

Pricing Energy Storage in Real-time Market

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Abstract—The problem of pricing utility-scale energy storage resources (ESRs) in the real-time electricity market is considered. Under a rolling-window dispatch model where the operator centrally dispatches generation and consumption under forecasting uncertainty, it is shown that almost all uniform pricing schemes, including the standard locational marginal pricing (LMP), result in lost opportunity costs that require out-of-the-market settlements. It is also shown that such settlements give rise to disincentives for generating firms and storage participants to bid truthfully, even when these market participants are rational price-takers in a competitive market. Temporal locational marginal pricing (TLMP) is proposed for ESRs as a generalization of LMP to an in-market discriminative form. TLMP is a sum of the system-wide energy price, LMP, and the individual state-of-charge price. It is shown that, under arbitrary forecasting errors, the rolling-window implementation of TLMP eliminates the lost opportunity costs and provides incentives to price-taking firms to bid truthfully with their marginal costs. Numerical examples show insights into the effects of uniform and non-uniform pricing mechanisms on dispatch following and truthful bidding incentives.

Index Terms—Energy storage resources, rolling-window look ahead dispatch, incentive compatibility, out-of-the-market settlements, locational marginal pricing.

I. INTRODUCTION

With the deepening penetration of renewable generation, demand profiles in many electricity markets have shown characteristics of a “duck-curve”, creating frequent and rapid up/down ramp events that pose significant operational challenges. One way to support ramping is to use multi-interval look-ahead dispatch that anticipates the rise and fall of demand. Another is to deploy utility-scale storage resources that reduce the need for fast ramps by traditional generators. In both cases, the dispatch model changes from single-interval to multi-interval dispatch models.

The standard implementation of a look-ahead dispatch is the *rolling-window dispatch*, where the operator uses demand and renewable forecasts in the next few intervals to produce a dispatch plan for the subsequent intervals. Only the dispatch for the immediate interval is binding. Despite the simplicity and popularity of rolling-window dispatch, pricing generation and consumptions from a rolling-window dispatch is challenging. Wilson points out in [1] that the rolling-window dispatch and forecasting errors can cause pricing distortions, resulting in undervaluation of generators’ intertemporal ramping capabilities. It is widely recognized

that the rolling-window implementation of the standard locational marginal pricing (LMP) imposes lost opportunity costs (LOC) on generators that have to be compensated by out-of-the-market uplifts. Such uplifts are discriminative and lack of transparency [2], [3]. A significant side effect of such uplifts is that it can create incentives for a generation firm to bid strategically to maximize its profit [3].

We consider the problem of pricing multi-interval dispatch when utility-scale energy storage resources (ESRs) are part of the real-time electricity market. Under FERC Order 841 [4], ESRs must be able to participate in the market-clearing process as both buyers and sellers, and they are entitled to receive applicable out-of-the-market uplifts. Because it is difficult to audit the actual costs of ESR operations, it is highly desirable that the pricing mechanism is at some level incentive-compatible, which ensures that ESR participants bid truthfully.

Standard LMP does not guarantee incentive compatibility. Nonetheless, it is reassuring that price-taking and profit-maximizing firms in a competitive market bid truthfully under the single-interval dispatch and LMP models. When the dispatch and pricing models change from single-interval to multiple-interval settings, it is not clear how market participants, especially ESRs, react to the change of incentives. Will a price-taking ESR participant who bids truthfully under the single-interval LMP model bids strategically to take advantage of the presence of out-of-the-market uplifts?

A. Related Work

Although incentive issues arising from multi-interval dispatch and pricing models have long been recognized [1], it is only recently that pricing multi-interval dispatch in the real-time market is brought into attention, with emphasis on the lack of dispatch-following incentives in standard rolling-window pricing schemes [5]–[11]. A particularly relevant work is [9] that considers explicitly the participation of ESRs and the roles of LOC.

The lack of dispatch following incentives can be addressed by providing out-of-the-market uplifts to generators. The discriminative and non-transparent nature of such uplifts has led to proposals of improvements, including the price-preserving multi-interval pricing (PMP) [12], the constraint-preserving multi-interval pricing (CMP) [8], and the Multi-settlement LMP (MLMP) [6], [9].

