Enhancements of Extended Locational Marginal Pricing – Advancing Practical Implementation

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SUMMARY

Price formation is critical to efficient wholesale electricity markets that support reliable operation and efficient investment. The Midcontinent Independent System Operator (MISO) developed the Extended Locational Marginal Pricing (ELMP) with the goal of more completely reflecting resource costs and generally improving price formation to better incent market participation. MISO developed ELMP based on the mathematical concept of convex hull. However, considering the computational challenges and the existing market structure, MISO implemented an approximate version of ELMP. This paper presents enhancements to ELMP to bring the practical implementation of ELMP closer to the theoretical ideal and to achieve greater benefits of ELMP in production. The Special Ordered Set of Type Two (SOS2) piece-wise linear cost function formulation is used to tighten the approximation of, and under certain conditions exactly match, the convex hull of the cost function. Regulation commitment logic is also enhanced to maintain optimality under degeneracy conditions while providing flexibility for real-time regulation scheduling and pricing. Simulation results on the MISO system illustrate expected benefits. With the increasing interests in inter-temporal constraints, the on-going work on ELMP ramp modelling is also discussed.

KEYWORDS

Convex hull, convex envelope, electricity market, extended locational marginal pricing, ramp modeling, regulation commitment

1. INTRODUCTION

The bid-based, security-constrained, economic dispatch model with locational prices provides the foundation of electricity market design in the organized markets of the United States. These prices incentivize market participants to follow the Regional Transmission Organization or Independent System Operator (RTO/ISO) commitment and dispatch instructions so that the power grid is operated reliably and efficiently. These prices also serve as important signals for bilateral contracts and long-term investment decisions. However, given the practical realities of operating a complex electric system subject to non-convexity and constantly changing conditions, price suppression and resulting uplift have posed fundamental challenges to price formation. In particular, market clearing prices do not typically reflect certain components of a resource's operating costs (e.g., startup costs) or the costs of resources that are dispatched at their operating limits. In theory, unit commitment and other lumpy decisions can create situations where locational prices alone cannot fully support the commitment solution. Reducing price suppression and uplift has been a key focus area of the Federal Energy Regulatory Commission (FERC) and the subject of recent price-formation proceedings [1].

The Midcontinent Independent System Operator (MISO) manages one of the largest electricity markets in the world. At the core of its day ahead and real time markets are the Security Constrained Unit Commitment (SCUC) and Security Constrained Economic Dispatch (SCED) calculations which co-optimize energy and ancillary services. Initially, the dual solutions from SCED were used to calculate locational marginal price (LMP) for energy and market clearing prices (MCP) for ancillary services. In the SCED calculation, all commitment variables were fixed, and fixed startup and no-load costs were not reflected in prices. As a result, LMPs and MCPs would not necessarily fully cover the commitment and dispatch costs for some generators, even if all committed generation was needed to meet demand. This issue is fundamentally due to the non-convexity of the SCUC problem. Make-whole uplift payments have been used to compensate for generation costs not covered by market prices, but these payment settlements are not transparent and can mute efficient locational market price signals.

The extended locational marginal price (ELMP) [4] restores the support of an economic solution model with minimum reliance on uplift payments. Here, uplift payments include both opportunity costs and make whole payments. A convex hull price is the slope of the convex hull of the total cost function, and is thus non-decreasing with respect to demand. Such a price minimizes the total uplift payment, defined by the duality gap between the SCUC problem and its Lagrangian dual. Nevertheless, solving the full convex hull price is computationally expensive, and no commercial solvers are currently available. There are also market design complexities in its application to real-time prices which are executed on a rolling window basis every five minutes. MISO implemented an approximation of convex hull pricing, or ELMPs [5]. Under MISO's ELMP implementation, fixed costs from quick-start resources can be incorporated into the clearing prices through partial commitment [6]. Many variants of convex hull pricing have been explored in academic literature. The accumulated experiences from different RTO/ISO implementations have also been a significant source of advancement, such as PJM's "Proposed Enhancements to Energy Price Formation" [2], [3].

This paper presents two improvements based on MISO ELMP production experiences. The first improvement is a re-formulation of the piecewise linear (PWL) incremental energy curve. Between 2013 and 2016, MISO evaluated various options for the performance of its day ahead market clearing engine. The reformulation of the PWL energy offer curve brought about a 30% reduction in mixed integer programming SCUC problem solve times in some of the hardest cases [8][9]. Subsequently, this PWL enhancement was found to be equivalent to the convex envelope total cost formulation in [7][10]. As proven in [9], this formulation produces the convex envelope of the single interval PWL cost function, and is also the tightest modeling of the PWL cost function. MISO thus explored its application to the single interval ELMP implementation [10] and simulated the enhancement in its production system.

