Optimizing the Operation and Deployment of Battery Energy Storage

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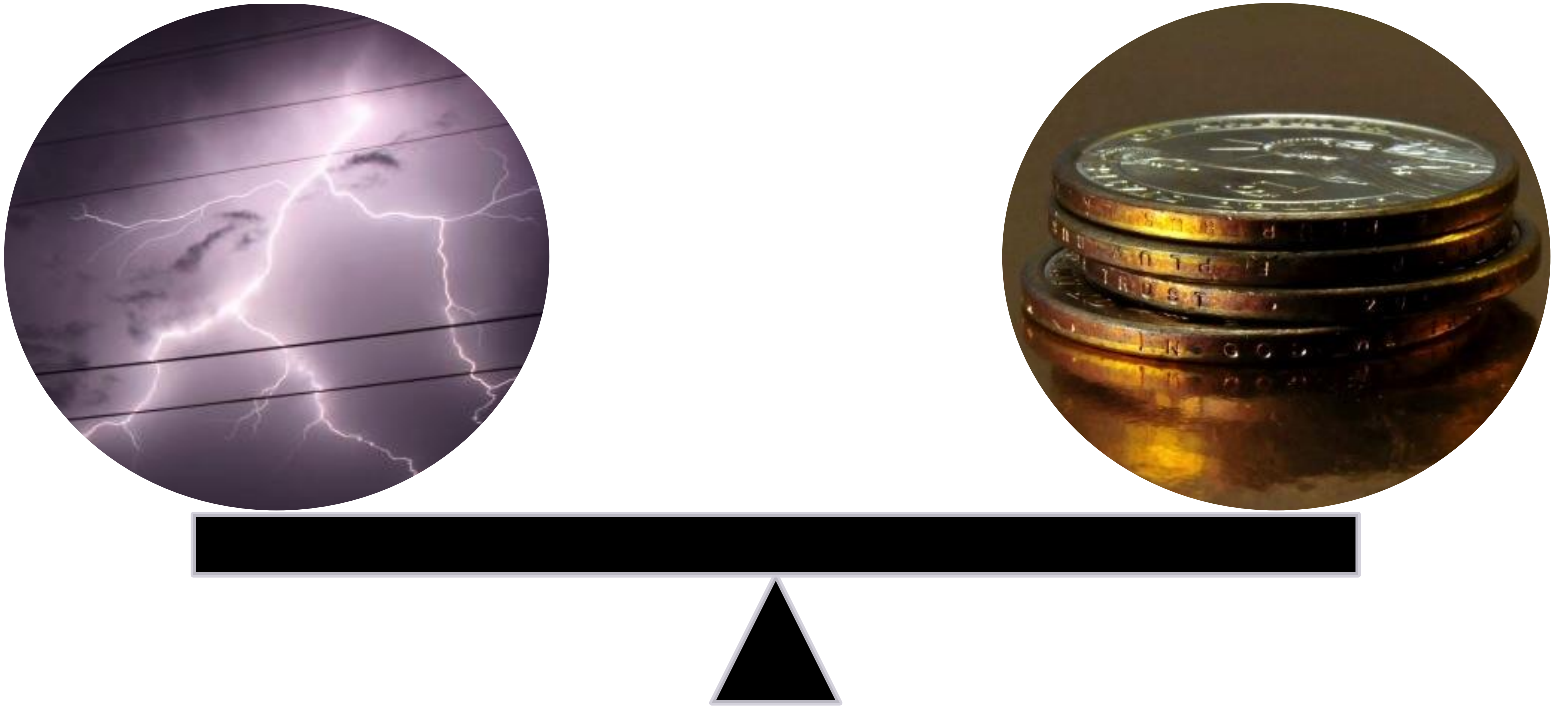
ELECTRICAL & COMPUTER ENGINEERING

Reliable supply

Maximize profits **Minimize cost**

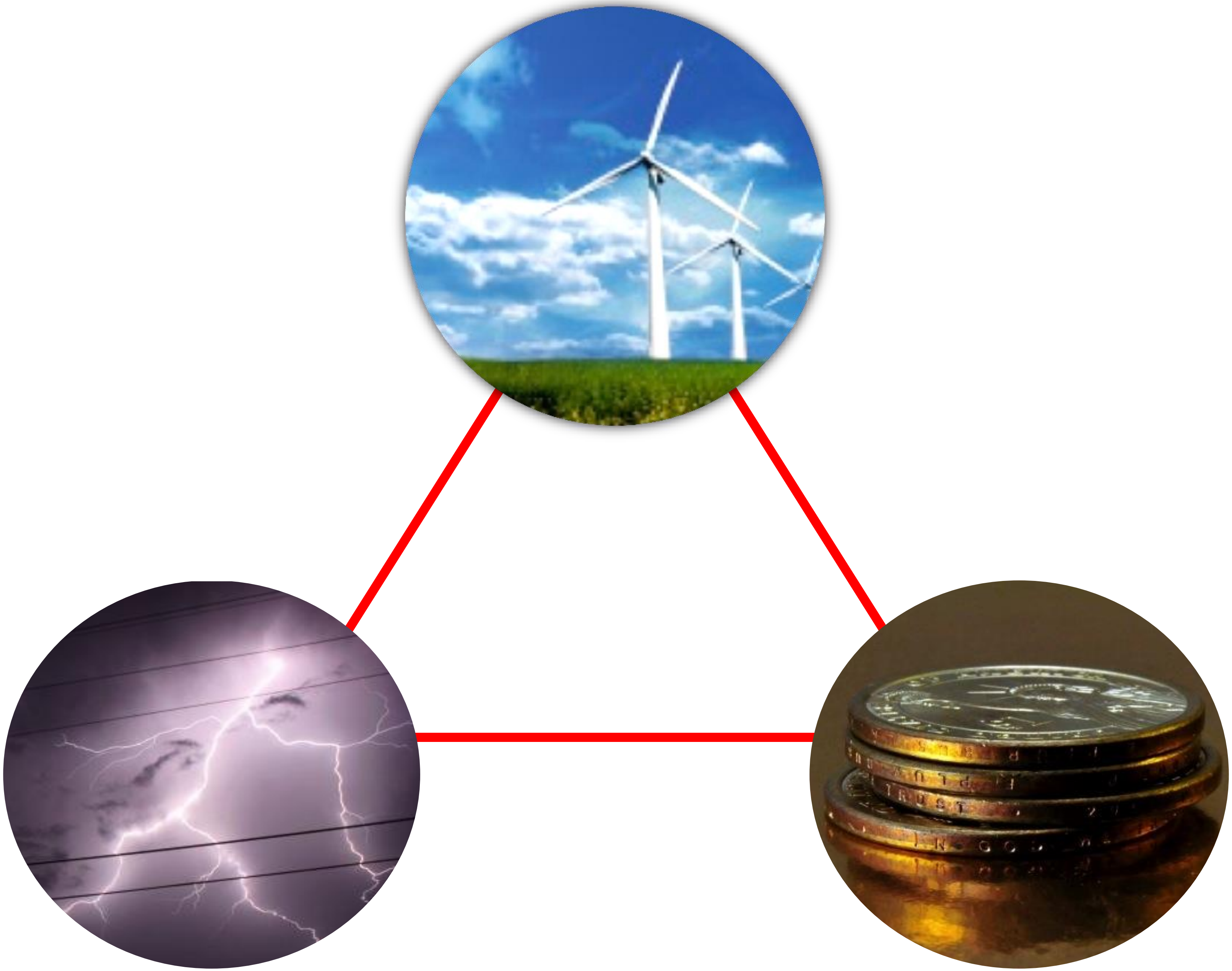
Balance Economics and Reliability



Be Green

Intermittency?

Stochasticity?



Is battery energy storage the solution?

What can we do with battery energy storage?

- Arbitrage
  - Buy low, Sell high
  - Charge when the sun shines, discharge in the evening
- Frequency regulation
  - Fast power electronics control
- Reserve capacity
  - Help deal with contingencies
- Peaking capacity
  - Avoid building expensive generators
- Mitigate transmission congestion
  - Avoid building new lines
- Provide resiliency

Will power systems be replaced by energy systems?

Q: How can we make money with storage?

A: Currently, with some difficulty

What are the issues?

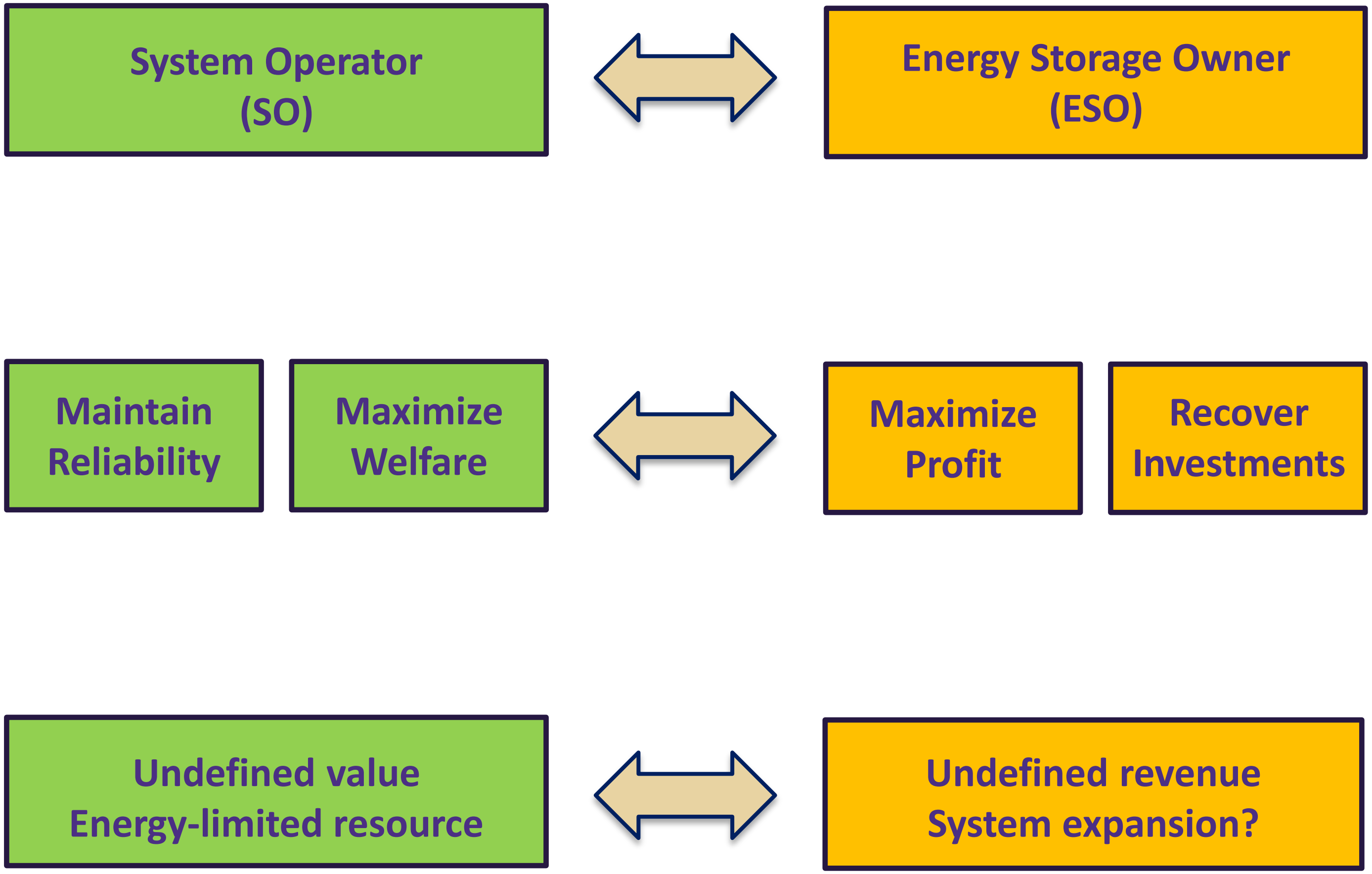
- High investment cost
- Low efficiency
- Uncertainty about competing technologies
- Battery degradation

Using storage for arbitrage

- Need large price differences to cover:
  - Losses in the battery
  - Investment cost

- Focus on spatio-temporal arbitrage
  - Congestion amplifies price differences
  - Where should the battery be located?
- What are the optimal locations and sizes of batteries in a congested transmission network?

Optimal from which perspective?



System Operator (SO) ⟷ Energy Storage Owner (ESO)

Maintain Reliability | Maximize Welfare ⟷ Maximize Profit | Recover Investments

Undefined value
Energy-limited resource ⟷ Undefined revenue
System expansion?

