

# **MISO MARKET PERFORMANCE: AN OPEN-SOURCE AGENT-BASED TEST BED**

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## **ABSTRACT**

In April 2005 the Midwest Independent System Operator (MISO) undertook a major restructuring of its wholesale power market design. The primary objective of our project has been to develop an agent-based computational test bed suitable for exploring the efficiency, reliability, and fairness of this new market design for purposes of research, teaching, and training. The first version of our test bed, AMES (V1.31), was released as open-source software at the IEEE PES General Meeting in June 2007. A more powerful version, AMES (V2.02), was released as open-source software at the IEEE PES General Meeting in July 2008. This final project report discusses the core capabilities of AMES (V2.02) and summarizes project research findings obtained to date using this test bed.

## **1 INTRODUCTION**

The primary objective of this project has been to develop an open-source software (OSS) test bed, AMES, to facilitate the systematic examination of the efficiency, reliability, and fairness of market performance under FERC's market design as implemented in the MISO in April 2005. The release of AMES as OSS is intended to encourage the cumulative development of this test bed by multiple researchers in directions appropriate for their specific needs. It is also intended to encourage continual dialog with market stakeholders and regulators leading to successive refinements and improvements of the test bed.

Section 2 of this report briefly summarizes project research findings obtained to date using the AMES test bed, as well as research in progress. Section 3 outlines key features of the current version of AMES (V2.02). A more detailed discussion of several specific project research findings is provided in Section 4, and a complete list of project publications, reports, and presentations is provided in Section 5.

## **2 PROJECT RESEARCH SUMMARY**

### **2.1 LMP Separation and Volatility in Restructured Wholesale Power Markets**

In several studies [1,4,11] we have used the AMES test bed to explore LMP separation and volatility over time under alternative demand and supply-offer price-cap scenarios when profit-seeking GenCos have learning capabilities permitting them to report strategic supply offers to the market operator.

The AMES test bed is currently being used to conduct systematic computational experiments to explore spatial correlations among GenCo supply offers and LMPs, and to examine the importance of GenCo pivotal status in the determination of LMPs. In the future, we plan to explore possible alternative OPF formulations to reduce LMP volatility while retaining efficiency and reliability.

## **2.2 Two-Settlement Systems (Day-Ahead and Real-Time Markets)**

In several studies [1,4,10,11,12] we have focused on efficiency and fairness aspects of LMP-settled day-ahead electric power markets in the absence of shocks and disturbances.

To permit a more comprehensive integrated evaluation of the reliability, efficiency, and fairness of market operations in restructured wholesale power markets, we are currently expanding the AMES test bed to include the parallel operation of day-ahead and real-time markets. Demand and fuel prices will be allowed to vary over time, creating uncertainty for GenCo suppliers and market operators. We will include GenCo scheduled maintenance plans, security-constrained unit commitment (SCUC) to clear the day-ahead market, and security-constrained economic dispatch (SCED) to clear the real-time market. We will seek to understand how the operation of two-settlement systems and associated markets (e.g., FTR) might be enhanced through improved LMP decomposition and other design alterations.

## **2.3 Effects of Learning Behaviors in Restructured Wholesale Power Markets**

In several studies [1,4,5,7,10,11,12] we have explored what happens when GenCos participating in day-ahead electric power markets have reinforcement learning (RL) capabilities permitting them to engage in both economic and physical capacity withholding. These studies have shown that, in the absence of special market power mitigation efforts by the market operator, pivotal GenCos have considerable market power enabling them to raise prices at the expense of market performance (efficiency). Moreover, GenCos are successfully able to learn to exercise this market power, even using very simple forms of RL.

We are currently expanding the AMES test bed to permit the exploration of the effects of LSE and GenCo learning capabilities under more realistic wholesale power market operating conditions. We will also consider the development of new learning methods (e.g., adaptation of learning parameters) more specifically tailored for wholesale power markets. In addition, we will also seek to understand how these “normative” findings relate to the bid/offer behaviors of real-world LSEs and GenCos.

