Optimizing Investments in Energy Storage

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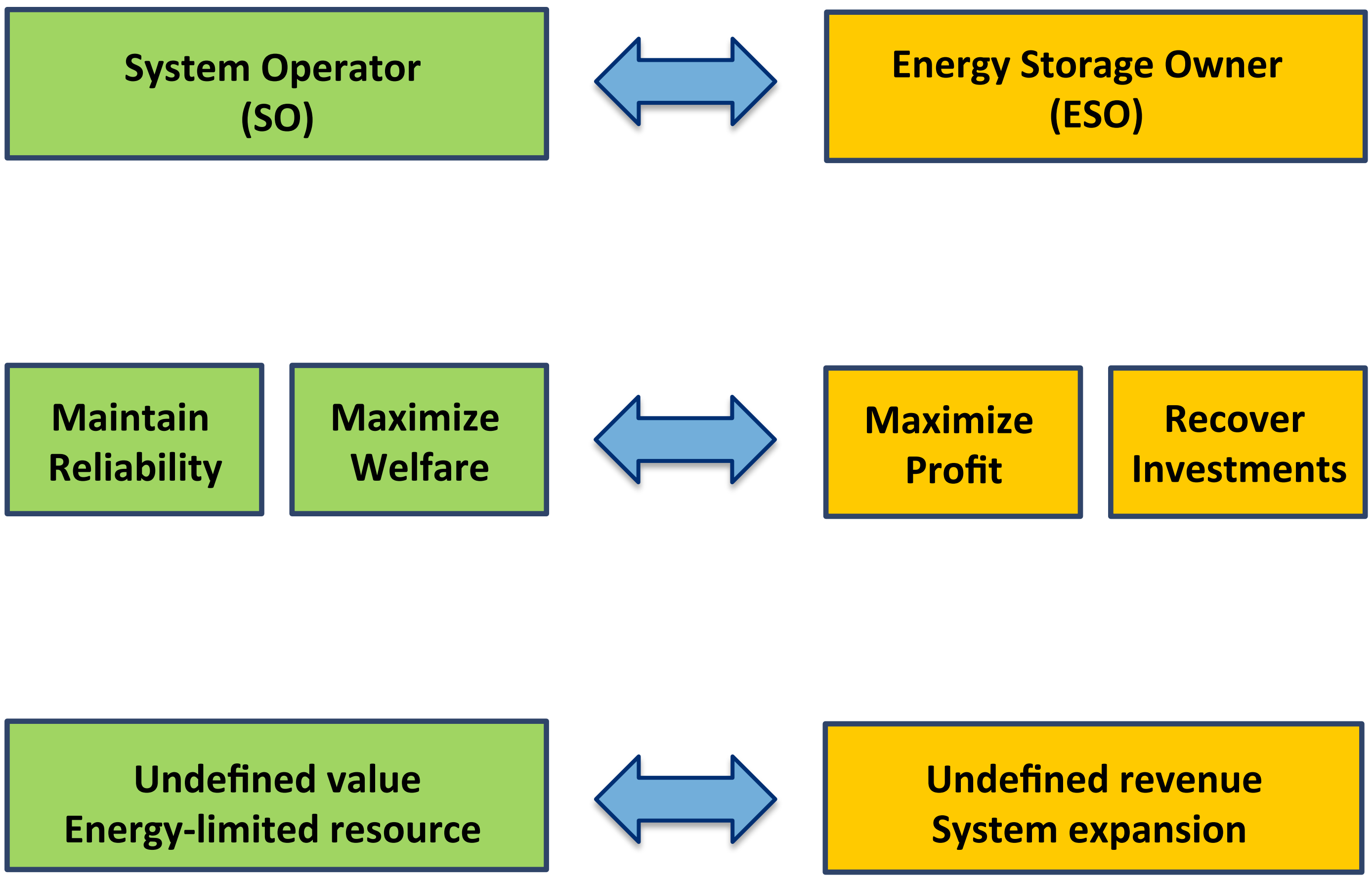
Goal

- Optimize location and size of energy storage
- Maximize benefits from spatio-temporal arbitrage

➢ Consider congestion in transmission

➢ Consider uncertainty on renewable generation

Optimal from which perspective?



Optimal from which perspective?

- Perspective leads to different problem formulations
  - Problem 1: SO perspective
  - Problem 2: Mixed SO-ESO perspective
  - Problem 3: ESO with transmission expansion

Problem I: SO Perspective

- SO invests in storage to maximize welfare
  - Benevolent monopolist
- SO's objective:

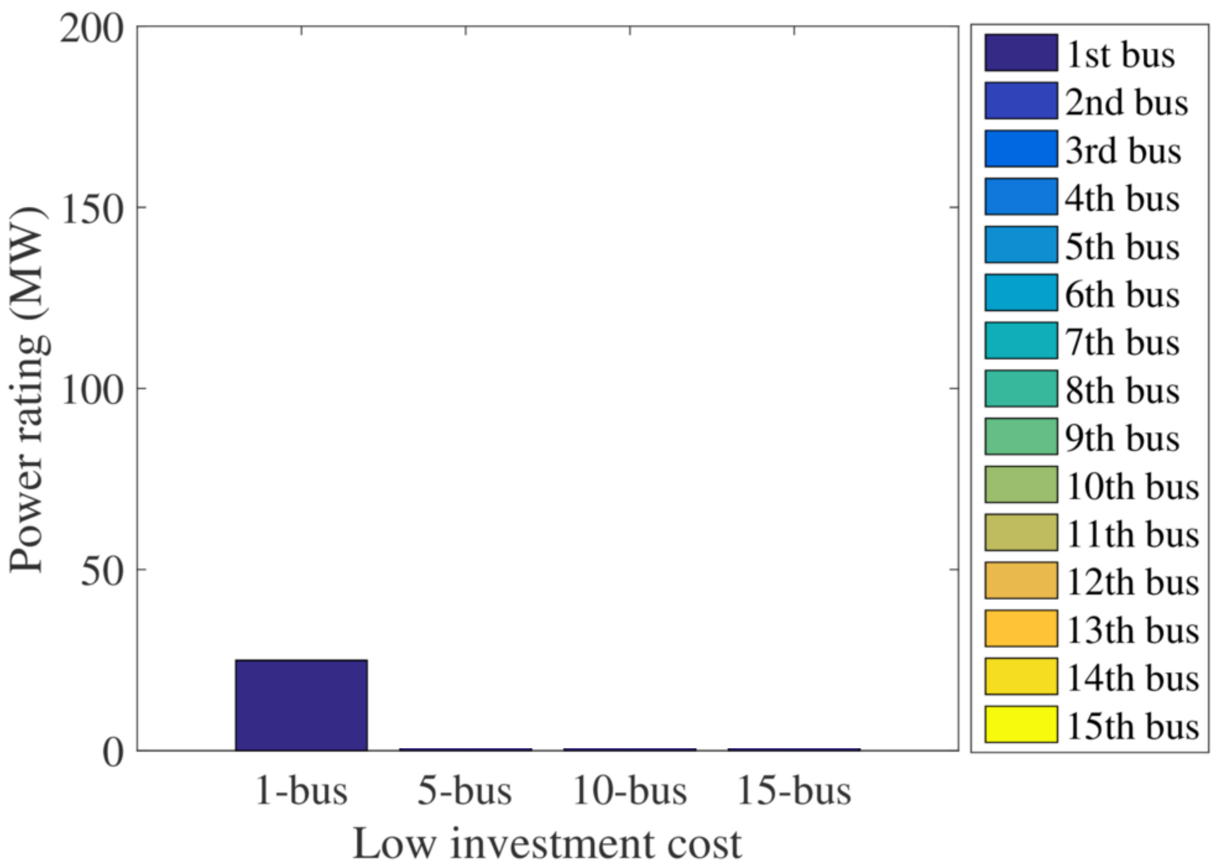
  Minimize (operating cost + investment cost in energy storage)
- Subject to constraints on:
  - Investments in energy storage
  - Operation of energy storage
  - System operation: generation and transmission limits
- Consider stochastic renewable generation
- Consider congestion in the transmission network (dc model)
- Formulation scalable to systems with 1000's of buses

Problem I: Test System and Data

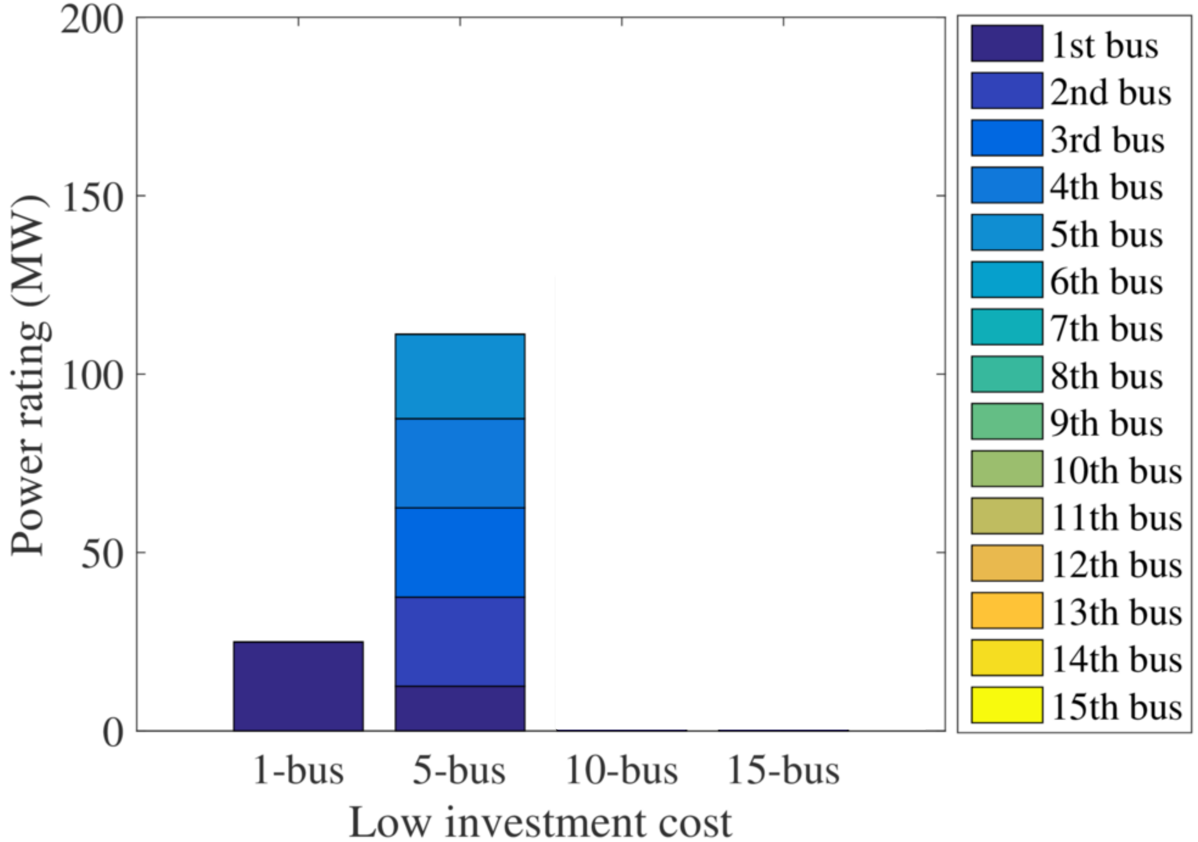
- Three storage investment cost scenarios (ARPA-E):
  - High: $75/kWh and $1300/kW
  - Medium: $50/kWh and $1000/kW
  - Low: $20/kWh and $500/kW
- Round-trip efficiency of 0.81
- 10-year lifetime
- 5% annual interest rate

