ISO Net Surplus Collection & Allocation in Wholesale Power Markets under LMP

Presenter
Leigh Tesfatsion
Professor of Economics
Courtesy Professor of Mathematics and Electrical & Computer Engineering
Iowa State University, Ames, Iowa
https://www2.econ.iastate.edu/tesfatsi/
tesfatsi@iastate.edu

Electric Energy Economics (E3) Group
Iowa State University, Ames, IA
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Presentation Outline

- **ISO net surplus (congestion rent) determination in wholesale power markets with congestion managed by LMP**

- **Context for computational experiments: AMES Testbed**

  \[ AMES = \textbf{A}gent-based \textbf{M}odeling of \textbf{E}lectricity \textbf{S}ystems \]


- Wholesale power markets to be managed by *market operators with no ownership stake (ISOs/RTOs)*

- **Two-settlement system:** Concurrently operating day-ahead market & real-time balancing market

- Transmission grid congestion to be managed by means of *Locational Marginal Pricing (LMP)*, where

  \[ LMP(k,T) \text{ determined at grid bus } k \text{ for an operating period } T \]

  \[ \equiv \text{ least cost to system of servicing one additional MW of maintained power usage at bus } k \text{ during } T \]

- *Market power mitigation* by outside agency
Seven US Energy Regions Have Adopted FERC’s Basic Market Design to Date (2011)

☑️ = FERC Market Design Adopted
Exhibit 7-2: Data Flow for Day-Ahead Energy and Operating Reserve Market

Focus of Talk

- Power Marketers
- External Generation Owners
- Market Portal
  - Submit:
    - Resource Offers & Demand Bids
    - Virtual Bids & Virtual Supply Offers
    - Financial/Physical Bilateral Transactions
  - Publish:
    - DAM Results/LMP
  - Post:
    - Binding Trans. Constraints
    - Binding Flowgate Lim/Flows
    - Aggregate Demand Bids
  - Market Portal
    - Submit:
      - Financial/Physical Bilateral Transactions
      - Price Sensitive Demand Bids
      - Fixed Demand Bids
      - Virtual Bids/Supply Offers

- Market Portal
  - Public & Private Market Information for MPs

- Midwestern ISO
  - Market Portal
    - Send: Schedule of Operation
      - Submit:
        - Planned Transmission Outages
        - Transmission Availability Info.

- Resource Owners
  - Transmission Owners
  - Contact: Transmission Outage Requests
  - Enter: Financial Schedules

- PSS
  - Validate: Interchange Schedules
  - Market Portal
    - Report:
      - Planned Generation Outages
      - Generation Availability Info.
    - Submit:
      - Updates to Commit Status
      - Hourly Schedule of Operation
      - Resource Offers
      - Self Schedules
      - Financial/Physical Bilateral Transactions
      - Virtual Bids/Supply Offers

- External Balancing Authorities
### Key ISO Day-Ahead and Real-Time Market Activities During Each Operating Day D

<table>
<thead>
<tr>
<th>Time</th>
<th>Day-Ahead Market (DAM) for day D+1</th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00</td>
<td>ISO collects bids &amp; offers from LSEs &amp; GenCos</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Day-Ahead Market (DAM) for day D+1</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:00</td>
<td>ISO evaluates LSE demand bids and GenCo supply offers</td>
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<table>
<thead>
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<th>Time</th>
<th>Day-Ahead Market (DAM) for day D+1</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:00</td>
<td>ISO solves D+1 DC OPF and posts D+1 dispatch and LMP schedule</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Day-Ahead Market (DAM) for day D+1</th>
</tr>
</thead>
<tbody>
<tr>
<td>23:00</td>
<td>Day-ahead settlement</td>
</tr>
</tbody>
</table>