## **3 KEY FEATURES OF THE AMES TEST BED V2.02**

The latest version of AMES (V2.02) incorporates, in simplified form, core features of the wholesale power market design proposed by the U.S. FERC in 2003; see Fig. 1. A detailed description of many of these features can be found in [1,4,5,6,7,12]. Below is a summary description of the logical flow of events in the AMES wholesale power market test bed as currently implemented:

- Traders
  - LSEs (bulk-power buyers)
  - GenCos (bulk-power sellers with learning capabilities)
- Independent System Operator (ISO)
  - Day-ahead hourly scheduling via bid/offer-based DC optimal power flow (OPF)
  - System reliability assessments
- Two-settlement process
  - Day-ahead market (double auction, financial contracts)
  - Real-time market (settlement of differences)
- AC transmission grid
  - LSEs and GenCos located at user-specified buses across the transmission grid
  - Congestion managed via locational marginal pricing

Fig. 1 AMES test bed architecture

- The AMES wholesale power market operates over an AC transmission grid starting on day 1 and continuing through a user-specified maximum day (unless terminated earlier in accordance with a user-specified stopping rule). Each day  $D$  consists of 24 successive hours  $H = 00, 01, \dots, 23$ .
- The AMES wholesale power market includes an *Independent System Operator (ISO)* and a collection of energy traders consisting of *Load-Serving Entities (LSEs)* and *Generation Companies (GenCos)* distributed across the buses of the transmission grid. Each of these entities is implemented as a software program encapsulating both methods and data.
- The objective of the ISO is the reliable attainment of appropriately constrained operational efficiency for the wholesale power market, i.e., the maximization of total net benefits subject to generation and transmission constraints.
- In an attempt to attain this objective, the ISO undertakes the daily operation of a Day-Ahead Market settled by means of *locational marginal pricing (LMP)*, i.e., the determination of prices for electric power in accordance with both the locating and timing of its injection into, or withdrawal from, the transmission grid.
- The objective of each LSE is to secure power for its downstream (retail) customers. During the morning of each day  $D$ , each LSE reports a demand bid to the ISO for the Day-Ahead Market for day  $D+1$ . Each demand bid consists of two parts: a fixed demand bid (i.e., a 24-hour load profile); and 24 price-sensitive demand bids (one for each hour), each consisting of a linear demand function defined over a purchase capacity interval. LSEs have no learning capabilities; LSE demand bids are user-specified at the beginning of each simulation run.
- The objective of each GenCo is to secure for itself the highest possible net earnings each day. During the morning of each day  $D$ , each GenCo  $i$  uses its current action choice probabilities to choose a supply offer from its action domain  $AD_i$  to report to the ISO for use in all 24 hours of the Day-Ahead Market for day  $D+1$ . Each supply offer in  $AD_i$  consists of a linear marginal cost

function defined over an operating capacity interval. GenCo  $i$ 's ability to vary its choice of a supply offer from  $AD_i$  permits it to adjust the ordinate/slope of its reported marginal cost function and/or the upper limit of its reported operating capacity interval in an attempt to increase its daily net earnings.

