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

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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 = Agent-based Modeling of Electricity Systems

* Illustrative findings: H. Li and L. Tesfatsion, "ISO net surplus collection & allocation in U.S. wholesale power markets under locational marginal pricing," *IEEE Transactions on Power Systems,* Vol. 26, to appear.

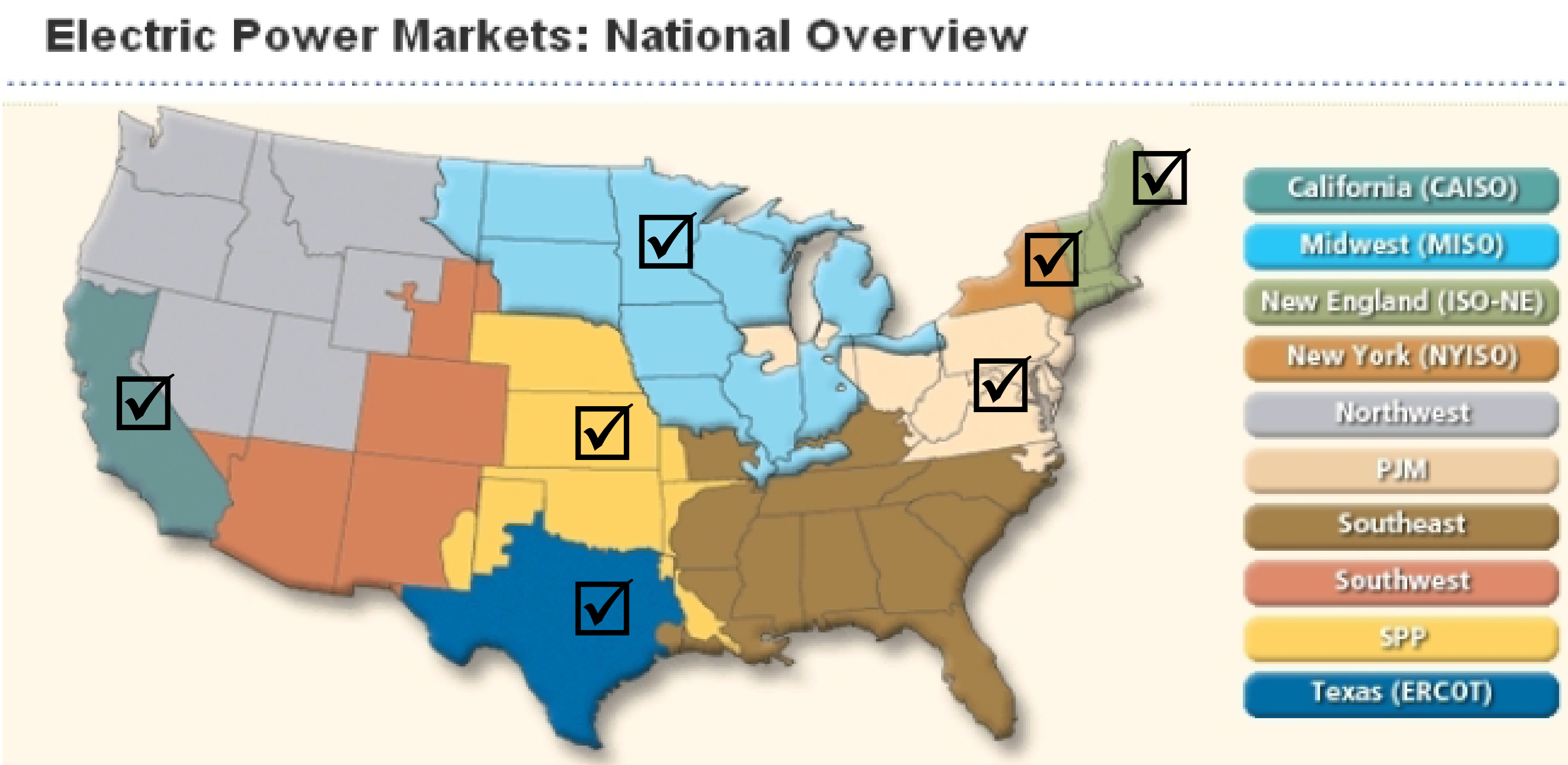
U.S. Federal Energy Regulatory Commission (FERC) Market Design Proposed for U.S.

- 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 via ***Locational Marginal Prices (LMPs),*** where

  LMP at bus k ≅ least cost to system of servicing one more MW of fixed demand at bus k

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

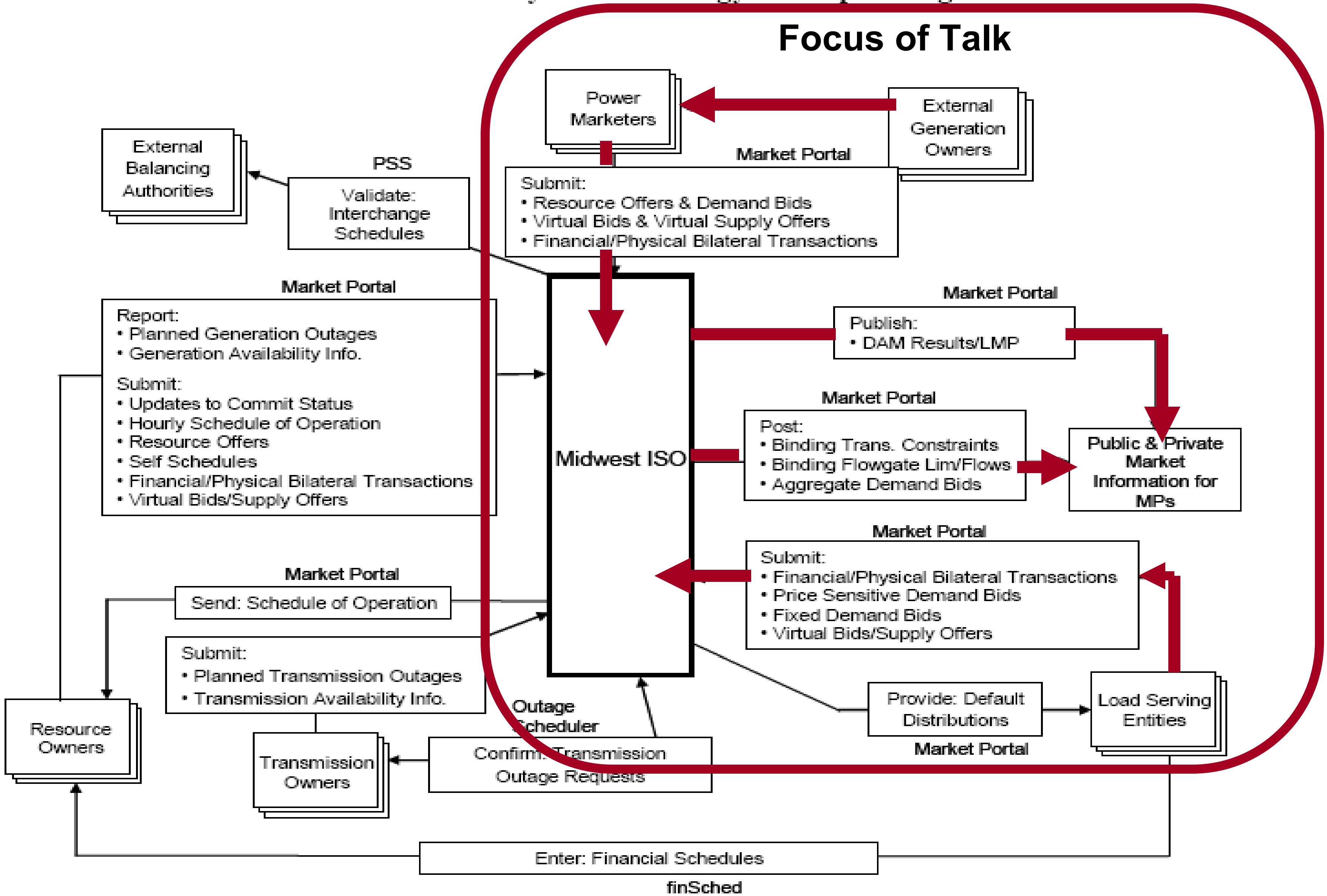
Seven US Energy Regions Have Adopted FERC's Market Design to Date



