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

Dispatchable Generating Units

Energy Storage Devices

Power System Operator

Day-ahead Continuous-time Unit Commitment Model

Power and Ramping Trajectories for Generating Units

Marginal Price Trajectory

Energy, Power and Ramping Trajectories of Energy Storage

Value of Energy Stored in Energy Storage
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: $\dot{\mathbf{G}}(t) = (\dot{G}_1(t), \ldots, \dot{G}_K(t))^T$

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

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

- 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 → a variational problem\(^1\):

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

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

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

Continuous-time Modeling of Energy Storage Operation

Generic Energy Storage Device

- **ES Differential State Equation:** \( \frac{dE^s(t)}{dt} = \eta_c D^s(t) - \eta_d G^s(t) \), \( t \in T \)
- **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:** \( U^S(D^s(t), \dot{D}^s(t)) \)
- **Discharging Cost Function:** \( C^S(G^s(t), \dot{G}^s(t)) \)
Continuous-time Co-Optimization of Energy Generation and Storage

\[
\begin{align*}
\min_{\dot{G}(t), \dot{G}^s(t), \dot{D}^s(t)} & \int_{\mathcal{T}} \mathcal{C}^G(G(t), I(t)) \, dt + \int_{\mathcal{T}} \mathcal{C}^S(G^s(t)) \, dt - \int_{\mathcal{T}} U^S(D^s(t)) \, dt, \\
\text{s.t.} & \quad \frac{dE^s(t)}{dt} = \eta_c D^s(t) - \eta_d^{-1} G^s(t), \quad t \in \mathcal{T}, (\gamma^{s,E}(t)), \\
& \quad 1^T_K G(t) + 1^T_R G^s(t) = D(t) + 1^T_R D^s(t), \quad t \in \mathcal{T}, (\lambda(t)), \\
& \quad h(G(t), I(t), G^s(t), D^s(t)) \leq 0, \quad t \in \mathcal{T}, (\gamma(t)) \\
& \quad f(\dot{G}(t), \dot{G}^s(t), \dot{D}^s(t)) \leq 0, \quad t \in \mathcal{T}, (\mu(t)) \\
& \quad G(0) = G^0, \quad G^s(0) = G^{s,0}, \quad D^s(0) = D^{s,0}, \quad E^s(0) = E^{s,0}.
\end{align*}
\]
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.
Theorem (Continuous-time Marginal Price)

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Optimality Conditions:

- Pontryagin Minimum Principle (PMP)
- Adjoint Equations
- First Order Conditions
- Complementarity Slackness Conditions
- Jump and Transversality Conditions
Net Incremental Surplus of Stored Energy (NISSE)

Definition (Net Incremental Surplus of Stored Energy)

The adjoint function $\gamma_{s,E}^{r}(t)$ 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).
Definition (Net Incremental Surplus of Stored Energy)

The adjoint function $\gamma^s_E(t)$ 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).

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

   $$\gamma^s_E(t_{c1}^r) = \frac{1}{\eta^c_r} \left( \frac{\partial U^S(D^s_r(t))}{\partial D^s_r(t)} \right) \bigg|_{t=t_{c1}^r - \lambda(t_{c1}^r)}$$

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

   $$\gamma^s_E(t_{d1}^r) = \gamma^s_E(t_{c2}^r) - \int_{t_{c2}^r}^{t_{d1}^r} \left( \nu^s_r(t) \right) dt$$
Closed-form Price Formula when ES is Idle

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

\[
\lambda(t) = \sum_{k \in (K^u_t \cup K^r_t)} IC^G_k(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K^r_t} \left( \mu^G_k(t) - \mu^G_k(t) \right) \frac{\partial G_k(t)}{\partial D(t)}
\]
Closed-form Price Formula when ES is Idle

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

\[ \lambda(t) = \sum_{k \in (K_t^u \cup K_t^r)} IC_k^G(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K_t^r} \left( \dot{\mu}_k^G(t) - \overline{\mu}_k^G(t) \right) \frac{\partial G_k(t)}{\partial D(t)} - \sum_{r \in (R_t^u \cup R_t^r)} IU_r^S(t) \frac{\partial D_r^s(t)}{\partial D(t)} + \sum_{r \in R_t^r} \left( \dot{\mu}_r^s, D(t) - \overline{\mu}_r^s, D(t) \right) \frac{\partial D_r^s(t)}{\partial D(t)} \]
Case 2: Generating units and ES devices in charging state set the price

