# Valuation of Commercial Lithium-ion Battery Technologies in North America Wholesale Electricity Markets


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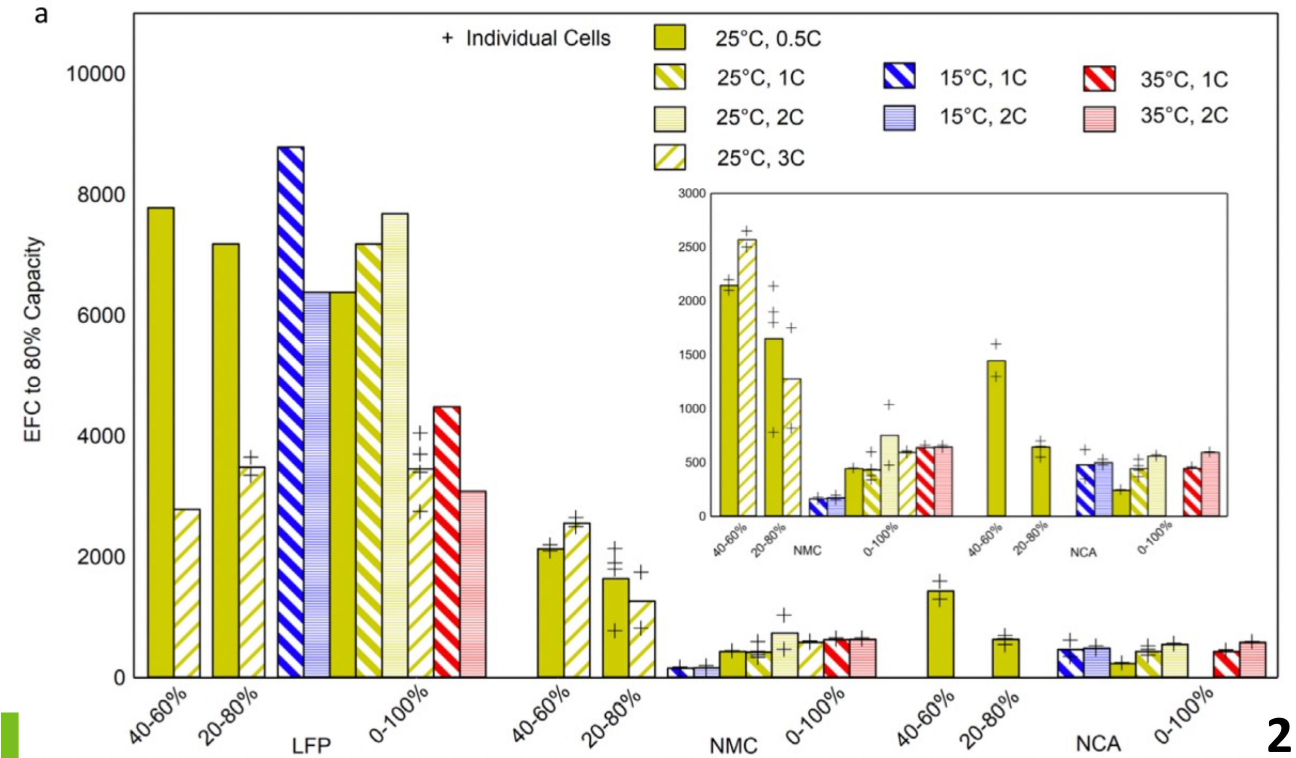
# Lithium-ion Batteries

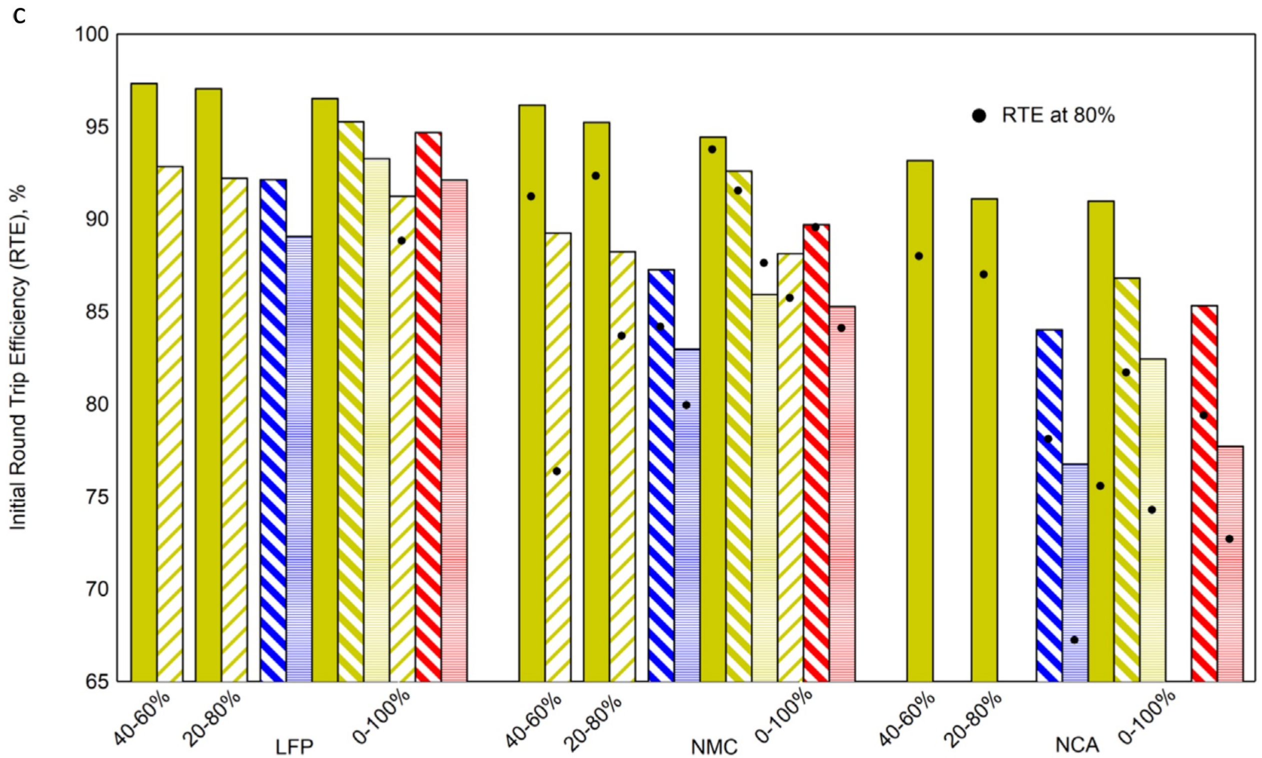
- LFP – Lithium Iron Phosphate battery
- NMC – Lithium Nickel Manganese Cobalt battery
- NCA - Lithium Nickle Cobalt Aluminum battery