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: System Operator’s Perspective

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

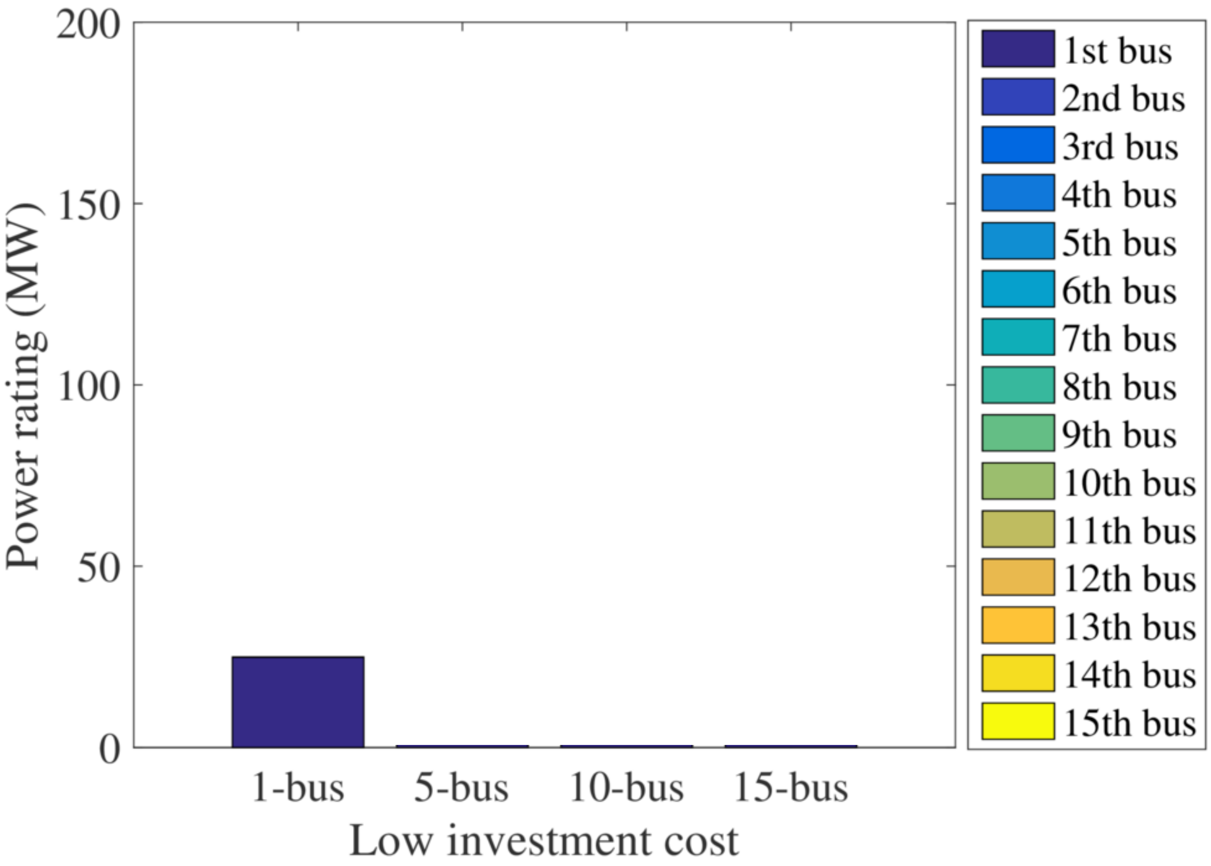
  Minimize (operating cost + investment cost in energy storage)
- Subject to constraints on:
  - Investments in energy storage
  - Operation of energy storage
  - System operation: generation and transmission limits
- Consider stochastic renewable generation
- Consider congestion in the transmission network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

Problem I: Test System and Data

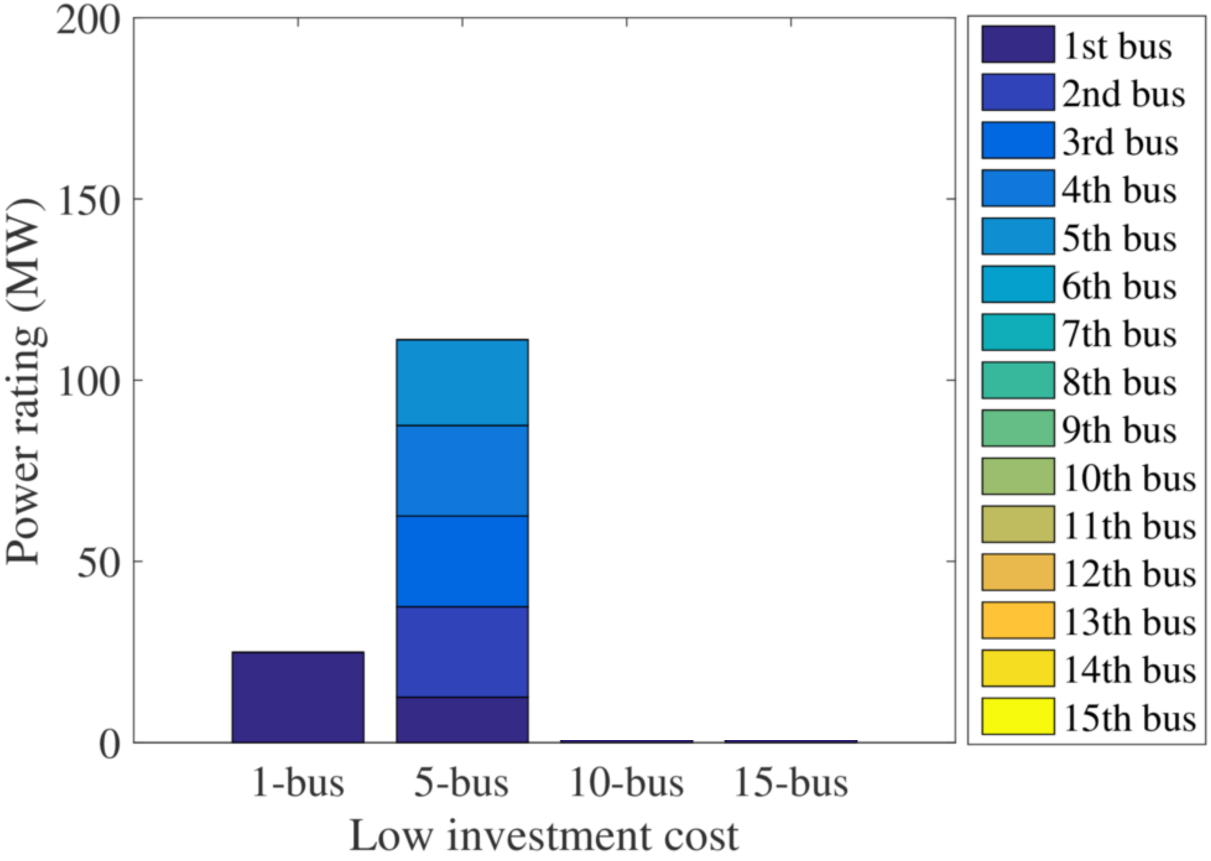
- Three storage investment cost scenarios (ARPA-E):
  - High: $75/kWh and $1300/kW
  - Medium: $50/kWh and $1000/kW
  - Low: $20/kWh and $500/kW
- Round-trip efficiency of 0.81
- 10-year lifetime
- 5% annual interest rate

- 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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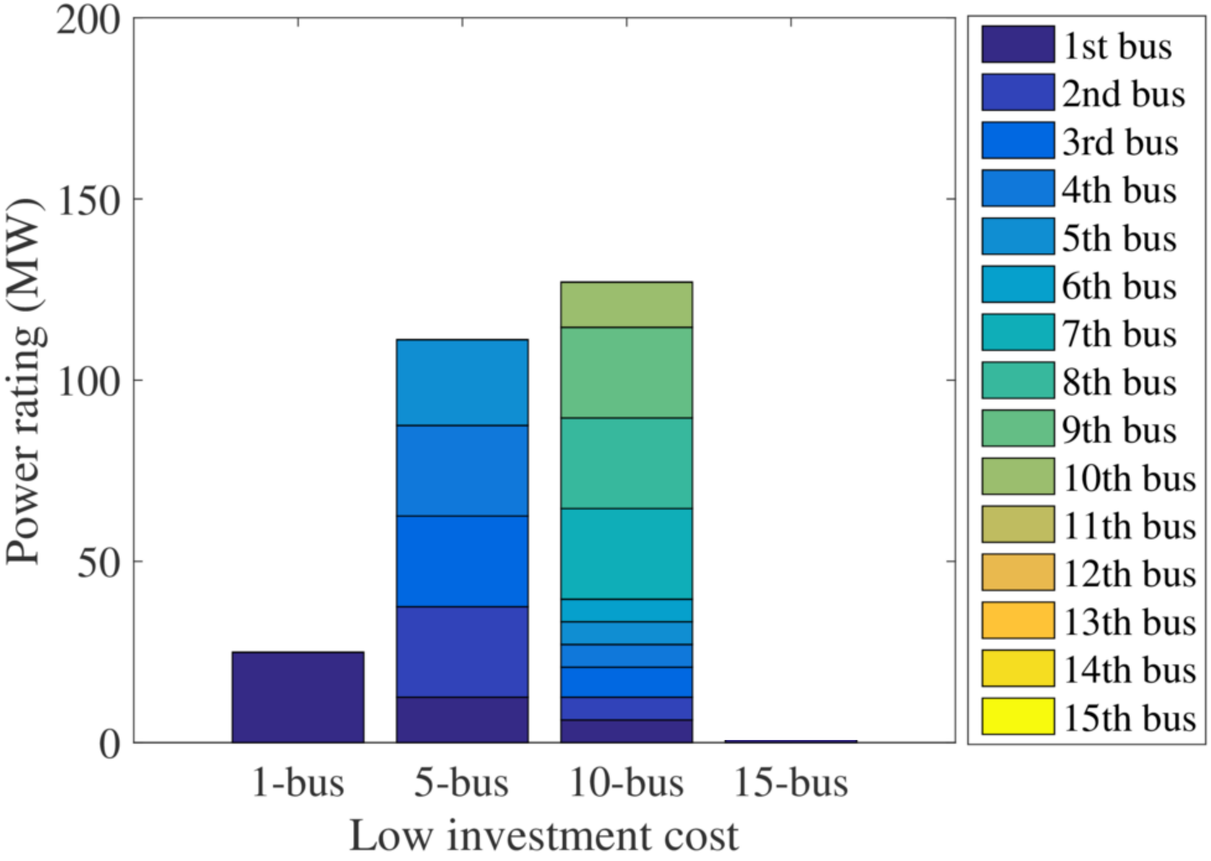

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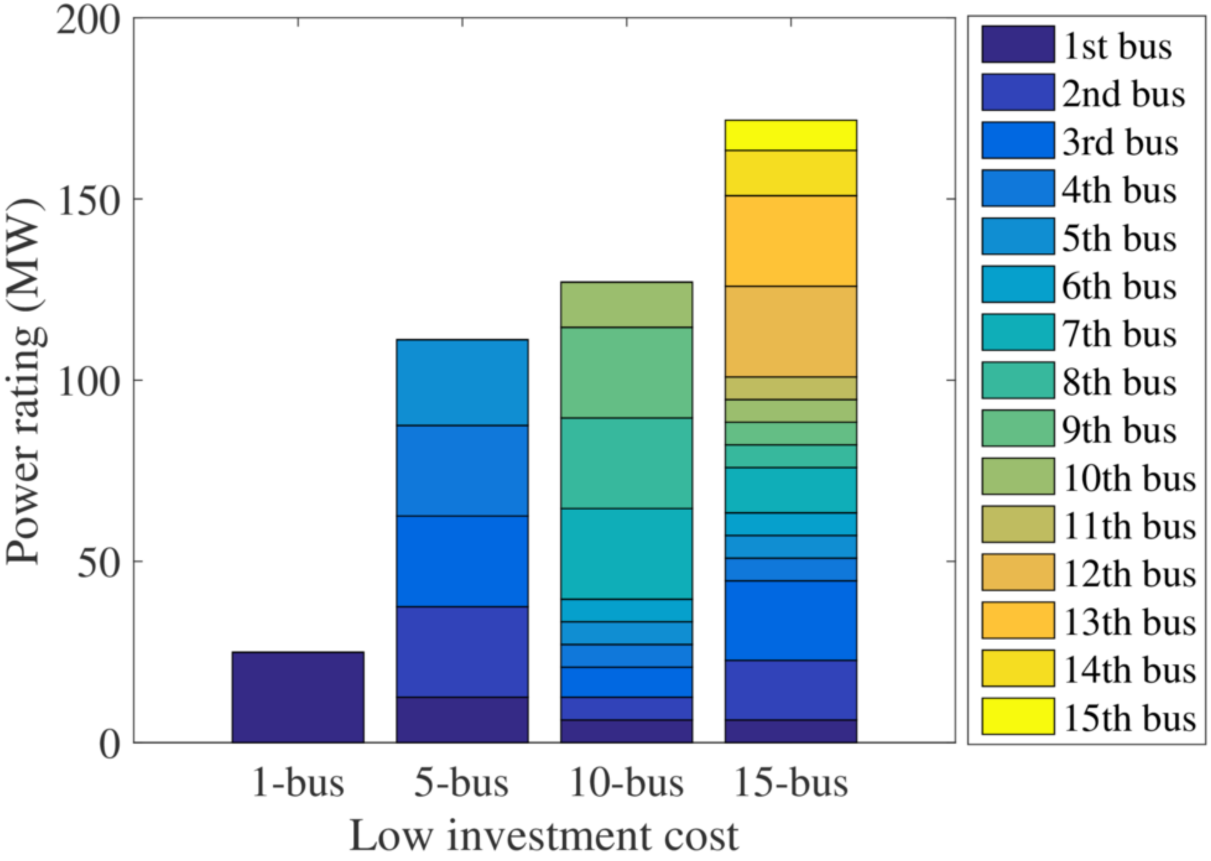
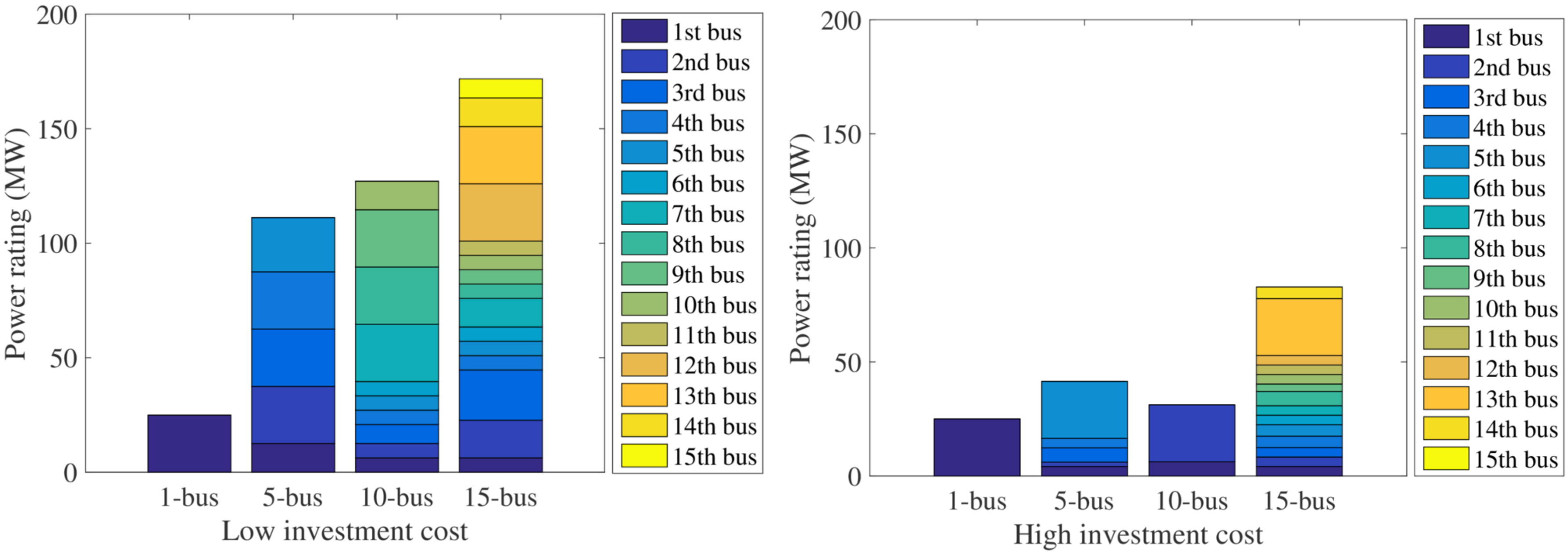


