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

Presenter

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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 **=** ***A*****gent-based** ***M*****odeling of** ***E*****lectricity** ***S*****ystems**

* **Illustrative findings:** Hongyan Li & Leigh Tesfatsion, "ISO net surplus collection and allocation in U.S. wholesale power markets under locational marginal pricing," *IEEE Transactions on Power Systems,* Vol. 26, Issue 2, 2011, pp. 627-641.

U.S. Federal Energy Regulatory Commission (FERC): Proposed Wholesale Power Market Design

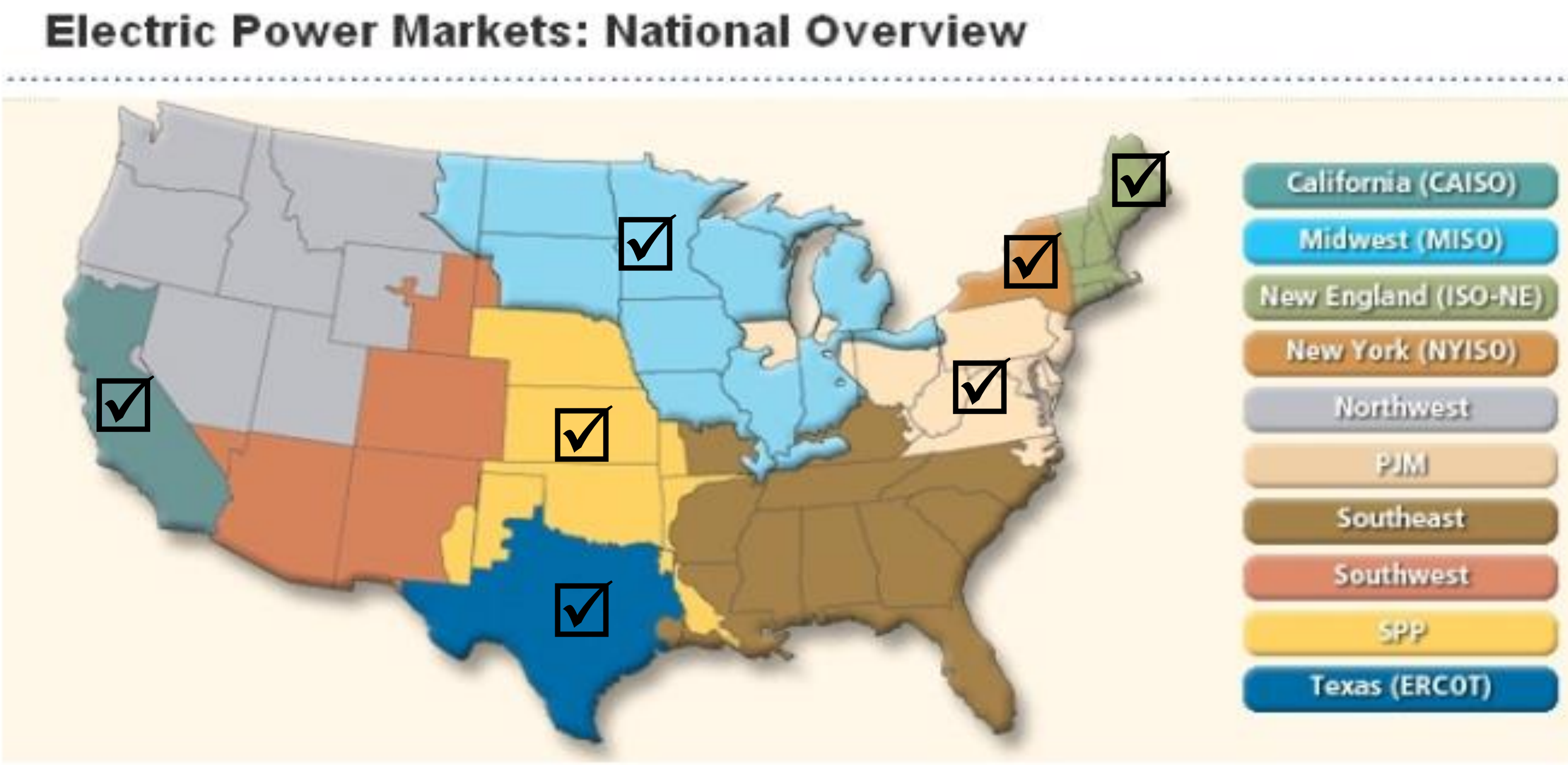
- Wholesale power markets to be managed by ***market operators with no ownership stake (ISOs/RTOs)***
- ***Two-settlement system:*** Concurrently operating day-ahead market & real-time balancing market
- Transmission grid congestion to be managed by means of ***Locational Marginal Pricing (LMP),*** where

  LMP(k,T) determined at grid bus k for an operating period T

  ≅ least cost to system of servicing one additional MW of maintained power usage at bus k during T

- ***Market power mitigation*** by outside agency

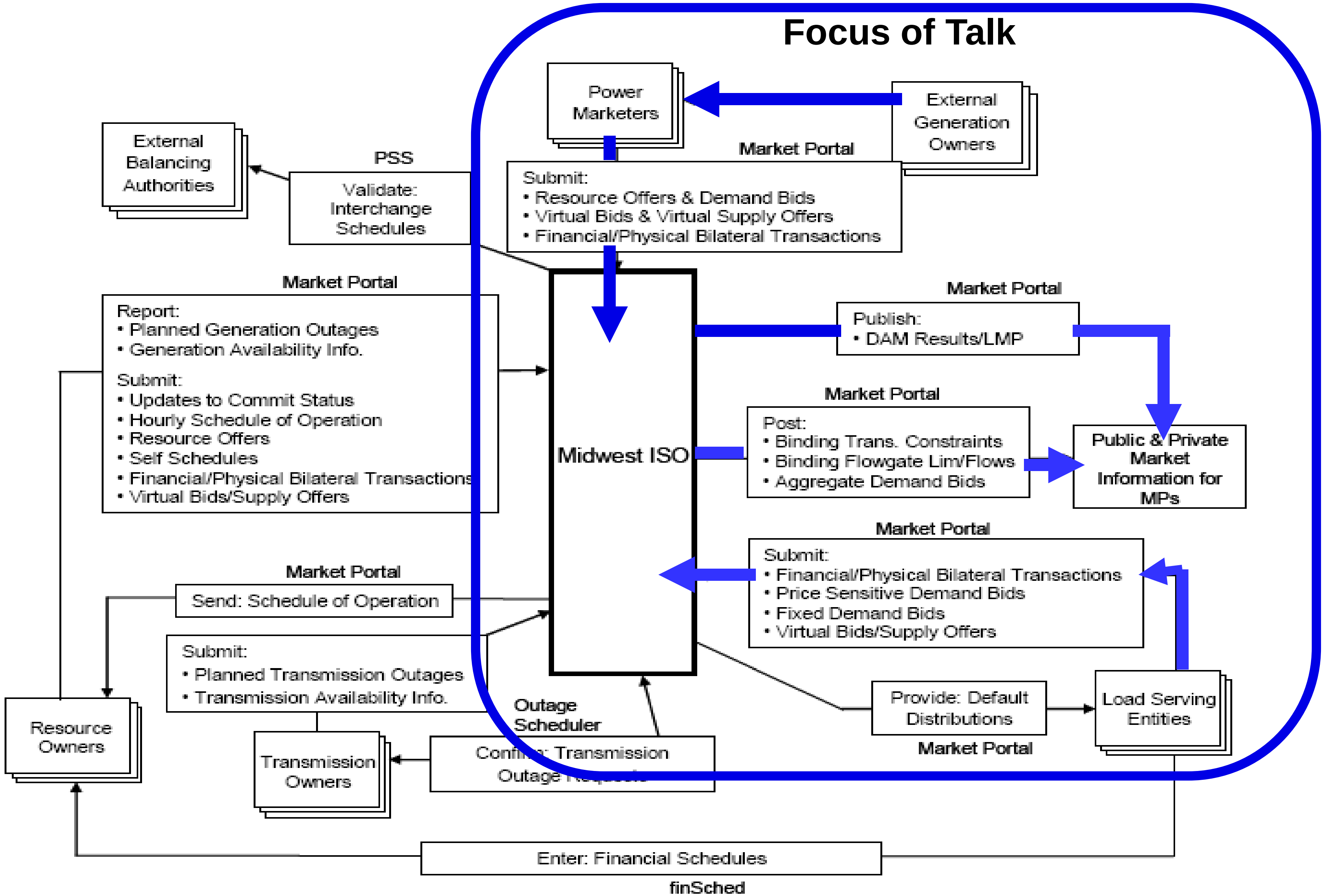
Seven US Energy Regions Have Adopted FERC's Basic Market Design to Date (2011)