Preger, Yuliya, Heather M. Barkholtz, Armando Fresquez, Daniel L. Campbell, Benjamin W. Juba, Jessica Romàn-Kustas, Summer R. Ferreira, and Babu Chalamala. "Degradation of commercial lithium-ion cells as a function of chemistry and cycling conditions." *Journal of The Electrochemical Society* 167, no. 12 (2020): 120532.

**Cycle life vs. cycle range**




**Efficiency vs. cycle range**



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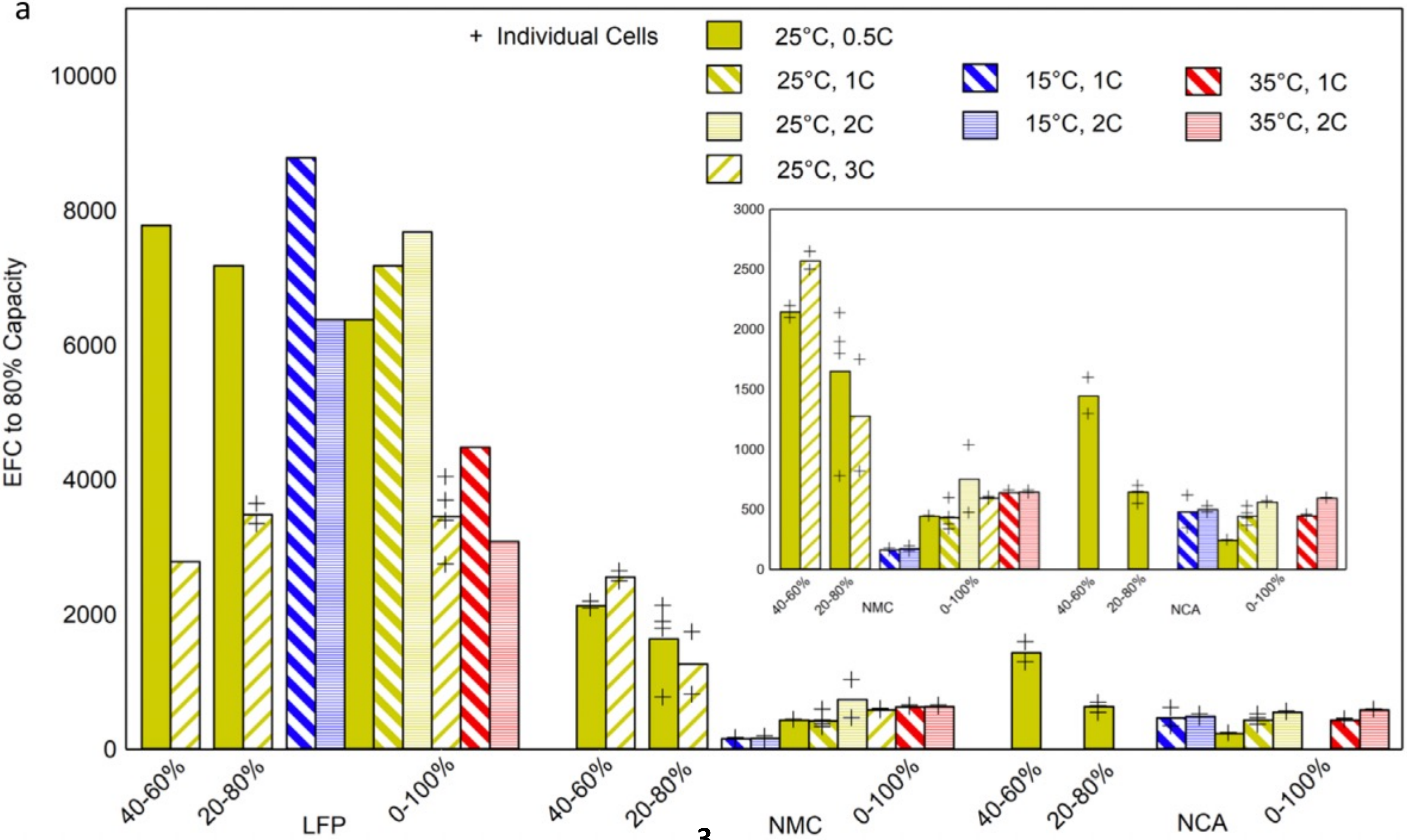
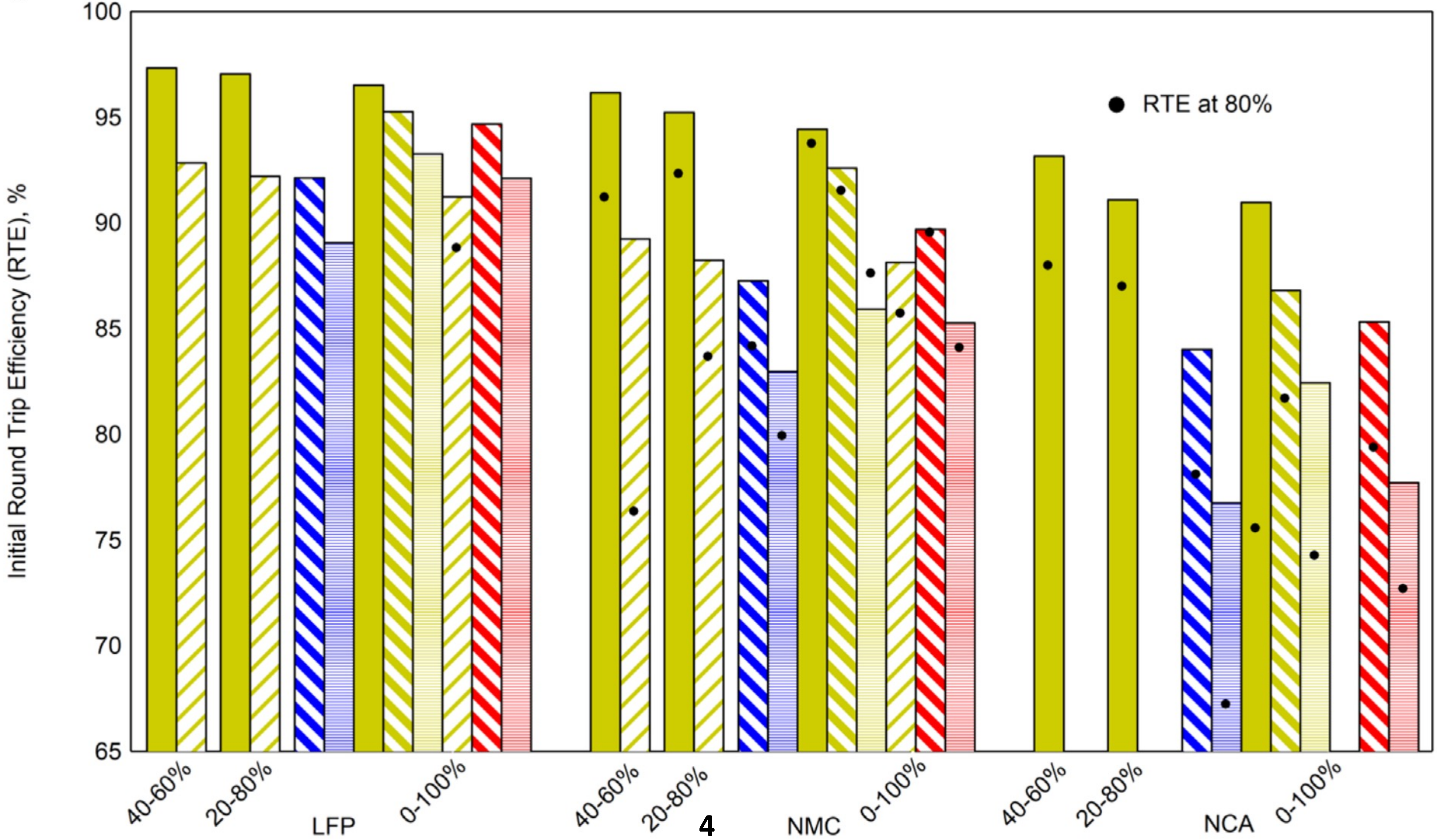


+ Individual Cells
25°C, 0.5C
25°C, 1C
25°C, 2C
25°C, 3C
15°C, 1C
15°C, 2C
35°C, 1C
35°C, 2C
EFC to 80% Capacity
0
2000
4000
6000
8000
10000
40-60%
20-80%
LFP
0-100%
40-60%
20-80%
NMC
0-100%
40-60%
20-80%
NCA
0-100%
0
500
1000
1500
2000
2500
3000

C



Initial Round Trip Efficiency (RTE), %
100
95
90
85
80
75
70
65
RTE at 80%
40-60%
20-80%
LFP
0-100%
40-60%
20-80%
NMC
0-100%
40-60%
20-80%
NCA
0-100%

# Battery Energy Storage Valuation

- Discounted revenue a storage could collect throughout its lifetime
  - Assuming optimal operation planning
- Technology-specific parameters
  - Efficiencies, degradation rate,…
  - Storage duration (power-to-energy ratio)
- Application
  - Market/Service type
  - Location

# Opportunity Valuation

## And why not using levelized cost of energy (LCOE)

- LCOE for storage has to assume a fixed operating pattern
  - i.e., one full cycle per day over 10 years
  - Not accurate as storage can adjust operation strategy based on markets

- Proposed: Maximize storage capacity value given its degradation mechanism
  - Cycle battery aggressively – makes more money today but shortens battery lifetime
  - Cycle battery conservatively – less money today but prolongs battery lifetime
  - Calendar degradation – battery losses capacity spontaneously (negative interest rate!)