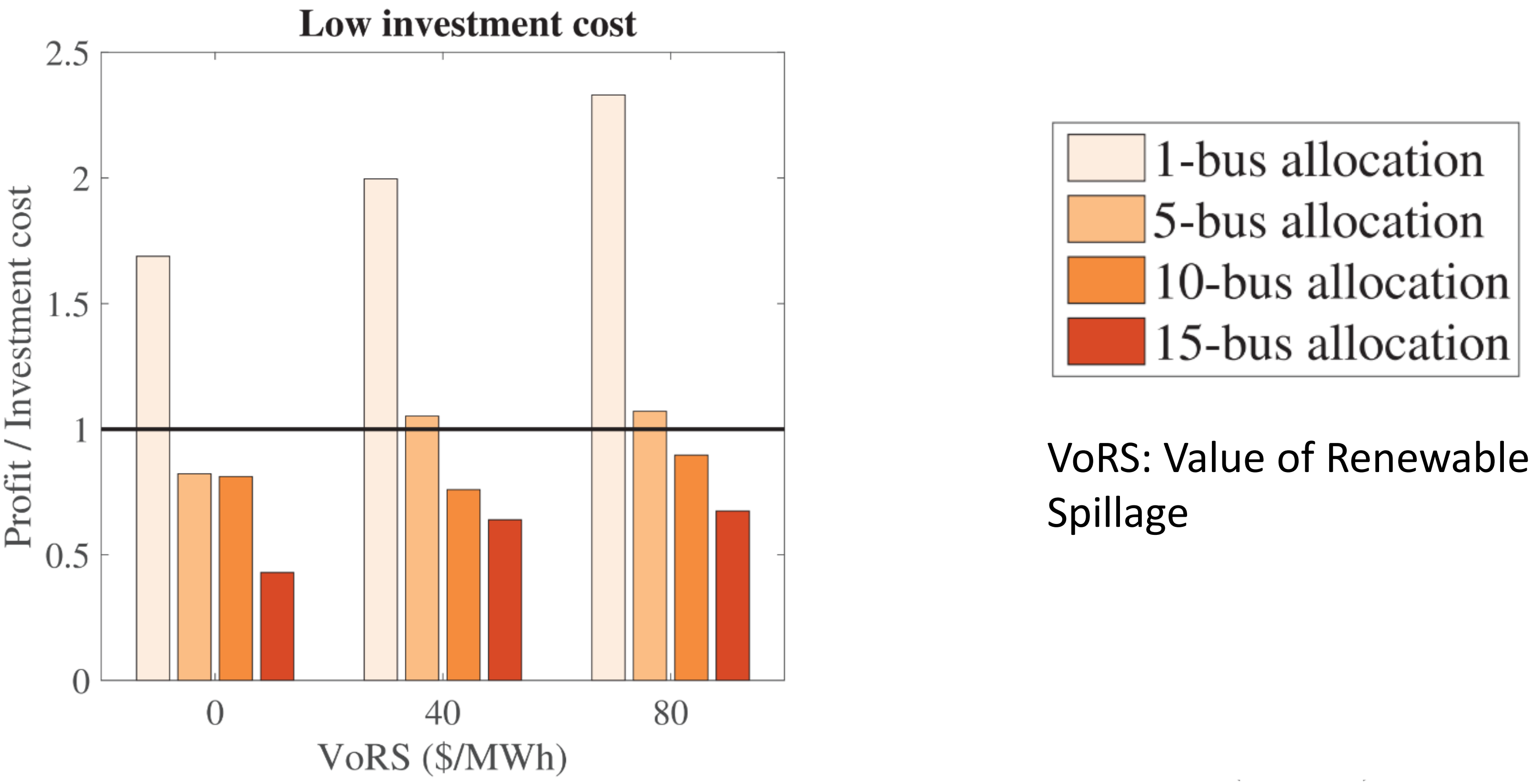
SO Perspective: Impact of the Capital Cost



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

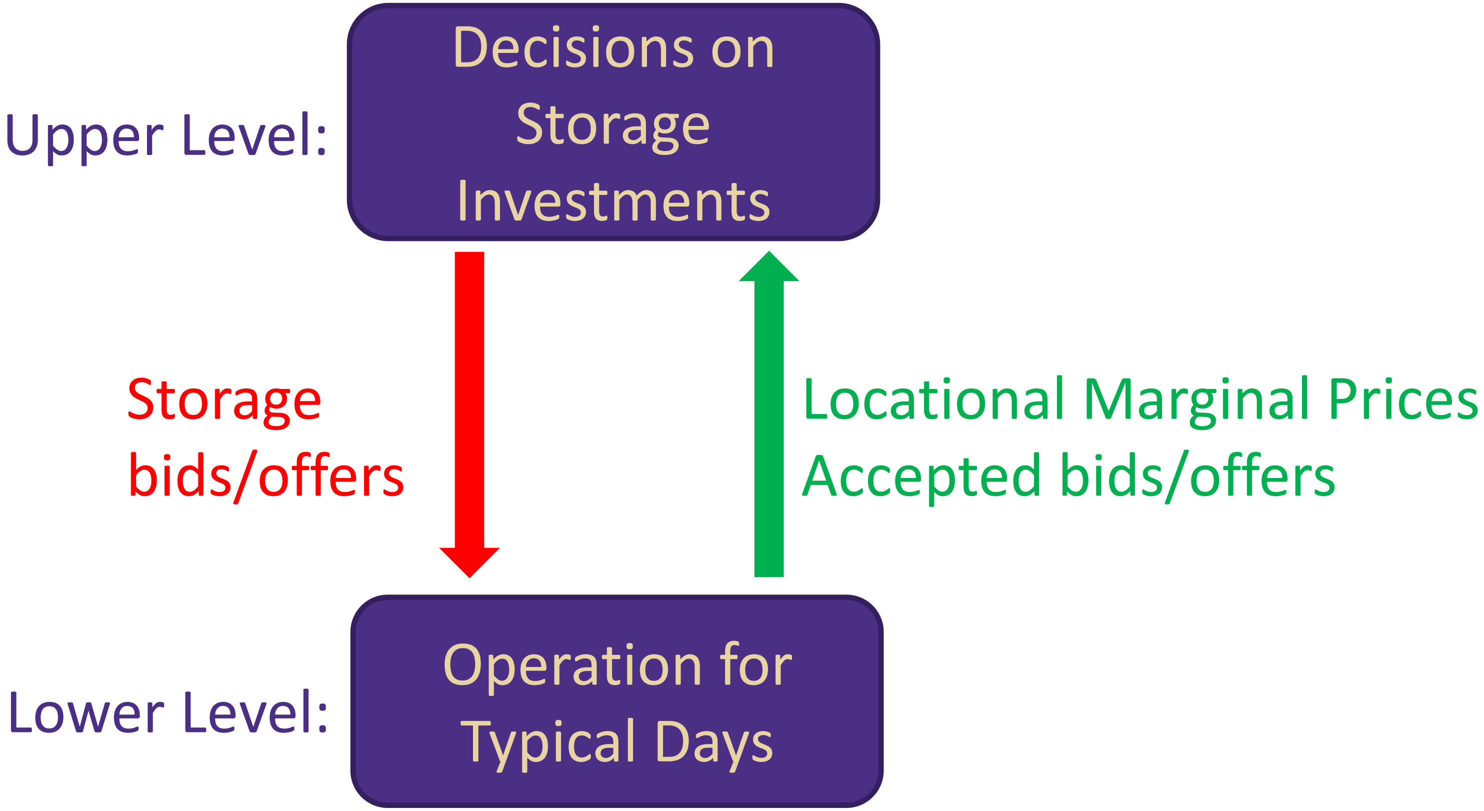
SO Perspective: Impact of Wind Spillage

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



Upper Level:

Decisions on Storage Investments

Storage bids/offers

Locational Marginal Prices
Accepted bids/offers

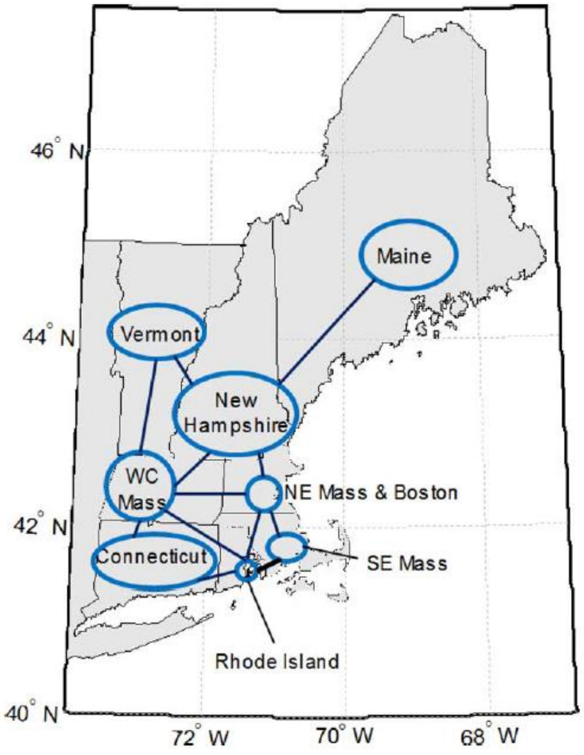
Lower Level:

Operation for Typical Days

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

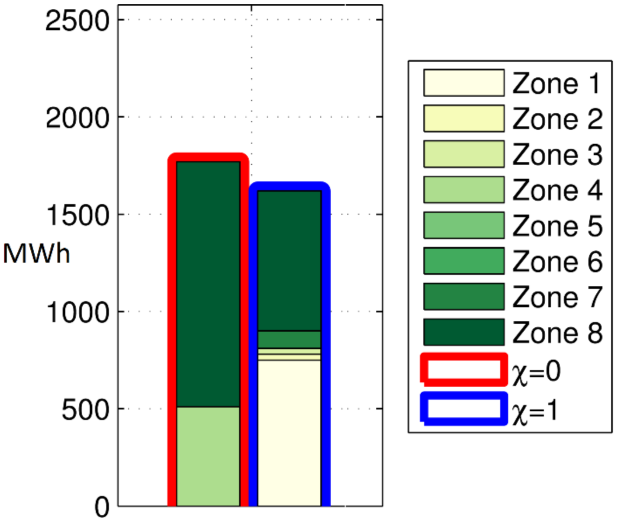
- ARPA-e projections on storage cost and characteristics



Problem II: Impact of the Rate of Return

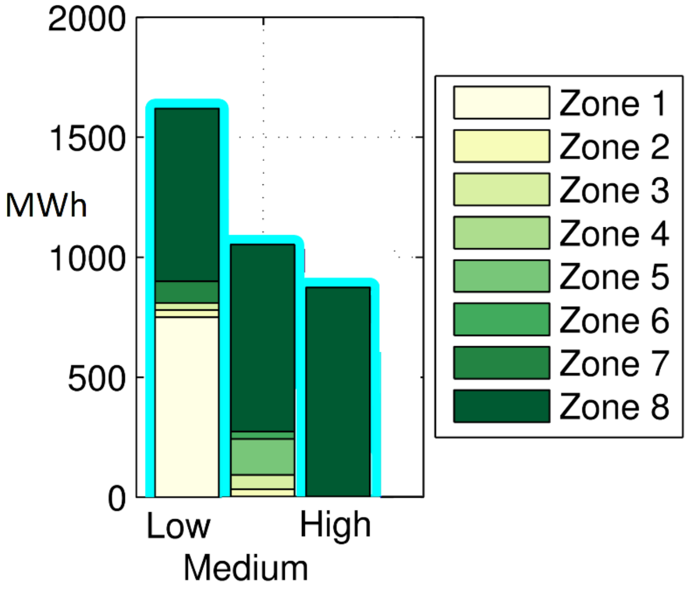
- Lifetime Profit ≥ χ ·Investment Cost
  - If $\chi > 1$ → Storage investment is profitable
  - If $\chi = 0$ → Same solution as problem I

