ESS Testing and Modeling of Stacked Application Duty Cycles

UC San Diego Energy Storage Research Webinar
11am Pacific Time, August 30th 2017
Overview

1. Economic Modeling Based Energy Storage Duty Cycle
2. Grid-integrated Energy Storage System Test Pads
3. Battery Cells and Modules Testing
Motivation:
To provide economic valuation of energy storage benefits and testing protocols for performance of energy storage systems under conditions similar to how they would operate in the California markets.
Economic Modeling and Valuation of wholesale and retail energy market using data from utilities or independent system operators and forecasting for real world economic valuation. Developing stacked application duty cycles to investigate better energy storage value proposition.
Stacked Application Duty Cycles

\[ p_{k,i} \]
Stacked Application Duty Cycles

\[ p_{k,i} \]

1. Demand Charge Management
2. Day-Ahead Energy Time Shifting
3. Real-Time Energy Time Shifting
4. Flexible Ramping
5. Frequency Regulation
Stacked Application Duty Cycles

- Retail Market
  - Demand Charge Management

Wholesale Market
- Day Ahead Market
  - Frequency Regulation
  - Energy Time Shifting

Real-Time Market
- Flexible Ramping
- Energy Time Shifting
Stacked Application Duty Cycles

\[ i = t_1 \ t_2 \ t_3 \ \ldots \ \ t_n \]
Stacked Application Duty Cycles
Stacked Application Duty Cycles

\[ p_{k,i} \]

\[ p_{k,i}^o \quad p_{k,i}^+ \quad p_{k,i}^- \]

\[ 0 < p_{k,i}^+ < W_k \cdot \bar{p}_k, \]

\[ 0 < p_{k,i}^- < (1 - W_k) \cdot \bar{p}_k, \]
Stacked Application Duty Cycles

\[ p_{k,i} \]

\[ p_{k,i}^o \quad p_{k,i}^+ \quad p_{k,i}^- \]

\[ p_{k,i}^o = p_{k,i}^+ - p_{k,i}^- \]
Stacked Application Duty Cycles

Mix Integer Linear Programming

\[
\begin{align*}
\text{minimize} \quad & J_{bat}(P, W) \\
\text{subject to} \quad & A(P, W) \leq B \\
& Aeq(P, W) = Beq
\end{align*}
\]

Revenue Model

\[
J_{bat}(P, W) = \sum_{i=1}^{N} \sum_{k=1}^{K} J_{ene,k,i}(p_{k,i}, w_{k,i}) + \sum_{i=1}^{N} \sum_{k=1}^{K} J_{app,k,i}(p_{k,i}, w_{k,i}).
\]
Stacked Application Duty Cycles

Mix Integer Linear Programming

\[
\begin{align*}
\text{minimize} & \quad J_{bat}(P, W) \\
\text{subject to} & \quad A(P, W) \leq B \\
& \quad A_{eq}(P, W) = B_{eq}
\end{align*}
\]

Power Constraints

\[
p_{k,i} = \{p_{k,i}^o, p_{k,i}^+, p_{k,i}^-\},
\]

\[
p_{k,i}^o = p_{k,i}^+ - p_{k,i}^-,
\]

\[
0 < p_{k,i}^+ < W_k \cdot \overline{p_k},
\]

\[
0 < p_{k,i}^- < (1 - W_k) \cdot \overline{p_k},
\]
Stacked Application Duty Cycles

Mix Integer Linear Programming

\[ \text{minimize} \quad J_{bat}(P, W) \]
\[ \text{subject to} \quad A(P, W) \leq B \]
\[ A_{eq}(P, W) = B_{eq} \]

SoC Constraints

\[ SoC_{bat,i} = SoC_0 + \sum_{i=1}^{n} \sum_{k=1}^{4} \left( \frac{\eta \cdot p_{k,i}^+ - p_{k,i}^-}{Q} \right) \Delta t \]
\[ + \frac{\eta \cdot \frac{1}{\gamma_i} p_{5,i}^+ - \frac{1}{\gamma_i} p_{5,i}^-}{Q} \Delta t, \]
\[ SoC_{bat} < SoC_{bat,i} < SoC_{bat}. \]
Stacked Application Duty Cycles

