Profitability of Merchant Investments in Battery Energy Storage Systems: Methods and Case Studies

Yury Dvorkin[1,2] Ricardo Fernandez-Blanco[2] Daniel Kirschen[2]
Hrvoje Pandzic[3] Jean-Paul Watson[4] Cesar Silva-Monroy[4]

[1]New York University [2]University of Washington

[3]University of Zagreb [4]Sandia National Laboratories

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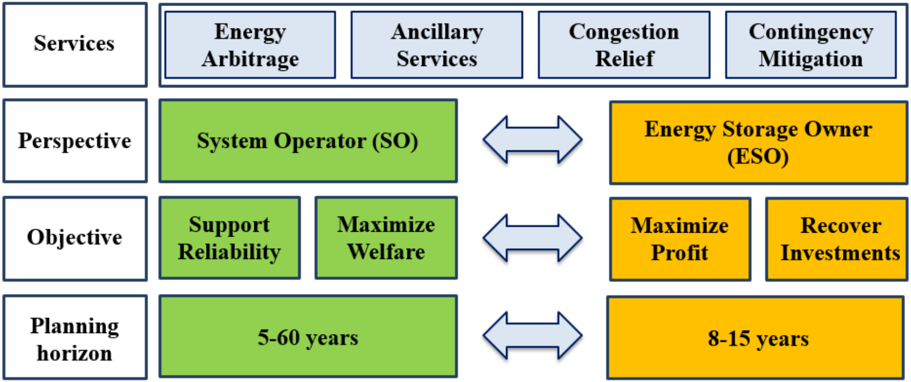
Two Perspectives on Storage Investments



Two Perspectives on Storage Investments

Services	**Energy Arbitrage**	**Ancillary Services**	**Congestion Relief**	**Contingency Mitigation**

		⇔	
Perspective	**System Operator (SO)**	⇔	**Energy Storage Owner (ESO)**
Objective	**Support Reliability**; **Maximize Welfare**	⇔	**Maximize Profit**; **Recover Investments**
Planning horizon	**5-60 years**	⇔	**8-15 years**
Operational concerns	**Energy-limited resource**	⇔	**Lost opportunity**
Barriers	**Undefined value**	⇔	**Expansion planning** **Undefined revenue streams**

Case I: ISO Perspective

Services	**Energy Arbitrage**	**Congestion Relief**
Perspective	**System Operator (SO)**	
Objective	**Support Reliability**	**Reduce Cost**
Planning decisions	**Siting and Sizing of Storage**	
Operations	**Detailed day-to-day system-wide model**	

Objectives:

- Justify ES investments by potential savings

Advantages:

- One decision-maker has all the system information
- Modeling simplicity & computational efficiency
- Intuitive trade-off between savings and investments

Case I: Objective Function

$$\min \overbrace{\sum_{b\in B} \left(C^{\text{p}} \cdot p_b^{\max} + C^{\text{s}} \cdot s_b^{\max}\right)}^{\text{Investment Cost}}$$
$$+ \overbrace{\sum_{e\in E}\sum_{t\in T}\sum_{i\in I} \pi_e \cdot C_i^{\text{g}} \cdot g_{e,t,i}\left(p_b^{\max}, s_b^{\max}\right)}^{\mathbb{E}(\text{Variable operating cost})} \quad (1)$$
$$+ \overbrace{\sum_{e\in E}\sum_{t\in T}\sum_{i\in I} \pi_e \cdot C_i^{\text{f}} \cdot u_{i,t}\left(p_b^{\max}, s_b^{\max}\right)}^{\mathbb{E}(\text{Fixed operating cost})},$$

where:

$p_b^{\max}, s_b^{\max} \in \mathbb{R}^{0+}$	–	Power and energy ratings of ES placed at bus b
$g_{e,t,i} \in \mathbb{R}^{0+}$	–	Power output of generator i at hour t on day e
$u_{e,t,i} \in \{0,1\}$	–	On/off status of generator i at hour t on day e
π_e	–	Weight of typical day e
$C_{[\cdot]}^{[\cdot]}$	–	Cost parameters as applicable

