

Agent-Based Computational Economics

A Constructive Approach to Economic Theory

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Presentation Outline

- * What is ACE and why should anyone care?
- * Example 1: Simple ACE market design study
- * Example 2: Real-world ACE project
 - Development and implementation of an *ACE framework* to test the dynamic performance of U.S. wholesale power market designs
 - Illustrative 5-node transmission grid test case results with & without learning traders

ACE Resources

- ◆ ACE Website

www.econ.iastate.edu/tesfatsi/ace.htm

- ◆ ACE Handbook (Tesfatsion & Judd, Handbooks in Economics Series, North-Holland, 2006, 904pp)

www.econ.iastate.edu/tesfatsi/hbace.htm

HANDBOOKS IN ECONOMICS 13

**HANDBOOK OF
COMPUTATIONAL
ECONOMICS**

**AGENT-BASED COMPUTATIONAL
ECONOMICS**

VOLUME 2

**Editors:
Leigh Tesfatsion
Kenneth L. Judd**



NORTH-HOLLAND

What is ACE?

- ◆ Computational study of economic processes as **dynamic systems of interacting agents**
- ◆ A **culture-dish approach** to the study of economic processes

ACE Culture-Dish Analogy

- ◆ Modeler constructs a virtual economic world populated by various **agent types**
- ◆ Modeler sets **initial world conditions**
- ◆ Modeler then steps back to observe how the **world develops over time** without intervention (no imposed equilibrium, rational expectations, etc.)
- ◆ World events are **driven by agent interactions**

ACE Agent Types

Agents = Encapsulated software programs representing individual, social, biological and/or physical entities

* **Cognitive agents** are capable (in various degrees) of

- **Adaptation**
- **Social communication**
- **Goal-directed learning**
- **Autonomy** (self-activation and self-determinism based on private internal processes)

* Behaviour & interaction patterns can **develop/evolve**

Four Main Strands of ACE Research

- ▣ **Empirical Understanding**
(e.g. possible explanations for observed macro patterns)
- ▣ **Qualitative Insight/Theory Generation**
(e.g. self-organization of decentralized markets)
- ▣ **Normative Understanding**
(e.g. market design)
- ▣ **Methodological Advancement**
(e.g. representation, visualization, empirical validation)

ACE and Market Design

Key Issue: Does the design ensure **efficient, fair, and orderly market outcomes over time** despite efforts to exploit it for individual gain?

ACE Approach:

- ◆ Construct an **agent-based world** capturing salient aspects of the market design.
- ◆ Introduce **self-interested traders with learning capabilities**. Let world evolve multiple times. Observe/evaluate market outcomes.

Example 1: Study of a Relatively Simple Double-Auction Electricity Market Design

- ◆ J. Nicolaisen, V. Petrov, L. Tesfatsion, *IEEE Transactions on Evolutionary Computation*, 5(5), 2001, pp. 504-523 (C++/MatLab)

- ◆ **Key Issue Addressed:**

Relative role of **structure vs. learning** in determining performance of a double-auction design for a day-ahead electricity market.

Agent-Based Electricity Research

(www.econ.iastate.edu/tesfatsi/aelect.htm)

- Argonne National Lab (Boyd, Cirillo, Conzelmann, Koritarov, Macal, North, Thimmapuram, Veselka,...)
- Carnegie Mellon U (Hines, Illic, Talukdar,...)
- CSIRO-Australia (Batten,...)
- Helsinki University (Hamalainen,...)
- Iowa State U (Liu, McCalley, Sun, Tesfatsion,...)
- London/Warwick Bus. Sch. (Bunn, Day, Oliveira,...)
- Los Alamos National Lab (Flaim,...)
- Pacific Northwest National Lab (Fathelrahman, Roop, Widergren,...)
- Sandia National Lab (NISAC/N-ABLE group,...)

Key Issues We Address

* Sensitivity of market performance to changes in **market structure:**

RCON = Relative seller/buyer **concentration**

RCAP = Relative demand/supply **capacity**

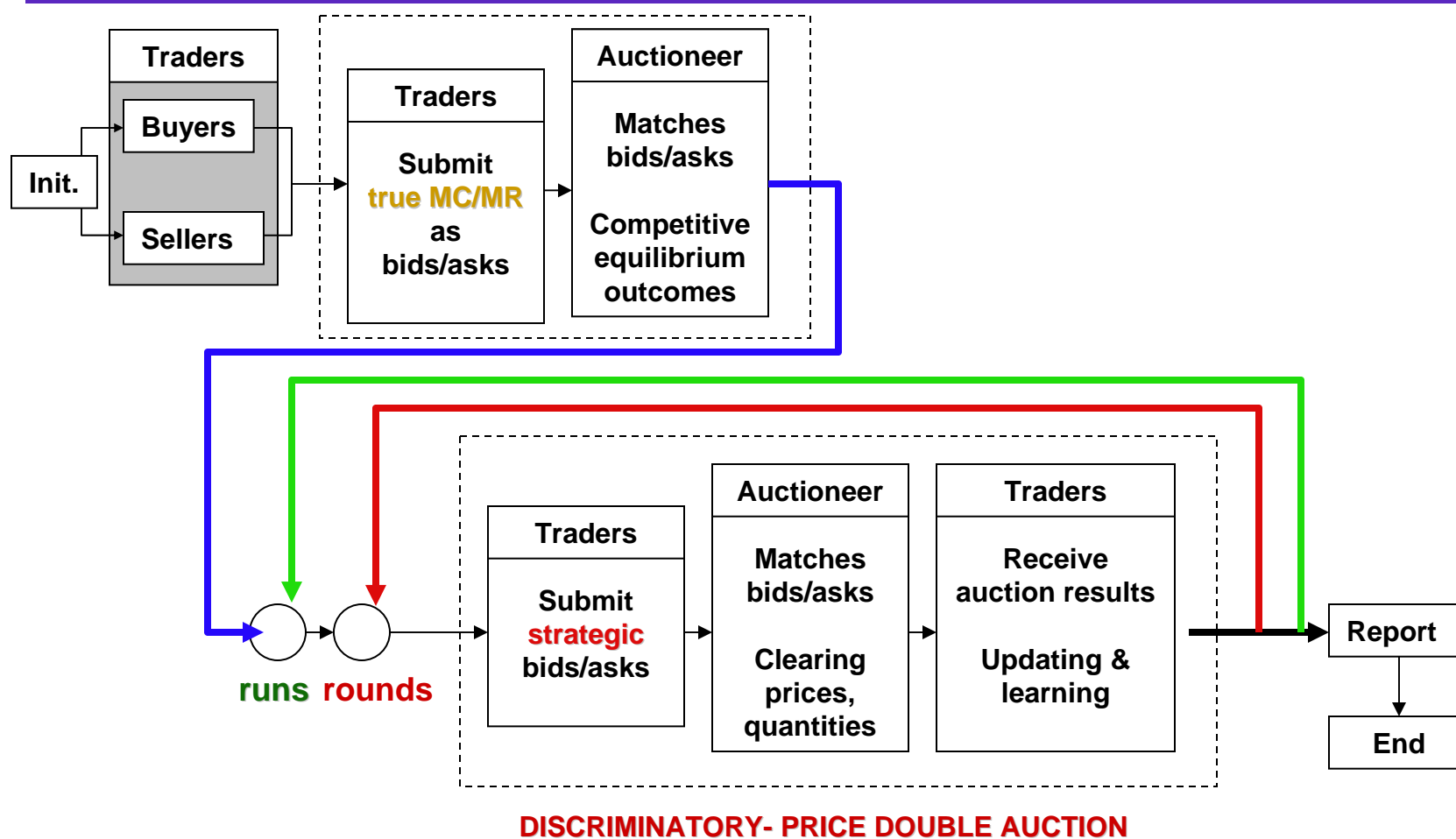
* Sensitivity of market performance to changes in **trader learning:**

Individual learning via **Reinforcement Learning (RL)**

Social mimicry via **Genetic Algorithms (GAs)**

Dynamic Activity Flow for the Double Auction

COMPETITIVE EQUILIBRIUM CALCULATION

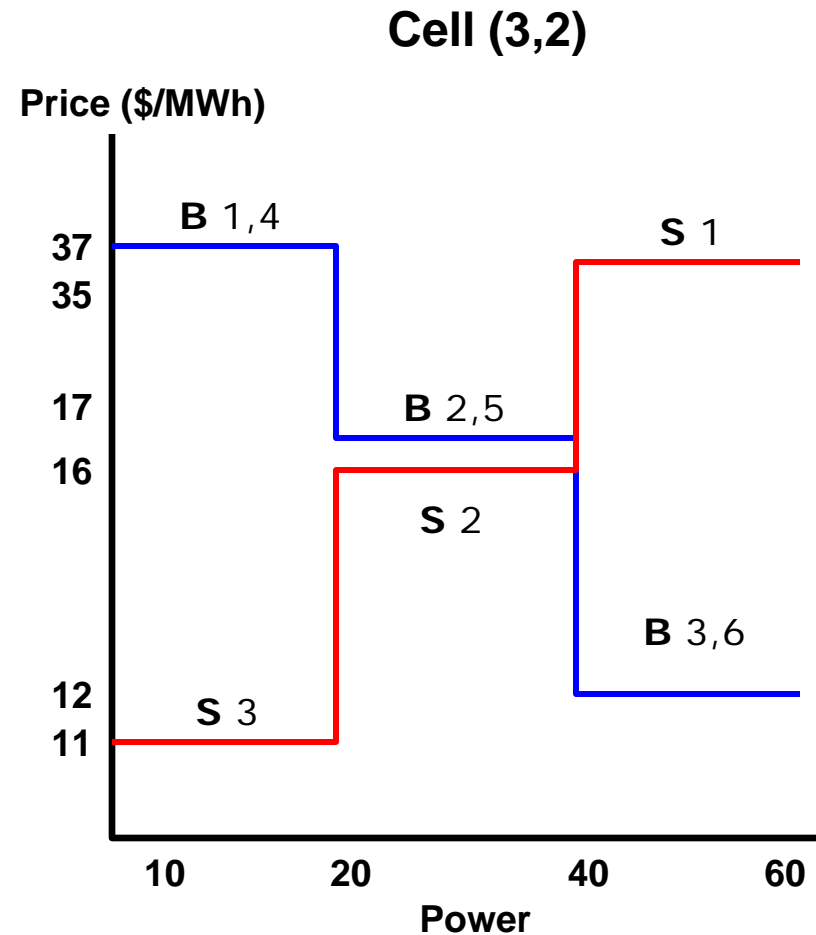
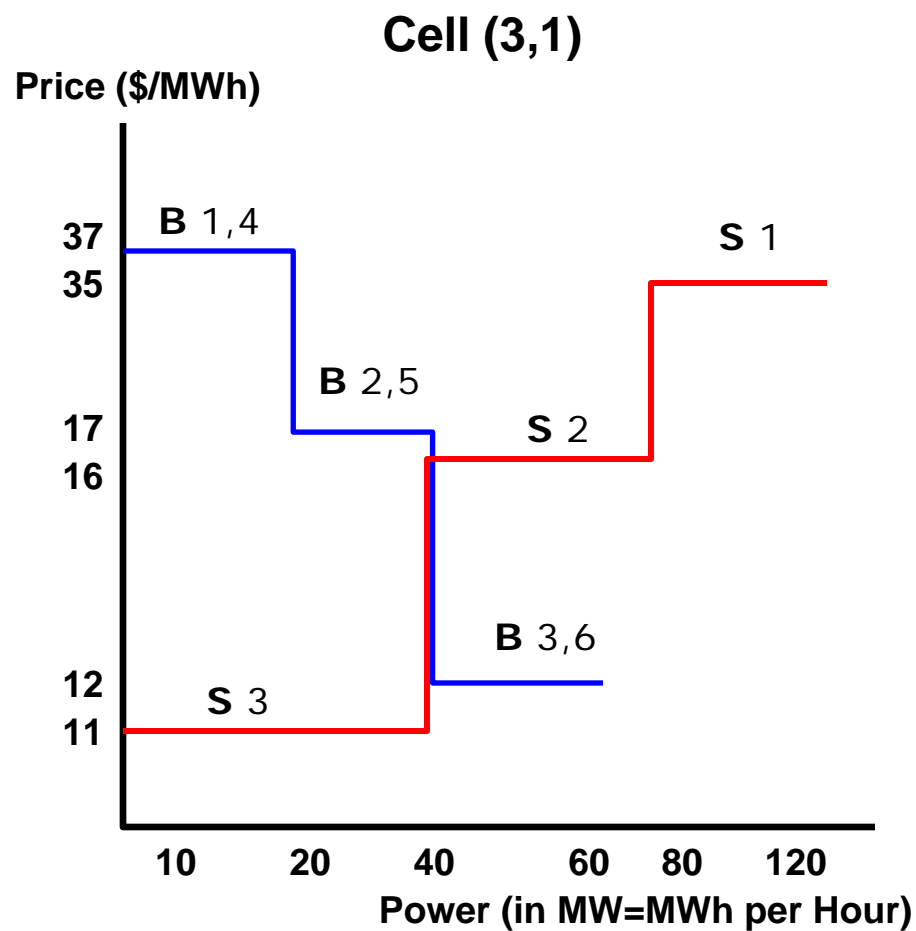


Structural Treatment Factor Values (tested for each learning treatment)

Ns = Number of Sellers
Nb = Number of Buyers
Cs = Seller Supply Capacity
Cb = Buyer Demand Capacity

		RCAP		
		1/2	1	2
R C O N	2	Ns = 6 Nb = 3 Cs = 10 Cb = 10	Ns = 6 Nb = 3 Cs = 10 Cb = 20	Ns = 6 Nb = 3 Cs = 10 Cb = 40
	1	Ns = 3 Nb = 3 Cs = 20 Cb = 10	Ns = 3 Nb = 3 Cs = 10 Cb = 10	Ns = 3 Nb = 3 Cs = 10 Cb = 20
	1/2	Ns = 3 Nb = 6 Cs = 40 Cb = 10	Ns = 3 Nb = 6 Cs = 20 Cb = 10	Ns = 3 Nb = 6 Cs = 10 Cb = 10

Aggregate True Demand and Supply per Hour



The Computational World

Public Access:

// **Public Methods**

The *World Event Schedule*, i.e., a system clock that permits inhabitants to time and synchronize activities (e.g., submission of asks/bids into the DA market);
Protocols governing trader collusion;
Protocols governing trader insolvency;
Methods for receiving data;
Methods for retrieving World data.