The second improvement is related to regulation commitment. In reality, a resource's dispatch range can be narrower when it is committed to provide regulating reserve, and a regulation commitment variable is used for each regulation qualified resource in SCUC engine to decide whether a unit is committed for regulation. SCED regulation clearing is then restricted to SCUC regulation committed units which could be a very limited pool of resources. When resources are re-dispatched in ELMP or under varying real-time system conditions, artificial regulation scarcities may be encountered within this limited pool, resulting in regulating reserve price spikes. An improved regulation clearing process was thus developed to allow more units for regulation clearing in the dispatch and pricing runs while maintaining optimality.

The rest of the paper is organized as follows. Section II presents a MIP formulation to tighten the piecewise linear function formulation. Section III introduces the improvement on ELMP regulation commitment. Section IV discusses the on-going work of ELMP ramp modeling and Section V concludes this paper.

2. PIECEWISE LINEAR INCREMENTAL ENERGY CURVE

MISO implemented a single interval approximation of the convex hull pricing to achieve a practical approximation that incorporates fixed costs. The initial method developed in 2011 allocates startup cost into individual intervals for a single interval implementation, and use a partial commitment variable to smooth out the fixed costs in approximation to the convex hull as shown in Fig.1. This approximation may result in more uplift and less efficient prices relative to a true convex hull price. The re-formulation of the piecewise linear (PWL) incremental energy curve is used to improve the approximation below.

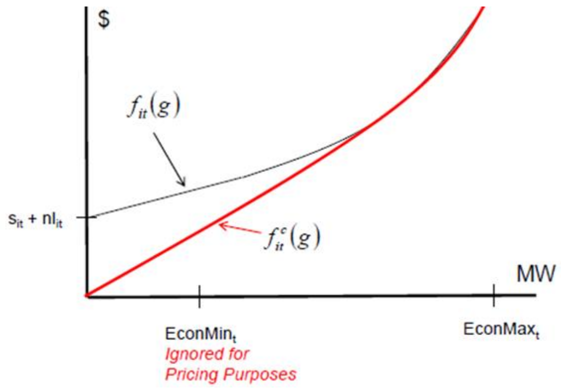

Fig. 1 Convex hull of energy offer curve

Consider a single-interval ELMP model. For simplicity of presentation without affecting the idea of the improved PWL formulation, reserves are not considered.

$$\boldsymbol{Min} \sum_{j\in J, t\in T}\{u_{j,t}\cdot F_{j,t} + C_{j,t}^{P}(p_{j,t})\} \qquad (1)$$

Subject to Power balance constraints, Transmission constraints, System wide reserve constraints and zonal reserve constraints, and Resource level constraints including

$$u_{j,t}\cdot \underline{P}_{j,t} \leq p_{j,t} \leq u_{j,t}\cdot \overline{P}_{j,t} \qquad \forall j\in J \qquad (2)$$

In this formulation, $u_{j,t}$ is the commitment variable for resource *j*. $p_{j,t}$ is the energy dispatch variable. $\underline{P}_{j,t}$ and $\overline{P}_{j,t}$ are the minimum and maximum limits, respectively. Startup costs are amortized over the minimum run time. $F_{j,t}$ is the allocated startup cost plus the non-load cost at interval t. ELMP solves the problem as a linear programming (LP) relaxation by treating $u_{j,t}$ as continuous variables between 0 and 1 (i.e., binary relaxation).

The incremental energy cost function is modeled as a monotonically non-decreasing piece-wise linear function (i.e. convex PWL function). In [8][9], a special order type 2 (SOS2) model was introduced to model this piece-wise linear (PWL) cost function $C_{j,t}^{P}(p_{j,t})$. It has greatly improved the performance of day-ahead unit commitment. The typical SOS2 PWL function can be formulated as follows:

Between pre-determined fixed points $0 = P_{j_0,t} \leq P_{j_1,t} \leq \cdots \leq P_{j_m,t}$, define a set of nonnegative **continuous** variables $\gamma_{j_0}, \gamma_{j_1}, \ldots, \gamma_{j_m}$ and the constraints:

$$\gamma_{j_0} + \gamma_{j_1} + \cdots + \gamma_{j_m} = 1 \quad (3)$$

$$p_{j,t} = \gamma_{j_0} \cdot P_{j_0,t} + \gamma_{j_1} \cdot P_{j_1,t} + \cdots + \gamma_{j_m} \cdot P_{j_m,t} \quad (4)$$

