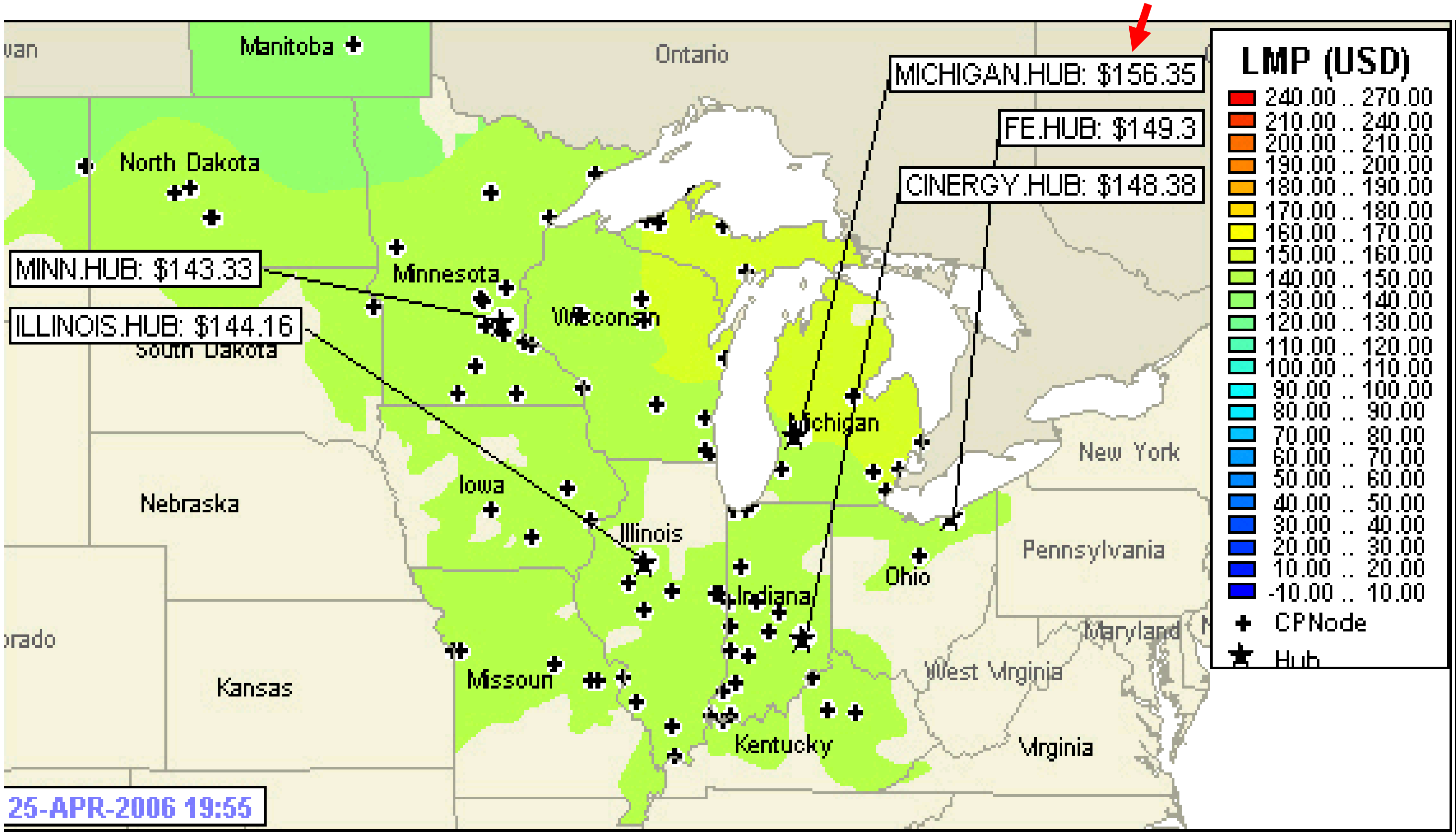
Midwest (MISO) Real-Time Market Hub Prices and Fixed Demand: 2006



MISO Real-Time Market Prices for Electric Power Can Exhibit Volatile Fluctuations Over Time

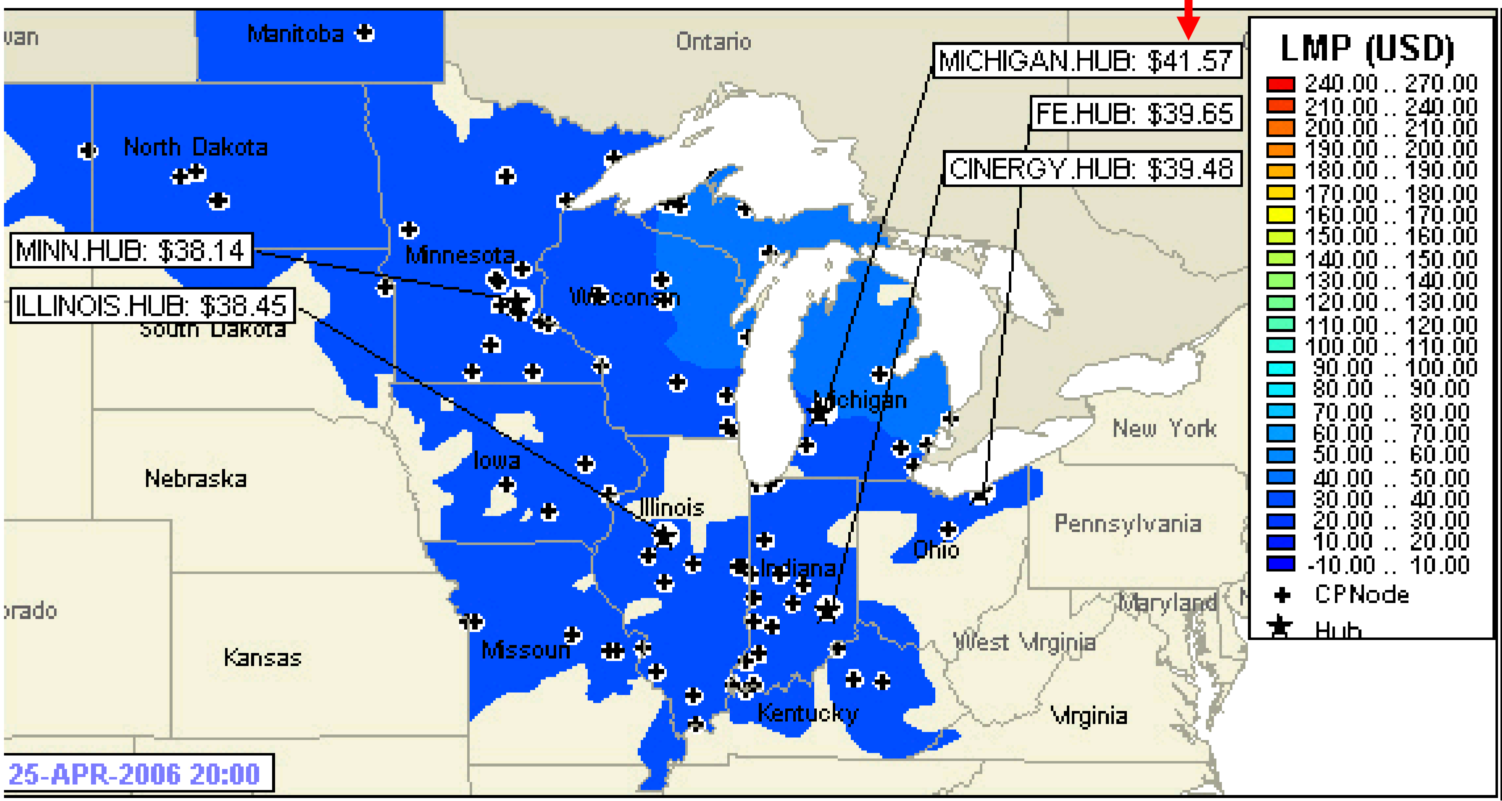
Example: April 25, 2006, at 19:55

Note this price,$156.35



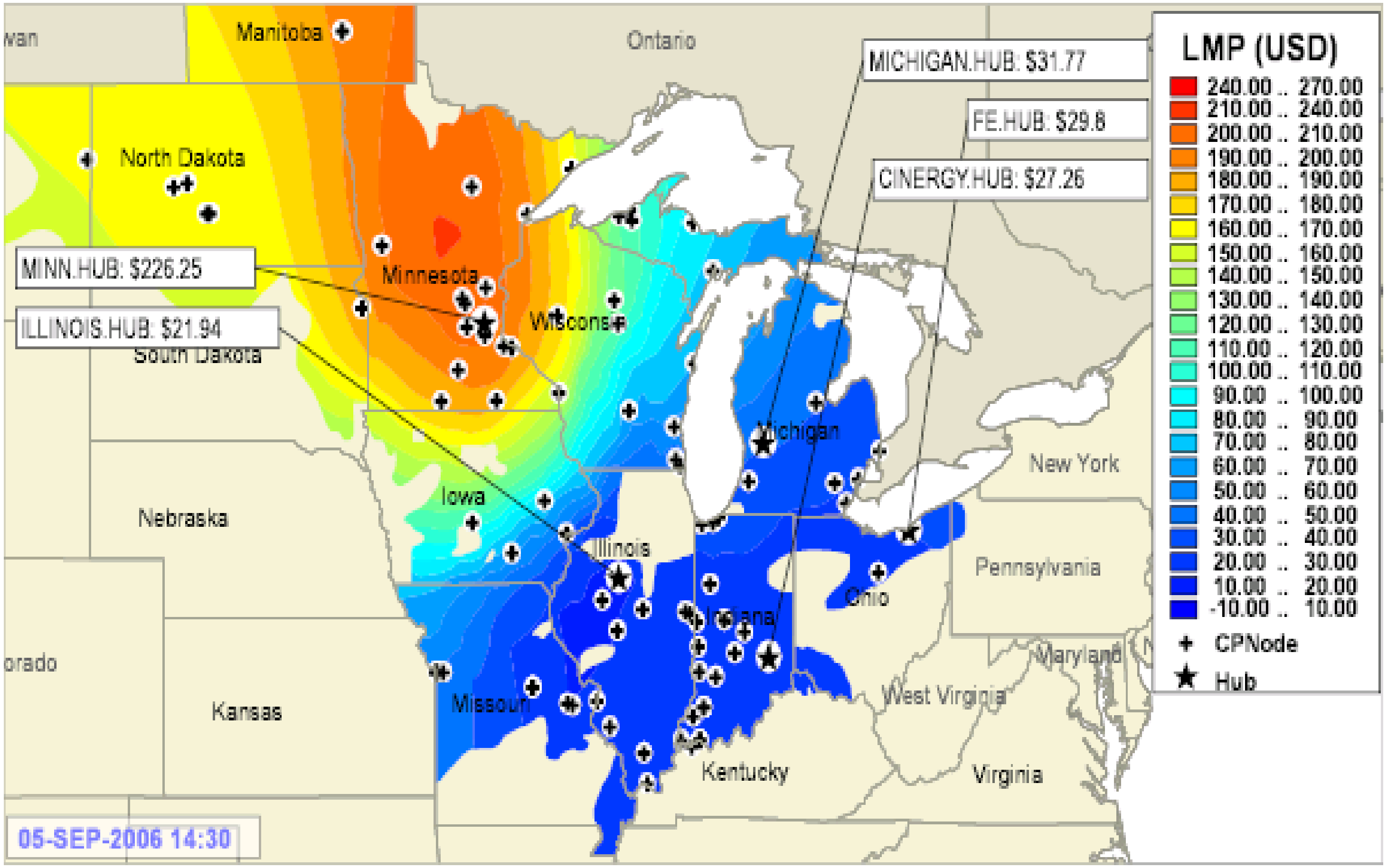
Five Minutes Later…

Now $41.57, a 73% drop in price in 5 minutes!

