Maximizing Return on Investment of a Grid-Connected Hybrid Electrical Energy Storage System

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Outline

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- Problem and proposed solution
- System overview
- Daily cost saving (DCS) problem
  - Problem formulation and solution
  - DoD-aware DCS problem
- Amortized annual profit maximization
  - Cycle life, energy density, maintenance cost and discount factor
  - Problem formulation and solution
- Simulation results
- Summary

Background

- The mismatch between electrical energy generation and consumption
- *Peak hours*: high energy consumption
  - Energy generation fluctuates within a much smaller range

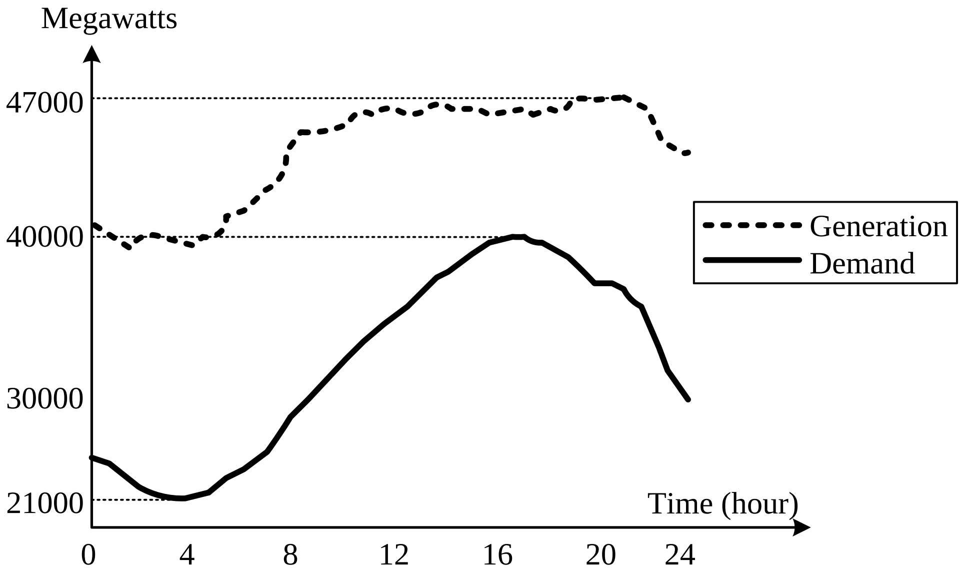


Figure 1. Electrical Energy Generation vs. Demand.

Background – Demand Side Management

- *Time-of-day* Pricing Policy
- *Demand Side Management* is required
  - Method 1: Directly shifting residential load demand from peak hours to off-peak hours
  - This is limited because many tasks are not transferrable in time
  - Method 2: Electrical Energy Storage (EES) System

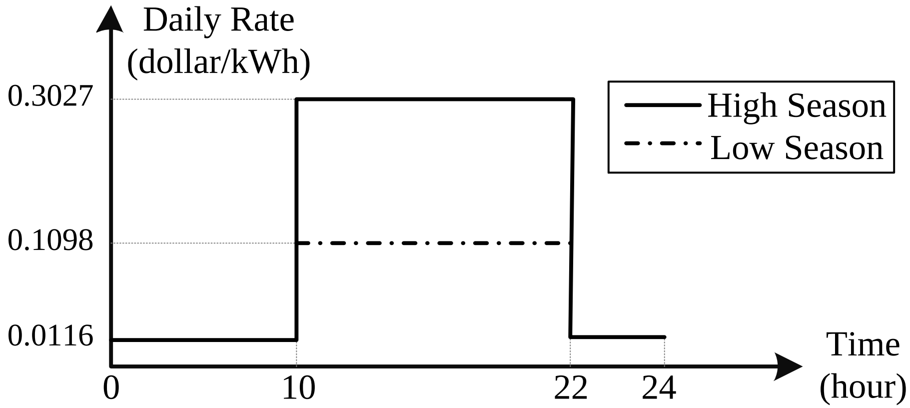


Figure 2. Daily Time-of-Day Energy Pricing.

