



Enhancements of Extended Locational Marginal Pricing – Advancing Practical Implementation

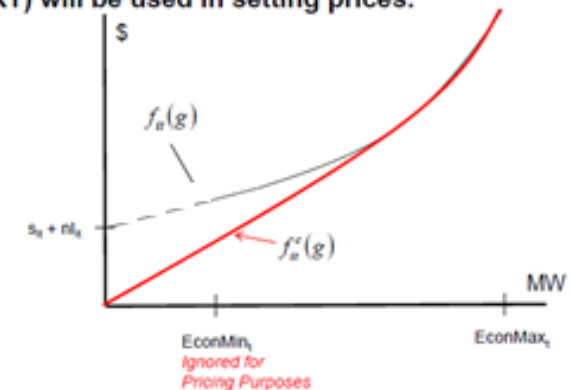
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Quick Review

- Why ELMP?
 - LMP /MCP derived from marginal costs is used to pay for cleared MW from resources
 - Unit commitment problem is **non-convex** due to binary decision variables (**indivisibility**)
 - Fixed costs (startup cost, no load cost)
 - Operating limits (EconMin>0, RegMin>EcoMin, RegMax<EcoMax)
 - Commitment constraints (min run time, min down time, etc.)
 - **Revenue from LMP may not be able to cover the total cost**
- ELMP:
 - Convex hull pricing can reflect fixed cost and result in the most efficient market clearing price

Total Cost Curve for Fast Start Resource or EDR in Period t Used in Approximate ELMP Method

- The slope of the convex hull approximation of the total cost curve in period t for a fast start resource (or EDR in RT) will be used in setting prices.



ELMP has been an important price formation effort to allow Fast Start Resources to set prices

- The Extended Locational Marginal Pricing (ELMP) was developed to allow Fast Start Resources* to set prices including their commitment costs
- Considering the computational challenges and the existing market structure, MISO implemented ELMP in a staged approach
 - Phase I: March, 01 2015
 - Phase II: May 01, 2017
- Continuing enhancements of ELMP include better approximation of full ELMP, extending eligibility of Fast Start Resources and others based on production experiences and emerging needs

Studies identified enhancements for near-term implementation or needs for further investigation

- Three short-term enhancements were studied
 - Convex Envelope
 - **IMM recommendation**
 - Real-Time Regulation Enhancement
- The enhancements were prototyped in ELMP engine
- Simulation were performed against production days

Day	Highlights	Daily Average ELMP-LMP
05/06/2018	modest day	\$0
05/15/2018	max gen alert; reg deficit	\$2.00
05/28/2018	miso hit 100F record	\$0.05
05/31/2018	largest ELMP impact	\$5.60

Convex Envelope is a mathematically tighter approximation to full ELMP

- Recently a convex primal formulation was developed that obtains tighter approximation of or even exact representation of full ELMP
 - Equivalent to MISO's Day-Ahead unit commitment formulation implemented in 2017 that contributed to the reduction of its solving time from 4 to 3 hours
- Simulation show modest price impacts
 - Resulting prices can be higher, lower or equal to production ELMP
 - Overall uplift reduced with higher prices helping to reduce make-whole payments and lower prices helping to avoid lost opportunity cost

Example of better ELMP results with improved PWL formulation

G1: Pmin=35MW, Pmax=65MW, No load cost \$100/h

[0,30MW] \$1/MWh [30, 50MW] \$5/MWh [50, 65MW] \$9/MWh

G2: Pmin=0MW, Pmax=60MW, All costs are 0

- Existing production ELMP formulation is in different PWL version but equivalent to the following SOS2 version:

$$\gamma_{j_1} + \dots + \gamma_{j_m} \leq 1$$

$$p_{j,t} = \gamma_{j_1} \cdot P_{j_1,t} + \dots + \gamma_{j_m} \cdot P_{j_m,t}$$

$$C_{j,t}^P(p_{j,t}) = \gamma_{j_1} \cdot C_{j_1,t}^P(P_{j_1,t}) + \dots + \gamma_{j_m} \cdot C_{j_m,t}^P(P_{j_m,t})$$

$$u_{j,t} \cdot \underline{P}_{j,t} \leq p_{j,t} \leq u_{j,t} \cdot \bar{P}_{j,t}$$