- 2024 WECC system
  - 240 buses, 448 lines, 71 thermal generators
  - 32 wind power and 7 solar power plants

SO Perspective: Optimal Siting and Sizing



SO Perspective: Optimal Siting and Sizing



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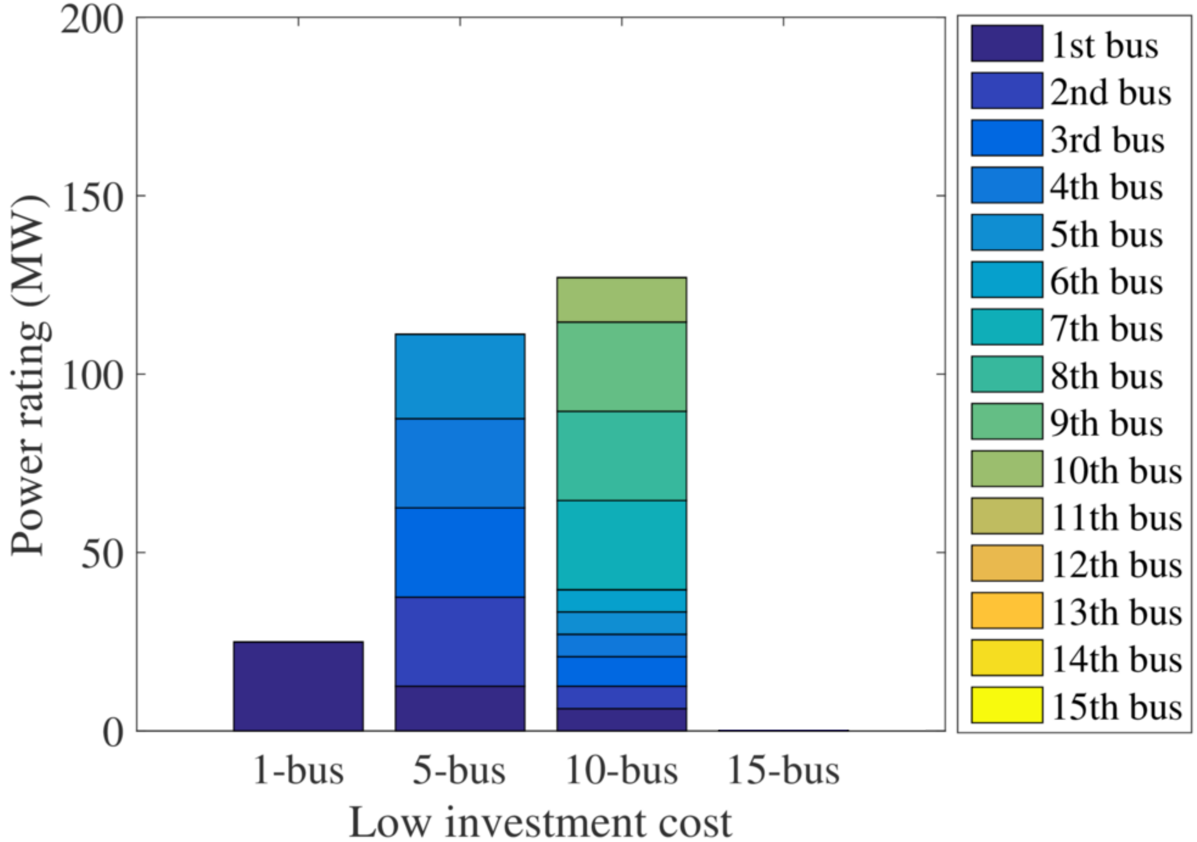
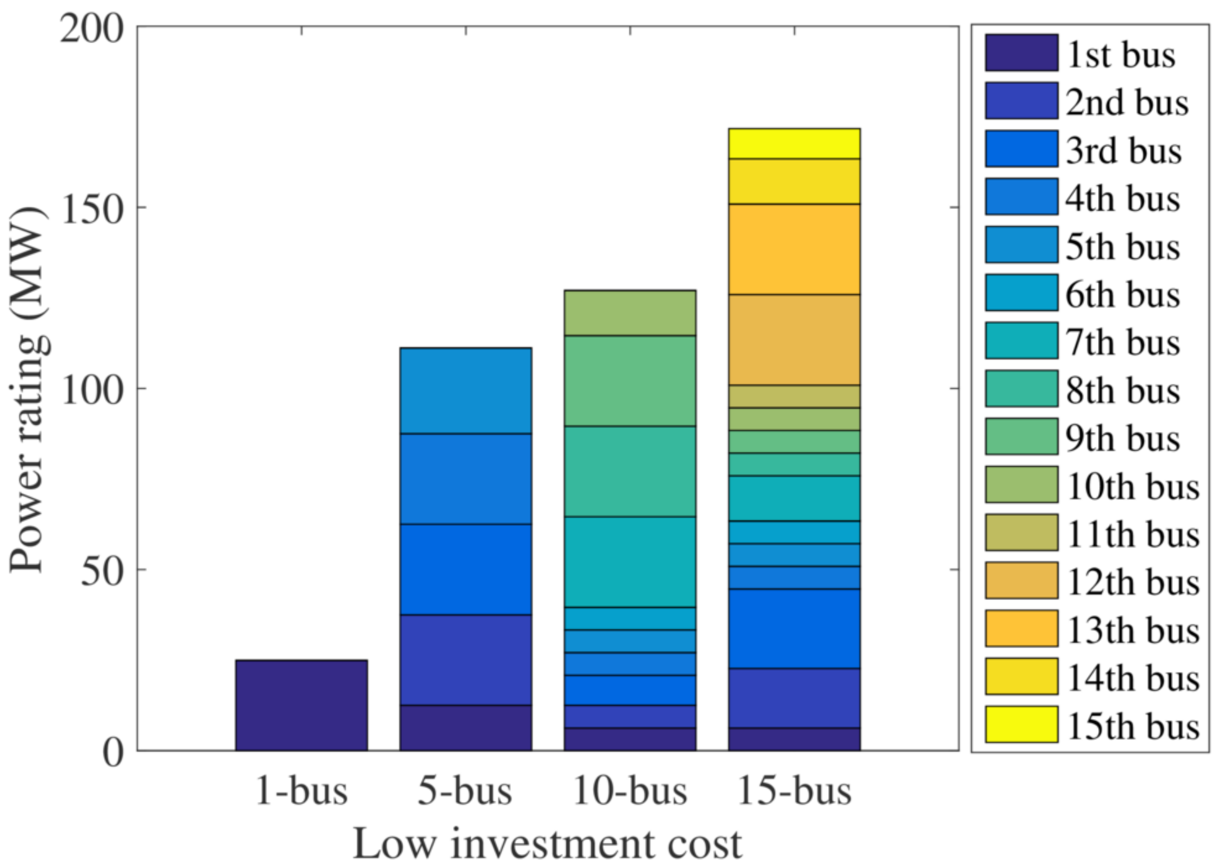
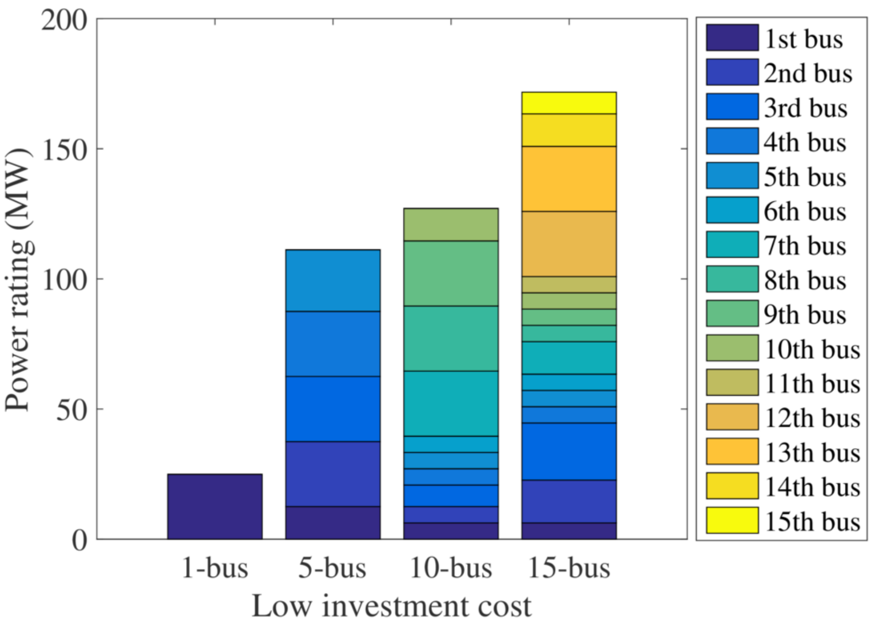
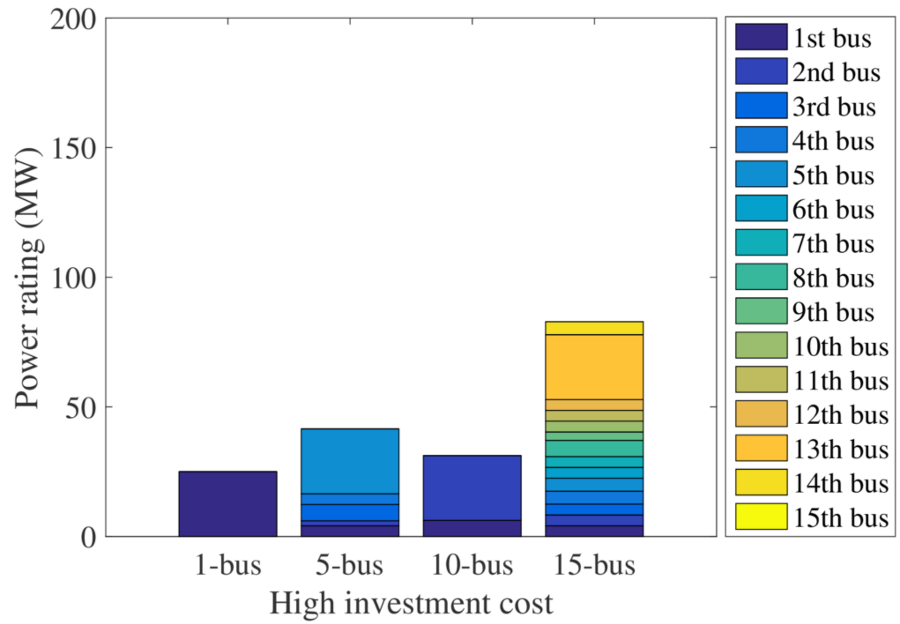