Case I: Constraints

- Binary logic on conventional generators
- Minimum up- and down-time constraints
- Start-up and shut down trajectories
- Dispatch constraints on conventional generators
- Dispatch constraints on renewables
- Network constraints (dc power flow model)
- Dispatch constraints on ES (constrained by p_b^{max} and s_b^{max})
- Nodal power balance constraints

Case I: Pros and Cons

- Pros:
  - Solved within tens of minutes with a reasonable optimality, even for large systems
  - Can be decomposed and parallelized

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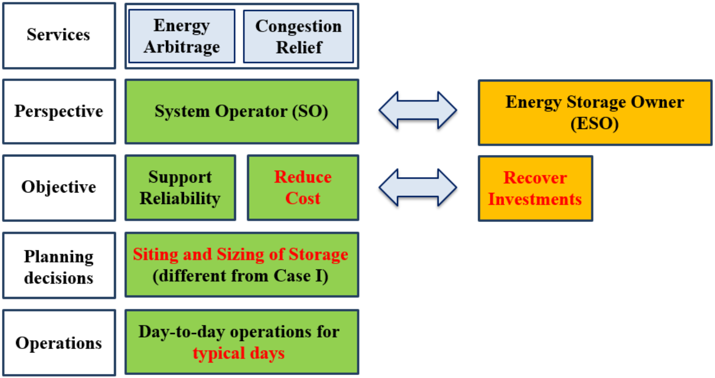
- Pros:
  - Solved within tens of minutes with a reasonable optimality, even for large systems
  - Can be decomposed and parallelized
- Cons:
  - Locational marginal prices ($\lambda_{e,t,b}$) are by-products of the optimization

$$\overbrace{\sum_{i \in I_b} g_{e,t,i}}^{\text{Injections from generators}} \overbrace{- \sum_{l|o(l)=b} f_{e,t,l} + \sum_{l|r(l)=b} f_{e,t,l}}^{\text{Injections from lines}} + \overbrace{\left(w^{\text{f}}_{e,t,b} - ws_{e,t,b}\right)}^{\text{Injections from renewables}}$$
$$\underbrace{-ch_{e,t,b}/\aleph^{\text{ch}} + dis_{e,t,b} \cdot \aleph^{\text{dis}}}_{\text{Injections from ES}} = \underbrace{d_{e,t,b}}_{Demand} : (\lambda_{e,t,b}), \forall e \in E, t \in T, b \in B.$$

  - Thus, there is no explicit way to relate the investment cost and the expected profit while optimizing investments
- To protect investment decisions ($p^{\max}_b$, $s^{\max}_b$) against insufficient profits, $\lambda_{e,t,b}$ must be factored into the optimization

Case II: ISO+ESO Perspective



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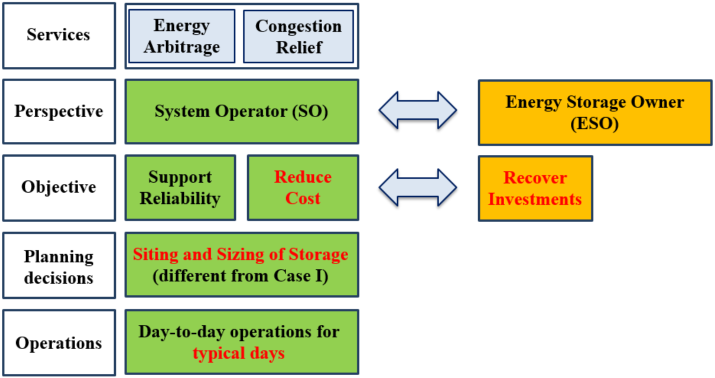


Objective:

- Protect ES investments against insufficient profits

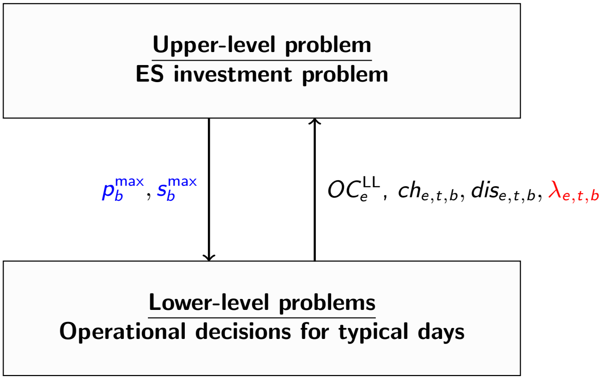
Advantages:

- Balances ISO savings & ESO profits

Disadvantages:

- More complex modeling
- Computationally demanding
- Assumes non-strategic behavior of ES

Case II: Overview



- Naturally fits the multi-level programming (Mathematical Programming with Equilibrium Constraints - MPEC) framework
- $\lambda_{e,t,b}$ are decision variables, i.e. can be used for explicitly relating the expected operating profit and investment cost.

Case II: Upper-Level Problem

$$\min \overbrace{\sum_{b \in B} \left(C^{\text{p}} \cdot p_b^{\max} + C^{\text{s}} \cdot s_b^{\max} \right)}^{\text{Investment cost } (IC)} + \overbrace{\underbrace{\sum_{e \in E} \left(\pi_e \cdot OC_e^{\text{LL}} \right)}_{\text{Optimized in the lower level (LL)}}}^{\mathbb{E}(\text{Operating Cost } (OC)\text{, as in Case I})}, \tag{2}$$

s.t.:

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s.t.:

$$\overbrace{\sum_{e\in E} \pi_e \cdot \sum_{b\in B} \sum_{t\in T} \lambda_{e,t,b} \cdot \left(dis_{e,t,b} \cdot \aleph^{\text{dis}} - ch_{e,t,b}/\aleph^{\text{ch}}\right)}^{\mathbb{E}(\text{Profit of ESO})} \geq \overbrace{\chi}^{\text{Rate-of-return}} \cdot IC, \quad (3)$$

$$IC \leq \underbrace{IC^{\text{max}}}_{\text{Investment Budget}}, \quad (4)$$

$\lambda_{e,t,b}$ – Energy prices (LMP)
χ, IC^{max} – ESO's investment parameters
$\aleph^{\text{ch}}$, $\aleph^{\text{dis}}$ – Charging/discharging efficiency

Case II: Lower-Level Problem

$$\min \overbrace{\sum_{b \in B} \left(C^{\mathrm{p}} \cdot p_b^{\max} + C^{\mathrm{s}} \cdot s_b^{\max} \right)}^{\text{Investment cost } (IC)} + \overbrace{\sum_{e \in E} \left(\pi_e \cdot OC_e^{\mathrm{LL}} \right)}^{\mathbb{E}(\text{Operating Cost } (OC), \text{ as in Case I})}, \tag{5}$$

s.t.:

$$\text{Investment constraints} \tag{6}$$

$$\text{Minimum up- and down-time constraints} \tag{7}$$

$$\text{Start-up and shut down trajectories} \tag{8}$$

$$\Big\{ \min \sum_{e \in E} (\pi_e \cdot OC_e^{\mathrm{LL}}), \tag{9}$$

$$\text{Dispatch of generators, renewables, storage + network constraints} \tag{10}$$

$$\text{Nodal power balance} : (\lambda_{e,t,b}). \Big\} \tag{11}$$

Case II: Solution Technique

- Reformulation into a single-level equivalent:
  - **Step 1**: Obtain the dual problem of the LL problems
  - **Step 2**: Invoke the strong duality theorem for the primal and dual LL problems
  - **Step 3**: Introduce the UL constraints