- Con: $\gamma_{j_1} + \dots + \gamma_{j_m} \leq u_{j,t}$

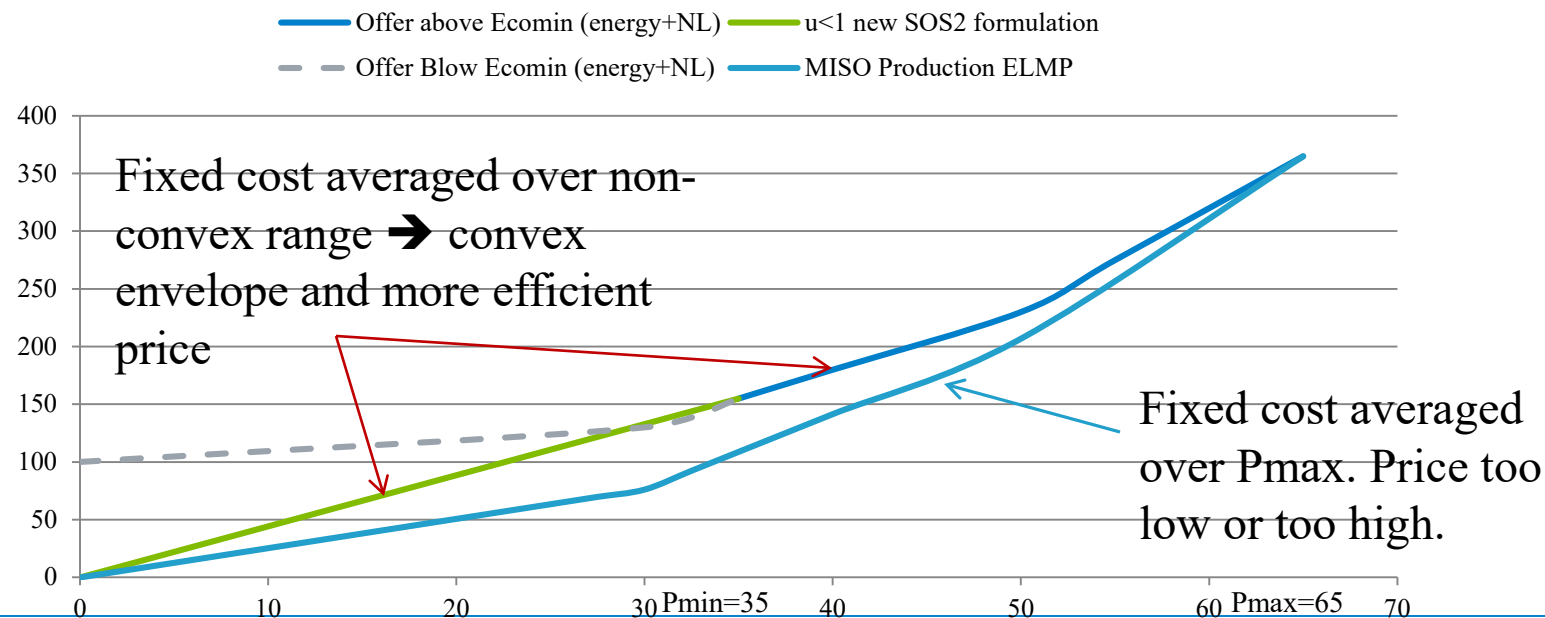
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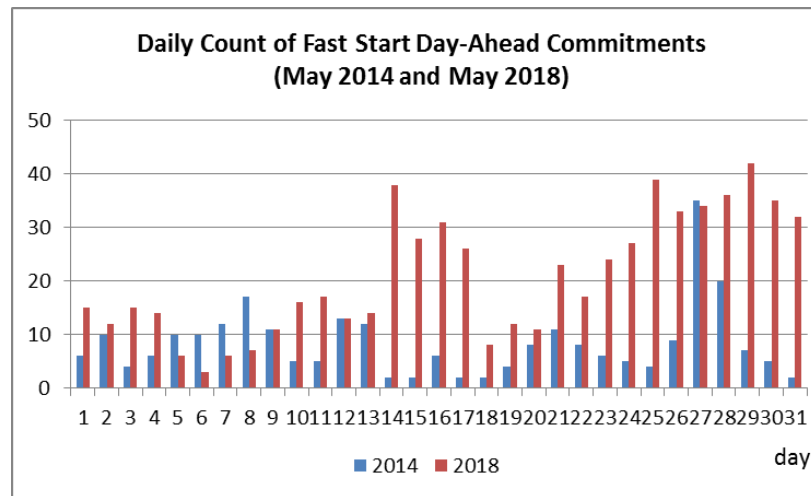
where $u_{j,t}$ is the binary commitment variable