- After receiving demand bids from LSEs and supply offers from GenCos during the morning of day  $D$ , the ISO determines and publicly reports hourly power dispatch levels and LMPs for the Day-Ahead Market for day  $D+1$  as the solution to hourly bid/offer-based DC optimal power flow (DC-OPF) problems. Transmission grid congestion is managed by the inclusion of congestion cost components in LMPs.
- At the end of each day  $D$ , the ISO settles all of the payment obligations for the Day-Ahead Market for day  $D+1$  on the basis of the LMPs for the Day-Ahead Market for day  $D+1$ .
- At the end of each day  $D$ , each GenCo  $i$  uses stochastic reinforcement learning to update the action choice probabilities currently assigned to the supply offers in its action domain  $AD_i$ , taking into account its day- $D$  settlement payment ("reward"). If the supply offer reported by GenCo  $i$  on day  $D$  results in a relatively good reward, GenCo  $i$  increases the probability of choosing this supply offer on day  $D+1$ , and conversely.
- There are no system disturbances (e.g., weather changes) or shocks (e.g., forced generation outages or line outages). Consequently, the binding financial contracts determined in the Day-Ahead Market are carried out as planned and traders have no need to engage in real-time (spot) market trading.
- Each LSE and GenCo has an initial holding of money that changes over time as it accumulates earnings and losses.
- There is no entry of traders into, or exit of traders from, the wholesale power market. LSEs and GenCos are currently allowed to go into debt (negative money holdings) without penalty or forced exit.

Data flow for the principal types of AMES traders participating in the Day-Ahead Market is depicted in Fig 2. As indicated in Fig. 3, AMES has a graphical user interface (GUI) with separate screens for carrying out many functions useful for research, teaching, and training purposes. These functions include: (a) creation, modification, analysis, and storage of case studies; (b) initialization and editing of the structural attributes of the transmission grid; (c) initialization and editing of the structural attributes of LSEs and GenCos; (d) specification of learning parameters for GenCos; (e) specification of simulation controls (e.g., the simulation stopping rule); and (f) customization of table and chart output displays.

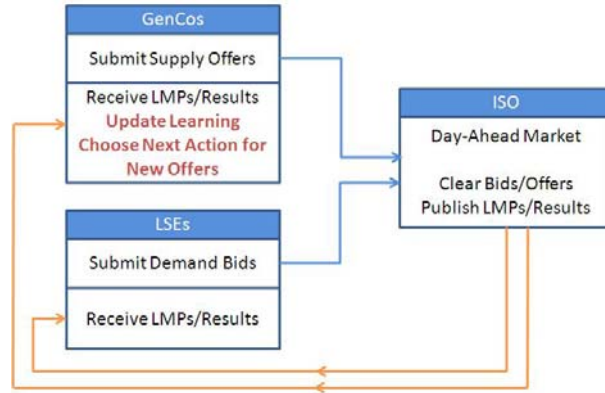


Fig. 2 Data flow for AMES traders in the Day-Ahead Market

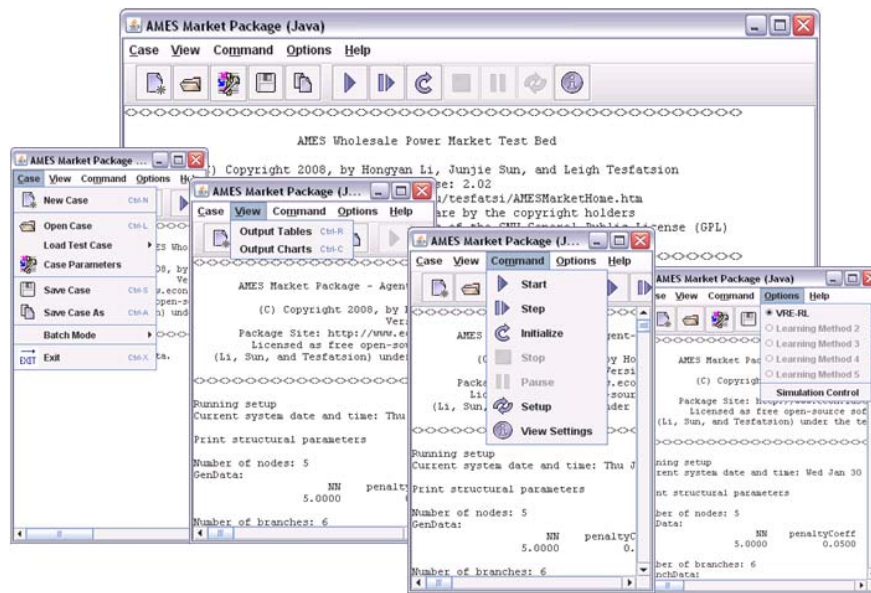


Fig.3 AMES Graphical User Interface (GUI)

