UTAH SMART ENERGY LAB

Scheduling and Pricing of Energy Storage in Electricity Market

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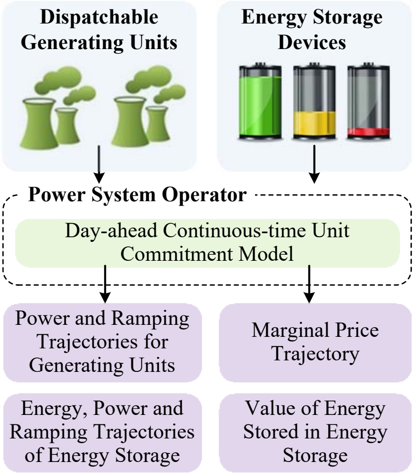
Motivation and Research Question

- How to valuate and price energy storage in electricity markets?
- How does energy storage impact the marginal electricity price?
- Does energy storage create any intertemporal correlation in marginal electricity prices?
- What is the monetary value of energy stored in energy storage?
- How does market-based and non-market operation of ES impact marginal prices?
- How does the energy storage charging/discharging offers/bids in market impact prices?

Energy Storage in Day-ahead Markets



Continuous-time Unit Commitment Model

- Assume $\Delta t \to 0$, so the set of K generating units are modeled by:
  - Continuous-time generation trajectories: $\mathbf{G}(t) = (G_1(t), \ldots, G_K(t))^T$
  - Continuous-time commitment variables: $\mathbf{I}(t) = (I_1(t), \ldots, I_K(t))^T$
  - Continuous-time ramping trajectories: $\dot{\mathbf{G}}(t) = (\dot{G}_1(t), \ldots, \dot{G}_K(t))^T$,

$$\dot{G}_k(t) \triangleq \frac{dG_k(t)}{dt}$$

[1] M. Parvania, R. Khatami, "Continuous-time Marginal Pricing of Electricity," *IEEE Transactions on Power Systems*, vol. 32, no. 3, pp. 1960-1969, 2017.

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- Cost function of generation and **ramping**: $C_k(G_k(t), \dot{G}_k(t), I_k(t))$

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- Cost function of generation and **ramping**: $C_k(G_k(t), \dot{G}_k(t), I_k(t))$

- Continuous-time Unit Commitment $\to$ a *variational problem*[1]:

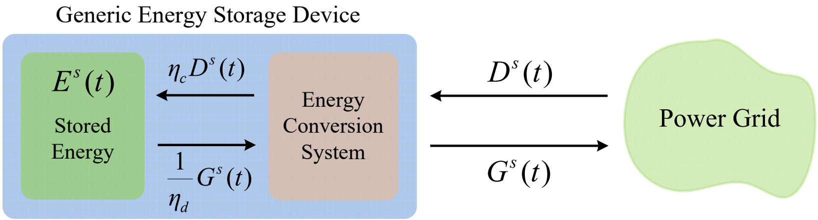
$$\min_{\mathbf{G}(t),\mathbf{I}(t)} \quad \int_{\mathcal{T}} C\big(\mathbf{G}(t), \dot{\mathbf{G}}(t), \mathbf{I}(t)\big)\, dt$$

$$\text{s.t.} \quad \mathbf{1}^T \mathbf{G}(t) = D(t), \qquad (\lambda(t)), \quad t \in \mathcal{T}$$

$$\mathbf{h}\big(\mathbf{G}(t), \dot{\mathbf{G}}(t), \mathbf{I}(t)\big) \leq 0, \quad (\gamma(t)), \quad t \in \mathcal{T}$$

[1] M. Parvania, R. Khatami, "Continuous-time Marginal Pricing of Electricity," *IEEE Transactions on Power Systems*, vol. 32, no. 3, pp. 1960-1969, 2017.