The incremental energy cost function is represented by:

$$C_{j,t}^{P}(p_{j,t}) = \gamma_{j_0} \cdot C_{j,t}^{P}(P_{j_0,t}) + \cdots + \gamma_{m} \cdot C_{j,t}^{P}(P_{j_m,t}) \quad (5)$$

The incremental energy offer is convex and satisfies:

$$0 = C_{j,t}^{P}(P_{j_0,t}) \leq C_{j,t}^{P}(P_{j_1,t}) \leq \cdots \leq C_{j,t}^{P}(P_{j_m,t}). \quad (6)$$

In this model, at most two consecutive variables in (3) can be nonzero for convex cost functions. The piecewise linear incremental energy offer formulation in MISO's ELMP was formulated differently but is mathematically equivalent. However, considering constraints (3) and (4), and the fact that cost curves always start at $C_{j,t}^{P}(P_{j_0,t}) = 0$ with $P_{j_0,t} = 0$, constraints (3)-(6) can be reformulated as:

$$\gamma_{j_1} + \cdots + \gamma_{j_m} \leq u_{j,t} \quad (3a)$$

$$p_{j,t} = \gamma_{j_1} \cdot P_{j_1,t} + \cdots + \gamma_{j_m} \cdot P_{j_m,t} \quad (4a)$$

$$C_{j,t}^{P}(p_{j,t}) = \gamma_{j_1} \cdot C_{j,t}^{P}(P_{j_1,t}) + \cdots + \gamma_{jm} \cdot C_{j,t}^{P}(P_{j_m,t}) \quad (5a)$$

Note for some systems, $C_{j,t}^{P}(0)$ may be non-zero, but this can be easily adjusted by moving $C_{j,t}^{P}(0)$ to no-load cost. Constraint (3a) links generation dispatch variables to commitment variables.

In [7], a convex primal formulation for convex hull pricing was introduced. It proves that a binary relaxation approach can achieve convex hull pricing if (1) individual generator cost functions have convex envelope formulations, and (2) individual generator constraints have convex hull formulations. In [9], it is proven that the least cost function from LP relaxation of the MIP problem under constraints (3a)-(5a) is the convex envelop of the original PWL cost function.

With this approach, the ELMP implemented by MISO, which is equivalent to (3)-(6), may be improved to a convex envelope formulation (3a)-(5a). It can be illustrated by a simple example. Consider a generator unit, G1, with three segments on its incremental energy offer: $1/MWh between [0,30MW], $5/MWh between (30MW,50MW], and $9/MWh between (50MW, 65MW). Assume the no load cost is $100/h, the minimum limit Pmin is 35MW, and maximum limit is 65MW. Assume another generator unit, G2, has a $0/MWh energy offer with a dispatch range between 0MW and 60MW. The cost function is (0, 0) and the solid blue line in Fig. 2 is between 35MW and 65MW. It is non-convex due to fixed costs and Pmin.

Figure 2 compares the LP relaxation solution under the convex envelope SOS2 PWL formulation (3a)-(5a) (red line) and the traditional LP relaxation solution under formulation (3)-(6) (green line). As shown in Table I, under the SOS2 formulation, the price below the minimum limit (35MW) is the cost $155 at 35MW averaged over the 35MW range. Above 35MW, it overlaps with the original cost curve. Together, the SOS2 and the original cost curves form the convex envelope of the original cost function. The LP relaxation implemented in MISO for quick-start resources [6] as shown in the green line and Table II is not as tight as the convex envelope formulation. The fixed cost is averaged over the maximum limit 65MW under current ELMP implementation. When load is between 60MW and 90MW, the ELMP price from LP relaxation is $2.54/MWh under the current MISO implementation.

The cost for G1 at its minimum limit of 35MW is not covered by this price, and as a result the generator still requires a make whole payment. The price from the LP relaxation under the convex envelope formulation is $4.43, and this price does cover the cost at 35MW for G1. When load is above 95MW, u1 is solved below 1 under current ELMP. This is because the no load cost is averaged over the maximum limit of G1. The ELMP price is higher than the LMP derived from true marginal cost of G1, even though the LMP can cover the unit's total cost. Importantly, the ELMP price incentivizes G1 to deviate and move up from its dispatch target. With the convex envelope formulation, u1 is solved at 1 when load is above 95MW. ELMP equals to LMP, and there is no incentive for G1 to deviate from its dispatch target.