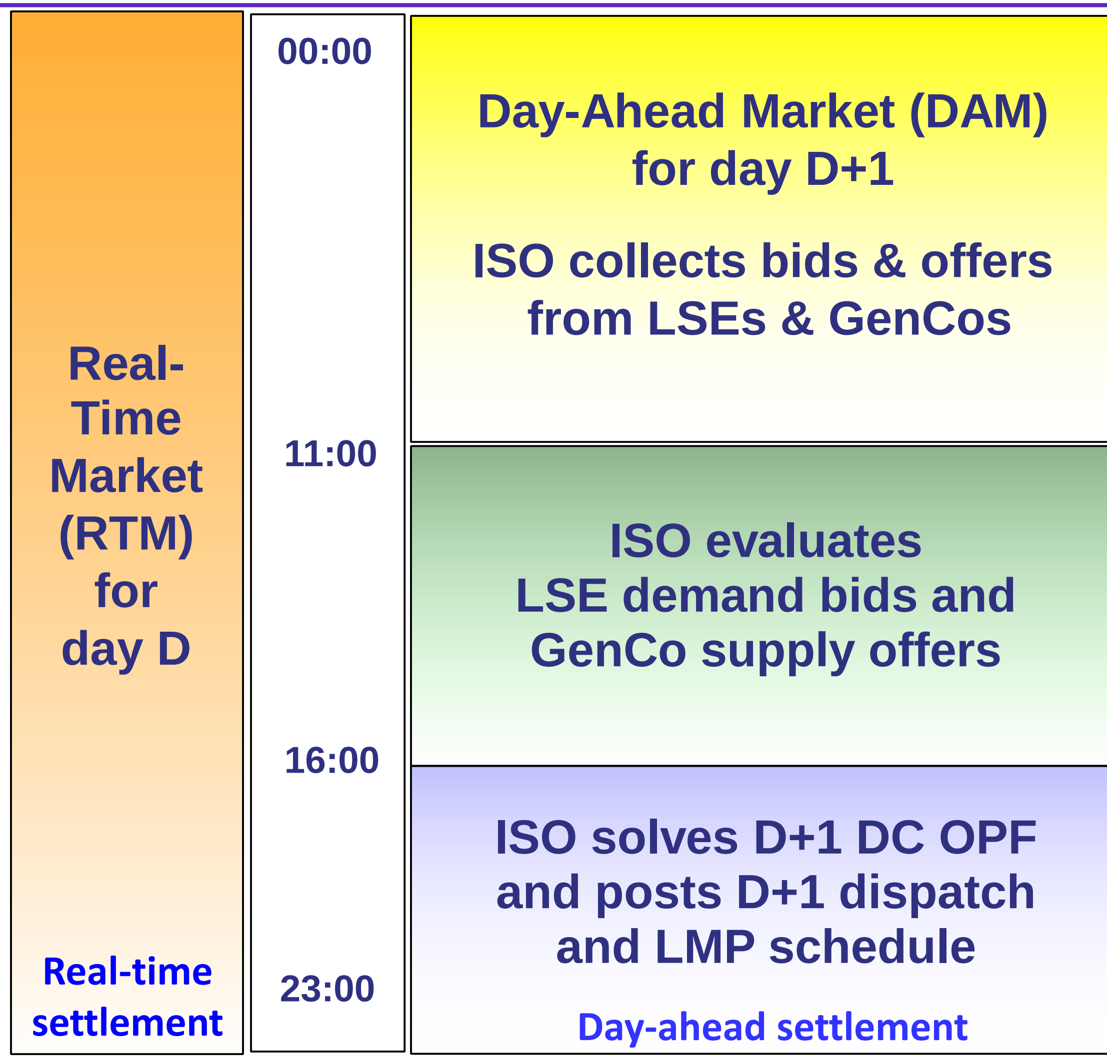
☑ = FERC Market Design Adopted

MISO BPM-002-r8 (7 July 2010), p. 7-3

Exhibit 7-2: Data Flow for Day-Ahead Energy and Operating Reserve Market



Key ISO Day-Ahead and Real-Time Market Activities During Each Operating Day D



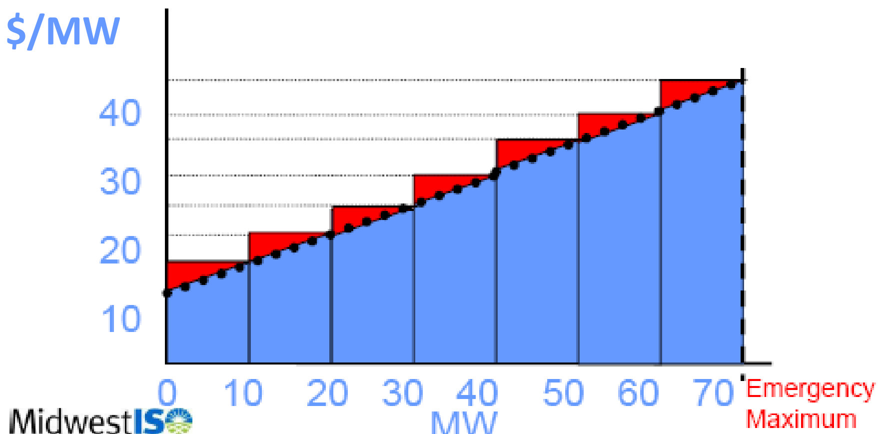
MISO Form of GenCo Supply Offers Submitted to a DA/RT Market M(T) for an operating period T

Minimum acceptable price $/MW ("sale reservation price") for each successive increase ΔMW of power (MW) to be maintained during T

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



$/MW	MW
10	0
15	10
20	20
25	30
30	40
35	50
40	60
45	70

ΔMW
10
10
10
10
10
10
10
10

MidwestISO
Energizing the Heartland

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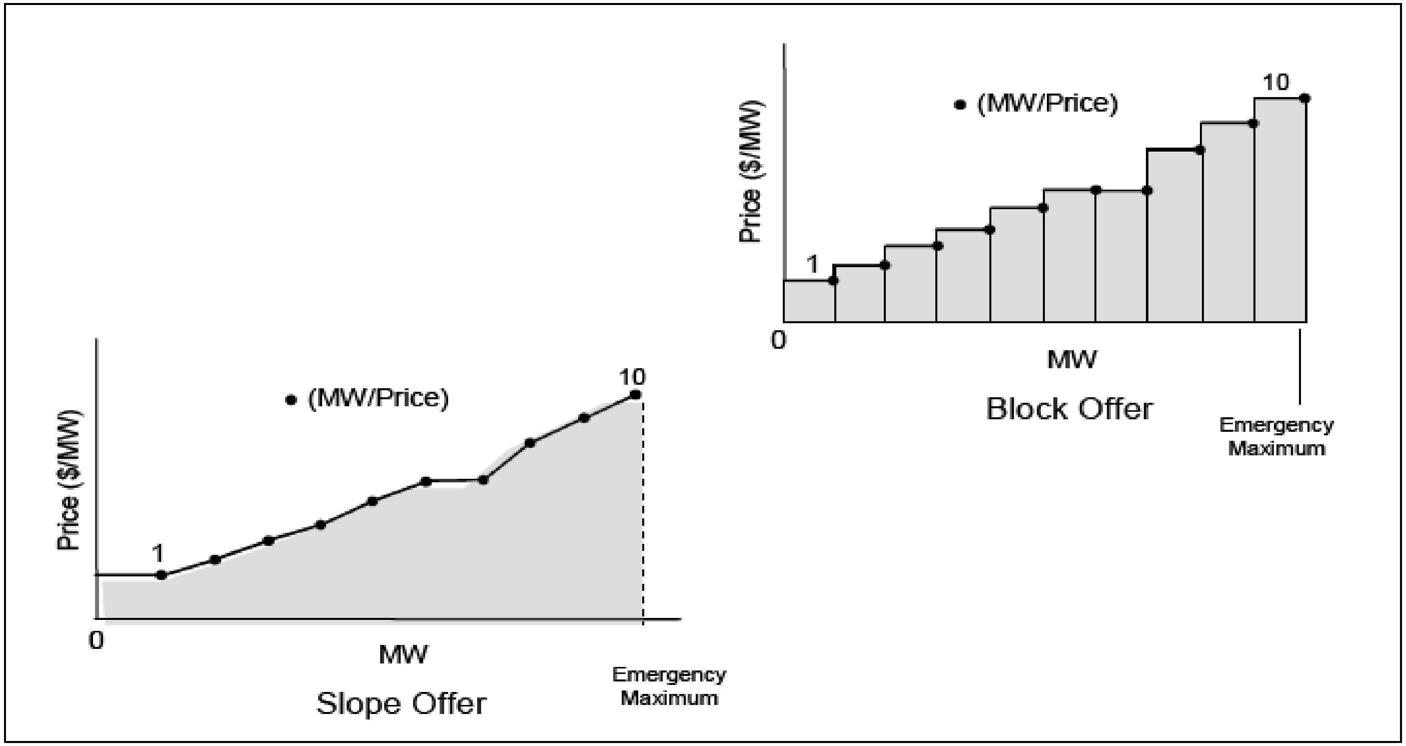
Form of GenCo Supply Offers in MISO

BPM-002-r8, 4.2.2.2.1, p. 4-26 (July 7, 2010)