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\lambda(t) = \sum_{k \in (K^u_t \cup K^r_t)} IC_k^G(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K^r_t} \left( \mu^G_k(t) - \bar{\mu}^G_k(t) \right) \frac{\partial G_k(t)}{\partial D(t)} \\
- \sum_{r \in (R^u_t \cup R^r_t)} IU_r^S(t) \frac{\partial D_r^s(t)}{\partial D(t)} + \sum_{r \in R^r_t} \left( \dot{\mu}^{s,D}_r(t) - \bar{\mu}^{s,D}_r(t) \right) \frac{\partial D_r^s(t)}{\partial D(t)}
\]

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

\[
IU_r^S(t) \triangleq \frac{\partial U^S(D_r^s(t))}{\partial D_r^s(t)} - \eta_r^c \gamma_r^{s,E}(t_r^{c1})
\]
Case 3: Generating units and ES devices in discharging state set the price

\[
\lambda(t) = \sum_{k \in (K_{tu} \cup K_{tr})} IC_k^G(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K_{tr}} \left( \mu_k^G(t) - \bar{\mu}_k^G(t) \right) \frac{\partial G_k(t)}{\partial D(t)} \\
+ \sum_{r \in (R_{tu} \cup R_{tr})} IC_r^S(t) \frac{\partial G_r^s(t)}{\partial D(t)} + \sum_{r \in R_{tr}} \left( \mu_r^{s,G}(t) - \bar{\mu}_r^{s,G}(t) \right) \frac{\partial G_r^s(t)}{\partial D(t)}
\]
Closed-form Price Formula when ES is Discharging

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

\[
\lambda(t) = \sum_{k \in (K_u^t \cup K_r^t)} IC^G_k(t) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{k \in K_r^t} \left( \mu^G_k(t) - \bar{\mu}_k^G(t) \right) \frac{\partial G_k(t)}{\partial D(t)} + \sum_{r \in (R_u^t \cup R_r^t)} IC^S_r(t) \frac{\partial G^s_r(t)}{\partial D(t)} + \sum_{r \in R_r^t} \left( \mu^{s,G}_r(t) - \bar{\mu}_r^{s,G}(t) \right) \frac{\partial G^s_r(t)}{\partial D(t)}
\]

- \(IC^S_r(t)\) is incremental discharging cost rate of ES device \(r\):

\[
IC^S_r(t) = \frac{\partial C^S(G^s_r(t))}{\partial G^s_r(t)} - \frac{1}{\eta^d_r} \gamma^{s,E}_r(t^{d1}_r)
\]
Function Space Solution Paradigm

Time Discretization Model
Function Space Solution Paradigm

Time Discretization Model

Function Space Model

Function Space

Scheduling and Pricing of Energy Storage
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

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<th>Hourly Model</th>
<th>Continuous-time Model</th>
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<td><strong>$3,315.7</strong></td>
<td><strong>$3,876.9</strong></td>
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Simulation Results: IEEE-RTS + CAISO Load

Study 2: System Operation with Operator-owned ES

- ES Power Trajectory (MW)
  - Hourly Power
  - Continuous-time Power

- ES Energy Trajectory (MWh)
  - Hourly Energy
  - Continuous-time Energy

- ES Ramping Trajectory (MW/Min)
  - Hourly Ramping
  - Continuous-time Ramping

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Simulation Results: IEEE-RTS + CAISO Load

- **Study 2: System Operation with Operator-owned ES**

![ES Power Trajectory (MW)](image)

- **ES Energy Trajectory (MWh)**

![ES Ramping Trajectory (MW/Min)](image)

- **Study 3: Market-based System Operation with ES Bidding in Market**

![ES Power Trajectory (MW)](image)

- **ES Energy Trajectory (MWh)**

![ES Ramping Trajectory (MW/Min)](image)
Simulation Results: IEEE-RTS + CAISO Load

- **Study 2: System Operation with Operator-owned ES**

- **Study 3: Market-based System Operation with ES Bidding in Market**
Software Implementation: Metis

![Metis - v1.0](image)

<table>
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<tr>
<th>Min Generation (MW)</th>
<th>Max Generation (MW)</th>
<th>Min Generation Cost ($)</th>
<th>Startup Cost ($)</th>
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<th>Min Down Time (h)</th>
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Software Implementation: Metis

![Graph of Energy over Time](image)

- Variables:
  - Generation
    - Power Generation (MW)
  - Generation Ramping
  - Total Cost
  - Electricity Prices ($/MW)
  - Energy Storage
    - Charge
      - Charge Power
      - Charge Ramping
    - Discharge
      - Discharge Power
      - Discharge Ramping
  - Energy
  - NISSE
  - Execution Time

Select graph to display: Energy 1
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


Acknowledgment

Thanks!

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https://usmart.ece.utah.edu