



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

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Outline

- Background
- 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

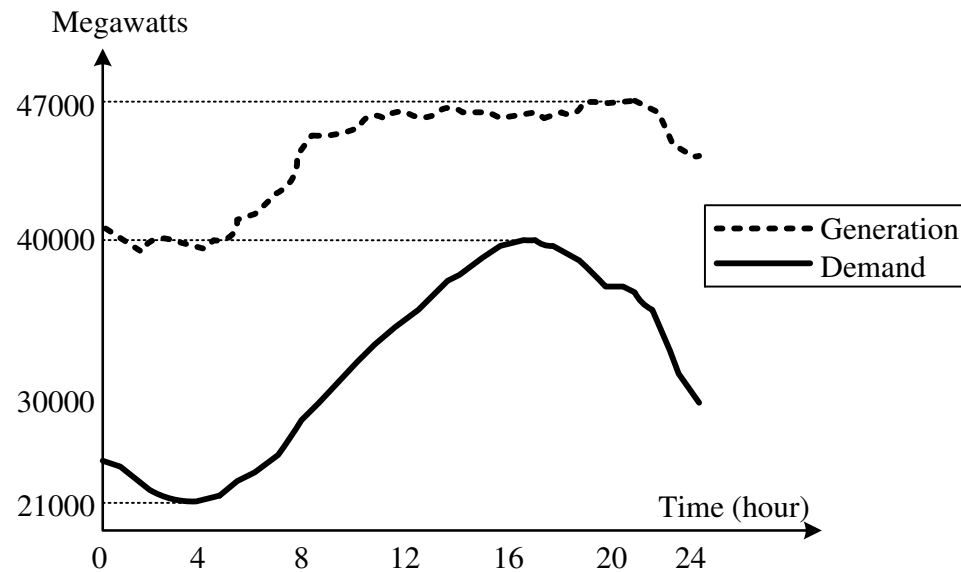


Figure 1. Electrical Energy Generation vs. Demand.

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

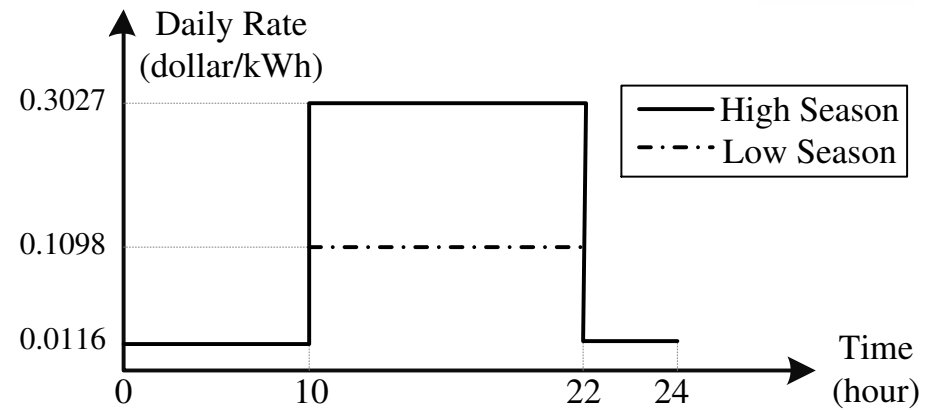


Figure 2. Daily Time-of-Day Energy Pricing.