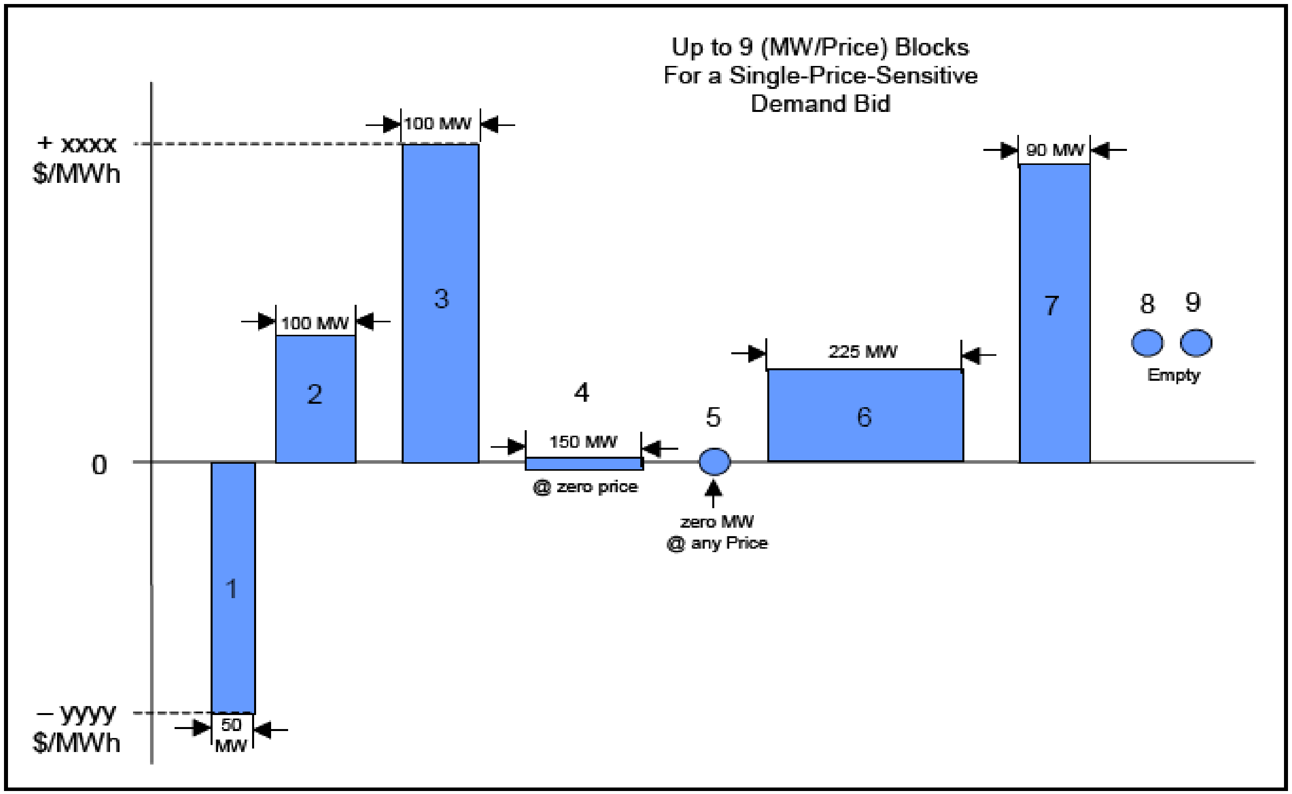
Exhibit 4-11: Types of Energy Offers



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).

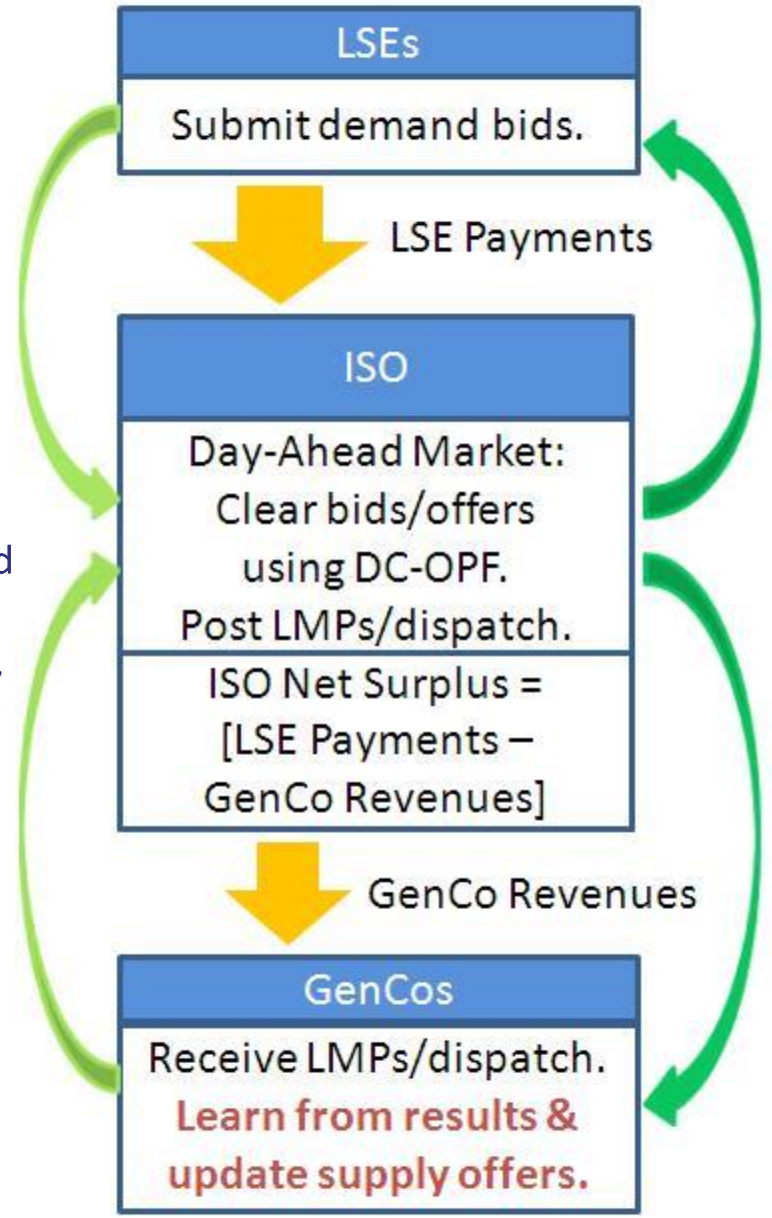
Illustrative computational experiments implemented by the AMES Wholesale Power Market Test Bed:

ISO net surplus collections in a **D**ay-**A**head **M**arket (**DAM**) settled by **L**ocational **M**arginal **P**ricing (**LMP**).

Hongyan Li & Leigh Tesfatsion, “ISO net surplus collection and allocation in U.S. wholesale power markets under locational marginal pricing,” *IEEE Transactions on Power Systems 26(2),* 2011, 627-641.

https://dx.doi.org/10.1109/TPWRS.2010.2059052

DAM activities on a typical day D to plan for next-day operations:



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

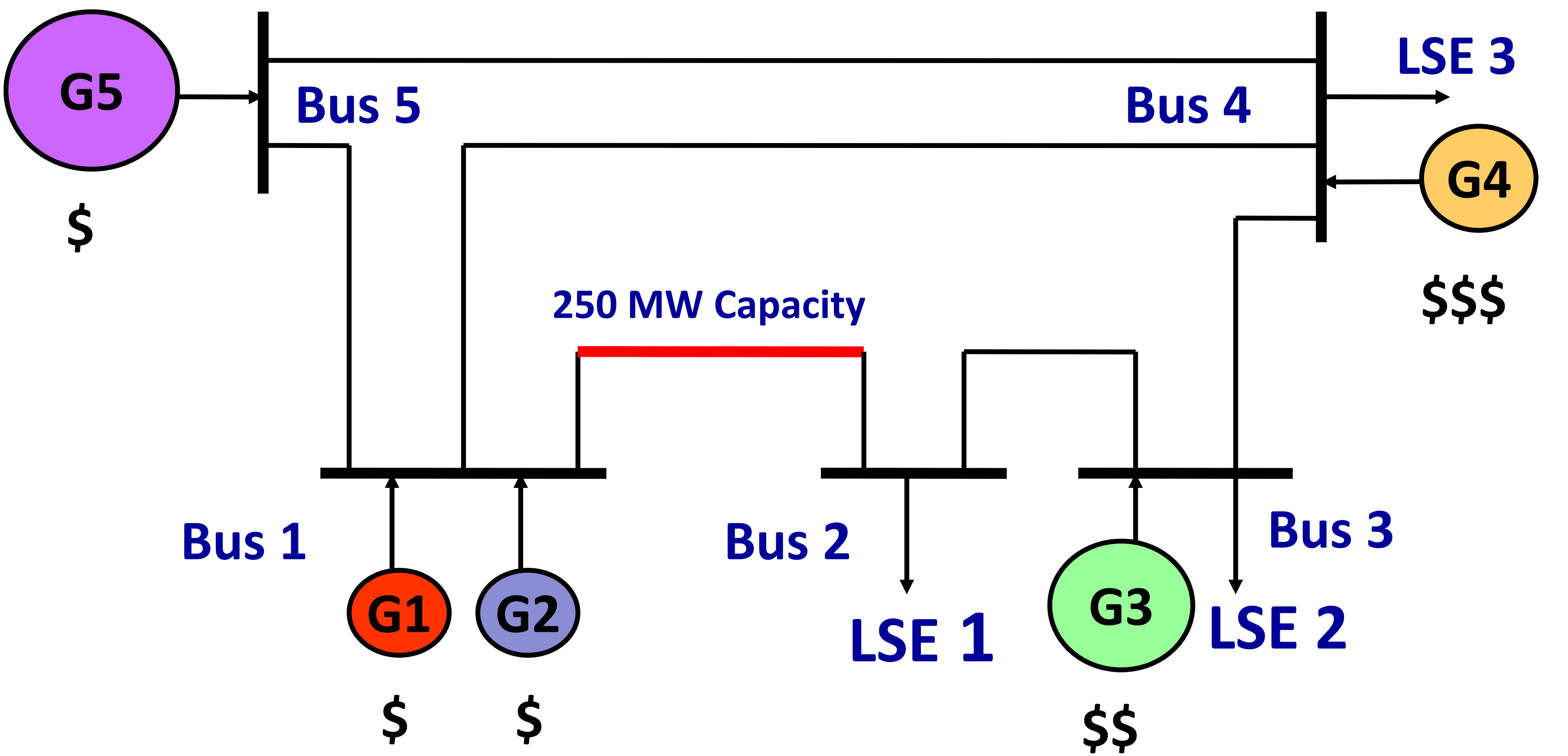
- **Two-settlement system**
  - **Day-Ahead Market** (double auction, financial contracts)
  - **Real-Time Market** (pricing of deviations from DAM dispatch)

- **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 during operating period T** = Least cost of servicing one additional MW of maintained ("fixed") power demand at bus k during T.