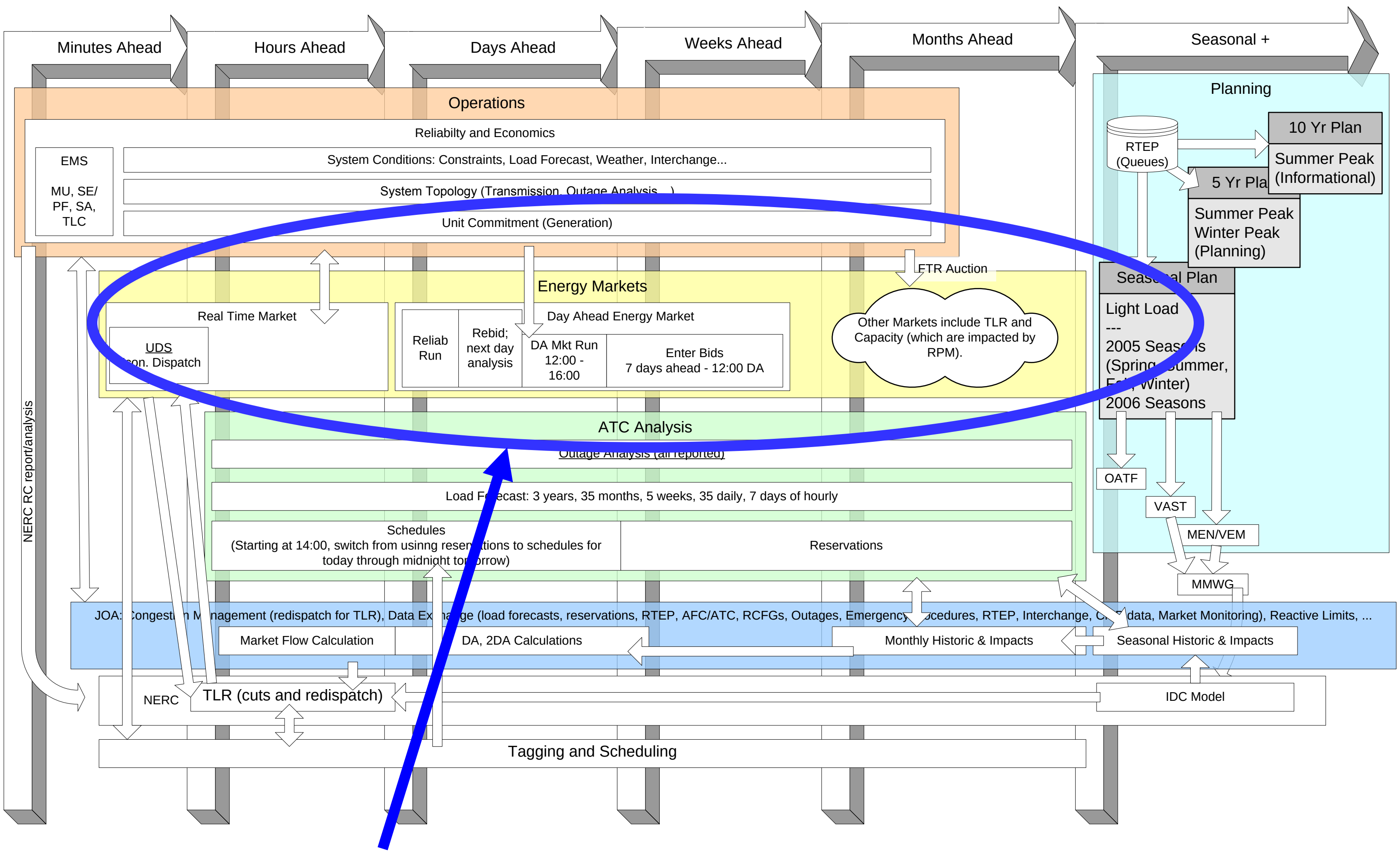


MISO Real-Time Market Prices for Electric Power Can Exhibit Strong Contemporaneous Price Separation

Example: September 5, 2006, 14:30



Complicated Organization of a Typical U.S. Wholesale Power Market Operating Under FERC Design



Current focus of our test-bed project = Two-settlement system under LMP.

AMES Market Test Bed

Key Features and Release History

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

➢ **Research/teaching/training-grade test bed**
(2-500 pricing nodes)

- **Operational validity** (“simple but not too simple”)
- Permits **dynamic** testing with **learning traders**
- Permits **intensive experimentation** with alternative scenarios
- **Free open-source Java implementation** (full access to code)
- **Flexible & modular** (easy to modify test bed features)
- **V1.31 released** (IEEE Power & Energy Soc. Gen. Meeting, 2007)
- **V2.02 released** (IEEE Power & Energy Soc. Gen Meeting, 2008)

NOTE: As detailed at the AMES homepage, linked at the top of this slide, successive additional versions of AMES with increased capabilities have been developed and released as open source software since 2008.

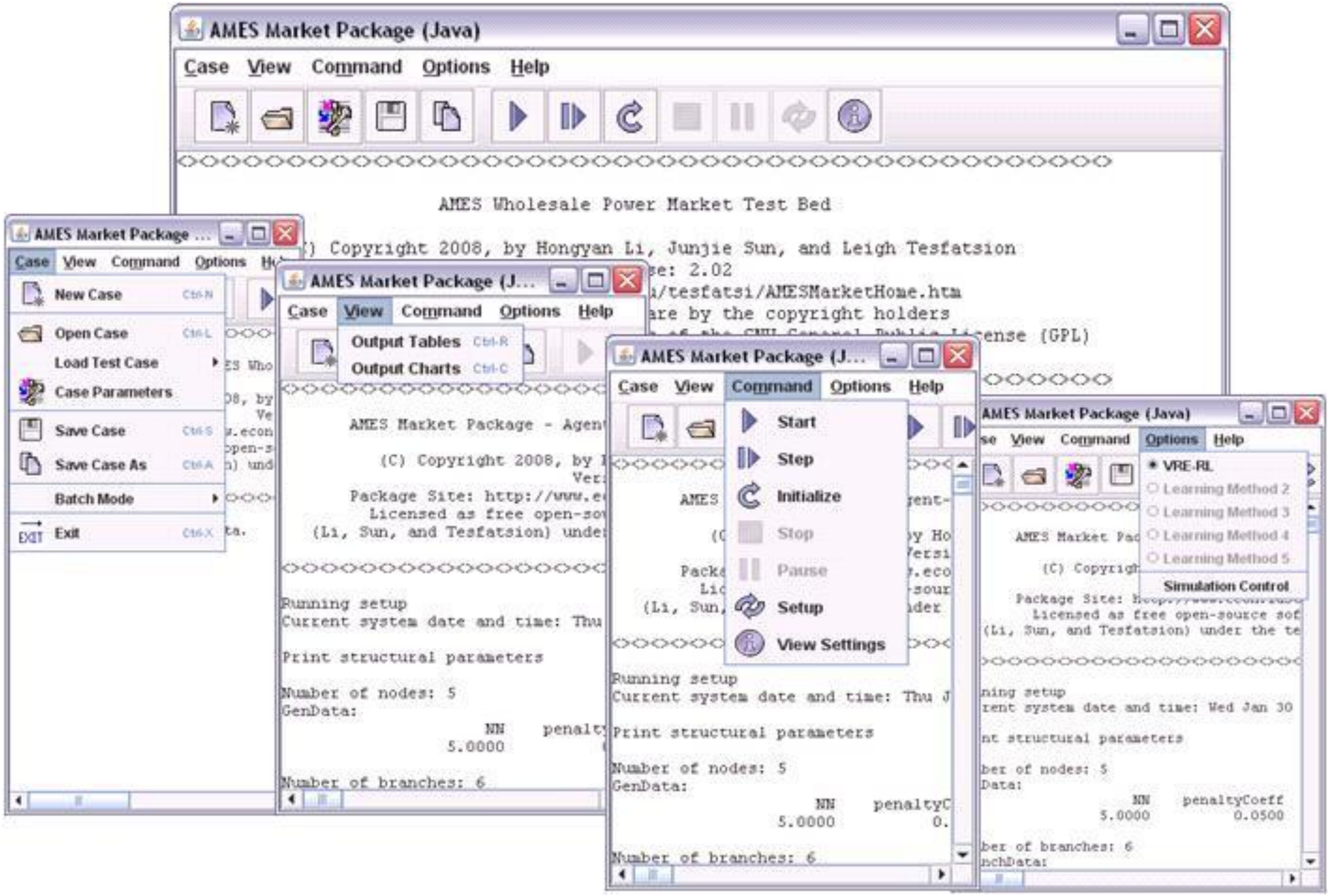
AMES Market Test Bed:

Flexible and Modular Architecture

- **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,…)
- **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 Market Test Bed Graphical User Interface (GUI)

Tool Bar and Menus for Data Input and Output Displays

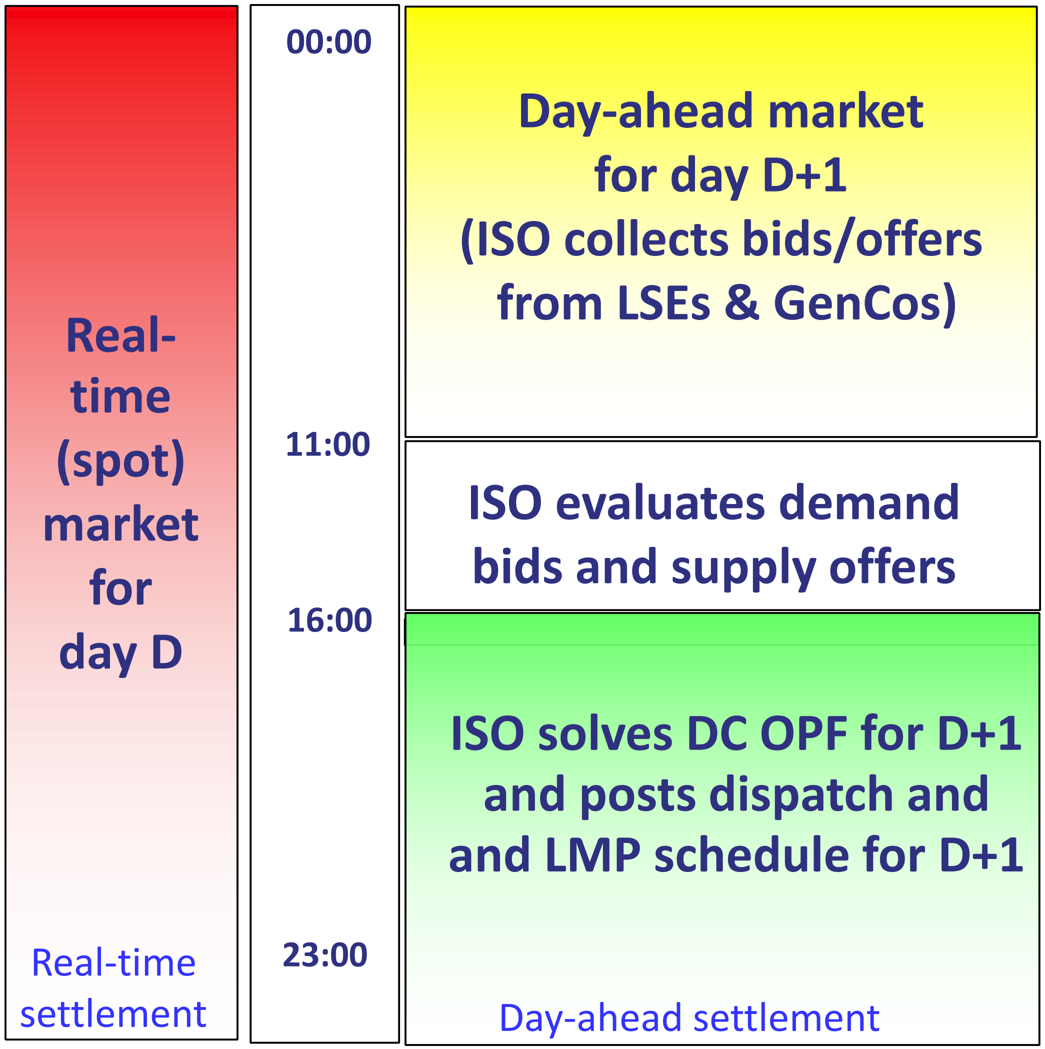


AMES Architecture: Current Implementation
(based on business practices manuals for MISO/ISO-NE)