Continuous-time Modeling of Energy Storage Operation



- ES Differential State Equation: $\frac{dE^s(t)}{dt} = \eta^c D^s(t) - {\eta^d}^{-1} G^s(t), \ t \in \mathcal{T}$
- Charging Ramping Trajectories: $\frac{dG^s(t)}{dt} = \dot{G}^s(t)$
- Discharging Ramping Trajectories: $\frac{dD^s(t)}{dt} = \dot{D}^s(t)$
- Charging Utility Function: $U^S\left(D^s(t), \dot{D}^s(t)\right)$
- Discharging Cost Function: $C^S\left(G^s(t), \dot{G}^s(t)\right)$

Continuous-time Co-Optimization of Energy Generation and Storage

$$\min_{\dot{\mathbf{G}}(t),\dot{\mathbf{G}}^s(t),\dot{\mathbf{D}}^s(t)} \int_{\mathcal{T}} C^G\big(\mathbf{G}(t),\mathbf{I}(t)\big)\,dt + \int_{\mathcal{T}} C^S\big(\mathbf{G}^s(t)\big)\,dt - \int_{\mathcal{T}} U^S\big(\mathbf{D}^s(t)\big)\,dt,$$

$$\text{s.t.}\quad \frac{d\mathbf{E}^{\mathbf{s}}(t)}{dt} = \eta^c\mathbf{D}^s(t) - {\eta^d}^{-1}\mathbf{G}^s(t),\ \ t\in\mathcal{T},\ \ \left(\gamma^{s,E}(t)\right),$$

$$\mathbf{1}_K^T\mathbf{G}(t)+\mathbf{1}_R^T\mathbf{G}^s(t)=D(t)+\mathbf{1}_R^T\mathbf{D}^s(t),\ \ t\in\mathcal{T},\ \ (\lambda(t)),$$

$$\mathbf{h}\big(\mathbf{G}(t),\mathbf{I}(t),\mathbf{G}^s(t),\mathbf{D}^s(t)\big)\le 0,\quad t\in\mathcal{T},\quad (\gamma(t))$$

$$\mathbf{f}\big(\dot{\mathbf{G}}(t),\dot{\mathbf{G}}^s(t),\dot{\mathbf{D}}^s(t)\big)\le 0,\quad t\in\mathcal{T},\quad (\mu(t))$$

$$\mathbf{G}(0)=\mathbf{G}^0,\mathbf{G}^s(0)=\mathbf{G}^{s,0},\mathbf{D}^s(0)=\mathbf{D}^{s,0},\mathbf{E}^s(0)=\mathbf{E}^{s,0}.$$

Continuous-time Marginal Price of Generation and Storage

Theorem (Continuous-time Marginal Price)

Consider the optimal control problem of co-optimizing energy generation and storage. For any optimal solution of the problem, the optimal Lagrange multiplier trajectory $\lambda(t)$ *associated with the continuous-time power balance constraint is the rate at which the objective functional is changed due to an incremental variation in load* $\delta D(t)$ *at time* t*, and is* **continuous-time marginal price of energy generation and storage**.

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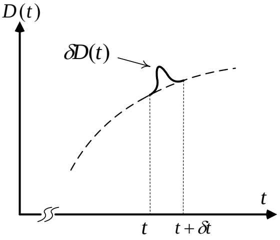
Optimality Conditions:

- Pontryagin Minimum Principle (PMP)
- Adjoint Equations
- First Order Conditions
- Complimentarity Slackness Conditions
- Jump and Transversality Conditions



Net Incremental Surplus of Stored Energy (*NISSE*)

Definition (Net Incremental Surplus of Stored Energy)

The adjoint function $\gamma_r^{s,E}(t)$ associated with the ES state equation represents the net surplus of incremental change in the energy stored at ES device r at time t, and is defined as the net incremental surplus of stored energy (*NISSE*).

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- *NISSE* is set at the start of charging and stay constant:

$$\gamma_r^{s,E}(t_r^{c1}) = \frac{1}{\eta_r^c}\left(\frac{\partial U^S\left(D_r^s(t)\right)}{\partial D_r^s(t)}\Big|_{t=t_r^{c1}} - \lambda(t_r^{c1})\right)$$

- *NISSE* stays constant during discharging unless ES is fully charged:

$$\gamma_r^{s,E}(t_r^{d1}) = \gamma_r^{s,E}(t_r^{c2}) - \int_{t_r^{c2}}^{t_r^{d1}} \left(\overline{\nu}_r^{s,E}(t)\right) dt$$

Closed-form Price Formula when ES is Idle

Case 1: Generating units set the marginal price (ES is idle)

$$\lambda(t) = \sum_{k \in (K_t^u \cup K_t^r)} IC_k^G(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K_t^r} \left(\dot{\underline{\mu}}_k^G(t) - \dot{\overline{\mu}}_k^G(t) \right) \frac{\partial G_k(t)}{\partial D(t)}$$

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- The continuous-time marginal price provides a price signal that reflects the impacts of continuous-time load variations on the operating conditions of the system.
- The continuous-time marginal price embeds the ramping limitations of generating units in electricity prices.