Table I LP relaxation from convex envelope PWL formulation

Total Load	p_1	u_1	γ_1	γ_2	γ_3	Objective	Shadow Price of Power Balace Equation
65	5	0.143	0.107	0.036	0	$22.14	$4.43
77.5	17.5	0.5	0.375	0.125	0	$77.50	$4.43
80	20	0.572	0.429	0.143	0	$88.57	$4.43
85	25	0.715	0.536	0.179	0	$110.71	$4.43
87.5	27.5	0.785	0.589	0.196	0	$121.79	$4.43
90	30	0.857	0.643	0.214	0	$132.86	$4.43
95	35	1	0.75	0.25	0	$155.00	$4.43
100	40	1	0.5	0.5	0	$180.00	$5.00
110	50	1	0	1	0	$230.00	$5.00
125	65	1	0	0	1	$365.00	$9.00

Table II LP relaxation from non-convex envelope PWL formulation

Total Load	p_1	u_1	γ_1	γ_2	γ_3	Objective	Shadow Price of Power Balace Equation
65	5	0.077	0.167	0	0	$12.69	$2.54
77.5	17.5	0.269	0.583	0	0	$44.42	$2.54
80	20	0.308	0.667	0	0	$50.77	$2.54
85	25	0.833	0.833	0	0	$63.46	$2.54
87.5	27.5	0.423	0.917	0	0	$69.81	$2.54
90	30	0.462	1	0	0	$76.15	$6.54
95	35	0.538	0.75	0.25	0	$108.85	$6.54
100	40	0.615	0.5	0.5	0	$141.54	$6.54
110	50	0.769	0	1	0	$206.92	$6.54
125	65	1	0	0	1	$365.00	$10.53

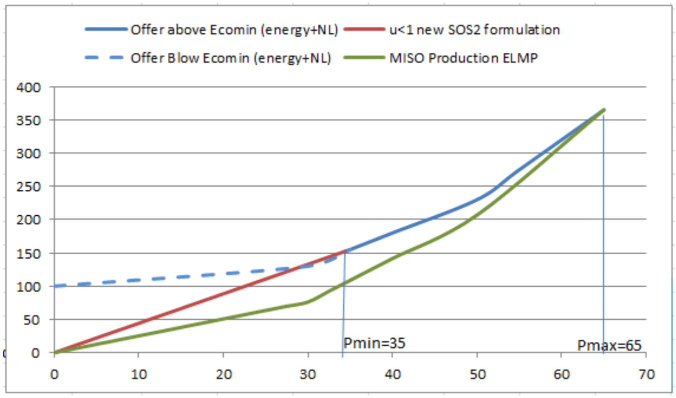

Fig. 2 Comparison of LP Relaxation Total Cost under Convex Envelope and Non-Convex Envelope PWL Formulation

The convex envelope formulation is further solved for practical large-scale system. We prototyped the enhancement in the ELMP engine and simulated the pricing impact against 1,152 production cases representing various system conditions. As expected, simulation results show that ex-post prices under the convex envelope formulation can be both higher and lower relative to ELMP II. The average daily price difference varies from $0/MWh to a $0.08/MWh reduction. A close review of the cases with price differences showed that when prices decrease, there were usually fast-start resources partially committed above the tangent point ($u_{j,t}= 1$), while when prices increase, there were usually fast-start resources partially committed below the tangent point ($u_{j,t}< 1$). Uplift payments are evaluated as the difference between maximum profit and actual profit, including both make-whole payments and lost opportunity costs:

$$\pi^{ExPost} \cdot p^{ExPost} + \pi r^{ExPost} \cdot r^{ExPost} - \sum_{j\epsilon J, t\in T}\left\{u^{ExPost}{}_{j,t} \cdot F_{j,t} + C_{j,t}^{p}\left(p^{ExPost}{}_{j,t}\right) + C_{j,t}^{r}\left(r^{ExPost}{}_{j,t}\right)\right\} \quad (7)$$

$$- \pi^{ExAnte} \cdot p^{ExAnte} - \pi r^{ExAnte} \cdot r^{ExAnte} - \sum_{j\epsilon J, t\in T}\left\{F_{j,t} + C_{j,t}^{p}\left(p^{ExAnte}{}_{j,t}\right)\right\} - C_{j,t}^{r}\left(r^{ExAnte}{}_{j,t}\right) \quad (8)$$

Where π^{ExPost} and πr^{ExPost} are the ex-post ELMP energy and reserve prices, π^{ExAnte} and πr^{ExAnte} are the ex-ante LMP energy and reserve prices, p^{ExPost} and r^{ExPost} are ex-post energy and reserve clearing MW, p^{ExAnte} and r^{ExAnte} are ex-ante energy and reserve clearing MW, $C_{j,t}^{r}\left(r^{ExPost}{}_{j,t}\right)$ and

$C^r_{j,t}(r^{ExAnte}{}_{j,t})$ are ex-post and ex-ante reserve costs. As expected, uplift payments trended down under the convex envelope formulation.