**Real-Time Market (RTM) for day D**

**Real-time settlement**
Resource Offers
Energy Offer Curves

- An Offer Curve is an offer to sell generation by a Resource
  - Slope ("true") vs. block ("false") offer
  - Monotonically increasing in price and non-decreasing in MW
  - Can vary hourly by location (CPNode)
  - Can submit up to 10 MW/price pairs
  - Previous DA offer carries over to DA and the previous day’s RT offer carries over to RT if no supply offer is submitted for the next day
The MP may designate whether the MW/Price pairs are considered as a slope or block Offer. The MW values are accepted to the 10th of a MW and the Offer values from -$500 to $1,000. The MW/Price pairs must be monotonically increasing for price and strictly increasing for MW (e.g., 40 MW @ $2.00, 50
LSE Price-Sensitive Demand Bids in MISO
BPM-002-r8, 4.3.2, 4-84 (July 7, 2010)

MPs may submit the Bid blocks in any order as illustrated in Exhibit 4-35; however, when queried after submittal, the Price-Sensitive Demand Bid blocks will appear sorted in descending price order, starting with the highest priced block (#3 in the example).
ISO Net Surplus Extraction: A 2-Bus Example with Linear Supply & Demand Curves [adapted from Harold Salazar, ISU 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 with generation capacity \( C_1 > M \); note G1 receives only \( LMP_1 \) per unit for its power supply M.

ISO collects the difference as:

\[
\text{ISO Net Surplus} = \left[ \text{LSE Payments} - \text{GenCo Revenues} \right]
= M \times [LMP_2 - LMP_1]
\]
Calculation of Total Net Surplus (TNS) for the 2-Bus Example

**ISO Net Surplus:**
\[ INS = M \cdot [LMP_2 - LMP_1] \]

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

**LSE Net Surplus:**
Area B

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

**ISO Objective (DC-OPF):**
\[ \max TNS \text{ subject to system constraints (power-balance, transmission, & gen)} \]
For each hour of DAM, ISO maximizes $\text{TNS}^R$ subject to constraints

\[
\max \; \text{TNS}^R
\]

with respect to LSE real-power price-sensitive demands, GenCo real-power generation levels, and voltage angles

\[
p_{Lj}, \; j = 1, \ldots, J; \quad p_{G_i}, \; i = 1, \ldots, I; \quad \delta_k, \; k = 1, \ldots, K
\] (16)

subject to

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

\[
\sum_{i \in I_k} p_{Gi} - \sum_{j \in J_k} p_{Lj} - \sum_{km} P_{km} = \sum_{j \in J_k} p_{Lj}
\] (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 $km$:

\[
|P_{km}| \leq P_{km}^H
\] (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 $I$:

\[
\delta_1 = 0
\] (21)

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 $k = \text{base voltage } V_o$

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

Lagrange multiplier ("shadow price") solution for the bus-k balance constraint (17) gives locational marginal price $\text{LMP}_k$ at bus k

$\text{TNS}^R =: \text{Total Net Surplus based on reported GenCo supply offers & reported LSE demand bids}$
AMES Wholesale Power Market Testbed
https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

➢ Wholesale Traders
  ▪ GenCos (bulk sellers) with learning capabilities
  ▪ LSEs (bulk buyers)

➢ Independent System Operator (ISO)
  ▪ System reliability assessments
  ▪ Day-ahead scheduling via bid/offer based DC optimal power flow (OPF)
  ▪ Real-time dispatch

➢ Two-settlement system
  ▪ Day-ahead market (double auction, financial contracts)
  ▪ Real-time balancing market (pricing deviations from DAM) – in prep

➢ 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 maintained (“fixed”) power demand at bus k.
Illustrative computational experiments implemented via AMES: ISO net surplus collections in day-ahead energy markets under LMP.