# Dynamic Programming

## Ramsey's problem of optimal saving

https://en.wikipedia.org/wiki/Dynamic_programming

- A person with initial capital $k_0$
- Everyday $t$
  - Receive interest rate $\gamma$
  - Spent $c_t$ and receive a utility (pleasure): $\ln(c_t)$
  - Remaining balance: $k_{t+1} = (1+\gamma)k_t - c_t$
- Objective: maximize lifetime utility $\max \sum b^t \ln(c_t)$
- Solution using backward induction – start from the last day of life

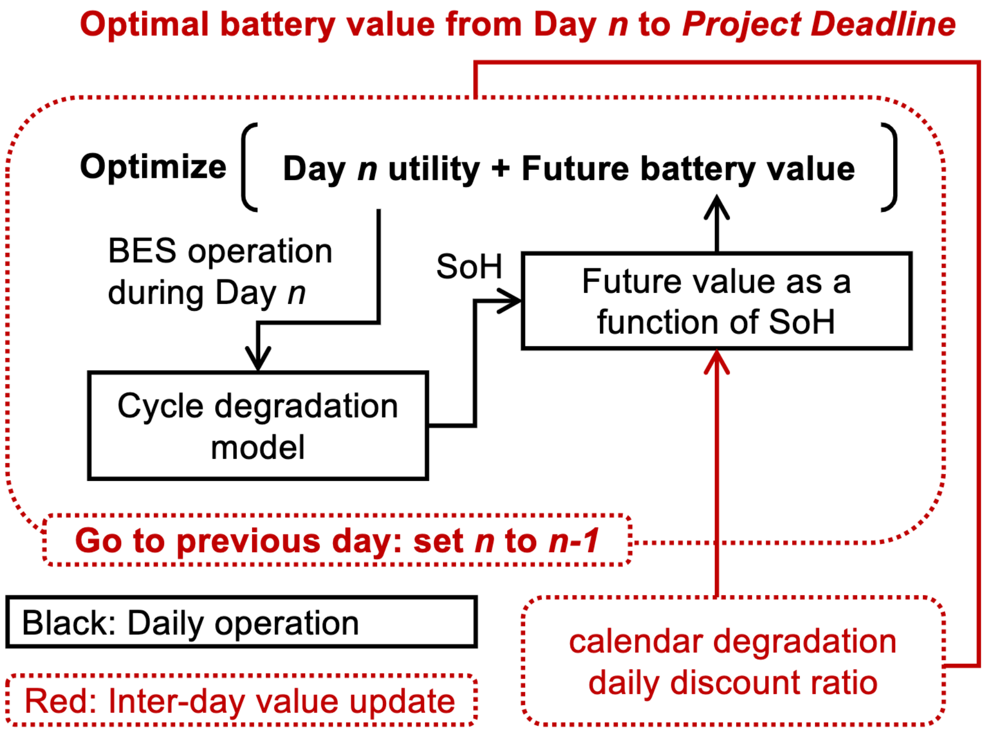
# Dynamic Valuation Framework

## Battery economic valuation using dynamic programming

$$V_n(E_n) := \max_{\boldsymbol{p}_n \in \mathcal{P}(E_{n+1})} O_n(\boldsymbol{p}_n) + \gamma V_{n+1}(E_{n+1})$$

$$E_{n+1} = E_n - D_{\text{cyc}}(\boldsymbol{p}_n) - D_{\text{cal}}$$

- V – time varying storage capacity value
- E – remaining battery capacity (state-of-health)
- O – utility function/market revenue
- p – battery charge/discharge profile
- $\gamma$ – daily discount ratio
- D – degradation functions
- n – index of days