Mix Integer Linear Programming

\[
\begin{align*}
\text{minimize} & \quad J_{bat}(P, W) \\
\text{subject to} & \quad A(P, W) \leq B \\
& \quad A_{eq}(P, W) = B_{eq}
\end{align*}
\]

Demand Charge Revenue

\[
J_{1,\text{ene}} = \sum_{i=1}^{N} E_{tou}(p_{1,i}^o + L_i) \Delta t - \sum_{i=1}^{N} E_{tou}(L_{r_i}) \Delta t
\]

\[
J_{1,\text{app}} = E_{dc} \max \{p_{1,i}^o + L_i - L_{pk_i}, 0\}, \quad i = 1, 2, \ldots, N
\]
Stacked Application Duty Cycles

Mix Integer Linear Programming

\[
\text{minimize}_{P,W} \quad J_{bat}(P,W) \\
\text{subject to} \quad A(P,W) \leq B \\
A_{eq}(P,W) = B_{eq}
\]

Energy Time Shifting

\[
J_{2,ene} = \sum_{i=1}^{N} E_{da}(p_{2,i}^o) \Delta t,
\]

![Power vs Time Graph]
Stacked Application Duty Cycles

Mix Integer Linear Programming

\[
\begin{align*}
\text{minimize} \quad & J_{bat}(P, W) \\
\text{subject to} \quad & A(P, W) \leq B \\
& A_{eq}(P, W) = B_{eq}
\end{align*}
\]

Ramping Revenue

\[
J_{4, app} = -\sum_{i=1}^{N} (E_{fr, down} \Delta p_{4,i}^+ + E_{fr, up} \Delta p_{4,i}^-) \Delta t
\]

\[
\Delta p_{4,i}^+ = \max\{(p_{4,i}^o) - (p_{4,i-1}^o), 0\}
\]

\[
\Delta p_{4,i}^- = \max\{- (p_{4,i}^o) + (p_{4,i-1}^o), 0\}
\]
Stacked Application Duty Cycles

Mix Integer Linear Programming

\[
\begin{align*}
\text{minimize} \quad & J_{bat}(P, W) \\
\text{subject to} \quad & A(P, W) \leq B \\
& A_{eq}(P, W) = B_{eq}
\end{align*}
\]

Regulation Revenue\[ J_{5,app} = \]

\[
- \left( C^+_{FQ} \sum_{i=1}^{N} \frac{1}{\gamma_i} P^+_i + C^-_{FQ} \sum_{i=1}^{N} \frac{1}{\gamma_i} P^-_i \right) \Delta t
\]

\[
- \left( E^+_{FQ} \sum_{i=1}^{N} M^+_i \frac{1}{\gamma_i} P^+_i + E^-_{FQ} \sum_{i=1}^{N} M^-_i \frac{1}{\gamma_i} P^-_i \right) \Delta t.
\]

Power [MW]
Battery Specs:
1MW / 2MWh / 90% Eff.
Stacked Application Duty Cycles

- Power Profile
  - Stacked
  - Single Application

- Energy Throughput
  - Stacked
  - Single Application

- Revenue Breakdown
  - DC: DC
  - DA: DA
  - RT: RT
  - FR: FR
  - FQ: FQ

- Stacked application revenue
- Single application revenue from RT only
Stacked Application Duty Cycles

![Revenue Breakdown Graph](image)

- Stacked Application Revenue
- Stacked Application Revenue Without FQ

**Average Revenue ($/Day)**

- 1MW/2MWh: $398
- 1MW/4MWh: $443
- 1MW/8MWh: $520

**Legend**: DC: DC, DA: DA, RT: RT, FR: FR, FQ: FQ
Grid integrated energy storage test pads

Battery Grid-Connected Testing that leverages the highly diversified UCSD micro-grid and offers the unique capability to validate integrated energy storage solutions under a realistic setting.
Grid integrated energy storage test pads

The deployed system and happy customers
Li-ion battery module testing

Battery Cell and Module Level Testing
which offers battery evaluation from electro-chemistry characteristics to energy market readiness.
Battery module testing

A flow battery system being tested in the module testing lab.
Thank You

Project link
https://cer.ucsd.edu/research/energy-storage/ARPA-E_CHARGES.html

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