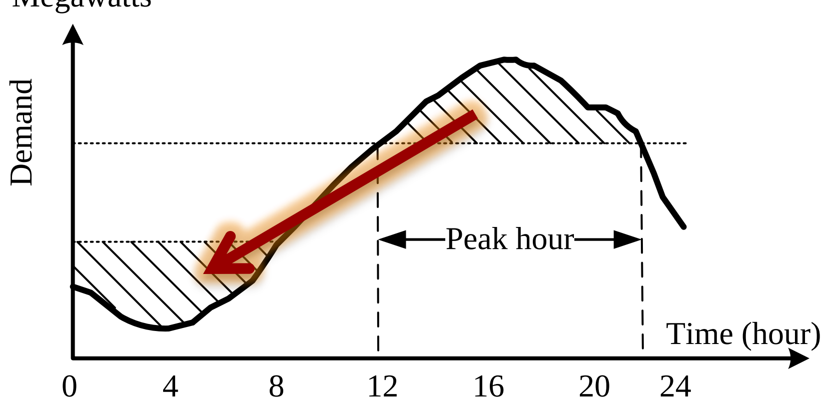


Figure 3. Demand Side Management.

Background – HEES Systems

- State-of-the-art EES systems are homogeneous
- The desirable features of an ideal EES system
  - High charge/discharge efficiency
  - High energy density
  - Low cost per unit capacity
  - Long cycle life
- None of the existing EES elements can simultaneously fulfill all the desired features
- A novel technology: Hybrid EES systems
  - Exploit the strengths of each type of EES element and hide their weaknesses
  - There lacks a practical analysis of HEES systems' profitability and a proper design methodology to maximize their profits

Background – Practical Factors

- Rate capacity effect
  - The charge loss rate inside a battery increases superlinearly with the increase of battery discharge current. The equivalent current:

$$I_{eq} = \left(\frac{I_{disch}}{I_{ref}}\right)^k I_{ref} \qquad I_{ref} = Q/20 \qquad (1)$$

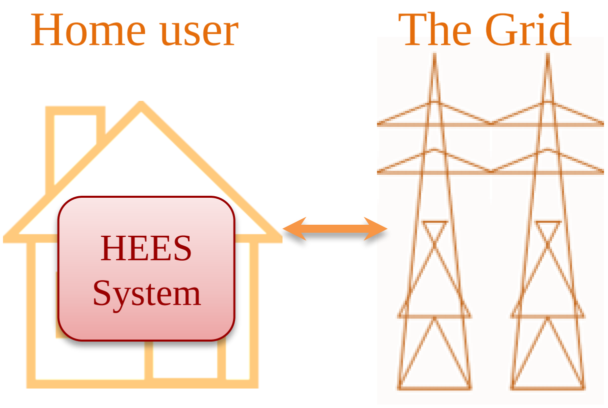
  - Peukert's constant k: reflects the efficiency of the discharging process
  - Lead-acid: 1.3 to 1.4; Li-ion: around 1.1

$k \geq 1$ → I_{disch} ↑ Efficiency ↓

- Unit cost of EES elements
  - Supercapacitor: \$20-50/Wh; lead-acid: \$0.1-0.2/Wh
- Power losses due to power conversion circuits
  - Internal resistance, switching power losses, etc.

Problem

- A home user wants to build a HEES system: how to maximize its return on investment (ROI)?
- Taking into consideration:
  - Pricing policy
  - Capital cost of EES elements
  - Maintenance cost
  - HEES system efficiency
  - HEES system lifetime
  - Energy density
  - Investment discount factor (considering time-value of money)



Proposed Solution

- Step 1: Maximize the **daily** energy cost saving
  - Given specification of the HEES system
  - Controls the charging and discharging of each EES bank
  - Further improvement: adding limits on the depth of discharge (DoD) for lifetime extension
- Step 2: Find the optimal design and specification of the HEES system to maximize **annual** profit
  - Under monetary budget constraint and volume constraint