		ELMP non-convex envelope formulation (equivalent to current production)						ELMP convex envelope formulation					
Total Load	P ₁	u ₁	y ₁	y ₂	y ₃	Objective	Shadow Price of Power Balace Equation	u ₁	y ₁	y ₂	y ₃	Objective	Shadow Price of Power Balace Equation
65	5	0.077	0.17	0	0	\$12.69	\$2.54	0.143	0.107	0.04	0	\$22.14	\$4.43
77.5	17.5	0.269	0.58	0	0	\$44.42	\$2.54	0.5	0.375	0.13	0	\$77.50	\$4.43
80	20	0.308	0.67	0	0	\$50.77	\$2.54	0.571	0.429	0.14	0	\$88.57	\$4.43
85	25	0	0.83	0	0	\$63.46	\$2.54	0.714	0.536	0.18	0	\$110.71	\$4.43
87.5	27.5	0.423	0.92	0	0	\$69.81	\$2.54	0.786	0.589	0.2	0	\$121.79	\$4.43
90	30	0.462	1	0	0	\$76.15	\$6.54	0.929	0.643	0.21	0	\$132.86	\$4.43
95	35	0.538	0.75	0.3	0	\$108.85	\$6.54	1	0.75	0.25	0	\$155.00	\$4.43
100	40	0.615	0.5	0.5	0	\$141.54	\$6.54	1	0.5	0.5	0	\$180.00	\$5.00
110	50	0.769	0	1	0	\$206.92	\$6.54	1	0	1	0	\$230.00	\$5.00
125	65	1	0	0	1	\$365.00	\$10.53	1	0	0.333	0.667	\$365.00	\$9.00



IMM recommendation: Include Day-Ahead Committed Fast Start Resources

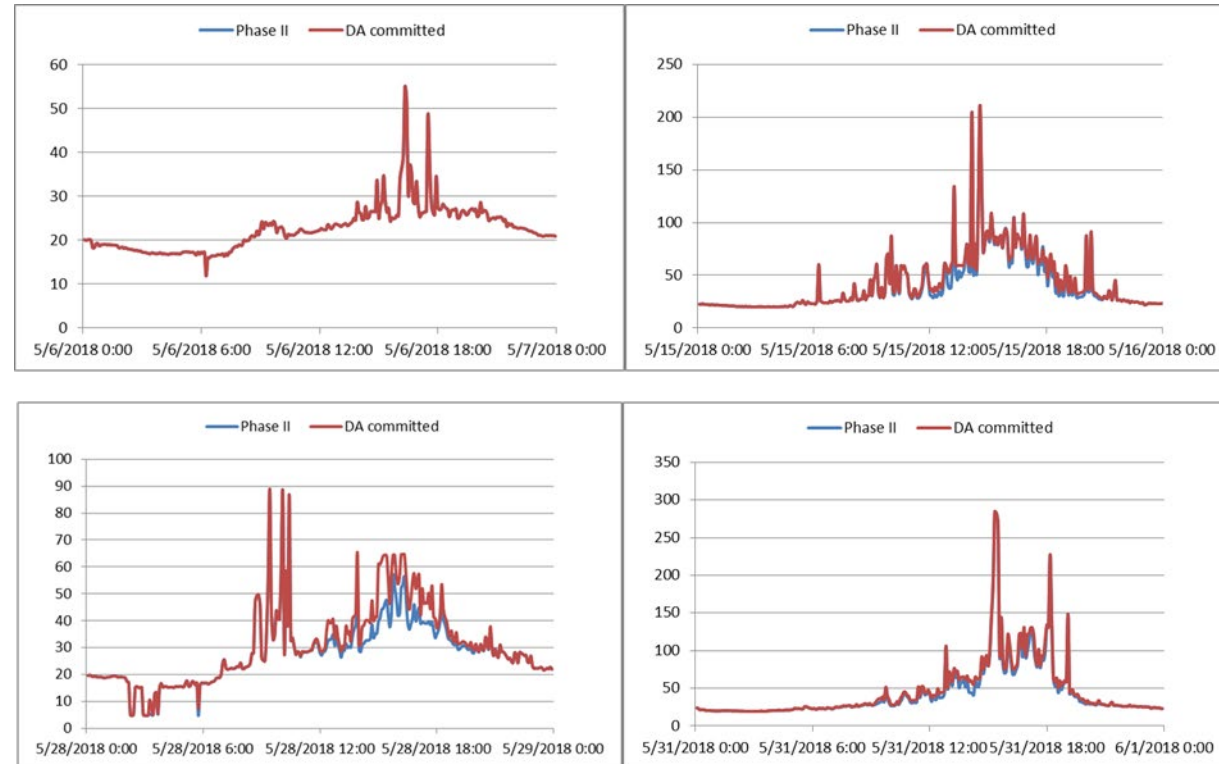
- Currently Fast Start Resources committed in the Day-Ahead market are not eligible for ELMP in the Real-Time market
 - DA commitments are binding and costs are sunk in RT
 - Historically, few 10-minute Fast Start Resources were committed in Day-Ahead and pricing impacts were trivial
- More Fast Start Resources are committed in DA as a result of expansion of Fast Start Resources and generation fleet changes