Day-ahead market activities on a typical operating day D:
5-Bus Test Case Implemented via AMES
(“Lally” 5-bus test case commonly used in RTO/ISO 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
**AMES LSE Hourly Demand-Bid Formulation**

- **Hourly demand bid for each LSE j**

  **Fixed + Price-Sensitive Demand Bid**

  - **Fixed** demand bid =: $p_{Fj}^L$ (MW)
  - **Price-sensitive** demand bid
    =: Inverse demand function for real power $p_{Sj}^L$ (MW) over a purchase capacity interval:

    $$ F_j(p_{Sj}^L) = c_j - 2d_j p_{Sj}^L $$

    $$ 0 \leq p_{Sj}^L \leq SLMax_j $$

  Retail resale price $r$ for $p^F$
Treatment Factor 1: Demand-Bid Price Sensitivity (from 100% fixed to 100% price sensitive)

For LSE $j$ in Hour $H$:

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

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

$$R = \frac{\text{SLMax}_j}{p_{Fj} + \text{SLMax}_j}$$

$R = 0.0$ (100% Fixed Demand)

$R = 0.5$

$R = 1.0$ (100% Price-Sensitive Demand)
Fixed-Demand Load Profiles for the 5-Bus Test Case with 100% Fixed Demand (R=0.0)

Peak Hour 17
Off-Peak Hour 4
AMES Total Demand & Supply Curves for Hours 4 and 17 for the 5-Bus Test Case with R=0.2 and No Learning

“Merit-order” supply curve $S$, i.e., effects of transmission line congestion on $S$ are not depicted here.
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):

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

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

GenCos can learn to report higher-than-true marginal costs and/or to report lower-than-true maximum capacity.
Learning Treatments: GenCos use VRE Learning

(VRE =: Variant of Roth-Erev stochastic reinforcement learning)