System Overview

- The HEES system
  - HEES banks + power conversion circuits

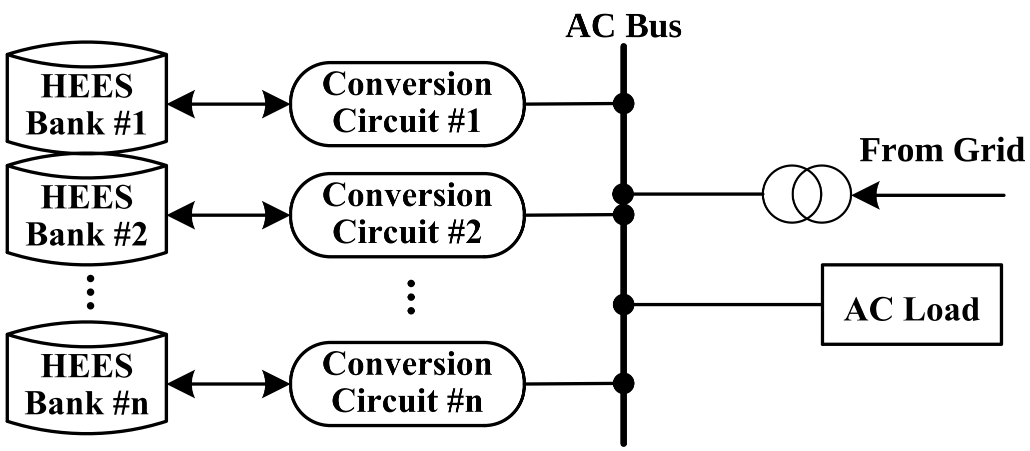


Figure 4. HEES System Structure.

Daily Cost Saving Problem (DCS Problem)

Given:

1) Battery capacity (in Ah): Q_x, Q_y (x stands for Li-ion and y stands for lead-acid as a case study in this paper);
2) Battery's terminal voltage: V_{bat};
3) The 24-hour electrical energy price: $r_i, i = 1, \ldots, 24$. (We define the peak hours index set as $PK = \{11, 12, \ldots, 22\}$, and base hours index set as $BS = \{1, 2, \ldots, 10, 23, 24\}$);
4) Residential load power profile $P_i^{load}, i = 1, \ldots, 24$;
5) Batteries' rate capacity effect coefficients k_x, k_y;
6) DC-AC converters' power conversion efficiency: η.

Find: Discharge current $x_{11}, \ldots, x_{22}$, $y_{11}, \ldots, y_{22}$ of two battery banks during peak hours. Indices 11 to 22 indicate peak hours, from 10:00 AM to 9:59 PM.

DCS Problem (cont'd)

Maximize: The daily energy cost saving:

New base hour cost

New peak hour cost

$$DCS = \sum_{i=1}^{24} r_i P_i^{load} - \sum_{i \in BS} r_i \left(P_i^{load} + \frac{x_c + y_c}{\eta} \cdot V_{bat}\right) - \sum_{i \in PK} r_i \left(P_i^{load} - \eta(x_i + y_i) V_{bat}\right) \quad (2)$$

Original cost

$$= \sum_{i \in PK} r_i \eta \cdot (x_i + y_i) V_{bat} - \sum_{i \in BS} r_i \frac{x_c + y_c}{\eta} V_{bat}$$

where $x_c = \frac{1}{12} \sum_{i \in PK} (\frac{20 x_i}{Q_x})^{k_x} \frac{Q_x}{20}$, $y_c = \frac{1}{12} \sum_{i \in PK} (\frac{20 y_i}{Q_y})^{k_y} \frac{Q_y}{20}$.

Subject to:

1) Battery capacity constraint:

$$\sum_{i \in PK} (\frac{20 x_i}{Q_x})^{k_x} \frac{Q_x}{20} \leq Q_x, \sum_{i \in PK} (\frac{20 y_i}{Q_y})^{k_y} \frac{Q_y}{20} \leq Q_y \quad (3)$$

where $\frac{Q_x}{20}$ and $\frac{Q_y}{20}$ are the reference discharge current.

2) Load power constraint:

$$\eta(x_i + y_i) \cdot V_{bat} \leq P_i^{load}, i = 11 \sim 22 \quad (4)$$

DCS Problem (Simulation Results)

- DCS problem is a convex optimization problem
  - It has convex objective function and convex inequality constraints
  - Solved optimally in polynomial time using standard optimization tools
- $f_i(Q_x,Q_y)$: max saving of the i^{th} day
- Simulation Results
  - Maximum annual cost saving $F(Q_x,Q_y)$ by summing up the daily optimization results $f_i(Q_x,Q_y)$.
  - Stored in a look-up table (LUT)