It turns out that, at a more fundamental level, LOC (thus out-of-the-market uplifts) cannot be eliminated by uniform pricing mechanisms [10]. The necessity of uplifts under uniform pricing schemes highlights the need to understand

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ramifications of such uplifts [2], [13], especially from an incentive-compatibility perspective. To this end, there is little published work in the context of rolling-window dispatch with ESR participations.

The temporal locational marginal pricing (TLMP) [7], [10], [11] is a nonuniform generalization of LMP that prices generation based on its contribution to meeting the demand. Unlike uniform pricing that discriminates generation with out-of-the-market uplifts, TLMP discriminates *inside* the market clearing process, therefore eliminating the need of uplifts under arbitrary forecasting error.

B. Summary of Contributions

This paper addresses incentive issues when pricing generation and ESRs under the rolling-window dispatch and pricing models. The main contribution is twofold. First, we show that most uniform pricing schemes cannot provide dispatch-following and truthful-bidding incentives for price-taking generators and ESRs. The lack of dispatch-following incentives implies that out-of-the-market uplifts are necessary. We demonstrate through examples that uplift payments result in price-taking ESRs deviating from truthful bidding.

Second, we consider whether a non-uniform (discriminative) pricing mechanism can provide both dispatch-following and truthful-bidding incentives. We show that TLMP, generalized to include ESR participations, not only eliminates the need of out-of-the-market uplifts but also makes truthful-bidding locally optimal for price-taking ESRs.

II. ROLLING-WINDOW DISPATCH AND PRICING MODELS

Consider the rolling-window dispatch of N generators and M ESRs in a single-bus model over a scheduling horizon $\mathcal{H} = \{1, \dots, T\}$ of T intervals. With superscript G , D , and C for generator, ESR discharging power, and charging power, respectively, let $\mathbf{G}_t = \{\mathbf{G}_t^G, \mathbf{G}_t^D, \mathbf{G}_t^C\}$, where $\mathbf{G}_t^G = [\mathbf{g}^G[t], \dots, \mathbf{g}^G[t+W-1]]$ be the matrix of all generation variables in the W -interval look-ahead window with $\mathbf{g}^G[t] = (g_{1t}^G, \dots, g_{Nt}^G)$ being the generation vector in interval t . Similarly, $\mathbf{G}_t^D$ and $\mathbf{G}_t^C$ represent discharging and charging power of the ESR, respectively. And $\mathbf{E}_t = [E_{ij}]$ is the matrix of state of charge (SOC) with E_{ij} being the SOC of the i th ESR in interval j .

The rolling-window dispatch policy, $\mathcal{G}^{\text{R-ED}}$, is defined by a sequence of W -interval look-ahead economic dispatch policies ($\mathcal{G}_t^{\text{R-ED}}, t = 1, \dots, T$). At time t , $\mathcal{G}_t^{\text{R-ED}}$ solves a W -interval economic dispatch optimization in interval $\mathcal{H}_t = \{t, \dots, t+W-1\}$ using (i) the realized dispatch $\mathbf{g}^{\text{R-ED-G}}[t-1]$ and SOC in interval $t-1$ and (ii) the load forecast $(\hat{d}_t, \dots, \hat{d}_{t+W-1})$ in W intervals, assuming the forecast of the first interval is accurate, $\hat{d}_t = d_t$. Let $\{f_{nt}^G\}$, $\{f_{it}^D\}$ and $\{f_{it}^C\}$ respectively represent bid-in costs of generator, ESR discharging power, and ESR charging power. The total bid-in cost $F_t(\mathbf{G}_t)$ for the t -th rolling-window dispatch can be computed by

$$F_t(\mathbf{G}_t) := \sum_{t'=t}^{t+W-1} \left(\sum_{n=1}^N f_{nt'}^G(g_{nt'}^G) + \sum_{i=1}^M (f_{it'}^D(g_{it'}^D) - f_{it'}^C(g_{it'}^C)) \right).$$