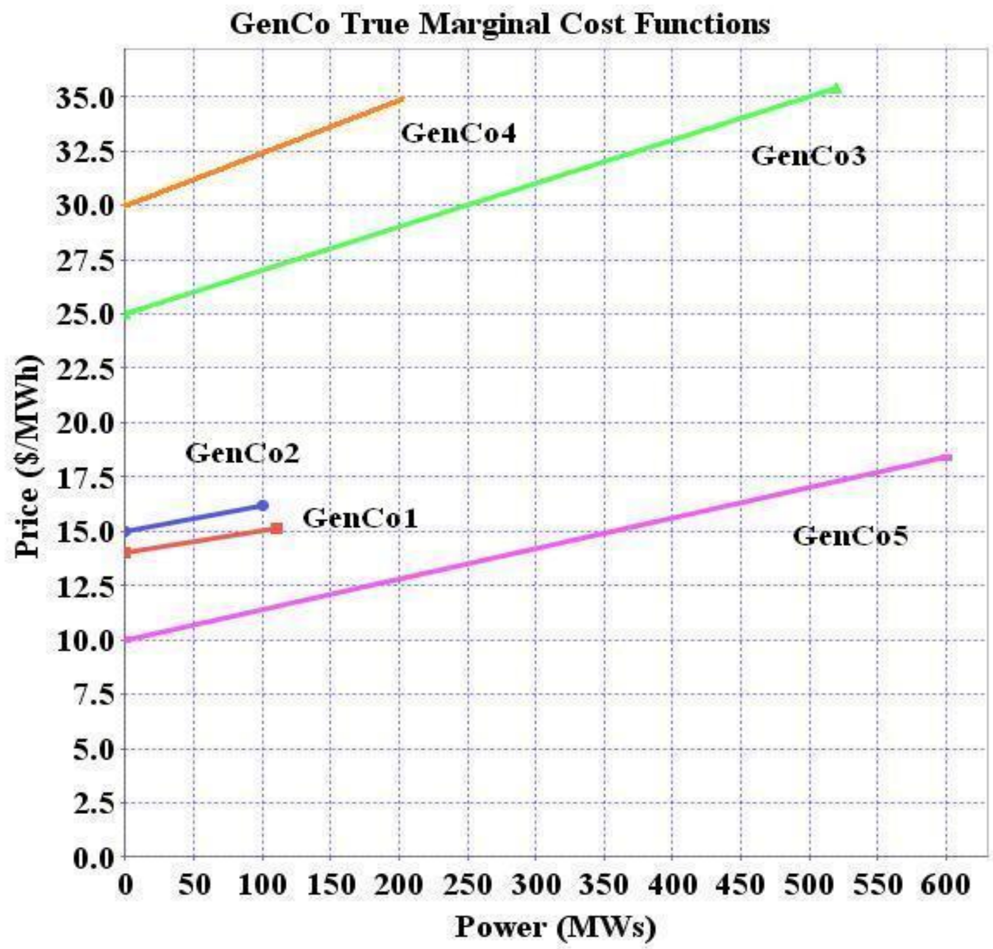
5-Bus Test Case Implemented via AMES

("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 Capacity & Marginal Cost Attributes for each Hour H of Day D+1



LSE Hourly Demand Bids: Two-Part Formulation

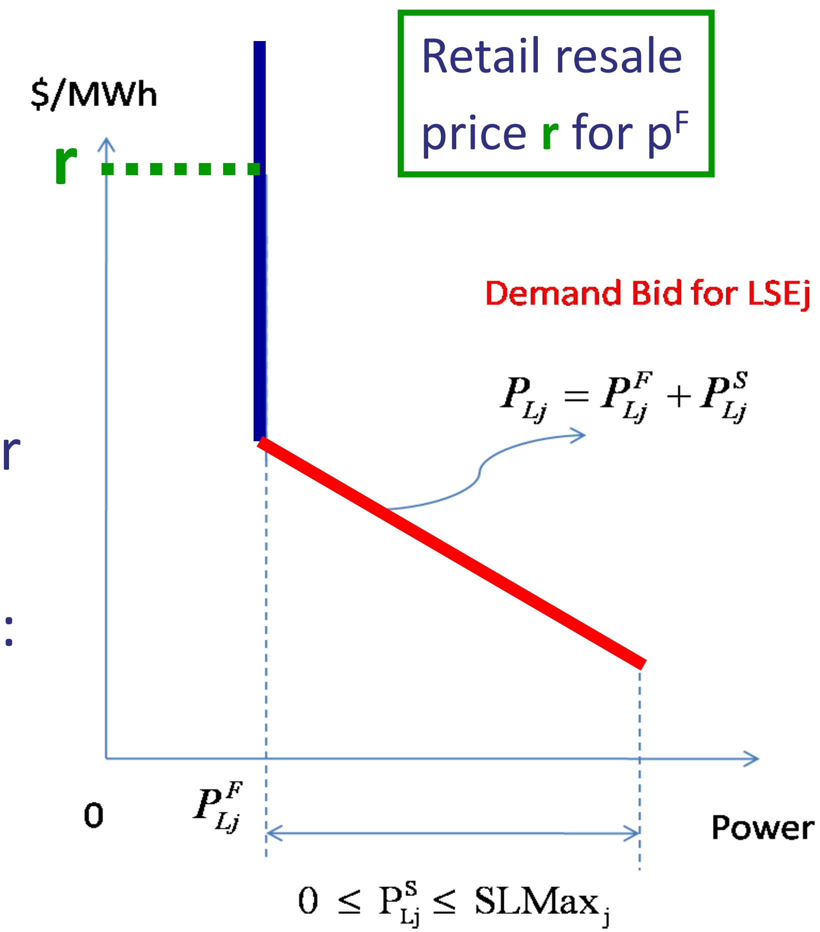
- Hourly demand bid for each LSE j

Fixed + Price-Sensitive Demand Bid

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

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

$$0 \leq p^S_{Lj} \leq SLMax_j$$

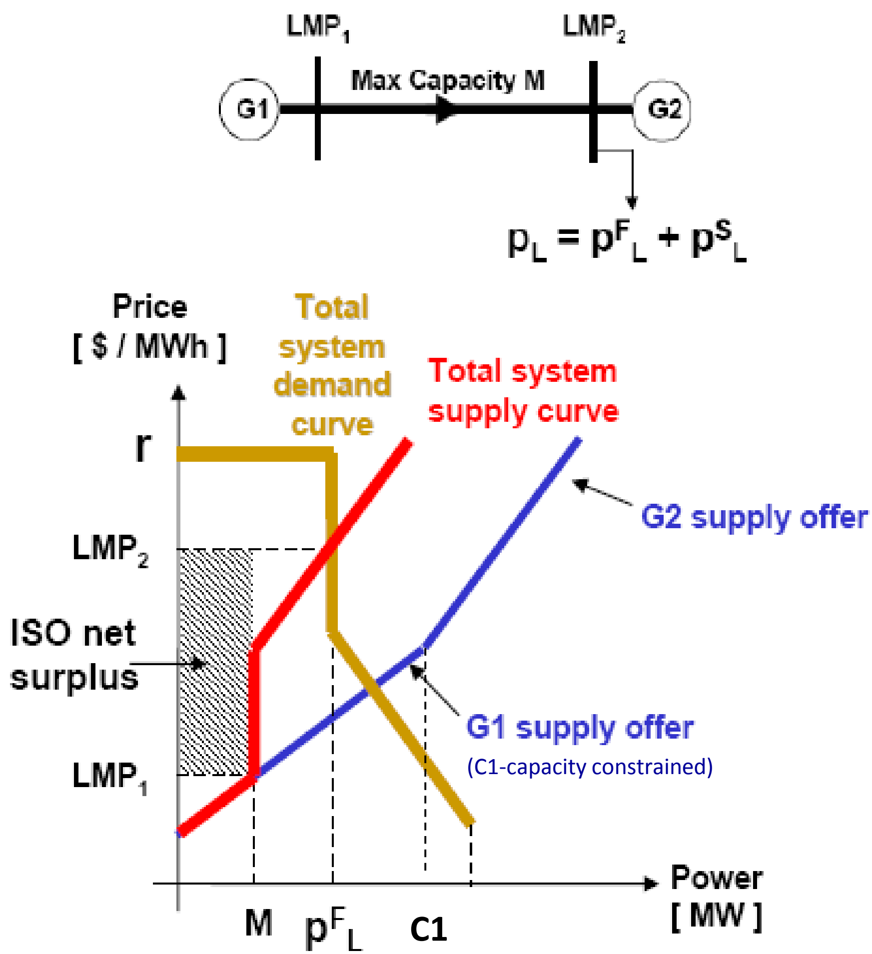


ISO Optimization Problem (DC Optimal Power Flow) for hour H on day D+1:

Maximize Total Net Surplus (TNS) subject to system constraints

2-Bus Illustration

(Adapted from Harold Salazar, ISU ECpE M.S. Thesis, 2008)



Given the line capacity limit M, the <u>cleared</u> LSE load at bus 2 = p^F_L. The LSE receives price r ($/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 ($/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 ($/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:

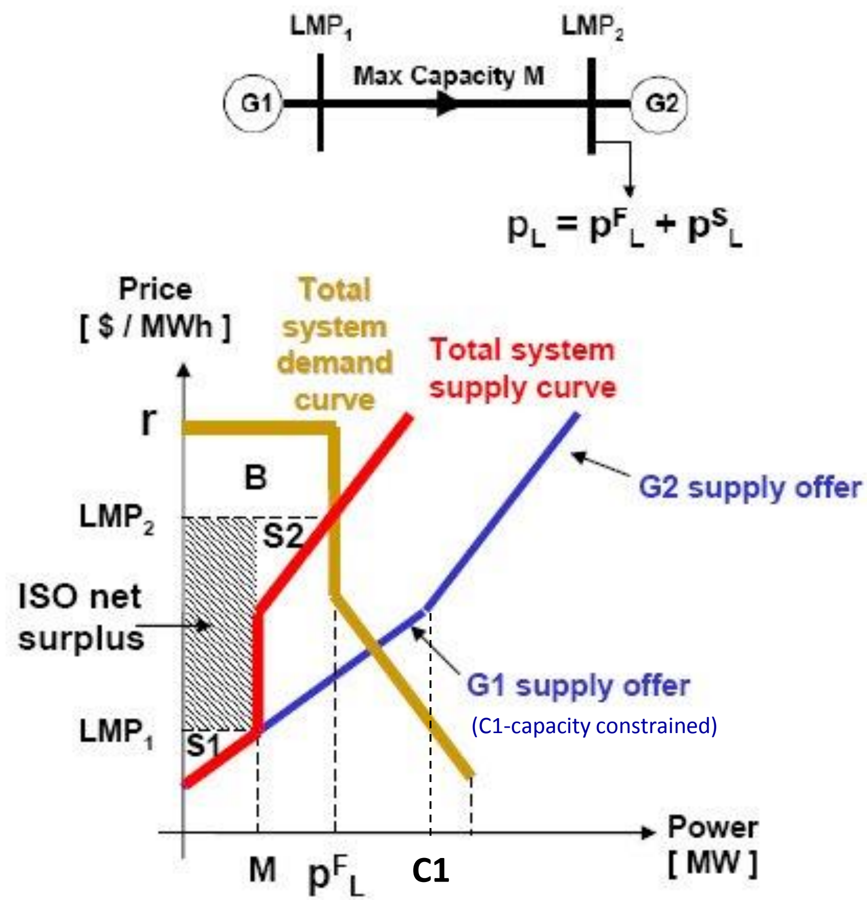
ISO Net Surplus

=: [LSE Payments - GenCo Revenues]

= $LMP_2 \times p^F_L - M \times LMP_1 - [p^F_L - M] \times LMP_2$

= $M \times [LMP_2 - LMP_1]$ = [**Shaded Figure Area**]

Two-Bus Illustration … Continued



ISO Net Surplus (INS):

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.

Treatment Factor #1: Demand-Bid Price Sensitivity

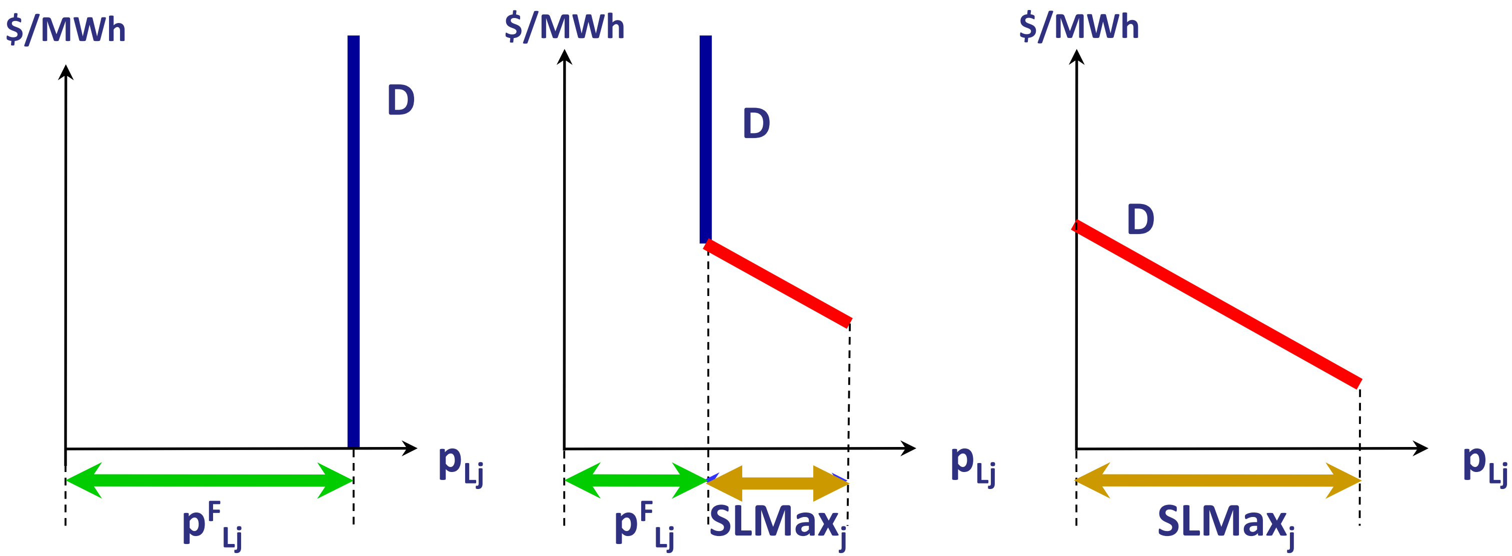
(from 100% fixed to 100% price sensitive)

For LSE j during each hour H:

p^F_{Lj} =: Fixed demand for real power (MWs)

$SLMax_j$ =: Maximum potential price-sensitive demand (MWs)

$R = SLMax_j / [p^F_{Lj} + SLMax_j]$ = Measure of Demand-Bid Price Sensitivity



R=0.0 (100% Fixed Demand)

R=0.5

R=1.0 (100% Price-Sensitive Demand)

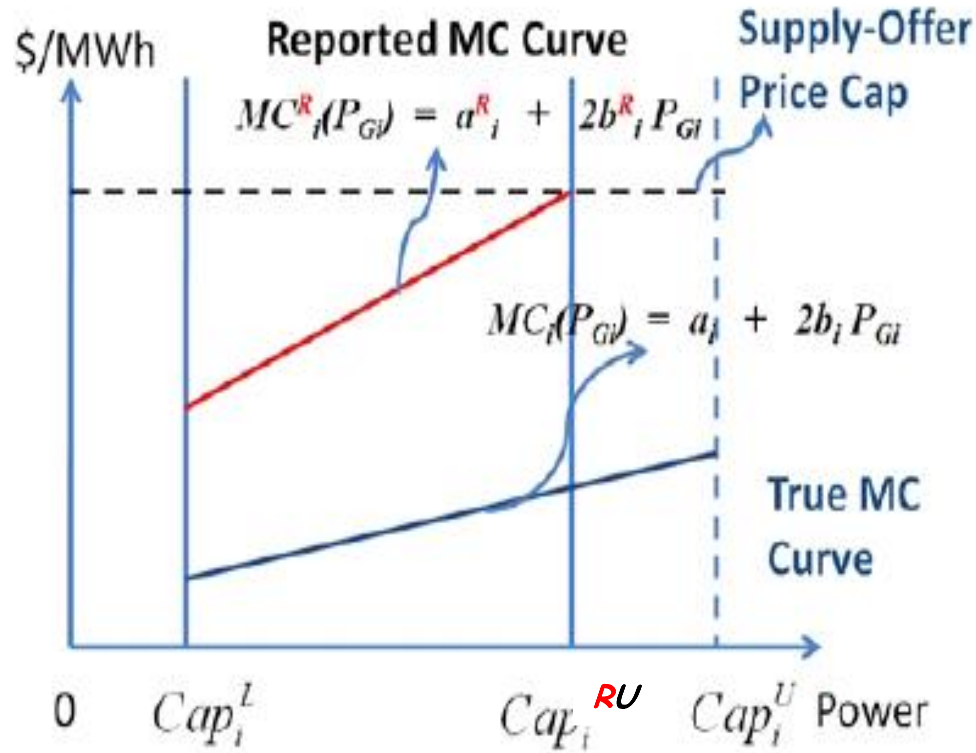
Treatment Factor #2: GenCo Learning Capabilities
(No Learning vs. Learning)

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

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

$$Cap^L_i \leq p_{Gi} \leq Cap^{RU}_i$$

GenCos can learn to report ***higher-than-true*** marginal costs and/or to report ***lower-than-true*** maximum capacity.