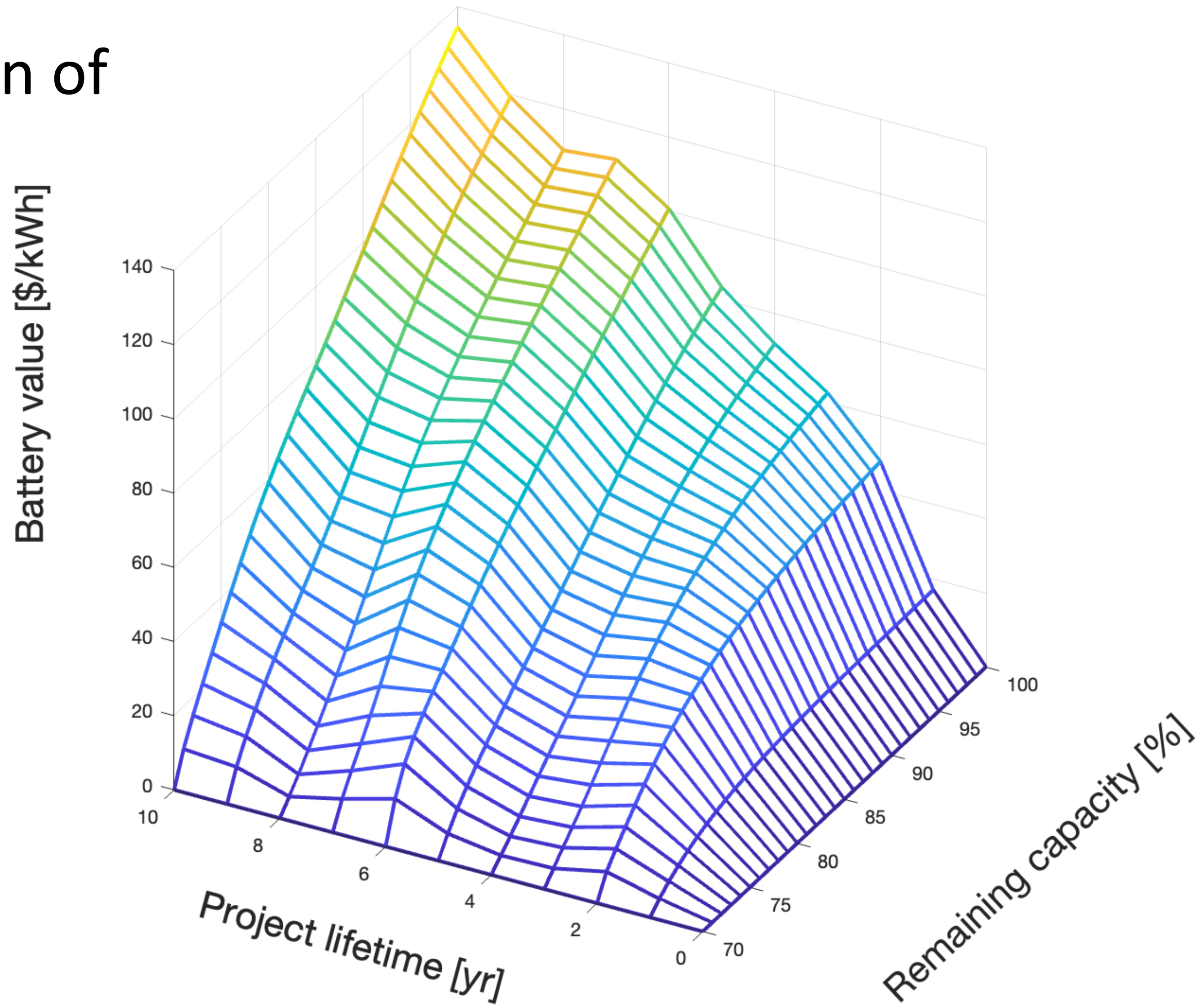



**Solution method using piece-wise linear value function approximation and backward induction**

Xu, Bolun. "Dynamic valuation of battery lifetime." *IEEE Transactions on Power Systems* 37, no. 3 (2021): 2177-2186.