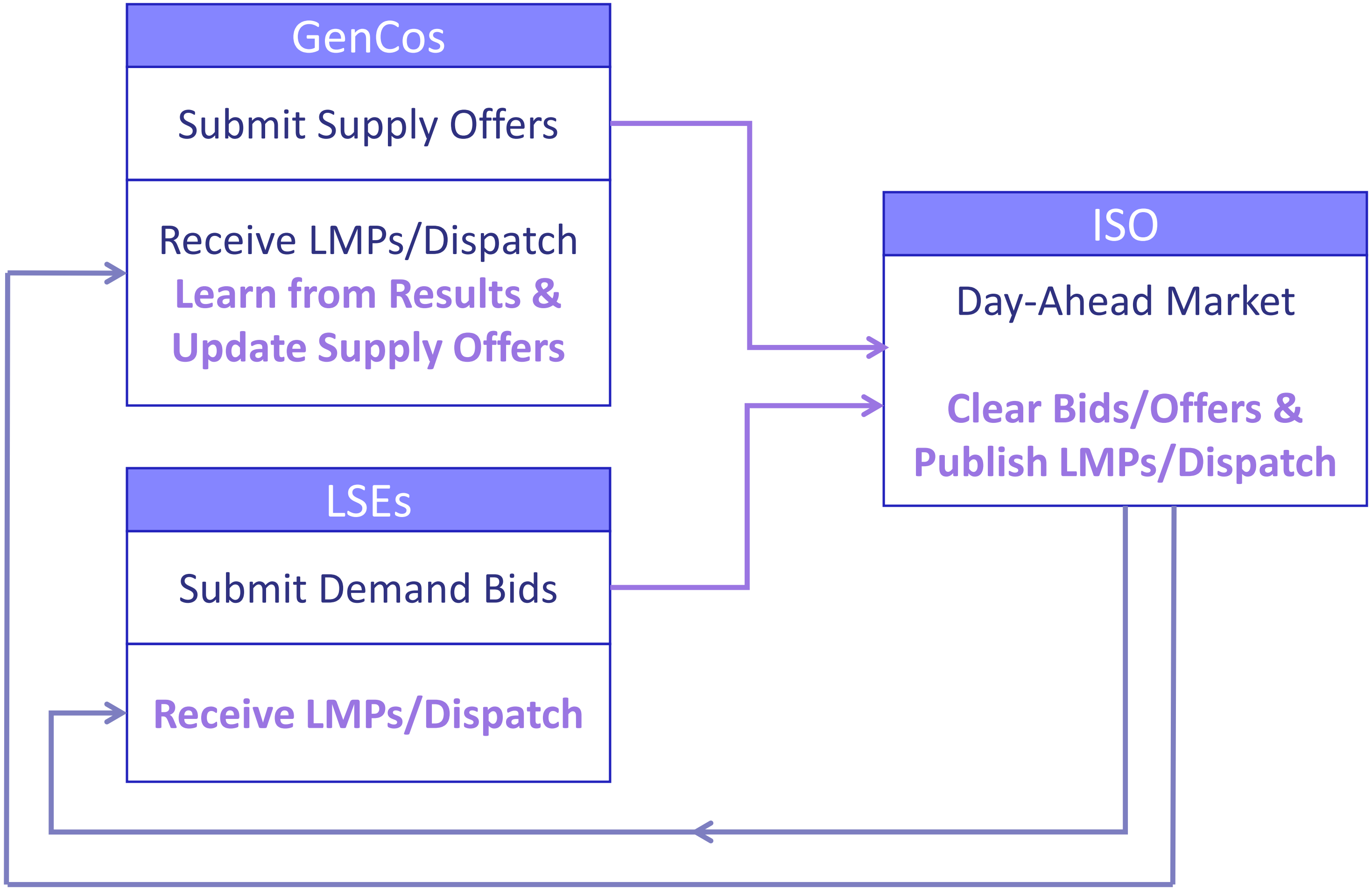
- **Traders**
  - GenCos (sellers)
  - LSEs (buyers)
  - GenCo learning abilities
- **Independent System Operator (ISO)**
  - System reliability assessments
  - Advance scheduling via **bid/offer based Optimal Power Flow (OPF)**
  - Real-time dispatch
- **Two-settlement system**
  - **Day-Ahead Market (DAM):** Double auction (offers/bids, financial contracting)
  - **Real-Time Market (RTM):** One-sided auction (offers, financial contracting)
- **AC transmission grid**
  - **Generation Companies (GenCos)** & **Load-Serving Entities (LSEs)** located at various buses across the transmission grid
  - Grid Congestion managed via **Locational Marginal Pricing (LMP)** determined by ISO via bid/offer-based DAM/RTM Optimal power flow optimizations.

Activities of ISO During Each Operating Day D:

Timing Adopted from Midwest ISO (MISO)



Day-Ahead Market Data Flow for AMES GenCos, LSEs, and ISO



Form of LSE Demand Bids

- Hourly demand bid for each LSE j

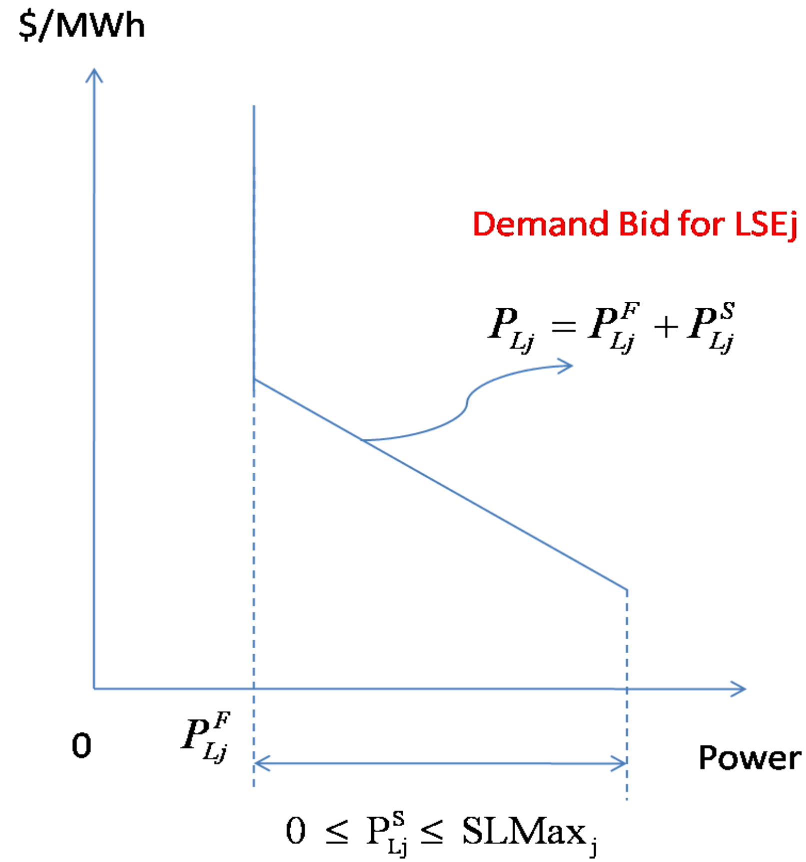
Fixed + Price-Sensitive Demand Bids

- **Fixed** demand bid = p^F_{Lj} (MWs)
- **Price-sensitive** demand bid

  = Linear demand function for real power p^S_{Lj} (MWs) over a purchase capacity interval:

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

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



What do AMES GenCos Learn?

Hourly Supply Offers for the Day-Ahead Market

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

$$MC^{R}_{i}(p_{Gi}) = a^{\mathbf{R}}_{i} + 2b^{\mathbf{R}}_{i}\, p_{Gi}$$

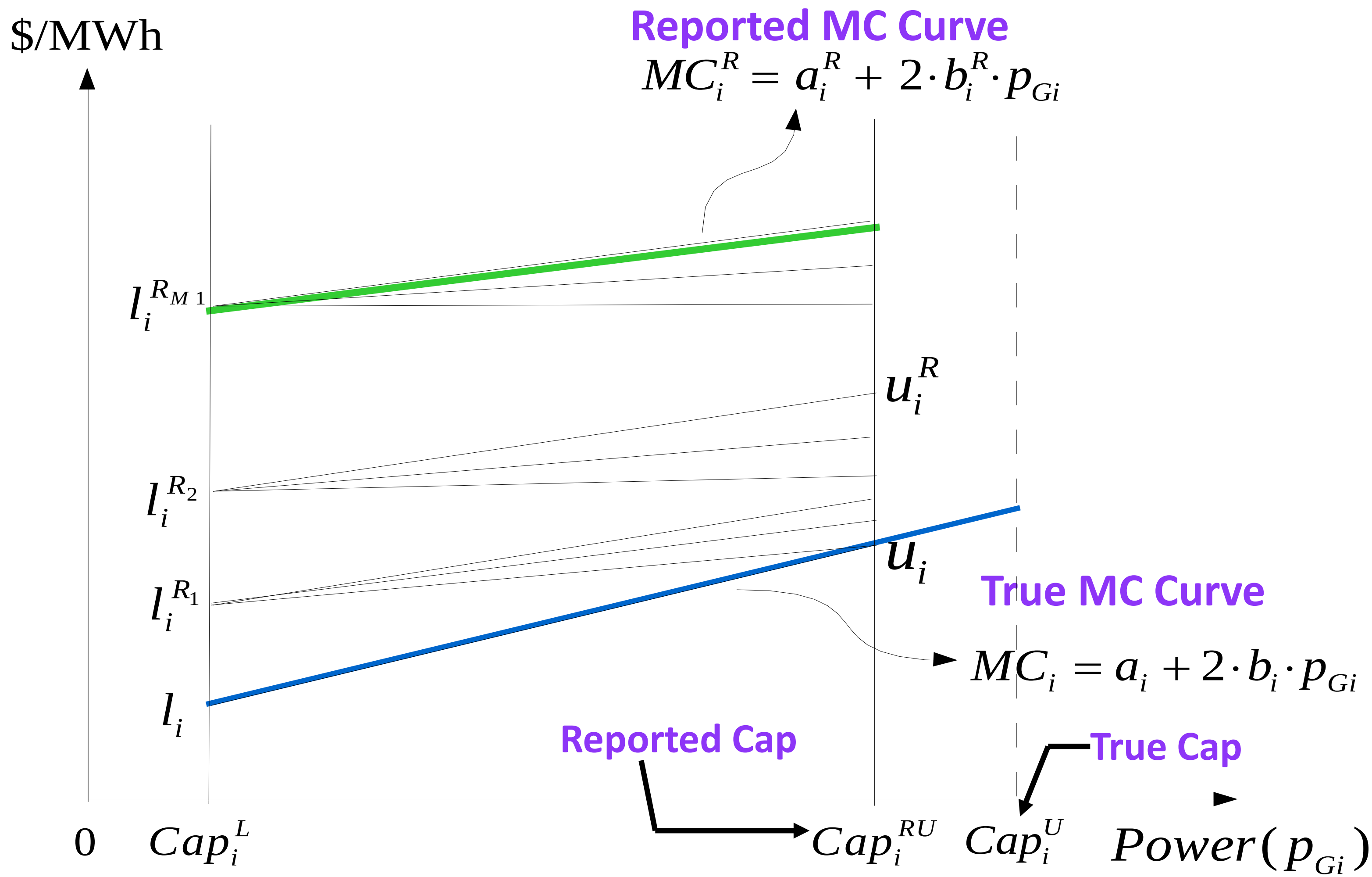
$$Cap_{i}^{L} \leq p_{Gi} \leq Cap_{i}^{\mathbf{R}U}$$

GenCos can strategically report ***higher-than-true*** marginal costs and/or ***lower-than-true*** physical generation capacity.