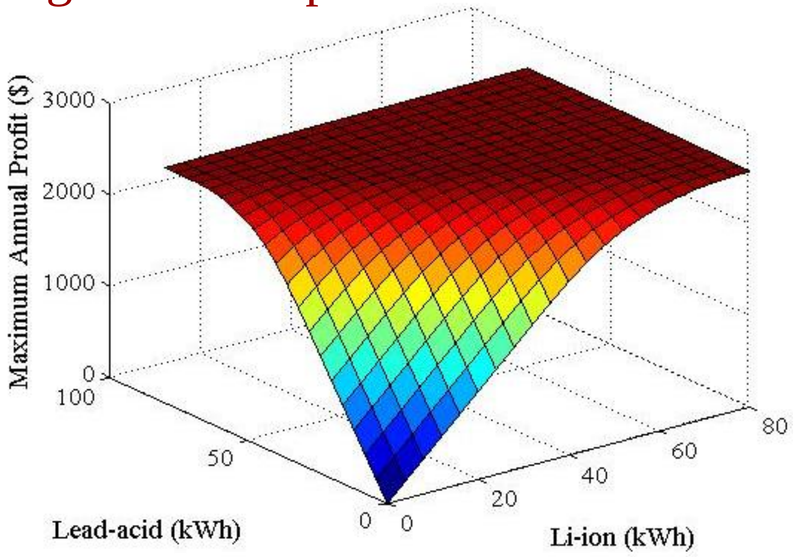
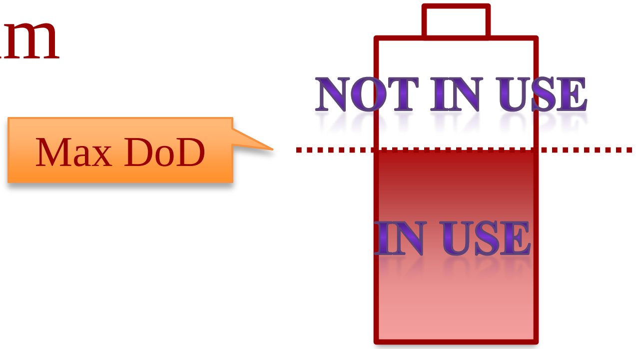


Figure 5. Maximum Annual Energy Cost Saving.

DoD-Aware DCS Problem

- Capacity degradation
  - Fully charging and discharging of batteries result in fast capacity degradation
  - Use only parts of the overall capacities extends service time superlinearly
  - Therefore, we add a maximum DoD limit



DoD-Aware DCS Problem (cont'd)

- Solution: Find the equivalent original DCS problem $f_i(Q_x, Q_y)$
  - $f_i(Q_x, Q_y, d_x, d_y)$: the maximum daily energy cost saving of the i^{th} day
  - Proof: it is an underestimation to use the original DCS problem to approximate the DoD-aware result:

$$\hat{f}_i(Q_x, Q_y, d_x, d_y) \geq f_i({d_x}^{\frac{1}{k_x}} Q_x, {d_y}^{\frac{1}{k_y}} Q_y) \quad (5)$$

- Estimation error

Table 1. Estimation error percentage of different days.

Day	Q_x	Q_y	d_x	d_y	f_i	$\hat{f}_i$	(%)
1	20	20	0.6	0.6	2.185	2.210	1.14
100	5	20	0.6	0.6	1.361	1.382	1.45
200	10	10	0.8	0.8	4.191	4.199	0.171
300	20	5	0.6	0.9	1.469	1.478	0.563

- Annual cost saving:

$$\hat{F}(Q_x, Q_y, d_x, d_y) \geq F({d_x}^{\frac{1}{k_x}} Q_x, {d_y}^{\frac{1}{k_y}} Q_y) \quad (6)$$

Amortized Annual Profit Maximization

- Equivalent to the annual ROI
  - With given monetary budget and system volume limit.
- Profit = saving – cost
- Taking practical factors into consideration
  - Cycle life
  - Energy density
  - Maintenance cost
  - Discount factor

Amortized Annual Profit Maximization – Cycle Life & Energy Density

- Battery's lifetime: 80% capacity
- Lifetime superlinearly extended with smaller DoDs.
  - 75% DoD – 4605 cycles
  - 100% DoD – 1560 cycles
- Overall volume limits for residential usage.
- Unit volume: volume divided by max stored energy.
  - Lead-acid – 12.5L/kWh
  - Li-ion – 2L/kWh