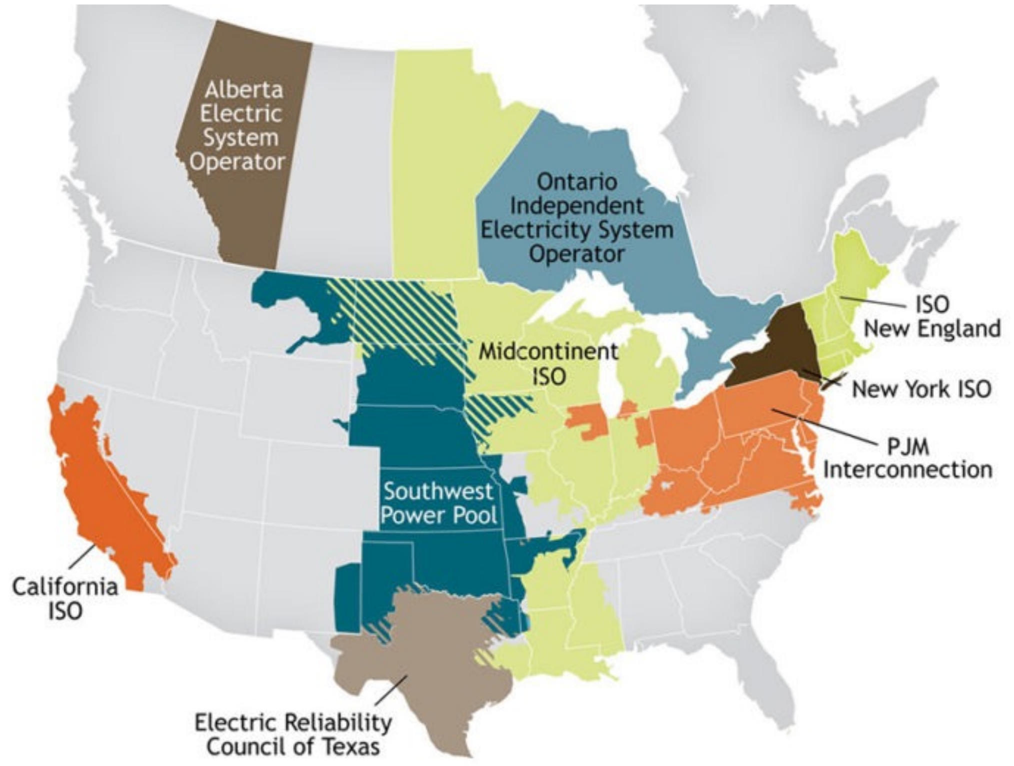
# Example Results

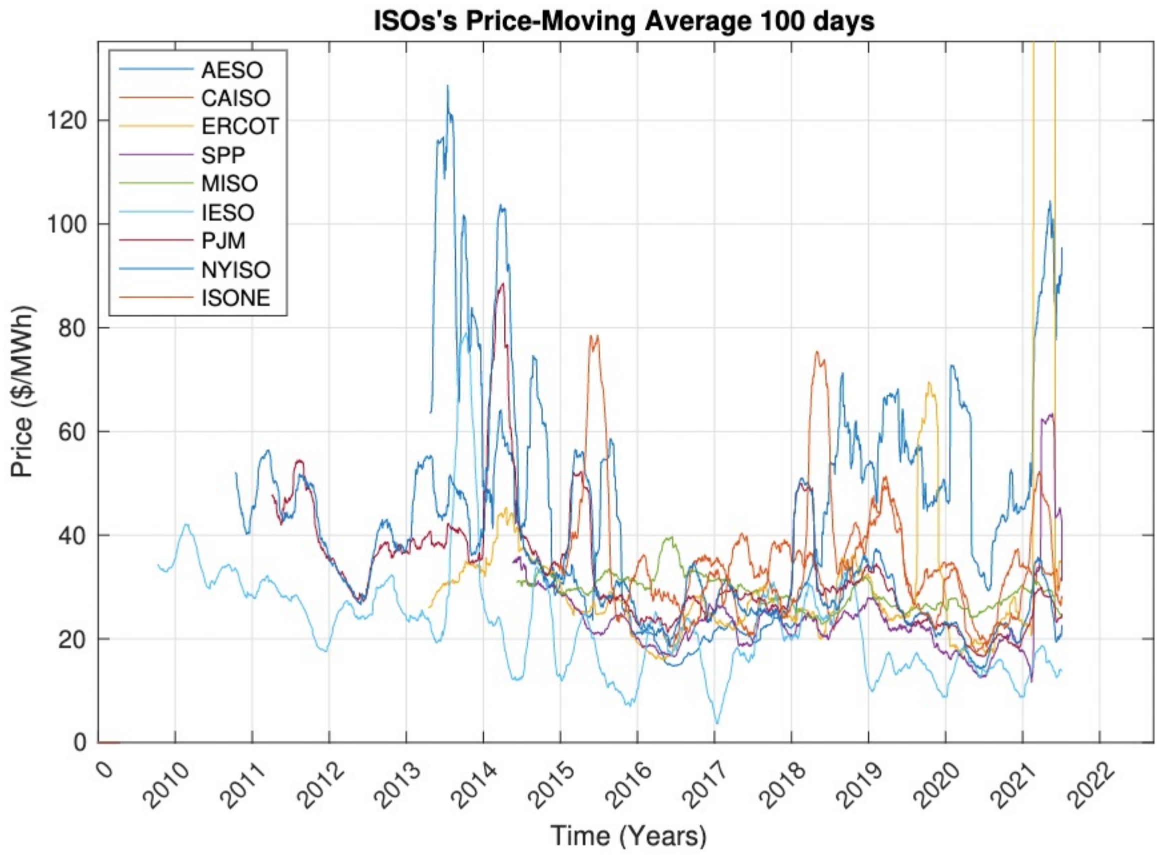
- Value of the battery is a function of
  - Technology
  - Application
  - Time
