AMES Wholesale Power Market Test Bed

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Originally Presented: 21 March 2012
(some figures/refs have been updated)
Presentation Outline

- Wholesale power market design proposed in 2003 by the U.S. Federal Energy Regulatory Commission (FERC), the basis of the AMES test bed architecture
- Basic features and capabilities of the AMES test bed
  
  \textbf{AMES} = Agent-based \textbf{M}odeling of \textbf{E}lectricity \textbf{S}ystems
  
  \url{https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm}

- Illustrative Dynamic 5-Bus Test Case Results
- On-Line Resources
In April 2003 the U.S. Federal Energy Regulatory Commission (FERC) proposed a wholesale electric power market design for common adoption throughout U.S.

Over 60% of North American generation now operates under some version of FERC design.

Adopters to Date: New York (NYISO), Mid-Atlantic States (PJM), Texas (ERCOT), New England (ISO-NE), California (CAISO), Midwest/Manitoba (MISO), & Southwest (SPP)
FERC Wholesale Power Market Design Adopters (2015)
U.S. Wholesale Electric Power Transmission Grid
Core Features of FERC’s Market Design

- Market to be managed by an *Independent System Operator (ISO)* or *Regional Transmission Organization (RTO)* having no ownership or financial stake

- **Two-settlement system:** Concurrent operation of day-ahead (forward) & real-time (spot) markets

- Transmission grid congestion managed via *Locational Marginal Prices (LMPs)*, where:

  - \( \text{LMP}(k,T) \, \text{($/MWh)} \) at a grid bus \( k \) during an operating period \( T \) is the least system cost of servicing a maintained power demand (MW) at \( b \) during \( T \) increased by 1 additional MW from current level.

- Oversight & market power mitigation by outside agency
Complexity of FERC Market Design

Example: MISO Business Practices Manual 001
DART = Day-Ahead and Real-Time Markets

DAM/RTM Two-Settlement System: Core of FERC Design = Main focus of AMES Test Bed
Typical ISO/RTO Two-Settlement System Activities on a Single Day D-1

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Day-Ahead Market (DAM) for day D</td>
</tr>
<tr>
<td></td>
<td>ISO/RTO collects bids/offers from Load-Serving Entities and Generation Companies</td>
</tr>
<tr>
<td>11:00</td>
<td>ISO/RTO solves SCUC/SCED (DC Optimal Power Flow)</td>
</tr>
<tr>
<td>13:00</td>
<td>ISO/RTO posts dispatch schedule and LMPs for day D</td>
</tr>
<tr>
<td>23:00</td>
<td>Day-ahead settlement</td>
</tr>
</tbody>
</table>

Real-Time Market (RTM) consisting of multiple market processes during day D-1

Real-time settlement
Typical ISO/RTO Two-Settlement System Activities on Successive Days D-1 and D

Who

Market Participants

ISO/RTO

Generators, ISO/RTO

ISO/RTO

What

Demand bids & supply offers submitted to the day-ahead market for day D

Posting of day-ahead dispatch and LMP schedule

Adjust day-ahead offers, adjust day-ahead schedule

Dispatch signals and calculation of real-time LMPs

When

Day Ahead

5 A.M.

11 A.M.

How

SCUC/SCED

Real Time

Operating Hour

Reliability Assessment

Morning of Day D-1

Afternoon of Day D-1 Thru Operating Hour on Day D
Potential Volatility of RTM LMPs under FERC’S Market Design
Real-Time LMPs ($/MWh) 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!
Real-Time LMPs ($/MWh) in Midwest ISO (MISO)
September 5, 2006, 14:30

Note this price, $226.25
Five Minutes Later...

79% drop in price in 5 minutes!
Problem: FERC’s market design is a complicated mix of features

Difficult to model and study using standard analytical and statistical tools

AMES Approach: Develop an agent-based test bed permitting careful experimental testing of

- the FERC market design
- new/modified market design features
AMES Wholesale Power Market Test Bed: Homepage
https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- Research/teaching/training grade open-source test-bed
- Operational validity ("simple but not too simple")
- Permits dynamic testing with learning traders
- Permits intensive experimentation with alternative scenarios
- Free open-source Java/Python implementation (full access to code)
- Flexible & modular (easy to modify test bed features)
- V1.31 released (IEEE PES General Meeting, June 2007)
- V2.05 released (IEEE PES General Meeting, July 2009)
- V5.0 released (GitHub Code/data Repository, 2020)
- All version releases to date are posted at the AMES Homepage, above
AMES (V2.05) Architecture
(based on business practice manuals for 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)
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

◆ Any AMES decision-maker can be a learning agent
  — Java Reinforcement Learning Module (JReLM)
  — “Tool-Box” permitting experimentation with a wide variety of learning methods (Roth-Erev, Temp Diff/Q-learning,...)