Closed-form Price Formula when ES is Charging

Case 2: Generating units and ES devices in charging state set the price

$$\lambda(t) = \sum_{k \in (K_t^u \cup K_t^r)} IC_k^G(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K_t^r} \left(\dot{\underline{\mu}}_k^G(t) - \dot{\bar{\mu}}_k^G(t) \right) \frac{\partial G_k(t)}{\partial D(t)}$$

$$- \sum_{r \in (R_t^u \cup R_t^r)} IU_r^S(t) \frac{\partial D_r^s(t)}{\partial D(t)} + \sum_{r \in R_t^r} \left(\dot{\underline{\mu}}_r^{s,D}(t) - \dot{\bar{\mu}}_r^{s,D}(t) \right) \frac{\partial D_r^s(t)}{\partial D(t)}$$

Closed-form Price Formula when ES is Charging

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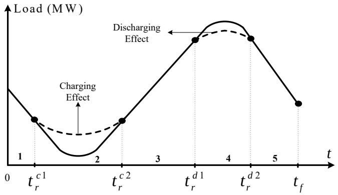
$$- \sum_{r\in(R_t^u \cup R_t^r)} IU_r^S(t)\frac{\partial D_r^s(t)}{\partial D(t)} + \sum_{r\in R_t^r}\left(\dot{\underline{\mu}}_r^{s,D}(t) - \dot{\bar{\mu}}_r^{s,D}(t)\right)\frac{\partial D_r^s(t)}{\partial D(t)}$$

- $IU_r^S(t)$ is *incremental charging cost rate of ES device* r:

$$IU_r^S(t) \triangleq \frac{\partial U^S\left(D_r^s(t)\right)}{\partial D_r^s(t)} - \eta_r^c \gamma_r^{s,E}(t_r^{c1})$$



Closed-form Price Formula when ES is Discharging

Case 3: Generating units and ES devices in discharging state set the price

$$\lambda(t) = \sum_{k \in (K_t^u \cup K_t^r)} IC_k^G(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K_t^r} \left(\underline{\dot{\mu}}_k^G(t) - \bar{\dot{\mu}}_k^G(t) \right) \frac{\partial G_k(t)}{\partial D(t)}$$
$$+ \sum_{r \in (R_t^u \cup R_t^r)} IC_r^S(t) \frac{\partial G_r^s(t)}{\partial D(t)} + \sum_{r \in R_t^r} \left(\underline{\dot{\mu}}_r^{s,G}(t) - \bar{\dot{\mu}}_r^{s,G}(t) \right) \frac{\partial G_r^s(t)}{\partial D(t)}$$

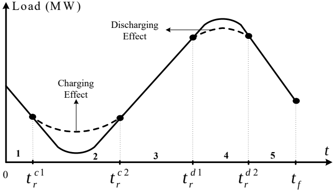
Closed-form Price Formula when ES is Discharging

Case 3: Generating units and ES devices in discharging state set the price

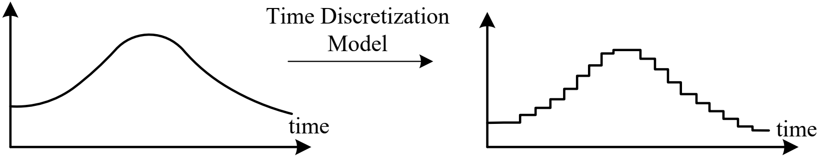
$$\lambda(t) = \sum_{k\in(K_t^u \cup K_t^r)} IC_k^G(t)\frac{\partial G_k(t)}{\partial D(t)} + \sum_{k\in K_t^r}\left(\dot{\underline{\mu}}_k^G(t) - \dot{\bar{\mu}}_k^G(t)\right)\frac{\partial G_k(t)}{\partial D(t)}$$
$$+ \sum_{r\in(R_t^u \cup R_t^r)} IC_r^S(t)\frac{\partial G_r^s(t)}{\partial D(t)} + \sum_{r\in R_t^r}\left(\dot{\underline{\mu}}_r^{s,G}(t) - \dot{\bar{\mu}}_r^{s,G}(t)\right)\frac{\partial G_r^s(t)}{\partial D(t)}$$