SO Perspective: Optimal Siting and Sizing



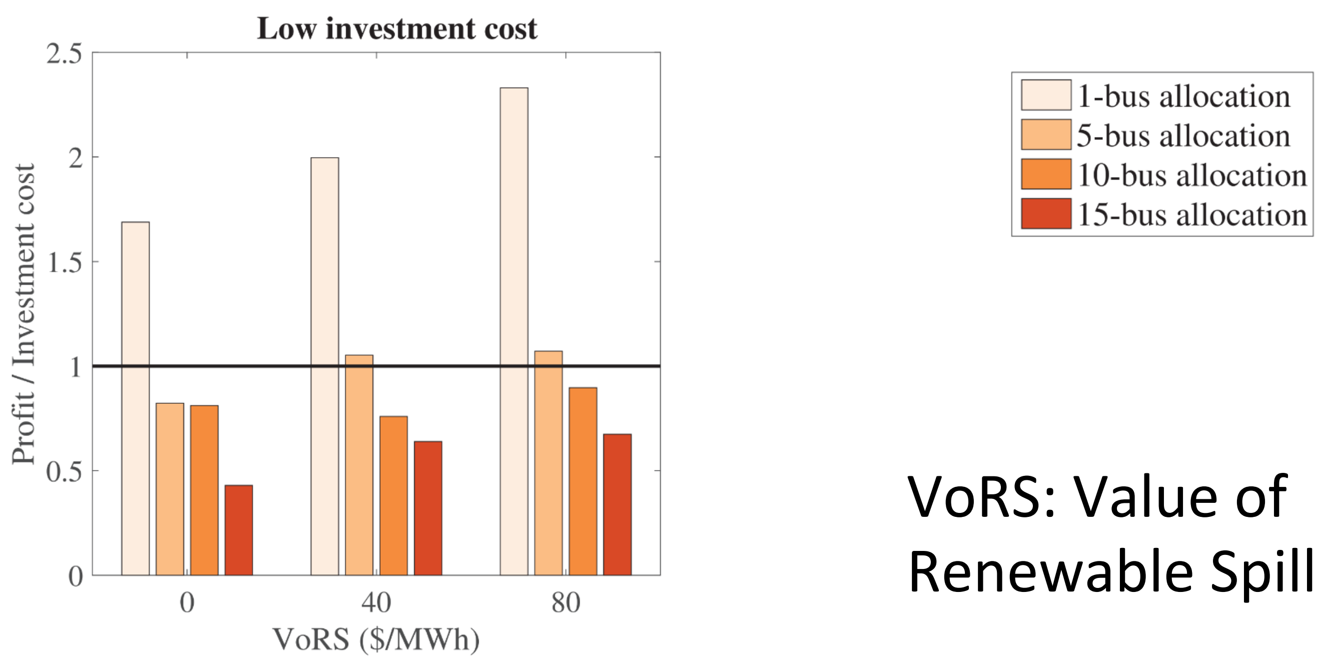
SO Perspective: Impact of the Capital Cost





- The investment cost is the primary driver of sizing decisions
  - As the capital cost increases, the installed storage capacity decreases

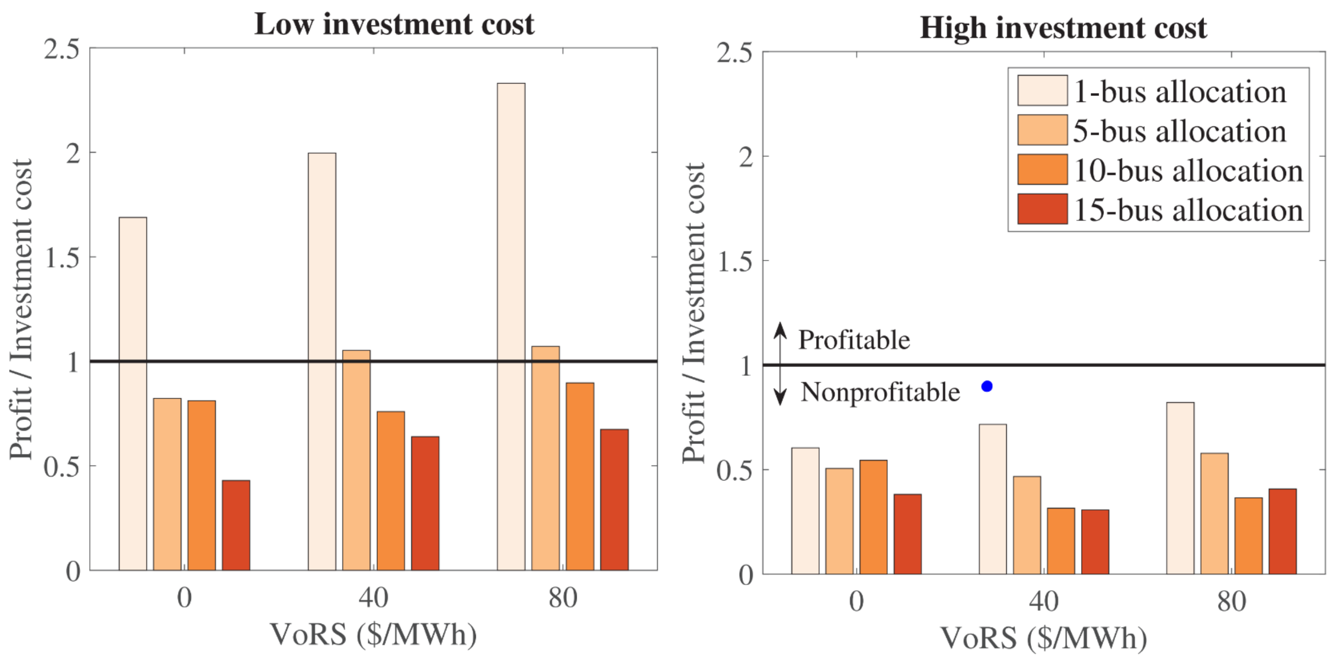
SO Perspective: Impact of Wind Spillage



VoRS: Value of Renewable Spillage

- Rate-of-return (Profit/Cost) is sensitive to value of wind spillage

SO Perspective: Impact of Wind Spillage



- Insufficient profit from spatio-temporal arbitrage under the high capital cost scenario