  - Remaining capacity (State-of-Health)



# Wholesale Electricity Markets

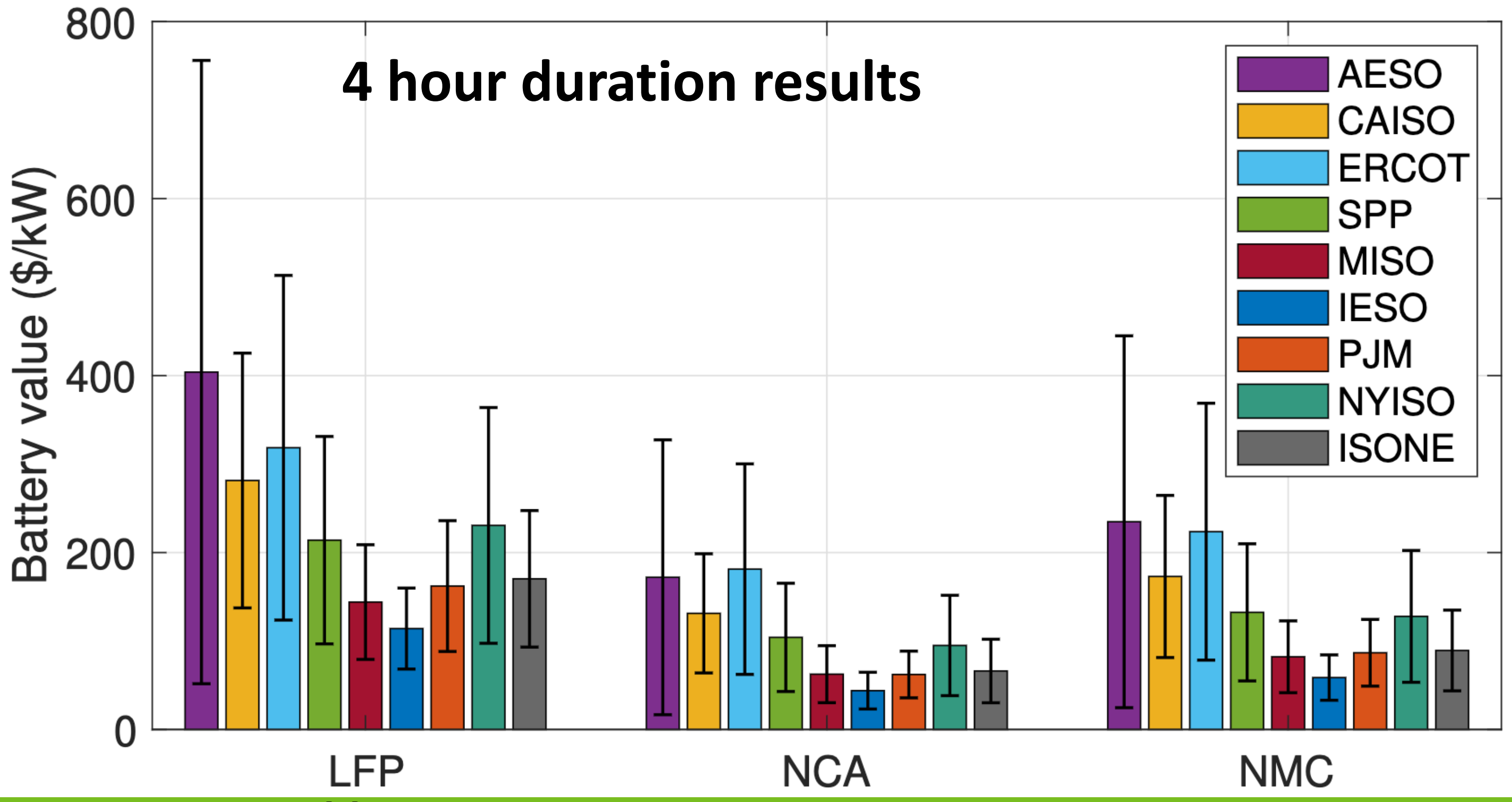
- Use price arbitrage for energy storage valuation
- Nine markets in North America