## 4 ILLUSTRATIVE RESEARCH FINDINGS

### 4.1 LMP separation and volatility

From FERC’s market design and ISOs’ Business Practice Manuals (BPM), LSE demand bids for the day-ahead market are mixtures of fixed (price-insensitive) demands and price-sensitive demands. When we look at real data for day-ahead markets, using MISO’s data as an example, currently the price-sensitive demand is only about 1% of the total bid-in demand for the day-ahead market. Thus the question arises, what is LMP response if we systematically change the percentage of price-sensitive demand from 0% to 100%?

In addition, another related question is what if the ISO imposes a price cap on GenCo supply offers for the day-ahead market? Do LMPs have a controllable upper limit? Will this give profit-seeking GenCos an incentive to report smaller-than-true maximum capacities? To answer these questions,

AMES(V2.02) has been used to run systematic experiments to explore average LMP dynamic response to changes in demand-bid price sensitivity and supply-offer price cap levels.

This section presents illustrative experimental findings for a 5-bus test case; more detail findings are reported in [1,4,11].

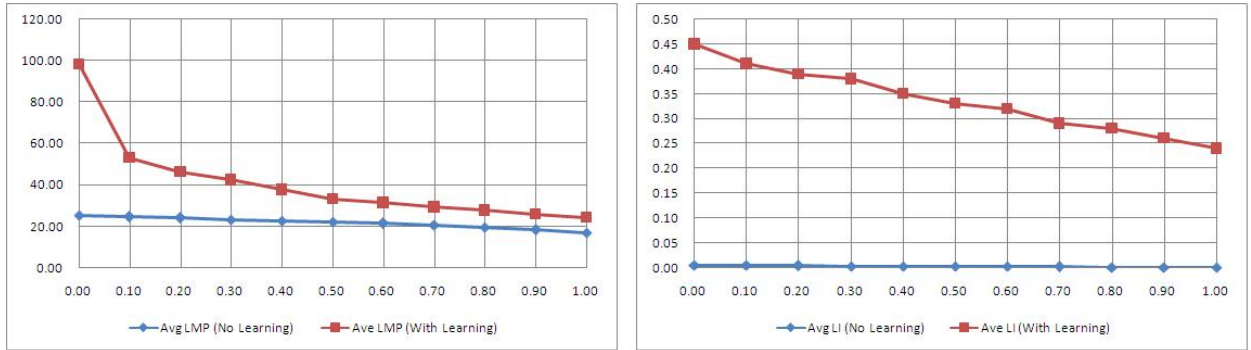


Figure 4. Comparison of average LMPs and average Lerner Index (LI) levels as demand-bid price sensitivity varies from 0% to 100%, both with and without GenCo learning

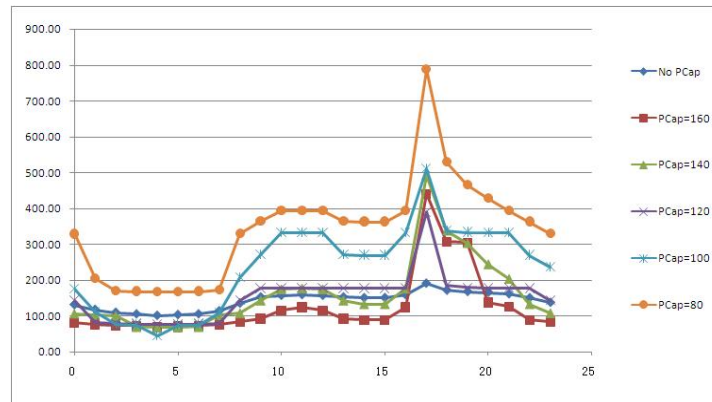


Figure 5. Average hourly LMPs during the final market day under alternative supply-offer price caps with 100% fixed demand (no demand-bid price sensitivity) and with GenCo learning.