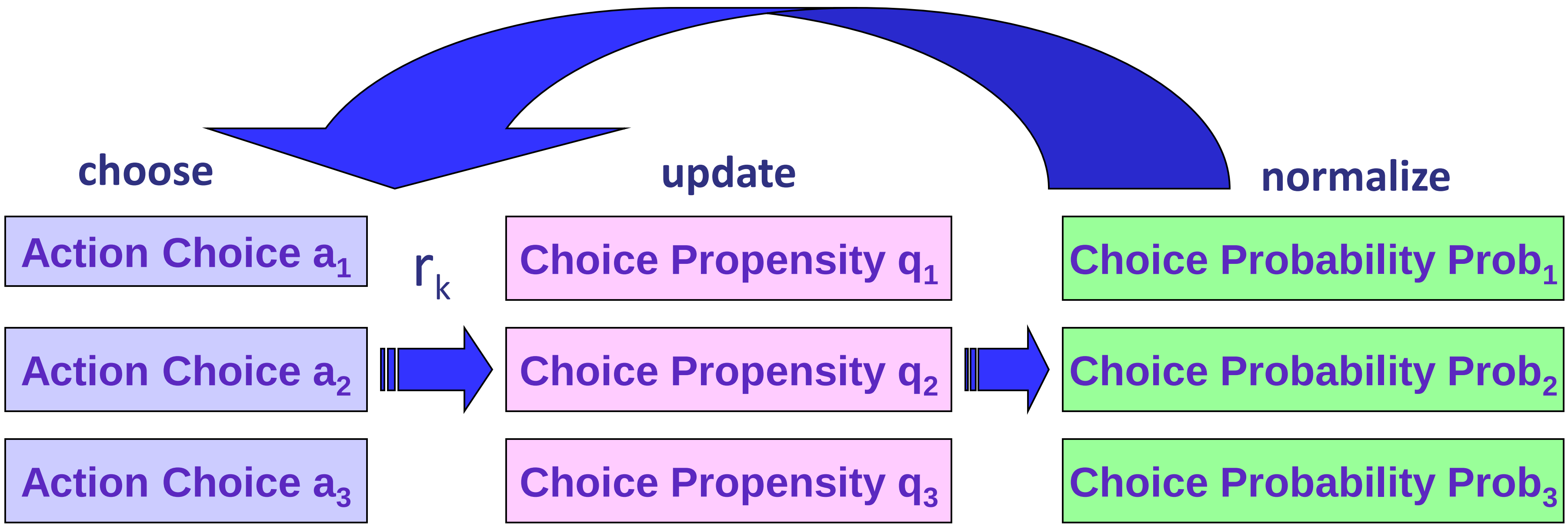
GenCo i's Action Domain

Collection of possible reported marginal cost functions

MC_i^R over possible reported operating capacity intervals



AMES(V2.02): GenCos Use VRE Reactive Reinforcement Learning



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

DC Optimal Power Flow (OPF) Module for AMES(V2.02)

GenCos report hourly supply offers and LSEs report fixed & price-sensitive hourly demand bids to the ISO for the Day-Ahead Market

Minimize

$$\sum_{i=1}^{I}[a_i^R p_{Gi} + b_i^R p_{Gi}^2] - \sum_{j=1}^{J}[c_j p_{Lj}^S - d_j {p_{Lj}^S}^2] + \pi \left[\sum_{km \in BR} [\delta_k - \delta_m]^2\right]$$

w.r.t. $\quad p_{Gi},\ i = 1, ..., I;\ p_{Lj}^S,\ j = 1, ..., J;\ \delta_k,\ k = 1, ..., K$

GenCo-reported total variable costs

LSE gross buyer surplus

Subject to

$$\sum_{i \in I_k} p_{Gi} - \sum_{j \in J_k} (p_{Lj}^F + p_{Lj}^S) - \sum_{km \text{ or } mk \in BR} B_{km}[\delta_k - \delta_m] = 0$$

$$|B_{km}[\delta_k - \delta_m]| \leq P_{km}^U$$

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

$$0 \leq p_{Lj}^S \leq SLMax_j$$

$$\delta_1 = 0$$

Fixed and price-sensitive sensitive demand bids for LSE j

Shadow price for this bus km balance constraint gives LMP for bus k

Operating capacity interval for GenCo i

Purchase capacity interval for LSE j

Illustrative Experimental Findings
AMES (V2.02)

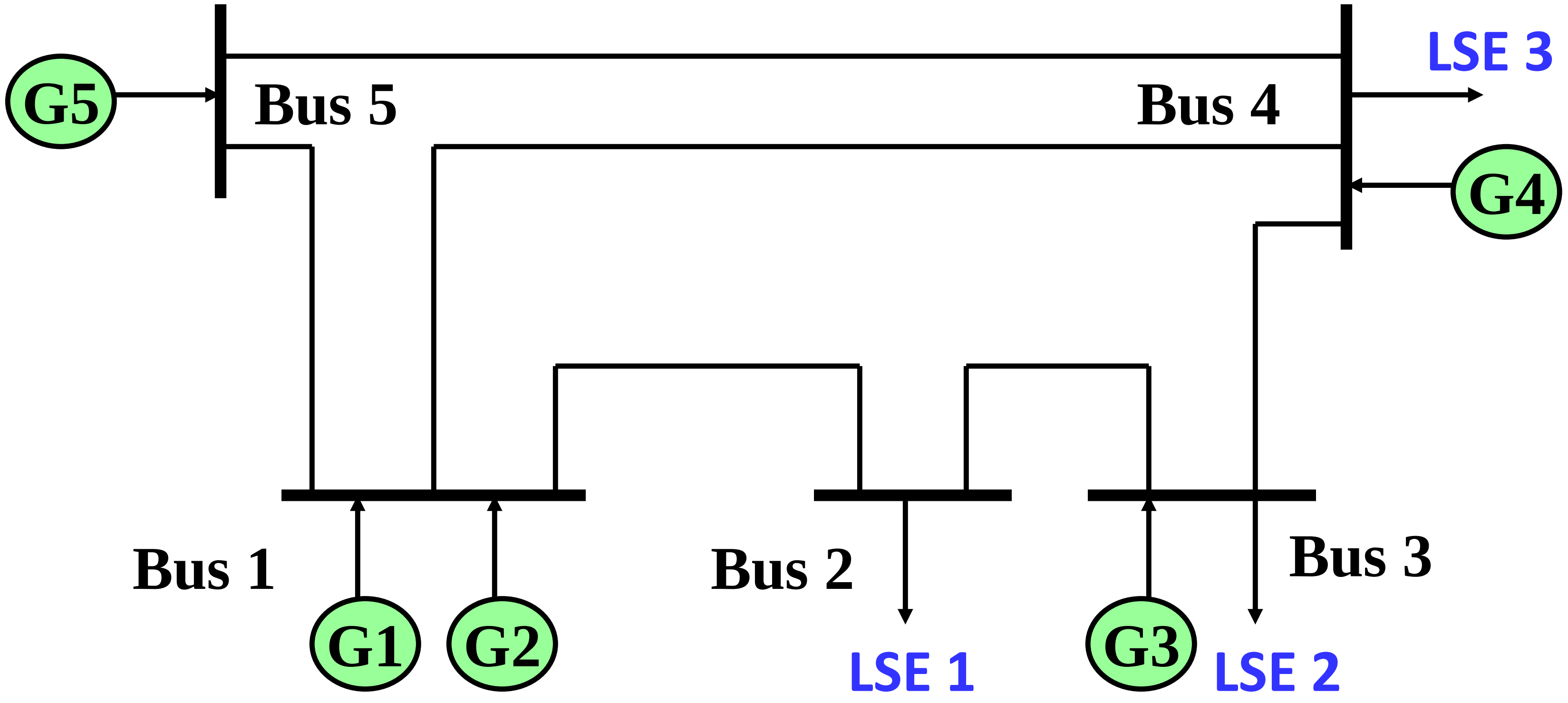
- H. Li, J. Sun, L. Tesfatsion, **"Separation and Volatility of Locational Marginal Prices in Restructured Wholesale Power Markets,"** ISU Econ WP No. 09009, June 2009.
  https://www2.econ.iastate.edu/tesfatsi/LMPSeparationVolatility.LST.pdf

- **Focus:** Dynamic LMP response and spatial LMP-GenCo supply offer correlations under a range of treatments:
  - **price-sensitivity** of LSE demand bids [0 to 100%)]
  - **learning capabilities** [absent or present]
  - **supply-offer price cap** [no cap, high cap, mod cap, low cap]

5-Bus Transmission Grid Test Case

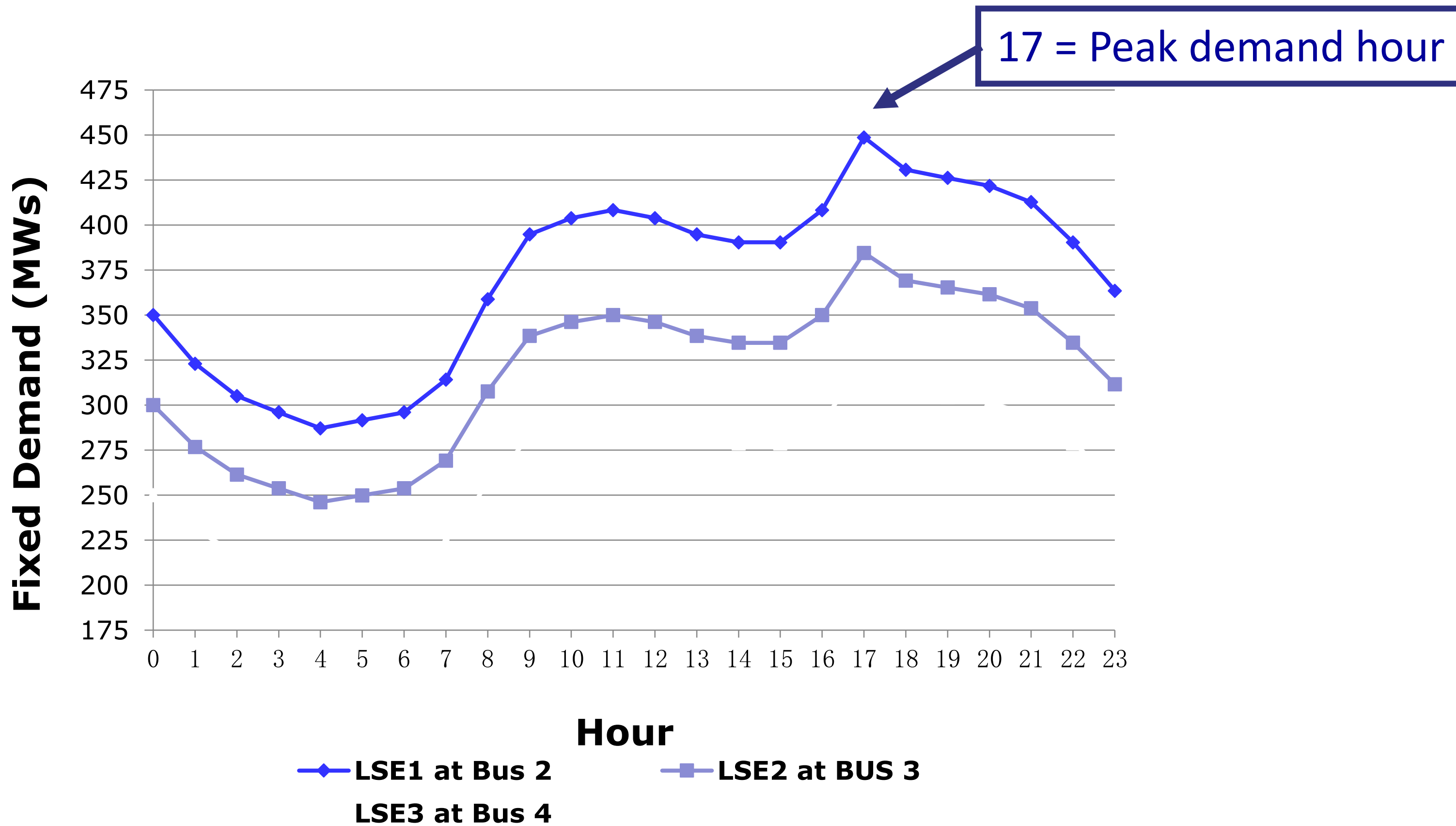
(John Lally Test Case used in many ISO business practice/training manuals)