Simulation prices increased over ELMP II

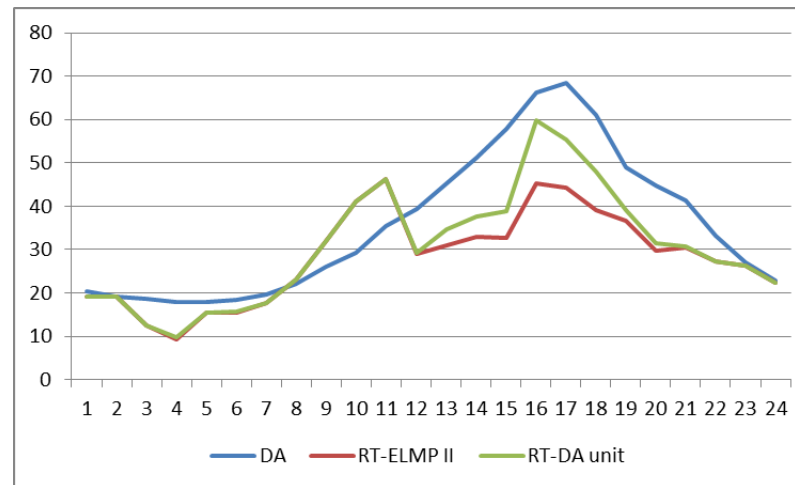
- Depending on the operating day, prices can increase up to \$2/MWh

	5/6/2018	5/15/2018	5/28/2018	5/31/2018
ELMP II	\$0.00	\$2.00	\$0.05	\$5.60
DA Units	\$0.00	\$3.74	\$2.07	\$7.79



Results show better Day-Ahead and Real-Time price convergence

- On a particular day of 5/28/2018 when MISO hit 100F, only a modest ELMP impact was observed in production
 - Fast Start Resources were heavily committed in the Day-Ahead market but did not participate in the Real-Time pricing
- By including these units, Real-Time prices increased more than \$2/MWh on average



Recommend for evaluation of near-term implementation on legacy system

Regulation commitment

- Regulation commitment ur to recognize narrow dispatch range for regulating units

$$\underline{P}_{j,t} \leq p_{j,t} + cr_{j,t} \leq \bar{P}_{j,t} \quad \text{if } ur_{j,t} = 0$$

$$\underline{PR}_{j,t} \leq p_{j,t} + reg_{j,t} + cr_{j,t} \leq \overline{PR}_{j,t} \quad \text{if } ur_{j,t} = 1$$

Handling regulation commitment in ELMP

- If a resource regulation dispatch range and economic dispatch range are the same and is not in the money to clear regulation, SCUC may solve at the following two equivalent outcome:

Solution 1: $\text{RegMW}=0$, $\text{ur}=0$

Solution 2: $\text{RegMW}=0$, $\text{ur}=1$

- Under solution 1, the resource cannot clear regulation in ELMP run. May result in artificial price spike.

Handling regulation commitment in ELMP

- If a resource regulation dispatch range and economic dispatch range are the same and is not in the money to clear regulation with $\text{RegMW}=0$, set $\text{ur}=1$ to allow the resource to clear regulation in the pricing run.