- 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



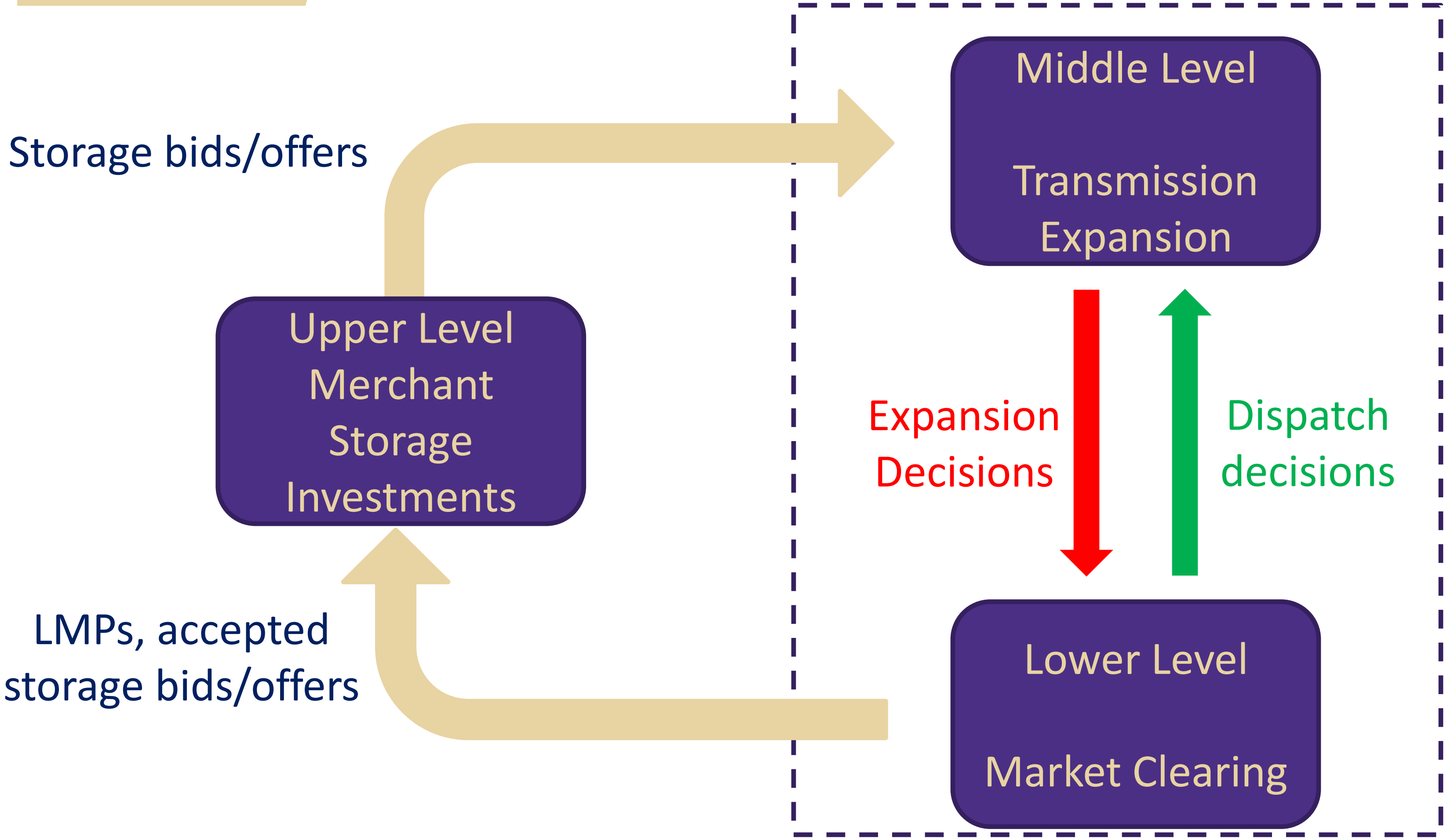
Case III: Merchant ESO Perspective

- 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



Storage bids/offers

Middle Level

Transmission Expansion

Upper Level Merchant Storage Investments

Expansion Decisions

Dispatch decisions

LMPs, accepted storage bids/offers

Lower Level

Market Clearing

Solved using a CCG-type decomposition

Problem III: 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
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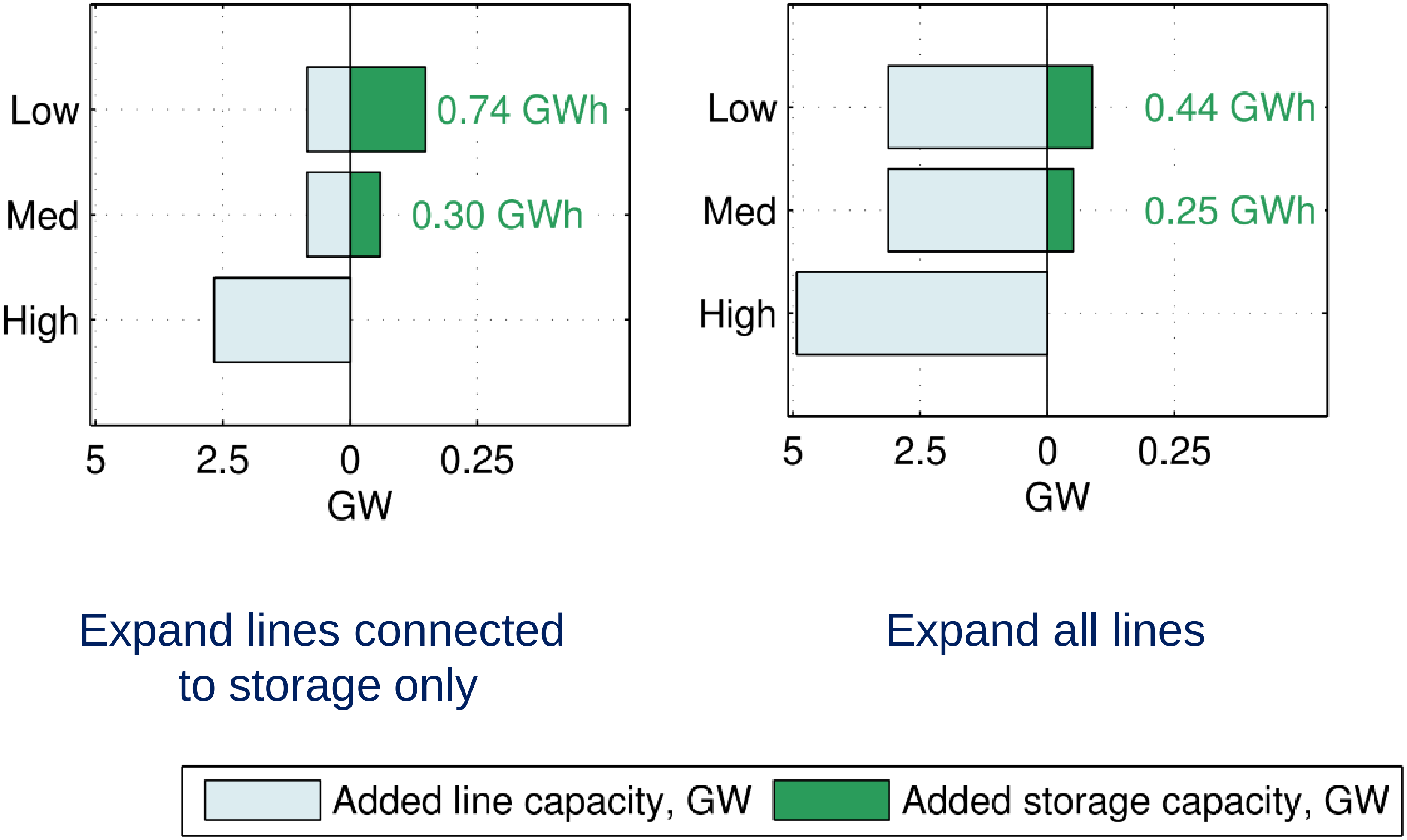
Effect of Transmission Expansion

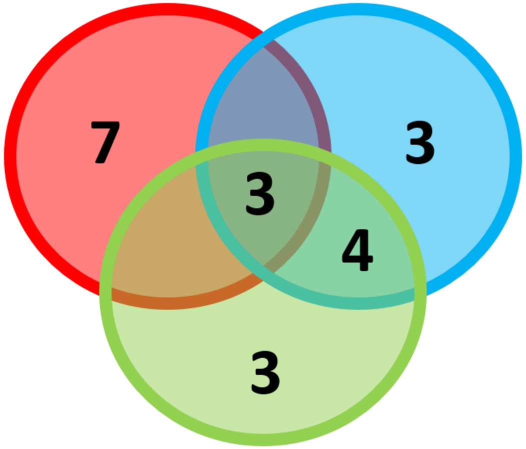


Expand lines connected to storage only

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:



- Best locations on optimization perspective
- Merchant storage will not locate batteries at the best locations from a system perspective

Battery Degradation

- Battery manufacturers provide a warranty
  - –XXXX charge/discharge cycles
  - –YY years

- But cycle characteristics are usually carefully defined
  - –1 cycle per day
  - –80% depth of discharge

- Usually not the way we want to use the battery

Cost of battery degradation

- Cost of replacing the battery at the end of its life
- Fixed life (cycles per manufacturer’s warranty)

  → treat degradation cost as a capital cost
- Variable life (irregular cycles)

  → treat degradation cost as an operating cost
- Need a predictive cost model that can be used to optimize battery operation
  - Is this charge/discharge cycle worth it?

Battery Degradation Factors

- Calendar life
- Ambient temperature
- Humidity
- Over charge
- Over discharge
- Cell temperature
- Current rate (C-rate)

Not affected by battery cycling

- Cycle average state of charge (SoC)
- Cycle depth

Affected by operation decisions

Cycle aging

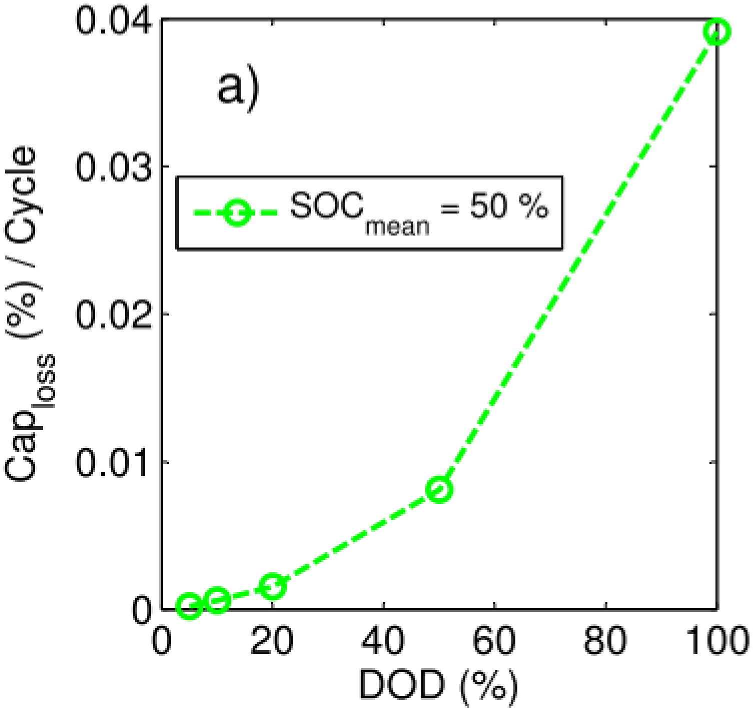
Heuristic model of cycle aging

- Based on experimental data
- $\Psi(\mathrm{d})$: how much battery life is lost after a cycle with depth "d"