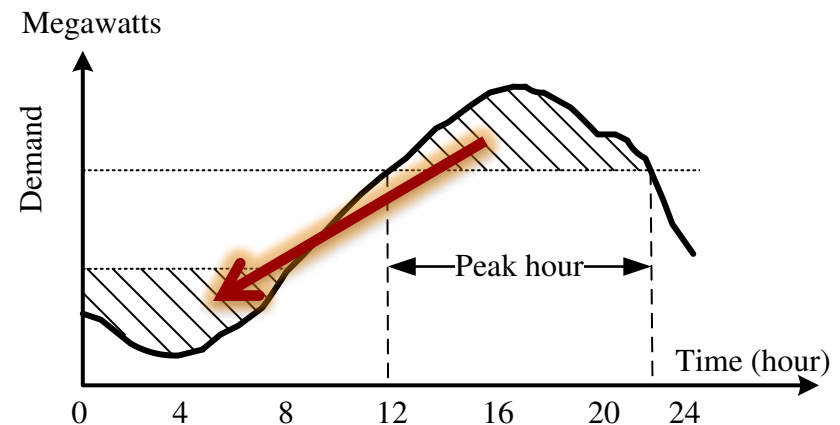


Figure 3. Demand Side Management.

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:

$$I_{eq} = \left(\frac{I_{disc h}}{I_{ref}}\right)^k I_{ref} \quad I_{ref} = Q/20 \quad (1)$$

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



- Unit cost of EES elements

- Supercapacitor: \$20-50/Wh; lead-acid: \$0.1-0.2/Wh

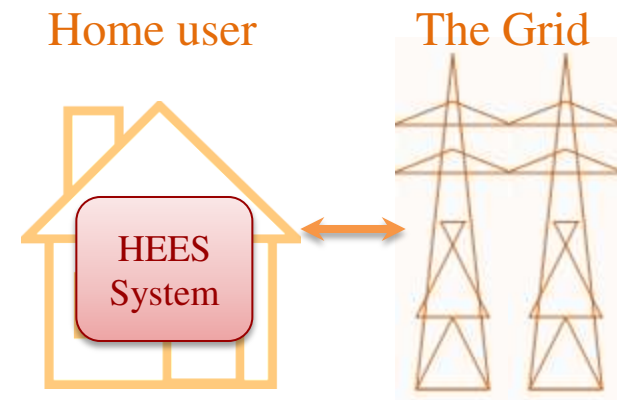
- Power losses due to power conversion circuits

- 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

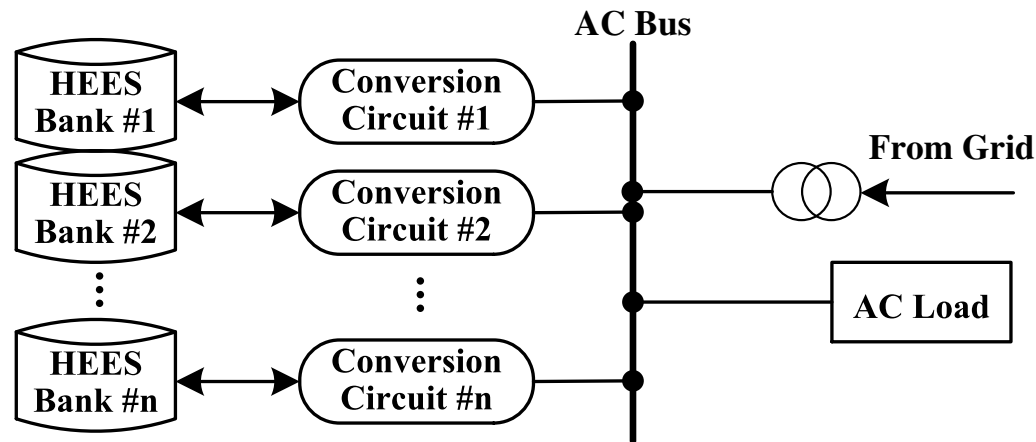


Figure 4. HEES System Structure.



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: $r_i, i = 1, \dots, 24$. (We define the peak hours index set as $PK = \{11, 12, \dots, 22\}$, and base hours index set as $BS = \{1, 2, \dots, 10, 23, 24\}$);
- 4) Residential load power profile $P_i^{load}, i = 1, \dots, 24$;
- 5) Batteries' rate capacity effect coefficients k_x, k_y ;
- 6) DC-AC converters' power conversion efficiency: η .