Private Access:

// **Private Methods**

Methods for gathering, storing, and sending data;

// **Private Data**

World attributes (e.g., spatial configuration);
World inhabitants (DA market, buyers, sellers);
World inhabitants' methods and data.

The Computational DA Market

Public Access:

// **Public Methods**

getWorldEventSchedule(clock time);
Protocols governing the public posting of asks/bids;
Protocols governing matching, trades, and settlements;
Methods for receiving data;
Methods for retrieving Market data.

Private Access:

// **Private Methods**

Methods for gathering, storing, and sending data.

// **Private Data**

Data recorded about sellers (e.g., seller asks);
Data recorded about buyers (e.g., buyer bids);
Address book (communication links).

A Computational DA Trader

Public Access:

// **Public Methods**

getWorldEventSchedule(clock time);
getWorldProtocols (collusion, insolvency);
getMarketProtocols (posting, matching, trade, settlement);
Methods for receiving data;
Methods for retrieving Trader data.

Private Access:

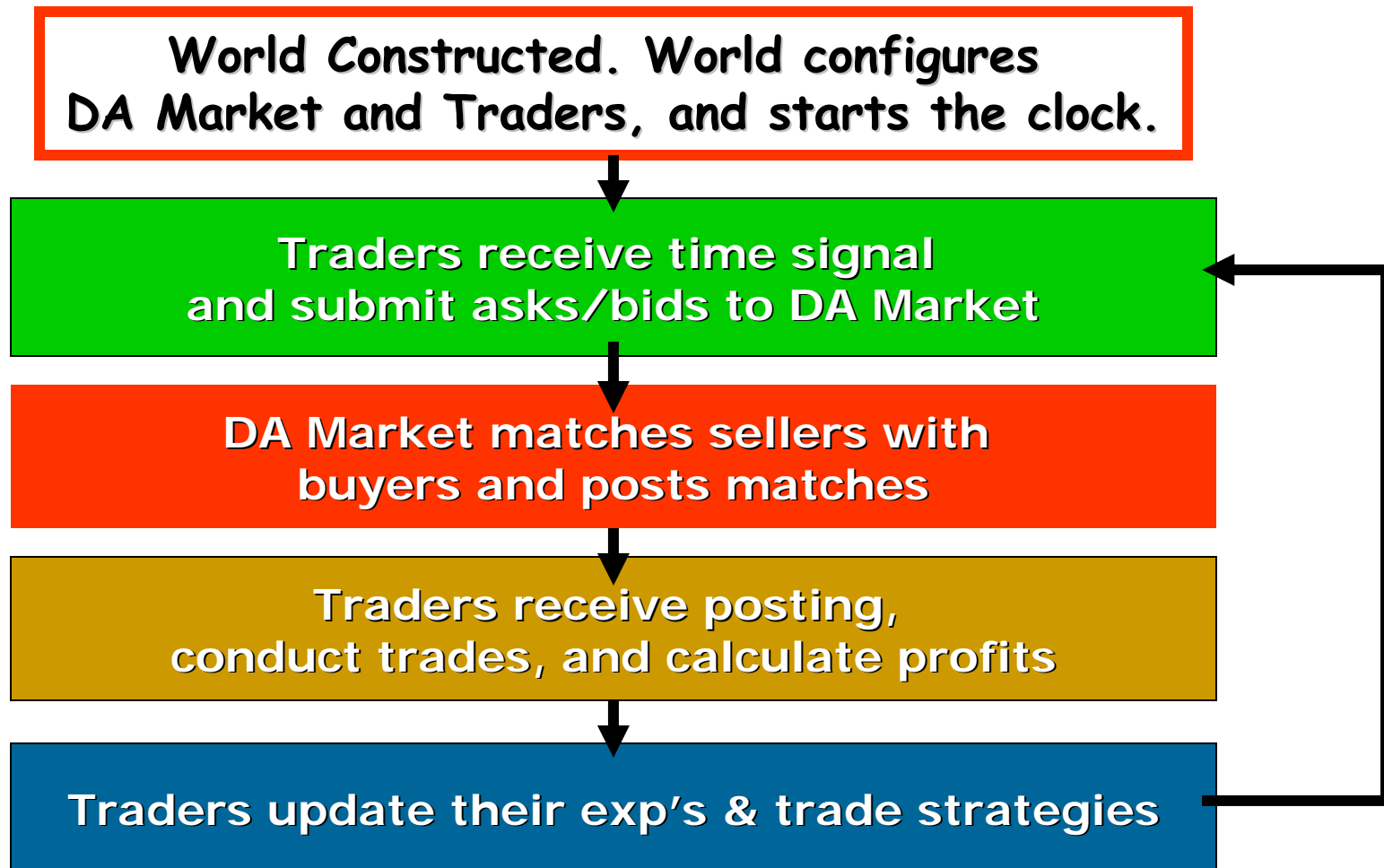
// **Private Methods**

Methods for gathering, storing, and sending data;
Methods for calculating expected & actual profit outcomes;
Method for updating my ask/bid strategy (**LEARNING**).

// **Private Data**

Data about me (history, profit function, current wealth,...);
Data about external world (rivals' asks/bids, ...);
Address book (communication links).

Dynamic Flow of DA Market



Summary of Policy-Relevant DA Findings

- **Market Efficiency:** Generally high when traders use Roth-Erev individual RL but not when traders use GA social mimicry (*type of learning can matter*).
- **Structural Market Power:** Microstructure of the DA market is strongly predictive for the relative market power of traders (*rule details matter*).
- **Strategic Market Power:** Traders are not able to change their relative market power through learning (*importance of countervailing power*).

Example 2: A Real-World Market Design Project

Dynamic Testing of Wholesale Power Market Designs: An Open-Source Agent-Based Framework

Joint research by

Junjie Sun

(Economics Ph.D. Candidate, ISU)

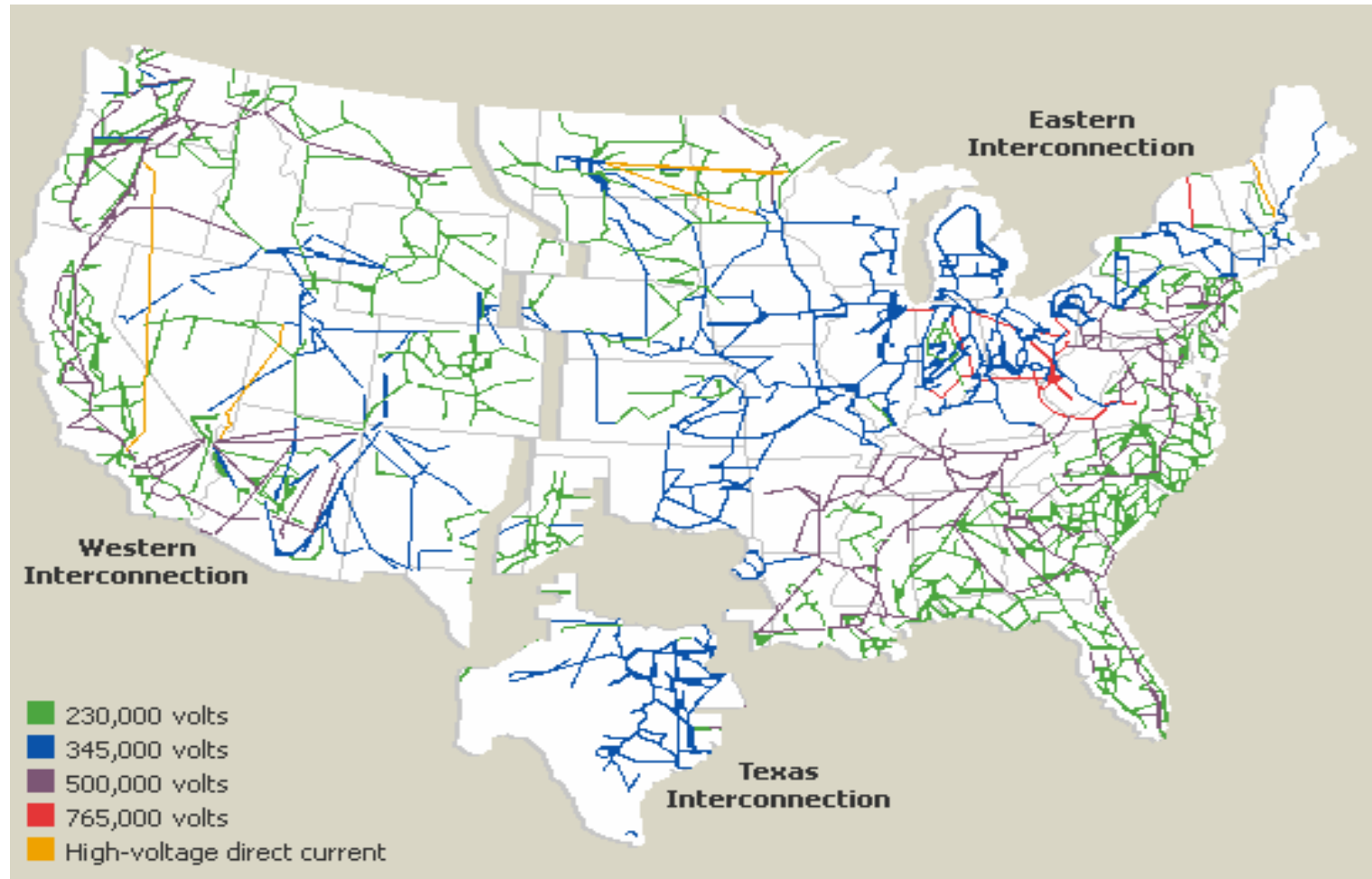
Leigh Tesfatsion

(Professor of Economics and Mathematics, ISU)

funded in part by the
**National Science Foundation, the
ISU Electric Power Research Center, & Alliant Energy**

Work in Progress

U.S. Wholesale Electric Power Grid



Project Context

- ❑ In April 2003, U.S. FERC proposed a **Wholesale Power Market Platform (WPMP)** for common adoption by all U.S. wholesale power markets
- ❑ About 50% of electric power generating capacity in the U.S. is now operating under some version of the WPMP market design

Our Basic Project Goal: Systematically examine dynamic performance of the WPMP market design as implemented in the U.S.

FERC's WPMP: Core Features

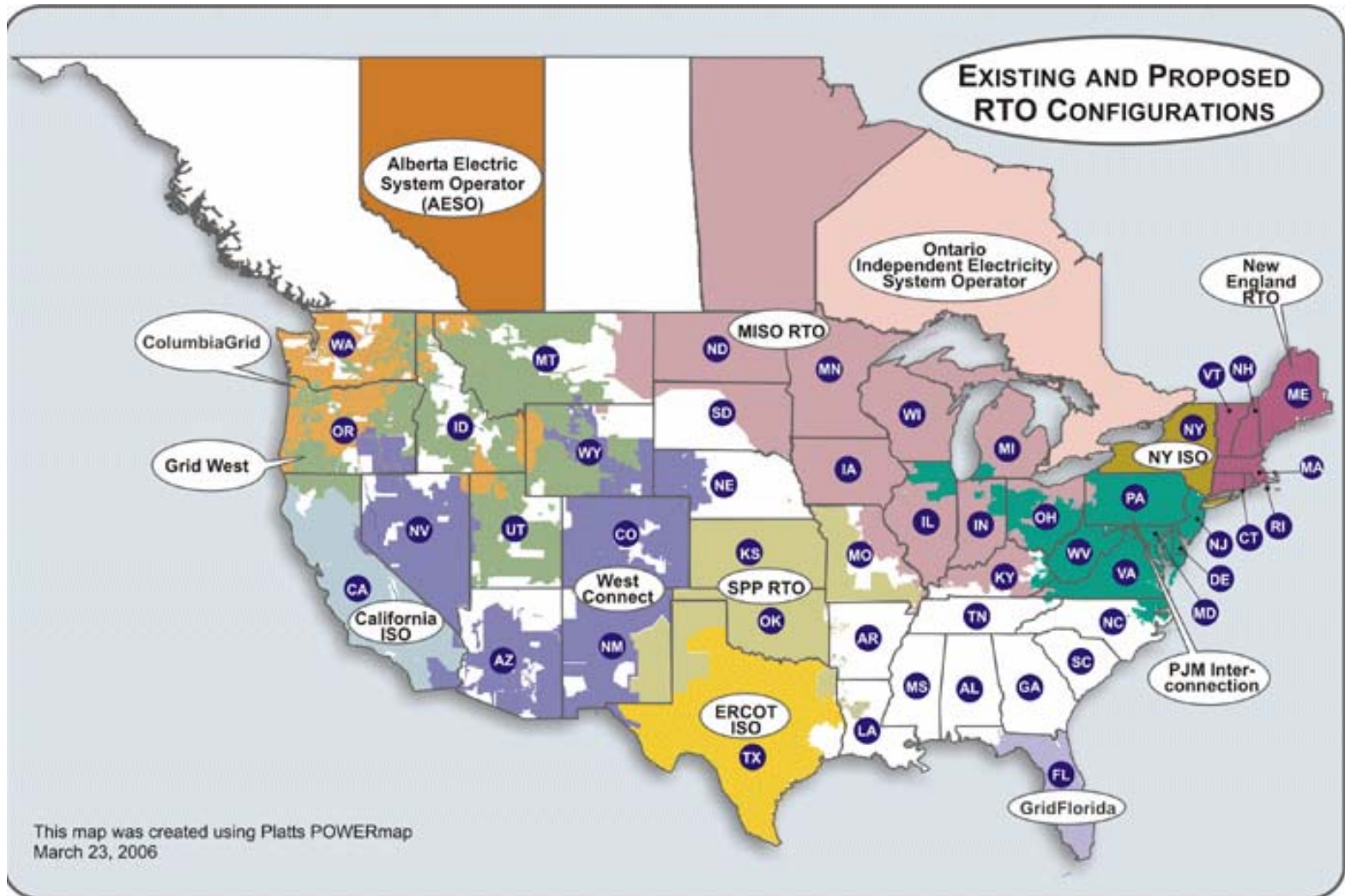
- Independent System Operator (ISO) or Regional Transmission Organization (RTO)
- Day-ahead & real-time markets for power
- Congestion managed via Locational Marginal Pricing (LMP)
- Financial transmission rights (FTRs)
- ISO oversight & market power mitigation

FERC's WPMP Design Adopted in U.S.?