The rolling-window dispatch policy is defined by

$$\begin{aligned} \mathcal{G}_t^{\text{R-ED}} : \text{minimize} \quad & F_t(\mathbf{G}_t) \\ \text{subject to:} \quad & \forall n, \forall i \\ & \lambda_{t'} : \sum_{n=1}^N g_{nt'}^G + \sum_{i=1}^M (g_{it'}^D - g_{it'}^C) = \hat{d}_{t'}, \\ & (\underline{\delta}_{it'}, \bar{\delta}_{it'}) : \underline{E}_i \leq E_{it'} \leq \bar{E}_i, \\ & (\underline{\rho}_{nt'}, \bar{\rho}_{nt'}) : 0 \leq g_{nt'}^G \leq \bar{g}_n^G, \\ & (\underline{\rho}_{it'}^D, \bar{\rho}_{it'}^D) : 0 \leq g_{it'}^D \leq \bar{g}_i^D, \\ & (\underline{\rho}_{it'}^C, \bar{\rho}_{it'}^C) : 0 \leq g_{it'}^C \leq \bar{g}_i^C, \\ & (\underline{\mu}_{nt'}, \bar{\mu}_{nt'}) : -\underline{r}_n \leq g_{n(t'+1)}^G - g_{nt'}^G \leq \bar{r}_n, \\ & \quad \quad \quad t \leq t' \leq t+W, \\ & \phi_{it'} : E_{i(t'-1)} + \xi^C g_{it'}^C - g_{it'}^D / \xi^D = E_{it'}, \\ & \quad \quad \quad t+1 \leq t' \leq t+W. \\ \text{Boundary intertemporal constraints:} \\ & \phi_{it} : E_{i(t-1)}^{\text{R-ED}} + \xi^C g_{it}^C - g_{it}^D / \xi^D = E_{it}, \\ & \bar{\mu}_{n(t-1)} : g_{nt}^G - g_{n(t-1)}^{\text{R-ED-G}} \leq \bar{r}_n, \\ & \underline{\mu}_{n(t-1)} : g_{n(t-1)}^{\text{R-ED-G}} - g_{nt}^G \leq \underline{r}_n, \end{aligned} \quad (1)$$

where $\xi^D, \xi^C \in (0, 1]$ are charging and discharging efficiency coefficients. The 3rd to 6th rows are capacity and ramping constraints. In (1), the dual variables* ($\lambda_{t'}, \phi_{it'}$) are respectively associated with the power balance equation and SOC intertemporal equation in interval t' , and $(\underline{\delta}_{it'}, \bar{\delta}_{it'}, \underline{\mu}_{nt'}, \bar{\mu}_{nt'}, \underline{\rho}_{nt'}, \bar{\rho}_{nt'}, \underline{\rho}_{it'}^D, \bar{\rho}_{it'}^D, \underline{\rho}_{it'}^C, \bar{\rho}_{it'}^C)$ are dual variables for the lower and upper limits for SOC, ramping and power respectively[†]. Let $\xi = \xi^D \xi^C$, by assuming $\frac{\partial}{\partial g_{it'}^D} f_{it'}^D(g_{it'}^D) > \frac{\partial}{\partial g_{it'}^C} f_{it'}^C(g_{it'}^C) / \xi, \forall i, \forall t'$, constraints $g_{it'}^D g_{it'}^C = 0$ can be exactly relaxed in most cases [14].

Let $(g_{nt}^*, g_{it}^{D*}, g_{it}^{C*})$ and (λ_t^*) be the solution to (1). The rolling-window dispatch, $\mathcal{G}^{\text{R-ED}} = \{\mathbf{G}^{\text{R-ED-G}}, \mathbf{G}^{\text{R-ED-D}}, \mathbf{G}^{\text{R-ED-C}}\}$, and rolling-window LMP (R-LMP), $\pi^{\text{R-LMP}}$, in interval t are given by policy $\mathcal{G}^{\text{R-ED}}$ with

$$\begin{aligned} g_{nt}^{\text{R-ED-G}} &:= g_{nt}^*, \quad g_{it}^{\text{R-ED-D}} := g_{it}^{D*}, \quad g_{it}^{\text{R-ED-C}} := g_{it}^{C*}, \\ E_{it}^{\text{R-ED}} &= E_{it}^*, \quad \pi_t^{\text{R-LMP}} := \lambda_t^*. \end{aligned} \quad (2)$$

