PRICING ROLLING-WINDOW DISPATCH UNDER UNCERTAINTY: INCENTIVE COMPATIBILITY

Lang Tong

School of Electrical & Computer Engineering

Cornell University, Ithaca, NY

Joint work with Ye Guo and Cong Chen

Presented at PSERC Webinar

3/9/2021

Pricing rolling-window dispatch: issues

- Uncertainty
  - Dispatch decisions rely on inaccurate forecasts.
- Rolling-window dispatch
  - Ramping constraints couple decisions across space and time.
  - Rolling-window dispatch is a practical (albeit suboptimal) solution.
  - A rolling-window dispatch produces an immediately clearing decision and advisory future decisions.
- Pricing rolling-window dispatch
  - Generators incur opportunity costs when following dispatch signals.
  - Incentives: (i) dispatch-following, (ii) truthful bidding, and (iii) truthful revelation of generation parameters.

Main results:

"Pricing multi-interval dispatch under uncertainty: Part I, II"
IEEE Transactions on Power Systems (early access)

- Price discrimination is unavoidable.
  - No uniform pricing leads to a market equilibrium. Uplift payments outside the market are necessary. Price discrimination is unavoidable.
  - Uplifts create incentives for strategic bidding for price takers.
- Temporal locational marginal pricing (TLMP)
  - Prices generation by its marginal contribution to meeting the demand:

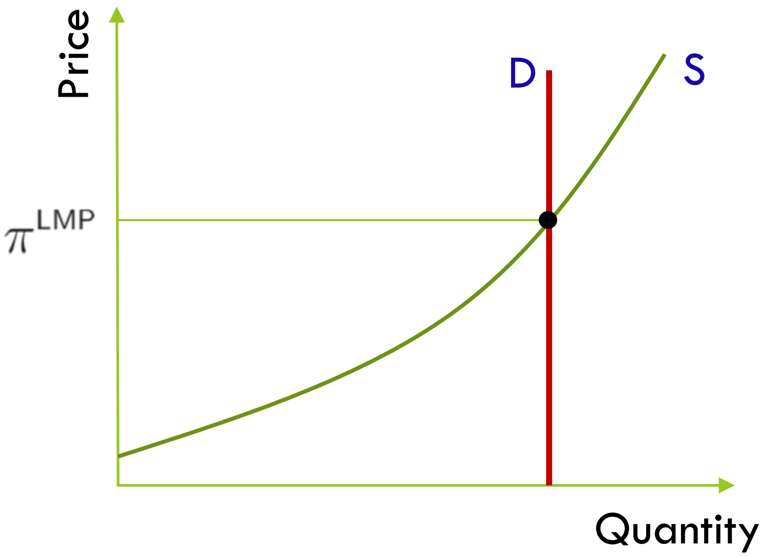
    TLMP = energy price (LMP) + ramping shadow price.

  - Leads to an equilibrium that guarantees dispatch-following incentives.
  - Provides truthful bidding incentives for price takers.
  - Other properties: ISO revenue adequacy, incentives for truthful revelation of ramp limits and enhancing ramp capability.
  - Performance: incentives, revenue adequacy (ISO), welfare distribution.

Outline

- Locational marginal pricing (LMP)
  - From single-interval to multi-interval LMP.
  - Rolling-window LMP and the missing money problem.
  - Dispatch-following and truthful-bidding incentives.
- Temporal locational marginal pricing (TLMP)
  - Non-uniform marginal cost pricing.
  - Dispatch following and truthful bidding incentives under TLMP.
  - Other properties of TLMP + numerical examples.
- Pricing battery storage participation

Locational marginal pricing (LMP)



$$\underset{\mathbf{g}\in\mathcal{G}}{\text{minimize}} \;\; F(\mathbf{g}) = \sum_i f_i(g_i)$$

$$\text{subject to} \; \sum_i g_i = d \quad (\lambda)$$

$$\Rightarrow \begin{cases} \mathbf{g}^* = (g_i^*) \\ \lambda^* \end{cases}$$

$$\pi^{\text{LMP}} = \lambda^* = \frac{\partial}{\partial d} F(\mathbf{g}^*)$$

- **Dispatch following incentive:** Given π^{LMP}, profit max. generators produce $\mathbf{g}^*$.
- **Truthful bidding incentive:** In a competitive market, profit max. generators are price takers who bid with their true marginal costs.

LMP is incentive compatible in a competitive market.

Multi-interval locational marginal pricing (LMP)

minimize $\quad F(\mathbf{G})$

$\mathbf{G} = [\mathbf{g}_1, \cdots, \mathbf{g}_T]$

Subject to network/gen constraints

$$\sum_i g_{it} = d_t \quad (\lambda_t) \quad \text{Power balance}$$

$$-\underline{\mathbf{r}} \leq \mathbf{g}_t - \mathbf{g}_{t-1} \leq \bar{\mathbf{r}} \quad (\underline{\boldsymbol{\mu}}_t, \bar{\boldsymbol{\mu}}_t)$$

$$\Rightarrow \quad \begin{cases} \mathbf{G}^* = (\mathbf{g}_t^*) \\ \boldsymbol{\lambda}^* \end{cases}$$

$$\boldsymbol{\pi}^{\text{LMP}} = \boldsymbol{\lambda}^* = \left(\frac{\partial}{\partial d_t} F(\mathbf{G}^*)\right)$$

LMP	π_1^{LMP}	π_2^{LMP}			π_T^{LMP}
Dispatch	g_{i1}^*	g_{i2}^*			g_{iT}^*

- **Dispatch-following incentive (gen. equilibrium)):**

  Given $\boldsymbol{\pi}^{\text{LMP}}$, profit max. gen. produce $\mathbf{G}^*$.

- **Truthful bidding incentive:**

  Price takers bid with their true marginal costs.

Multi-interval LMP is incentive compatible.

Remark: General equilibrium does not guarantee partial equilibrium.