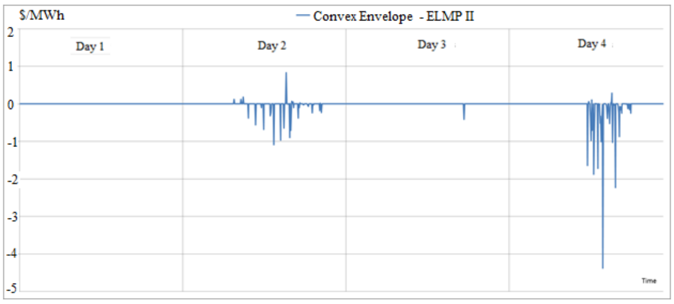

Figure 3. Price Difference between Convex Envelope and Production ELMP over the 5-minute Intervals of Sampled Days

Table III Uplift Reduction under the Convex Envelope Formulation as Compared to ELMP II Production

Sample Day	1	2	3	4
Uplift reduction	0	-$814	-$116	-$1,112

3. IMPROVEMENT ON REGULATION COMMITMENT LOGIC

In reality, a resource's dispatch range can be narrower when it is committed to provide regulating reserve. In MISO practice, a regulation commitment variable is used for each regulation-qualified resource in SCUC engine to decide whether a unit is committed for regulation.

$$ur_{j,t} \cdot \underline{PR}_{j,t} + (u_{j,t} - ur_{j,t}) \cdot \underline{P}_{j,t} \leq p_{j,t} - reg_{j,t}$$
$$p_{j,t} - reg_{j,t} + cr_{j,t} \leq (u_{j,t} - ur_{j,t}) \cdot \overline{P}_{j,t} + ur_{j,t} \cdot \overline{PR}_{j,t} \quad \forall j \in J \tag{9}$$

Where $u_{j,t}$ and $ur_{j,t}$ are binary variables in SCUC and $ur_{j,t}$ is for regulation commitment. A unit can have different operational limits depending on whether or not it is on regulation (i.e. $\underline{P}_{j,t} \leq \underline{PR}_{j,t}$ and $\overline{PR}_{j,t} \leq \overline{P}_{j,t}$). This operating characteristic is further illustrated below.

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

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

(10)

Currently after the SCUC run, binary variables are fixed at SCUC solved values, either at 0 or at 1, within SCED run. If $ur_{j,t}$ is fixed at 0 for a resource, it cannot clear for regulation, i.e., $reg_{j,t}$=0.

Theoretically, SCED and SCUC should have identical models except that in SCED, all binary variables are fixed at SCUC solution. Clearing results between the two models should be identical. By fixing regulation commitment binary variables at SCUC solution values, total capacity is guaranteed not to drop in SCED clearing. Nevertheless, in practice, there can be modeling differences such as in in ELMP pricing where we relax EconMin, and system conditions changes such as load or wind forecast errors. With regulation committed resources fixed at the SCUC solution, SCED regulation clearing has been limited to "REG-Commit" resources (usually a small pool of about 30-40 units).

This logic can be too conservative, since the capacity from resources with equivalent regulating and economic limits is not impacted by regulation selection, i.e., there is a degeneracy when $ur_{j,t} = 0 \text{ or } 1$ are both optimal solutions. A set of resources has the same economic and regulating dispatch range, i.e., $\underline{P}_{j,t}$ = $\underline{PR}_{j,t}$and $\overline{PR}_{j,t}$ =$\overline{P}_{j,t}$. These resources could be committed for energy but not economic to clear regulation, i.e., with $reg_{j,t} = 0$ in SCUC optimal solution. For those resources, the SCUC solution is not impacted by $ur_{j,t}$ and the SCUC objective is identical under (11) or (12) when $reg_{j,t} = 0$ in SCUC optimal solution:

$$u_{j,t} = 1,\ ur_{j,t} = 1, reg_{j,t} = 0,\ \underline{P}_{j,t} = \underline{PR}_{j,t},\ \overline{PR}_{j,t} = \overline{P}_{j,t} \qquad (11)$$
$$u_{j,t} = 1, ur_{j,t} = 0, reg_{j,t} = 0,\ \underline{P}_{j,t} = \underline{PR}_{j,t},\ \overline{PR}_{j,t} = \overline{P}_{j,t} \qquad (12)$$

By setting $ur_{j,t}$ to 1 on resources with equivalent regulating and economic limits, SCED will continue to clear $reg_{j,t} = 0$ so long as the underlying SCED and SCUC models remain consistent. When conditions between SCUC and SCED differ, this difference may cause regulation clearing on this set of resources to diverge. By fixing these resources at $ur_{j,t} = 0$, the SCED solution is unnecessarily restrictive, and could occasionally cause artificial regulation MCP spikes when the system has adequate resources to satisfy (12) in SCUC and to clear regulation on these resources in SCED due to the slight difference between SCUC and SCED.