Case II: Solution Technique

- Reformulation into a single-level equivalent:
  - **Step 1**: Obtain the dual problem of the LL problems
  - **Step 2**: Invoke the strong duality theorem for the primal and dual LL problems
  - **Step 3**: Introduce the UL constraints
- Steps 1-3 lead to the single-level equivalent:

$$\min \overbrace{\sum_{b \in B} \left(C^{\mathrm{p}} \cdot p_b^{\max} + C^{\mathrm{s}} \cdot s_b^{\max} \right)}^{\text{Investment cost } (IC)} + \overbrace{\sum_{e \in E} \left(\pi_e \cdot OC_e^{\mathrm{LL}} \right)}^{\mathbb{E}(\text{Operating Cost } (OC)\text{, as in Case I})},$$

subject to:

- UL (investment) constraints, Eq. (6)-(8) ← nonlinear!!!
- Primal LL (operational) constraints, Eq. (10)-(11)
- Dual LL (operational) constraints
- Conditions of the strong duality theorem

Case II: Linearization of the Single-Level Equivalent

- The profit constraint is non-linear due to the product of continuous primal and dual LL variables:

$$\sum_{e \in E} \pi_e \cdot \underbrace{\sum_{b \in B} \sum_{t \in T} \lambda_{e,t,b} \cdot \left(dis_{e,t,b} \cdot \aleph^{\text{dis}} - ch_{e,t,b} / \aleph^{\text{ch}} \right)}_{P_e} \geq \chi \cdot IC. \quad (12)$$

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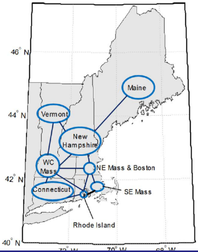
- Eq. (12) can be exactly linearized using KKT-conditions and complimentary slackness properties
- This linearization suggests the following analytic conclusions:
  - Profit (P_e) is proportional to the investment decisions ($p_b^{\max}$ and $s_b^{\max}$) and to the dual variables of ES dispatch constraints of the LL problem
  - In a perfectly competitive market, P_e is driven by the value provided by ES to the system.
  - This value can be itemized for the power and energy capacity of ES

ISO New England test system:

- Market-based view of the system
- 8 market zones, 13 transmission corridors, 76 thermal generators
- 2030 renewable portfolio & load expectations
- ARPA-e projections on ES capital costs and characteristics:
  - 0.81 – ES round-trip efficiency (rather conservative)
  - 10 years – ES lifetime (realistic)
  - 5% – Annual interest rate (rather optimistic)
  - Three capital cost scenarios: High ($75/kWh and $1300/kW), Medium ($50/kWh and $1000/kW), Low ($20/kWh and $500/kW)



Impact of the Minimum Profit Constraint

- Parameter $\chi \geq 1$ ensures the full investment recovery
  - $\chi = 0 \rightarrow$ Eq. (31) is inactive $\rightarrow$ Case I
  - $\chi = 1 \rightarrow$ Eq. (31) is active $\rightarrow$ Case II

$$\sum_{e \in E} \sum_{t \in T} \sum_{b \in B} \lambda_{e,t,b} \cdot (dis_{e,t,b} - ch_{e,t,b}) \geq \chi \cdot IC \tag{13}$$

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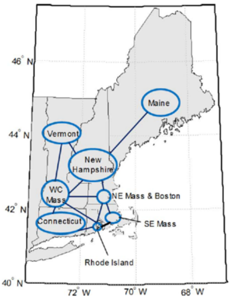

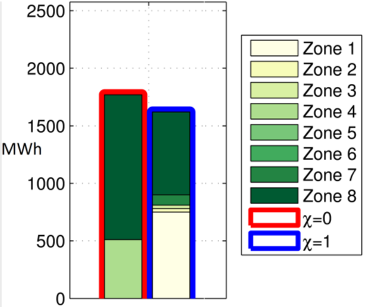

- The profit constraints drive both the siting and sizing decisions
  - Reduction in the cumulative rating
  - More diversity in locations