- Mid-Atlantic (PJM) implements similar plan (1998)
- New York (NYISO) implements similar plan (1999)
- New England (ISO-NE) implements similar plan (2003)
- California (CAISO) files to adopt version (2003)
- Midwest (MISO) **files to adopt** version (7/2003), **withdraws filing** (10/2003), **refiles** (3/2004), and then **adopts** design (4/2005)
- Southwest (SPP) adopts version (5/2006)
- **Opposition** from states in Southeast and Northwest

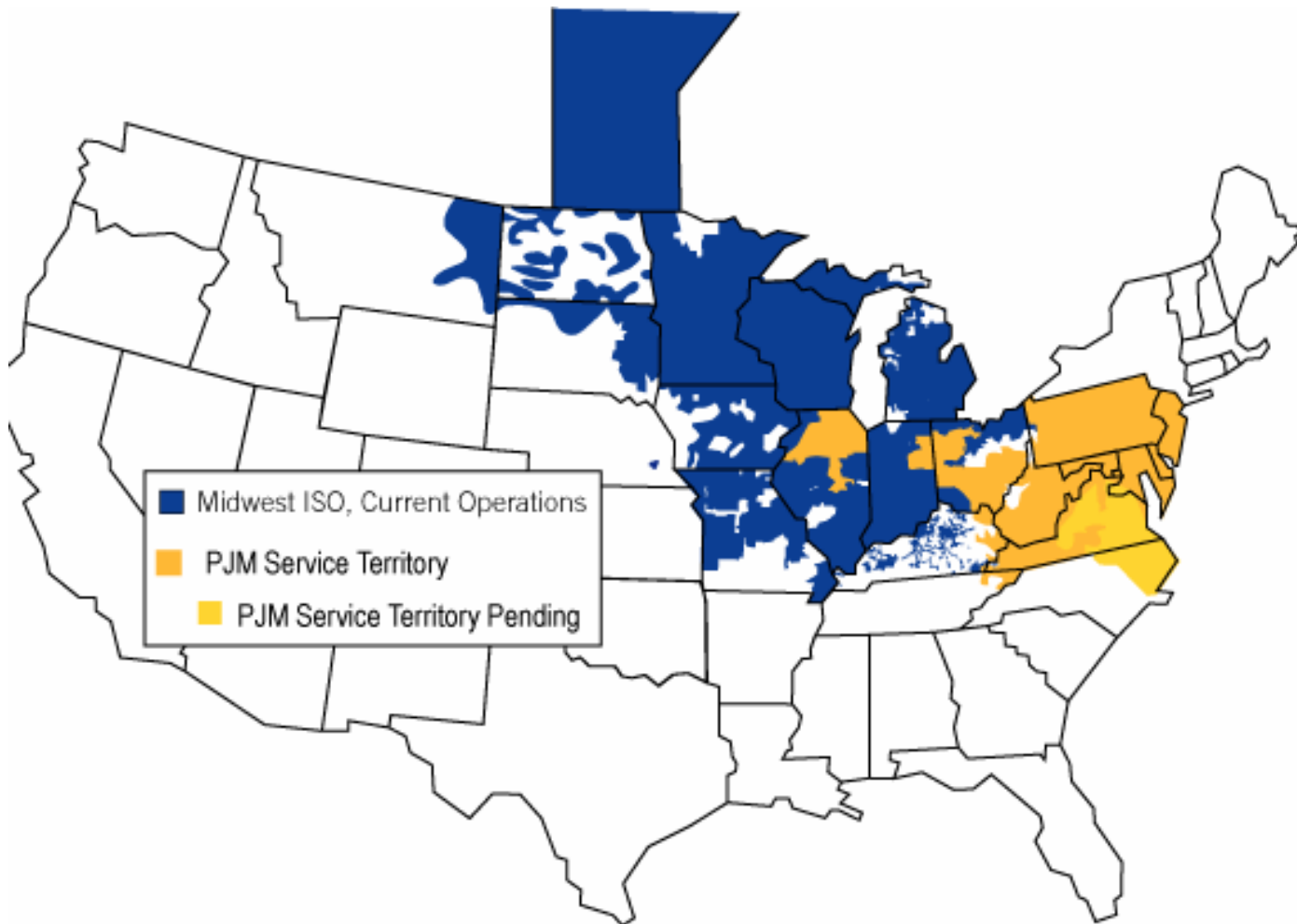
Existing and Proposed ISO/RTO Regions

<http://www.ferc.gov/industries/electric/indus-act/rto/rto-map.asp>



Midwest ISO - PJM Interconnection

<http://www.miso-pjm.com/>



Why Resistance to FERC's WPMP Market Design Proposal?

- **Stakeholders in Midwest**

A key cited problem:

Lack of sufficient performance testing.

- **Stakeholders in Southeast and Northwest**

Key cited problems:

Lack of sufficient performance testing;

Questions about suitability given special local conditions (TVA, hydroelectric power...).

Project Objectives

- ❑ **PROBLEM:** WPMP = Complicated Design
 - ➔ Difficult to capture salient aspects of WPMP market design for dynamic performance testing using standard analytical and statistical tools
- ❑ **Alternative:** Construct an ACE framework (Java/RepastJ) with learning traders that permits intensive experimental testing of performance under the WPMP market design

Project Objectives ... Continued

□ Target Framework Features

- **Research/training grade model** (from 2 to 500 pricing nodes)
- Operational validity (structure, rules, behavioral dispositions)
- Permits dynamic testing with learning traders
- Permits intensive sensitivity experiments
- Open source (full access to implementation)
- Easy modification (extensible/modular architecture)

□ Who should care?

- **Academic researchers/teachers** (qualitative understanding)
- **Industry stakeholders** (learn rules, test business strategies)
- **Policy makers** (efficient and reliable market design)

Basic Approach Taken in Project: Iterative Participatory Modeling (Barreteau et al.)

- ◆ Joining together with industry stakeholders and researchers from multiple disciplines in a **repeated looping** through 4 stages of analysis:
 - Field work and data collection;
 - Scenario discussion/role-playing games;
 - Agent-based model development;
 - Intensive computational experiments.

Our "AMES" Framework: Key Features

(Based on Business Practices Manuals for MISO/ISO-NE)

➤ **Traders**

- Sellers and buyers
- Follow market rules
- **Learning abilities**

➤ **Independent System Operator**

- System reliability assessments
- Day-ahead bid-based unit commitment
- Real-time dispatch

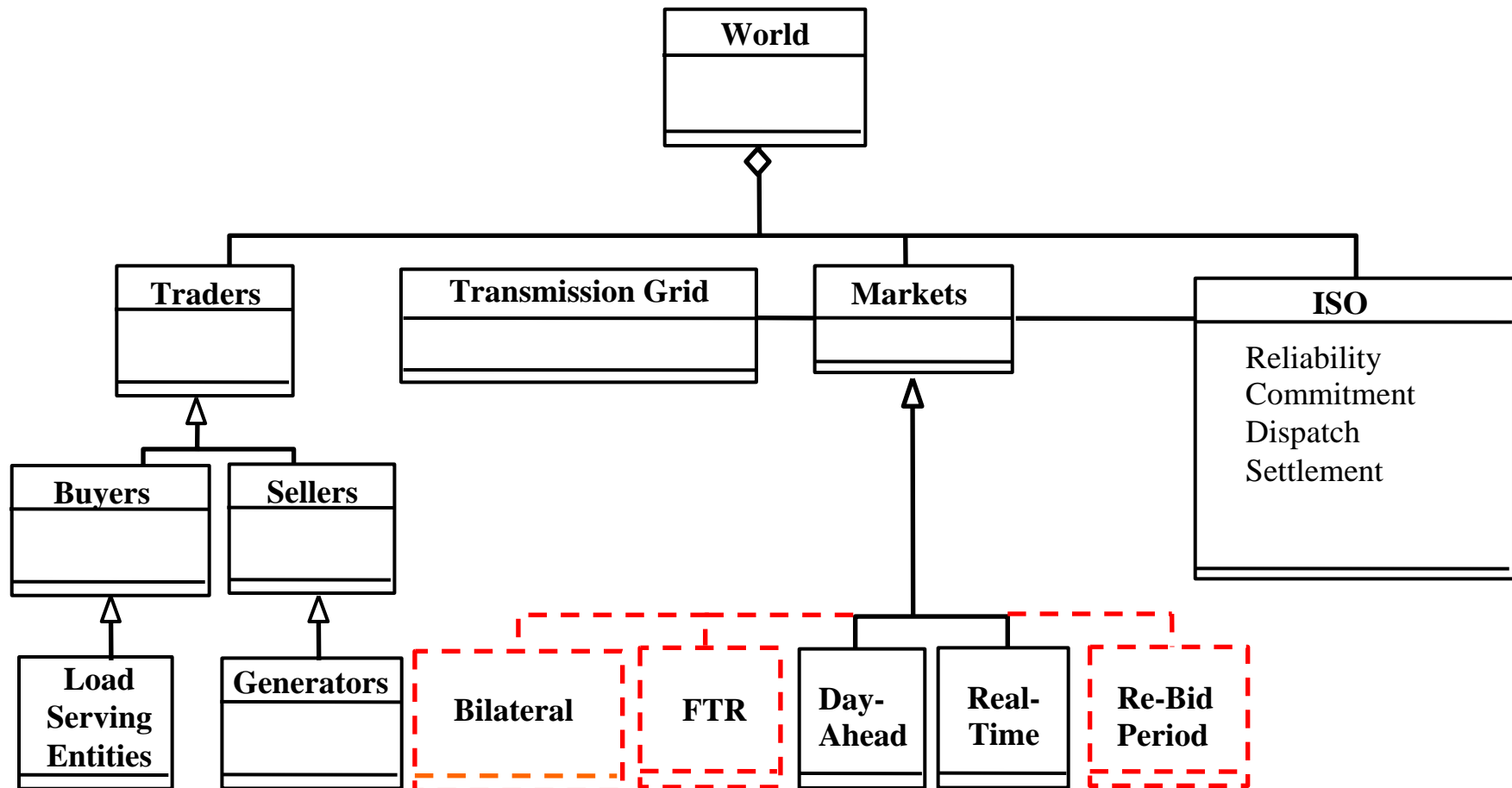
➤ **Two-settlement process**

- Day-ahead market (double auction, financial contracts)
- Real-time market (settlement of differences)

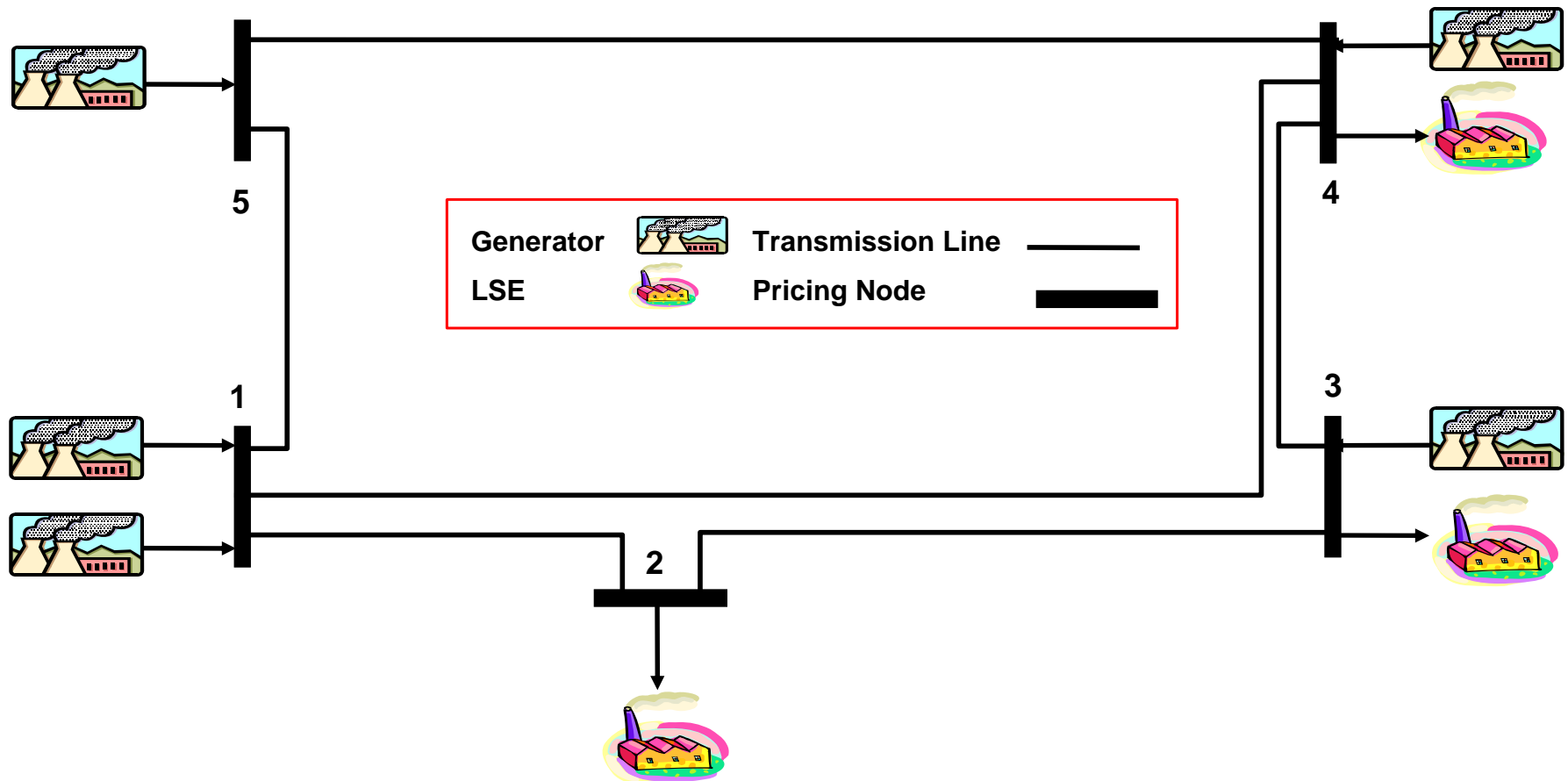
➤ **AC transmission grid**

- Sellers/buyers located at various transmission nodes
- Congestion managed via Locational Marginal Pricing (LMP)

AMES Framework: Agent Hierarchy



An Illustrative Transmission Grid



A Computational Generator (Seller)

Public Access:

// **Public Methods**

getMarketProtocols(posting, trade, settlement);
getMarketProtocols(ISO market power mitigation);
Methods for receiving data;
Methods for retrieving Seller data.