◆ SCED implemented via an extensible DC-OPF module
  — Bid/offer-based DC Optimal Power Flow Module (DCOPFJ)
  — Permits experimentation with various DC OPF formulations

◆ Output displays and test case templates
  — Customizable chart/table displays & 5-bus/30-bus test cases
AMES Graphical User Interface (GUI)
Tool Bar/Menus for DAM Data Input and Output Displays
Illustration of AMES Dynamics with No Shocks
(day-ahead contracts fulfilled as planned)
### Activities of AMES ISO During a Typical Day D-1

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td><strong>Day-Ahead Market (DAM)</strong> held on day D-1 for Operating Day D</td>
</tr>
<tr>
<td></td>
<td>ISO collects energy bids &amp; offers from LSEs &amp; GenCos.</td>
</tr>
<tr>
<td>11:00</td>
<td>ISO solves SCED (bid/offer based DC OPF) to determine dispatch schedule &amp; LMP at each grid bus B for each hour H of Day D.</td>
</tr>
<tr>
<td>16:00</td>
<td><strong>ISO posts dispatch schedule and LMPs for Day D.</strong></td>
</tr>
<tr>
<td>23:00</td>
<td><strong>Day-ahead settlement</strong></td>
</tr>
</tbody>
</table>
## Public Access:

### Public Methods
- `getWorldEventSchedule( clock time, ... );`
- `getMarketProtocols( bid/offer reporting, settlement, ... );`
Methods for receiving data;
Methods for retrieving stored ISO data;

## Private Access:

### Private Methods
- Methods for gathering, storing, posting, & sending data;
- Method for solving hourly DC optimal power flow;
- Methods for posting schedules and carrying out settlements;
- Methods for implementing market power mitigation;

### Private Data
- Historical data (e.g., cleared bids/offers, market prices,...);
- Address book (communication links);
Hourly demand bid for each LSE $j$

**Fixed + Price-Sensitive Demand Bid**

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

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

$$0 \leq p^S_{Lj} \leq \text{SLMax}_j$$
AMES Load-Serving Entity
(Wholesale Energy Buyer)

Public Access:

// Public Methods
getMarketProtocols(posting, trade, settlement);
getMarketProtocols(ISO market power mitigation);
Methods for receiving data;
Methods for retrieving LSE data;

Private Access:

// Private Methods
Methods for gathering, storing, and sending data;
Methods for forecasting customer energy demands;
Methods for calculating own expected & actual net earnings;

// Private Data
Own downstream demand, grid location, current wealth…;
Data recorded about external world (prices, dispatch,…);
Address book (communication links);
AMES GenCos are learning agents who report strategic supply offers to the ISO for the Day-Ahead Market.

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

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

$$\text{Cap}_i^L \leq p_{Gi} \leq \text{Cap}_i^{RU}$$

GenCos can learn to report higher-than-true marginal costs and/or to report lower-than-true maximum capacity.
AMES Generation Company
(Energy Producer and Seller)

Public Access:

// Public Methods
getWorldEventSchedule( clock time,... );
getMarketProtocols( ISO market power mitigation,... );
Methods for receiving data;
Methods for retrieving GenCo data;

Private Access:

// Private Methods
Methods for gathering, storing, and sending data;
Methods for calculating own expected & actual net earnings;
Method for updating own supply offers (LEARNING);

// Private Data
Own capacity, grid location, cost function, current wealth... ;
Data recorded about external world (prices, dispatch,...);
Address book (communication links);
Agent learning in AMES is implemented via the JReLM module.