Five power sellers G1,…,G5 and three power buyers LSE1, LSE2, LSE3:



Benchmark Case:

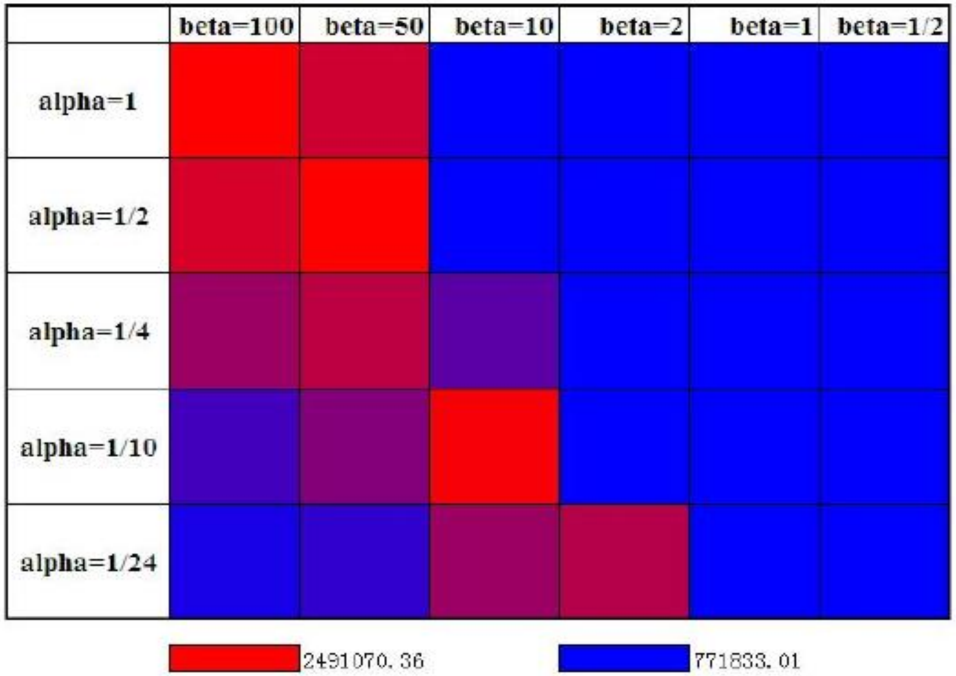
100% fixed demand, no Generation Company (GenCo) learning, and no imposed supply-offer price cap



Daily LSE Fixed Demand (Load) Profiles

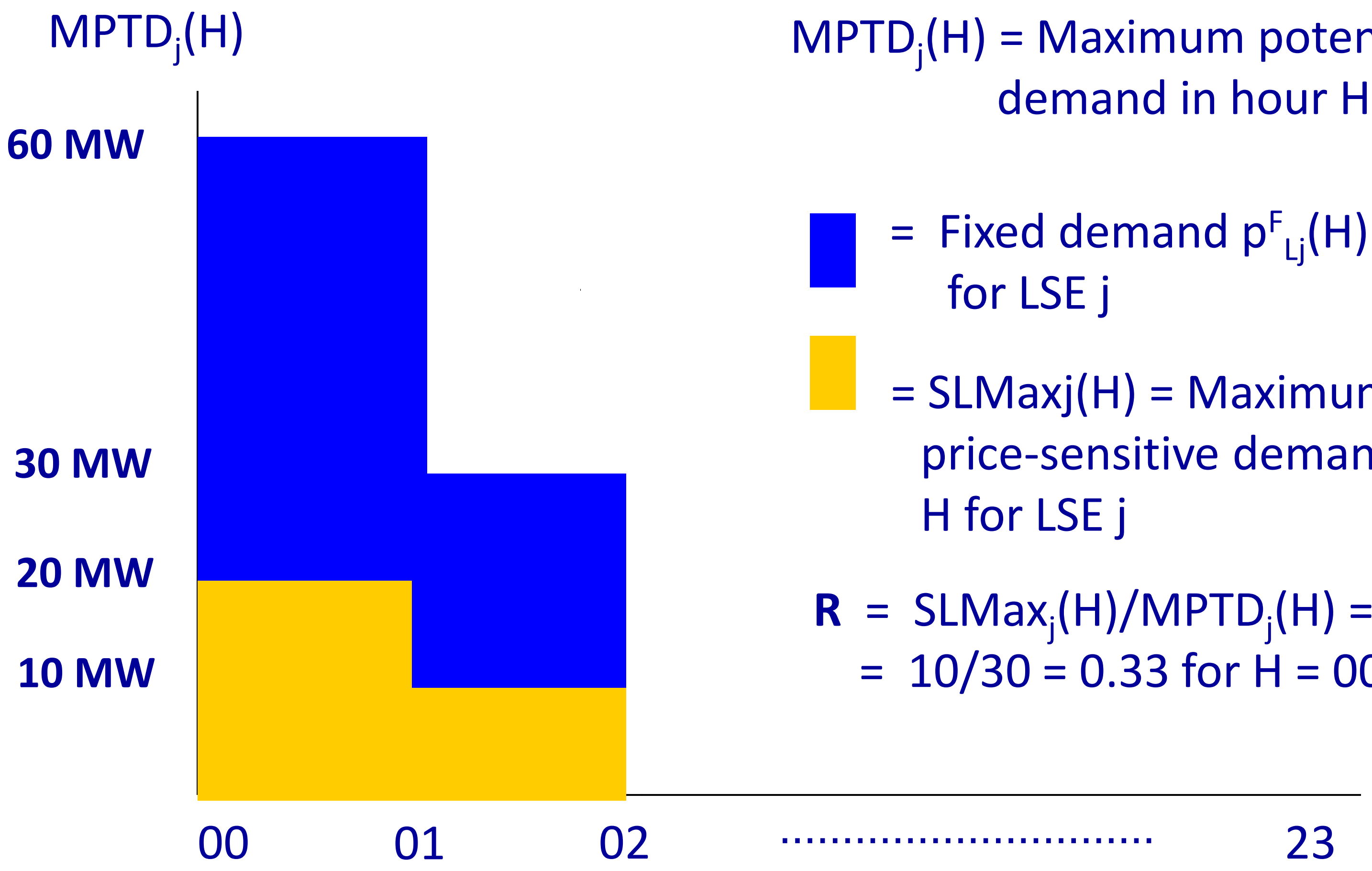
Initial Learning Calibration Experiments: GenCo "Sweet Spot" Learning

(red → highest net earnings)



A heat-map depiction of average daily net earnings (Avg DNE) outcomes under alternative (α,β) VRE learning parameter combinations.

Relative Demand-Bid Price Sensitivity Measure R from R=0.0 (0%) to R=1.0 (100%): Illustration for R=0.33



$MPTD_j(H)$ = Maximum potential total demand in hour H for LSE j

(Blue) = Fixed demand $p^F_{Lj}(H)$ in hour H for LSE j

(Yellow) = SLMaxj(H) = Maximum potential price-sensitive demand in hour H for LSE j

R = $SLMax_j(H)/MPTD_j(H)$ = 20/60 = 10/30 = 0.33 for H = 00,…,23

Lerner Index (LI): Measure of Market Power

- The LI for any GenCo i supplying a positive amount of power P_{Gi} is defined as follows:

$$\mathrm{LI}_i(P_{Gi}) = \frac{[\mathrm{LMP}_{k(i)} - \mathrm{MC}_i(\mathrm{P}_{Gi})]}{\mathrm{LMP}_{k(i)}}$$

Given binding capacity constraint on GenCo i, can have $\mathrm{LI}_i > 0$ ***without*** exercise of market power by GenCo i.

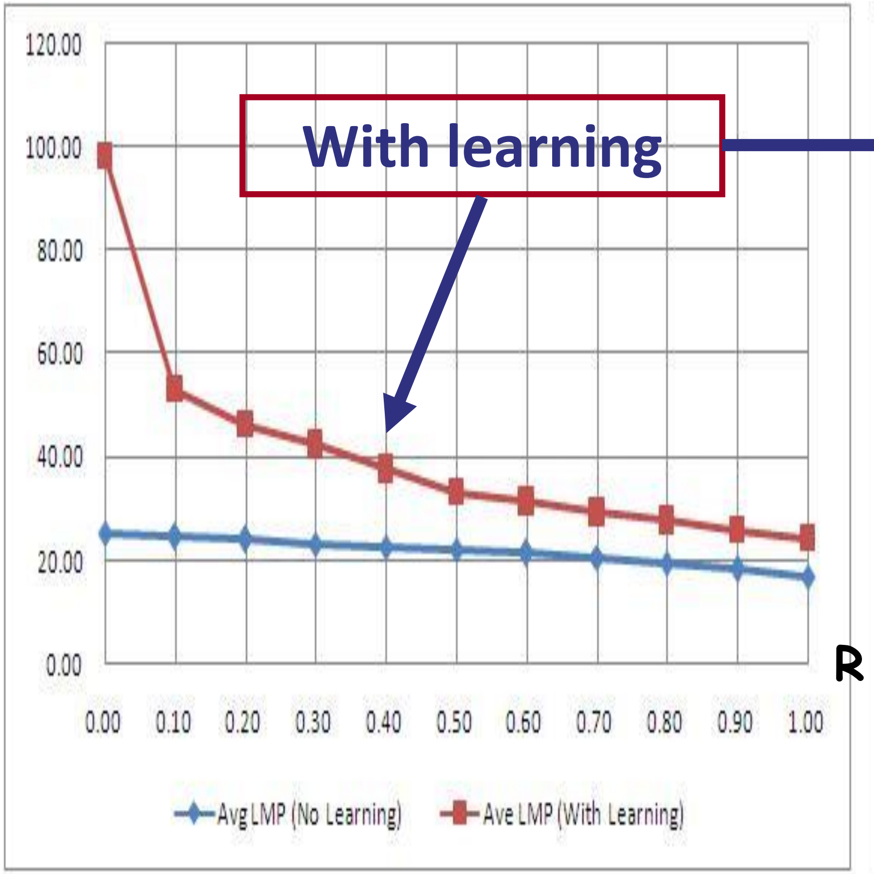
- Typically, LI measures are calculated on an hourly basis.

- LI is commonly used as a measure of ***Market Power***, defined for a GenCo as ability to affect market price in its own favor.

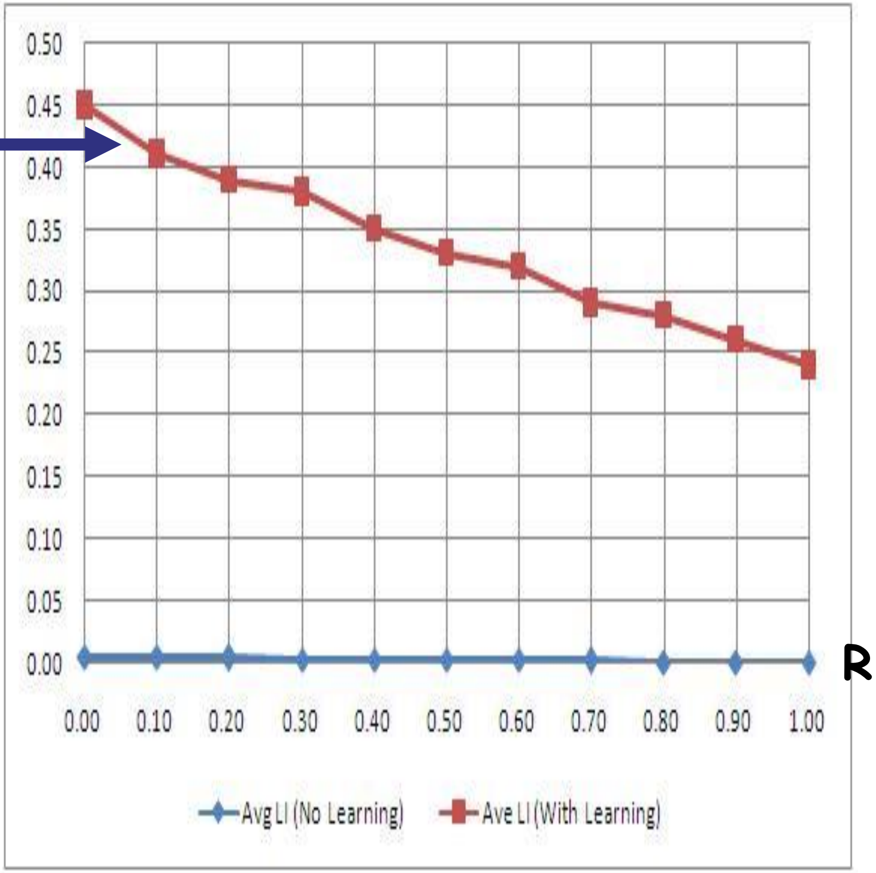
Average LMP and LI Levels as Demand-Bid Price Sensitivity Varies

from R=0.0 (0%) to R=1.0 (100%), both with and without GenCo Learning

Avg LMP (locational marginal price)



Avg LI (Lerner Index)



LMP Results with Price-Sensitive Demand Bids

with no supply-offer price cap & with/without GenCo learning

- **BOTTOM LINE:**

  Even with 100% price-sensitive demand bids (R=1),

  average prices are much higher under GenCo learning !