Private Access:

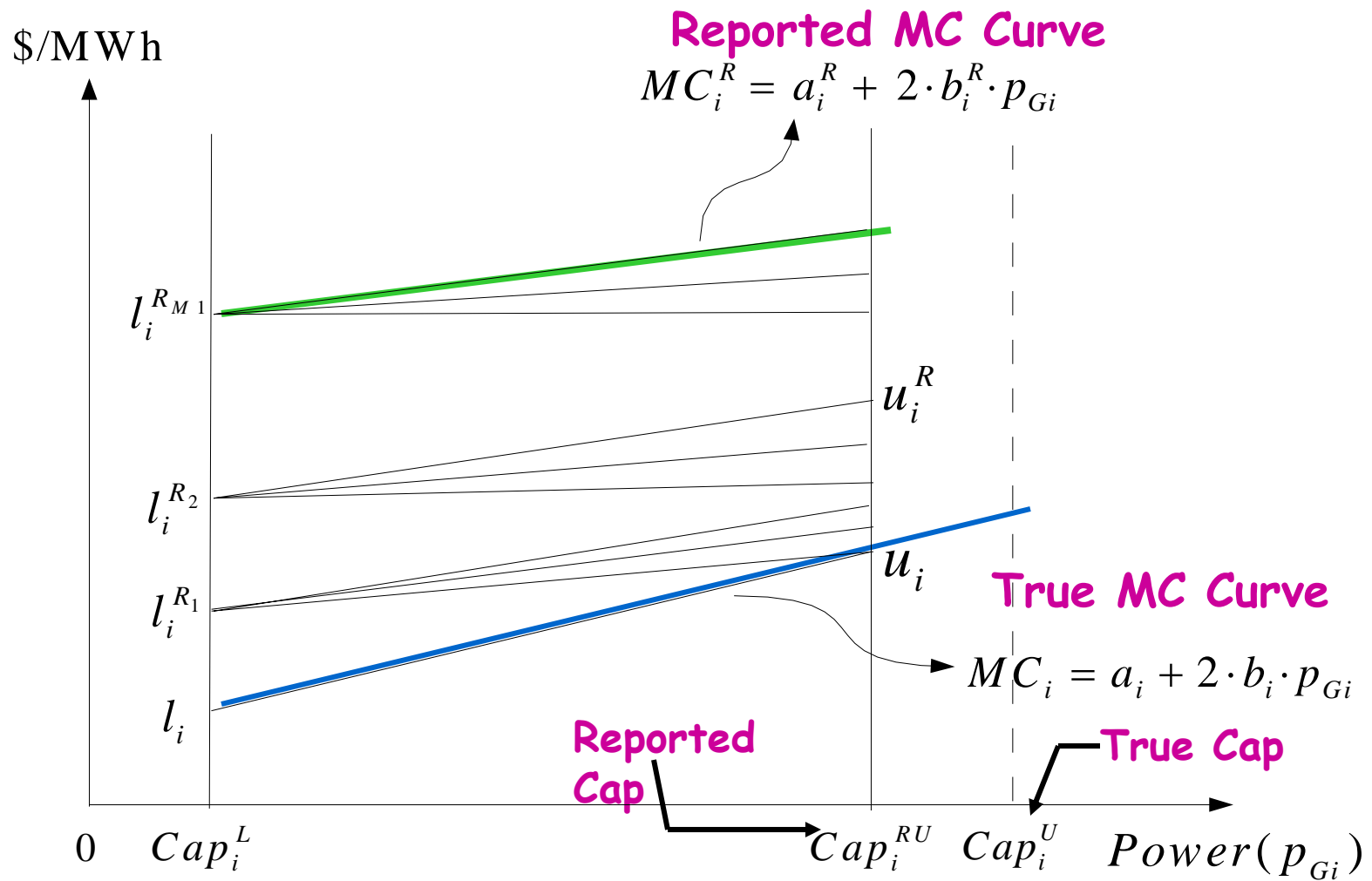
// **Private Methods**

Methods for gathering, storing, and sending data;
Methods for calculating expected & actual profit outcomes;
Method for updating my supply offers (**LEARNING**).

// **Private Data**

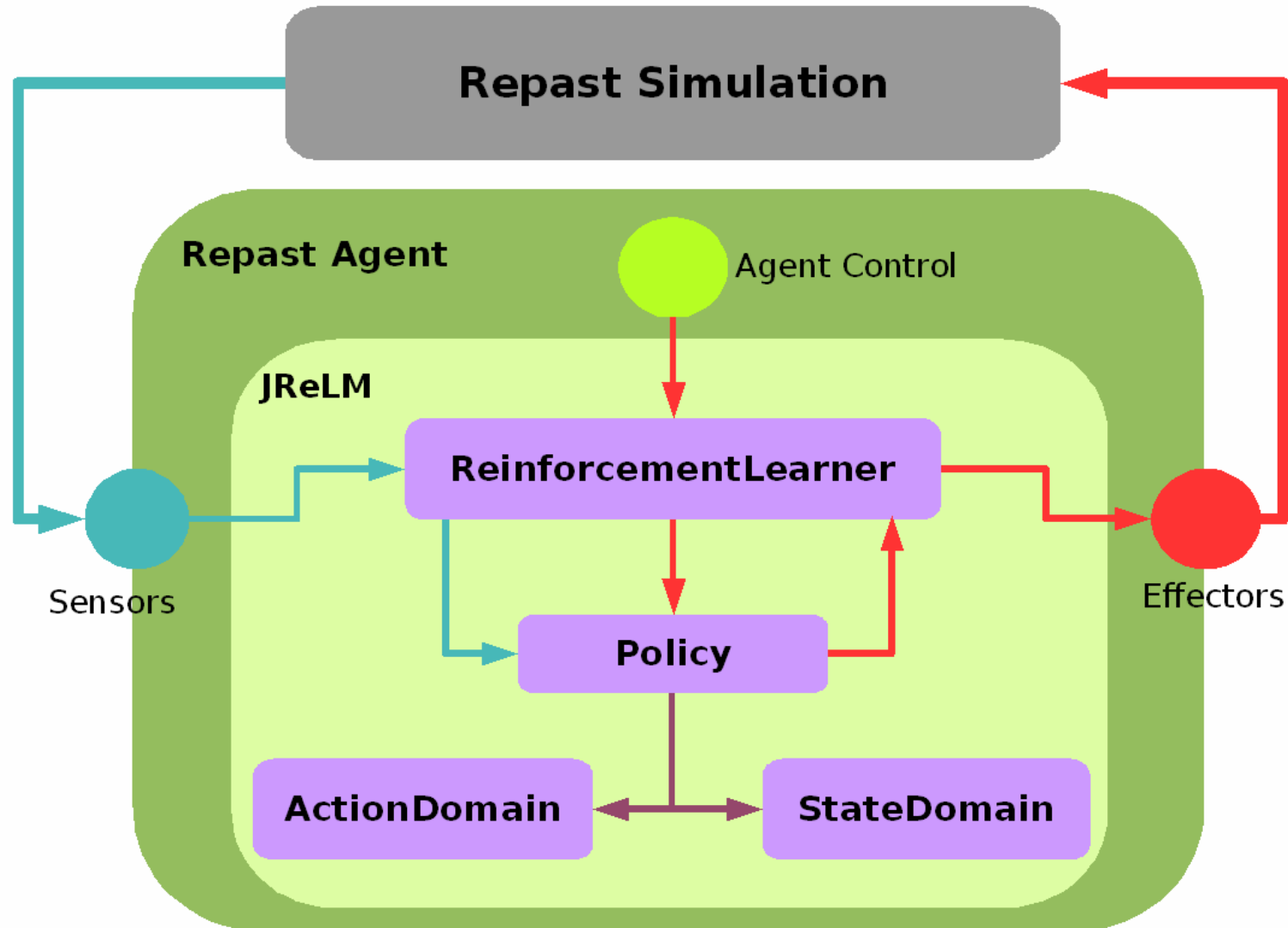
My capacity, grid location, cost fct., current wealth... ;
Data recorded about external world (dispatch schedule...);
Address book (communication links).

Generator i 's Action Domain (Potential Reported Marginal Cost Curves MC_i^R)

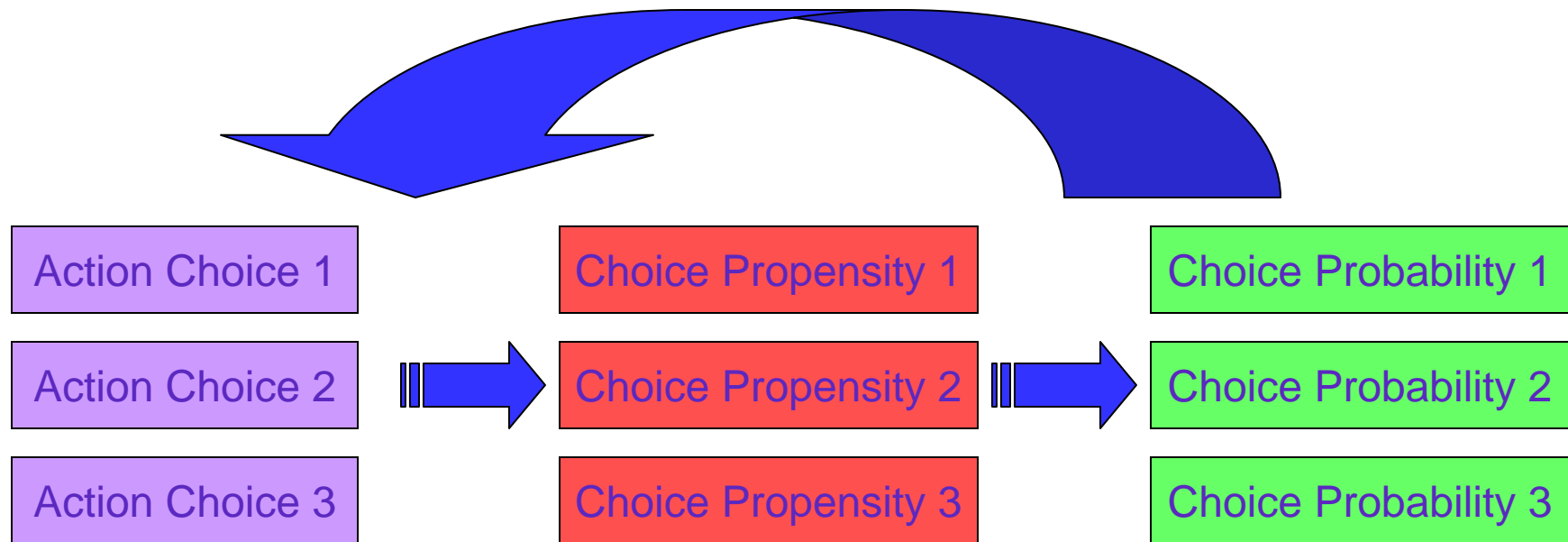


JReLM Learning Module

(Charles J. Gieseler, M.S. Thesis, 2005)



Roth-Erev Reinforcement Learning



- Each trader maintains action choice propensities, normalized to action choice probabilities to select actions. A good (bad) reward for action \tilde{a} results in strengthening (weakening) of propensity for \tilde{a} .

Activities of AMES ISO During Each Operating Day D

Real-Time (Spot) Market for D	00:00	Day-Ahead Market for D+1
	11:00	ISO evaluates demand bids and supply offers
	17:00	Re-Bid Period for D+1
	18:00	ISO solves D+1 DC OPF problem & posts D+1 commitment/LMP schedule
	23:00	

DC Optimal Power Flow (DC OPF) Problem Solved by AMES ISO for Each Hour of the Day-Ahead Market

Minimize

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

w.r.t. $p_{Gi}, i = 1, \dots, I; \delta_k, k = 1, \dots, K$

subject to

Balance constraints:

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

LMP for node k = Shadow price for node k balance constraint

Branch flow (thermal) constraints:

$$|B_{km} (\delta_k - \delta_m)| \leq P_{km}^U$$

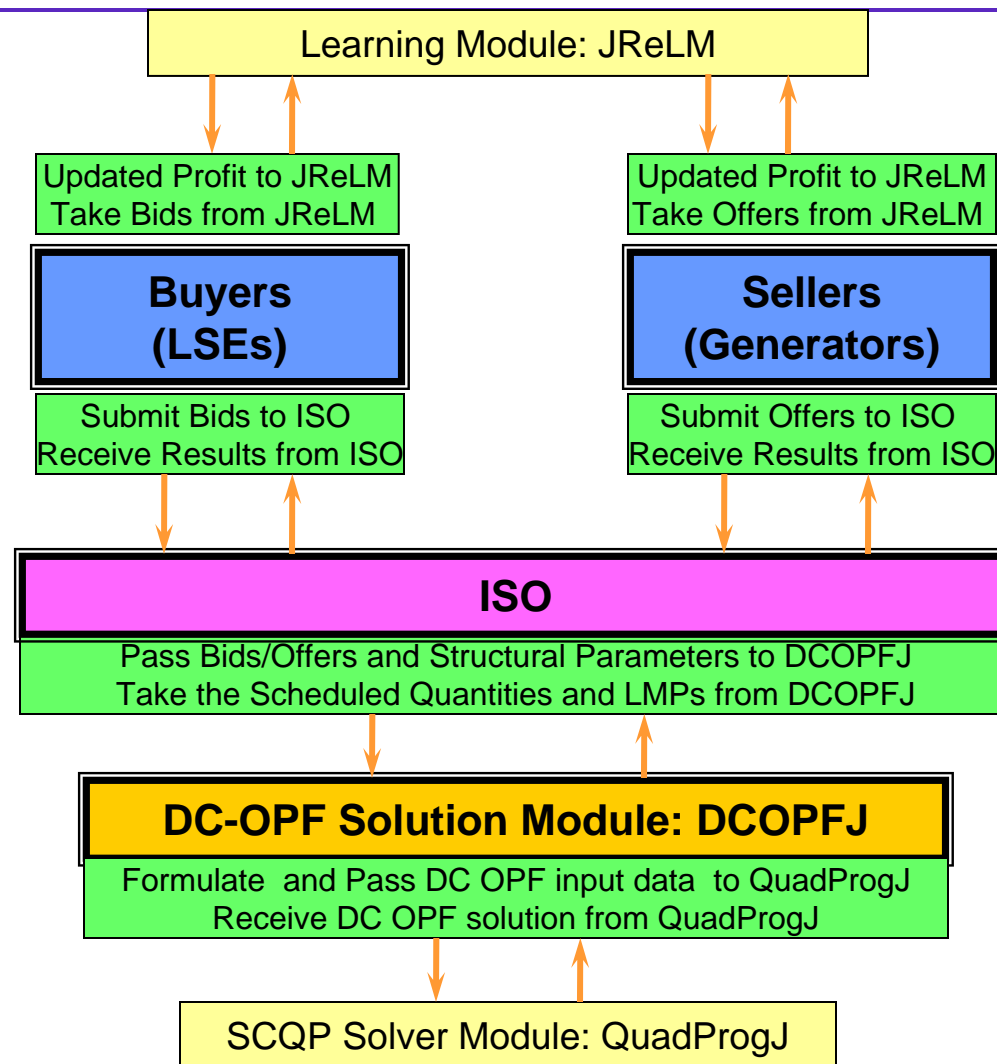
Reported production capacity constraints:

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

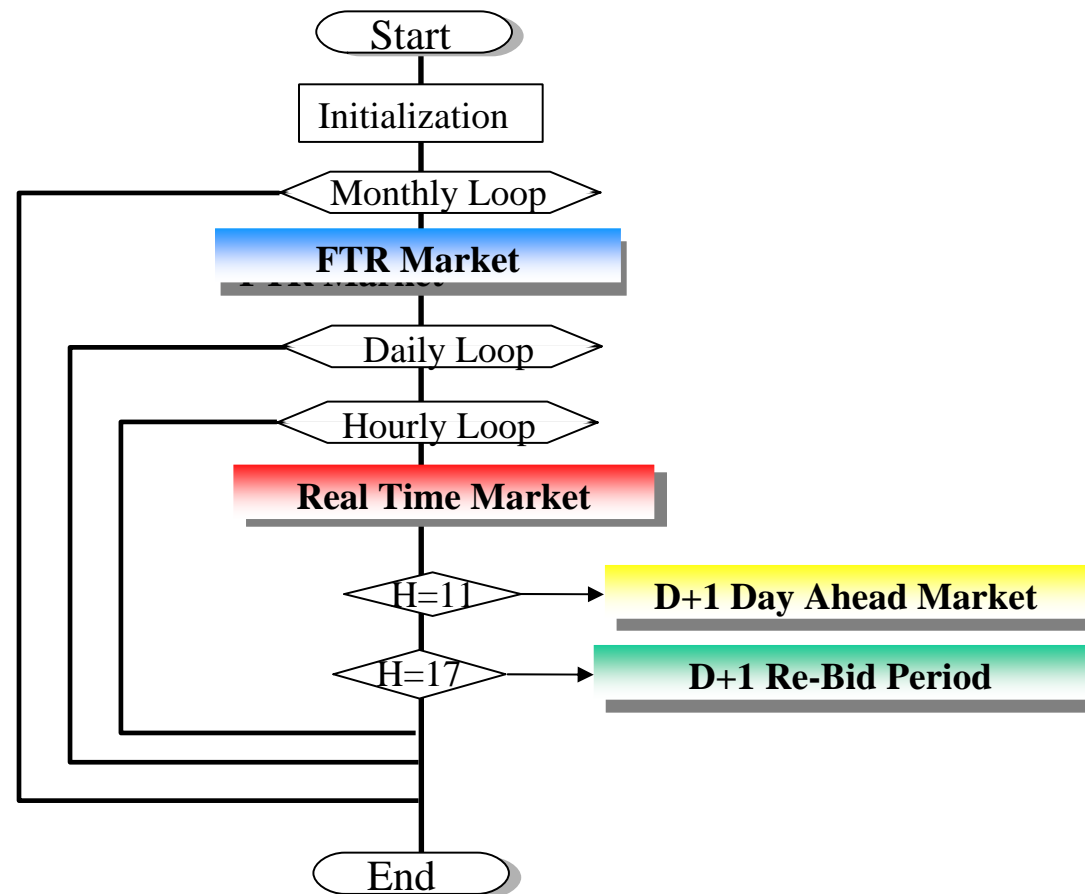
Voltage angle setting at reference node 1:

$$\delta_1 = 0$$

Two Key AMES Framework Components: Learning Module & DC-OPF Solution Module

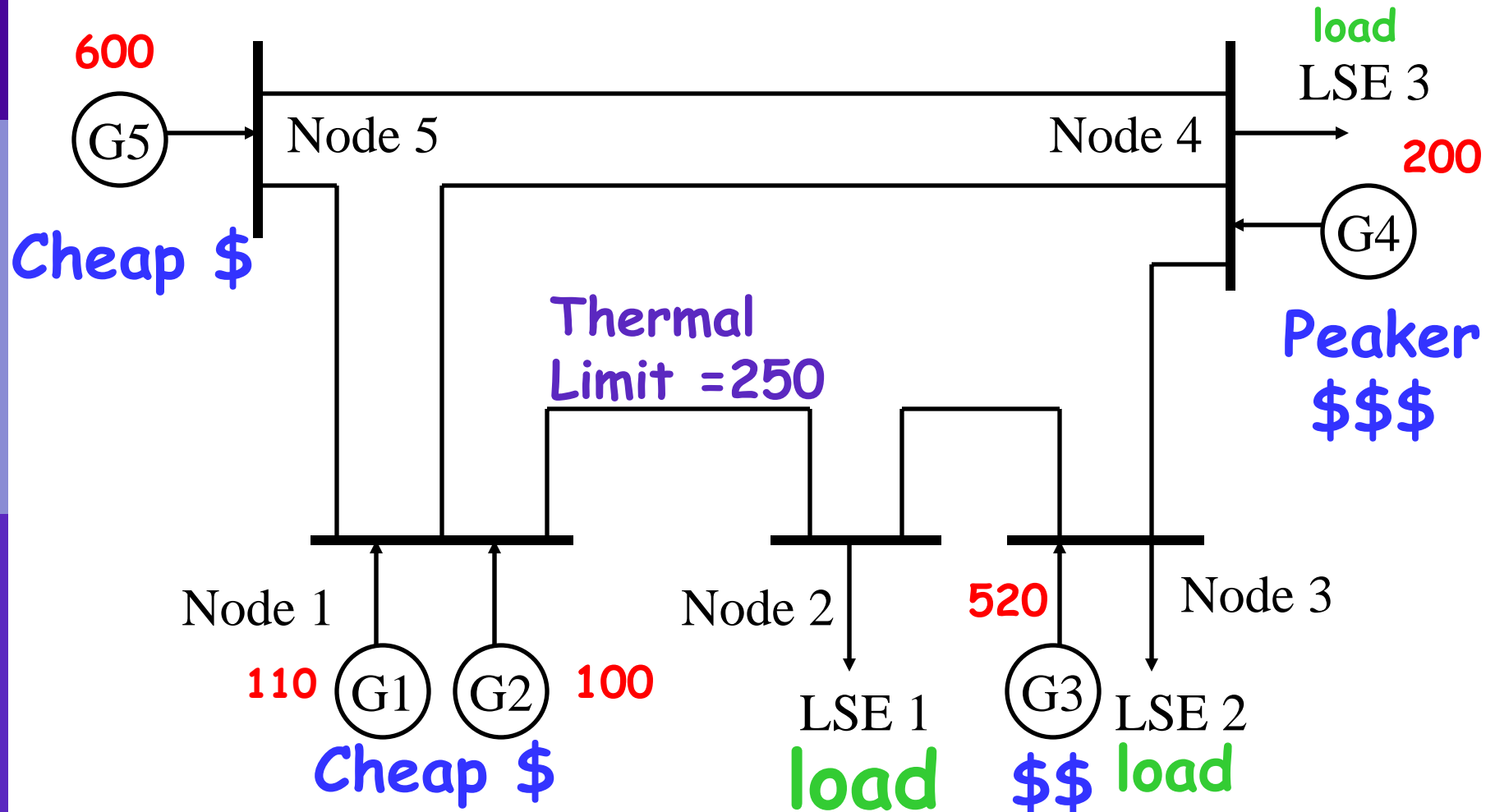


AMES Market Dynamics: Overview

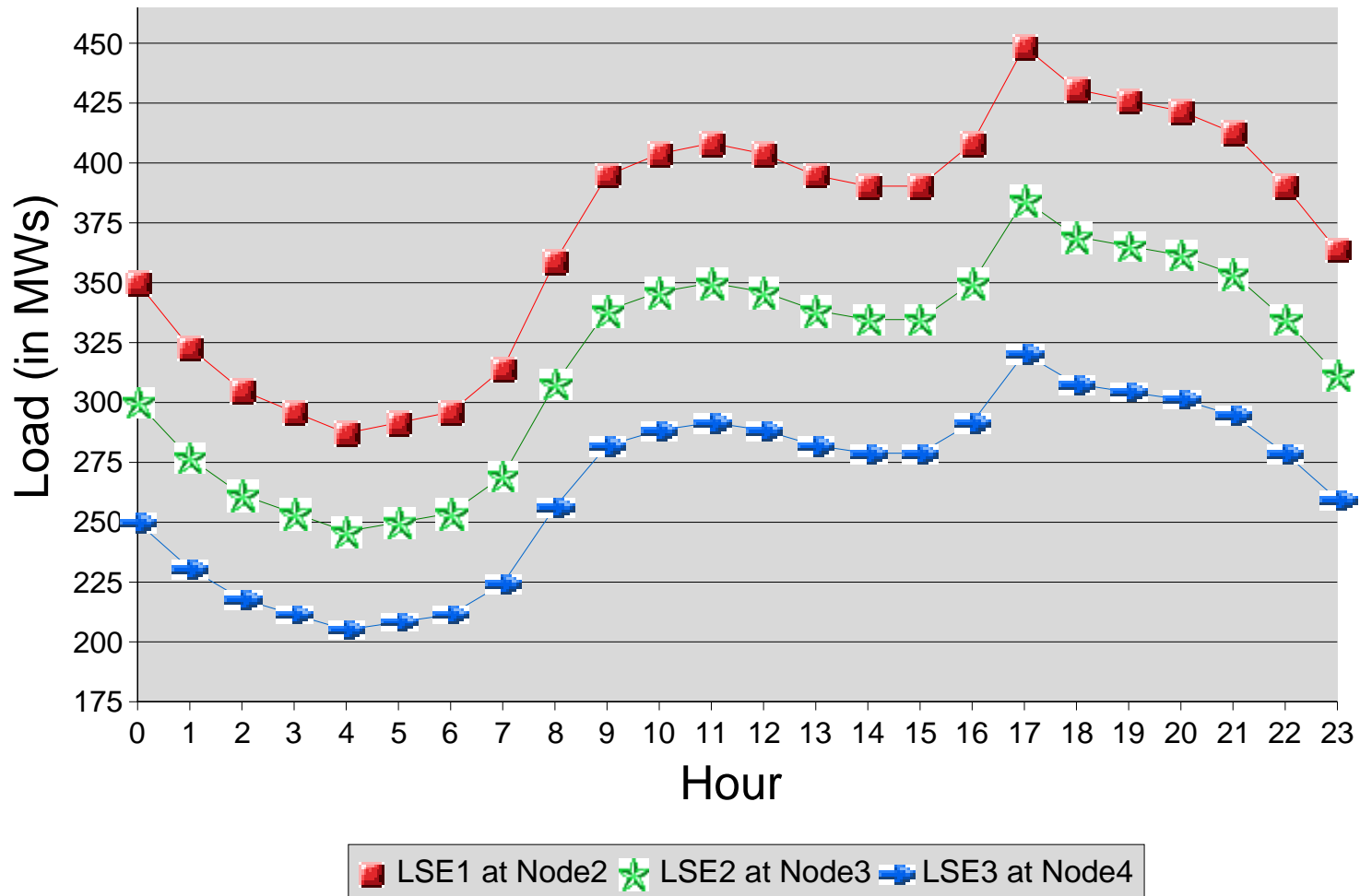


Illustrative 5-Node Test Case

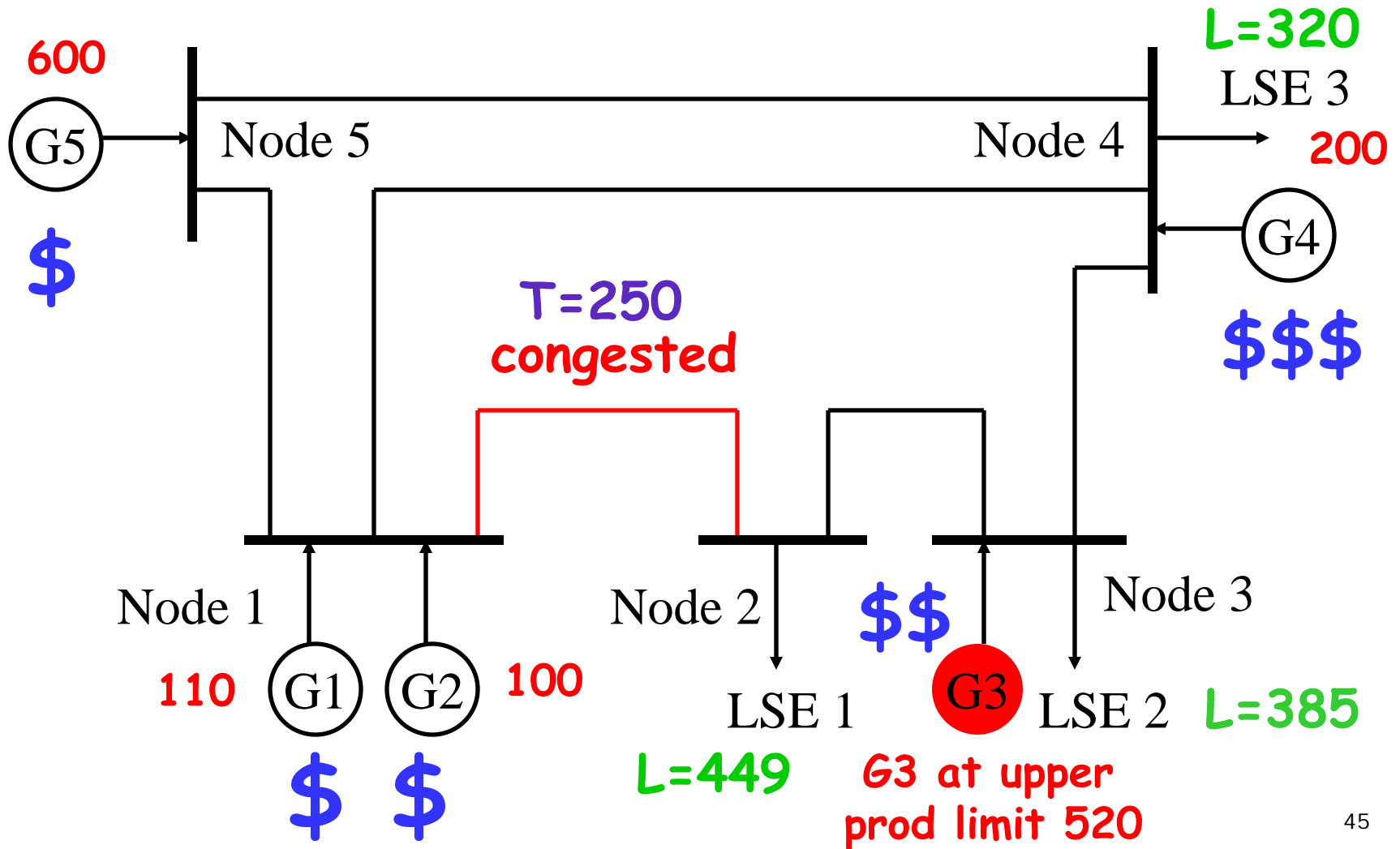
(Dynamic Extension of Static ISO-NE/PJM Training Example)