III. DISPATCH-FOLLOWING INCENTIVES AND LOC

A. Lost opportunity cost of ESR

The LOC payment of individual ESR is a measure of dispatch-following incentives, defined by the difference between the payment that would have been received had the ESR self-scheduled and the payment received within the market clearing process. Under the uniform pricing, let π be

*Dual variables for equality constraints are defined in the Lagrangian function $\mathcal{L} = F_t(\mathbf{G}) - \sum_{t'} \lambda_{t'} (\sum_{n=1}^N g_{nt'}^G + \sum_{i=1}^M (g_{it'}^D - g_{it'}^C) - \hat{d}_{t'}) - \sum_{i,t'} \phi_{it'} (E_{i(t'-1)} + \xi^C g_{it'}^C - g_{it'}^D / \xi^D - E_{it'})$.

[†]It's assumed throughout the paper that all dual variables for inequality constraints are defined in a way to be always non-negative.

the vector of prices over $\mathcal{H}$. The LOC over the scheduling horizon $\mathcal{H}$ is given by[‡]

$$\text{LOC}(\pi, \mathbf{g}^{\text{R-ED-D}}, \mathbf{g}^{\text{R-ED-C}}) = Q(\pi) - \left(\pi^T \mathbf{g}^{\text{R-ED-D}} - \pi^T \mathbf{g}^{\text{R-ED-C}} - \sum_{t=1}^T f_t^{\text{D}}(g_t^{\text{R-ED-D}}) + \sum_{t=1}^T f_t^{\text{C}}(g_t^{\text{R-ED-C}}) \right), \quad (3)$$

where $Q(\pi)$ is the maximum profit the ESR would have received through the individual profit maximization

$$\begin{aligned} Q(\pi) = \underset{\{\mathbf{p}^{\text{D}}, \mathbf{p}^{\text{C}}, \mathbf{e}\}}{\text{maximize}} \quad & \pi^T \mathbf{p}^{\text{D}} - \sum_{t=1}^T f_t^{\text{D}}(p_t^{\text{D}}) \\ & + \sum_{t=1}^T f_t^{\text{C}}(p_t^{\text{C}}) - \pi^T \mathbf{p}^{\text{C}} \\ \text{subject to} \quad & \\ \psi : \quad & \xi^{\text{C}} \mathbf{p}^{\text{C}} - \mathbf{p}^{\text{D}} / \xi^{\text{D}} = \mathbf{B} \mathbf{e}, \\ (\underline{\omega}, \bar{\omega}) : \quad & \underline{\mathbf{E}} \leq \mathbf{e} \leq \bar{\mathbf{E}}, \\ (\underline{\zeta}^{\text{D}}, \bar{\zeta}^{\text{D}}) : \quad & \mathbf{0} \leq \mathbf{p}^{\text{D}} \leq \bar{\mathbf{g}}^{\text{D}}, \\ (\underline{\zeta}^{\text{C}}, \bar{\zeta}^{\text{C}}) : \quad & \mathbf{0} \leq \mathbf{p}^{\text{C}} \leq \bar{\mathbf{g}}^{\text{C}}, \end{aligned} \quad (4)$$

where $\mathbf{B}$ is $T \times T$ lower bidiagonal matrix with 1 as diagonals and -1 left next to diagonals.

B. Conditions for dispatch following incentives

With the LOC uplift, the revenue of an ESR is maximized for the given price. Therefore, if $\text{LOC} = 0$, there is no incentive for the ESR to deviate from the dispatch. The following theorem, parallel to Theorem 2 of [10], shows that uniform pricing schemes in general cannot eliminate LOC, thus unable to support dispatch-following incentive for ESR.

