AMES Wholesale Power Market Test Bed

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(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

AMES = Agent-based Modeling of Electricity Systems
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

Exhibit 2-3: DART Components Overview

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</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 &amp; posts dispatch set-points and LMP schedule for D</td>
</tr>
<tr>
<td>16:00</td>
<td>ISO/RTO opens “re-offer period” for generation, reassesses resource needs for day D, &amp; changes day D schedule as needed</td>
</tr>
<tr>
<td>23:00</td>
<td>Day-ahead settlement</td>
</tr>
</tbody>
</table>

- **Real-Time Market (RTM)** open all 24 hours of 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

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

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!
AMES Computational Modeling Approach

- **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>Day-Ahead Market (DAM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>Day-Ahead Market (DAM) 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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>ISO solves SCED (bid/offer based DC OPF) to determine dispatch set-points &amp; LMP schedule for each hour of operating day D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:00</td>
<td></td>
</tr>
<tr>
<td>16:00</td>
<td>ISO posts dispatch set-points and LMP schedule for each hour of operating day D.</td>
</tr>
<tr>
<td>23:00</td>
<td>Day-ahead settlement</td>
</tr>
</tbody>
</table>

Real-Time Market (RTM) processes during day D-1

Real-time settlement
### AMES ISO (Independent System Operator)

#### 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);
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

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

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

  $0 \leq p^S_{Lj} \leq \text{SLMax}_j$
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 the maximization of Total Net Surplus subject to transmission & generation power capacity constraints (2-bus example adapted from Harold Salazar, ISU ECpE M.S. Thesis, 2008)

Cleared load = $p^F_L$. LSE at bus 2 pays LMP$_2 >$ LMP$_1$ for each unit of $p^F_L$. M units of $p^F_L$ are supplied by cheaper G1 at bus 1 who receives only LMP$_1$ per unit.

$r =$ Rate charged by the LSE to its retail customers on flat-rate contracts.

ISO net revenue stream:

**ISO Net Surplus**

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

\[
= M \times [\text{LMP}_2 - \text{LMP}_1]
\]
Total Net Surplus (TNS)  
2-Bus Example ... Continued

ISO Net Surplus:  
INS = M x [LMP_2 - LMP_1]

GenCo Net Surplus:  
Area S1 + Area S2

LSE Net Surplus:  
Area B

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

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

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

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

$r$ = Non-revenue TNS

$p^F$ = Revenue from TNS

Max Total GenCo Capacity

True Total Supply and Demand Curves at Hour 17

$/$MWh

Power (MW)
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:

\[ TNS(H, D) \]

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

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

where

\[ GS_j(H, D) = [r \cdot p_{L_j}^F(H, D) + \int_0^{p_{L_j}^S(H, D)} F_{jHD}(p)dp] \]

\[ C_i^a(H, D) = \int_0^{p_{Gi}(H, D)} \text{MC}_i(p)dp \]

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
Lagrange multiplier (or “shadow price” ) solution for the bus-k balance constraint (17) gives the price \( L_{MP_k} \) at bus \( k \).

**DC-OPF formulation** is derived from AC-OPF under three assumptions:

(a) Resistance on each branch \( k = 0 \)

(b) Voltage magnitude at each bus \( k = \text{base voltage } V_o \)

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

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 \( D \).

\[
\max \quad TNS^R \\
\text{with respect to LSE real-power price-sensitive demands, GenCo real-power generation levels, and voltage angles}
\]

\[
P_j^S, j = 1, \ldots, J; P_{Gi}, i = 1, \ldots, I; \delta_k, k = 1, \ldots, K (16)
\]

subject to

(i) a real-power balance constraint for each bus \( k = 1, \ldots, K \):

\[
\sum_{i \in I_k} P_{Gi} - \sum_{j \in J_k} P_j^S - \sum_{km} P_{km} = \sum_{j \in J_k} P_{Lj} (17)
\]

where, letting \( x_{km} \) (ohms) denote reactance for branch \( km \), and \( V_o \) denote the base voltage (in line-to-line kV),

\[
P_{km} = [V_o]^2 \cdot [1/x_{km}] \cdot [\delta_k - \delta_m]
\]