Daily LSE Load Profiles for 5-Node Test Case

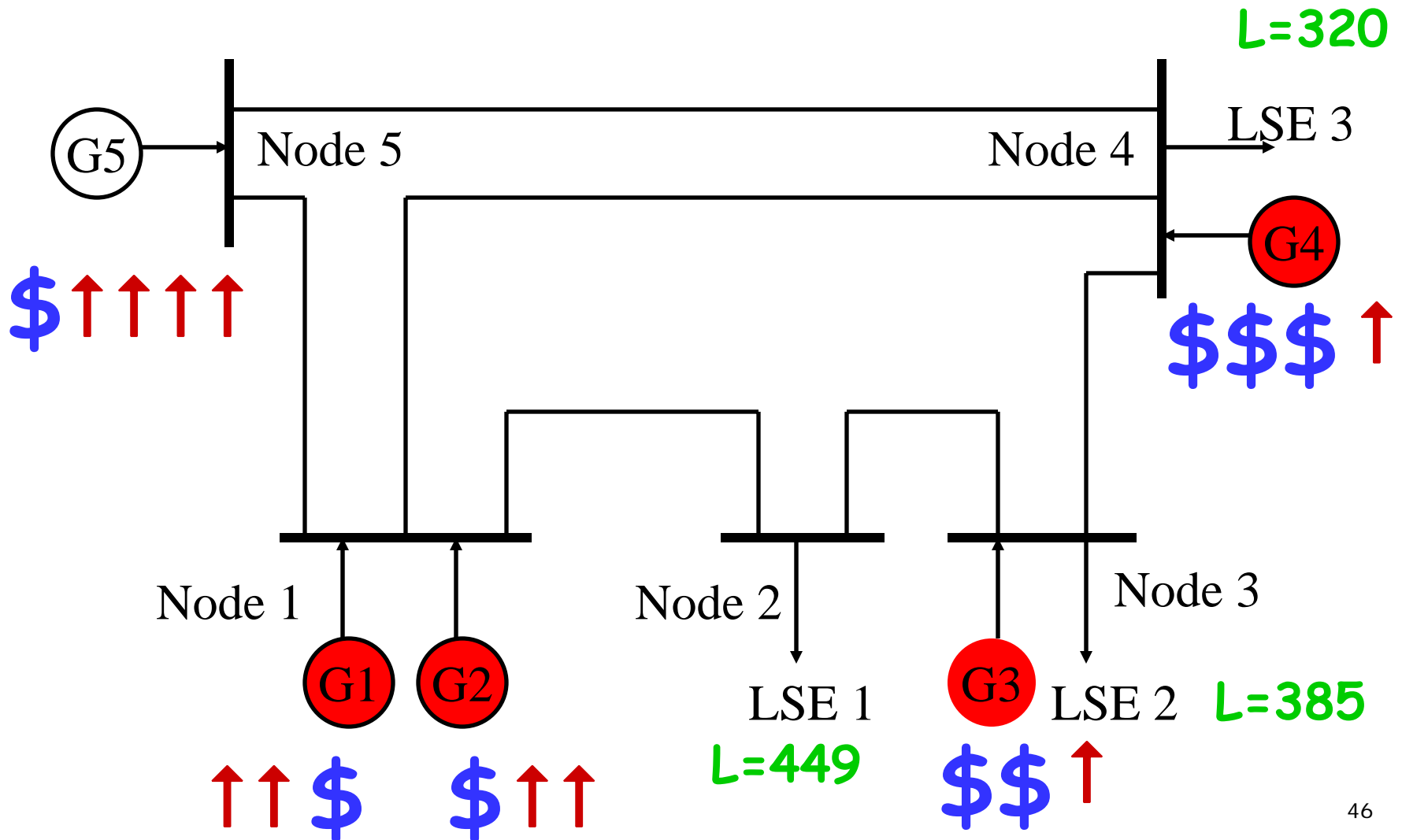


Day 40-Hour 17 Constraints: No Learning (Assuming Gen supply offers = True MC curves)



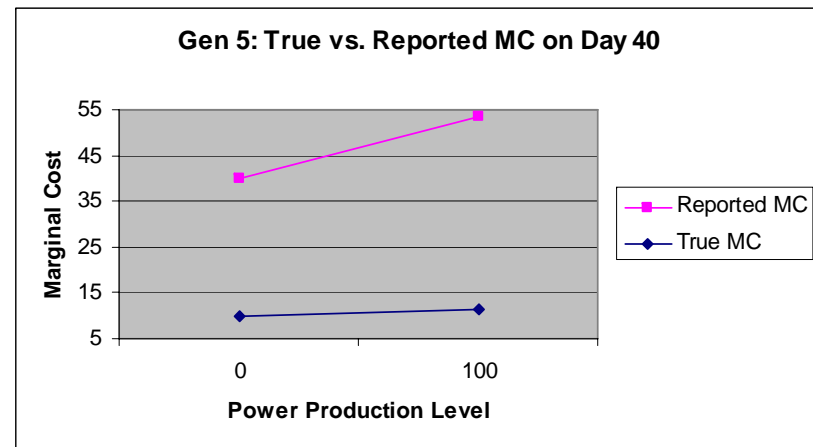
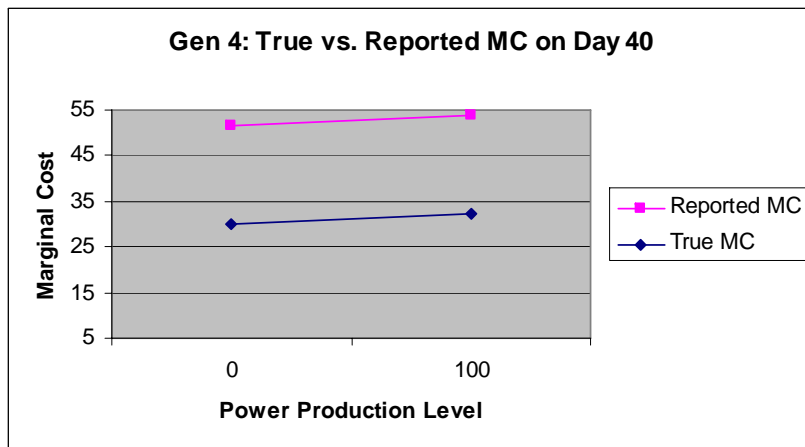
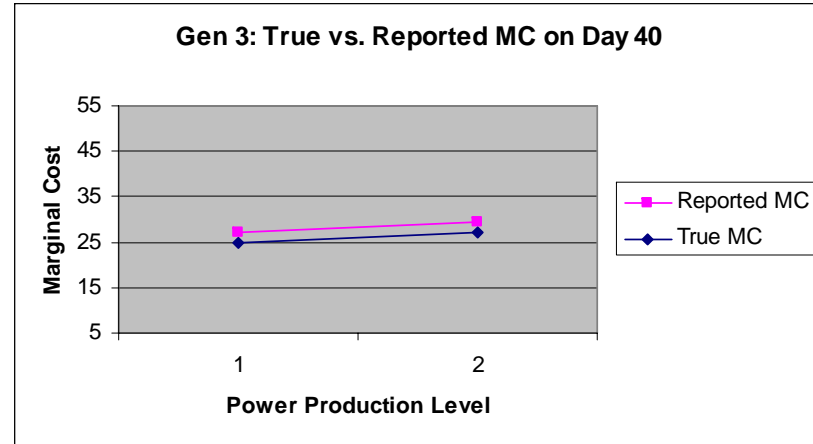
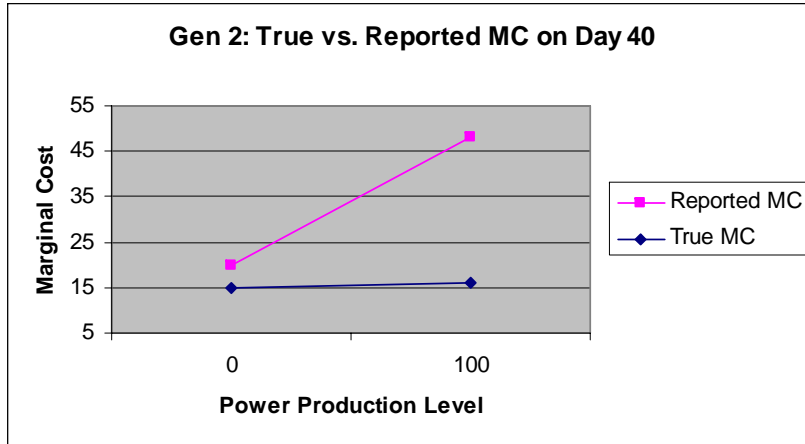
Day 40-Hour 17 Constraints: With Gen Learning

(Each Generator i has converged to $\text{Prob}(a_i^*) = 0.999$)