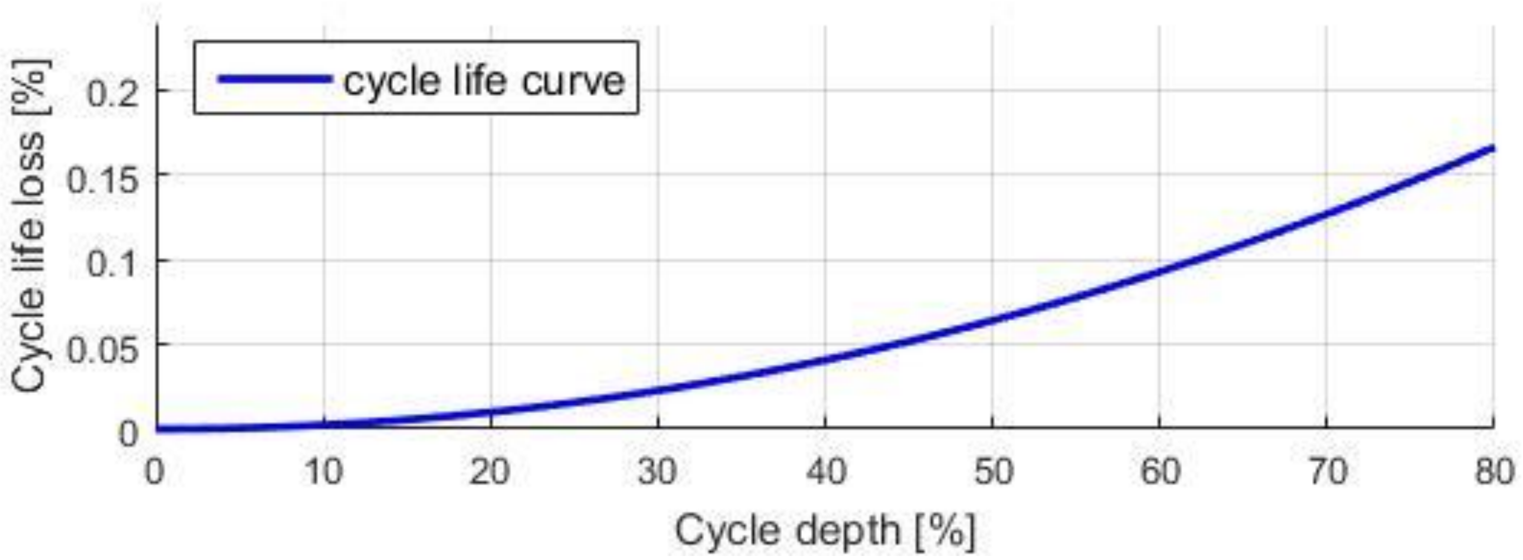
$$\Psi(d) = k_1 d^{k_2}$$

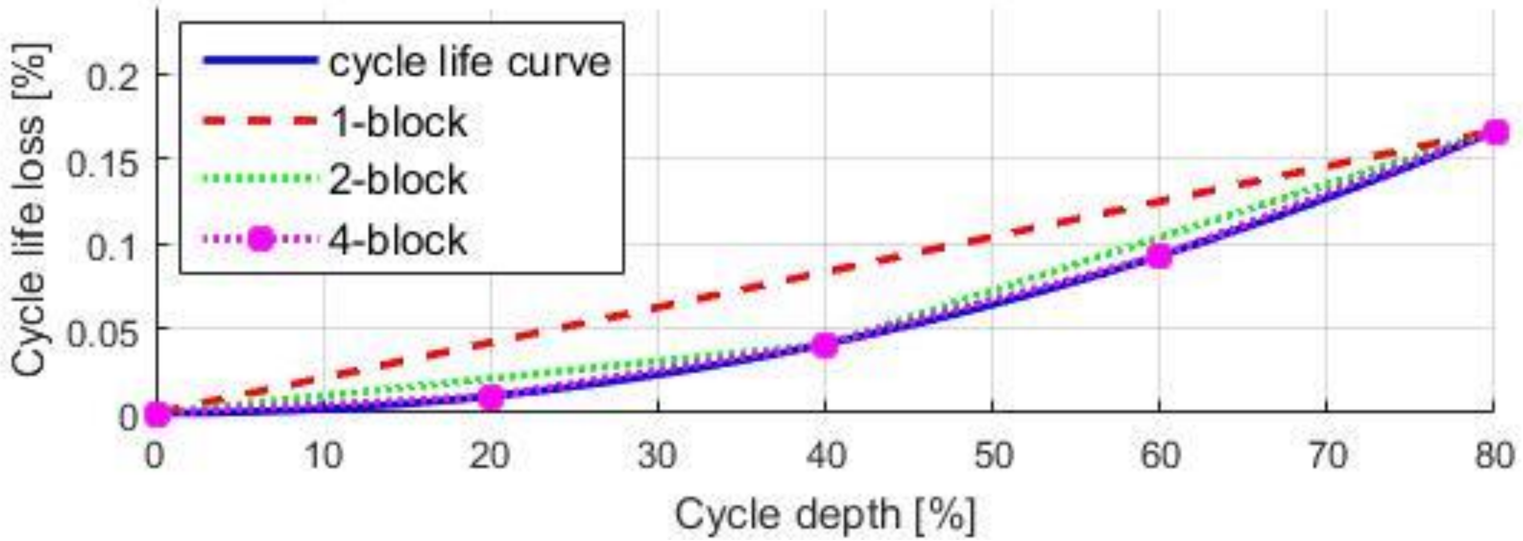
- Total cycle life loss after a series of cycle depths $d_1, \ldots, d_N$