Impact of Capital Cost Scenarios

- Three capital costs scenarios (C^{p} and C^{s}):

$$\sum_{e \in E} \sum_{t \in T} \sum_{b \in B} \lambda_{e,t,b} \cdot (dis_{e,t,b} - ch_{e,t,b}) \geq \chi \cdot IC, \tag{14}$$

$$IC = C^{\mathrm{p}} \cdot p_b^{\max} + C^{\mathrm{s}} \cdot s_b^{\max} \tag{15}$$

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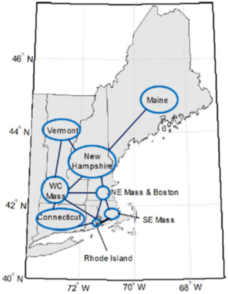

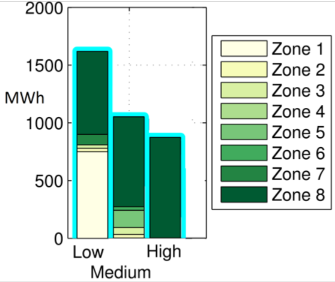

- High capital cost scenario:
  - No need for siting optimization
  - Similar decisions to the centralized planning
- Medium & Low capital cost scenarios:
  - Lower capital cost → variety in sizing and siting

Impact of the ES Market Power

- Market power mitigation by capping LMPs:

$$\sum_{e \in E} \sum_{t \in T} \sum_{b \in B} \lambda_{e,t,b} \cdot (dis_{e,t,b} - ch_{e,t,b}) \geq \chi \cdot IC, \tag{16}$$

$$(1 - \Delta\lambda) \cdot \lambda^{\text{ref}}_{e,t,b} \geq \lambda_{e,t,b} \geq (1 + \Delta\lambda) \cdot \lambda^{\text{ref}}_{e,t,b} \tag{17}$$

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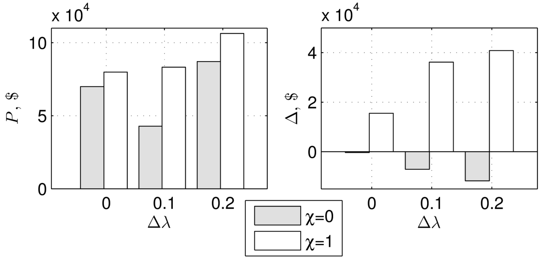

- Exercising market power increases the ESO profit (P) with the profit-constrained investment ($\chi = 1$)
- Exercising market power reduces the ESO net profit ($\Delta = P - IC$) with the profit-unconstrained investment ($\chi = 0$)
  - Primarily due to the limited look-ahead capabilities.

Impact of Coordinated Operations

- Previously, the ESO profitability was enforced in a coordinated (system-wide) fashion, i.e.:

$$\sum_{e \in E} \sum_{t \in T} \sum_{b \in B} \lambda_{e,t,b} \cdot (dis_{e,t,b} - ch_{e,t,b}) \geq \chi \cdot IC. \tag{18}$$

- However, in practice ES can be operated independently, i.e.:

$$\sum_{e \in E} \sum_{t \in T} \lambda_{e,t,b} \cdot (dis_{e,t,b} - ch_{e,t,b}) \geq \chi \cdot IC_b, \quad \forall b \in B. \tag{19}$$

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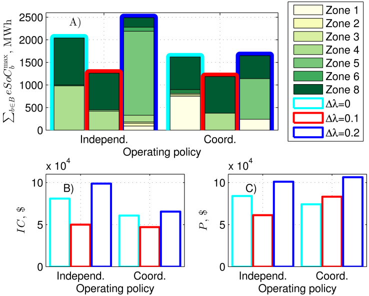
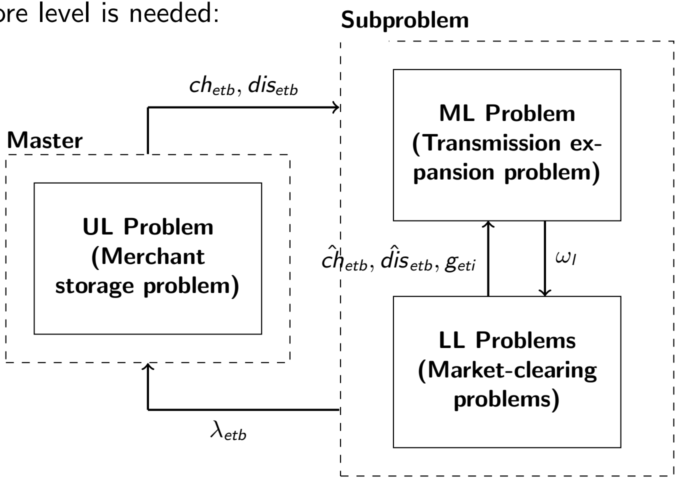