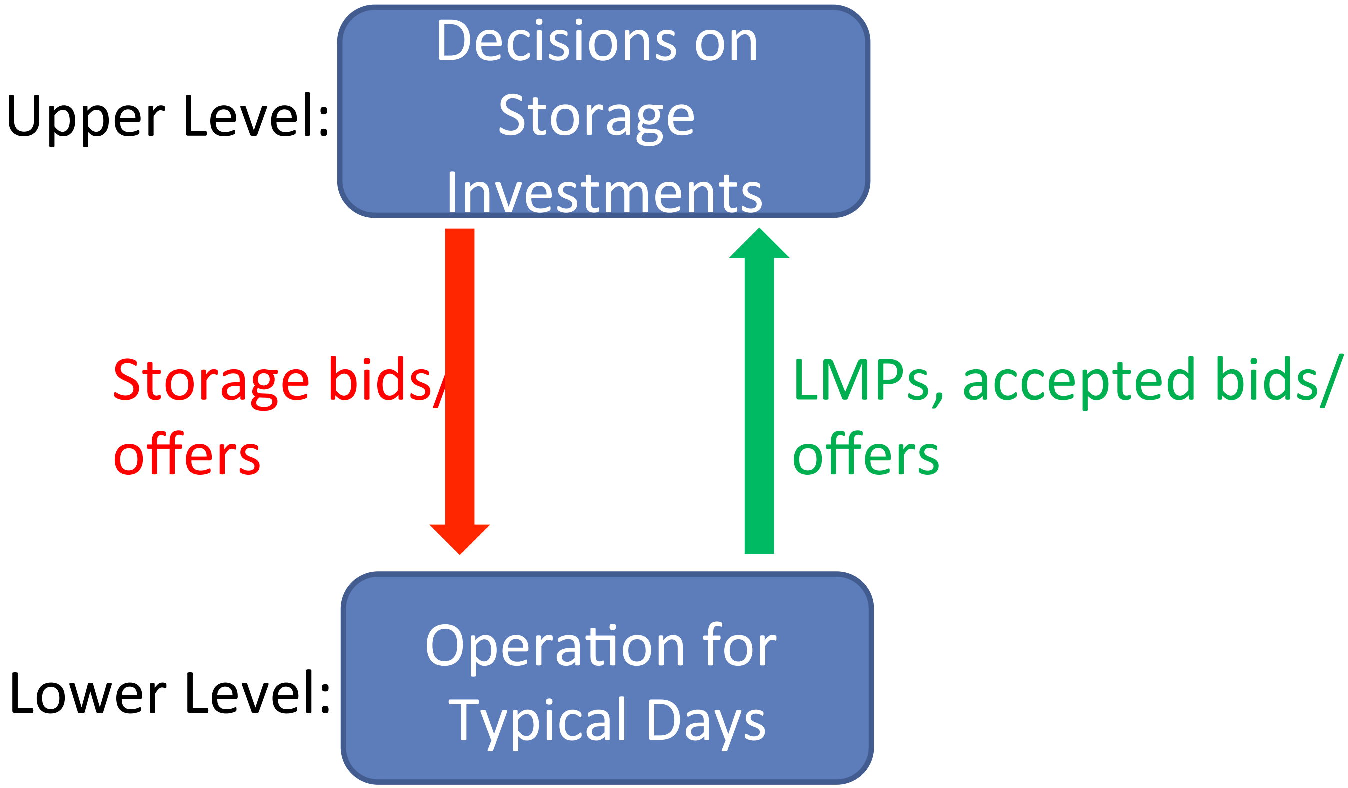
Problem II: Mixed SO+ESO Perspective

- Optimal location and size of merchant energy storage in a centrally operated system

- Modified integrated optimization
  - Minimize (operating cost + cost of investment in storage)
  - Subject to constraints on operation and investments

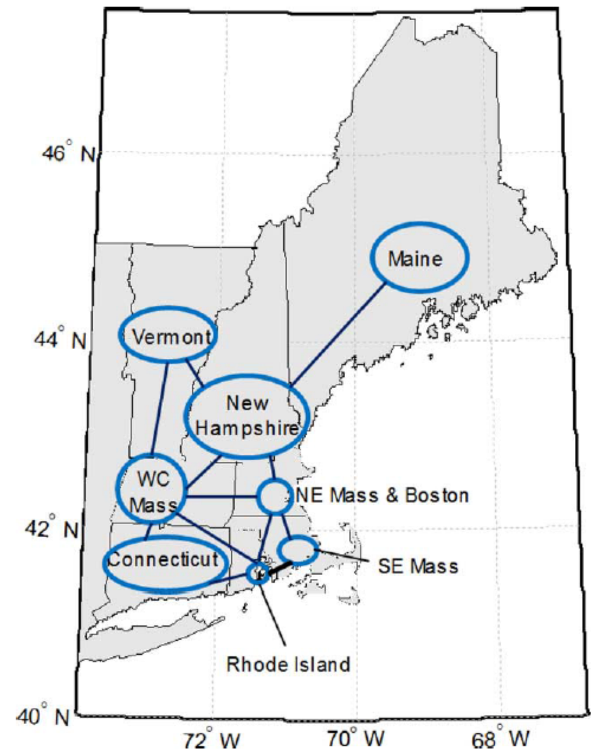
- Add a minimum profit constraint:
  - Lifetime net revenue $\geq \chi \cdot$ Investment Cost
  - χ is a given rate of return