$$\sum_{i=1}^{N} \Psi(d_i)$$

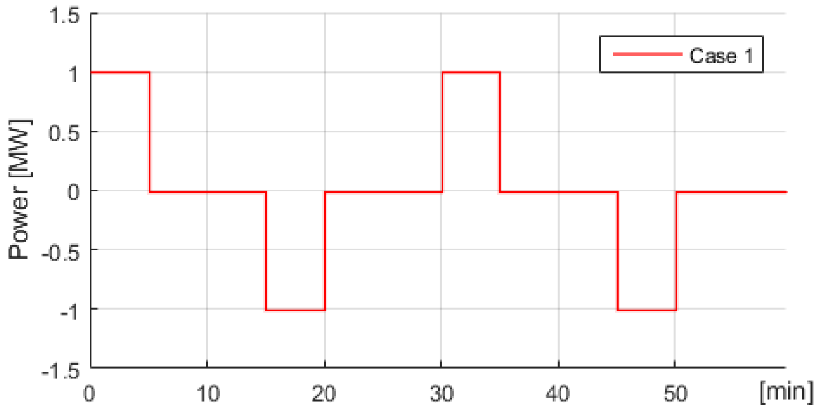


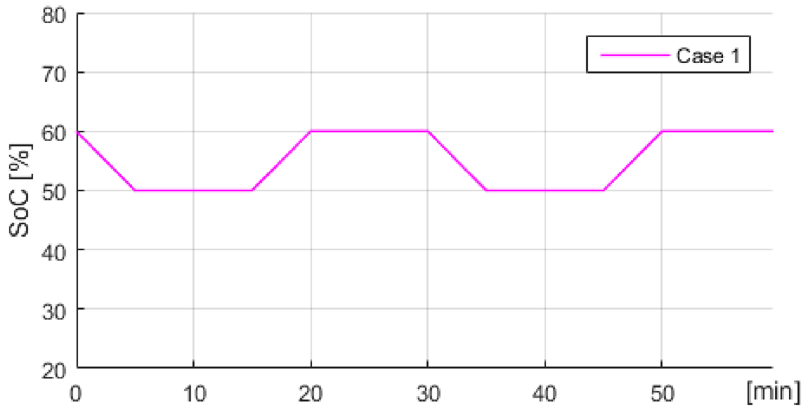
Battery cycle life curve

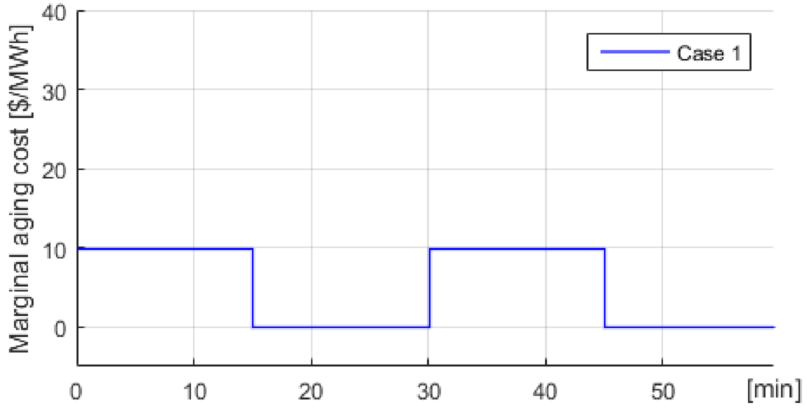


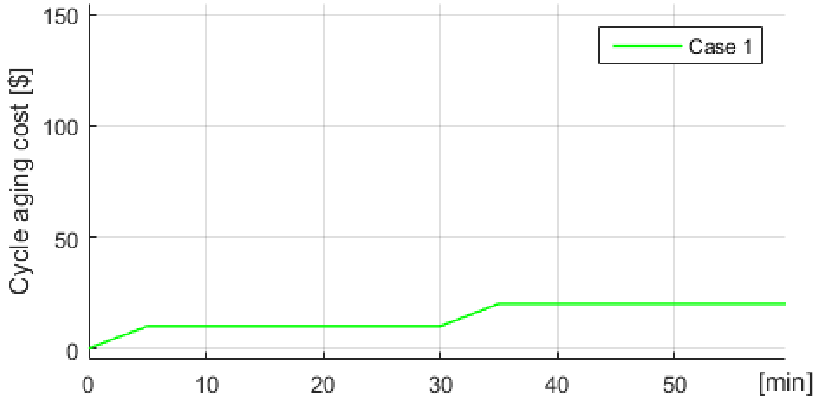


A simple example

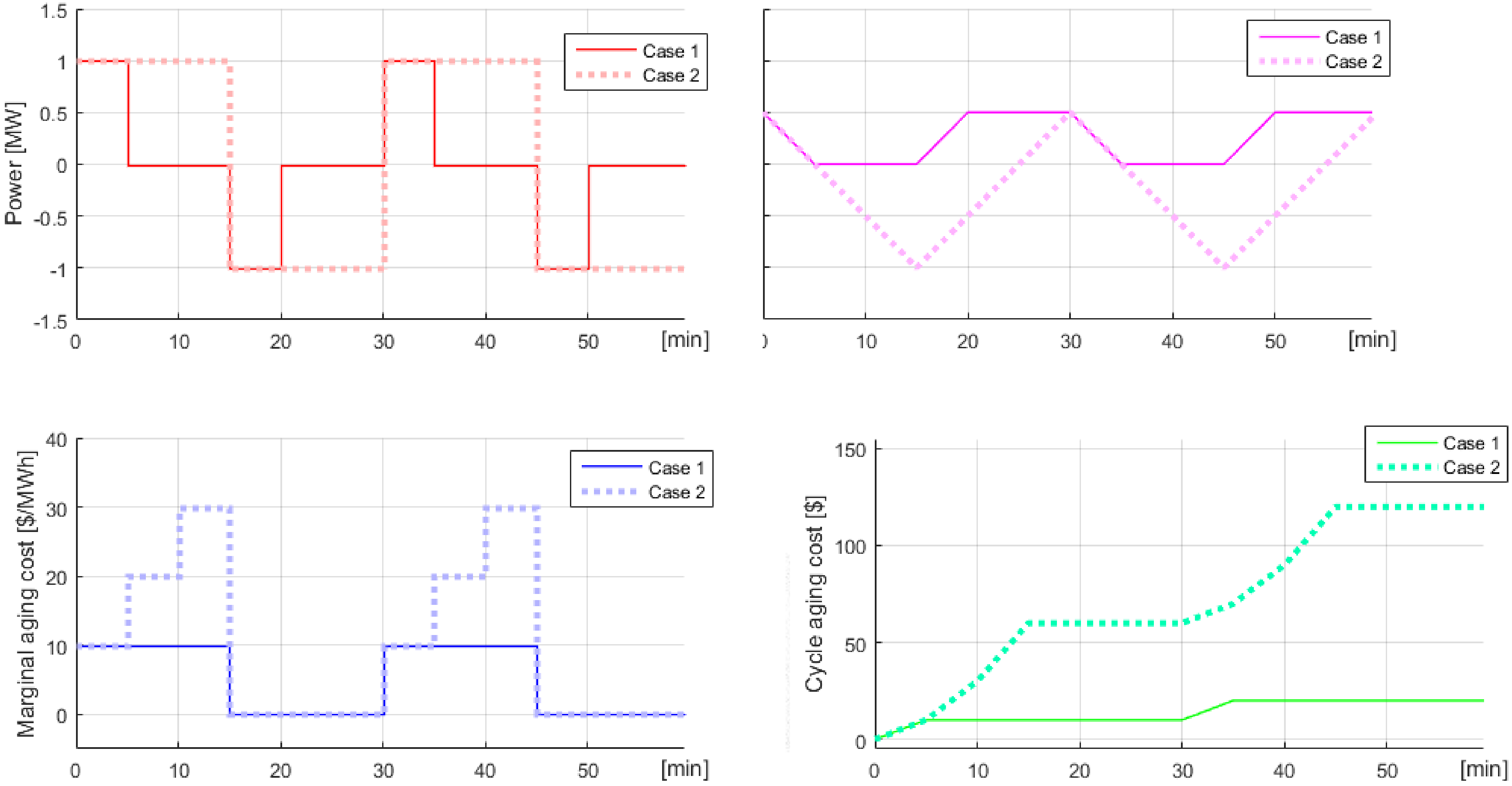








Same example with deeper cycles

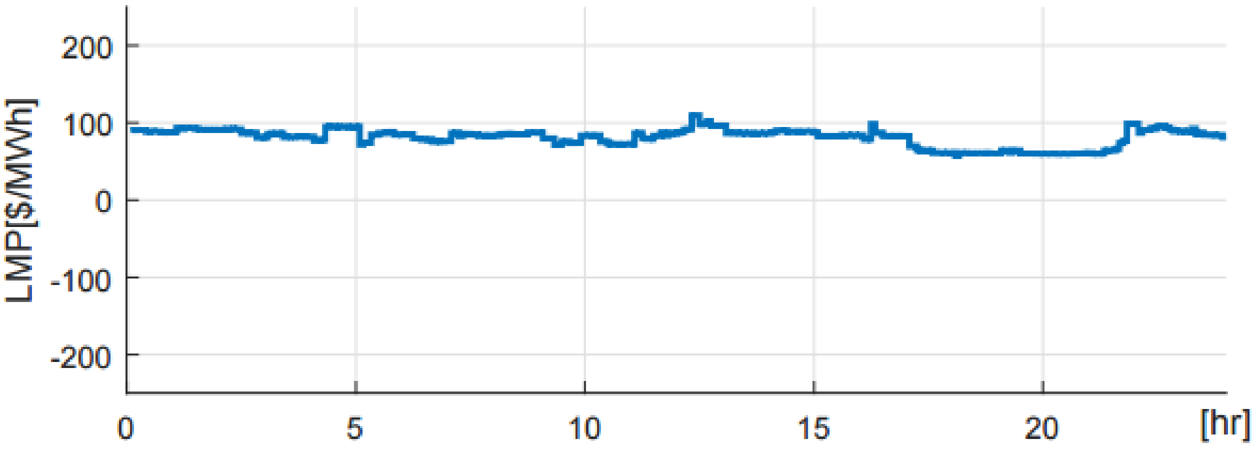


Incorporating cycle aging in dispatch

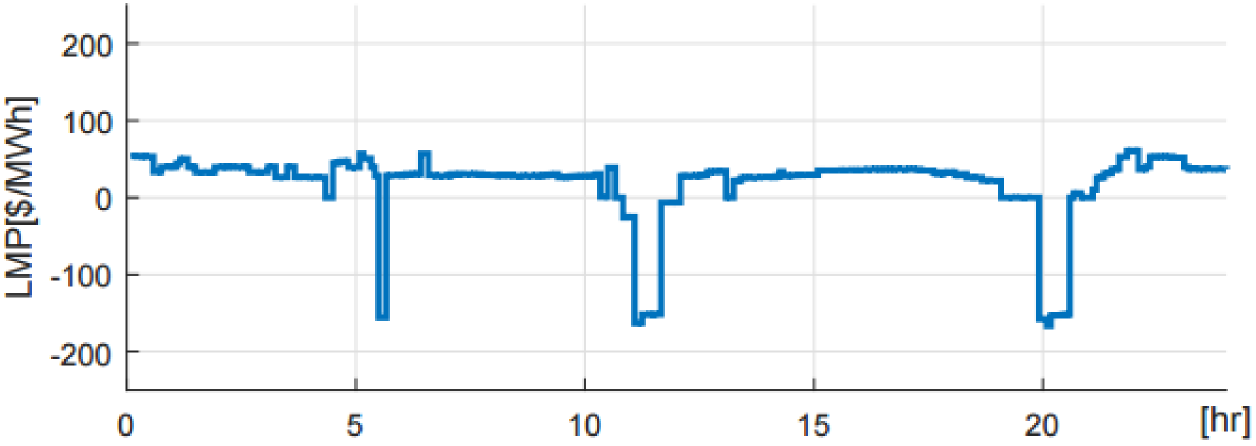
- Perspective of a battery owner
  - Optimizes its bids & offers to maximize actual profit

- Assumptions:
  - Has perfect forecast of prices
  - Acts as a price taker
  - Revenue opportunities:
    - Energy arbitrage
    - Provision of reserve

Prices for energy arbitrage



(a) An example of stable market prices (Jan 7, 2015).



(b) An example of highly variable market prices (Jan 2, 2015).

(Data: ISO New England)

Reserve market

- Commitment to increase or decrease output in case of a generator outage or a sudden change in renewable production

- Remunerated separately from energy market

- Limits storage's ability to perform arbitrage:
  - Power capacity (MW)
  - Energy capacity (MWh)

Problem formulation

Objective function: profit maximization

Cycle
aging
cost

$$\underbrace{\max_{\mathbf{p},\mathbf{g},\mathbf{d},\mathbf{q},\mathbf{e},\mathbf{v},\mathbf{u}}}_{\text{Dispatch variables}} \quad \Omega := \sum_{t=1}^{T} M\left[\lambda_t^{\mathrm{e}}(g_t - d_t) + \lambda_t^{\mathrm{q}} q_t\right] - C$$

Energy
price

Discharging
power

Charging
power

Reserve
price

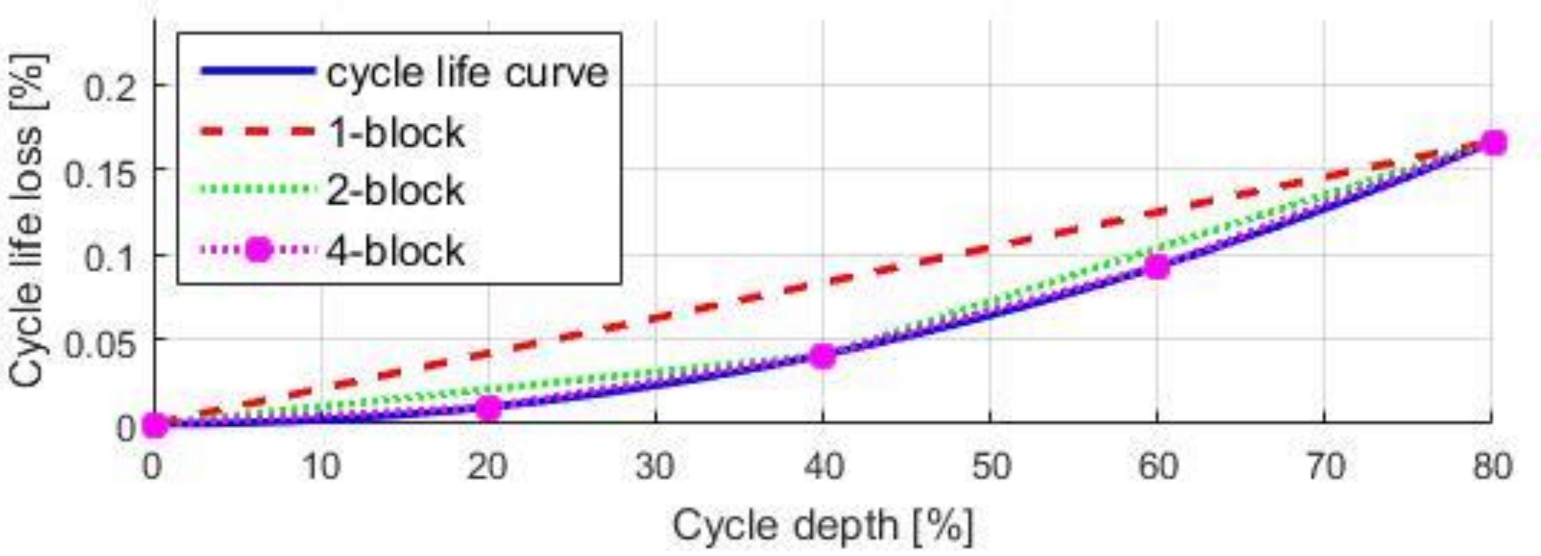
Reserve
capacity

Cycle aging cost

$$C = \sum_{t=1}^{T} \sum_{j=1}^{J} M c_j p_{t,j}^{\text{dis}}$$

Discharge power on segment *j*

Marginal cost of segment *j*



Constraints

Constraints on dispatch:

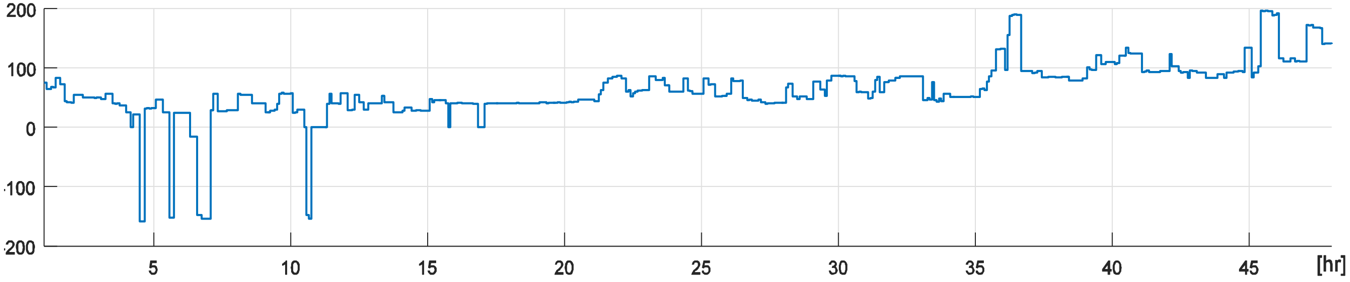
$$
\begin{aligned}
d_t &= \textstyle\sum_{j=1}^{J} p_{t,j}^{\mathrm{ch}} \eta^{\mathrm{ch}} \\
g_t &= \textstyle\sum_{j=1}^{J} p_{t,j}^{\mathrm{dis}} / \eta^{\mathrm{dis}} \\
d_t &\leq D(1 - v_t) \\
g_t &\leq G v_t \\
e_{t,j} - e_{t-1,j} &= M(p_{t,j}^{\mathrm{ch}} - p_{t,j}^{\mathrm{dis}}) \\
e_{t,j} &\leq \overline{e}_j \\
E^{\min} \leq \textstyle\sum_{j=1}^{J} e_{t,j} &\leq E^{\max} \\
e_{1,j} &= e_j^0 \\
\textstyle\sum_{j=1}^{J} e_{T,j} &\geq E^{\mathrm{final}}
\end{aligned}
$$

Constraints on reserve:

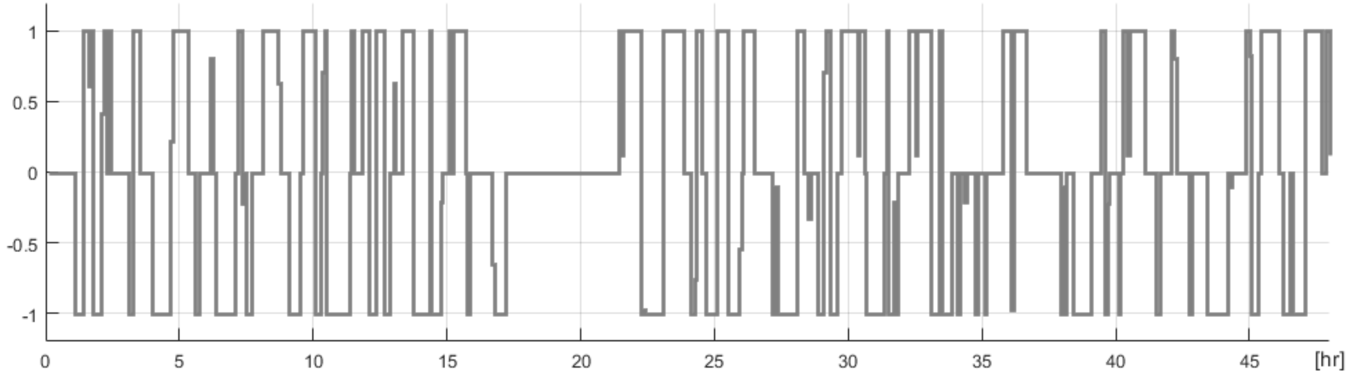
$$
\begin{aligned}
d_t - d_t^{\mathrm{q}} &\leq D(1 - u_t) \\
g_t - g_t^{\mathrm{q}} &\leq G(1 - u_t) \\
d_t^{\mathrm{q}} &\leq D u_t \\
g_t^{\mathrm{q}} &\leq G u_t \\
g_t^{\mathrm{q}} + q_t - d_t^{\mathrm{q}} &\leq G u_t \\
q_t &\geq \varepsilon u_t \\
S(g_t^{\mathrm{q}} + q_t - d_t^{\mathrm{q}}) &\leq \textstyle\sum_{j=1}^{J} \overline{e}_j \,,
\end{aligned}
$$