- Coordinated operations affects siting and sizing decisions
  - Reduction in the cumulative rating, but higher profits
  - Less diversity in locations

Case III: How Can Transmission Expansion Be Modeled?

- One more level is needed:



- CCG decomposition is used to solve the tri-level model
    - Surprisingly computationally tractable!

Case III: Impact of Transmission Expansion on Storage Siting and Sizing with Different Storage Capital Costs

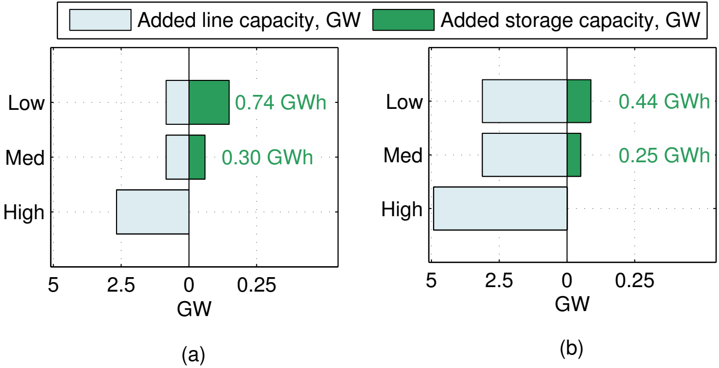
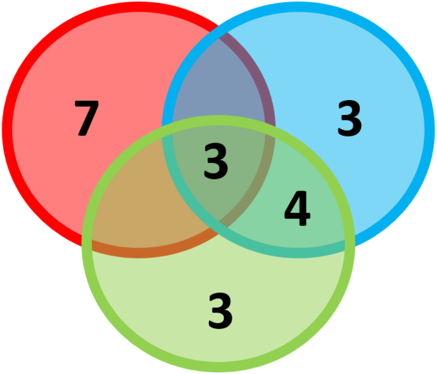


Figure: Line candidates include (a) lines directly connected to storage buses only; (b) all lines.

- The trade-off between storage and transmission decisions is sensitive to the capital cost scenario
- No feasible storage installations for the high capital cost scenario

Is There Any Value in Cases II and III?

- Siting decisions are greatly affected by the perspective considered
- Only three locations satisfy all three cases
- Cases II and III have 7 locations in common



The number of ES locations in Case I, Case II, and Case III.

(Data-Driven) Lessons Learned

- The proposed approach facilitates the integration of merchant ES into power systems
- Perspectives matter:
  - Different siting and sizing decisions
  - Different investment costs and profits
  - Different utilization
  - Annual welfare losses - 2.3% if Case I is used instead of Case II
  - Annual welfare losses - 2.5% if Case I is used instead of Case III
- Siting and sizing decisions are driven essentially by the capital cost
- Profit constraint is important for cases with:
  - Large investment budgets
  - Low investment costs
  - Ability to exercise market power
- Merchant ES can and will extract additional profits by influencing LMPs, which comes at the expense of a larger system-wide operating cost

Thank you!

References:

- Y. Dvorkin, R. Fernandez-Blanco, D. S. Kirschen, H. Pandzic, J. P. Watson, and C. A. Silva-Monroy, "Ensuring Profitability of Energy Storage," *IEEE Trans. Pwr. Syst.*, 2016. **[pdf]**
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