- **NEEDED:**

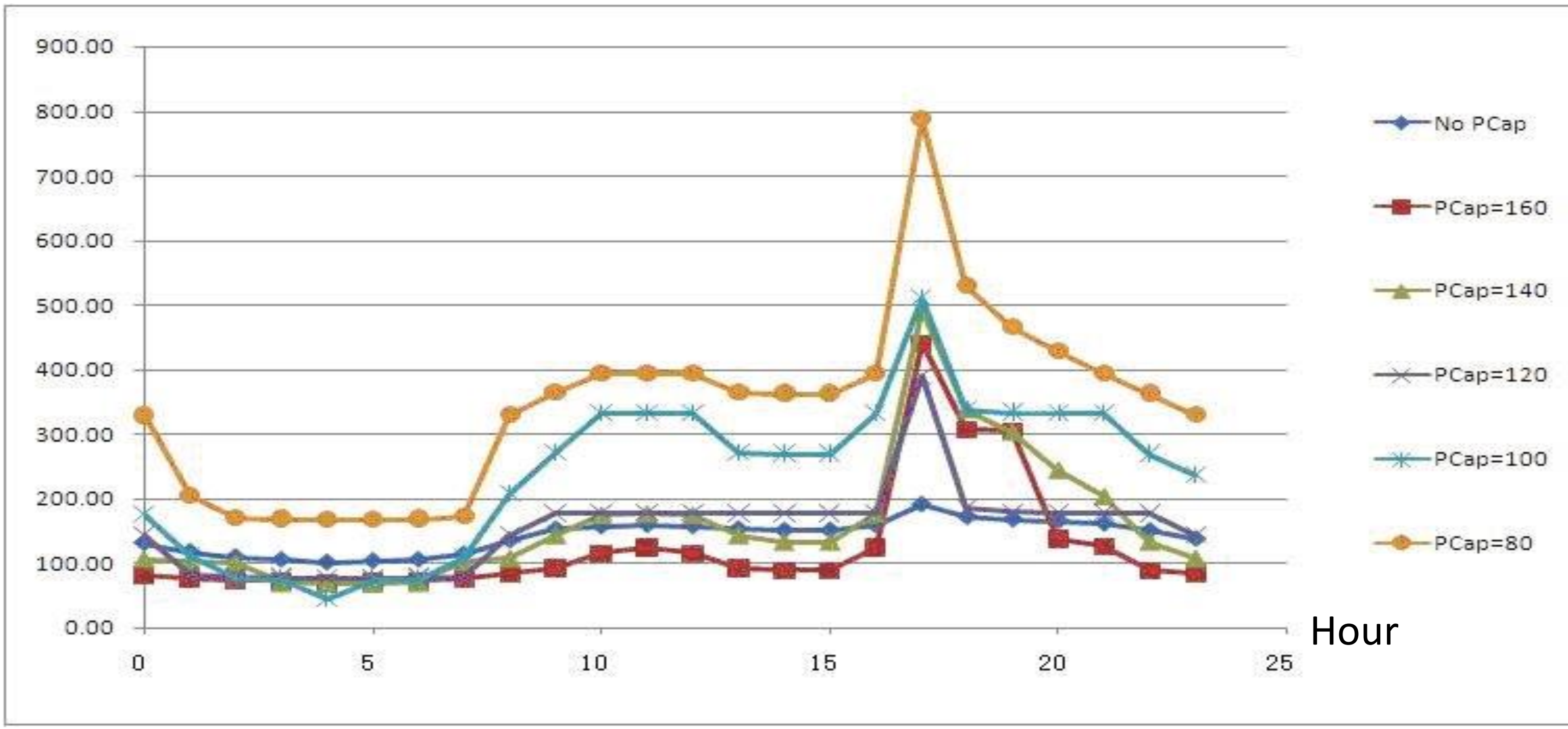
  Active demand-side bidding from LSEs reflecting better integration of wholesale/retail markets

  Countervailing power (active supply AND demand offers at wholesale level) could result in more competitive pricing.

Average LMP Under Varied Supply-Offer Price Caps

with 100% fixed demand and with GenCo Learning

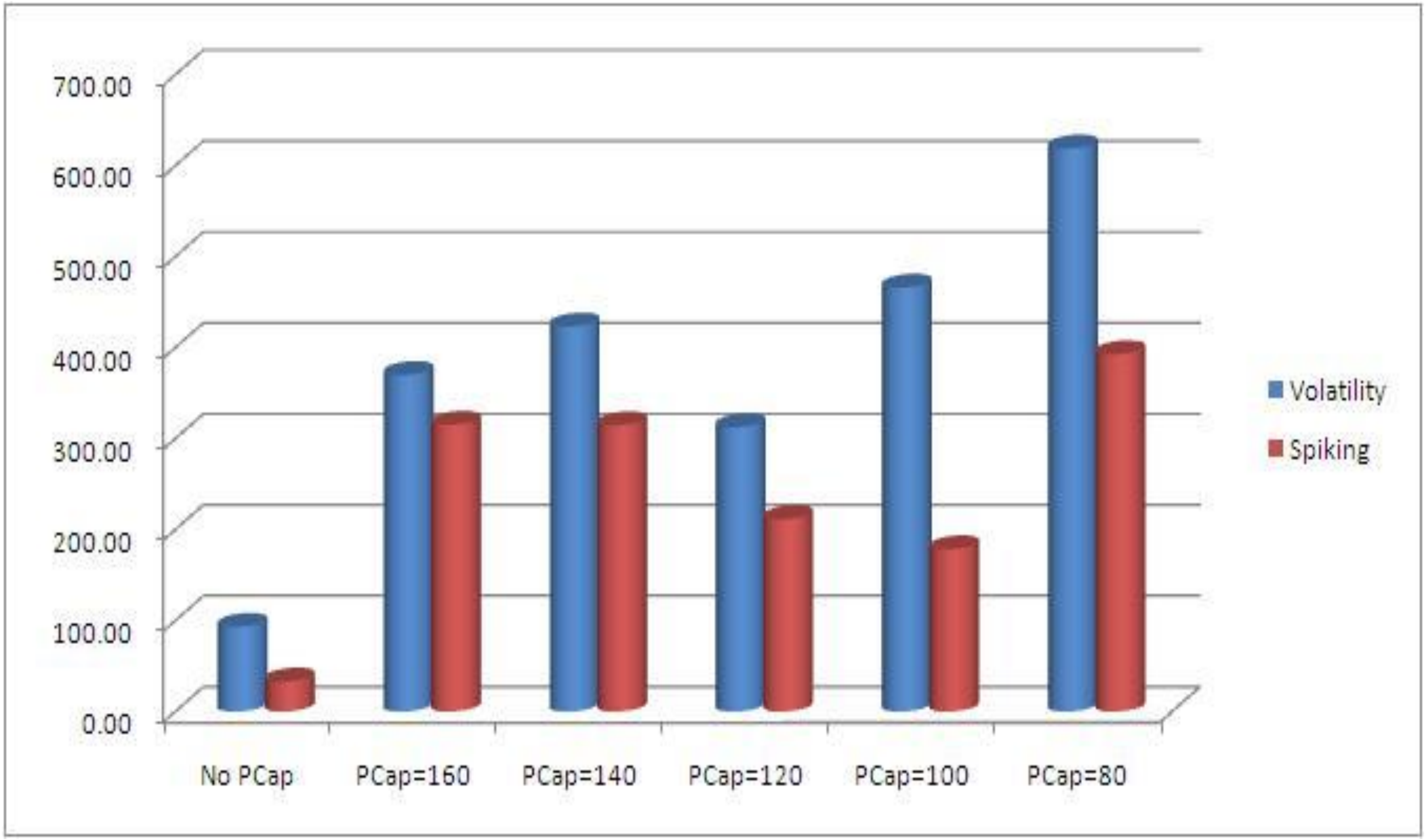
Avg LMP (locational marginal price)



NOTE: LMPs include $1000/MWh reserve price for hours in which offered supply is insufficient to meet demand (i.e., an “inadequacy event” occurs) .

Avg LMP Volatility/Spiking Under Supply-Offer Price Caps

with 100% fixed demand and with GenCo learning



Results for Varied Supply-Offer Price Caps

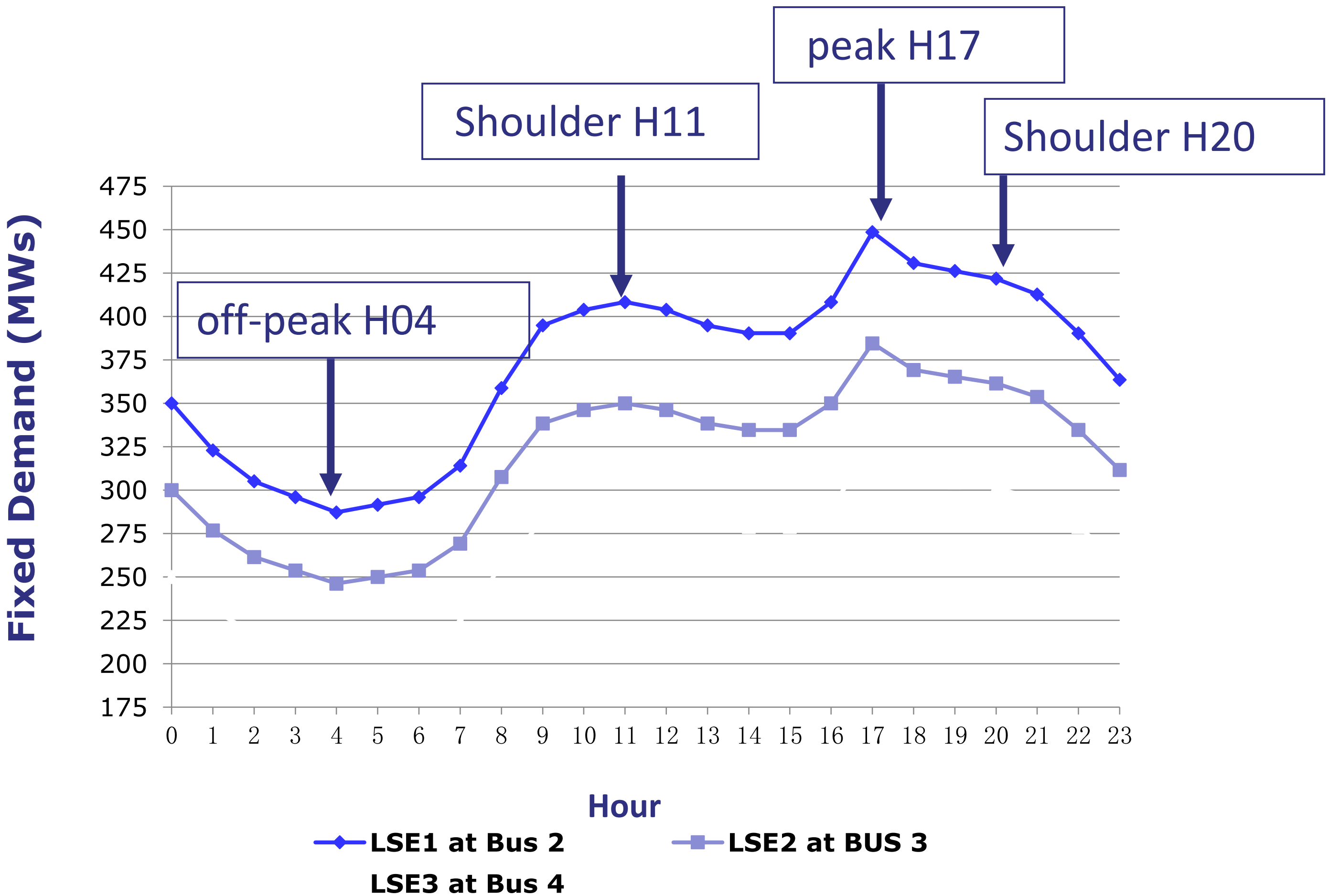
with 100% fixed demand and with GenCo learning

✸ **BOTTOM LINE:**

Supply-offer price caps can lead to increased LMP volatility/spiking and inadequacy events (S < D), especially around peak demand hours, even though average LMP declines!