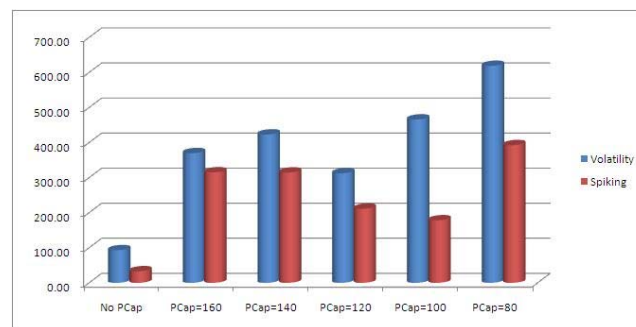


Figure 6. Average LMP volatility and spiking under varied supply-offer price caps with 100% fixed demand (no demand-bid price sensitivity) and with GenCo learning.

Figure 4 shows that, even with 100% demand-bid price sensitivity, average LMP is *much* higher under GenCo learning. This suggests that active demand-side bidding from LSEs reflecting better integration of wholesale and retail markets is needed. Countervailing power (active supply offers and active demand bids at the wholesale level) could help to ensure more competitive pricing.

As shown in Figures 5 and 6, for the tested scenario with 100% fixed demand (no demand-bid price sensitivity) and with GenCo learning, the introduction of a binding supply-offer price cap can in some cases induce more fluctuations in hourly LMPs while in other cases fluctuations are dampened. These results show that a supply-offer price cap is not necessarily an upper bound on LMPs. Moreover, setting an inappropriate level for this price cap can increase LMP volatility as well as causing other problems such as not enough total generation capacity.

#### **4.2 GenCo capacity withholding**

For FERC's market design, a key unresolved issue is the extent to which the complicated rules and regulations governing market operations under the design might encourage strategic bid/offer behaviors on the part of market participants that reduce overall market performance over time. A related issue is the extent to which grid congestion and load-pocket formation can be strategically manipulated to benefit certain market participants at the expense of others.

We have used AMES(V2.02) to conduct systematic physical and economic capacity-withholding experiments for a dynamic 5-bus test case under alternative demand-bid price sensitivity conditions ranging from 100% fixed demand (no demand-bid price sensitivity) to 100% demand-bid price sensitivity. This section summarizes some of this work; more detailed findings can be found in [1,8].

We first introduced a precise measure  $R$  for measuring the degree of demand-bid price sensitivity. An  $R$  value of 0.0 corresponds to 100% fixed demand (no demand-bid price sensitivity), and an  $R$  value of 1.0 corresponds to 100% demand-bid price sensitivity (no fixed demand). We then systematically explored a variety of different cases in which individual GenCos or groups of GenCos were permitted to engage in economic withholding and/or physical capacity withholding (shrinkage).

For example, in our Case 1 (5% maximum shrinkage for each GenCo), for each  $R$  value from 0.0 to 1.0 the five GenCos exhibited similar average capacity shrinkage percentages. However, for each  $R$  value the percentage change in average daily net earnings (Avg DNE) was positive for some GenCos and negative for others (relative to a no-shrinkage-permitted benchmark). In our Case 2 (10% maximum shrinkage for each GenCo), for each  $R$  value each GenCo's average capacity shrinkage percentage approximately doubled relative to Case 1. Nevertheless, for each  $R$  value the percentage change in each GenCo's Avg DNE was very similar in sign and magnitude to the Case 1 outcomes. These and other intriguing outcomes suggest there are many feedback effects and trade-offs among economic and physical capacity withholding in wholesale power markets that warrant further careful study.