Problem II: Bilevel Formulation



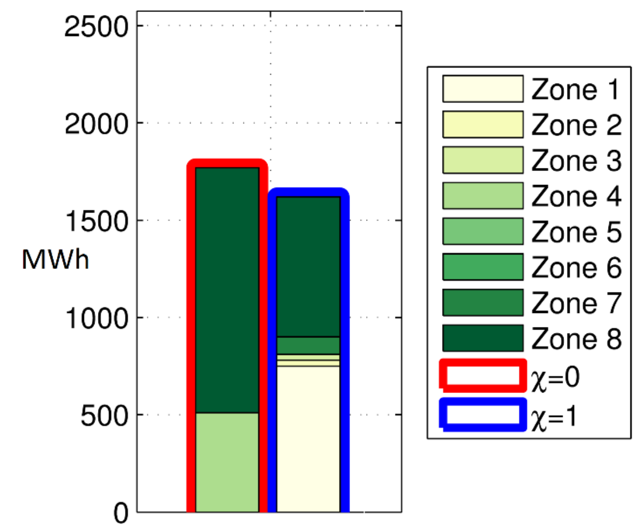
Problem II: Test System and Data

- 8-zone model of the ISO NE system
  - 8 market zones
  - 13 transmission corridors
  - 76 thermal generators
  - 2030 renewable portfolio & load expectations
- ARPA-e projections on storage cost and characteristics



Problem II: Impact of the Rate of Return

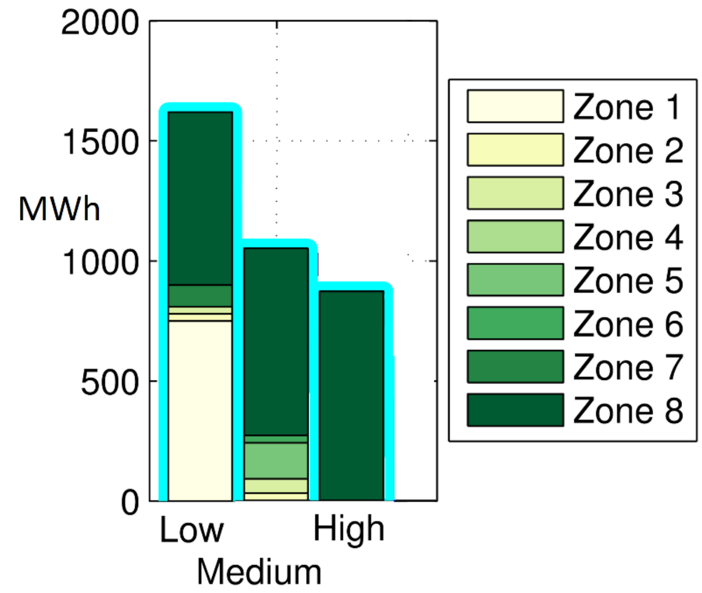
- Lifetime Profit $\geq \chi \cdot$ Investment Cost
  - If $\chi > 1 \rightarrow$ Storage investment is profitable
  - If $\chi = 0 \rightarrow$ *Same solution as problem I*



- Profit constraint affects both the siting and sizing decisions
  - Reduction in the total energy capacity installed
  - More diversity in locations

Problem II: Impact of the Capital Cost

- Results are strongly affected by the capital cost
- Total installed capacity of storage decreases when cost increases
- Under the highest capital cost scenario, storage is placed at the bus with the highest intra-day LMP variability