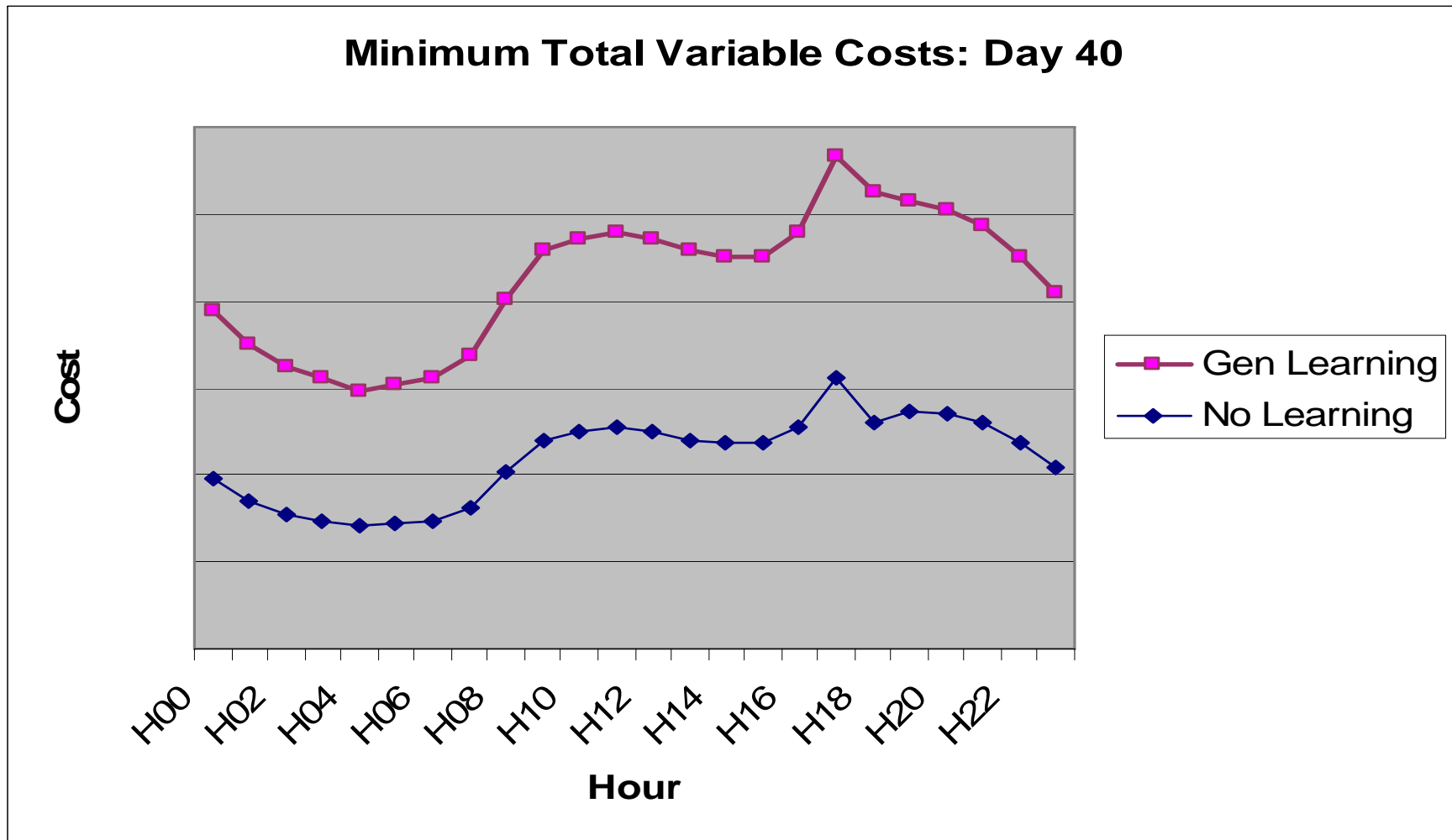


True Vs. Reported MC on Day 40

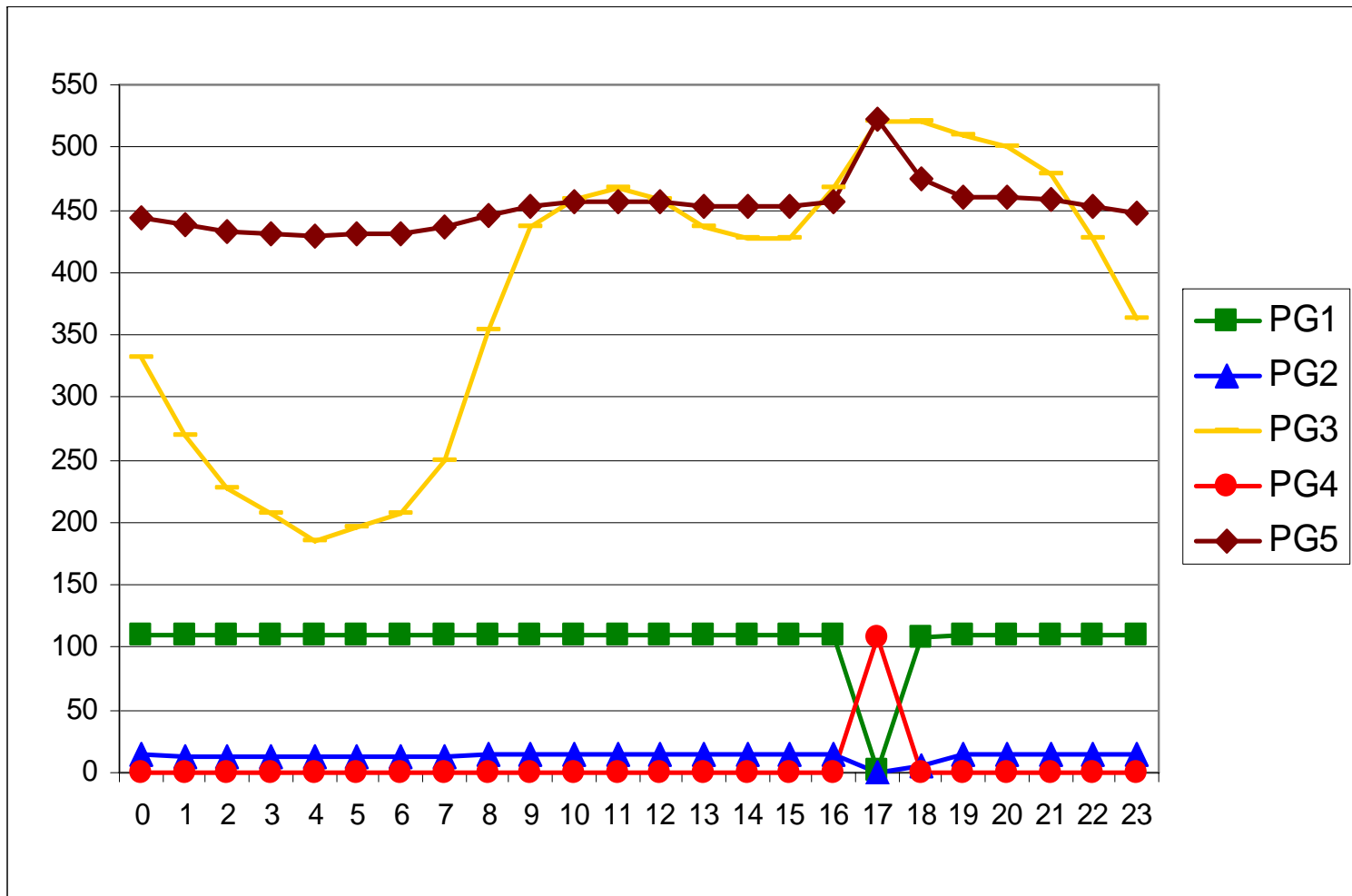
(Each Generator i has converged to $\text{Prob}(a_i^*) = 0.999$)



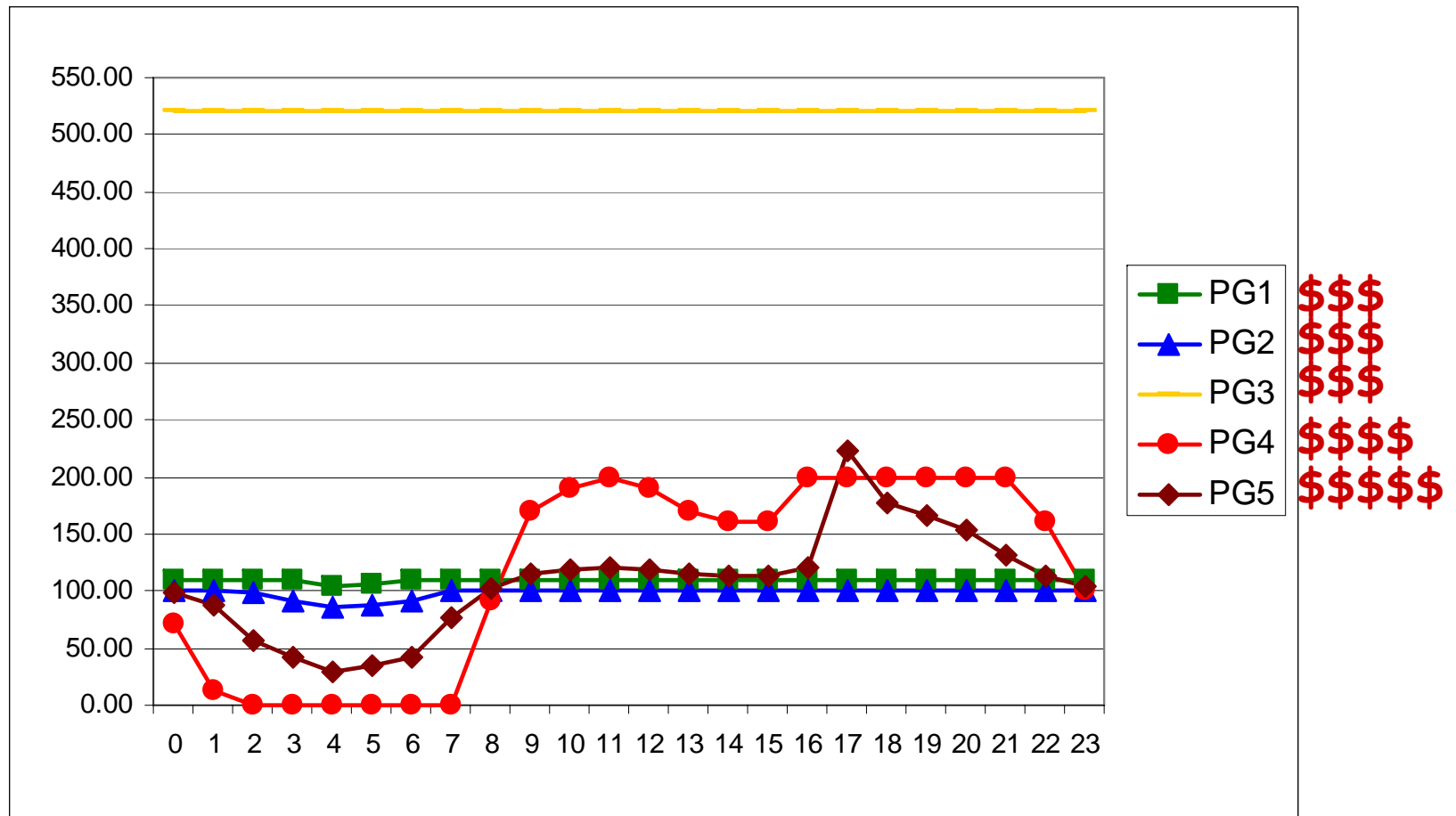
Min TVC on Day 40: Gen Learning Compared With No Learning



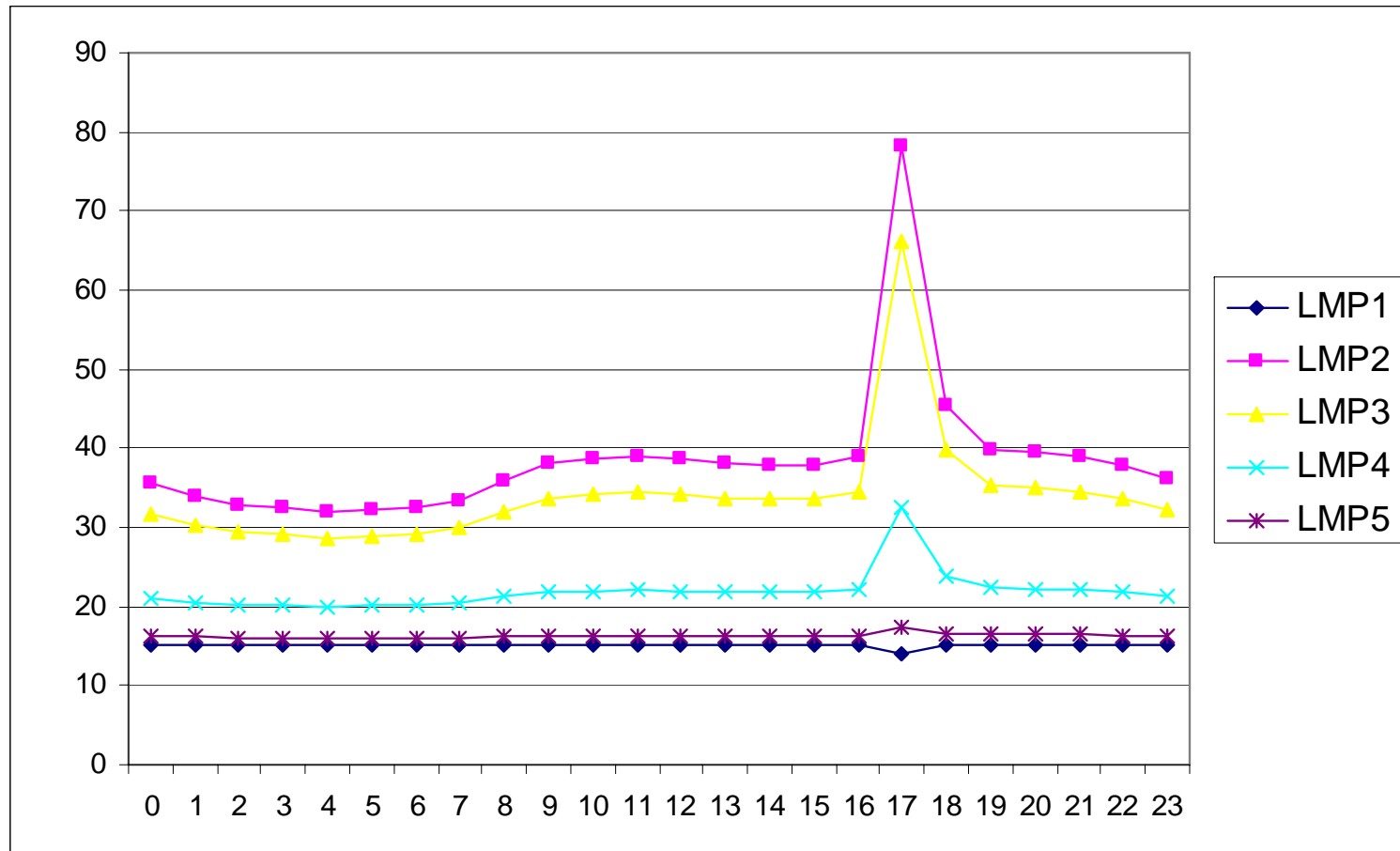
Day 40 - 24 Hour Production: No Learning (Assuming Gen supply offers = True MC curves)



Day 40 - 24 Hour Production: With Gen Learning (Each Generator i has converged to $\text{Prob}(a_i^*) = 0.999$)

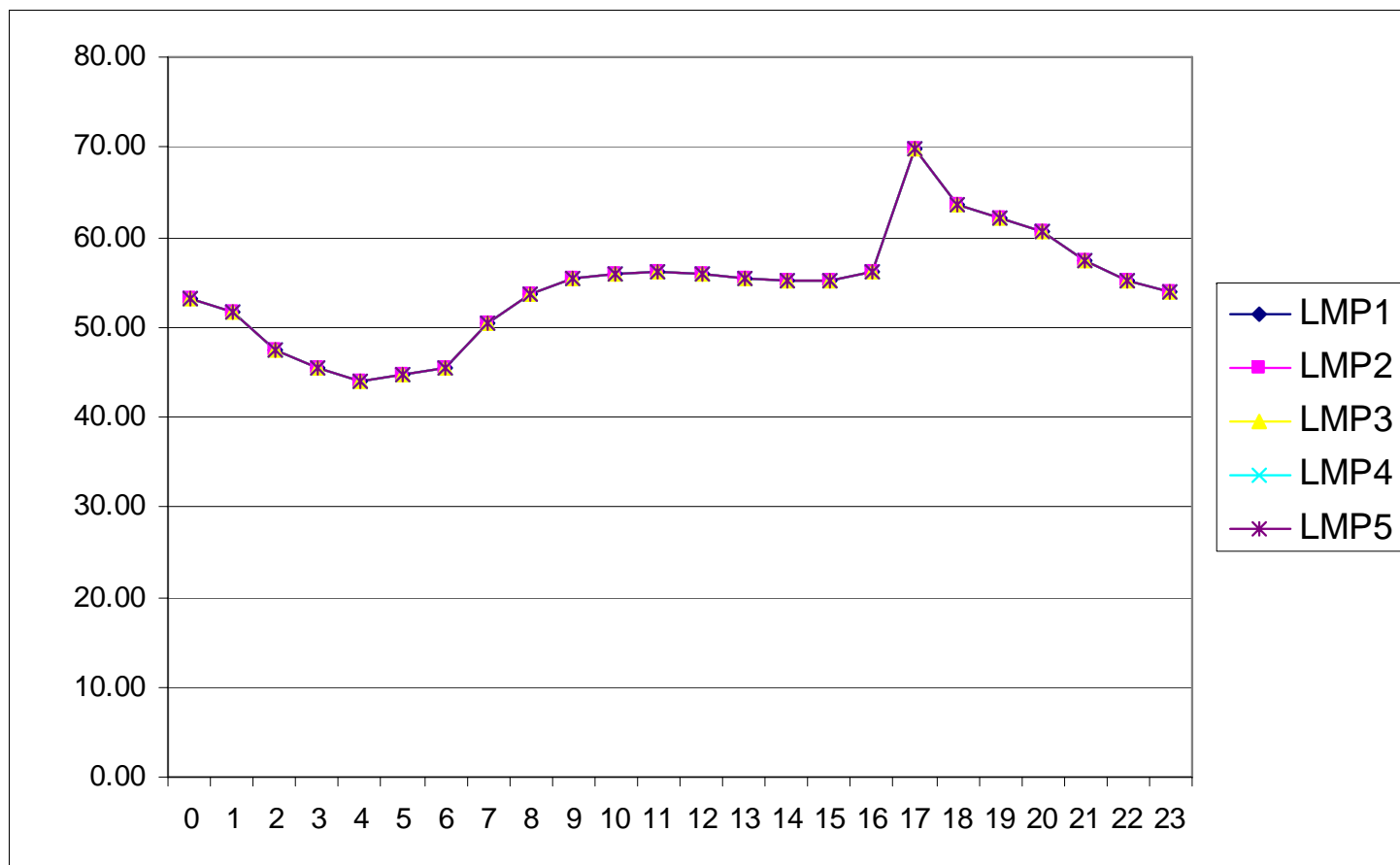


Day 40 - 24 Hour LMPs: No Learning (Assuming Gen supply offers = True MC curves)