## 5 PROJECT OUTPUT

### Project Home Page (Participants, Publications, Software, and Presentations):

[1] EPRC MISO project homepage: <http://www.econ.iastate.edu/tesfatsi/MISOEnergyGroup.htm>

### Project Software Releases:

[2] H. Li, J. Sun, and L. Tesfatsion, The AMES Market Package (Java): A Free Open-Source Test Bed for the Agent-Based Modeling of Electricity Systems, Version 2.02 released at the IEEE PES GM 2008, <http://www.econ.iastate.edu/tesfatsi/AMESMarketHome.htm> .

[3] J. Sun and L. Tesfatsion, DCOPFJ (Java): A Free Open-Source Solver for Bid/Offer-Based DC Optimal Power Flow Problems, Versions 1.0 and 2.0 released at the IEEE PES GM 2007, <http://www.econ.iastate.edu/tesfatsi/DCOPFJHome.htm> .

### Project Publications:

[4] H. Li, J. Sun and L. Tesfatsion, "Separation and Volatility of Locational Marginal Prices in Restructured Wholesale Power Markets", Working Paper, May 2009, under journal submission.

[5] H. Li and L. Tesfatsion, "Development of Open Source Software for Power Market Research: The AMES Test Bed", *Journal of Energy Markets*, to appear.

[6] L. Tesfatsion, "Auction Basics for Wholesale Power Markets: Objectives and Pricing Rules", *Proceedings*, IEEE PES GM, Calgary, Alberta, CA, July 26-30, 2009, to appear.

[7] H. Li and L. Tesfatsion, "The AMES Wholesale Power Market Test Bed: A Computational Laboratory for Research, Teaching, and Training", *Proceedings*, IEEE PES GM, Calgary, Alberta, CA, July 26-30, 2009, to appear.

[8] H. Li and L. Tesfatsion, "Capacity Withholding in Restructured Wholesale Power Markets: An Agent-Based Test Bed Study", *Proceedings*, IEEE PSCE, Seattle, WA, March 15-18, 2009.

[9] H. Liu, L. Tesfatsion, and A. A. Chowdhury, "Derivation of Locational Marginal Prices for Restructured Wholesale Power Markets", *Journal of Energy Markets*, Vol.2, No.1, 2009, 1-25.

[10] A. Somani and L. Tesfatsion, "An Agent-Based Test Bed Study of Wholesale Power Market Performance Measures", *IEEE Computational Intelligence Magazine*, Vol. 3, No. 4, Nov 2008, 56-72.

[11] H. Li, J. Sun, and L. Tesfatsion, "Dynamic LMP Response Under Alternative Price-Cap and Price-Sensitive Demand Scenarios", *Proceedings*, IEEE PES GM, Carnegie-Mellon University, Pittsburgh, July 20-24, 2008.

[12] J. Sun and L. Tesfatsion, "Dynamic testing of wholesale power market designs: An open-source agent-based framework," *Computational Economics*, vol. 30, pp. 291–327, 2007. Abridged version published in *Proceedings*, IEEE PES GM, Tampa, Florida, June 2007.

[13] J. Sun and L. Tesfatsion, "Open-source software for power industry research, teaching, and training: A DC-OPF illustration," *Proceedings, IEEE PES GM*, Tampa, Florida, June 2007.

#### **Project Presentations:**

[14] L. Tesfatsion, "Auction Basics for Wholesale Power Markets: Objectives and Pricing Rules", to be presented at the IEEE PES GM, Calgary, CA, July, 2009.

[15] H. Li and L. Tesfatsion, "The AMES Wholesale Power Market Test Bed: A Computational Laboratory for Research, Teaching, and Training", to be presented at the IEEE PES GM, Calgary, CA, July 26-30, 2009.

[16] H. Li and L. Tesfatsion, "Development of Open Source Software for Power Market Research: An Illustrative Case Study", to be presented at the IEEE PES GM, Calgary, CA, 2009.

[17] H. Liu, L. Tesfatsion, and A. A. Chowdhury, "Locational Marginal Pricing Basics for Restructured Wholesale Power Markets", to be presented at the IEEE PES GM, Calgary, CA, 2009.