Rolling-window dispatch and rolling-window pricing

Rolling-window dispatch

minimize $F_t(\mathbf{G})$

$\mathbf{G} = [\mathbf{g}_t, \cdots, \mathbf{g}_{t+W}]$

Subject to network/gen constraints

$$\sum_i g_{it} = \hat{d}_t \quad (\lambda_t)$$ Power balance

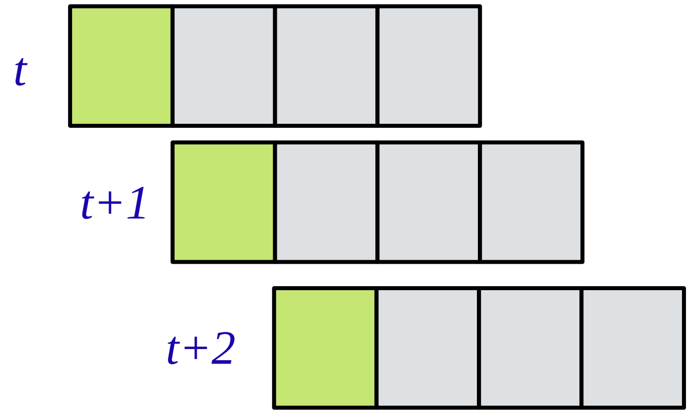
Look-ahead forecast

$$-\underline{\mathbf{r}} \leq \mathbf{g}_t - \mathbf{g}_{t-1} \leq \bar{\mathbf{r}} \quad (\underline{\boldsymbol{\mu}}_t, \bar{\boldsymbol{\mu}}_t)$$

Ramping constraints

Rolling-window LMP

$$\pi_t^{\text{RLMP}} = \lambda_t^*$$



The missing money problem and uplifts

t	\$20	\$25	\$28	\$30	\$40		
t+1		\$19	\$25	\$20	\$50	\$70	
t+2			\$10	\$20	\$18	\$80	\$90

- Suppose that the bid-in cost (willingness to generate of generator i is \$20.
- With forecasting uncertainty, rolling-window LMP does not provide dispatch following-incentives. (Why?)
- With uplift payments, the rolling-window LMP provides dispatch-following incentives.
- Uplift payments create strategic bidding incentives even for price takers.

Out-of-the-market settlement (uplift):

$$\Pi = \sum_t \pi_t^{\text{RLMP}} g_{it}^* + \Pi_i = \sum_t \pi_t^{\text{RLMP}} \tilde{g}_{it}^* \qquad (\tilde{g}_{it}^*) = \arg\max_{g \in \mathcal{G}_i} \sum_t \left(\pi_t^{\text{RLMP}} g_{it} - f_i(g_{it}) \right)$$

Rolling-window LMP is NOT incentive compatible.

Some alternative rolling-window pricing schemes

- Locational marginal pricing (LMP)
- Multi-settlement LMP (MLMP)
- Price-preserving multi-interval pricing (PMP)
- Constraint-preserving multi-interval pricing (CMP)

} Uplift minimizing pricing (PMP, CMP)

Theorem. *Under mild generator and ramping conditions, no uniform-pricing mechanism is incentive compatible.*

Y. Guo, C. Chen, and L. Tong, "Pricing multi-interval dispatch under uncertainty: Part I-dispatch following incentives," IEEE Transactions on Power Systems (early access), Feb. 2021

Outline

- Locational marginal pricing (LMP)
  - From single-interval to multi-interval LMP.
  - Rolling-window LMP and the missing money problem.
  - Dispatch-following and truthful-bidding incentives.
- Temporal locational marginal pricing (TLMP)
  - Non-uniform marginal cost pricing.
  - Dispatch following and truthful bidding incentives under TLMP.
  - Revenue adequacy, producer and consumer payments, etc.
- Pricing energy storage participants

TLMP: temporal-locational marginal price

Rolling-window dispatch

minimize $F_t(\mathbf{G})$

$\mathbf{G} = [\mathbf{g}_t, \cdots, \mathbf{g}_{t+W}]$

Subject to network/gen constraints

$$\sum_i g_{it} = \hat{d}_t \quad (\lambda_t)$$ Power balance

$$-\underline{\mathbf{r}} \leq \mathbf{g}_t - \mathbf{g}_{t-1} \leq \bar{\mathbf{r}} \quad (\underline{\boldsymbol{\mu}}_t, \bar{\boldsymbol{\mu}}_t)$$

Ramping constraints

Rolling-window LMP

$$\pi_t^{\mathrm{LMP}} = \lambda_t^*$$

Rolling-window TLMP

$$\pi_{dt}^{\mathrm{TLMP}} = \lambda_t^*$$ Demand

Energy Ramping

$$\pi_{it}^{\mathrm{TLMP}} = \lambda_t^* + \Delta_{it}$$ Generator i

Multiplier ramping

$$\Delta_{it} = \bar{\mu}_{it}^* - \bar{\mu}_{i(t-1)}^* - (\underline{\mu}_{it}^* - \underline{\mu}_{i(t-1)}^*)$$

TLMP is marginal cost pricing

Rolling-window dispatch

minimize $F_t(\mathbf{G})$ (Bid-in cost in window t)

$\mathbf{G} = [\mathbf{g}_t, \cdots, \mathbf{g}_{t+W}]$

Subject to network/gen constraints

$\sum_i g_{it} = \hat{d}_t \quad (\lambda_t)$ Power balance

$-\underline{\mathbf{r}} \leq \mathbf{g}_t - \mathbf{g}_{t-1} \leq \bar{\mathbf{r}} \quad (\underline{\boldsymbol{\mu}}_t, \bar{\boldsymbol{\mu}}_t)$

Ramp constraints

Demand

$$\pi_{0t}^{\text{TLMP}} = \frac{\partial}{\partial d_t} F_t(\mathbf{G}^*) = \lambda_t^*$$

Cost excluding generator i.