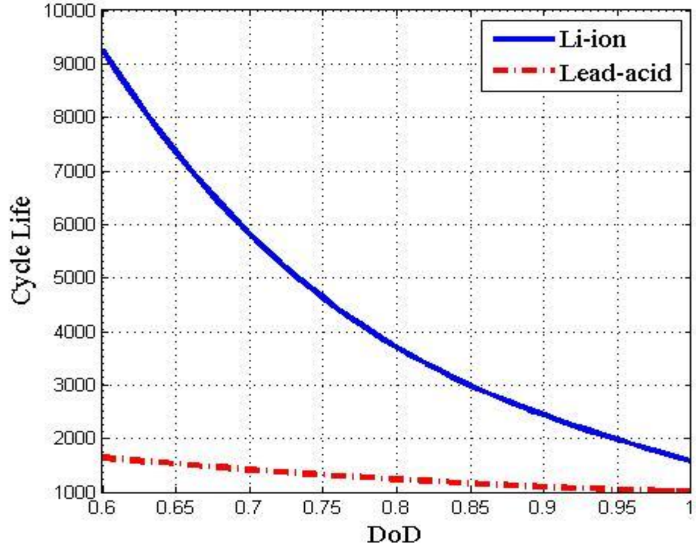


Figure 6. Cycle life vs. DoD of Li-ion and Lead-acid batteries.

Amortized Annual Profit Maximization – Maintenance Cost & Discount Factor

- Replacing the aged battery bank with a new one: lower extra cost.
  - Different types of EES elements do not break down together
- *M:* one-time maintenance fee of installation or replacement

- Time value of money
  - The HEES system has a lifetime of 10 years or more
- We must consider the discount factor when amortizing maintenance cost.
  - In terms of 5-year CD annual percentage yield of 2%

$$\gamma = 1/(1 + 2\%) = 0.9804$$

Amortized Annual Profit Maximization – Cost Calculation

- Profit = saving – cost
- Cost calculation: purchase cost + maintenance fee
  - Different types of EES elements do not break down together
- Calculating the amortized annual cost:

Amortized annual cost

Bank lifetime

Cost of installing a new bank

$$a_x + a_x \cdot \gamma^{-1} + a_x \cdot \gamma^{-2} + \cdots + a_x \cdot \gamma^{-L(d_x)+1} = Q_x p_x + M \quad (7)$$

$$a_x = (Q_x p_x + M) \times \frac{1 - \gamma^{-1}}{1 - \gamma^{-L(d_x)}} \quad (8)$$

Amortized Annual Profit Maximization – Problem Formulation

Given:

1) LUT of high season energy cost saving and low season saving: HT, LT;
2) Unit price of Li-ion and lead-acid batteries: p_x, p_y;
3) Unit volume of Li-ion and lead-acid batteries: v_x, v_y;
4) One-time maintenance fee: M;
5) Discount factor γ;
6) Budget B for initial investment and total volume limit V.

Find: Li-ion capacity and maximum DoD Q_x, d_x; lead-acid capacity and maximum DoD Q_y, d_y.

Maximize: amortized annual profit:

Annual Profit = Annual Saving − Annual Cost

$$= \hat{F}(Q_x, Q_y, d_x, d_y) - (Q_x p_x + M) \cdot \frac{1-\gamma^{-1}}{1-\gamma^{-L(d_x)}} - (Q_y p_y + M) \cdot \frac{1-\gamma^{-1}}{1-\gamma^{-L(d_y)}} \qquad (9)$$

From LUT

Amortized annual cost

Subject to:

1) Budget constraint: $Q_x p_x + Q_y p_y + M \le B$;
2) System volume constraint: $Q_x v_x + Q_y v_y \le V$.

Simulation Results

- System setup: Lead acid and Li-ion battery banks
- Different budget and volume
  - Compare the ROI of the HEES system with the average of these two EES systems
  - This improvement reaches 60%

