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:
  \[ \text{AMES} = \text{Agent-based Modeling of Electricity Systems} \]
- Illustrative experimental findings
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
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
Since 2000 Cal/Enron scandal, retail restructuring has been slowed/stopped.

Source: 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 permit 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.
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 join 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

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Retail & Wholesale Power System Operations

Source: http://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
Seaming in Progress

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 standard analytical & statistical tools!

Exhibit 2-3: DART Components Overview

Two-Settlement Power Market System under LMP

Core of FERC design

AMES focus to date
Project Work to Date: Wholesale Level

- Development and open-source release of **AMES** (*Agent-based Modeling of Electricity Systems*)

- **AMES** = ABM testbed with core FERC design features

- Used to test performance under FERC design

- Used to test performance under modifications of design

**amous 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)
  — “Tool box” 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)

00:00
Day-Ahead Market (DAM) for day D+1
ISO collects bids/offers from LSEs and GenCos

11:00
ISO evaluates LSE demand bids and GenCo supply offers

16:00
ISO solves D+1 DC OPF and posts D+1 dispatch and LMP schedule

23:00
Day-ahead settlement
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:

  \[
  F_j(p^S_{Lj}) = c_j - 2d_j p^S_{Lj}
  \]

  \[0 \leq p^S_{Lj} \leq SLMax_j\]
AMES GenCos are learners who report strategic supply offers to ISO for DAM

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

\[
MC_{i}^{R}(p_{Gi}) = a_{i}^{R} + 2b_{i}^{R}p_{Gi}
\]

\[
Cap_{i}^{L} \leq p_{Gi} \leq Cap_{i}^{RU}
\]

GenCos can learn to report \textit{higher-than-true} marginal costs and/or to report \textit{lower-than-true} maximum capacity.
ISO Goal is Max[Total Net Surplus] subject to trans & gen constraints: 2-bus example

Cleared load = \( p_{L}^{F} \). LSE at bus 2 pays \( LMP_{2} > LMP_{1} \) for each unit of \( p_{L}^{F} \). \( M \) units of \( p_{L}^{F} \) are supplied by cheaper \( G1 \) at bus 1 who receives only \( LMP_{1} \) per unit.

ISO collects difference:

**ISO Net Surplus**

\[
= \left[ \text{LSE Payments} - \text{GenCo Revenues} \right] \\
= M \times [LMP_{2} - LMP_{1}]
\]
Calculation of TNS: 2-Bus Example ... Cont'd

**ISO Net Surplus:**

\[ \text{INS} = M \times [\text{LMP}_2 - \text{LMP}_1] \]

**GenCo Net Surplus:**

Area S1 + Area S2

**LSE Net Surplus:**

Area B

**Total Net Surplus:**

\[ \text{TNS} = [\text{INS} + \text{S1} + \text{S2} + \text{B}] \]

**ISO Objective (DC-OPF):**

maximize \( \text{TNS} \) subject to trans/gen constraints.
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 \( V_0 \)

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

\[\text{TNS}^R = \text{Total Net Surplus based on reported GenCo marginal cost functions rather than true GenCo marginal cost functions.}\]

\[\text{Lagrangian multiplier (or "shadow price") solution for the bus-}k\text{ balance constraint (17) gives the LMP}_k\text{ at bus } k\]
Illustrative AMES Experimental Findings for a 5-Bus Test Case

**Definition:** *Incentive misalignment* $\rightarrow$

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

GenCo True Marginal Cost Functions

Price ($/MWh)

Power (MWs)

GenCo1

GenCo2

GenCo3

GenCo4

GenCo5
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 $\text{Prob}$, 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 $\text{Prob}_k$. 

- Choose
- Action Choice $a_1$
- Action Choice $a_2$
- Action Choice $a_3$

- Update
- Choice Propensity $q_1$
- Choice Propensity $q_2$
- Choice Propensity $q_3$

- Normalize
- Choice Probability $\text{Prob}_1$
- Choice Probability $\text{Prob}_2$
- Choice Probability $\text{Prob}_3$
**R Measure for Demand-Bid Price Sensitivity**

Note: In actual U.S. ISO energy regions, \( R \approx 0.01 \)

For LSE \( j \) in Hour \( H \):

\[
R = \frac{\text{SLMax}_j}{\text{p}_{Lj}^{F} + \text{SLMax}_j}
\]

- \( \text{p}_{Lj}^{F} \) = Fixed demand for real power (MWs)
- \( \text{SLMax}_j \) = Maximum potential price-sensitive demand (MWs)

\( R = 0.0 \) \( \Rightarrow \) (100% Fixed Demand)

\( R = 0.5 \) \( \Rightarrow \) (100% Price-Sensitive Demand)

\( R = 1.0 \)
LSE Hourly Fixed Demands for R=0.0

17 = Peak demand hour
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)

With GenCo Learning (Day 1000)
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:

- LSEs
  - Submit demand bids.
  - LSE Payments
- ISO
  - Day-Ahead Market: Clear bids/offers using DC-OPF.
  - Post LMPs/dispach.
  - ISO Net Surplus = [LSE Payments – GenCo Revenues]
  - GenCo Revenues
- GenCos
  - Receive LMPs/dispach.
  - Learn from results & update supply offers.
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  

- 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**

- **AMES Test Bed Homepage (Code/Manual/Publications)**
  www.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- **Agent-Based Electricity Market Research**
  www.econ.iastate.edu/tesfatsi/aelect.htm

- **Agent-Based Computational Economics Homepage**
  www.econ.iastate.edu/tesfatsi/ace.htm

- **ISU Electric Energy Economics (E3) Group**
  www.econ.iastate.edu/tesfatsi/E3GroupISU.htm