Generator

$$\pi_{it}^{\text{TLMP}} = \frac{\partial}{\partial d_t} F_t^{(-i)}(\mathbf{G}^*)$$

$$= \lambda_t^* + \Delta_{it}$$

$$\Delta_{it} = \bar{\mu}_{it}^* - \bar{\mu}_{i(t-1)}^* - (\underline{\mu}_{it}^* - \underline{\mu}_{i(t-1)}^*)$$

A dual perspective on TLMP

minimize $F(\mathbf{G})$

$\mathbf{G} = [\mathbf{g}_1, \cdots, \mathbf{g}_T]$

Subject to network/gen constraints

$$\sum_i g_{it} = d_t \quad (\lambda_t)$$

$$-\underline{\mathbf{r}} \leq \mathbf{g}_t - \mathbf{g}_{t-1} \leq \bar{\mathbf{r}} \quad (\underline{\boldsymbol{\mu}}_t, \bar{\boldsymbol{\mu}}_t)$$

$$\begin{aligned}
\mathcal{L}(\mathbf{G}, \lambda, \bar{\mu}, \underline{\mu}) &= \sum_{i,t} f_{it}(g_{it}) + \sum_t \lambda_t (d_t - \sum_i g_{it}) \\
&+ \sum_{i,t} \bar{\mu}_{it} \Big((g_{it} - g_{i(t-1)}) - \bar{r}_{it} \Big) \\
&+ \sum_{i,t} \underline{\mu}_{it} \Big(\underline{r}_{it} - (g_{it} - g_{i(t-1)}) \Big) \\
&= \sum_t \sum_i \Big(f_{i,t}(g_{it}) - \underbrace{(\lambda_t + \Delta_{it})}_{\pi_{it}^{\text{TLMP}}} g_{it} \Big) + \ldots
\end{aligned}$$

Negative surplus

Generator i's TLMP:

$$\pi_{it}^{\text{TLMP}} = \lambda_t^* + \Delta_{it}$$

TLMP is incentive compatible

Theorem (Incentive compatibility).

Under rolling-window dispatch and TLMP with arbitrary forecasting error,

- *it is optimal for a price taker to bid truthfully with its marginal cost, and*
- *the rolling-window dispatch optimizes individual generation profit.*

A closer look at TLMP

$$\pi_{it}^{\text{TLMP}} = \lambda_t^* + \Delta_{it}$$ Generator i

Multiplier ramping

- TLMP vs. LMP (uniform pricing)
  - TLMP = LMP without binding ramping constraints.
  - TLMP = energy price (public) + ramping price (private).
  - TLMP $\geq$ Marginal cost of generation in every interval (partial equilibrium).

- RTLMP vs RLMP (uniform pricing) + uplifts

	Uplifts	Discrimination level	Size of discrimination	Transparency	Consumer payment	Gen payment	Operator surplus
TLMP	0	In market with ramp price Δ_{it}	Not comparable	Semi	Small	Small	≥ 0
LMP (uniform)	≥ 0	Out of the market w. Π_i	Not comparable	Semi	Large	Large	≤ 0

Performance

"Pricing multi-interval dispatch under uncertainty: Part II"
IEEE Transactions on Power Systems (early access)

- Rolling-window economic dispatch
- Rolling-window pricing mechanisms:
  - Locational marginal pricing (LMP)
  - Temporal locational marginal pricing (TLMP)

    } Marginal cost pricing

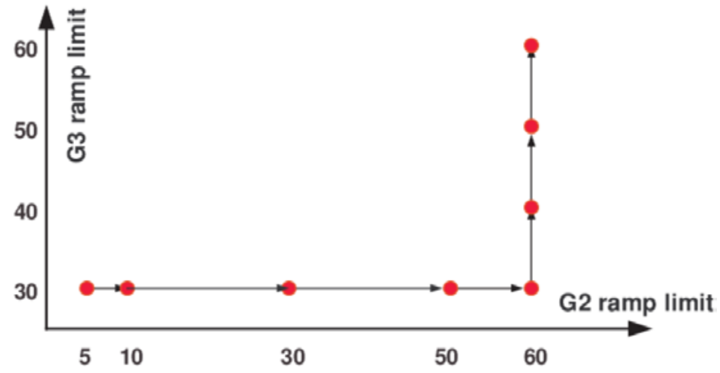
  - Price-preserving multi-interval pricing (PMP)
  - Constraint-preserving multi-interval pricing (CMP)

    } Uplift minimizing pricing

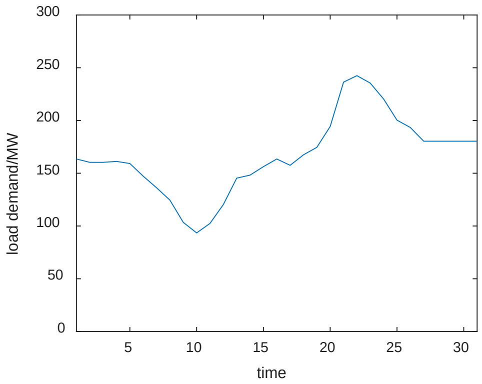
  - Multi-settlement LMP (MLMP)
- Metrics of evaluation
  - Dispatch following incentives
  - Ramp revelation incentives
  - Operator revenue adequacy
  - Generator profits & demand costs

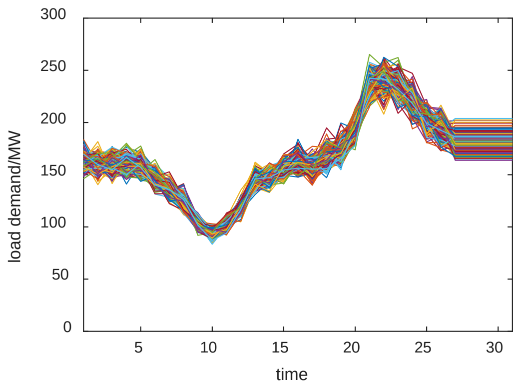
Simulation settings

	Capacity $\bar{g}_i$	Marginal cost c_i
G1	100	28
G2	100	30
G3	100	40



- Three generators with varying ramp rates
- G1 ramp rate fixed at 25
- G2 ramp rates from 10 to 60
- G3 ramp rates from 30 to 60