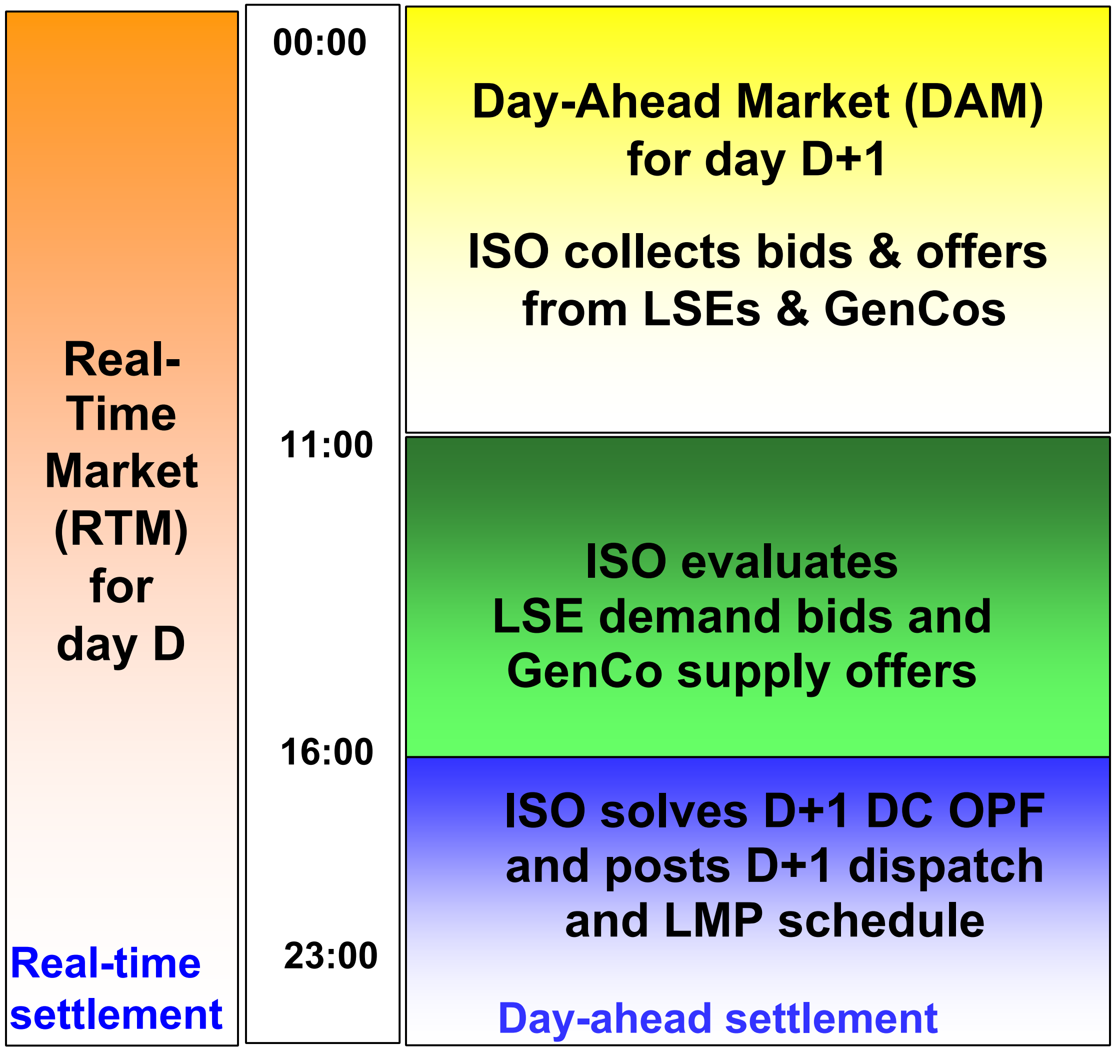
☑ = FERC Market Design Adopted

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



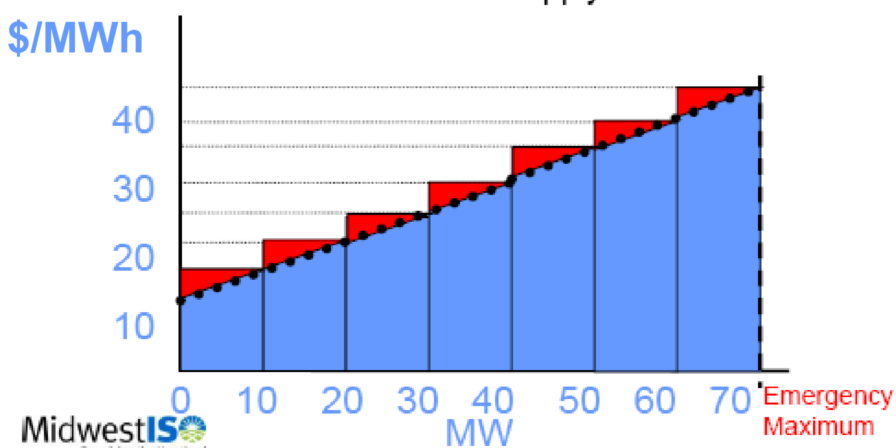
Form of GenCo Supply Offers in MISO

Resource Offers

Energy Offer Curves

Minimum acceptable price (sale reservation price) for each ΔMW

- 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	ΔMW
10	0	10
15	10	10
20	20	10
25	30	10
30	40	10
35	50	10
40	60	10
45	70	10