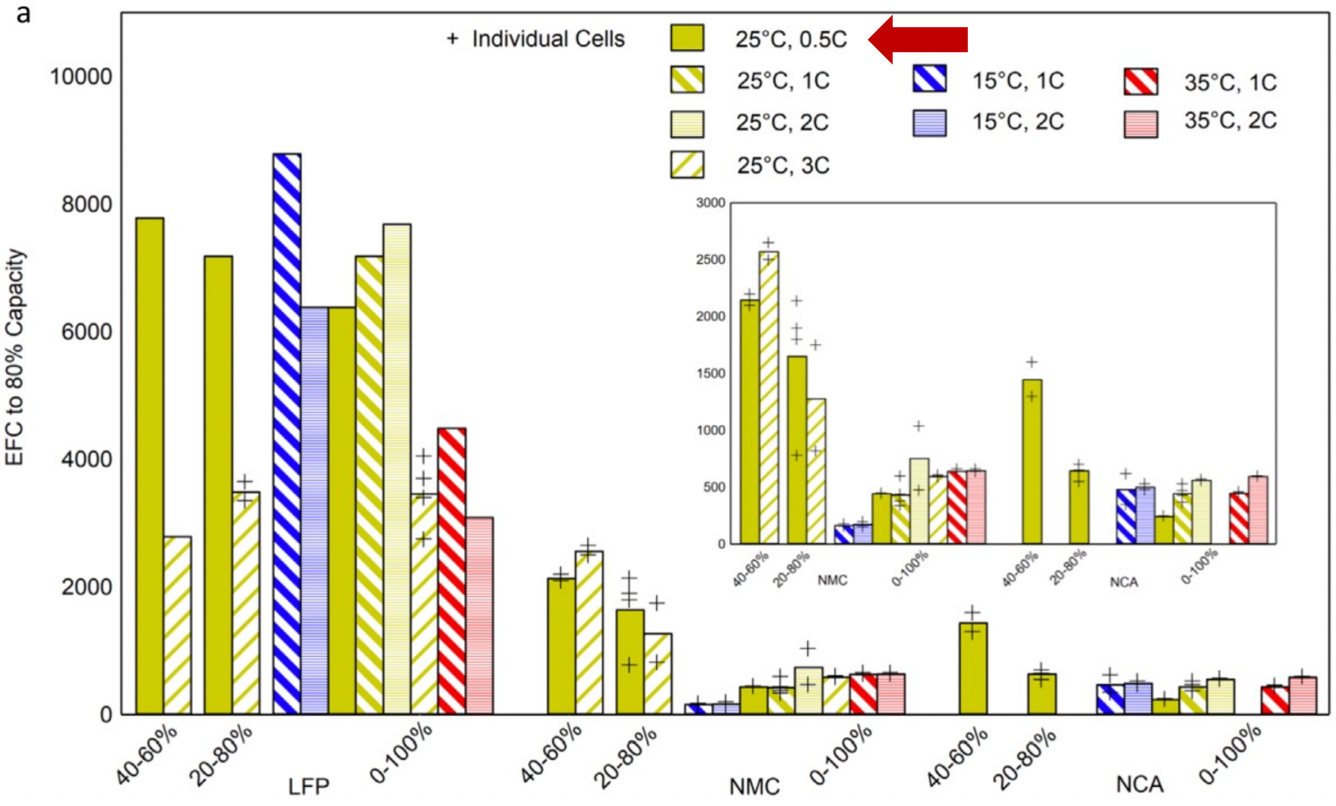
# Synthesizing Battery Value

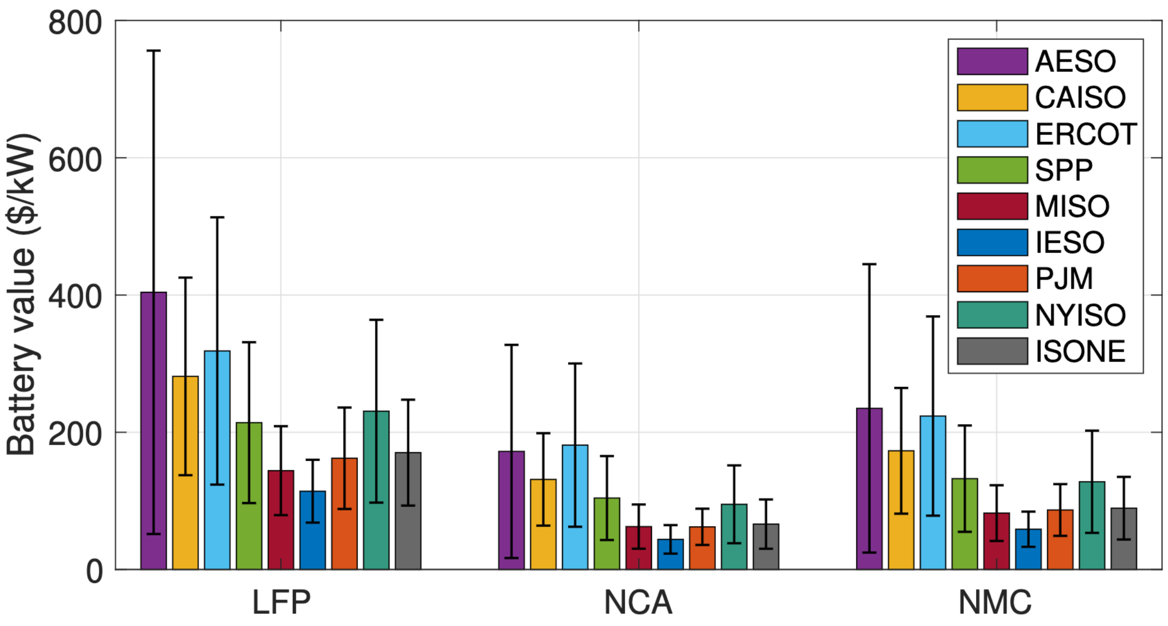
- Valuation using hourly real-time prices using zonal prices
- Perform valuation by repeating a single year price profile
- Per technology per location per calendar year