- $IC_r^S(t)$ is *incremental discharging cost rate of ES device r*:

$$IC_r^S(t) = \frac{\partial C^S(G^s(t))}{\partial G^s(t)} - \frac{1}{\eta_r^d}\gamma_r^{s,E}(t_r^{d1})$$



Function Space Solution Paradigm



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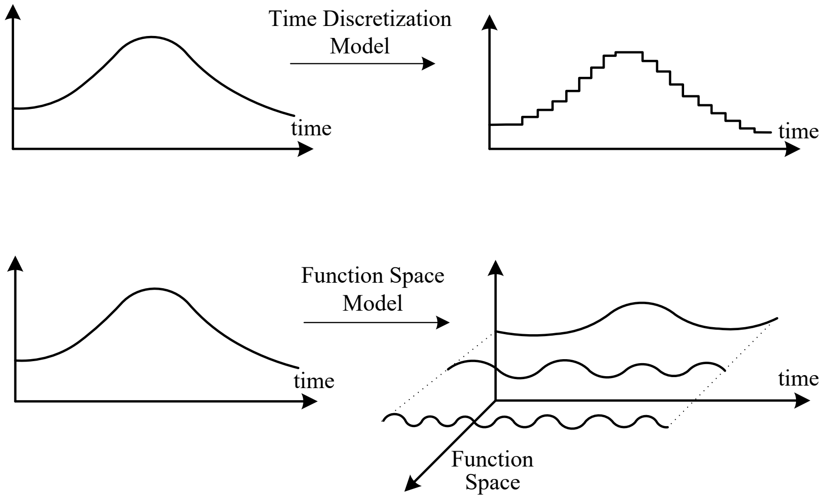


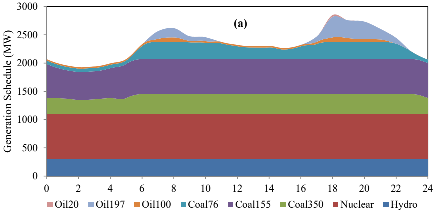
Simulation Results: IEEE-RTS + CAISO Load

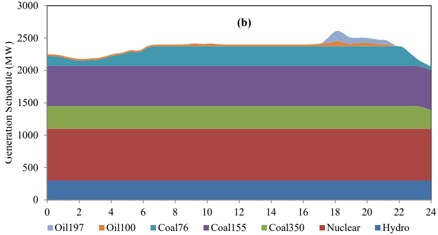
- Study 1: System Operation without ES
- Study 2: System Operation with Operator-owned ES
- Study 3: Market-based System Operation with ES Bidding in Market

	Hourly Model	Continuous-time Model
Study 1 - Operation Cost	$459,746.20	$461,006.40

	Hourly Model		Continuous-time Model	
	Operation Cost ($)	Cost Saving Compared to Case 1 ($)	Operation Cost ($)	Cost Saving Compared to Case 1 ($)
Study 2	449,246.7	10,499.5	450,041.3	10,965.1

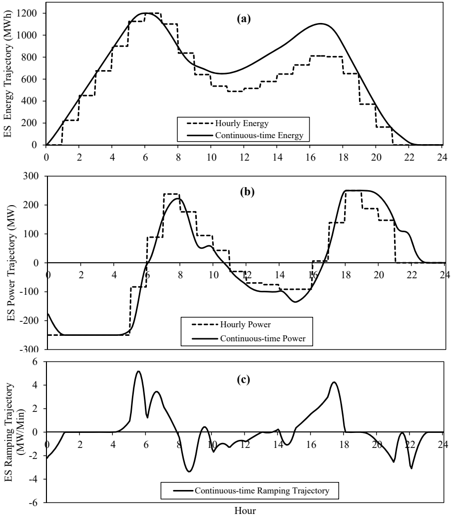
	Hourly Model		Continuous-time Model	
	Operation Cost ($)	Cost Saving Compared to Case 1 ($)	Operation Cost ($)	Cost Saving Compared to Case 1 ($)
Study 3	456,430.5	3,315.7	457,129.4	3,876.9