This problem occurred more frequently under ELMP. In the ELMP pricing run, the binary variables of quick-start resources are relaxed to solve binary relaxation and derive an approximate ELMP. In the initial ELMP implementation, if a resource has $ur_{j,t} = 0$ in SCUC, it was not able to clear regulation under ELMP. Quick-start-resource commitment variables are allowed to be solved at fractional values in ELMP. The range for clearing $p_{j,t} + reg_{j,t} + cr_{j,t}$ is $u_{j,t} \cdot (\ \overline{P'}_{j,t} - \underline{P'}_{j,t})$. If $0 < u_{j,t} < 1$ in ELMP solution, the range for clearing $p_{j,t} + reg_{j,t} + cr_{j,t}$ in ELMP is less than the range in SCED. Hence, regulation MCP can be higher under ELMP than under SCED. These higher regulation prices usually represent a desired outcome when the price increases reflect the fixed commitment cost for regulation.

However, price spikes may not be appropriate if the system actually has a surplus of regulation qualified resources not committed for regulation in SCUC and are economic for regulation under the higher price. Under the convex hull primal formulation approach in [8], both $u_{j,t}$ and $ur_{j,t}$ should be relaxed in the LP relaxation under multi-interval SCUC formulation. Under the current single interval ELMP implementation, only fast-start resources are allowed to be partially commitment (i.e., allowed to have $u_{j,t}$ solved as a continuous variable). Regulation commitment variables $ur_{j,t}$ of other resources are fixed at the SCUC solution. For resources with $\underline{P}_{j,t}$ = $\underline{PR}_{j,t}$and $\overline{PR}_{j,t}$ =$\overline{P}_{j,t}$, setting $u_{j,t}$ to 1 allows these resources to clear $reg_{j,t}$ in SCED and ELMP run when economic. The resulting prices can more accurately reflect online regulation availability and are closer to convex hull pricing.

The enhanced regulation clearing logic is thus developed to make the set of units satisfying (12) eligible to clear regulation in SCED and ELMP, i.e., set $ur_{j,t}$=1 to allow clearing regulation, if $u_{j,t}$=1, $\underline{P}_{j,t}$ = $\underline{PR}_{j,t}$and $\overline{PR}_{j,t}$ =$\overline{P}_{j,t}$ for regulation qualified resource *j*.

The new logic has been studied in production day-ahead cases to examine impacts on dispatch and pricing. Pricing results ($/MWh) shown in Fig. 4 for six sample days verified that the artificial RegMCP spikes under "Orig RegMCP" were effectively eliminated under the new regulation clearing logic ("New RegMCP"). The New RegMCP from the ELMP run is closer to ex-ante SCED RegMCP. Energy prices and RegMCP in other days were mostly unchanged.

The improved regulation clearing logic is further used in the real-time market to replace a manual regulation management tool that operators used to manually designate units as "REG-Commit" for regulation clearing as system conditions change in real-time. In addition, the regulation clearing process is more complicated in real-time. For instance, a unit offers three ramp rates in real-time: an up ramp rate, a down ramp rate, and a bi-directional ramp rate. The bi-directional ramp rate (≤ up/down ramp rate) is used when the unit is designated as "REG-Commit". Another complication involves the 5 minute real-time interval versus an hourly regulation selection process. The improved logic further considers ramp rate when adding units on regulation to the same capacity and flexibility as seen by SCUC. The enhanced logic was tested on the production MISO system, and simulation results demonstrate that more units are designated as “REG-Commit” under the enhanced logic, capturing most of the units that are currently manually designated as “REG-Commit” by the regulation management tool. This improvement also addressed stranded capacity or flexibility when units with narrower dispatch range or lower ramp rates are inappropriately designated as “REG-Commit”. As a result of the more efficient regulation clearing logic, system wide production costs were reduced, especially during regulation constrained intervals. Average production cost was reduced by \$1.8k~\$20k for the simulated days.