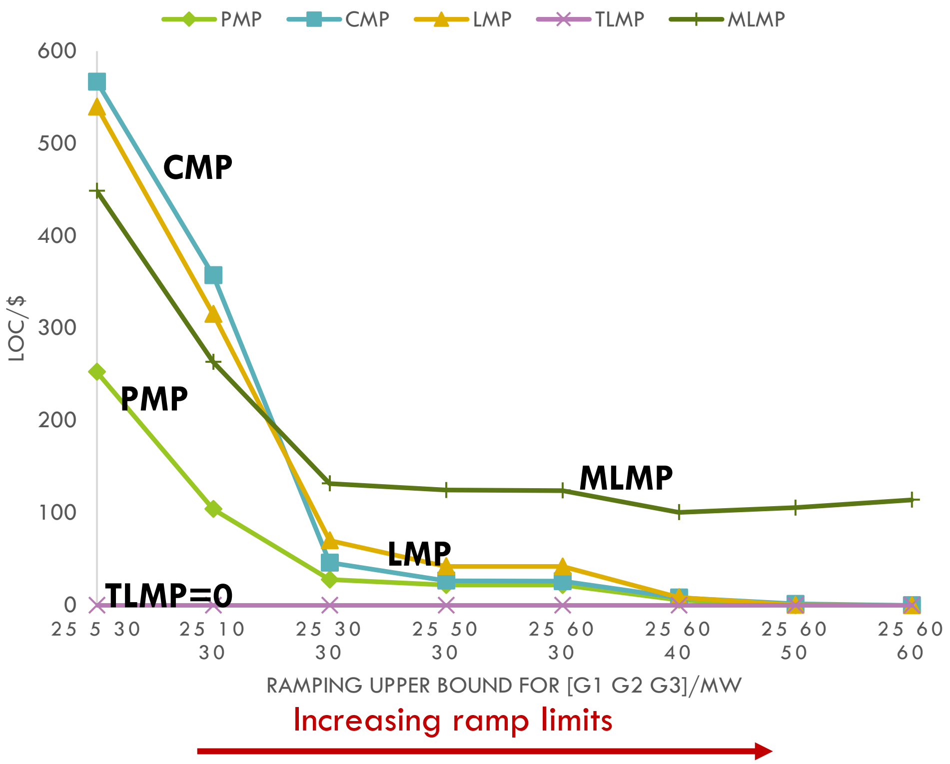




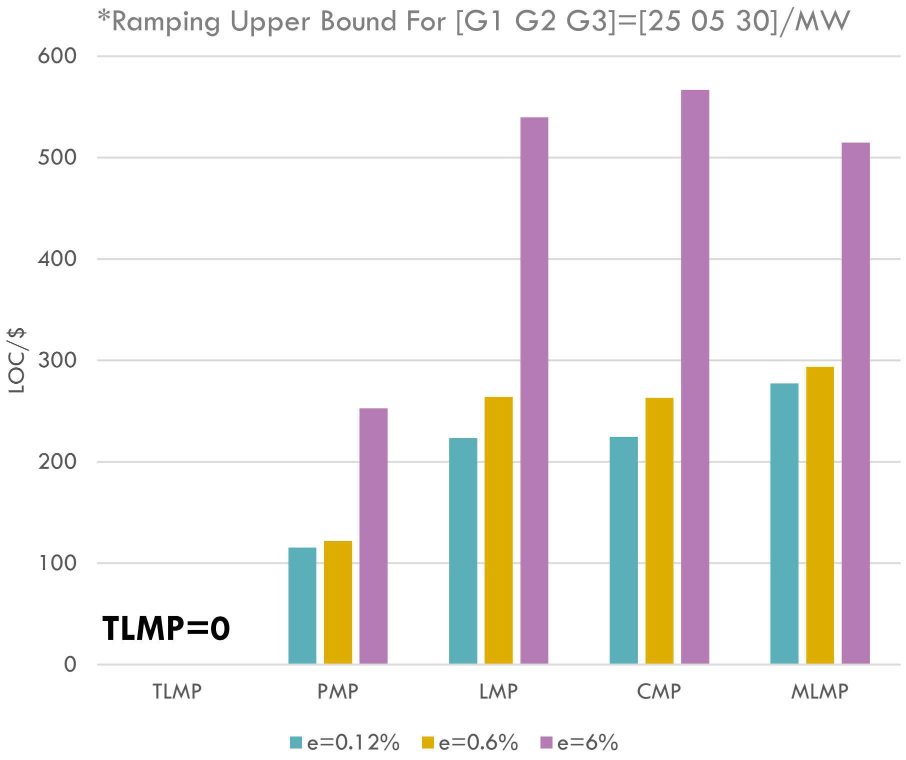
- Random demand with duck-curve average.
- Rolling Window dispatch w. 4 intervals