Storage dispatch ignoring cycle aging cost

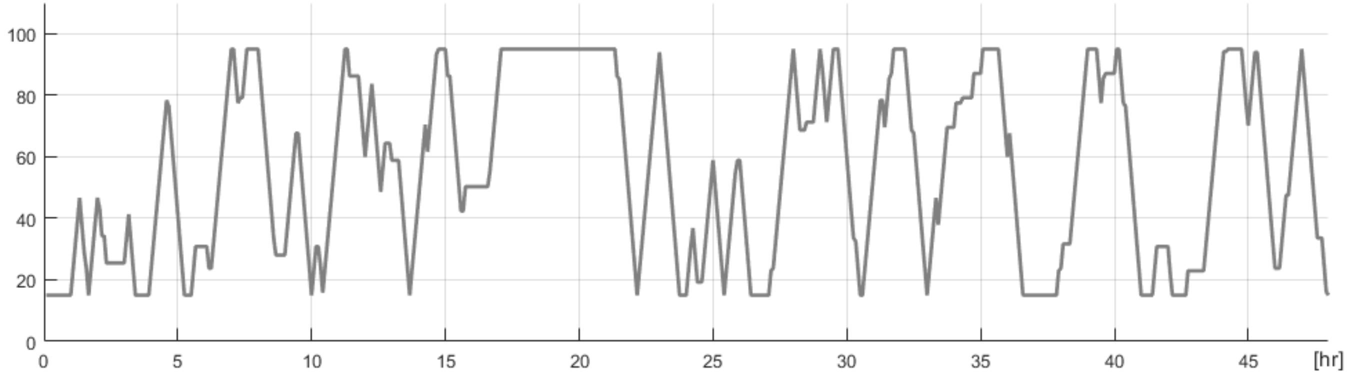
Real-time market prices over 48 hours



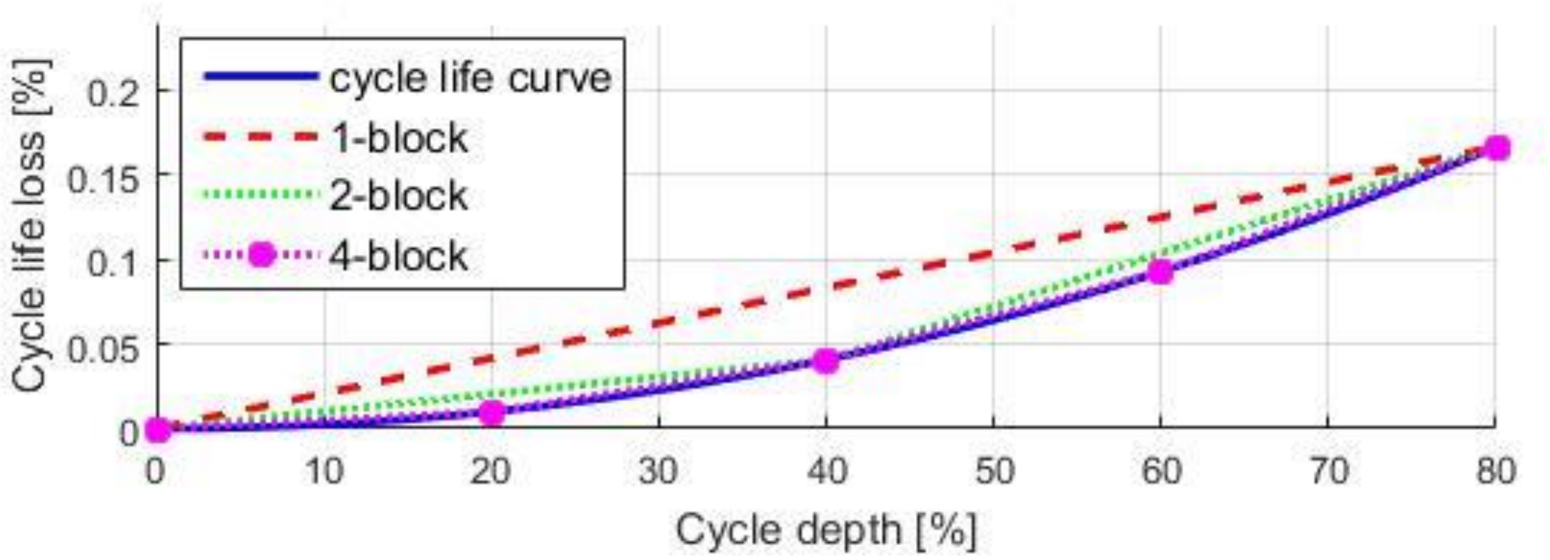
Power output



State of charge

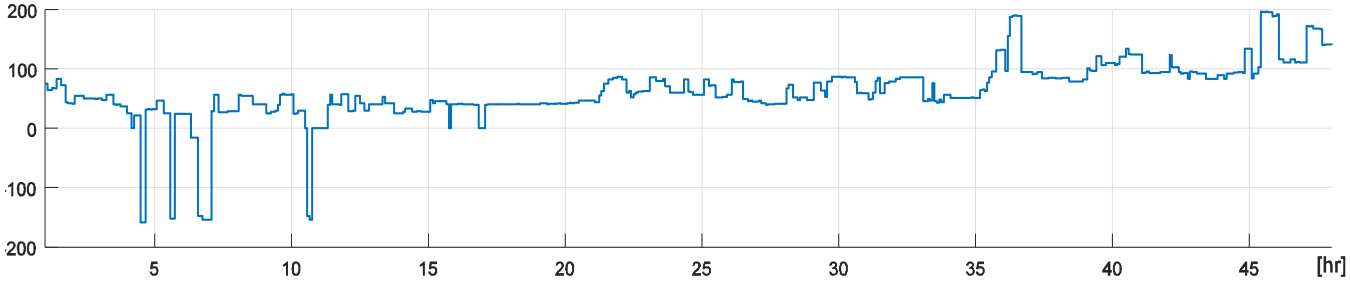


Cycle aging cost

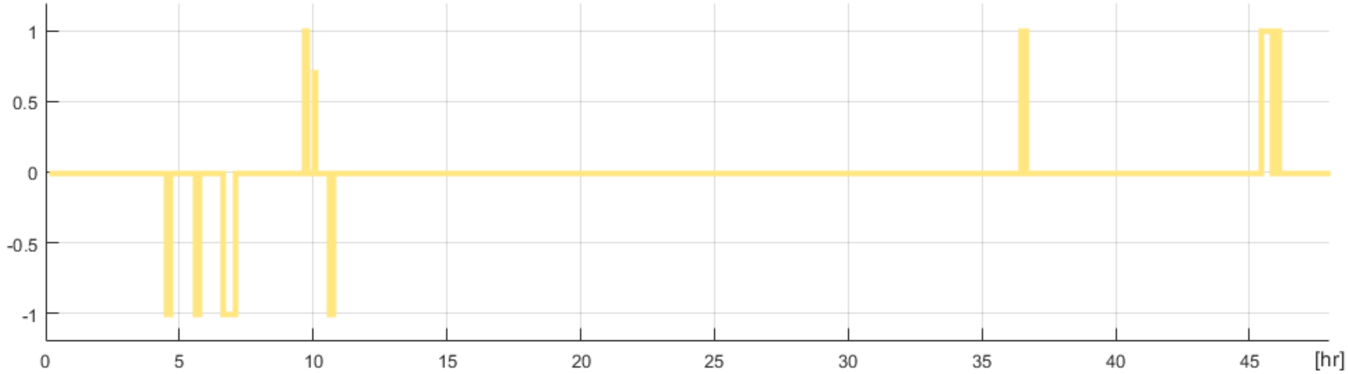


Storage dispatch with 1-block cycle aging

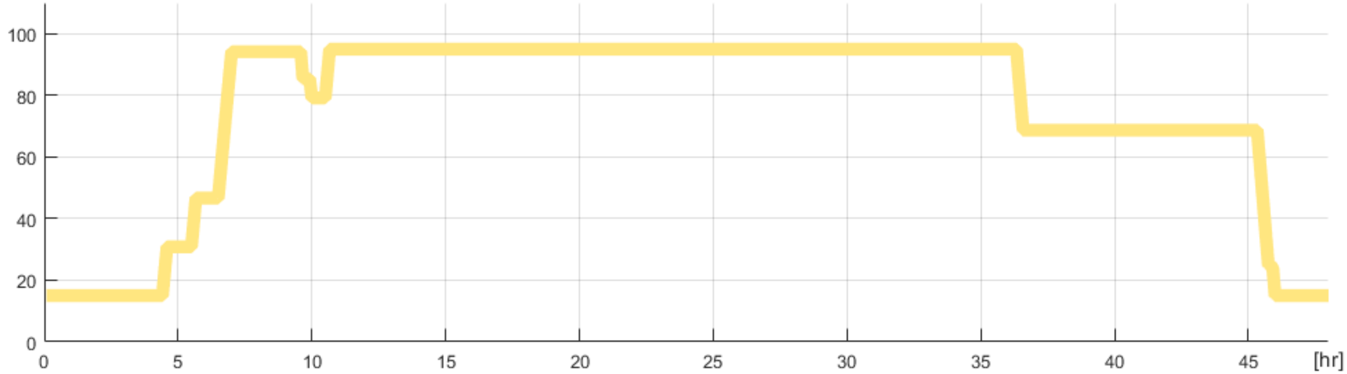
Price



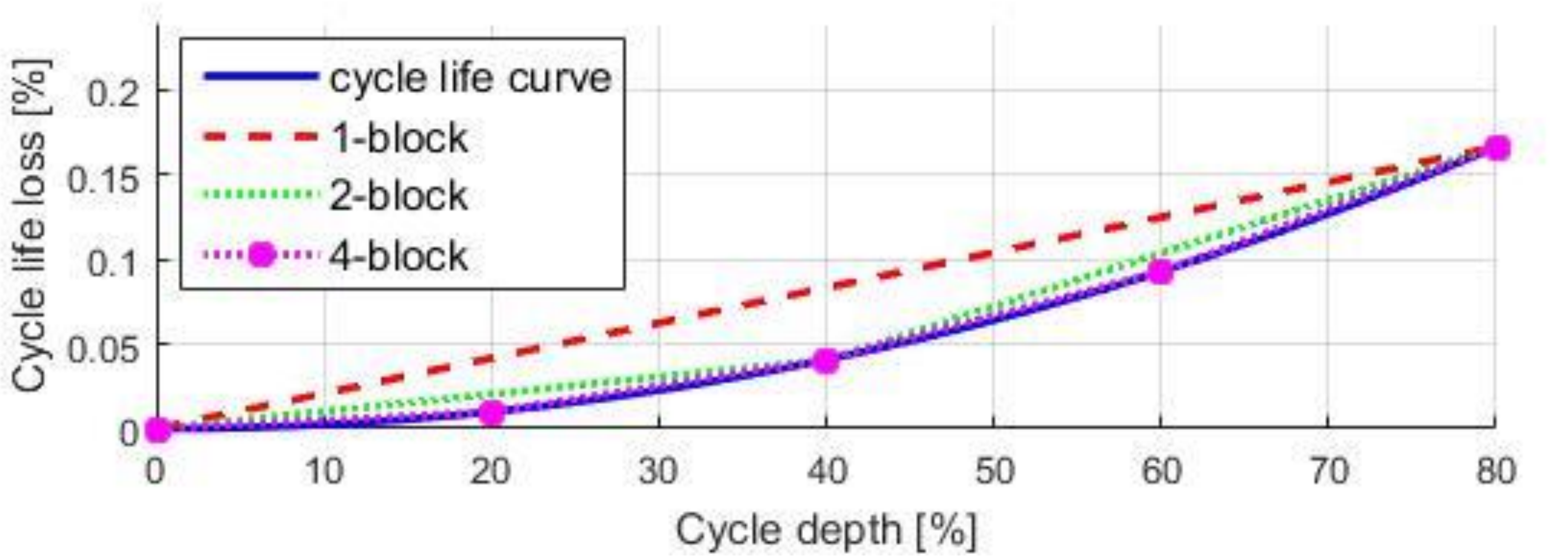
Power output



State of charge

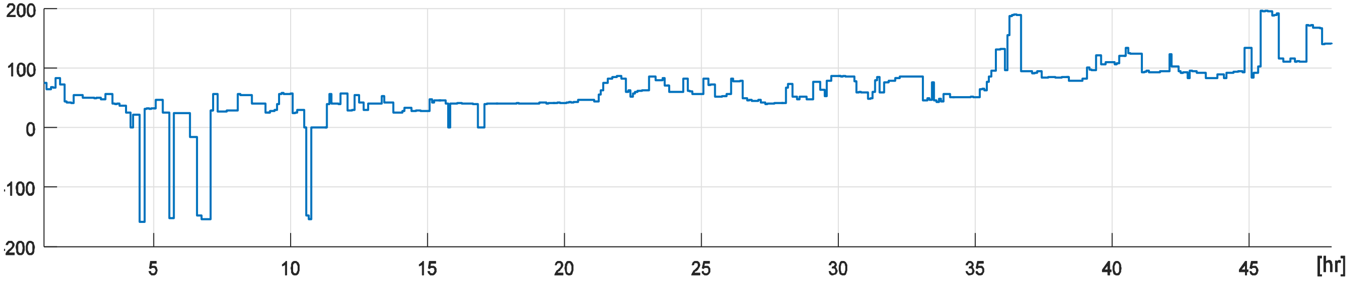


Cycle aging cost

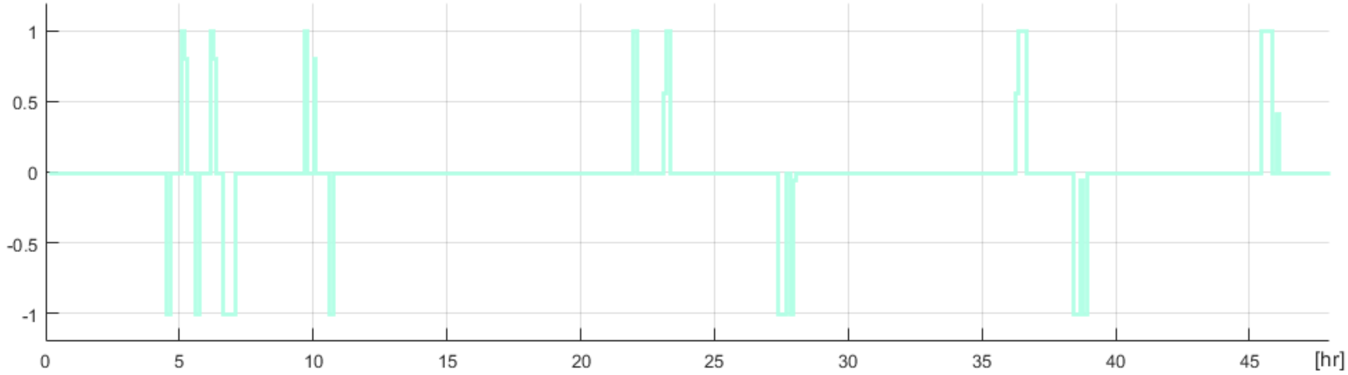


Storage dispatch with 2-block cycle aging

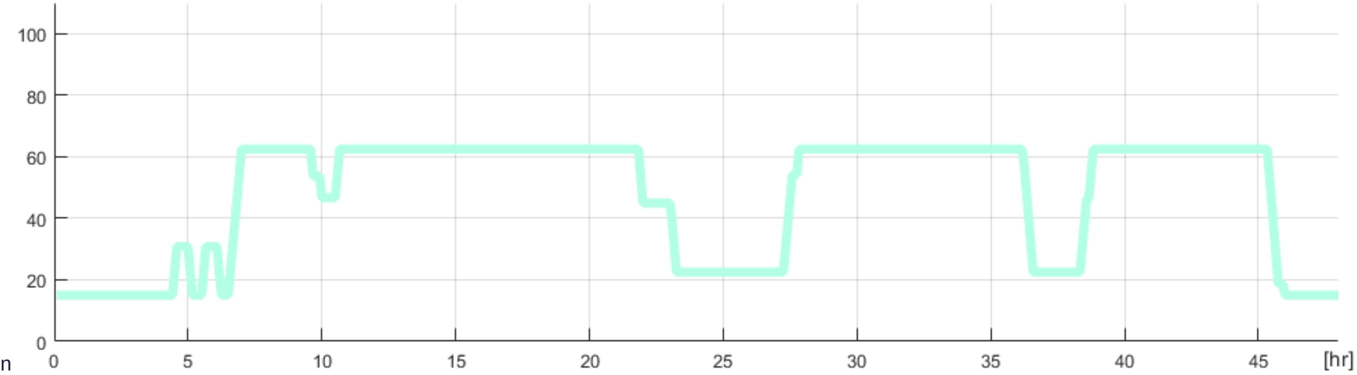
Price



Power output

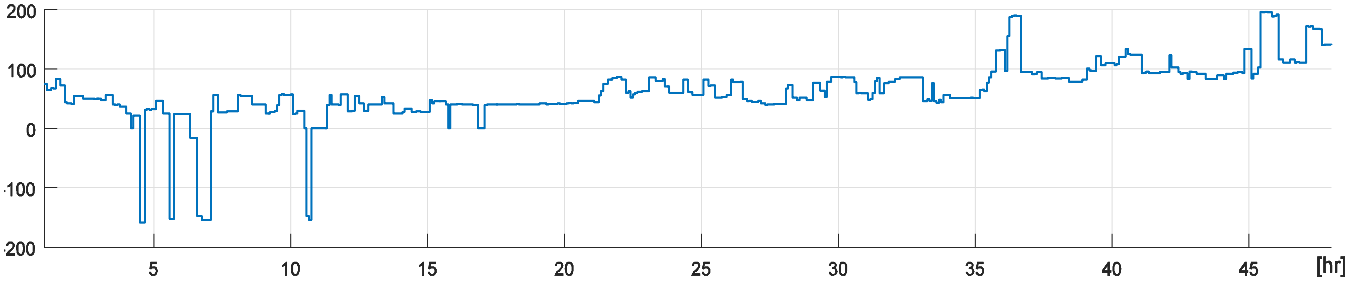


State of charge

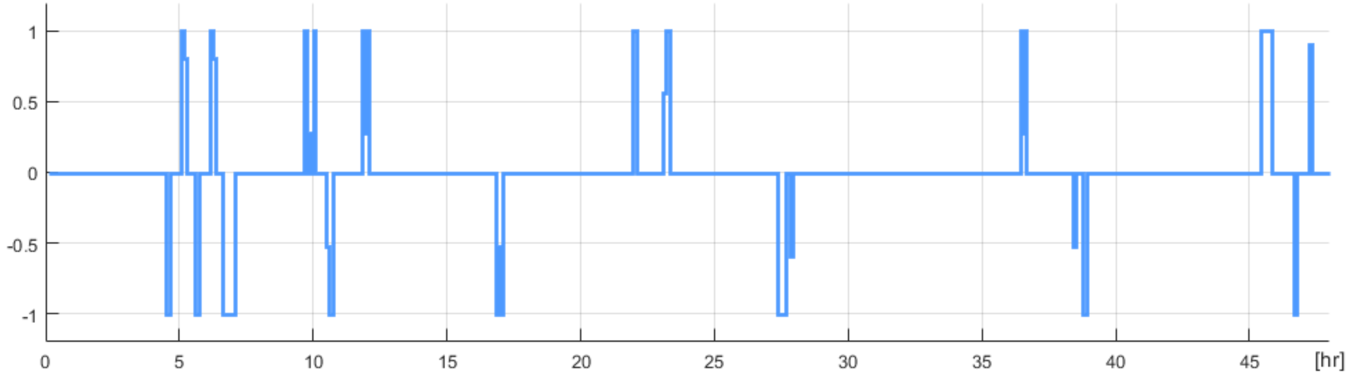


Storage dispatch with 4-block cycle aging

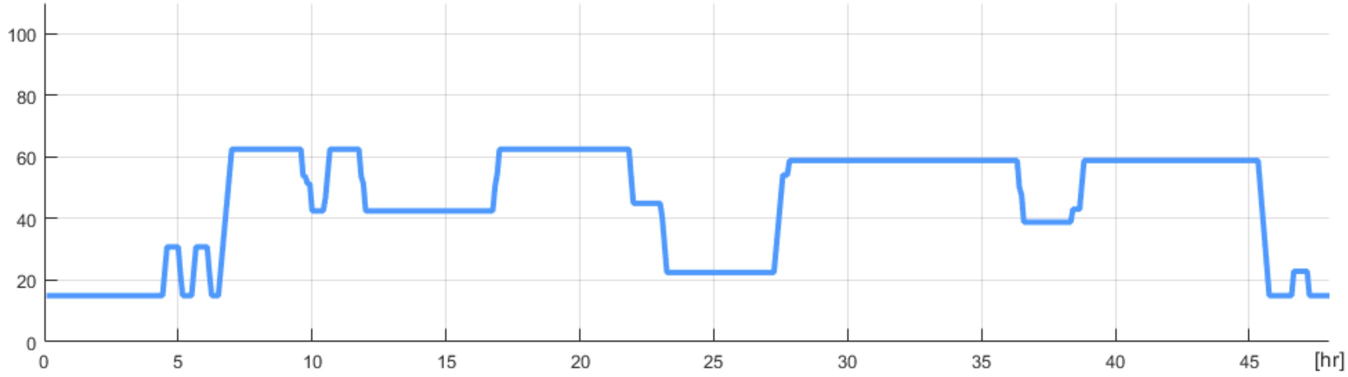
Price



Power output

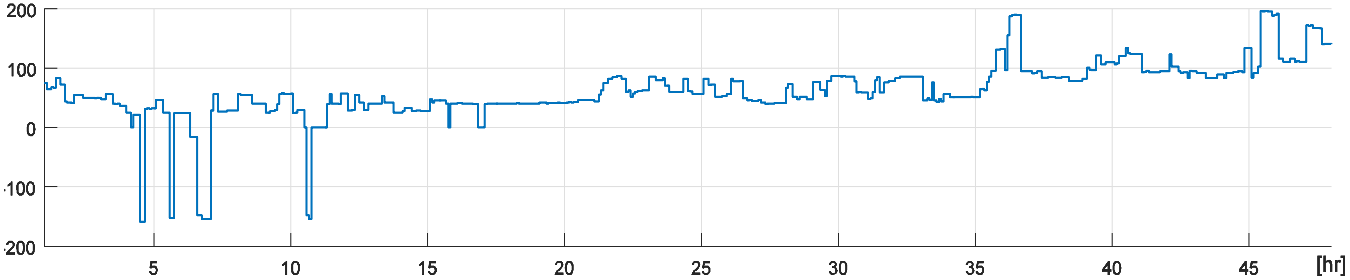


State of charge

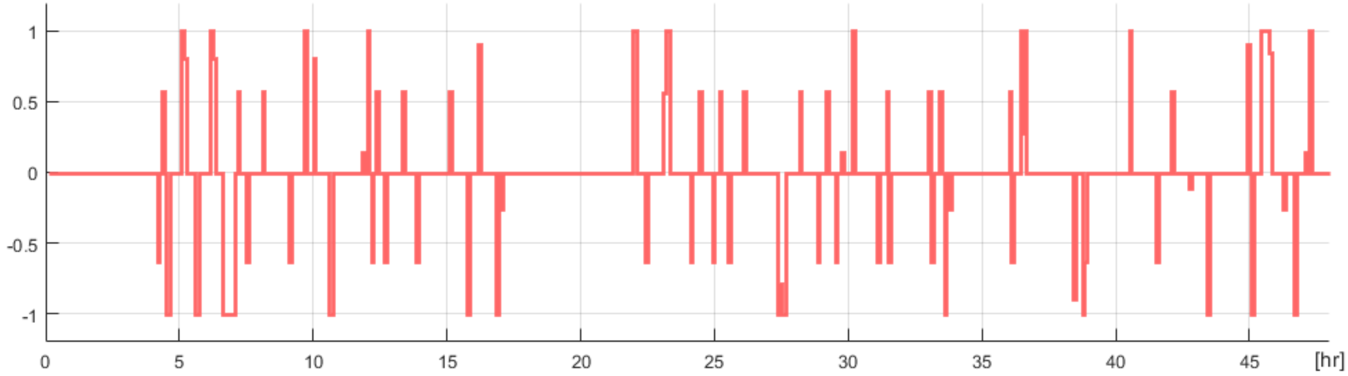


Storage dispatch with 16-block cycle aging

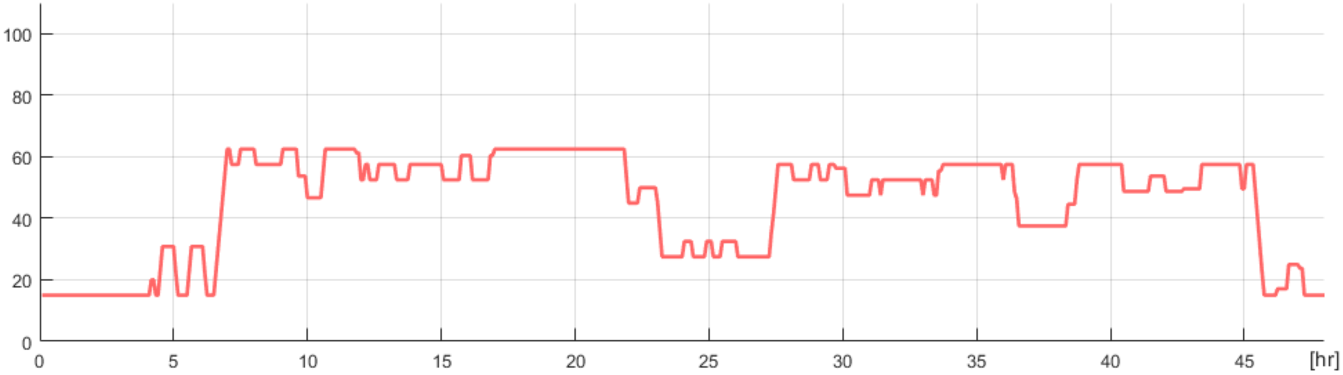
Price



Power output



State of charge



Profitability considering cycle aging

- Simulation over a full year of ISO New England market prices
- Energy and reserve markets
  - Day-ahead market (DAM) no reserve, hourly prices
  - Real-time market (RTM) 5-minute prices
- Battery data
  - Charging/discharging power rating: 20 MW
  - Energy capacity rating: 12.5 MWh
  - Charging and discharging efficiency: 95%
  - Maximum state of charge: 95%
  - Minimum state of charge: 15%
  - Battery cycle life: 3000 cycles at 80% depth
  - Battery shelf life: 10 years
  - Battery pack replacement cost: 300,000 $/MWh

Arbitrage in day ahead market

Optimization ignoring cycle aging