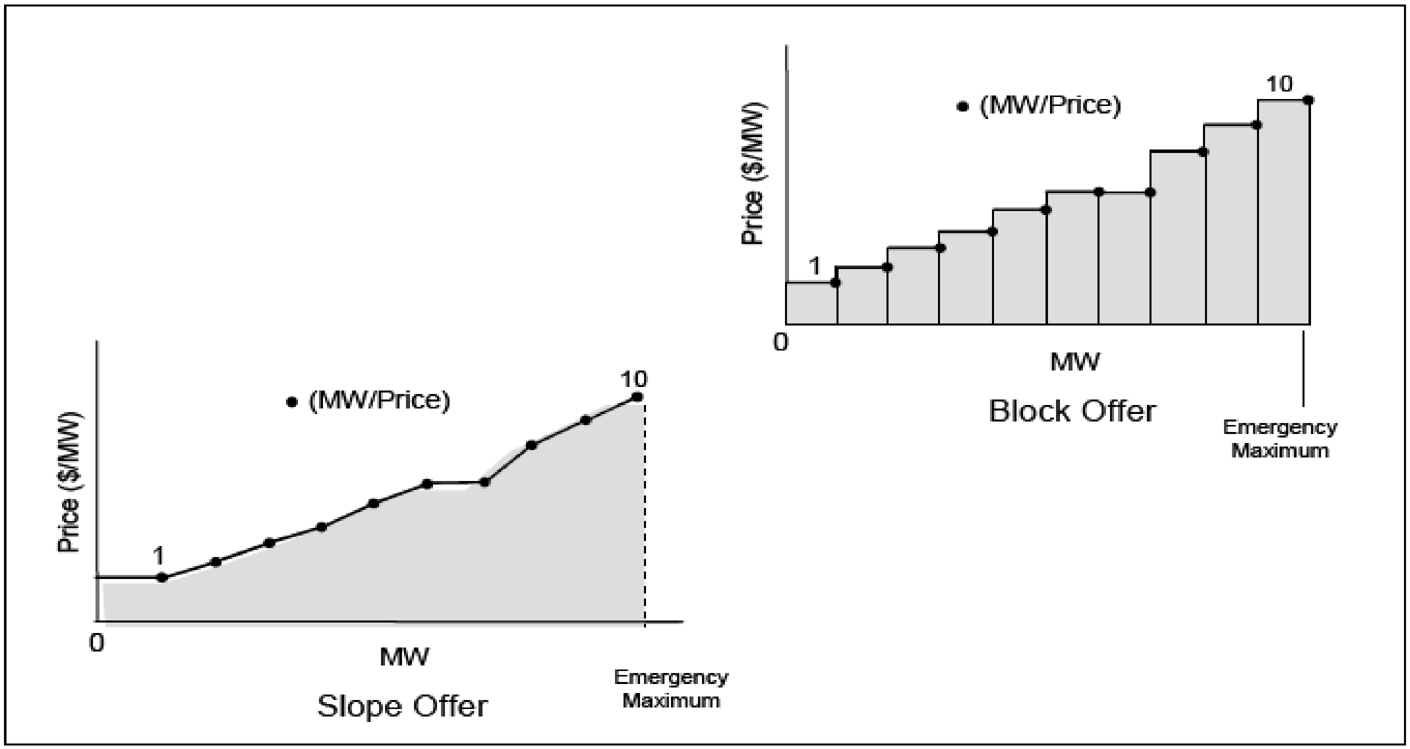
MidwestISO
Energizing the Heartland

31

Form of GenCo Supply Offers in MISO

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

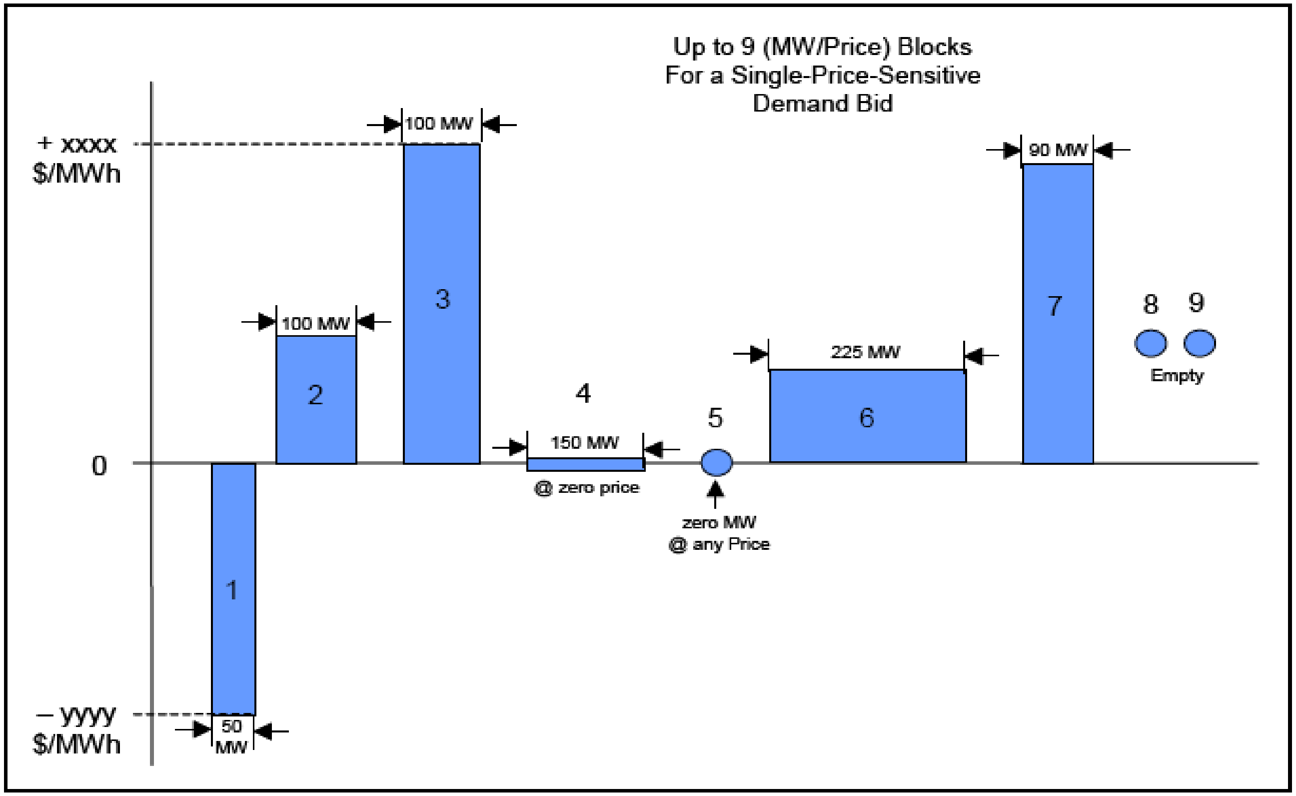
Exhibit 4-11: Types of Energy Offers



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

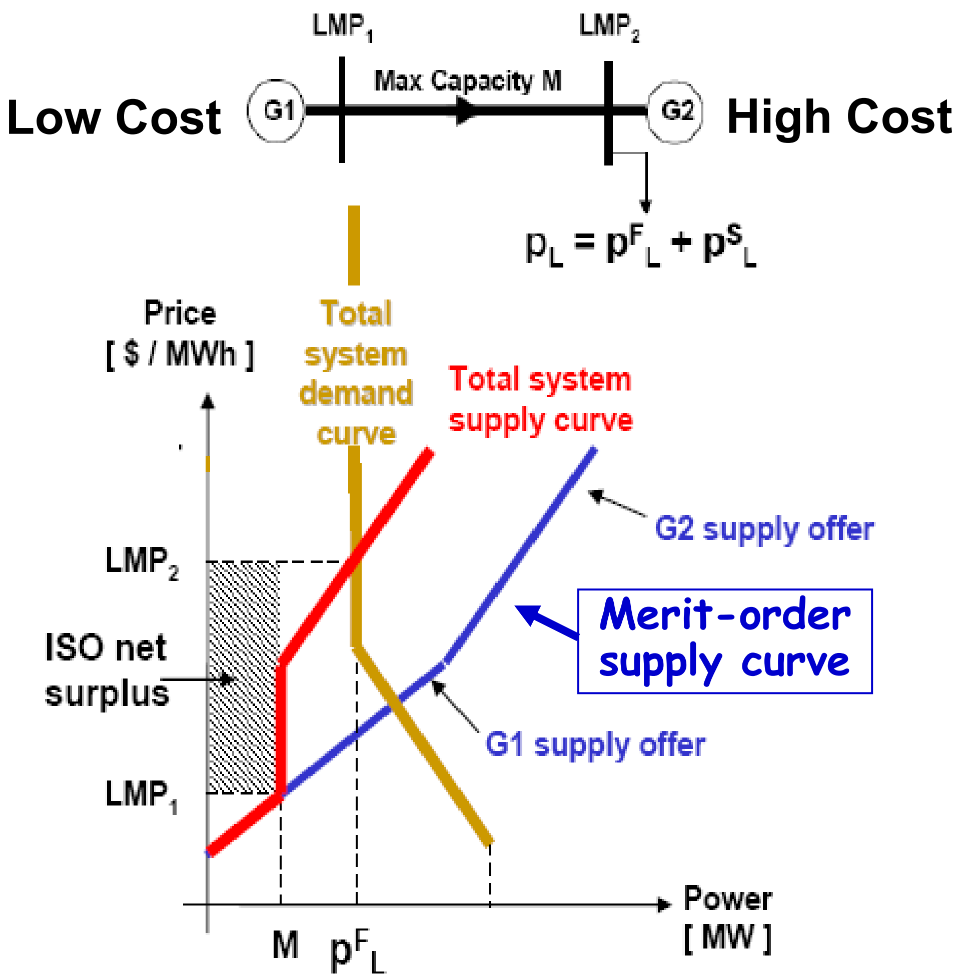
LSE Price-Sensitive Demand Bids in MISO

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: 2-Bus Example with Linear S/D Curves [adapted from H. Salazar (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.

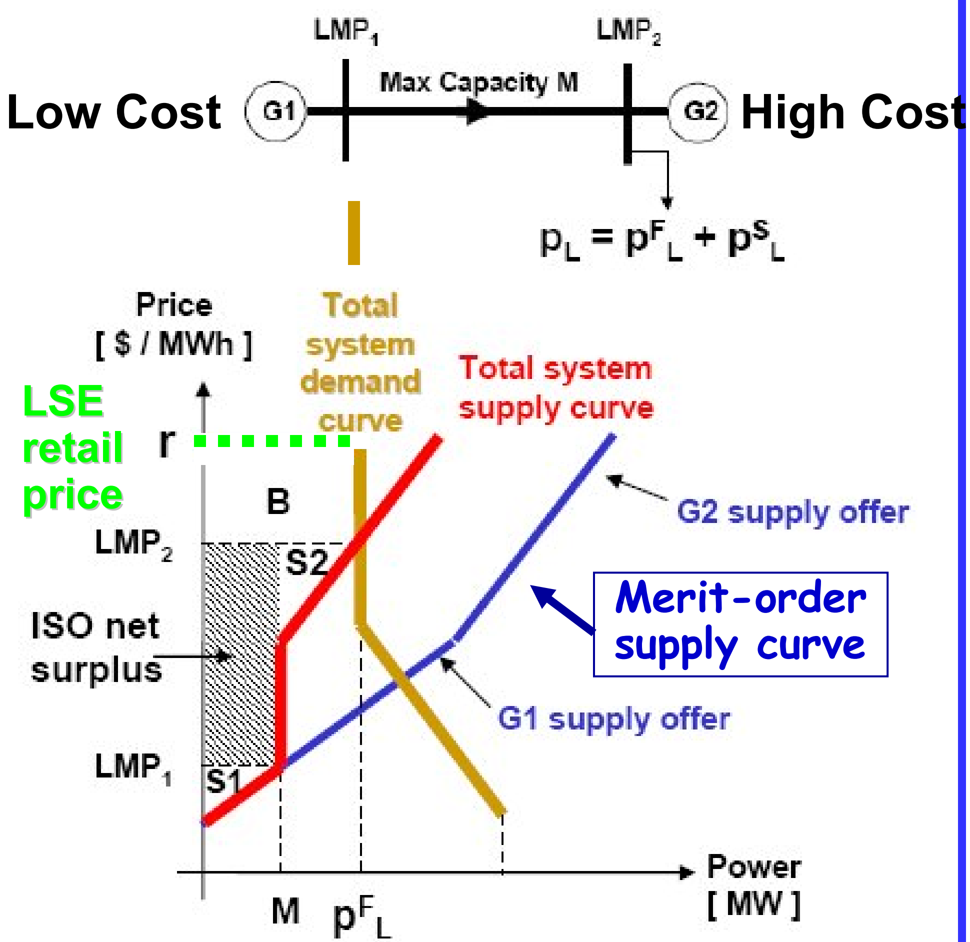
ISO collects difference:

ISO Net Surplus

= [LSE Payments
– GenCo Revenues]

= M x [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** s.t. transmission, generation, & balance constraints.