Dispatch-following incentives measured by LOC

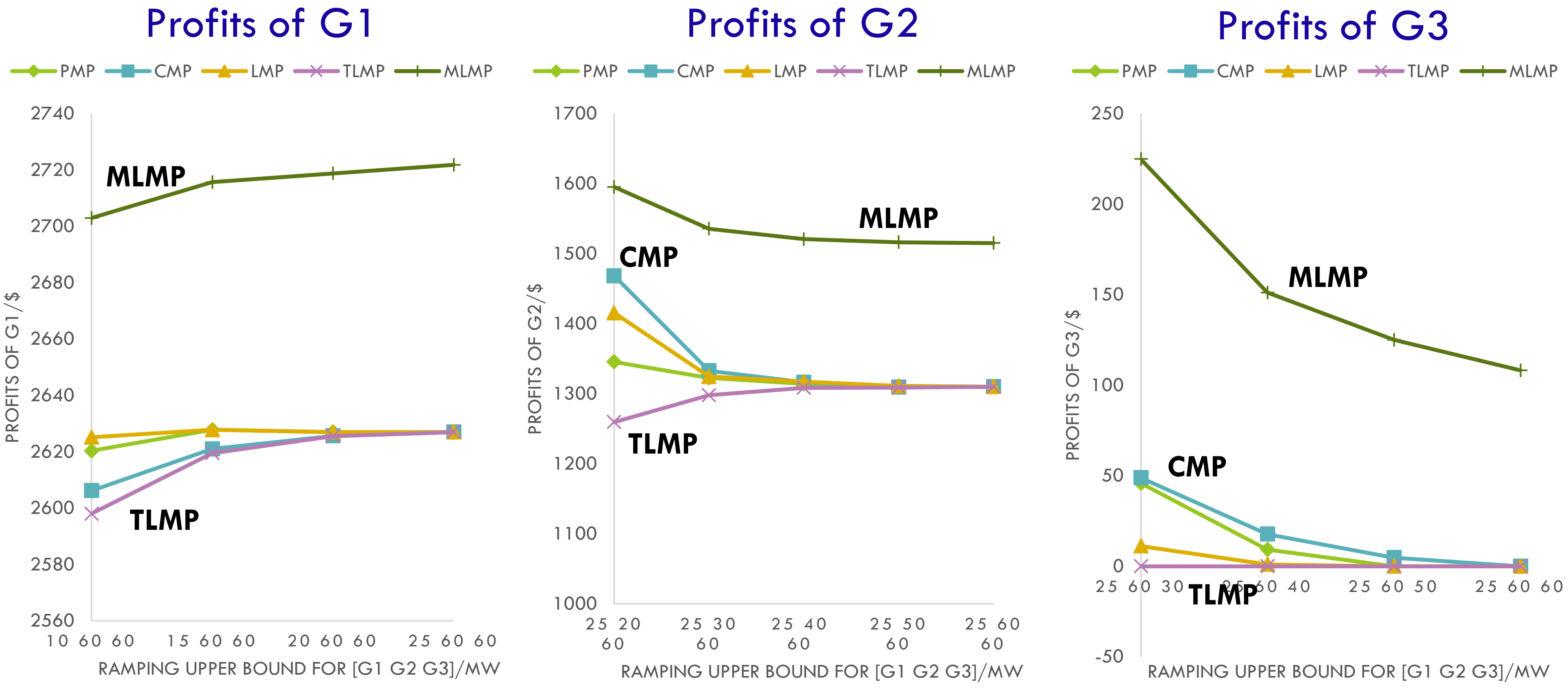
Loss-of-opportunity cost



Under different load forecast error



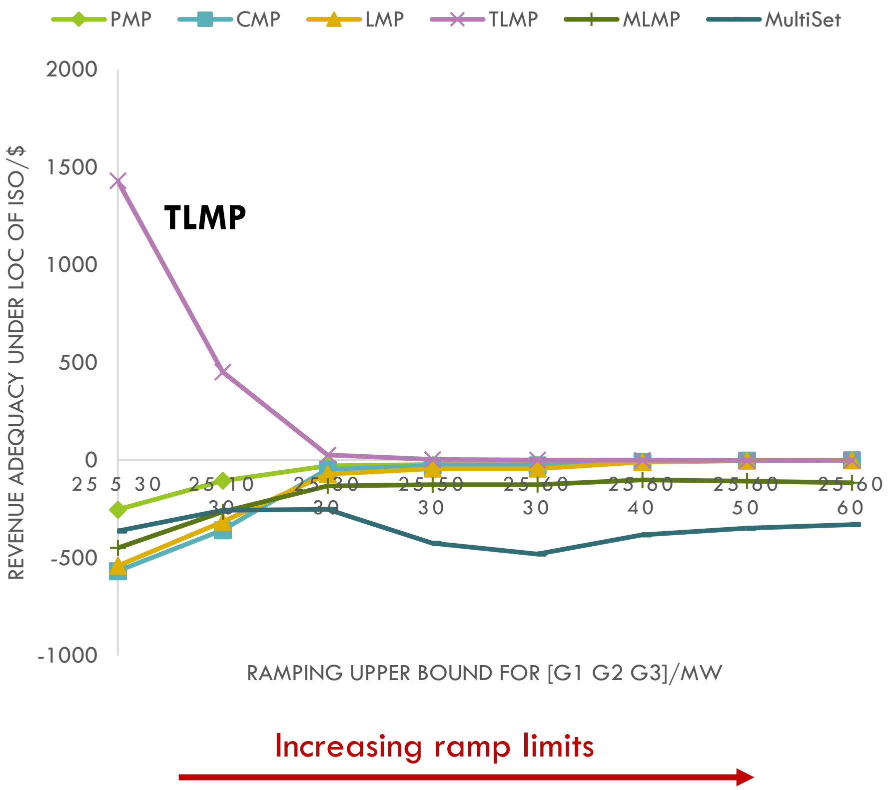
Incentives for truthful revelation of ramping limits



Increasing ramp limits

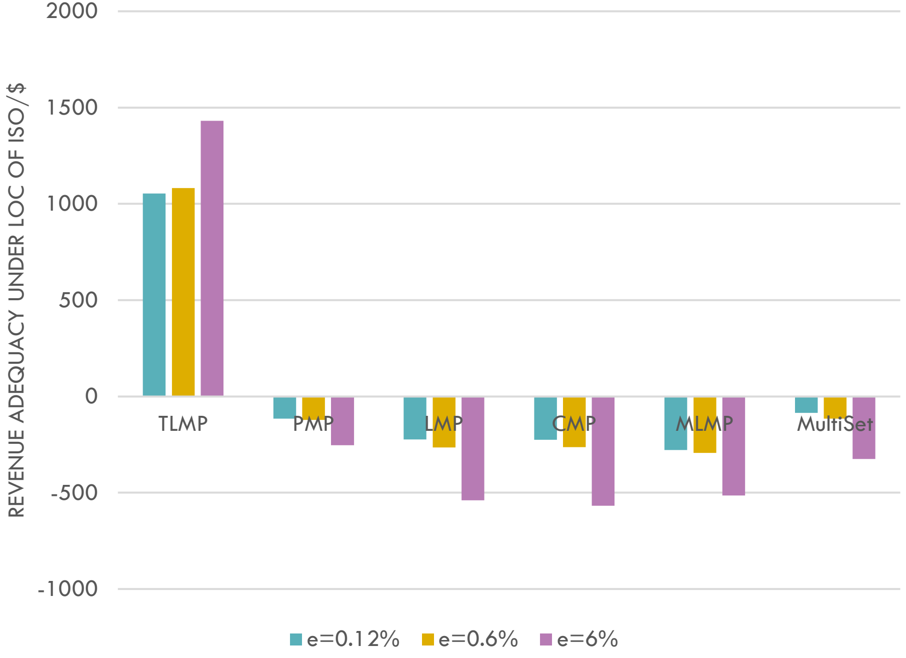
ISO surplus (including LOC payments)