Simulation Results: IEEE-RTS + CAISO Load

- Study 2: System Operation with Operator-owned ES



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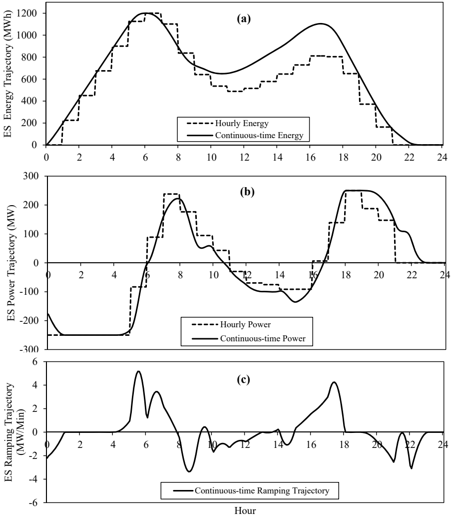

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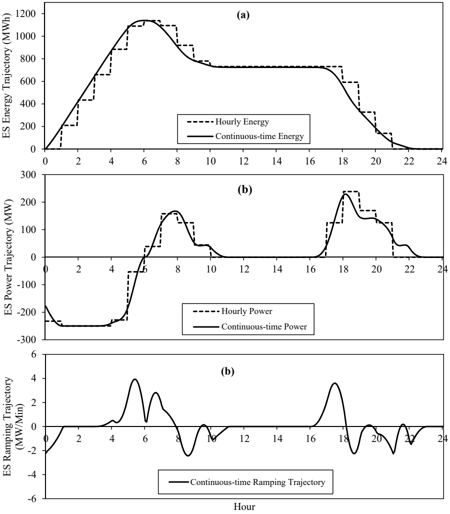

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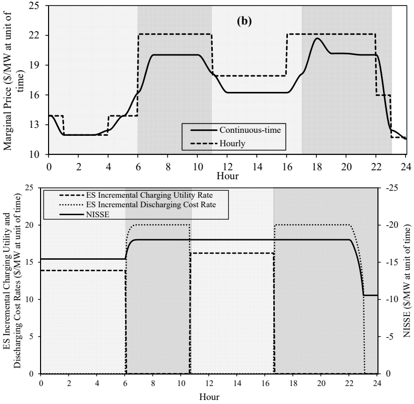