For each hour of DAM, ISO maximizes TNS^R subject to 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_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 $\sin(d_{km}) \cong d_{km}$

$$\max \quad TNS^R \tag{15}$$

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

$$p^S_{Lj},\ j = 1,...,J;\ p_{Gi},\ i = 1,...,I;\ \delta_k,\ k = 1,...,K \tag{16}$$

subject to

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

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

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:

$$|P_{km}| \leq P^U_{km} \tag{18}$$

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

$$\text{Cap}^L_i \leq p_{Gi} \leq \text{Cap}^U_i \tag{19}$$

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

$$0 \leq p^S_{Lj} \leq \text{SLMax}_j \tag{20}$$

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

$$\delta_1 = 0 \tag{21}$$

TNS^R = Total Net Surplus 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 Bid/Offer-Based DC-OPF Problem Formulation

AMES Wholesale Power Market Testbed

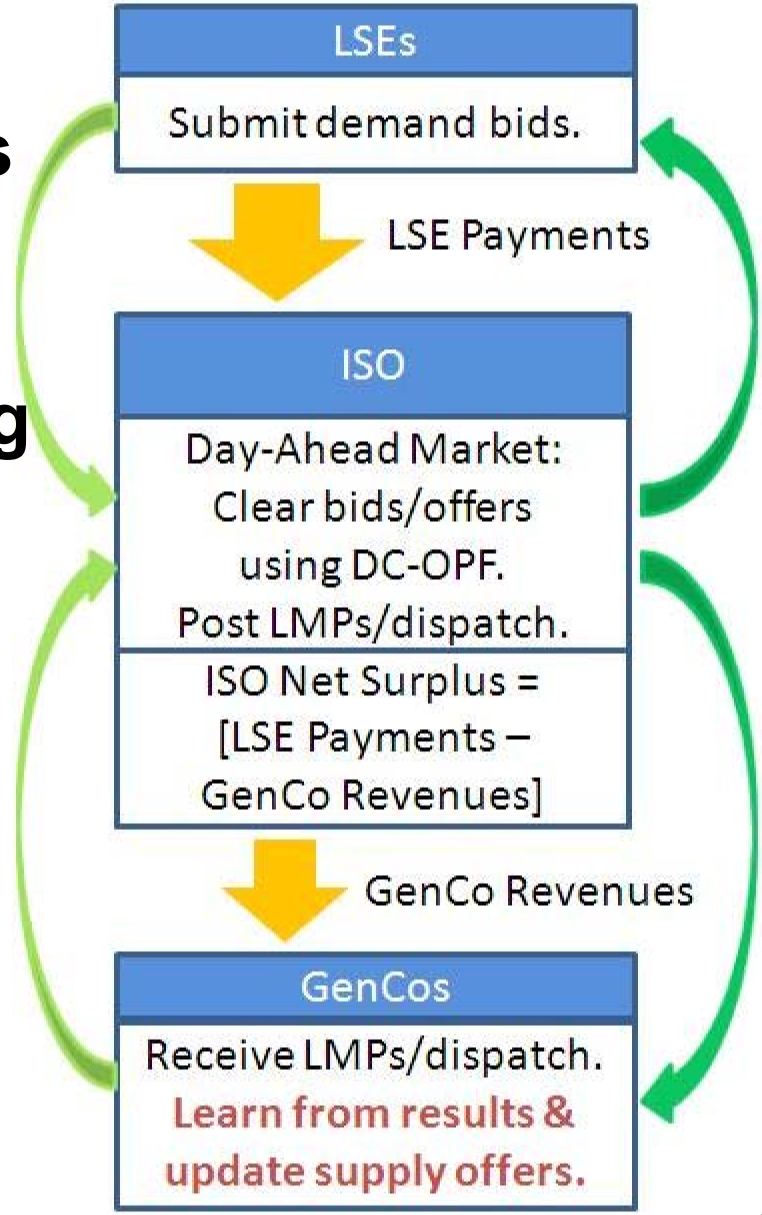
www.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- **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 fixed demand at bus k.

Illustrative computational experiments implemented via AMES: ISO net surplus collections in day-ahead energy markets under Locational Marginal Pricing

Li/Tesfatsion, *IEEE Transactions on Power Systems*, Vol. 26, to appear
http://dx.doi.org/10.1109/TPWRS.2010.2059052

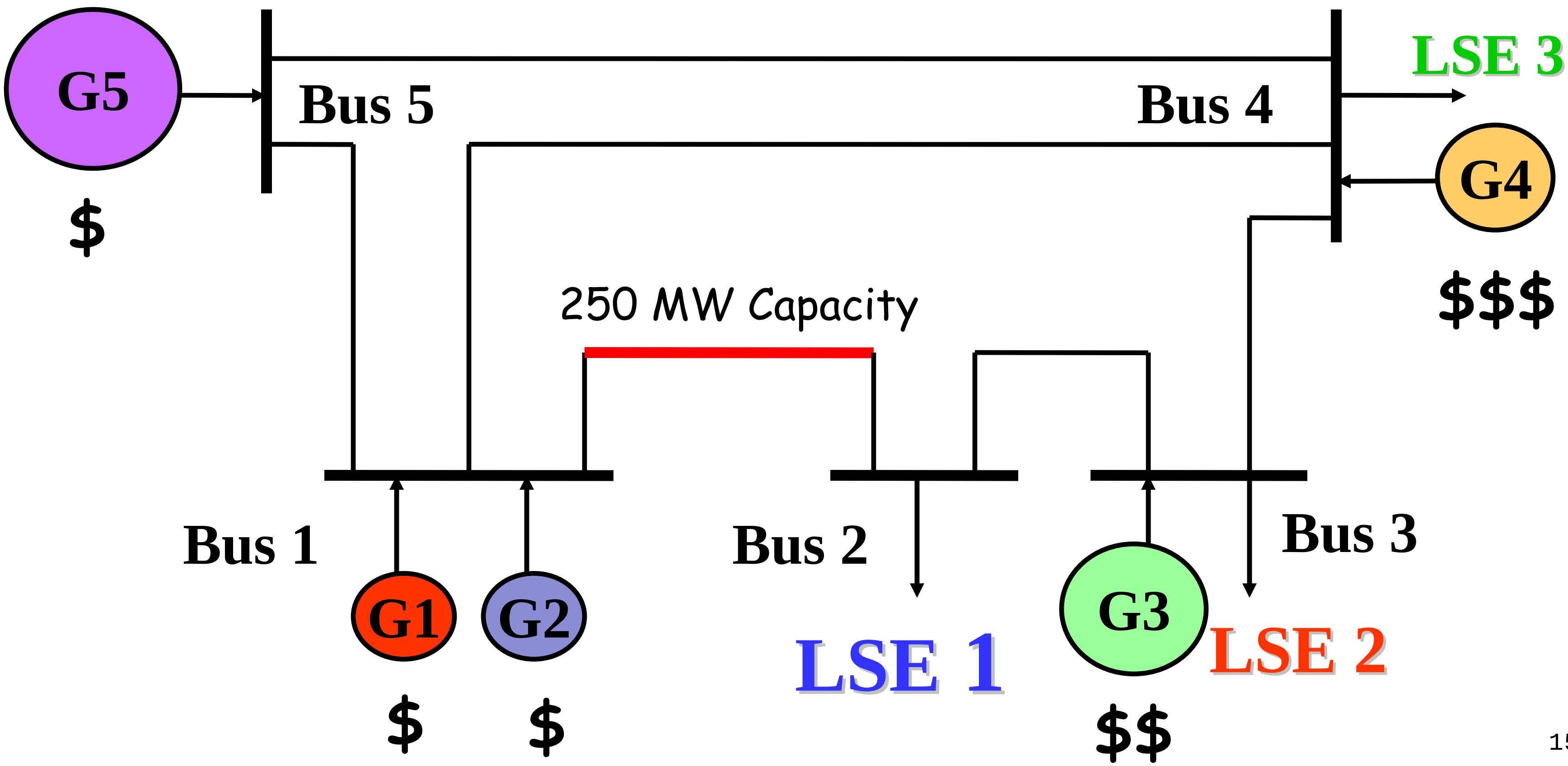
Day-ahead market activities
on a typical operating day D:



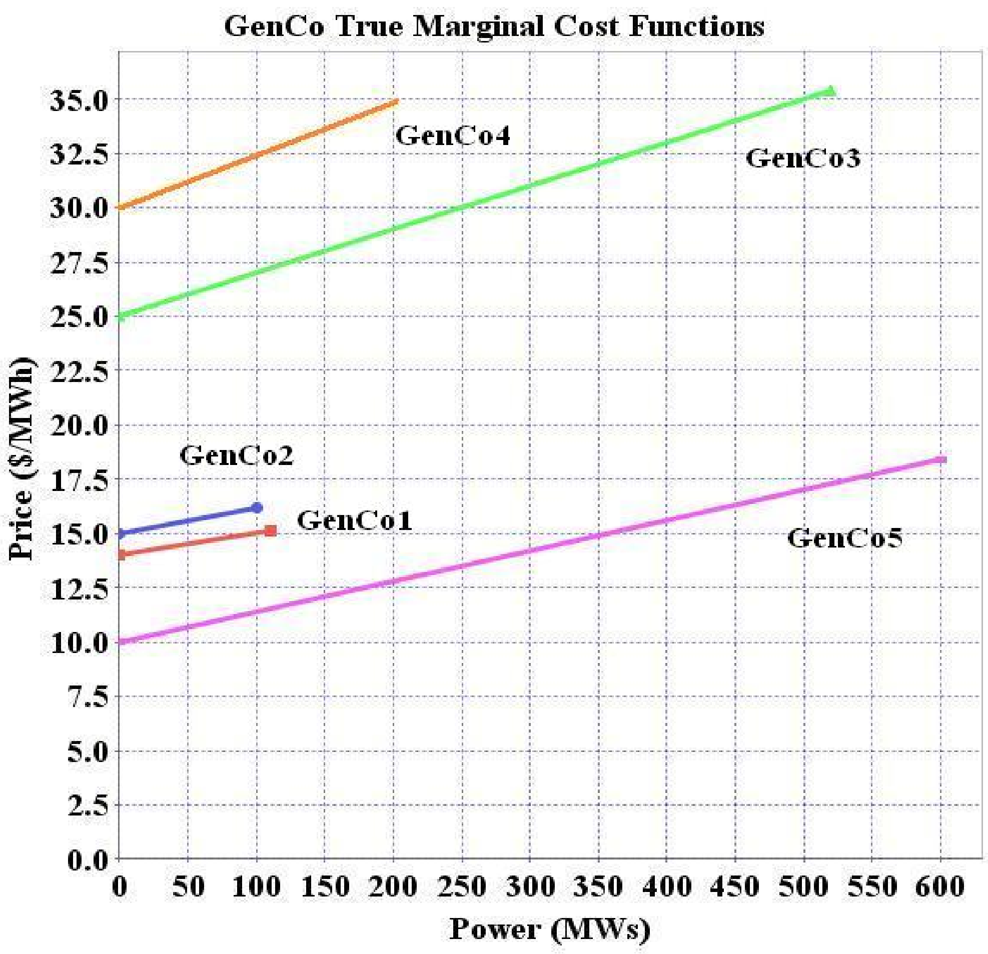
5-Bus Test Case Implemented via AMES

(Basic test case commonly used in ISO training manuals)

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



GenCo True Cost & Capacity Attributes



AMES LSE Hourly Demand-Bid Formulation

◆ Hourly demand bid for each LSE j

Fixed** + **Price-Sensitive Demand Bid

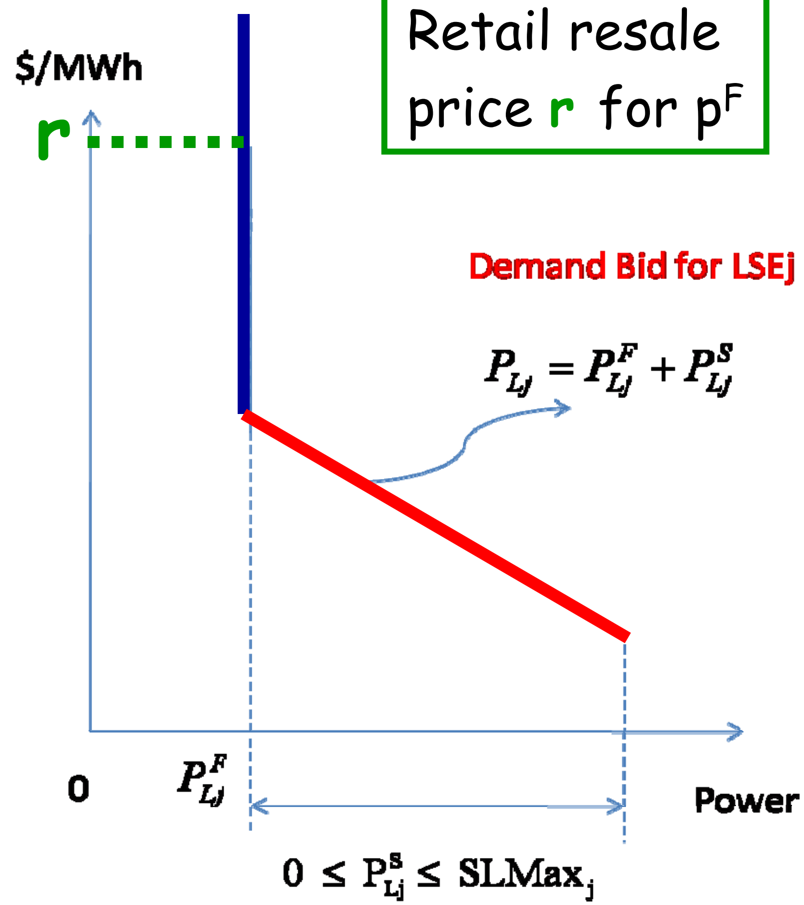
- **Fixed** demand bid = p^F_{Lj} (MWs)
- **Price-sensitive** demand bid

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

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

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

Retail resale price **r** for p^F



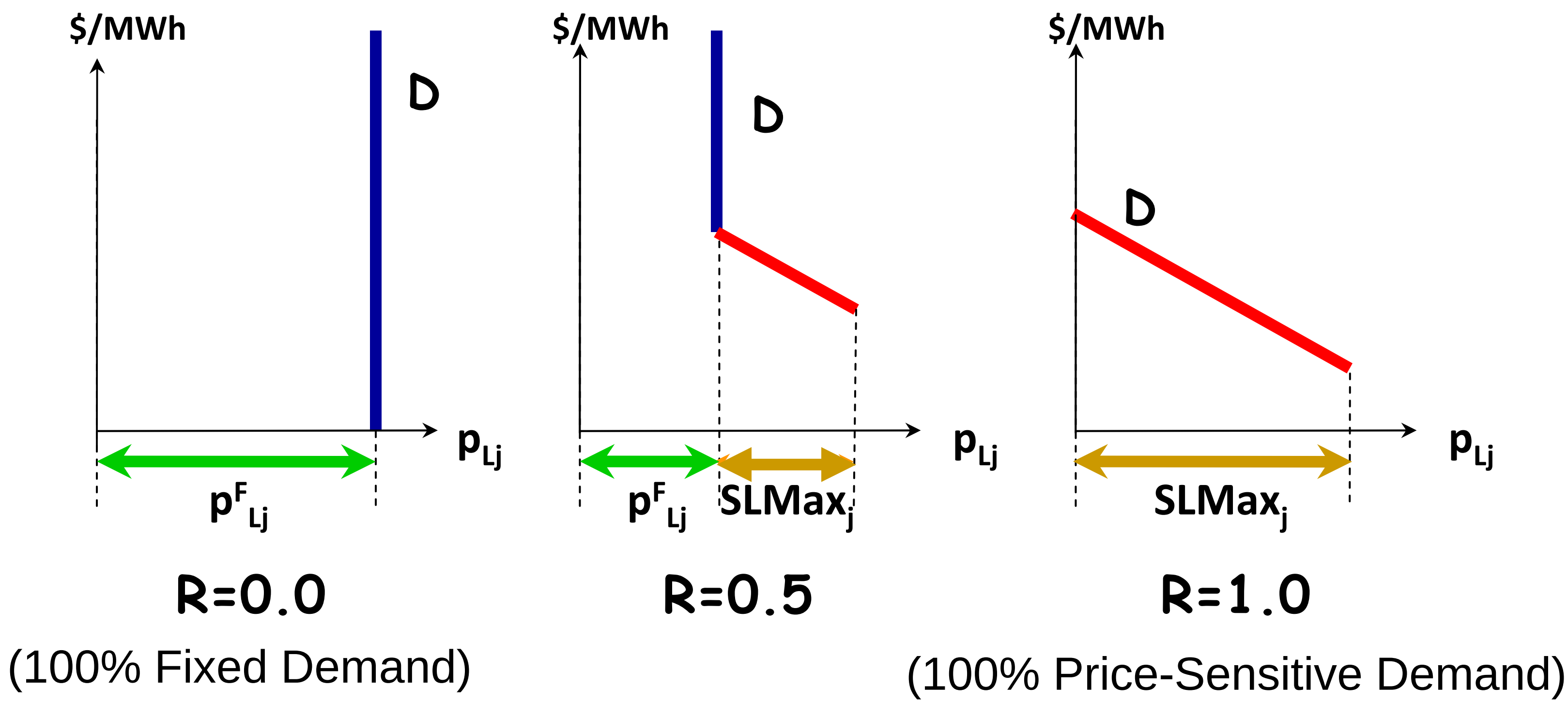
Treatment Factor 1: Demand-Bid Price Sensitivity
(from 100% fixed to 100% price sensitive)

For LSE j in Hour H:

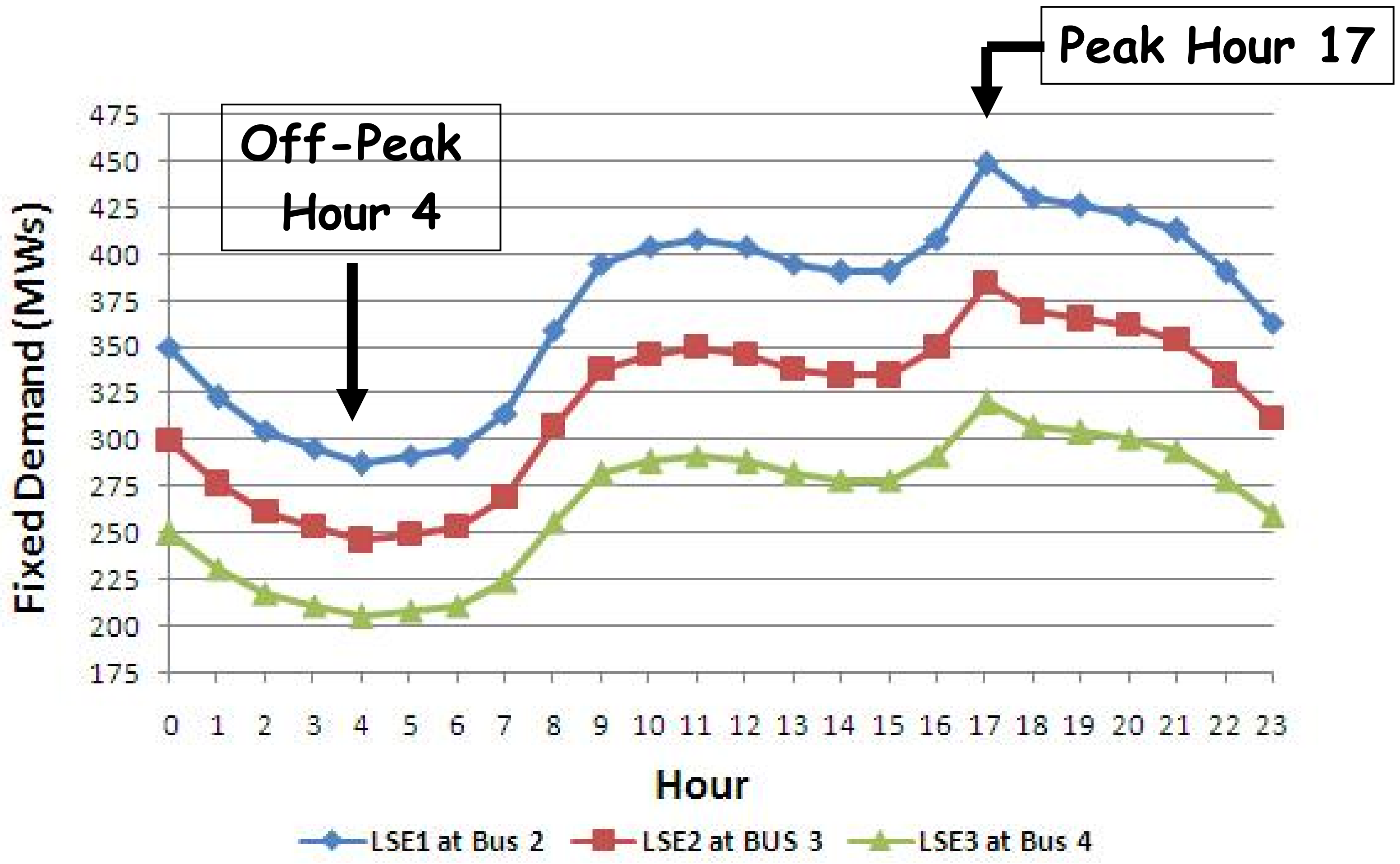
pF_{Lj} = Fixed demand for real power (MWs)

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

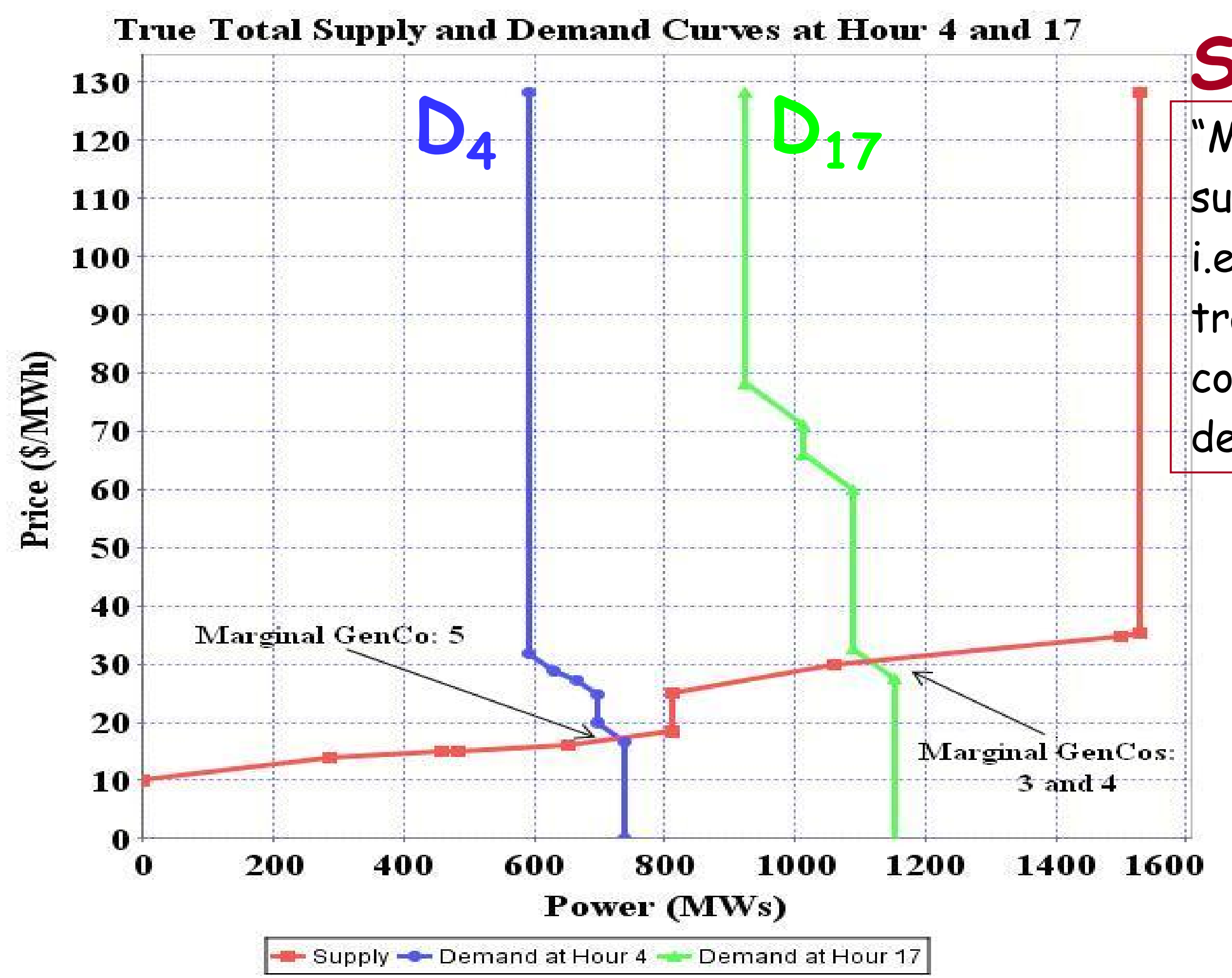
$$R = SLMax_j / [p^F_{Lj} + SLMax_j]$$



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



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, i.e., effects of transmission line congestion not depicted here.

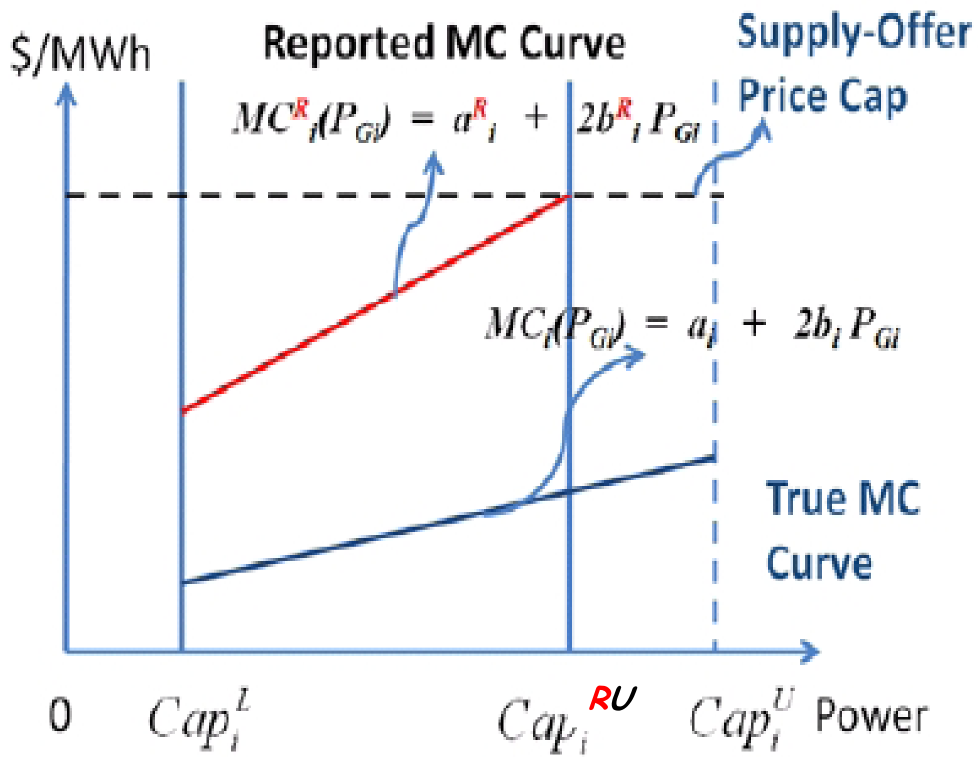
Treatment Factor 2: GenCo Learning Capabilities (No Learning vs. Learning)