The Java Reinforcement Learning Module (JReLM) was developed by Charles J. Gieseler, Comp Sci M.S. Thesis, 2005.
ISO goal is to maximize Total Net Surplus (TNS) subject to system constraints: A Two-Bus Example (Adapted from Harold Salazar, ISU ECpE M.S. Thesis, 2008)

Given the line capacity limit $M$, the cleared LSE load at bus 2 = $p_F^L$. The LSE receives price $r$ ($/\text{MWh}$) for the resale of $p_F^L$ at the retail level.

$M$ units of $p_F^L$ are supplied by GenCo G1 at bus 1 at price $LMP_1$ ($/\text{MWh}$); the line capacity limit $M$ prevents G1 from supplying any additional units. Remaining [$p_F^L - M$] units are supplied by GenCo 2 at bus 2 at the higher price $LMP_2$ ($/\text{MWh}$). The LSE at bus 2 pays $LMP_2$ for each unit of $p_F^L$.

As a result of these transactions, the ISO collects “ISO Net Surplus” defined as follows:

**ISO Net Surplus**

\[
= [ \text{LSE Payments} - \text{GenCo Revenues} ]
\]

\[
= LMP_2 \times p_F^L - M \times LMP_1 - [p_F^L - M] \times LMP_2
\]

\[
= M \times [ LMP_2 - LMP_1 ] = \text{[Shaded Figure Area]}
\]
Two-Bus Example ... Continued

**ISO Net Surplus:**
Area INS =: M x [LMP\(_2\) – LMP\(_1\)]

**GenCo Net Surplus:**
Area S1 + Area S2

**LSE Net Surplus:**
Area B =: p\(_F\)\(_L\) x [r – LMP\(_2\)]

**Total Net Surplus:**
TNS = [INS + S1 + S2 + B]

**ISO Optimization Objective:**
Maximize TNS subject to system constraints.
AMES Simulation Example: Total Net Surplus (TNS) in Hour 17 for a 5-Bus test case with no transmission congestion

$r = \text{Rate (fixed price) paid to LSEs by their retail customers with flat-rate contracts}$

$= \text{LSEs’ max willingness to pay for each MW of their fixed demand $p^F$ submitted to a day-ahead wholesale power market}$

$/$MWh

True Total Supply and Demand Curves at Hour 17

$\text{Max Total GenCo Capacity}$
AMES Calculation of TNS: General Form
(Note LMPs cancel out of TNS expression!)

Total Net Surplus for Hour H of Day D+1, based on Day D Supply Offers and Demand Bids:

\[ TNS(H, D) \]

\[ = LSE\text{NetSur}(H, D) + \text{GenNetSur}(H, D) + \text{ISONetSur}(H, D) \]

\[ = \sum_{j=1}^{J} GS_j(H, D) - \sum_{i=1}^{I} [C_i^a(H, D)] \]

where

\[ GS_j(H, D) = [r \cdot p_{L_j}^{F}(H, D) + \int_{0}^{p_{L_j}^{S}(H, D)} F_{jHD}(p)dp] \]

\[ C_i^a(H, D) = \int_{0}^{p_{GI}(H, D)} MC_i(p)dp \]

- LSE j’s gross surplus from its retail fixed demand sales
- LSE j’s gross surplus from its retail price-sensitive demand sales
- GenCo i’s total avoidable costs of production
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 \( \delta_{km} = [\text{delta}_k - \text{delta}_m] \) across each branch km is small so that \( \cos(\delta_{km}) \approx 1 \) and \( \sin(\delta_{km}) \approx \delta_{km} \)

Lagrange multiplier (or “shadow price”) solution for the bus-k balance constraint (17) gives the price LMP\(_k\) at bus k.

\[ TNS^R = \text{Total Net Surplus based on reported GenCo marginal cost functions rather than true GenCo marginal cost functions.} \]
AMES V2.06: ISO Solves DC-OPF via DCOPFJ Module

- DC-OPF raw data (SI)
- Per Unit conversion
- Form SCQP matrices
- QuadProgJ: An SCQP solver
- DCOPFJ Shell
- Solution output (SI)
- Per Unit SCQP output
Extension of AMES to an Integrated Retail/Wholesale (IRW) Power System Test Bed

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

Wholesale
AMES Test Bed
developed by ISU Team

Retail
GridLAB-D
developed by DOE/PNNL & ISU IRW Project Group
Illustrative AMES Experimental Findings for a 5-Bus Test Case