[18] L. Tesfatsion, "Stress-Testing of Institutional Arrangements via Agent-Based Modeling: Illustrative Results for U.S. Wholesale Power Markets," George Mason University, April 3, 2009.

[19] H. Li and L. Tesfatsion, "Capacity Withholding in Restructured Wholesale Power Markets: An Agent-Based Test Bed Study", presented at the IEEE PSCE, Seattle, WA, March 15-18, 2009.

[20] H. Li, J. Sun, and L. Tesfatsion, "Dynamic LMP Response Under Alternative Price-Cap and Price-Sensitive Demand Scenarios", Institute for Operations Research and Management Science (INFORMS), Washington DC, October 12-15, 2008.

[21] H. Li, J. Sun, and L. Tesfatsion, "Dynamic LMP Response Under Alternative Price-Cap and Price-Sensitive Demand Scenarios", IEEE PES GM, David L. Lawrence Convention Center, Pittsburgh, PA, July 21-24, 2008.

[22] H. Li, J. Sun, and L. Tesfatsion, "Dynamic Price Response Under Alternative Price-Cap and Price-Sensitive Demand Scenarios", Summer Meeting of the North American Econometric Society, Carnegie-Mellon University, Pittsburgh, PA, June 19-22, 2008.

[23] H. Li, J. Sun, and L. Tesfatsion, "Dynamic LMP Response Under Alternative Price-Cap and Price-Sensitive Demand Scenarios", International Industrial Organization Conference, Washington, D.C., May 16-18, 2008.

[24] L. Tesfatsion, "Agent-Based Test Beds for Critical Infrastructure Research, Teaching, and Training", DOE-NREL, Washington, D.C., February 22, 2008.

[25] L. Kiesling and L. Tesfatsion, "A Test Bed for the Integrated Experimental Study of Retail and Wholesale Power Market Designs: Seaming GridLab-D with AMES", Tele-Seminar and Webcast, sponsored by the Pacific Northwest National Laboratory (PNNL), February 15, 2008.

- [26] L. Tesfatsion, "Agent-Based Test Beds for Power Industry Research, Teaching, and Training", Tele-Seminar and Webcast, sponsored by the Power Systems Energy Research Center (PSERC), Cornell University, February 5, 2008.
- [27] L. Tesfatsion, "Agent-Based Test Beds for Critical Infrastructure Research, Teaching, and Training", Plenary Address, AGENT 2007, Northwestern University, November 17, 2007.
- [28] J. Sun and L. Tesfatsion, "Open-Source Software for Power Industry Research, Teaching, and Training: A DC-OPF Illustration", IEEE PES GM, Tampa, Florida, June 25-28, 2007.
- [29] H. Li, "Graphic User Interface (GUI) for the AMES Software Package: Test-Bed for the Study of Restructured Power Markets", Poster Session, IEEE PES GM, Tampa, Florida, June 25-28, 2007.
- [30] H. Li, J. Sun, and L. Tesfatsion, "An Agent-Based Computational Laboratory for Wholesale Power Market Design", IEEE PES GM, Tampa, Florida, June 25-28, 2007.
- [31] J. Sun and L. Tesfatsion, "Dynamic Testing of Wholesale Power Market Designs: An Agent-Based Computational Approach", North American Meetings of the Econometric Society, Duke University, Durham, NC, June 21-24, 2007.
- [32] J. Sun and L. Tesfatsion, "Dynamic Testing of Wholesale Power Market Designs: An Agent-Based Computational Approach", 13th International Conference on Computing in Economics and Finance, Society for Computational Economics, Montreal, Canada, June 14-16, 2007.
- [33] H. Li, "MISO Market Performance: An Open-Source Computational Test-Bed", Forty-Fourth Annual Meeting of the Electric Power Research Center, Power Affiliate Research Program, Schemann Building, Iowa State University, May 9, 2007.
- [34] J. Sun and L. Tesfatsion, "Dynamic Testing of Wholesale Power Market Designs: An Agent-Based Computational Approach", 5th Annual International Industrial Organization Conference (IIOC), Savannah, Georgia, April 14-15, 2007.
- [35] L. Tesfatsion, "Agent-Based Computational Economics: A Constructive Approach to Economic Theory" Allied Social Science Associations (ASSA) Annual Meeting, Chicago, IL, January, 2007.
- [36] L. Tesfatsion and J. Sun, "Agent-Based Test Beds for Market Design", Allied Social Science Association (ASSA) Annual Meeting, Chicago, IL, January 5-7, 2007.
- [37] J. Sun and L. Tesfatsion, "Dynamic Testing of Wholesale Power Market Designs: An Agent-Based Computational Approach", INFORMS annual meeting, Pittsburgh, PA, November 5-8, 2006.
- [38] J. Sun, "Dynamic Testing of Wholesale Power Market Designs: An Open-Source Agent-Based Framework", presented (poster session) at the Institute of Computational Economics (ICE) Summer School, University of Chicago and Argonne National Lab, July 17-22, 2006.