Theorem 1 (Uniform pricing and dispatch-following incentives). *Under the rolling-window dispatch, there does not exist a uniform pricing scheme under which all ESRs have zero LOC, if there exist ESR i and j and interval $t^* \in \mathcal{H}$ such that*

- 1) ESR i and j have distinct bid-in marginal costs for charging and discharging power;
- 2) both ESRs are “marginal” in t^* , i.e.,

$$g_{it^*}^{\text{R-ED-D}} \in (0, \bar{g}_i^{\text{D}}) \quad \text{or} \quad g_{it^*}^{\text{R-ED-C}} \in (0, \bar{g}_i^{\text{C}}),$$

$$g_{jt^*}^{\text{R-ED-D}} \in (0, \bar{g}_j^{\text{D}}) \quad \text{or} \quad g_{jt^*}^{\text{R-ED-C}} \in (0, \bar{g}_j^{\text{C}});$$

- 3) both ESRs don't reach SOC rate limits from t^* to the end of $\mathcal{H}$.

In our experimental evaluations using practical demand profiles, we find that these conditions hold with 3.4% - 85.8% of time under different parameter settings. So, in corresponding percentage of cases, R-LMP cannot support dispatch-following incentives of ESRs without uplift payments like LOC. See [15] for the proof and simulation.

[‡]The ESR index is dropped here and thereafter for brevity

IV. TRUTHFUL-BIDDING INCENTIVES

A. Bidding strategy of a price-taker

Consider a fixed ESR. Let $\mathbf{q}^{\text{D}}(\cdot) = (q_1^{\text{D}}(\cdot), \dots, q_T^{\text{D}}(\cdot))$ be the true cost curve during discharging over T intervals[§]. To analyze bidding strategies, we introduce a parametric form of the bid-in cost. Let $\mathbf{f}^{\text{D}}(\cdot | \boldsymbol{\theta}^{\text{D}}) = (f_t^{\text{D}}(\cdot | \theta_t^{\text{D}}))$ be the ESR's bid-in cost (supply) curve parameterized by $\boldsymbol{\theta}^{\text{D}} = (\theta_t^{\text{D}})$. Assume that, at $\boldsymbol{\theta}^{\text{D}} = \boldsymbol{\theta}^{\text{D}*}$, the bid-in cost is the true cost, i.e., $\mathbf{f}^{\text{D}}(\cdot | \boldsymbol{\theta}^{\text{D}*}) = \mathbf{q}^{\text{D}}(\cdot)$. Similarly, $\mathbf{q}^{\text{C}}(\cdot), \boldsymbol{\theta}^{\text{C}}, \mathbf{f}^{\text{C}}(\cdot | \boldsymbol{\theta}^{\text{C}})$ are defined for ESR's charging operation and $\boldsymbol{\theta} = \{\boldsymbol{\theta}^{\text{D}}, \boldsymbol{\theta}^{\text{C}}\}$. For a price-taking ESR, whose bid doesn't affect the market clearing price π , the profit is

$$\Pi(\boldsymbol{\theta}) = \pi^T \mathbf{g}^{\text{R-ED-D}}(\boldsymbol{\theta}) - \sum_{t=1}^T q_t^{\text{D}}(g_t^{\text{R-ED-D}}) + \sum_{t=1}^T q_t^{\text{C}}(g_t^{\text{R-ED-C}}) - \pi^T \mathbf{g}^{\text{R-ED-C}}(\boldsymbol{\theta}) + \text{LOC}(\pi, \mathbf{g}^{\text{R-ED-D}}(\boldsymbol{\theta}), \mathbf{g}^{\text{R-ED-C}}(\boldsymbol{\theta})), \quad (5)$$

where, $\mathbf{g}^{\text{R-ED-D}}(\boldsymbol{\theta}), \mathbf{g}^{\text{R-ED-C}}(\boldsymbol{\theta})$ are the rolling-window economic dispatch over the entire scheduling horizon when bid-in cost parameter vector is $\boldsymbol{\theta}$. The first four of (5) are storage surplus, and the last term is LOC computed from (3).