Profit of ISO



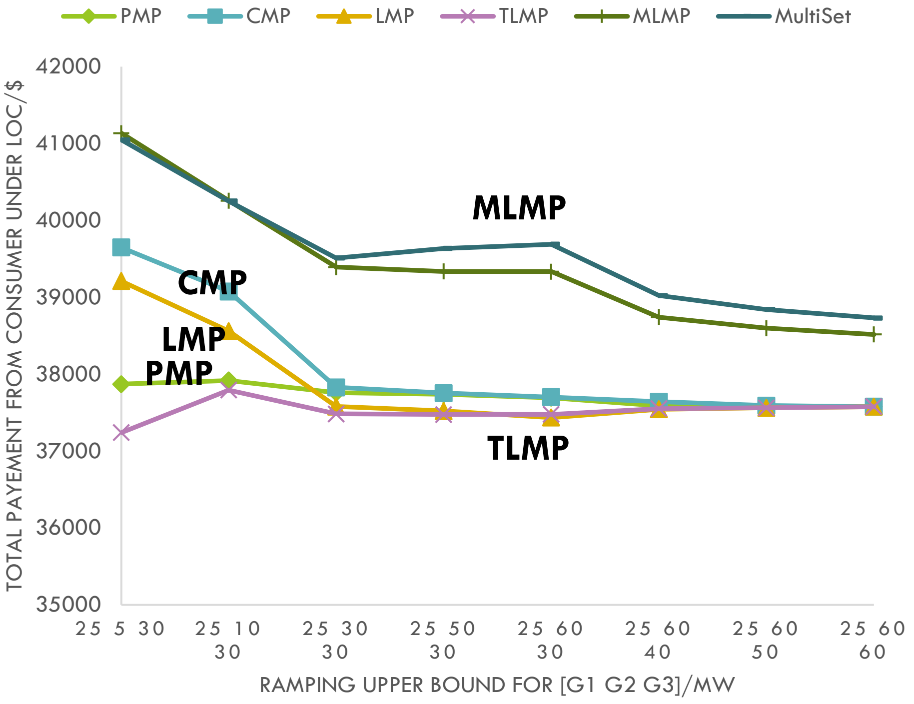
Under different load forecast error

*Ramping Upper Bound For [G1 G2 G3]=[25 05 30]/MW



Total consumer payment (incl rebate)