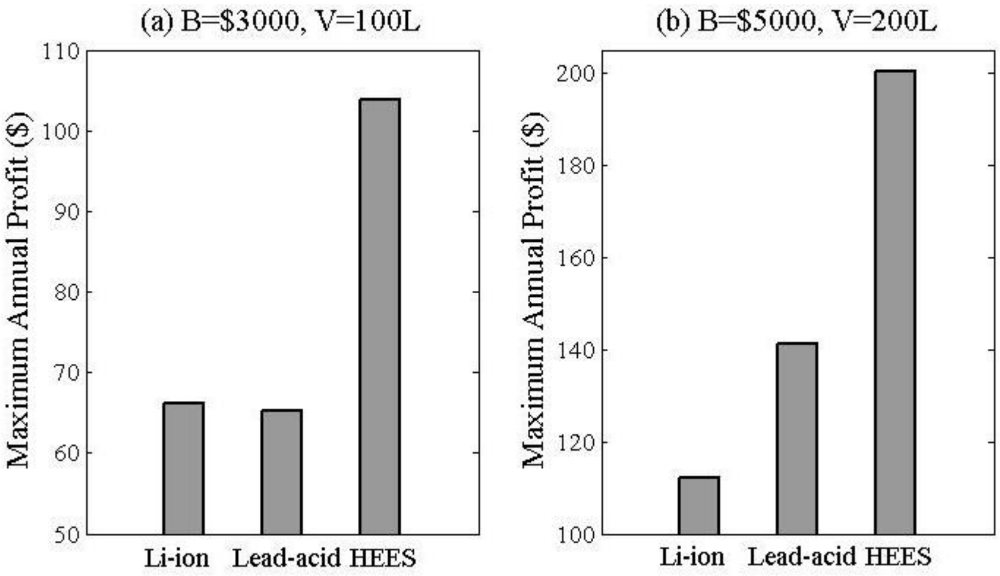


Figure 7. Maximum Annual Profit with Different Constraints.

Simulation Results (Cont'd)

- More simulation results with different (B,V) pairs
  - Diminishing marginal efficacy gain
  - Tight budget: lead-acid; small space: Li-ion

Table 2. Annual Profit Results with Current Battery Prices.

Budget ($)	Volume (L)	Lead-acid (kWh)	Li-ion (kWh)	Annual Profit ($)	Annual ROI
1000	50	3.86	0.81	34.88	3.49%
3000	50	3.23	4.53	76.65	2.55%
3000	100	7.38	3.58	103.87	3.46%
3000	200	15.67	1.69	158.30	5.28%
5000	30	0	8.84	112.12	2.24%
5000	50	2.68	8.22	118.95	2.38%
5000	100	6.84	7.25	145.93	2.92%
5000	200	15.08	5.39	200.36	4.01%

Simulation Results (Cont'd)

- Changing constraints
  - Prediction of decreasing Li-ion battery price
  - $0.3/Wh in 2015
- Annual profit prediction

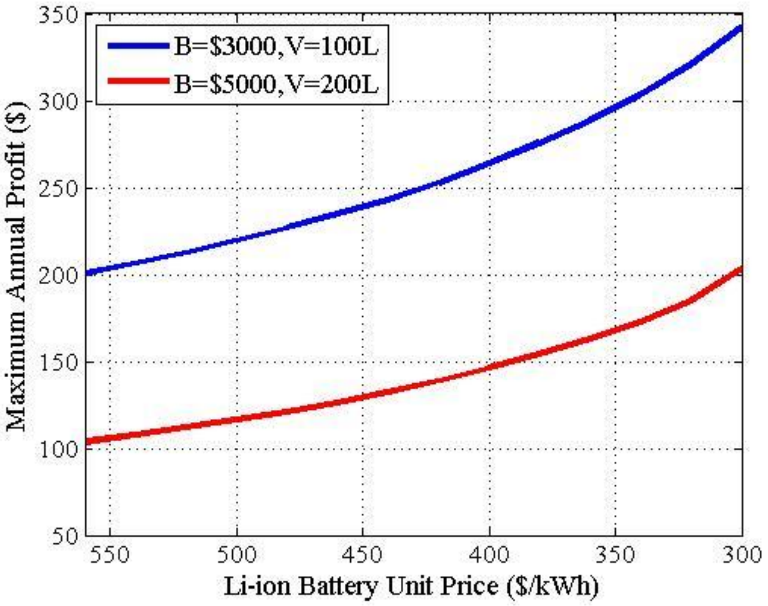


Figure 8. Maximum Annual Profit with Decreasing Li-ion Cost.

Summary

- This paper targets at providing a practical analysis of the profitability of a HEES system and a optimal design and management methodology to maximize the return of investment
- Problem: maximizing return on investment (ROI) of residential HEES systems
- Proposed two-step solution of HEES system design and management:
  - Daily cost saving maximization
  - Further taking lifetime into consideration by limiting maximum DoDs
  - Amortized annual saving maximization
- Improvements:
  - An annual ROI of over 5%
  - 60% higher than the average ROI of lead-acid battery-only system and Li-ion battery-only system

Thank you!