A rational ESR maximizes the total profit $\Pi(\boldsymbol{\theta})$ over bidding strategies parameterized by $\boldsymbol{\theta}$. We say that price π is incentive compatible if $\boldsymbol{\theta}^* = \{\boldsymbol{\theta}^{\text{D}*}, \boldsymbol{\theta}^{\text{C}*}\}$ corresponding to the true-cost bid is a local maximum of (5).

B. Conditions for truthful-bidding incentives

We now examine whether there exists a uniform pricing scheme under which a price-taking rational ESR would bid truthfully. Note that, in general, one would expect that a price-taking firm would not bid above its true cost in a competitive market because it will be substituted by another firm who has the same cost bids truthfully. The intertemporal constraints and the presence of out-of-the-market uplifts distorts the above argument. We show below that, for all practical purposes, uniform pricing cannot provide truthful bidding incentives even for price-taking ESRs.

Theorem 2 (Uniform pricing and truthful-bidding incentives). *Assume that the bidding curves of generators and ESRs are linear, and the rolling-window economic dispatch under truthful-biddings, $\mathbf{G}^{\text{R-ED}}(\boldsymbol{\theta}^*)$, is not dual-degenerate. If there exist ESR i and j and interval $t^* \in \mathcal{H}$ that satisfy the conditions 1)-3) of Theorem 1, then it is suboptimal for ESR i and j to bid truthfully under every uniform price that does not lead to dual degeneracy in (4).*

See [15] for the proof. Note that a uniform price that leads to dual degeneracy in (4) must lie in a low dimensional subspace defined by the KKT conditions, which means that uniform prices (almost everywhere) satisfy the non-dual-degeneracy conditions.

[§]The true cost can be evaluated approximately in practice [16].

V. TRUTHFUL BIDDING INCENTIVES UNDER TLMP

A. Temporal locational marginal pricing for ESRs

Here we extend the temporal locational marginal pricing (TLMP) for ESRs. As shown in [7], [10], TLMP is a non-uniform version of LMP defined by the marginal cost of generation and consumption. For an inelastic demand, the TLMP of consumption is the total cost increase due to the one-MW increase of the demand, which is the same as the standard LMP. For generators, the price of generation for generator i is defined by the cost reduction due to the one-MW increase of generator i 's production. TLMP for ESRs is similarly defined for charging and discharging separately.

Let $\mathbf{G}^*$ be the solution of the multi-interval economic dispatch in (1) and $(\lambda_t^*, \phi_t^*, \mu_t^*, \bar{\mu}_t^*, \delta_t^*, \bar{\delta}_t^*, \rho_t^*, \bar{\rho}_t^*)$ be the dual variables associated with the constraints in interval t . By the envelop theorem, TLMP in interval t for ESR, generators, and demand is defined by

$$\begin{aligned} \text{ESR } i \text{ discharging: } & \pi_{it}^{\text{TLMP-D}} = \lambda_t^* - 1/\xi^D \phi_{it}^*, \\ \text{ESR } i \text{ charging: } & \pi_{it}^{\text{TLMP-C}} = \lambda_t^* - \xi^C \phi_{it}^*, \\ \text{Generator } n: & \pi_{nt}^{\text{TLMP-G}} = \lambda_t^* + \Delta_{nt}^*, \\ \text{Demand: } & \pi_t^{\text{TLMP}} = \lambda_t^*, \end{aligned} \quad (6)$$

where $\Delta_{nt}^* := \Delta \mu_{nt}^* - \Delta \mu_{n(t-1)}^*$, $\Delta \mu_{nt}^* := \bar{\mu}_{nt}^* - \underline{\mu}_{nt}^*$, is defined by ramping constraints thus referred to as *ramping price*. Likewise, ϕ_{it}^* is defined by the SOC constraints thus referred to as *SOC price*. The interpretation of TLMP for ESR is therefore the sum of system-wide energy price λ_t and SOC price ϕ_{it}^* discounted by charging/discharging efficiencies. Likewise, TLMP for generator is the sum of system-wide energy price λ_t and the individual ramping price Δ_{it} [10]. Similar to the definition of R-LMP in (2), rolling-window TLMP (R-TLMP) is composed of TLMP in the binding interval for each look ahead window.