Find: Discharge current $x_{11}, \dots, x_{22}, y_{11}, \dots, y_{22}$ 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

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

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

Original cost

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

Subject to:

1) Battery capacity constraint:

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

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)

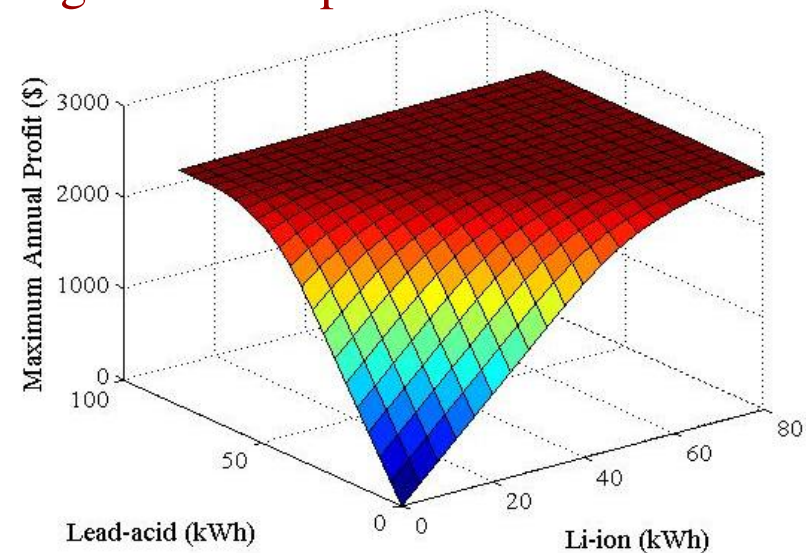
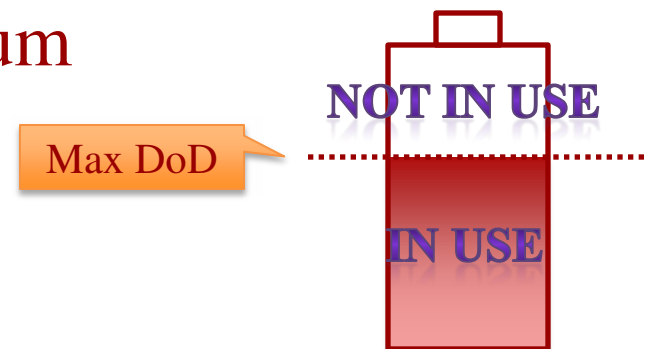


Figure 5. Maximum Annual Energy Cost Saving.



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

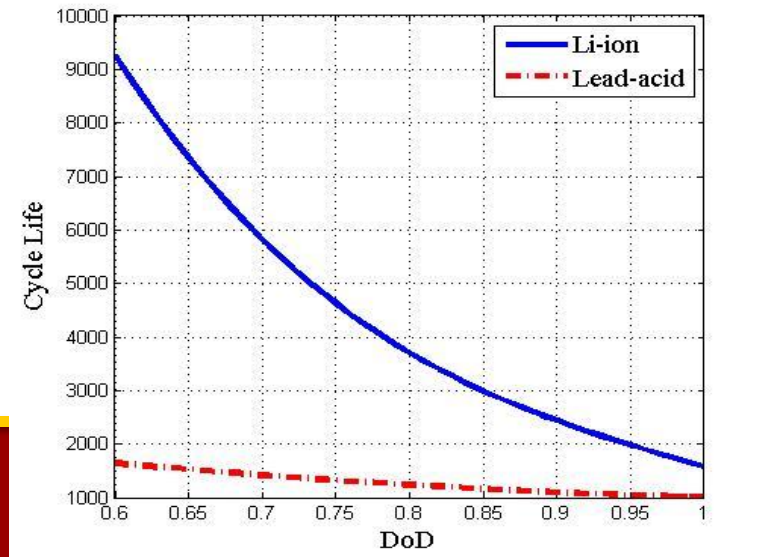


Figure 6. Cycle life vs. DoD of Li-ion and Lead-acid batteries.