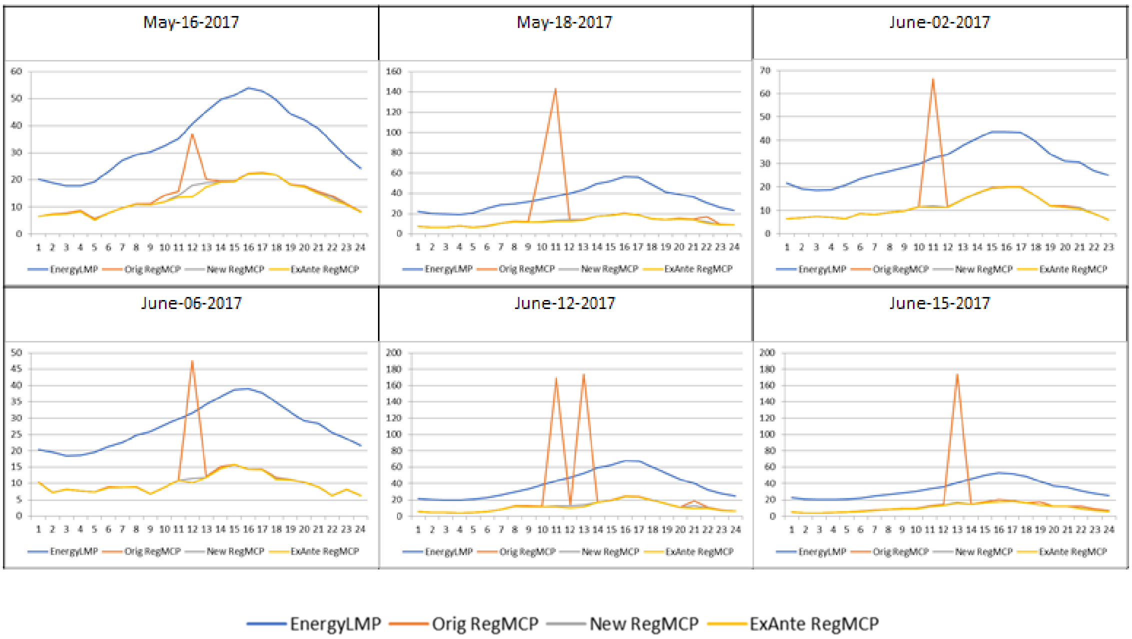

Fig.4. Comparison of DA RegMCP

4. ELMP RAMP MODELING

Under the Fast Start Pricing scheme, fast-start resources can be partially committed instead of using a pure on / off decision, so that fast-start resource can set prices in the ex-post process. A variation also allows relaxing the minimum generation limit to zero for fast-start resources. Nevertheless even with this method, some fast-start resources may not be able to set prices if constrained by ramp. The ramp modeling under ELMP thus needs to be improved for fast-start resources to more effectively set prices. In particular, it is important to differentiate between two sets of ramp rate constraints: 1) Inter-temporal Ramp, and 2) Startup / Shut-Down Ramp. Typically, a unit is ramp-constrained across intervals when it is online for dispatch.

$$-Ramp_{i,t} \leq Gen_{i,t} - Gen_{i,t-1} \leq Ramp_{i,t} \qquad (13)$$

During startup or shutdown periods, a different ramp limit is used to allow the unit to ramp from 0 to EconMin or EconMin to 0, where in-between the unit is in the starting or shut down process and is not for the RTO’s dispatch. Specifically, when an online fast-start resource is partially committed toward zero, it is essentially a shutdown and the ramp constraint for shut down is:

$$-ShutDownRamp_{i,t} \leq Gen_{i,t} - Gen_{i,t-1} \qquad (14)$$

or combining (1) and (2), the ramp down constraint can be uniformly formulated as:

$$Gen_{i,t-1} - Gen_{i,t} \leq ShutDownRamp_{i,t} \times On_{i,t-1} - (ShutDownRamp_{i,t} - Ramp_{i,t}) \times On_{i,t} \quad (15)$$

The lumpiness or non-convexity thus arises associated with the shutdown intervals, and the fast-start resource would not be able to set price if constrained by the normal ramp limit from being further dispatched down below EconMin. The nature of inter-temporal ramping in constraint (13) is different from the lumpiness issue in constraint (15), and the ELMP ramp modeling needs to be carefully developed to avoid any unintended consequences. Inappropriate relaxation of ramp-down limits may result in unnecessary divergence between dispatch and pricing. Solution options are explored to address the shutdown ramp issue without inadvertently affecting the inter-temporal ramp.