- [39] L. Tesfatsion, "Dynamic Testing of Wholesale Power Market Designs: An Open-Source Agent-Based Framework" VII Trento Summer School: Intensive Course on Agent-Based Computational Economics, Sardinia-Trento, Italy, July 17, 2006.
- [40] S. Widergren, J. Sun, and L. Tesfatsion, "Market Design Test Environments", IEEE PES GM, Montreal, Canada, June 2006.
- [41] L. Tesfatsion, "Agent-Based Computational Economics: A Constructive Approach to Economic Theory", Plenary Address, Computing in Economics and Finance (CEF'2006), sponsored by the Society for Computational Economics, Limassol, Cyprus, June 23, 2006.
- [42] L. Tesfatsion, "NSF Project & EPRC MISO Project: Brief Overview of Work to Date", Presented to a joint meeting of members from the Iowa Utilities Board and the ISU NSF/EPRC MISO projects, Heady 568B, 12-2:00pm, ISU, April 21, 2006.
- [43] L. Tesfatsion, "Dynamic Testing of Wholesale Power Market Designs: An Agent-Based Computational Approach", International Industrial Organization Conference (IIOC), Northeastern University, Boston, MA, April 8, 2006.

**PI-Directed Student Thesis Work:**

- H. Li, ECpE Ph.D. passed Ph.D. preliminary examination (December 2, 2008), dissertation work in progress. (Co-Major Adviser: L. Tesfatsion)
- N. Yu, ECpE Ph.D. dissertation work in progress. (Co-Major Adviser: L. Tesfatsion)
- Q. Zhou, ECpE Ph.D. dissertation work in progress. (Co-Major Adviser: L. Tesfatsion)
- Abhishek Somani, Econ Ph.D. dissertation work in progress. (Major Adviser: L. Tesfatsion)
- H. Zhao, Econ Ph.D. dissertation work in progress. (Co-Major Adviser: L. Tesfatsion)
- M. Pentapalli, *A Comparative Study of Roth-Erev and Modified Roth-Erev Reinforcement Learning Algorithms for Uniform-Price Double Auctions*. M.S. thesis, Iowa State University, March 2008. (Co-Major Adviser: L. Tesfatsion). This thesis uses the AMES test bed for three of five studied test cases.
- H. Liu, *Myth of Locational Marginal Price Unleashed: MISO Case Study*. M.S. creative component, Iowa State University, March 2008. (Major Adviser: L. Tesfatsion).
- J. Sun, *Testing Financial and Real Market Operations in Restructured Electricity Systems: Four Theoretical and Empirical Studies*. Economics Ph.D. dissertation, Iowa State University, December 2006. (Major Adviser: L. Tesfatsion)