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):

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

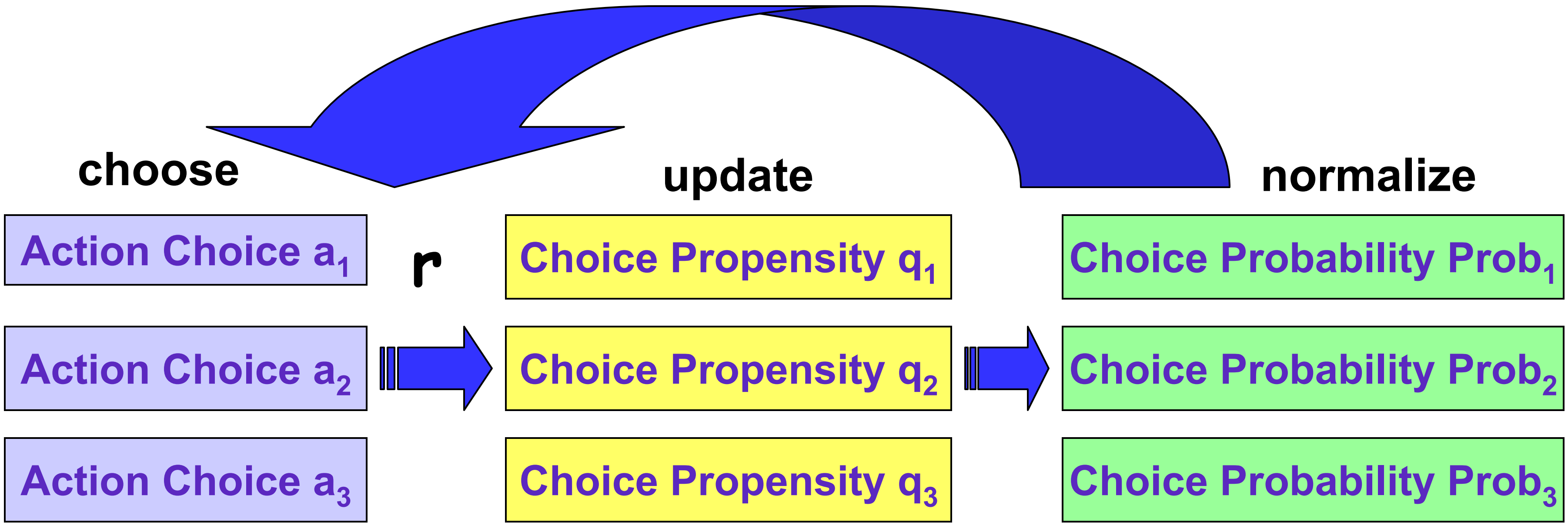
$$Cap^L_i \leq p_{Gi} \leq Cap^{RU}_i$$

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



Learning Treatments: GenCos use VRE Learning

(version 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 Demand Varies from R=0.0 (100% fixed) to R=1.0 (100% Price Sensitive)

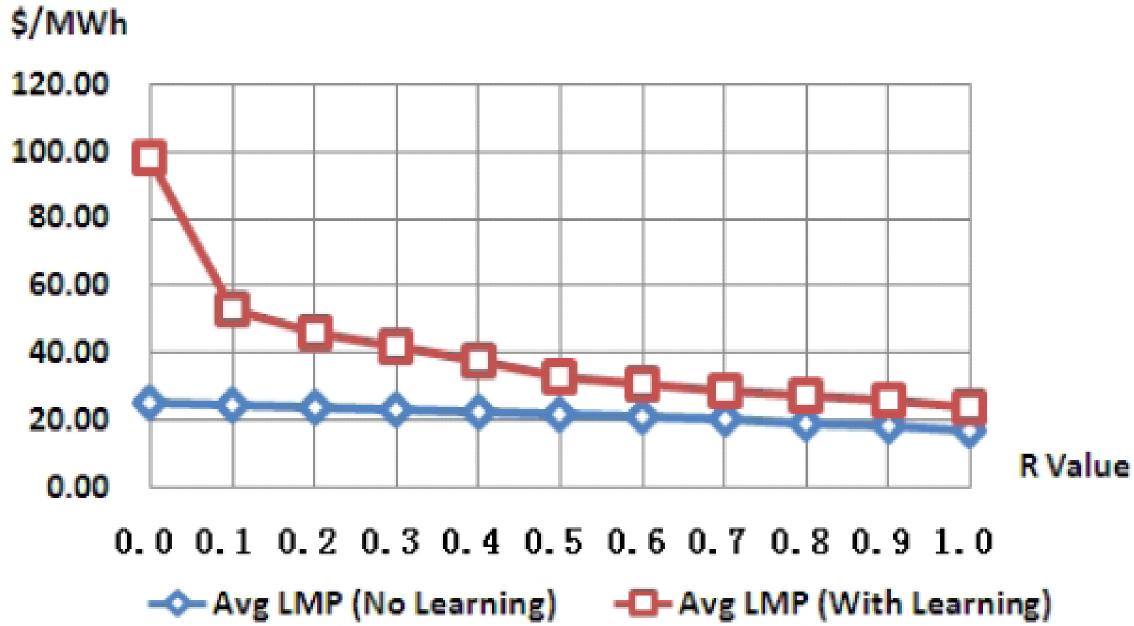


Fig. 7. Mean outcomes for average hourly LMP values on day 1000 for the benchmark 5-bus test case extended to include GenCo learning and LSE demand varying from R=0.0 (100% fixed) to R=1.0 (100% price sensitive).