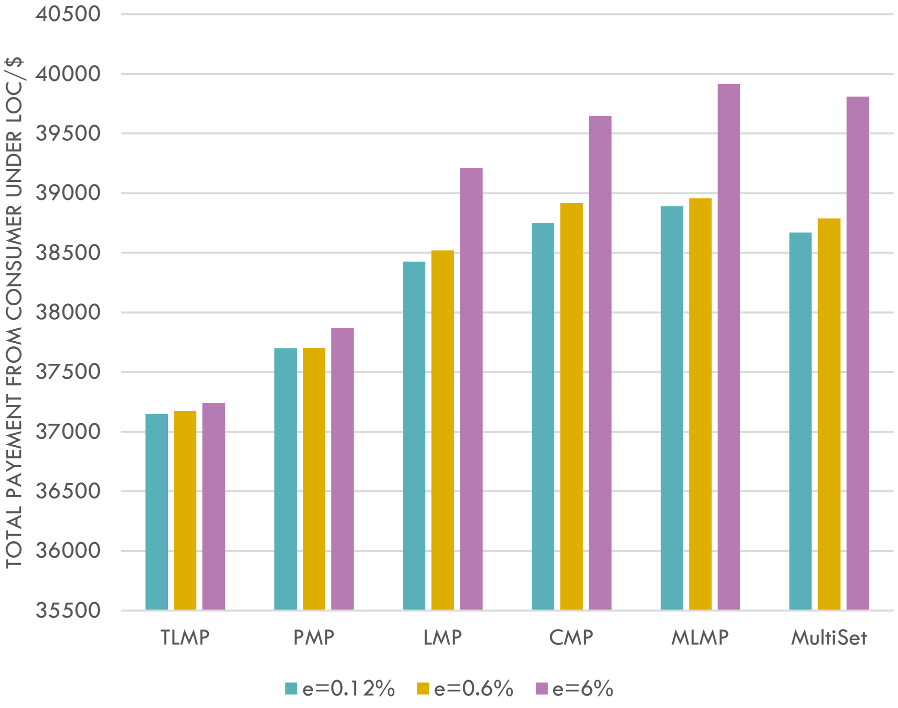
Consumer payment



Increasing ramp limits

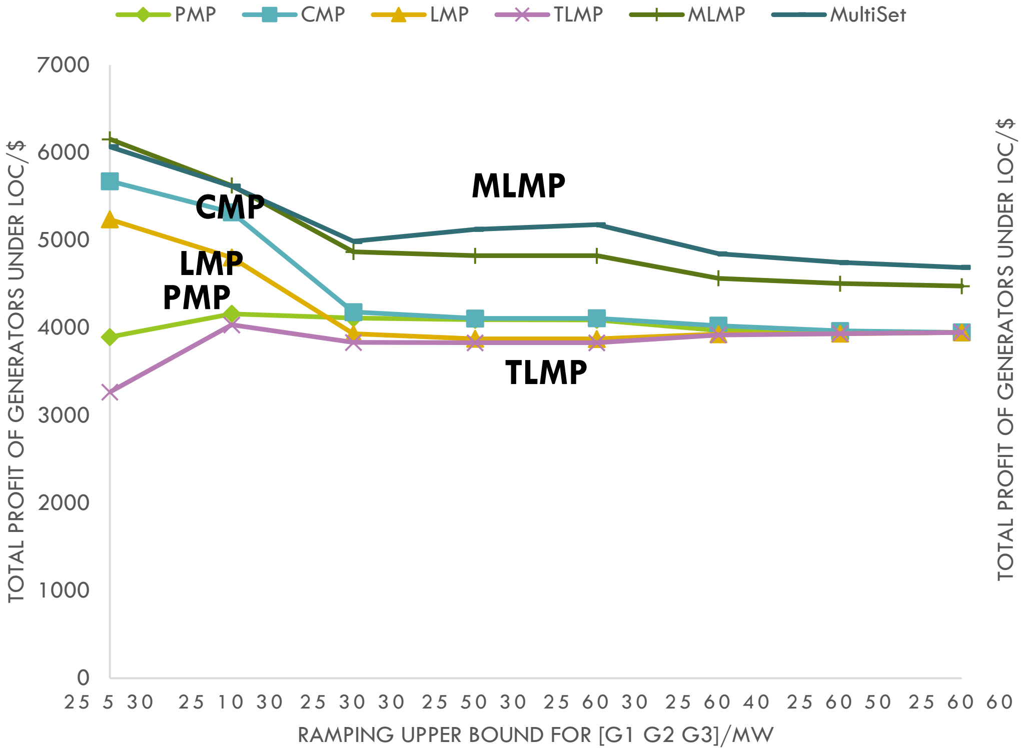
Under different load forecast error

*Ramping Upper Bound For [G1 G2 G3]=[25 05 30]/MW



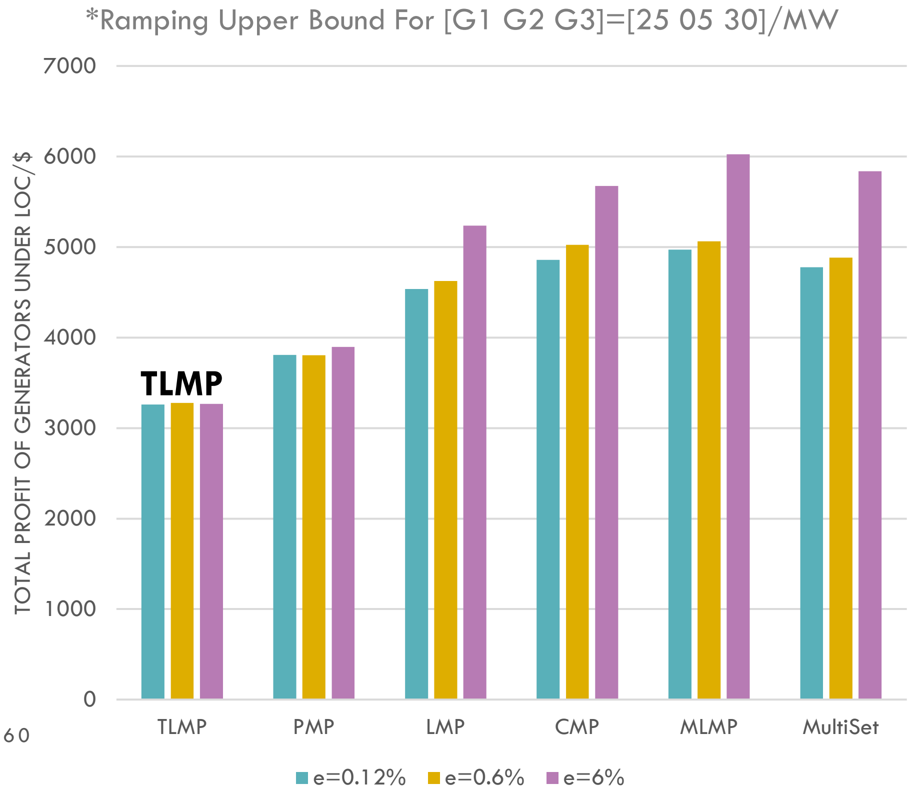
Total generator profit (incl. LOC)