The intuition behind the TLMP expression can be seen from the Lagrangian of the economic dispatch (1) with the optimal multipliers written as

$$\begin{aligned} \mathcal{L} = & \sum_{i,t} \left(f_{it}^D(g_{it}^D) - (\lambda_t^* + 1/\xi^D \phi_{it}^*) g_{it}^D + (\bar{\rho}_{it}^* - \rho_{it}^*) g_{it}^D \right) \\ & + \sum_{i,t} \left(-f_{it}^C(g_{it}^C) + (\lambda_t^* + \xi^C \phi_{it}^*) g_{it}^C + (\bar{\rho}_{it}^* - \rho_{it}^*) g_{it}^C \right) \dots \end{aligned} \quad (7)$$

where the rest of the terms above are independent of g_{it}^D and g_{it}^C . It is evident that, under TLMP, the multi-interval dispatch decouples into single-interval dispatch problems. So intertemporal constraints—SOC constraints—are decoupled under TLMP, which has significant ramifications in eliminating LOC for ESRs.

The following Theorem establishes that, under TLMP, the LOC for every ESR is zero, and it is locally optimal that every price-taker bids truthfully.

Theorem 3 (dispatch and bidding incentives under R-TLMP). *For ESR i , let $\mathbf{g}_i^{\text{R-ED-D}}, \mathbf{g}_i^{\text{R-ED-C}}$ be the rolling-window economic*

dispatch computed from (2) and π_i^D, π_i^C be its R-TLMP. Then, for all i and under arbitrary demand forecast error,

$$\text{LOC}(\pi_i^D, \pi_i^C, \mathbf{g}_i^{\text{R-ED-D}}, \mathbf{g}_i^{\text{R-ED-C}}) = 0, \quad (8)$$

and it is optimal for a price-taking ESR to bid truthfully with its marginal costs of charging and discharging.

See [15] for the proof. Intuitively, from the dispatch following incentive under TLMP, we know LOC in (5) is zero and the rolling window dispatch signal, *i.e.*, $\mathbf{g}_i^{\text{R-ED-D}}$ and $\mathbf{g}_i^{\text{R-ED-C}}$, is an optimal solution for (4). So a truthful-bidding ESR will receive the rolling window dispatch signal optimal for the individual profit maximization, *i.e.*, the optimal solution of (4) with $\mathbf{f}^D(\cdot|\theta^*) = \mathbf{q}^D(\cdot), \mathbf{f}^C(\cdot|\theta^*) = \mathbf{q}^C(\cdot)$ can maximize (5) with zero LOC.

VI. CASE STUDIES

We present here simulation results involving three generators and one ESR at a single bus to observe performances under multi-interval dispatch and pricing. More simulations about TLMP considering ramping prices of generators are analyzed in [11]. Detailed parameters are shown in Fig 1 with minimum generation limits all 0.1 MW and initial SOC 4 MWh. Linear bidding curves were adopted, and we evaluated the performance of benchmark schemes, *i.e.*, TLMP and LMP, by varying maximum SOC of ESR.

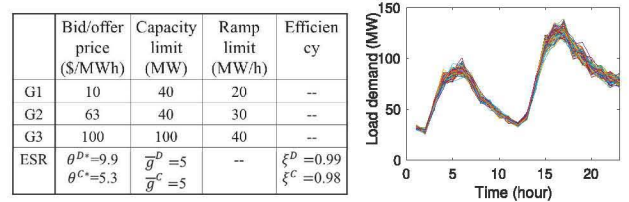


Fig. 1: Left: Parameter Settings. Right: demand traces.