(ii) a limit on real-power flow for each branch \( km \):

\[
|P_{km}| \leq P_{km}^B (18)
\]

(iii) a real-power operating capacity interval for each GenCo \( i = 1, \ldots, I \):

\[
\text{Cap}_{i}^L \leq P_{Gi} \leq \text{Cap}_{i}^U (19)
\]

(iv) a real-power purchase capacity interval for price-sensitive demand for each LSE \( j = 1, \ldots, J \):

\[
0 \leq P_{Lj}^S \leq \text{SLMax}_j (20)
\]

(v) and a voltage angle setting at angle reference bus 1:

\[
\delta_1 = 0 (21)
\]

**AMES Day-Ahead Market SCED (DC-OPF) Formulation**:

\[
\min \quad TNS^R \\
\text{subject to}
\]

TNS\(^R\) = 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) → DCOPFJ Shell → QuadProgJ: An SCQP solver

Per Unit conversion

Form SCQP matrices

Per Unit SCQP output

Solution output (SI)
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

seamed

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%]
5-Bus Transmission Grid
(used in many RTO/ISO business practice/training manuals)

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

Bus Transmission Grid

250 MW Capacity
Partial depiction of input data for the 5-bus test case:

<table>
<thead>
<tr>
<th>Base Values (d)</th>
<th>(S_o)</th>
<th>(V_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>

\(K^b\)
| \(\pi^c\) | 0.05 |

Branch

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>lineCap (d)</th>
<th>(X^e)</th>
</tr>
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<tr>
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<th>FCost</th>
<th>(a)</th>
<th>(b)</th>
<th>Cap (L)</th>
<th>Cap (U)</th>
<th>Init$</th>
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LSE

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<th>L-04</th>
<th>L-05</th>
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<tr>
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<td>L-23</td>
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<td>353.73</td>
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<tr>
<td>3</td>
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<td>291.61</td>
<td>320.44</td>
<td>307.67</td>
<td>304.39</td>
<td>301.22</td>
<td>294.78</td>
<td>278.83</td>
<td>259.61</td>
</tr>
</tbody>
</table>

\(a\) 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 \(P^U_{km}\) (in MWs) on the magnitude of real power flow in branch \(km\)

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

\(L-H\): Load (in MWs) for hour \(H\), where \(H=00,01,\ldots,23\)
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 $q_i$, normalized to choice probabilities $Prob_i$, 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 $Prob_k$. 

**R Measure for Demand-Bid Price Sensitivity**

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

For LSE $j$ in Hour $H$:

- $p_{Fj} = \text{Fixed demand for real power (MWs)}$
- $\text{SLMax}_j = \text{Maximum potential price-sensitive demand (MWs)}$

$$R = \frac{\text{SLMax}_j}{\text{LF}_{Lj} + \text{SLMax}_j}$$

**Graphs:**

- **$R=0.0$** (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 100) for R=0 under varied learning parameter settings
Li/Tesfatsion, *J. Econ. Behavior and Organization*, 2011

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

Learning matters!

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$\star$ = Selected settings for next experiments

= 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)

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](https://www2.econ.iastate.edu/tesfatsi/AMESMarketProject.pdf)

- **AMES Test Bed Homepage (Code/Manual/Publications)**
  [https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm](https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm)

- **Agent-Based Electricity Market Research**
  [https://www2.econ.iastate.edu/tesfatsi/aelect.htm](https://www2.econ.iastate.edu/tesfatsi/aelect.htm)

- **Agent-Based Computational Economics Homepage**
  [https://www2.econ.iastate.edu/tesfatsi/ace.htm](https://www2.econ.iastate.edu/tesfatsi/ace.htm)

- **Integrated Retail/Wholesale Power Systems Project**
  [https://www2.econ.iastate.edu/tesfatsi/IRWProjectHome.htm](https://www2.econ.iastate.edu/tesfatsi/IRWProjectHome.htm)