Generator profit

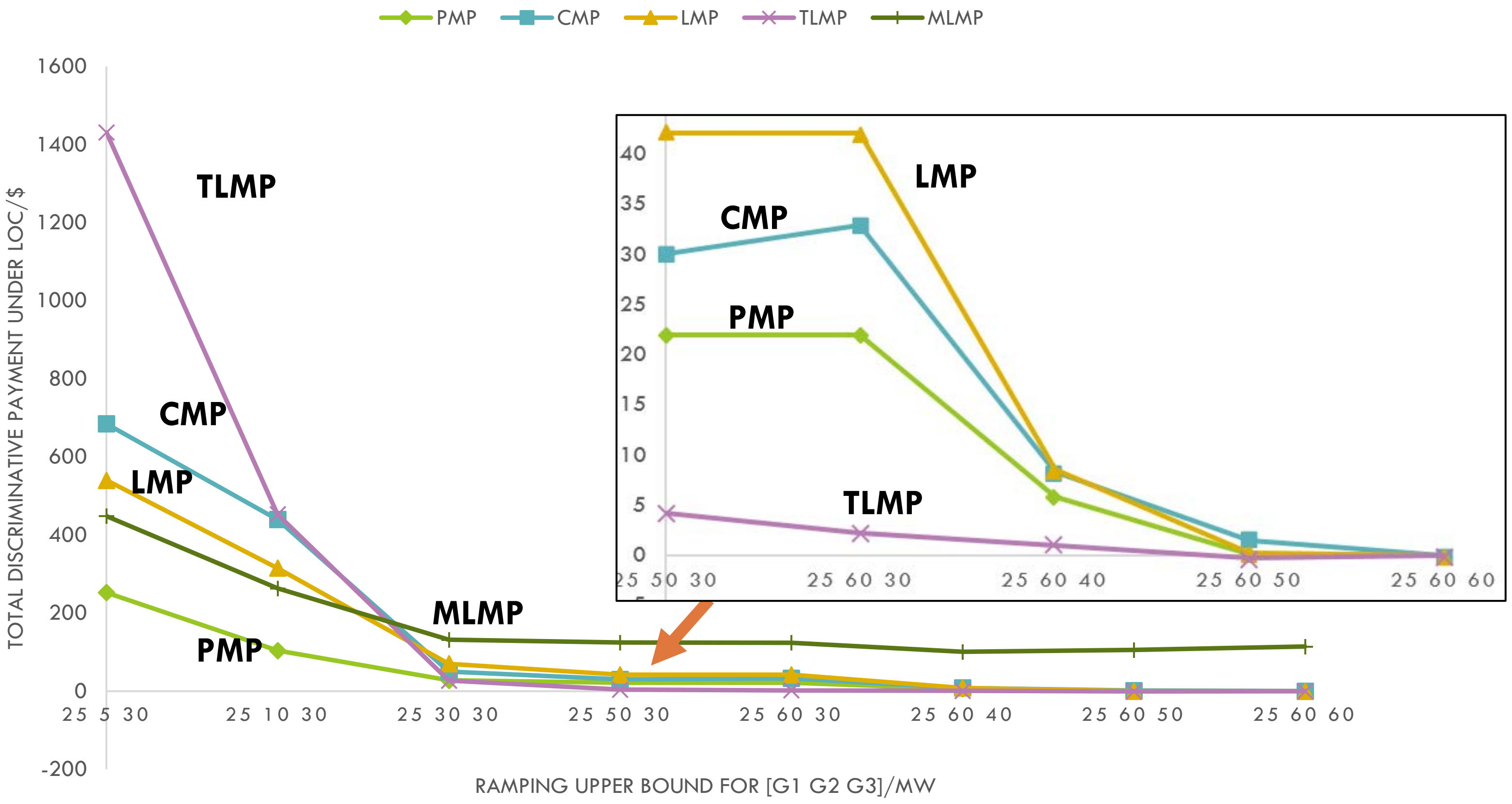


Increasing ramp limits

Under different load forecast error



Total discriminative payment under LOC



Increasing ramp limits

Pricing battery storage participation

- FERC order 841 mandates that
  - utility-scale battery storage can participate in energy market;
  - A battery storage participant is entitled uplift payments when it is "dispatched as load and the wholesale price is higher than the resource's bid price and when it is dispatched as supply and the wholesale price is lower than the resource's offer price."
- Battery storage resources have inter-temporal (SOC) constraints.
- TLMP for storage: TLMP = LMP + SOC price + Ramp price.
- All results on rolling-window TLMP applies to storage participation.

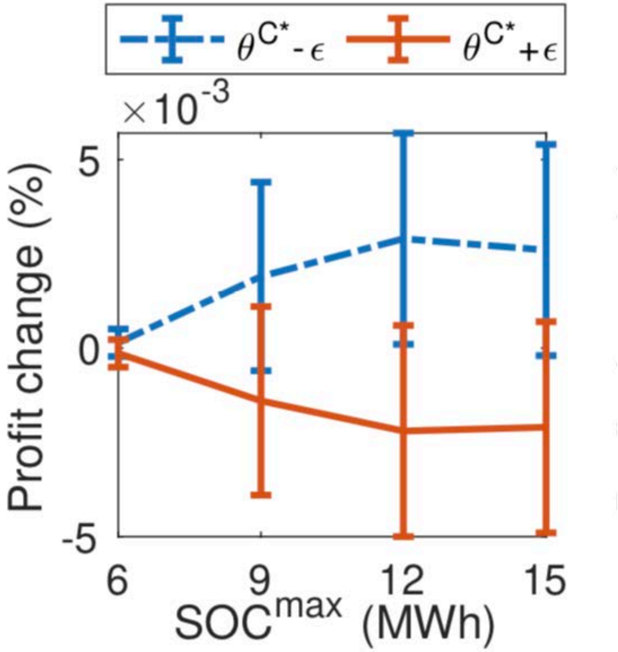
Multipliers of SOC constraints.

$$\begin{cases} \pi_{it}^{\text{TLMP-C}} = \lambda_t^* + \xi^{\text{C}} \phi_{it}^* + \Delta_{it}^{*\text{C}} \\ \pi_{it}^{\text{TLMP-D}} = \lambda_t^* + \frac{1}{\xi^{\text{D}}} \phi_{it}^* + \Delta_{it}^{*\text{D}} \end{cases}$$

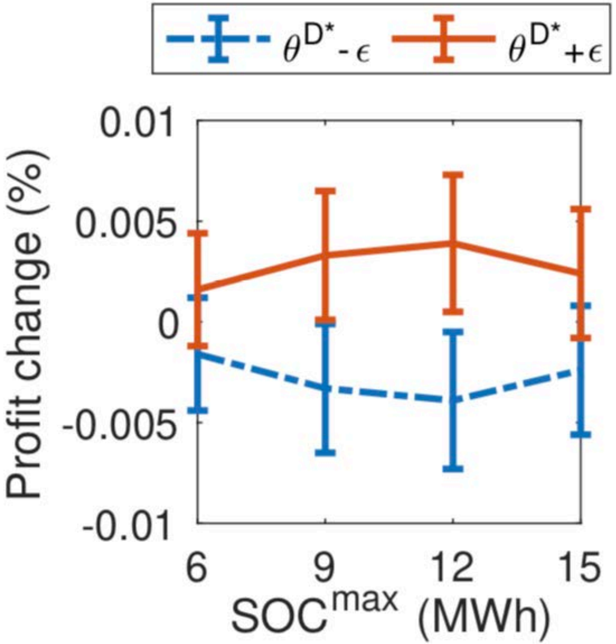
Charging/discharging parameters

C. Chen, L. Tong, and Y. Guo, "Pricing energy storage in real-time market," 2021 IEEE PESGM.

Truthful-bidding incentive issue under LMP



Charing profit



Discharging

Deviation from truthful bidding ($\epsilon = 0.01\$/MW$)

Conclusion and future work

- Pricing rolling-window dispatch is an open problem
  - There is no uniform equilibrium price. Discrimination is unavoidable.
  - Make-whole payment outside the market creates unintended consequences such as strategic bidding.
  - TLMP is a natural generalization of standard LMP to non-uniform pricing within the market clearing process (very different from PAB and VCG).
  - TLMP is incentive compatible under arbitrary forecasting error. It also generalizes key properties of LMP (e.g. rev. adequacy).

- On-going and future work
  - Pricing energy resources and DR.
  - Strategic behavior under LMP and TLMP outside the competitive equilibrium settings.