Maximization of TNS^R for hour H on day D+1

SI unit representation for the DC-OPF problem for each hour H of day D+1 solved by AMES ISO 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 d_{km} =: [$delta_k$ - $delta_m$] across each branch km is close to zero, implying $\cos(d_{km}) \cong 1$ and $\sin(d_{km}) \cong d_{km}$ in amplitude

$$\max \quad \mathrm{TNS}^R \qquad (15)$$

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

$$p^S_{Lj},\ j=1,\ldots,J;\ p_{Gi},\ i=1,\ldots,I;\ \delta_k,\ k=1,\ldots,K \qquad (16)$$

subject to

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

$$\sum_{i\in I_k} p_{Gi} - \sum_{j\in J_k} p^S_{Lj} - \sum_{km} P_{km} = \sum_{j\in J_k} p^F_{Lj} \qquad (17)$$

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:

$$|P_{km}| \leq P^U_{km} \qquad (18)$$

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

$$\mathrm{Cap}^L_i \leq p_{Gi} \leq \mathrm{Cap}^U_i \qquad (19)$$

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

$$0 \leq p^S_{Lj} \leq \mathrm{SLMax}_j \qquad (20)$$

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

$$\delta_1 = 0 \qquad (21)$$

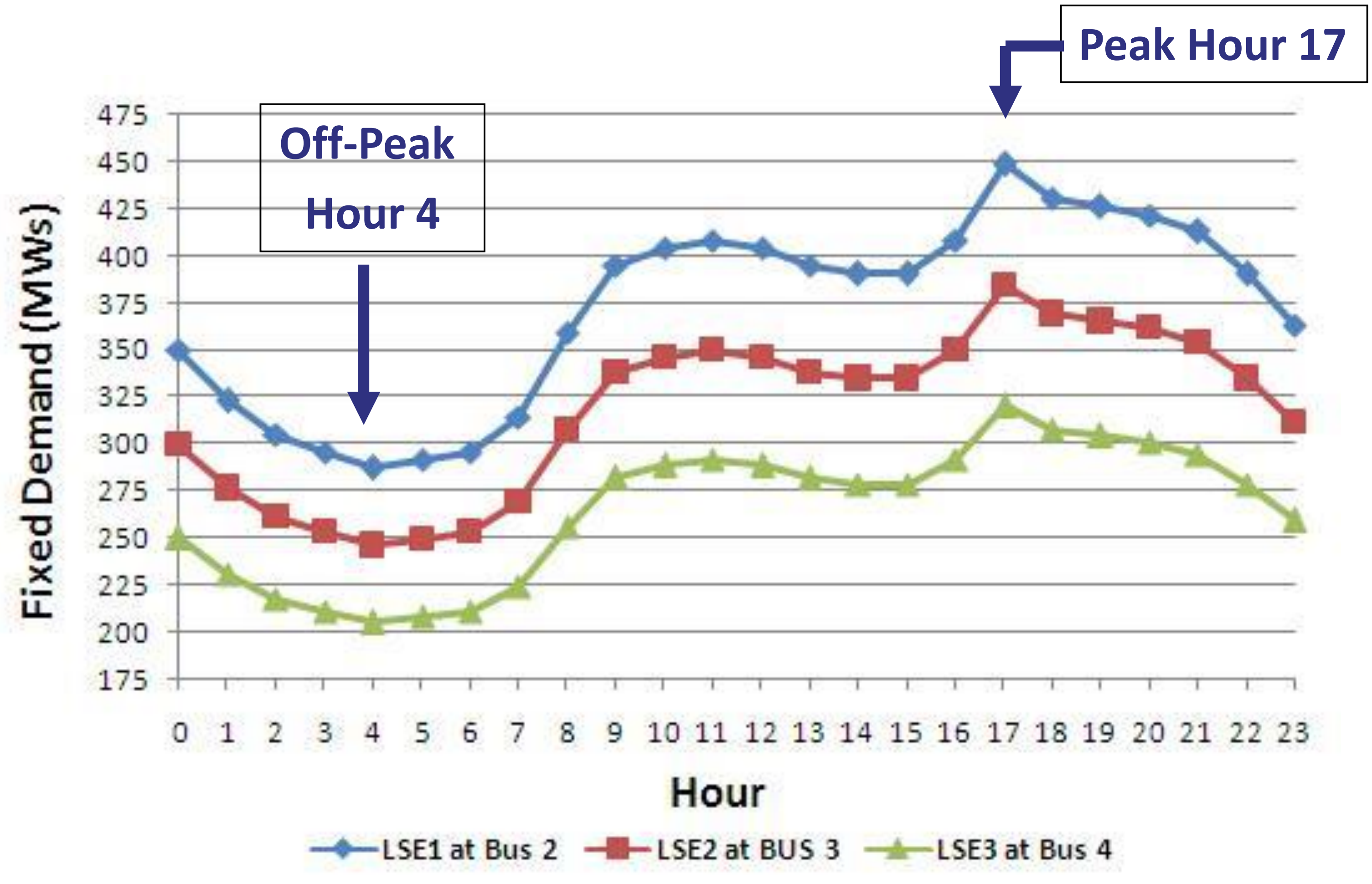
TNS^R =: "Total Net Surplus" (revenues minus costs) based on *reported* GenCo supply offers & *reported* LSE demand bids

Lagrange multiplier ("shadow price") solution for the bus-k balance constraint (17) gives locational marginal price LMP_k at bus k

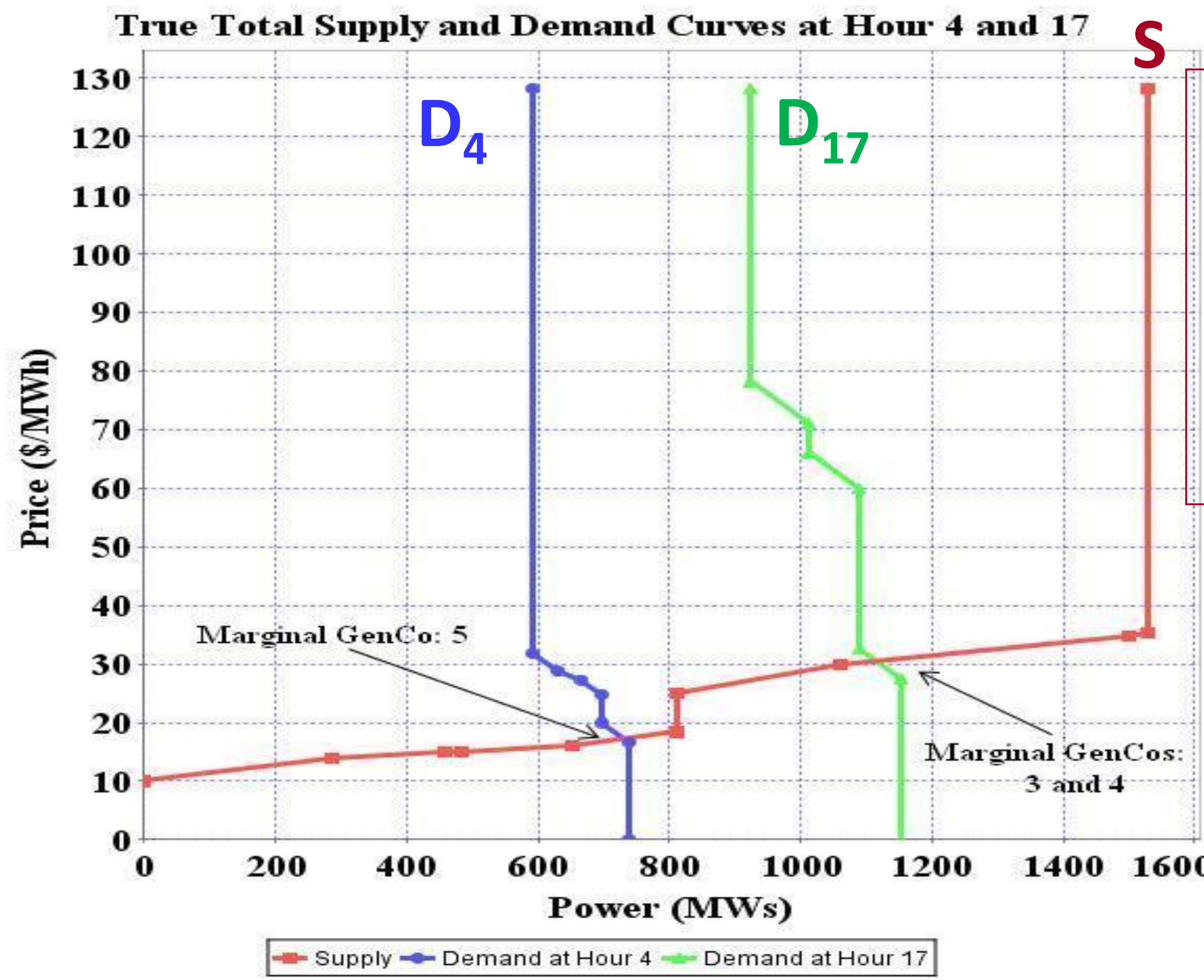
Standard Day-D Bid/Offer-Based DC-OPF Problem