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

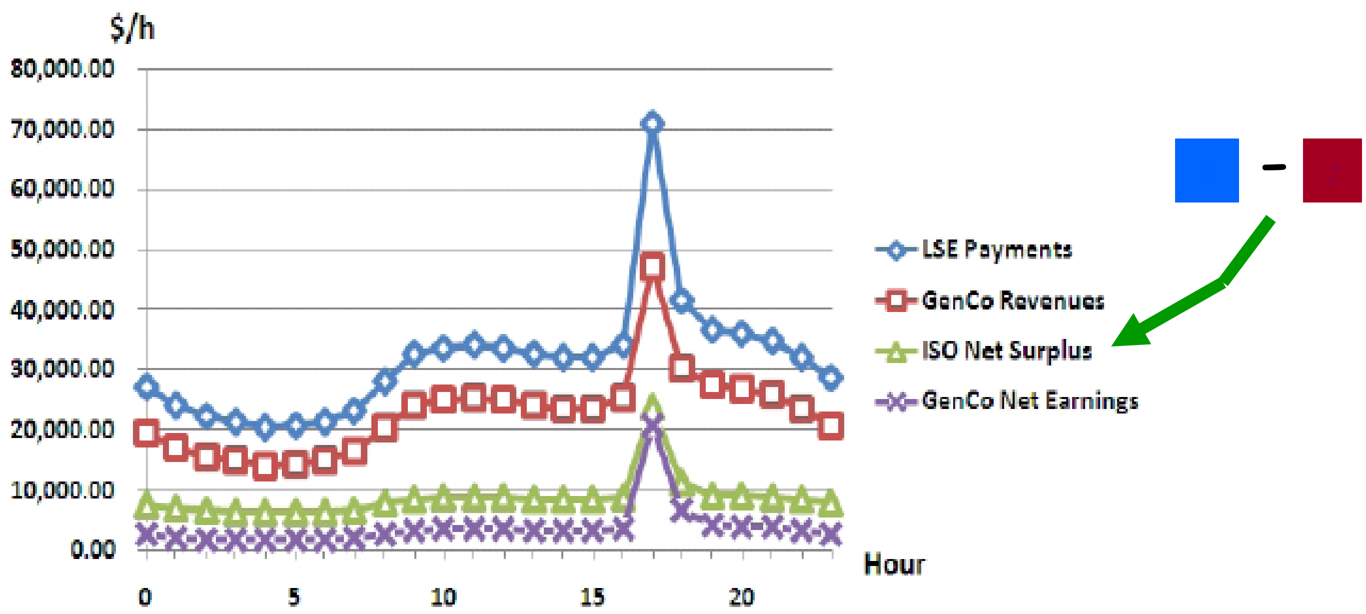
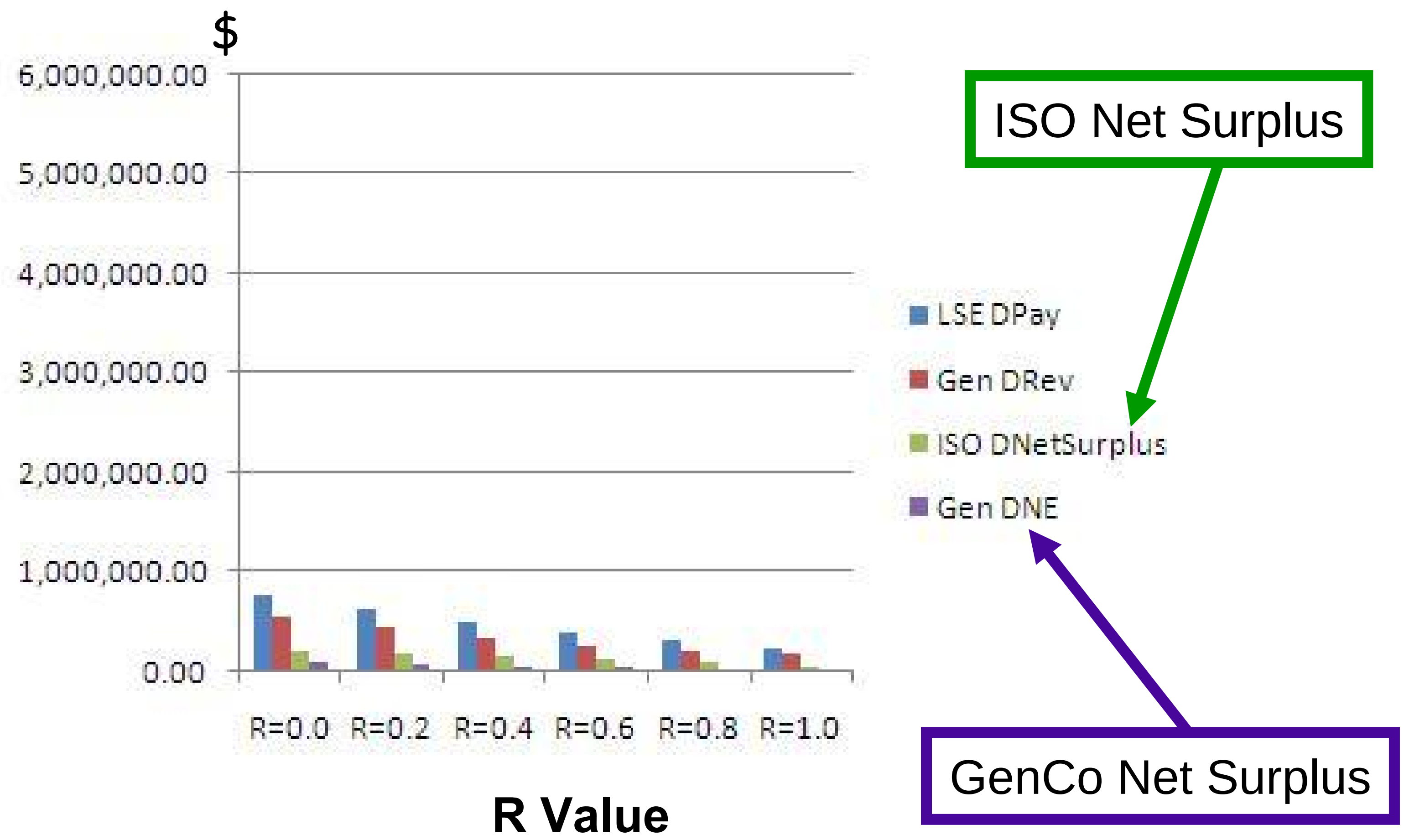


Fig. 6. LSE payments, GenCo revenues, ISO net surplus, and GenCo net earnings during a typical 24-hour day D for the benchmark 5-bus test case.

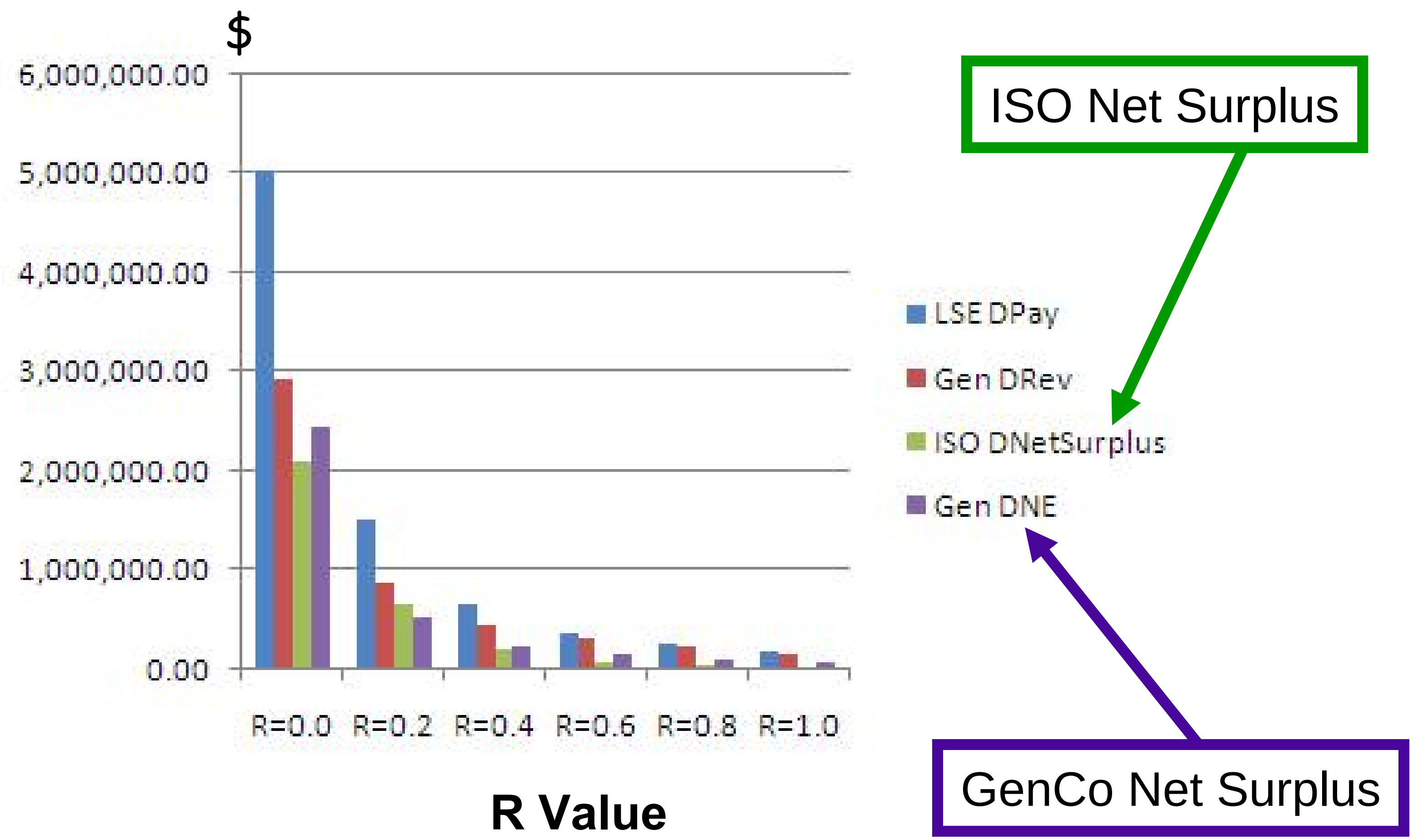
Net Surplus Results ***Without*** GenCo Learning:

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
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)
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)
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)
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
TNSLoss(1000)	47,762.98	24,943.36	23,544.27	26,107.87	28,327.03	30,160.80

No Learn

Learning

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 not well aligned with market efficiency***

- Demand conditions (low price elasticity) resulting in lower total net surplus tend to result in higher ISO net surplus

- ISO net surplus collections should be allocated for the ***ex ante*** remedy of structural/behavioral problems that encourage GenCo strategic supply offer behaviors that result in lower total net surplus (market inefficiency).

- Should not be used ***ex post*** for offsets of high LSE LMP payments and GenCo LMP risk hedge support (currently the typical way ISO net surplus collections are allocated)

On-Line Resources

- **Presentation Slides**

  www.econ.iastate.edu/tesfatsi/ISONetSurplusE3Talk.LT.pdf

- **Li/Tesfatsion IEEE TPWRS Article on ISO Net Surplus**

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

- **AMES Testbed 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 Comp Economics Homepage**

  www.econ.iastate.edu/tesfatsi/ace.htm