Option 1: Utilizing Partial Commitment Variable

ELMP allows fast-start resources to relax their dispatch minimums to zero by allowing the partial commitment of such resources for pricing purposes. That is, instead of an on (1) or off (0) commitment decision in reality, ELMP allows a fast-start resource to be partially committed between 0 and 1. When a fast-start resource is partially committed down from $On_{i,t-1}$ to $On_{i,t}$, it can be interpreted as that the resource is shut down by a fraction of ($On_{i,t-1}$ - $On_{i,t}$), and has a fraction of $On_{i,t}$ remaining committed. Therefore, the shutdown ramp limit can be used for the shutdown fraction, and the normal limit can be used for the remaining fraction. That is, by re-writing ramp down constraint (3), it can be obtained that:

$$Gen_{i,t-1} - Gen_{i,t} \leq ShutDownRamp_{i,t} \times (On_{i,t-1} - On_{i,t}) + Ramp_{i,t} \times On_{i,t} \qquad (16)$$

Compared to the ramp down constraint (13) that is used in the current ELMP model, the ramp limit can be relaxed to larger value that accounts for the shutdown. For example, a fast-start resource can generate between 100MW to 200MW and its Ramp Rate is 10MW/min. Under the existing ramp model (13), it can only ramp down 50MW over a 5-minute interval and will be ramp constrained even though EconMin is relaxed to 0. By using (16), the ex-post pricing can further dispatch the unit down by pushing the partial commitment variable $On_{i,t}$ toward 0 so that the ramp limit is pushed toward the larger value of $ShutDownRamp_{i,t}$. The costs associated with the dispatch and partial commitment will be able to eligible to participate in price setting. In addition, if the resource is ramping normally between two consecutive online intervals, i.e., $On_{i,t}$ toward 1, the ramp limit will be pushed toward $Ramp_{i,t}$.

The shutdown ramp is usually a larger limit than normal ramp to ensure that the unit can be dispatched down from anywhere to zero in shutdown periods. In the current unit commitment problem, it is set at EconMax. However, real time dispatch intervals are much shorter. Assuming a large shutdown ramp may cause significant divergence between ex-ante and ex-post even under the scenario when fixed cost is near zero. Other possibilities include $Gen_{i,t-1}$ or max {EconMin, $Ramp_{i,t}$}. Further studies are needed to determine the appropriate value for shutdown ramp.

Another challenge is related to the single-interval pricing model. To calculate price at t in Real-Time, $\overline{Gen}_{i,t-1}$ in (16) will be a known parameter based on the latest resource output. If the resource is partially committed or dispatched down in ex post pricing to $Gen_{i,t}$, in the next interval t+1 the unit will be ramping from $\overline{Gen}_{i,t}$ which can be different from $Gen_{i,t}$. For example, a unit that has low incremental energy cost and high no-load cost may be dispatched at EconMax. The ex-post pricing would try to dispatch the unit down toward zero at t, but in the next interval it will have to ramp from EconMax again. This can affect a unit being dispatched down to zero in ex post pricing if the down ramping process takes more than one interval. A large $ShutDownRamp_{i,t}$ can force the unit ramp to zero in one interval but may result in significant deviation if it takes several intervals to ramp the unit to zero in ex ante. Further studies are needed to understand the pricing impact in coordination with the value selection of $ShutDownRamp_{i,t}$.

Option 2: Utilizing information from ex ante

This option is to leverage the information from ex ante to detect the issue when the ramp-down limit should be relaxed. For example,

1) If the dispatch ex ante is close to EconMin, then the ramp-down limit may be relaxed to shutdown ramp to allow the unit to be dispatched down to zero when EconMin is relaxed to zero in ex post. Nevertheless, this approach may be limited in its effectiveness if a resource is shut down from a dispatch level above EconMin. For example, resources with high start-up and no-load costs but low incremental cost may be dispatched well above EconMin in ex ante where commitment costs are not considered, but could be dispatched toward zero when those costs are considered in ex-post pricing.

2) If the ramp rate constraint is binding in ex ante, it indicates an inter-temporal ramping situation and ramp rate may not be relaxed in ex post.

MISO continues to study this problem. The multi-interval pricing research could provide guidelines on the appropriate ramp modeling for current single-interval ELMP implementation.

5. CONCLUSION

This paper introduces two improvements for the single-interval approximation of ELMP. The first improvement is a tighter formulation of the PWL energy offer curve. The second improvement is better handling of regulation commitment. Both enhancements further improve price efficiency under the single-interval approximation of ELMP and bring the practical implementation closer to the ELMP theoretical ideal. The on-going work in addressing pricing complication caused by ramp constraints is also introduced.

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