Solved by AMES ISO on Day D for each hour H of day D+1

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



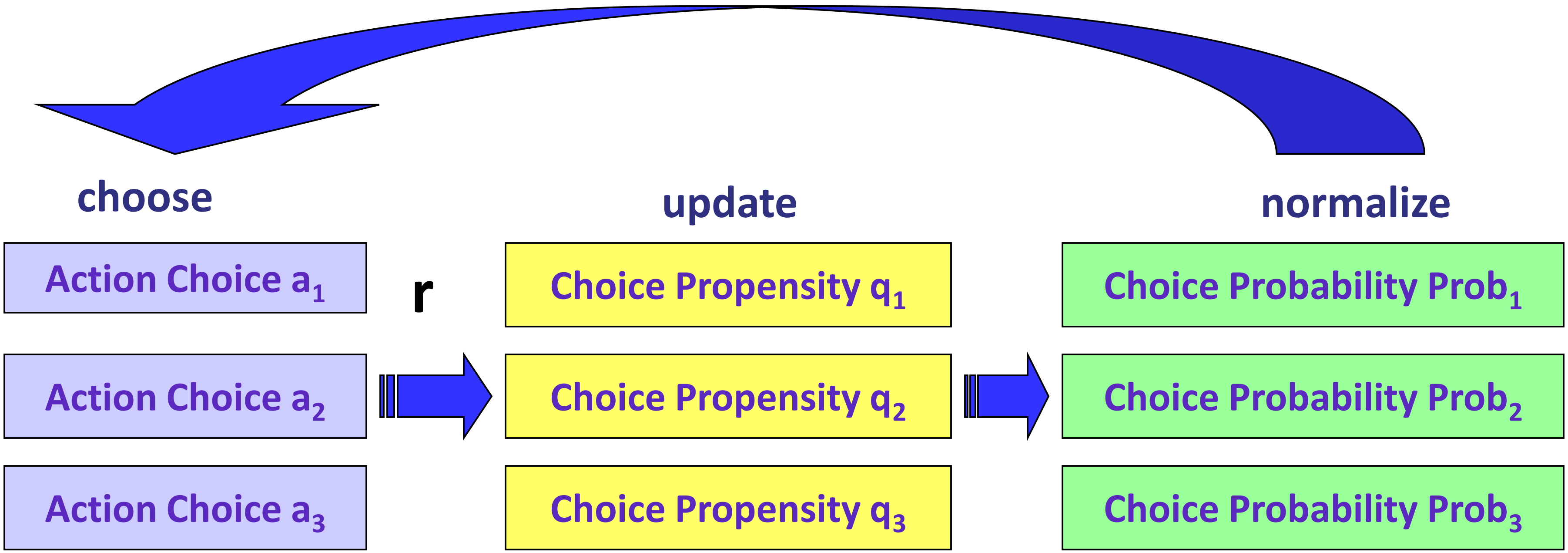
Total Demand & Supply Curves for Hours 4 and 17 for the 5-Bus Test Case with R=0.2 and No Learning



The depicted Total Supply Curve **S** is in "Merit-order," i.e., the effects on **S** of transmission line congestion are not shown.

Learning Treatments: GenCos use VRE Learning

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



- Each GenCo maintains action choice propensities q, normalized to choice probabilities 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 $Prob_k$.

LMP Findings as Price-Sensitivity of Demand Varies from R=0.0 (100% Fixed) to R=1.0 (100% Price-Sensitive)

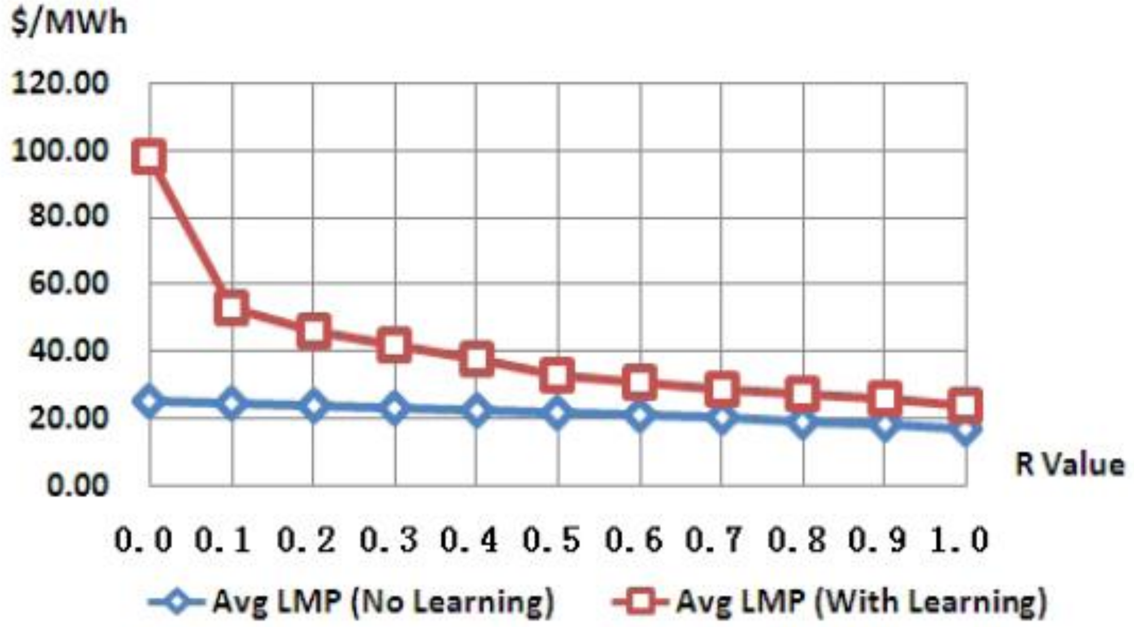


Fig. 7. Mean outcomes for average hourly LMP values on day 1000 for the benchmark 5-bus test case extended to include GenCo learning and LSE demand varying from R=0.0 (100% fixed) to R=1.0 (100% price sensitive).