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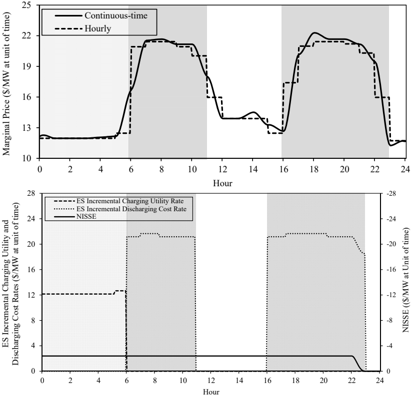
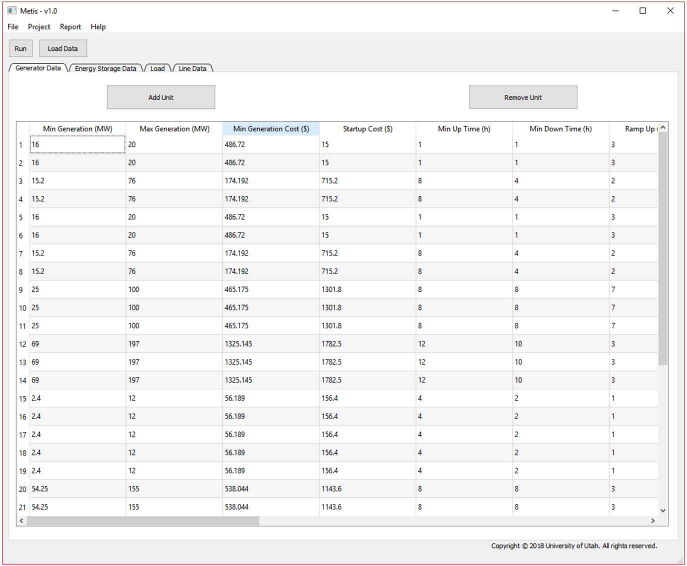
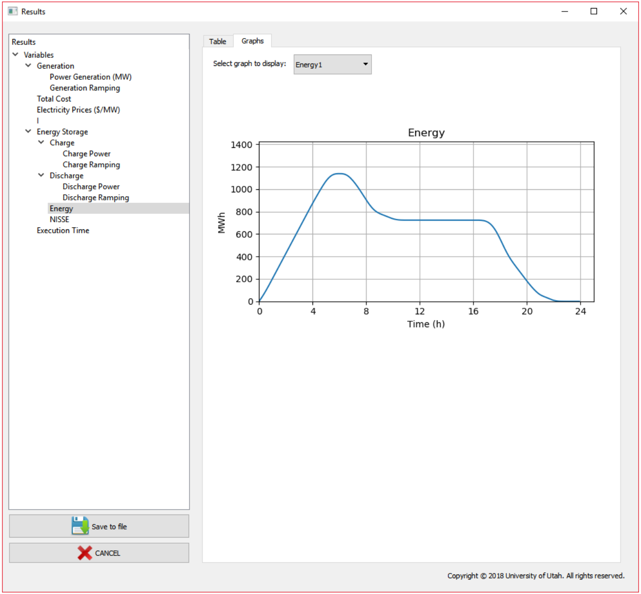


Software Implementation: Metis



	Min Generation (MW)	Max Generation (MW)	Min Generation Cost ($)	Startup Cost ($)	Min Up Time (h)	Min Down Time (h)	Ramp Up
1	16	20	486.72	15	1	1	3
2	16	20	486.72	15	1	1	3
3	15.2	76	174.192	715.2	8	4	2
4	15.2	76	174.192	715.2	8	4	2
5	16	20	486.72	15	1	1	3
6	16	20	486.72	15	1	1	3
7	15.2	76	174.192	715.2	8	4	2
8	15.2	76	174.192	715.2	8	4	2
9	25	100	465.175	1301.8	8	8	7
10	25	100	465.175	1301.8	8	8	7
11	25	100	465.175	1301.8	8	8	7
12	69	197	1325.145	1782.5	12	10	3
13	69	197	1325.145	1782.5	12	10	3
14	69	197	1325.145	1782.5	12	10	3
15	2.4	12	56.189	156.4	4	2	1
16	2.4	12	56.189	156.4	4	2	1
17	2.4	12	56.189	156.4	4	2	1
18	2.4	12	56.189	156.4	4	2	1
19	2.4	12	56.189	156.4	4	2	1
20	54.25	155	538.044	1143.6	8	8	3
21	54.25	155	538.044	1143.6	8	8	3

Software Implementation: Metis



Summary

- Continuous-time UC model capture the continuous-time variations of load and renewable resources, and tap the ramping flexibility of generating units and energy storage devices
- Continuous-time models define ramping trajectory as an explicit decision variable and enable accurate ramping valuation in markets
- Continuous-time UC model enables the definition of *continuous-time marginal electricity price*, which embeds the impacts of ramping and intertemporal ES operation in marginal price formation.
- Coming soon: ES scheduling in real-time (energy and AS) markets

Further Reading

- R. Khatami, M. Parvania, P. Khargonekar, "Scheduling and Pricing of Energy Generation and Storage in Power Systems," *IEEE Transactions on Power Systems*, vol. 33, no. 4, pp. 4308-4322, July 2018.
- M. Parvania, R. Khatami, "Continuous-time Marginal Pricing of Electricity," *IEEE Transactions on Power Systems*, vol. 32, no. 3, pp. 1960-1969, May 2017.
- M. Parvania, A. Scaglione, "Unit Commitment with Continuous-time Generation and Ramping Trajectory Models," *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 3169-3178, July 2016.

Acknowledgment

Thanks!

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