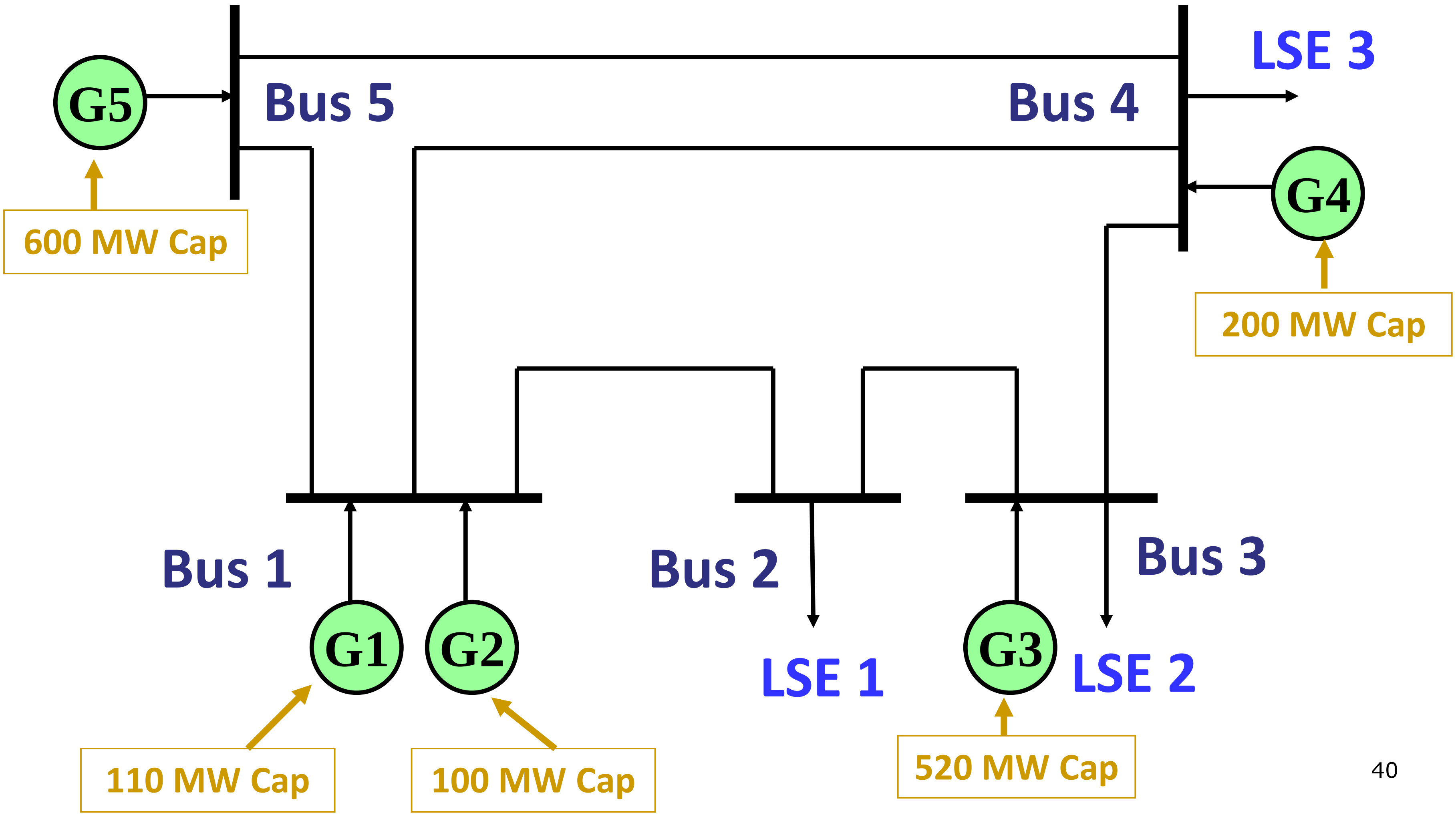
Daily LSE Fixed Demand (Load) Profiles:

Four Selected Hours for Cross-Correlation Studies



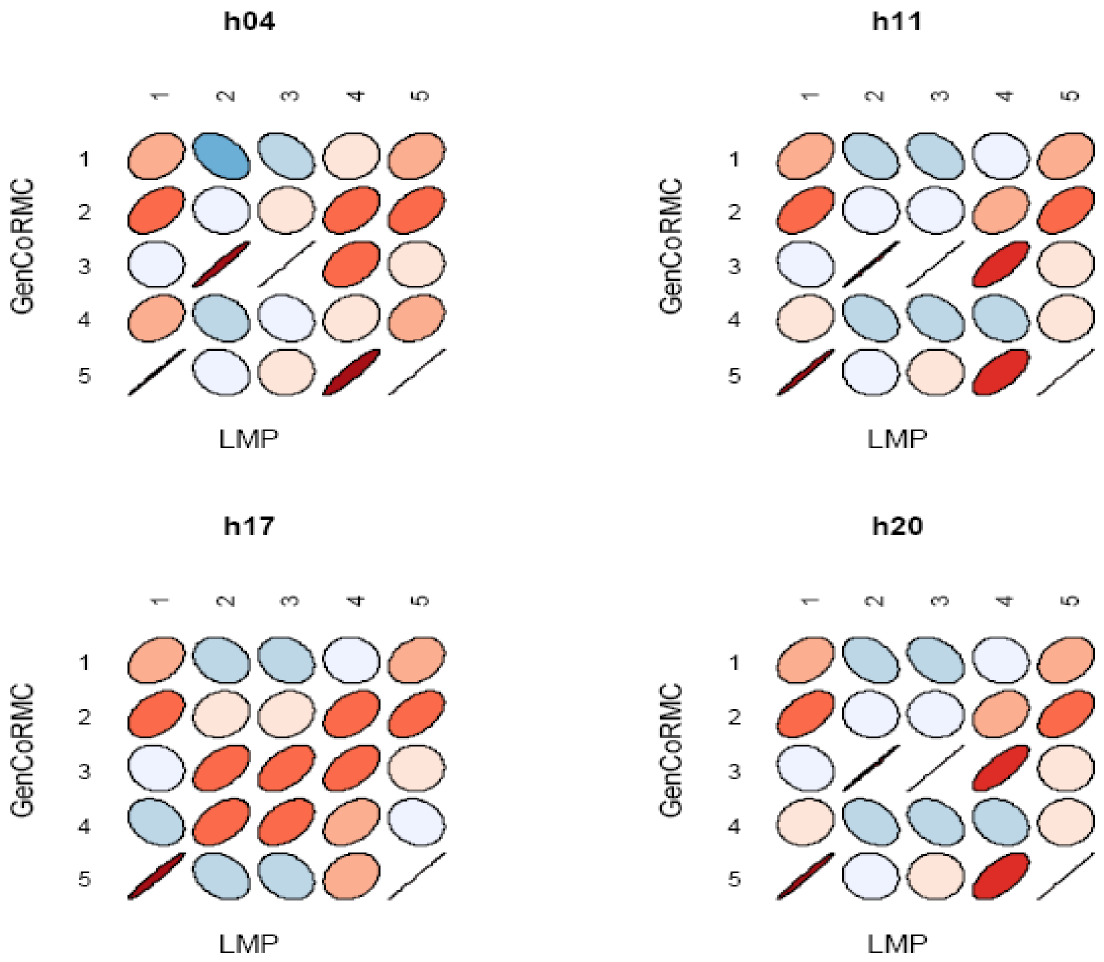
5-Bus Transmission Grid:

Largest GenCo = G5; Next Largest GenCo = G3

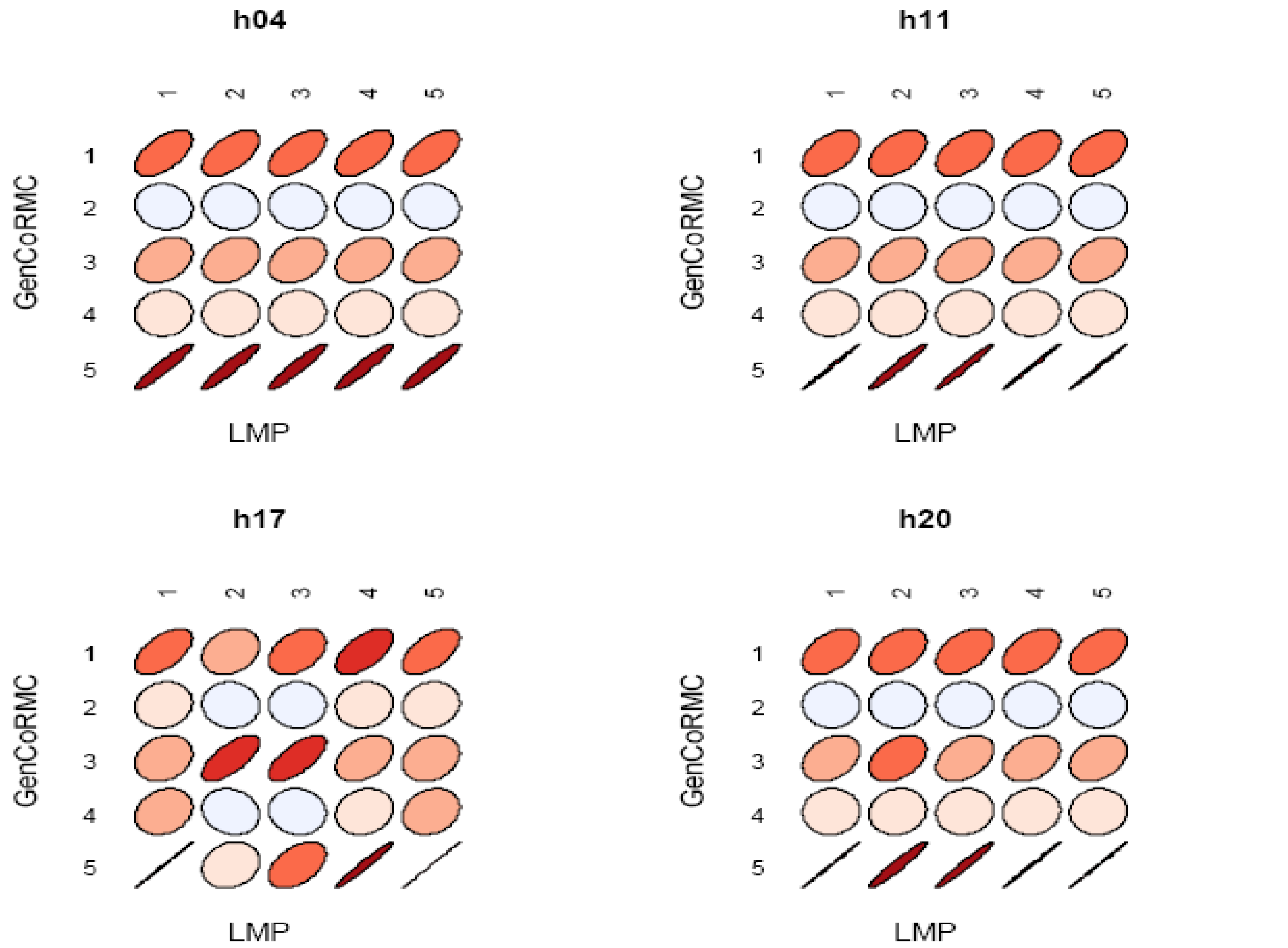


Correlations among GenCo-Reported MC and Bus LMPs with

100% fixed demand & GenCo learning

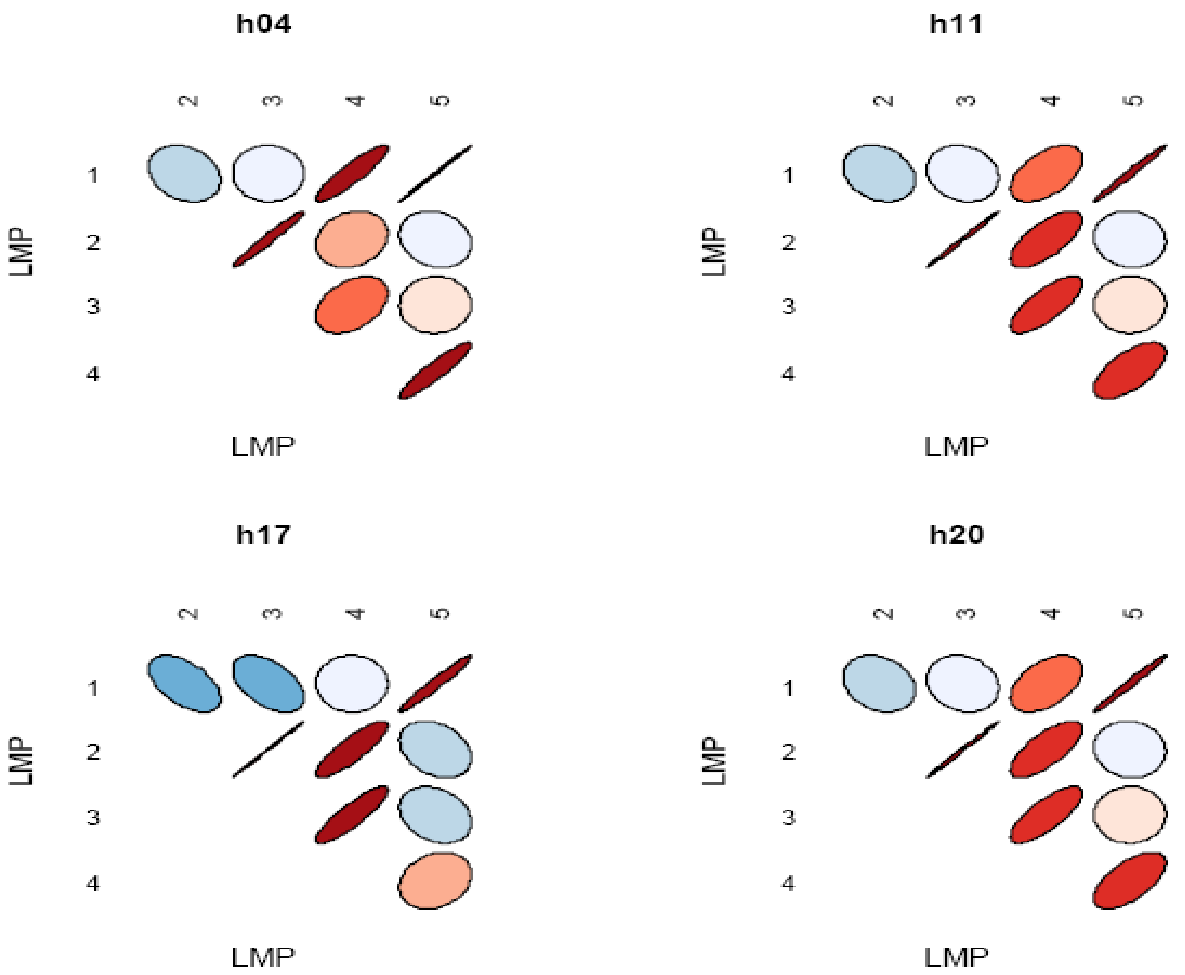


Correlations among GenCo-Reported MC and Bus LMPs with 100% price-sensitive demand & GenCo learning



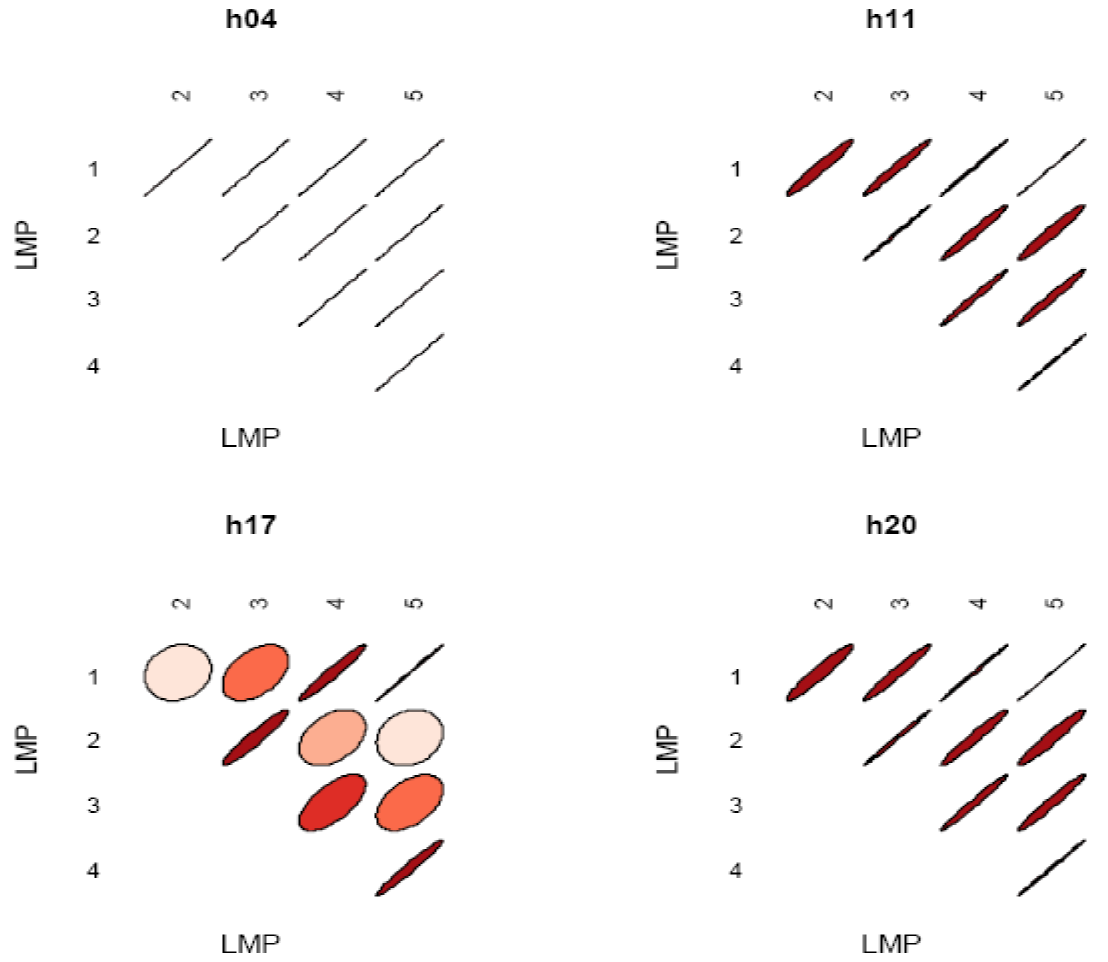
Correlations among Bus LMPs

with 100% fixed demand & GenCo learning



Correlations among Bus LMPs

with 100% price-sensitive demand & GenCo learning



MISO LMP Correlations between MidAmerican Energy Region & Neighboring Regions

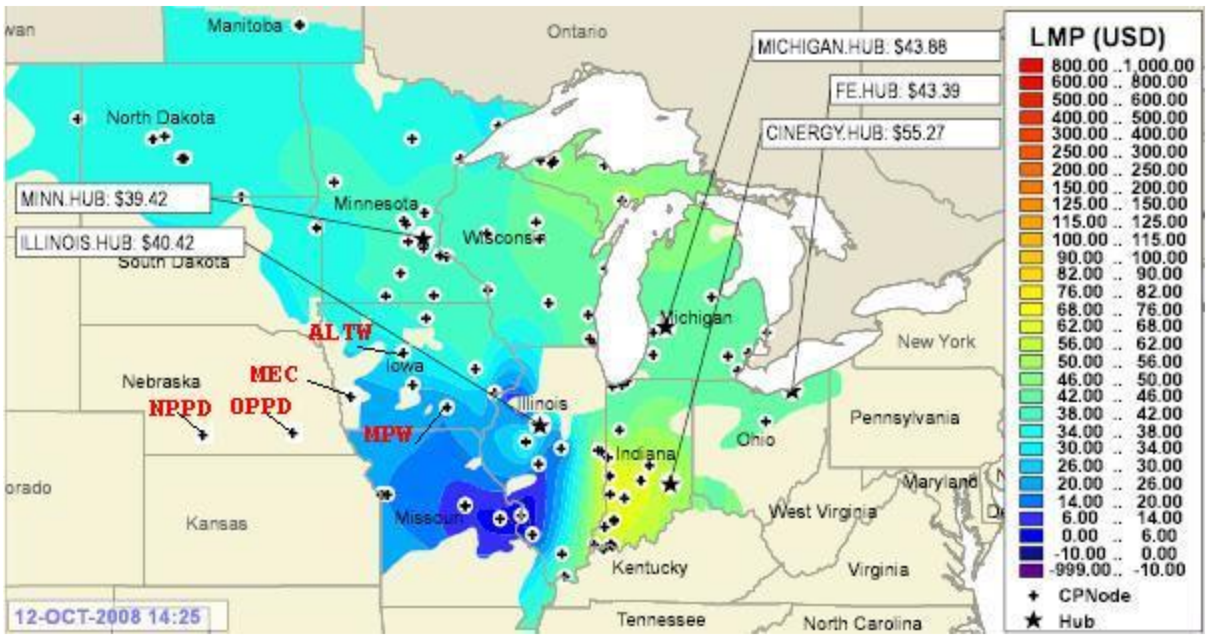


TABLE XXI

LMP Correlations Between the MidAmerican Energy (MEC) Balancing Authority and Neighboring Balancing Authorities for the MISO Day-Ahead and Real-Time Markets

	DA (8/1/2008)	DA (8/2/2008)	DA (8/3/2008)	DA (9/1/2008)	RT (8/1/2008)	RT (8/2/2008)	RT (8/3/2008)	RT (9/1/2008)
MEC-ALTW.MECB	0.998	0.997	0.999	1.000	0.994	0.971	0.974	1.000
MEC-MPW	0.996	0.994	0.998	1.000	0.996	0.970	0.973	1.000
MEC-OPPD	1.000	1.000	0.999	1.000	0.996	0.986	0.973	1.000
MEC-NPPD	0.998	0.998	0.995	0.998	0.983	0.930	0.824	1.000

Conclusions

- **Restructured wholesale power markets** are complex large-scale institutions encompassing physical constraints, administered rules of operation, and strategic human participants.
- **Agent-based test beds** permit the systematic dynamic study of such institutions through intensive computational experiments.
- For increased empirical validity, test beds should be **iteratively developed** with ongoing input from actual market participants.
- To increase usefulness for research/teaching/training and to aid knowledge accumulation, these test beds should be **open source**.

On-Line Resources

- **AMES Market Package Homepage (Code/Manuals/Pubs)**

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

- **Agent-Based Electricity Market Research**

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

- **Open-Source Software for Electricity Market Research, Teaching, and Training**

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