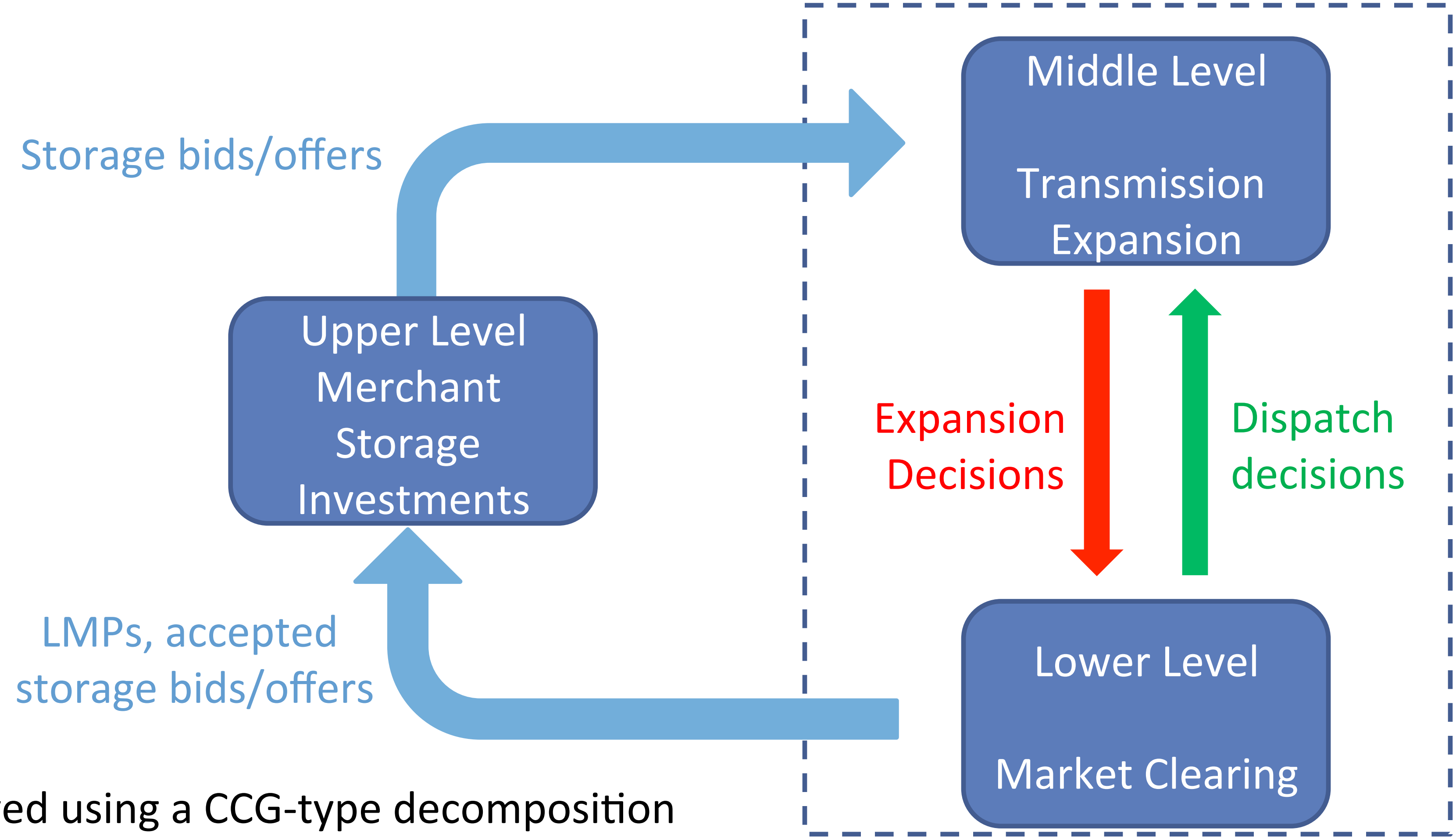
Case III: Merchant ESO Perspective

- ESO chooses the optimal locations and sizes that maximize its profits
- SO minimizes the system operating cost
- Effect of transmission expansion?

- Formulation:
  - ESO maximizes (Lifetime net revenue of ES – Cost of investment in storage)
  - SO minimizes (Operating cost + Cost of investment in transmission expansion)

- Constraints
  - System operation
  - Investments in energy storage
  - Profitability constraint: Revenue $\geq \chi \cdot$ Investment Cost

Trilevel Formulation



Solved using a CCG-type decomposition

Problem III: Test System and Data

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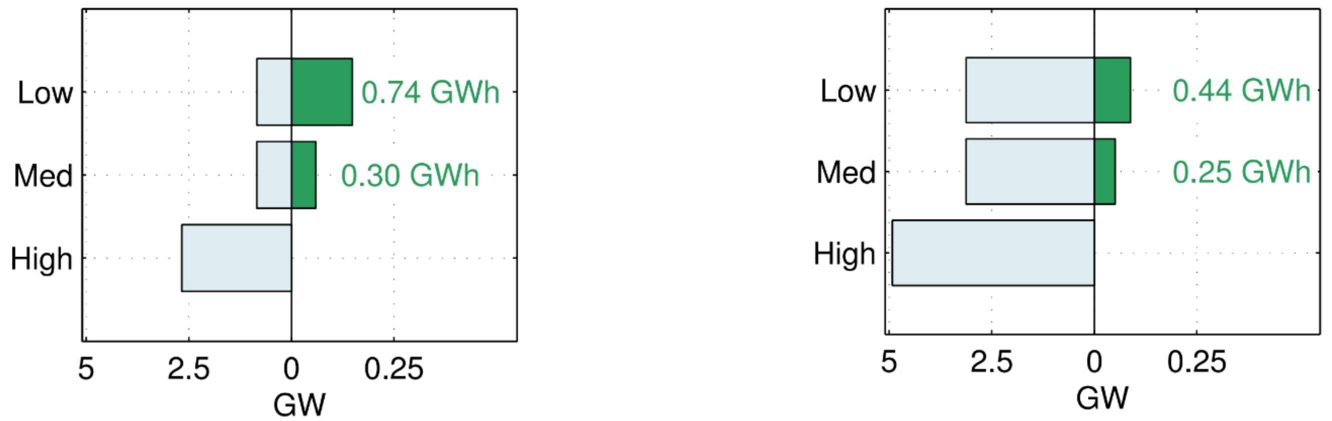
Effect of Transmission Expansion

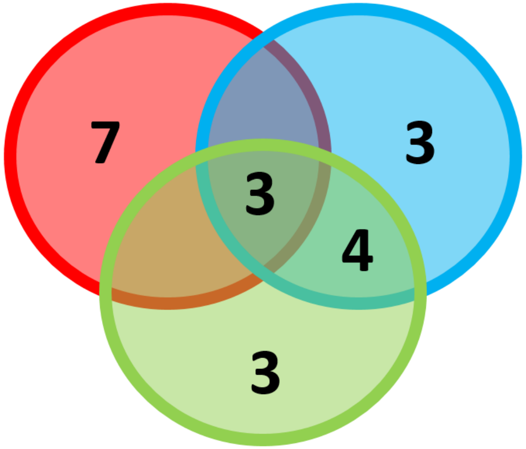


Expand lines connected to storage only

Expand all lines

Comparison

- Siting of 10 batteries for problems I, II, and III on the same WECC-240 system with the same input data:



- Only 3 locations are the same for all three problems
- Problems II and III have 7 out of 10 common locations
- Best locations from the SO's perspective are not necessarily the best locations from a merchant perspective

Summary

Problem I: SO Perspective

Problem II: Mixed SO - ESO Perspective

Problem III: ESO Perspective & Transmission Expansion

Merchant perspective

Applicability to a market environment

Modeling complexity

Open research questions:
Storage as a temporary measure

- Battery lifetime < Transmission line lifetime
- Need to optimize investments over the years

➢ Combinatorial explosion

➢ Tremendous uncertainty over system evolution

Open research questions:
Multiple uses of storage

- Not just spatio-temporal arbitrage
  - Frequency regulation
  - Reserve
  - Peak shaving
- Operational problem
  - How do we combine these applications?
  - State of charge constraints
  - Multiple beneficiaries
- Planning problem

Open research questions:
Battery degradation

- Complex phenomenon
- Depends on the chemistry of the battery:
  - Over charge
  - Over discharge
  - Cell temperature
  - Cycle average state of charge (SoC)
  - Current rate (C-rate)
  - Cycle depth
- How to incorporate degradation in optimal operation strategies?
- Impact on investment decisions?

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