Definition: *Incentive misalignment* → Institutional design fails to align incentives of power system participants with efficiency objectives (non-wastage of resources) and/or welfare objectives (socially desirable distribution of total net surplus to individual power system participants)

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%]
Five GenCo sellers G1,...,G5 and three LSE buyers LSE 1, LSE 2, LSE 3

5-Bus Transmission Grid
(used in many RTO/ISO business practice/training manuals)
Partial depiction of input data for the 5-bus test case:

<table>
<thead>
<tr>
<th>Base Values$^d$</th>
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<tr>
<td>$S_o$</td>
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<table>
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<th>$\pi^c$</th>
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<tr>
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<td>0.05</td>
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Branch

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<th>$X^e$</th>
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Gen ID | atNode | FCost | $a$ | $b$ | Cap$^L$ | Cap$^U$ | Init$^S$ |
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LSE

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<td>301.22</td>
<td>294.78</td>
<td>278.83</td>
<td>259.61</td>
</tr>
</tbody>
</table>

$^d$For simplicity, the base apparent power $S_o$ (MVA) and base voltage $V_o$ (kV) are chosen so base impedance $Z_o$ satisfies $Z_o = V_o^2 / S_o = 1$.

$^b$Total number of nodes

$^c$Soft penalty weight $\pi$ for voltage angle differences

$^d$Upper limit $P_{km}^U$ (in MWs) on the magnitude of real power flow in branch $km$

$^e$Reactance $X_{km}$ (in ohms) for branch $km$

$^f$L-H: Load (in MWs) for hour H, where H=00,01,...,23
GenCo True Cost & Capacity Attributes

GenCo True Marginal Cost Functions

- GenCo1
- GenCo2
- GenCo3
- GenCo4
- GenCo5

Price ($/MWh) vs Power (MWs)
In 5-bus study, AMES GenCos use VRE-RRL learning

(Version of Roth-Erev Reactive 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 $\text{Prob}_k$. 
R Measure for Demand-Bid Price Sensitivity

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

For LSE $j$ in Hour $H$:

$p_{F_{Lj}} = \text{Fixed demand for real power (MWs)}$

$\text{SLMax}_{j} = \text{Maximum potential price-sensitive demand (MWs)}$

$$R = \frac{\text{SLMax}_{j}}{[p_{F_{Lj}} + \text{SLMax}_{j}]}$$

- $R=0.0$ (100% Fixed Demand)
- $R=0.5$
- $R=1.0$ (100% Price-Sensitive Demand)
LSE Hourly Fixed Demands for R=0.0

17 = Peak demand hour
First Experiments: Avg GenCo net earnings (Day 1000) for R=0 under varied learning parameter settings ($\alpha$, $\beta$)
Li/Tesfatsion, J. Econ. Behavior and Organization, 2011

Small beta $\cong$ “zero-intelligence” budget-constrained trading.

Learning matters!

= Sweet-spot region
★ = Selected sweet spot learning-parameter setting for remaining experiments
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)

With GenCo Learning (Day 1000)
True Vs. Reported MC (Averaged)* for R=0.0 on Day 422
(Each Generator has converged with Prob ≥ 0.999)

*NOTE: 20-run averages. Typical convergence time = 62 days, max time = 422.
Omitted Gen 1 MC curve is similar to Gen 2’s.
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, *Comp Methods in Economic Dynamics*, 2011)

❑ **Bottom Line:**

For each tested R-value, prices (LMPs) are much higher under GenCo VRE-RRL learning due to strategic GenCo supply offers

❑ **Conjectured Need:**

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

❑ **Possible Means:**

*Integrated wholesale/retail restructuring* that encourages a greater array of price-sensitive retail contracts, & permits retail consumers to select their LSE suppliers
After 2000 Cal/Enron scandal, retail restructuring slowed or stopped altogether

Source: https://www.eia.doe.gov/cneaf/electricity/page/restructuring/restructure_elect.html
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 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-RRL 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)
On-Line Resources

- Presentation Slides
  https://www2.econ.iastate.edu/tesfatsi/AMESMarketProject.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

- Integrated Retail/Wholesale Power Systems Project
  https://www2.econ.iastate.edu/tesfatsi/IRWProjectHome.htm