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

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

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

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

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

Subject to:

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

Amortized
annual cost

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%

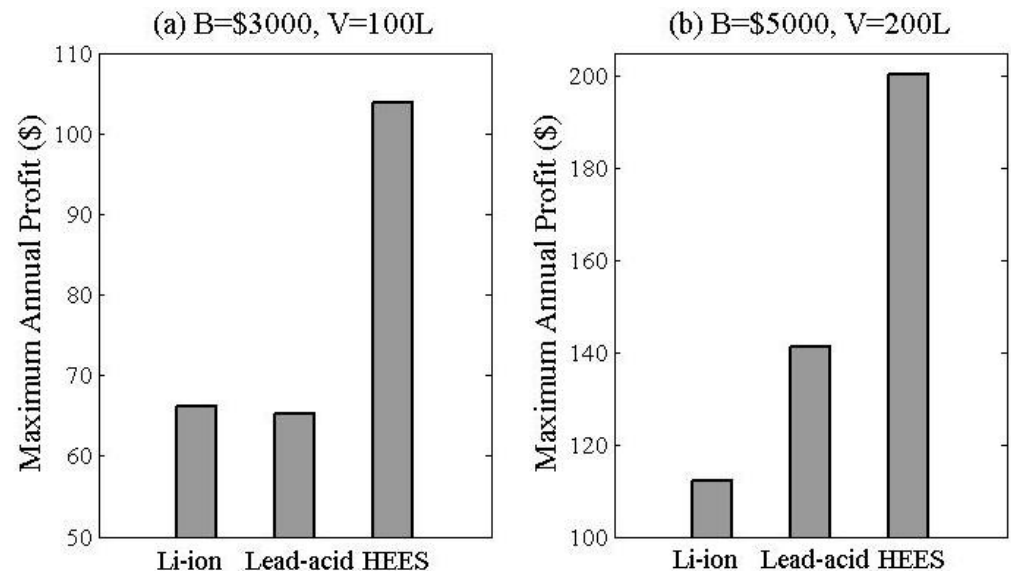


Figure 7. Maximum Annual Profit with Different Constraints.

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

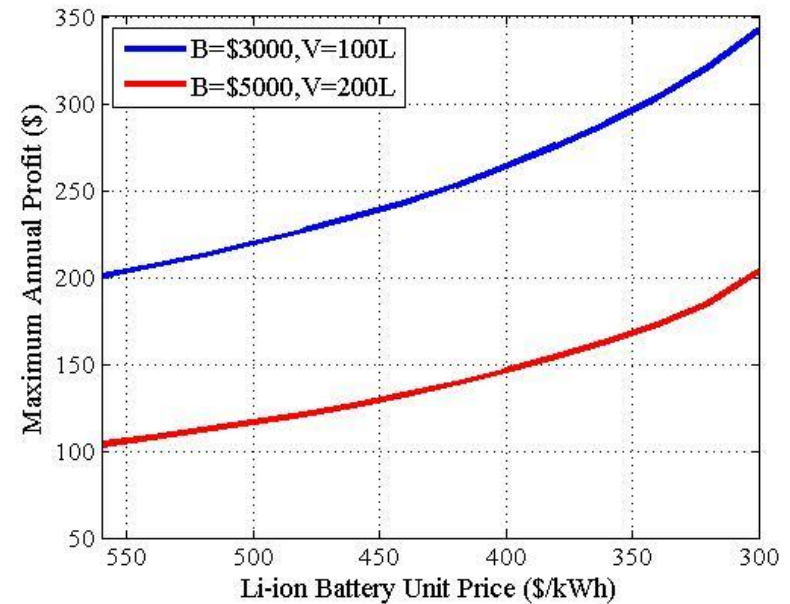


Figure 8. Maximum Annual Profit with Decreasing Li-ion Cost.



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!