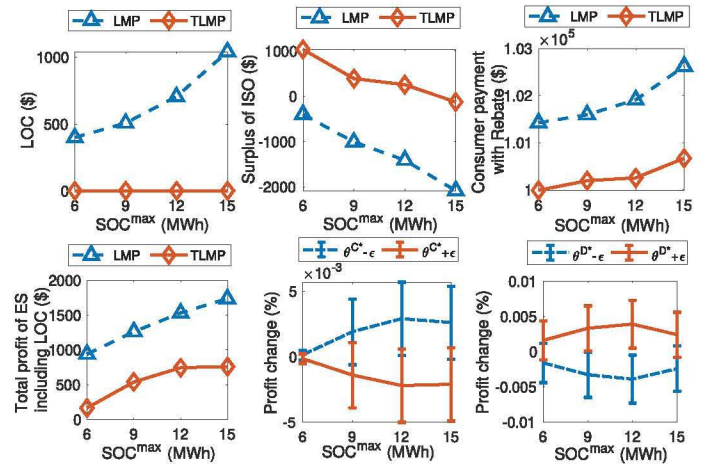


Fig. 2: Criteria under different maximum SOC. Top Left: LOC. Top Middle: Surplus of ISO. Top Right: Consumer payment with rebate. Bottom Left: Total profit of ESR. Bottom Middle: Profit change under LMP. Bottom Right: Profit change under LMP.

The right panel of Fig 1 shows the 500 realizations over 24 hour period generated from a CAISO load profile and a standard deviation of 4% of the mean value. We used a standard forecasting error model[¶] where the demand forecast $\hat{d}_{(t+k)|t}$ of d_{t+k} at time t had error variance $k\sigma^2$ with $\sigma = 0.6\%$ for all scenarios. All simulations were conducted with rolling-window optimization over the 24-hour scheduling period, represented by 24 time intervals. And the window size is 4 intervals in each rolling window optimization.

A. Dispatch-following incentives

Dispatch following incentives are measured by the LOC payment to ESR. A larger LOC payment represents higher incentive to deviate from the dispatch signal (in the absence of a LOC payment). Top left panel of Fig. 2 shows the total LOC payment from the ISO to ESR at different maximum SOC. As predicted by Theorem 3, ESR had strictly zero LOC under TLMP, and positive LOC under LMP.

B. Surplus of ISO, consumer payments and profit of ESR

Top middle panel of Fig. 2 shows the ISO's merchandising surplus including LOC payments. The results validated the fact that uniform pricing schemes, in general, had positive LOC, resulting in a deficit for the ISO. While, coupled with the fact that TLMP always had zero LOC, ISO had a positive merchandising surplus under TLMP in most cases.

We assumed that ISO will redistribute any deficit (and surplus) to the consumers to maintain financially neutral [17]. Top right panel of Fig. 2 shows the consumer payments under the assumption, where TLMP was the least expensive for the consumer. Correspondingly, because the operator has zero surplus, ESR had least profit under TLMP, which is shown in the bottom left panel of Fig. 2.

C. Truthfully bidding incentives

In this section, the expected profit changes (including LOC) over different load scenarios were compared when ESR deviated from the truthful marginal cost, $(\theta^{p*}, \theta^{c*}) = (9.9, 5.3)$ \$/MW, by $\varepsilon = 0.01$ \$/MW. The bottom middle panel of Fig. 2 shows expectations and standard deviation of the profit changes under the sample average R-LMP. When ESR varied charging bid to $\theta^{c*} - \varepsilon$, ESR had positive profit change on average; while the profit mostly decreased when charging bid was $\theta^{c*} + \varepsilon$. Similar observations can be made on the bottom right panel for discharging bids. So the ESR will decrease charging bids and increase discharging bids to make more profits. However, under R-TLMP, none scenarios was observed to have more profits when ESR deviated from truthful bids.

[¶]The forecast $\hat{d}_{(t+k)|t}$ at t of demand d_{t+k} is $\hat{d}_{(t+k)|t} = d_{t+k} + \sum_{i=1}^k \epsilon_k$ where ϵ_k is i.i.d. Gaussian with zero mean and variance σ^2 .

VII. CONCLUSIONS

This paper considers truthful-bidding and dispatch-following incentives when pricing utility-scale ESRs under rolling-window dispatch in the real-time wholesale electricity market. We show that almost all uniform pricing schemes need out-of-the-market uplifts and give incentives for generation firms and ESRs to bid untruthfully. It is therefore reasonable to consider nonuniform pricing schemes. Generalizing the standard LMP to a non-uniform pricing, TLMP eliminates the need of out-of-the-market settlements and provides incentive compatibility for price-taking firms.

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