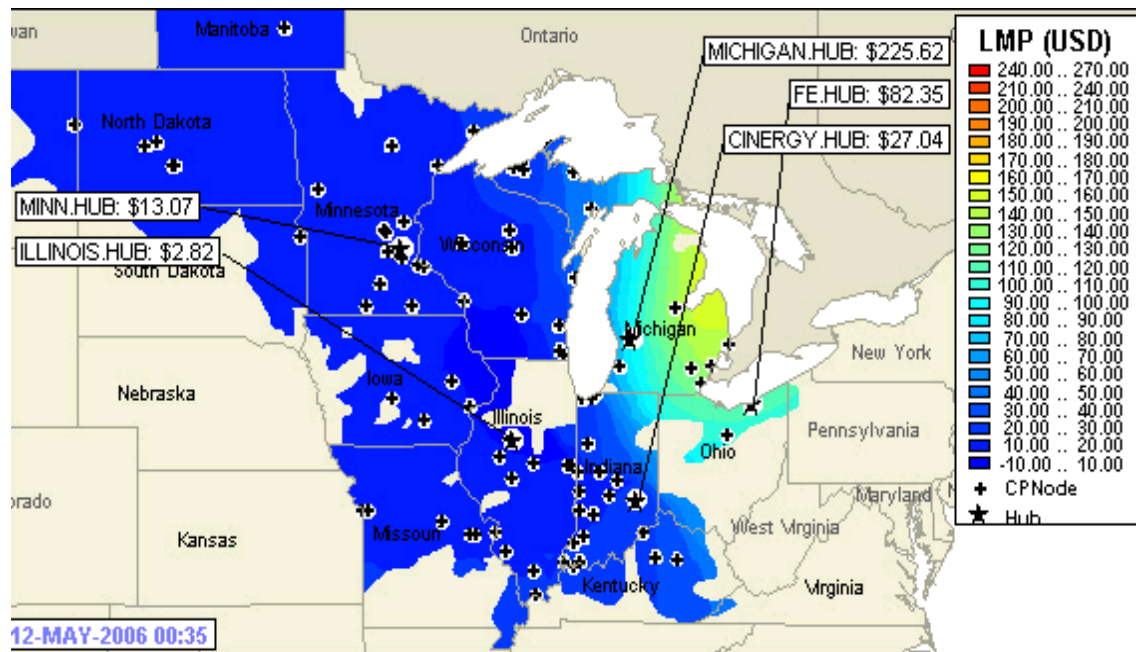


Day 40 - 24 Hour LMPs: With Gen Learning

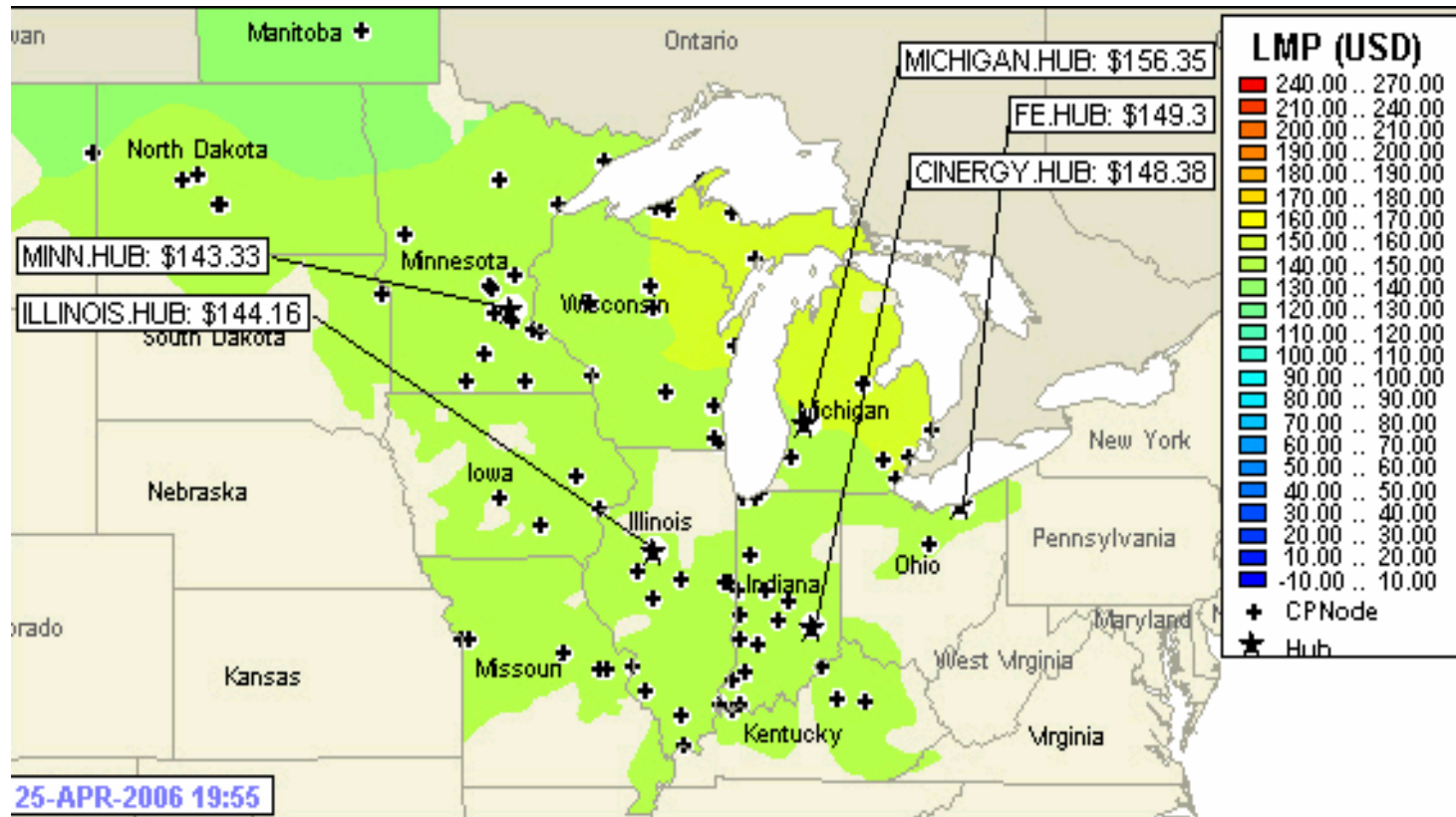
(Each Generator i has converged to $\text{Prob}(a_i^*) = 0.999$)



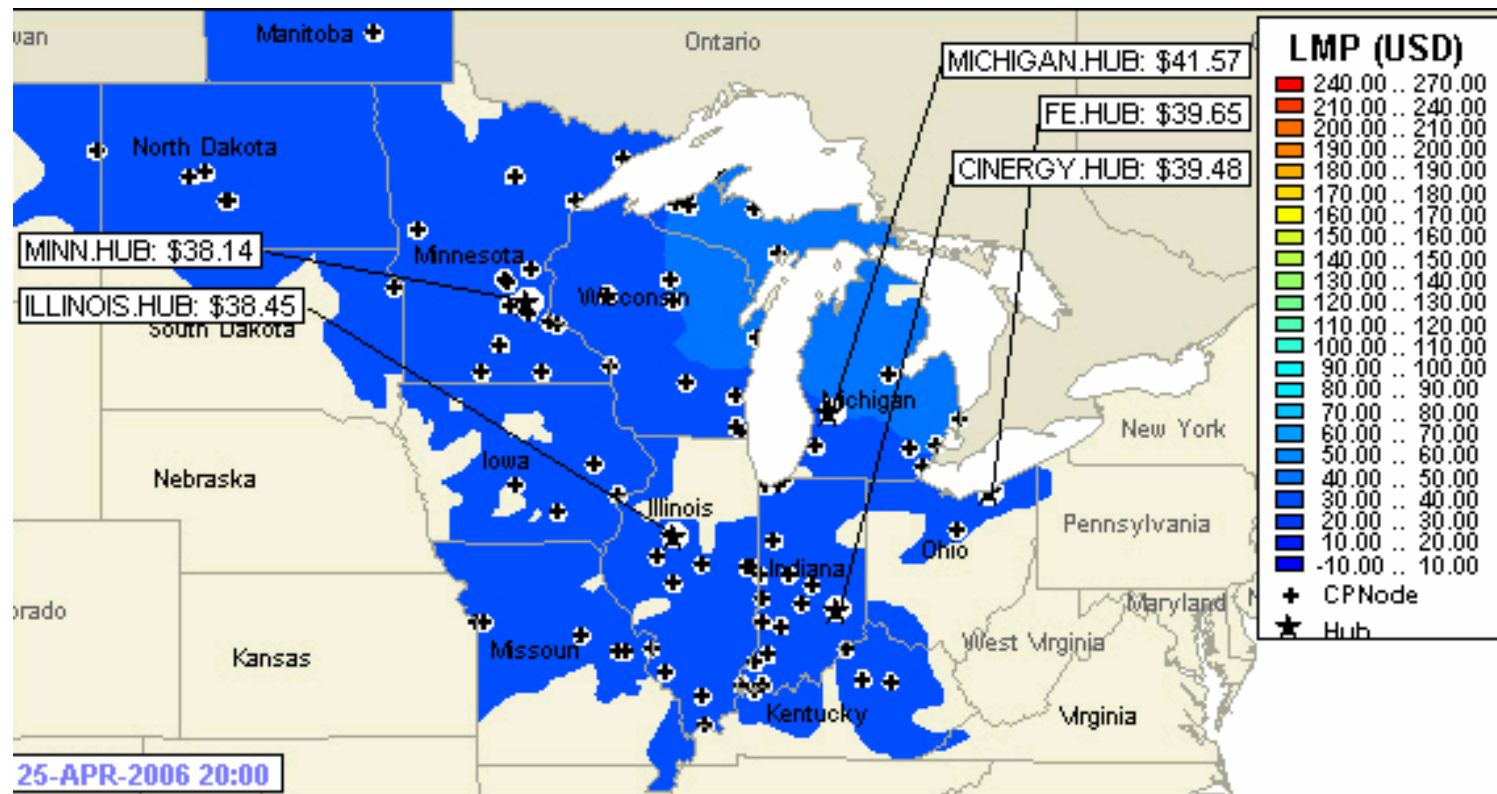
Dynamic MISO Real-Time LMP Contour Map (5/12/2006 at 00:35)



Dynamic MISO Real-Time LMP Contour Map (4/25/2006 at 19:55)



Dynamic MISO Real-Time LMP Contour Map (4/25/2006 at 20:00)



Recap of AMES Project Work to Date

□ AMES Framework Features Completed to Date

- **JReLM learning module** (Gieseler, MS Thesis, 2005) permits traders to be modeled with a range of empirically-based behavioral dispositions (trading strategies, learning modes)
- **DC-OPF solver module** (Sun/Tesfatsion, WP-06014, March 2006) permits ISO to solve repeatedly for LMPs and power production commitment & dispatch levels in day-ahead and real-time markets
- **Working dynamic wholesale power market model** (Sun/Tesfatsion, WP, June 2006) that integrates these two modules into a computational framework capturing core features of WPMP market design with learning Generators.

Experimental Design: Treatment Factor Ranges

- * Cournot supply behavior (Typical econ. lit. assumption) → Learned strategic supply beh. (Actual MISO/ISO-NE situation)
- * No trans./cap. constraints (Typical econ. lit. assumption) → Active trans./cap. constraints (Actual MISO/ISO-NE situation)
- No market power mitigation (Typical econ. lit. assumption) → ISO oversight & MP mitigation (Actual MISO/ISO-NE situation)
- Passive inelastic demand (Typical econ. lit. assumption) → Learned strategic demand beh. (Actual MISO/ISO-NE situation)
- No Financial Trans. Rights (Typical econ. lit. assumption) → Financial Trans. Rights market (Actual MISO/ISO-NE situation)
- No bilateral contracts (Typical econ lit. assumption) → Bilateral & ISO pool contracts (Actual MISO/ISO-NE situation)

Costs/Benefits of ACE for Econ Theory?

ON THE COST SIDE...

- ACE requires **detailed initial specifications** of structures, institutions, and behavioral dispositions.
- ACE requires construction of **dynamically complete process models** driven solely by agent interactions.
- ACE requires researchers to acquire facility with a **programming language or agent toolkit suitable for agent-based modeling** - e.g. Java, C++, C#, RepastJ, Netlogo,...

BUT ON THE BENEFITS SIDE...

- * ACE facilitates systematic experimental study of **microstructure** → **agent inter's** → **macro events**
- * ACE facilitates dynamic experimental study of **processes, coordination, performance...**
- * ACE facilitates the **calibration of structure, institutions, and behavioral dispositions to real-world data** (econometrics, human subject experiments, iterative participatory modeling...)
- * **ACE Website:**
www.econ.iastate.edu/tesfatsi/ace.htm