Annual market revenue (k$)	138.8
Annual loss of life from cycling (%)	24.4
Annual cycle aging cost (k$)	-913.8
Annual profit (k$)	-775.0
Remaining battery life (year)	2.9

Ignoring cycle aging causes an actual loss

Arbitrage in day ahead market

Optimization considering cycle aging

Annual revenue from arbitrage (k$)	138.8	21.3
Annual loss of life from cycling (%)	24.4	0.3
Annual cycle aging cost (k$)	-913.8	-11.3
Annual profit (k$)	-775.0	10
Remaining battery life (year)	2.9	9.7

Profit is positive but insufficient

Real-time market: arbitrage + reserve

Optimization ignoring cycle aging

Annual revenue from arbitrage (k$)	789.3
Annual revenue from reserve (k$)	13.8
Annual loss of life from cycling (%)	77.0
Annual cycle aging cost (k$)	-2887.5
Annual profit (k$)	-2101.3
Proportion of profit from reserve (%)	-
Remaining battery life (year)	1.1

Real-time price volatility increases revenues and battery degradation

Real-time market: arbitrage + reserve

Optimization considering cycle aging

Annual revenue from arbitrage (k$)	789.3	372.3
Annual revenue from reserve (k$)	13.8	29.8
Annual loss of life from cycling (%)	77.0	2.6
Annual cycle aging cost (k$)	-2887.5	-96.3
Annual profit (k$)	-2101.3	276.3
Proportion of profit from reserve (%)	-	40.2
Remaining battery life (year)	1.1	8.0

Providing reserve is more profitable because it does not cause battery cycle aging

Conclusions

- Batteries can have value for the system while not being profitable
- Arbitrage currently requires very large price differences to be profitable
- Battery degradation must be considered when calculating actual profitability
- Provision of reserve (and frequency regulation) are currently more profitable than arbitrage

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