- Each GenCo maintains action choice propensities $q_i$ normalized to choice probabilities $\text{Prob}_i$, 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 $\text{Prob}_k$. 

```
| Action Choice | $r$ | Choice Propensity $q_1$ | Choice Probability $\text{Prob}_1$
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<thead>
<tr>
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<tbody>
<tr>
<td>$a_1$</td>
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<td>$a_3$</td>
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<td>$a_1$</td>
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<tr>
<td>$a_3$</td>
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```
LMP Findings as Price-Sensitivity of Demand Varies from $R=0.0$ (100% Fixed) to $R=1.0$ (100% Price-Sensitive)

Fig. 7. Mean outcomes for average hourly LMP values on day 1000 for the benchmark 5-bus test case extended to include GenCo learning and LSE demand varying from $R=0.0$ (100% fixed) to $R=1.0$ (100% price sensitive).
ISO Net Surplus for Benchmark Case: No GenCo Learning, 100% Fixed Demand

Fig. 6. LSE payments, GenCo revenues, ISO net surplus, and GenCo net earnings during a typical 24-hour day D for the benchmark 5-bus test case.
Net Surplus Results **Without** GenCo Learning:
ISO and GenCo net surplus on Day 1000 as LSE demand varies from R=0.0 (100% fixed) to R=1.0 (100% price-sensitive)
Net Surplus Results **With** GenCo VRE Learning: Mean ISO and GenCo net surplus on Day 1000 as LSE demand varies from $R=0.0$ (100% fixed) to $R=1.0$ (100% price-sensitive)
ISO Net Surplus, Total Net Surplus (TNS), and **TNS Loss (Market Inefficiency)**

TABLE IV

*Comparison of net surplus outcomes on day 1000 for the 5-bus test case without learning (benchmark) versus with GenCo learning (means and standard deviations) as LSE demand varies from \( R = 0.0 \) (100% fixed) to \( R = 1.0 \) (100% price sensitive).*

<table>
<thead>
<tr>
<th></th>
<th>R=0.0</th>
<th>R=0.2</th>
<th>R=0.4</th>
<th>R=0.6</th>
<th>R=0.8</th>
<th>R=1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>GenNetSur(1000)</td>
<td>92,008.30</td>
<td>69,342.45</td>
<td>53,135.65</td>
<td>41,251.49</td>
<td>30,316.28</td>
<td>27,002.99</td>
</tr>
<tr>
<td>LSENetSur(1000)</td>
<td>6,118,410.39</td>
<td>4,937,440.19</td>
<td>3,739,406.53</td>
<td>2,530,696.32</td>
<td>1,317,250.86</td>
<td>95,531.85</td>
</tr>
<tr>
<td>ISO NetSur(1000)</td>
<td>209,411.07</td>
<td>184,253.35</td>
<td>159,977.47</td>
<td>131,939.70</td>
<td>93,483.24</td>
<td>43,003.42</td>
</tr>
<tr>
<td>TNS(1000)</td>
<td>6,419,829.76</td>
<td>5,191,035.99</td>
<td>3,952,519.65</td>
<td>2,703,887.51</td>
<td>1,441,050.38</td>
<td>165,538.26</td>
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</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>R=0.0</th>
<th>R=0.2</th>
<th>R=0.4</th>
<th>R=0.6</th>
<th>R=0.8</th>
<th>R=1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>GenNetSur(1000)</td>
<td>2,441,646.71</td>
<td>541,230.41</td>
<td>227,932.07</td>
<td>153,274.62</td>
<td>107,677.99</td>
<td>68,377.76</td>
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<tr>
<td></td>
<td>(153,782.17)</td>
<td>(73,333.88)</td>
<td>(14,969.93)</td>
<td>(161.70)</td>
<td>(51.51)</td>
<td>(18.22)</td>
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<tr>
<td>LSENetSur(1000)</td>
<td>1,832,799.11</td>
<td>3,977,731.25</td>
<td>3,494,823.67</td>
<td>2,467,054.80</td>
<td>1,273,364.42</td>
<td>52,119.91</td>
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<td>(1,043,543.03)</td>
<td>(980,836.96)</td>
<td>(231,030.43)</td>
<td>(42,475.32)</td>
<td>(29,287.77)</td>
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<td>ISO NetSur(1000)</td>
<td>2,097,620.96</td>
<td>647,130.97</td>
<td>206,219.65</td>
<td>57,450.22</td>
<td>31,680.94</td>
<td>14,879.79</td>
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<tr>
<td></td>
<td>(632,303.71)</td>
<td>(633,129.12)</td>
<td>(197,896.93)</td>
<td>(48,696.64)</td>
<td>(30,789.07)</td>
<td>(11,016.23)</td>
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<tr>
<td>TNS(1000)</td>
<td>6,372,006.78</td>
<td>5,166,092.63</td>
<td>3,928,975.39</td>
<td>2,677,779.64</td>
<td>1,412,723.35</td>
<td>135,377.46</td>
</tr>
<tr>
<td>TNS Loss (1000)</td>
<td>47,762.98</td>
<td>24,943.36</td>
<td>23,544.27</td>
<td>26,107.87</td>
<td>28,327.03</td>
<td>30,160.80</td>
</tr>
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</table>
Actual ISO Net Surplus Extractions: 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.
Key Implications of ISO Net Surplus Findings

- **ISO net surplus is not well-aligned with market efficiency**
- Demand conditions (low price elasticity) that result in **lower total net surplus** tend to result in **higher ISO net surplus**.
- ISO net surplus extractions should be used to reduce or offset unfair **structural** market advantages (e.g., pivotal location) and **strategic** market advantages (e.g., privileged information access) for subsets of market participants that then result in **market inefficiency**, i.e., in **lower total net surplus for market participants as a whole**.
- ISO net surplus extractions should **not** simply be used **ex post** as offsets of high LSE LMP payments and support for GenCo hedging against LMP volatility (price risk) — ignoring structural/strategic market advantages built into the market design.
On-Line Resources

- Presentation Slides
  https://www2.econ.iastate.edu/tesfatsi/ISONetSurplusE3Talk.LT.pdf

- Li/Tesfatsion IEEE TPWRS Article on ISO Net Surplus Extraction
  https://dx.doi.org/10.1109/TPWRS.2010.2059052

- AMES Testbed Homepage (Open-Source Code/Manuals/Publications)
  https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- Agent-Based Electricity Market Research
  https://www2.econ.iastate.edu/tesfatsi/aelect.htm