ISO Net Surplus for Benchmark Case:
No GenCo Learning, 100% Fixed Demand

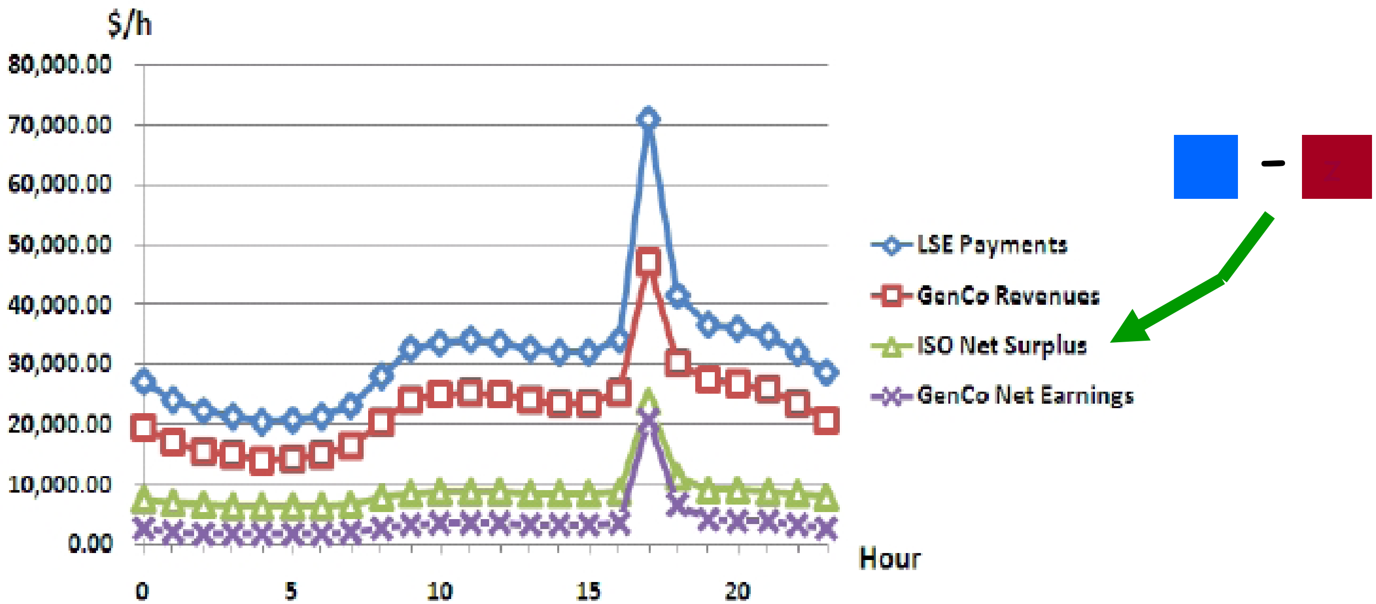
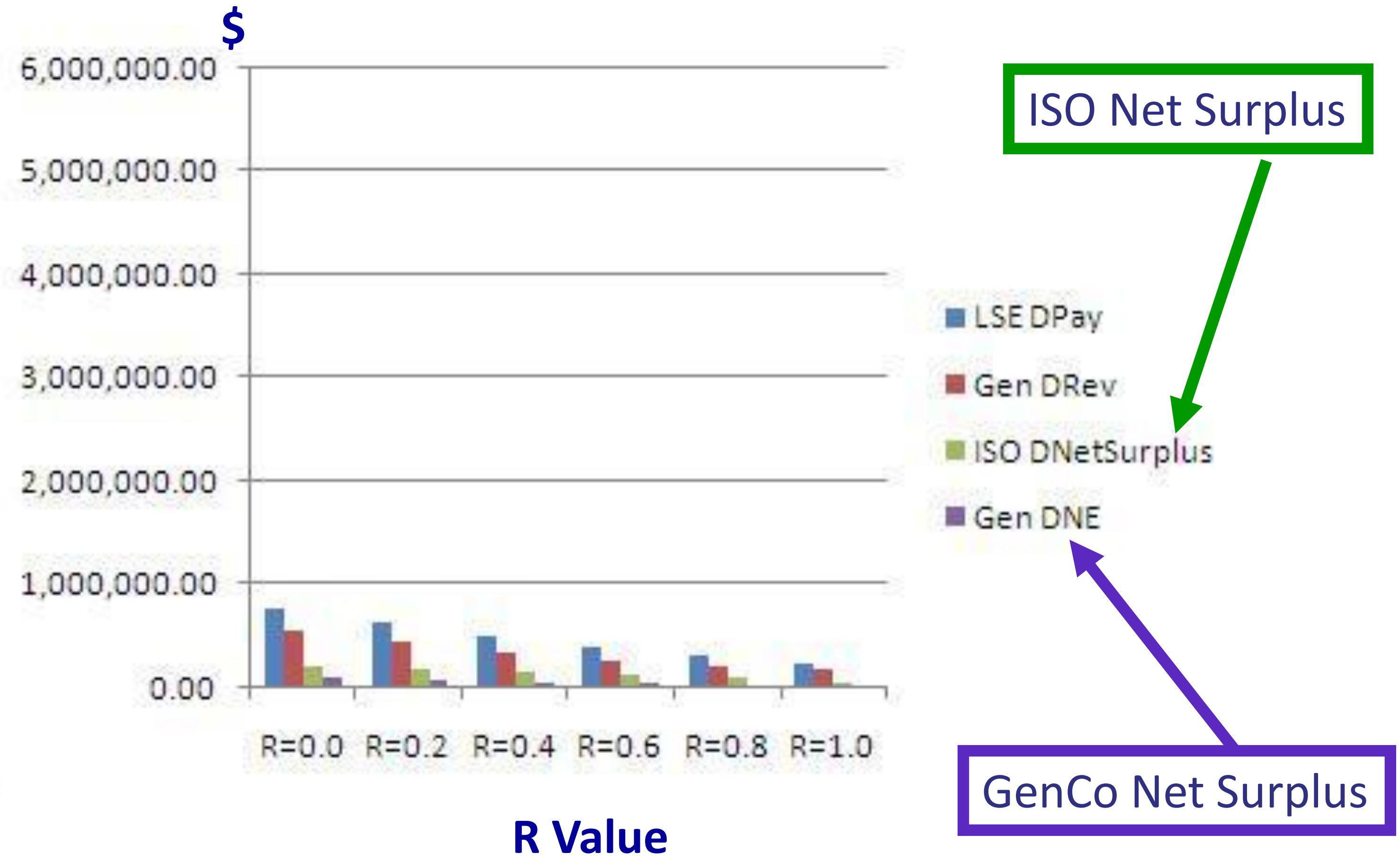


Fig. 6. LSE payments, GenCo revenues, ISO net surplus, and GenCo net earnings during a typical 24-hour day D for the benchmark 5-bus test case.

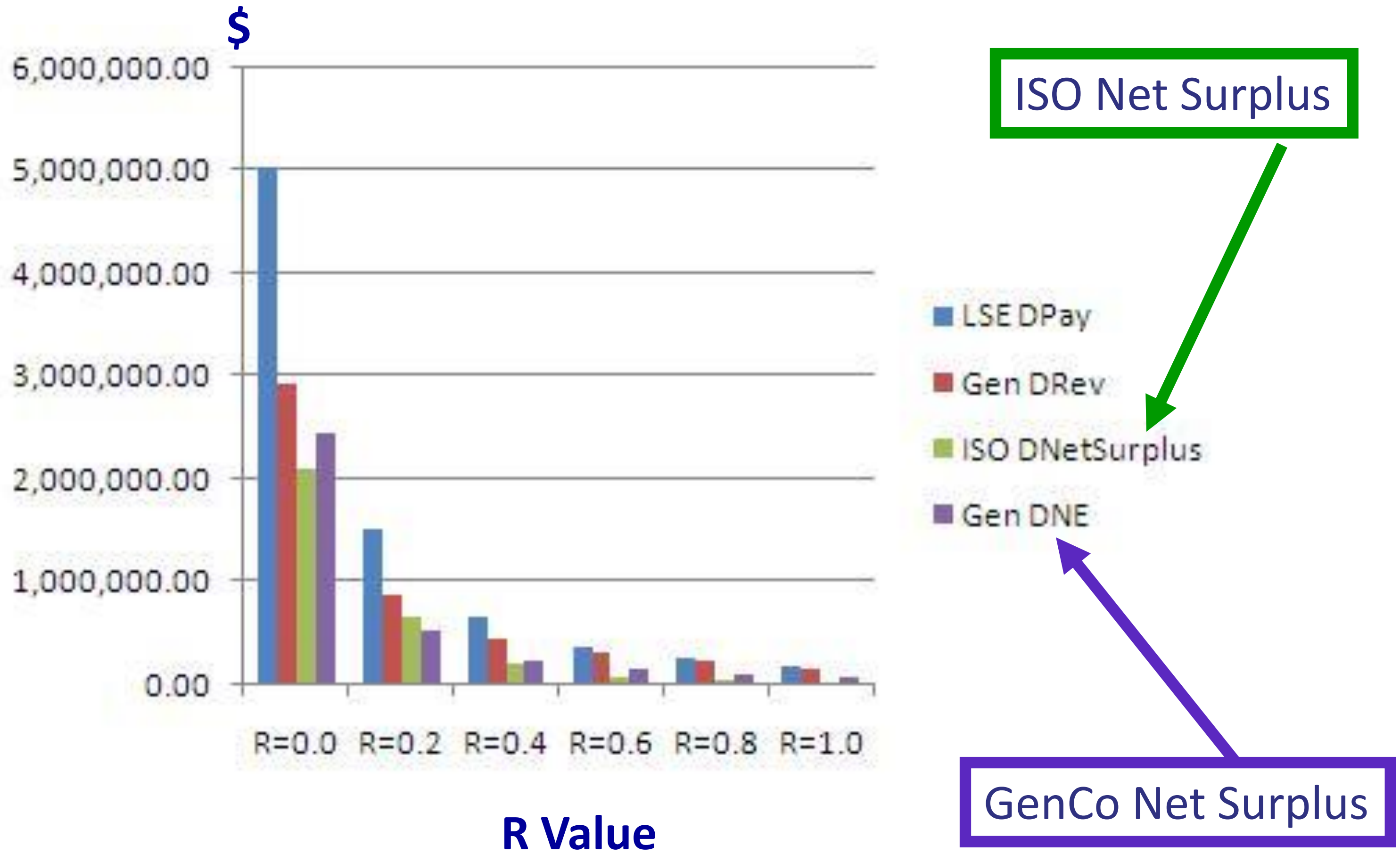
Net Surplus Results ****Without*** GenCo Learning:

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).

	R=0.0	R=0.2	R=0.4	R=0.6	R=0.8	R=1.0
GenNetSur(1000)	92,008.30	69,342.45	53,135.65	41,251.49	30,316.28	27,002.99
LSENetSur(1000)	6,118,410.39	4,937,440.19	3,739,406.53	2,530,696.32	1,317,250.86	95,531.85
ISONetSur(1000)	209,411.07	184,253.35	159,977.47	131,939.70	93,483.24	43,003.42
TNS(1000)	6,419,829.76	5,191,035.99	3,952,519.65	2,703,887.51	1,441,050.38	165,538.26
$\overline{\text{GenNetSur(1000)}}$	2,441,646.71 (153,782.17)	541,230.41 (73,333.88)	227,932.07 (14,969.93)	153,274.62 (161.70)	107,677.99 (51.51)	68,377.76 (18.22)
$\overline{\text{LSENetSur(1000)}}$	1,832,799.11 (1,043,543.03)	3,977,731.25 (980,836.96)	3,494,823.67 (231,030.43)	2,467,054.80 (42,475.32)	1,273,364.42 (29,287.77)	52,119.91 (24,563.47)
$\overline{\text{ISONetSur(1000)}}$	2,097,620.96 (632,303.71)	647,130.97 (633,129.12)	206,219.65 (197,896.93)	57,450.22 (48,696.64)	31,680.94 (30,789.07)	14,879.79 (11,016.23)
$\overline{\text{TNS(1000)}}$	6,372,006.78	5,166,092.63	3,928,975.39	2,677,779.64	1,412,723.35	135,377.46
$\overline{\text{TNSLoss(1000)}}$	47,762.98	24,943.36	23,544.27	26,107.87	28,327.03	30,160.80

No Learning

Learning

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*.
- 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