- Whiskers represent annual variation ranges

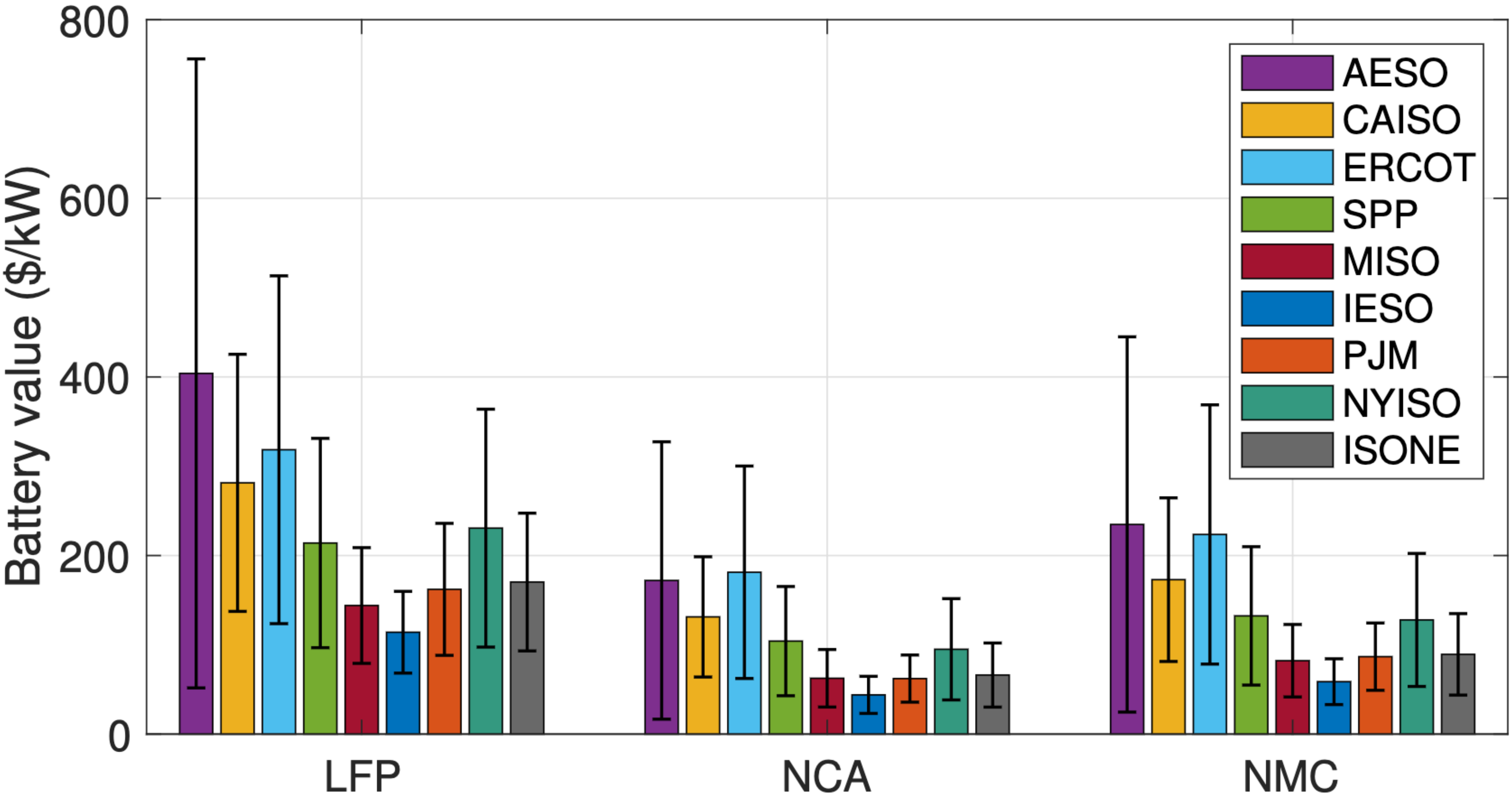


# Technology Comparison

- LFP has the highest value due to higher cycle life
- NMC/NCA obtained around 50% of value compared to LFP, despite their cycle life is only around 20% to 5% compared to LFP



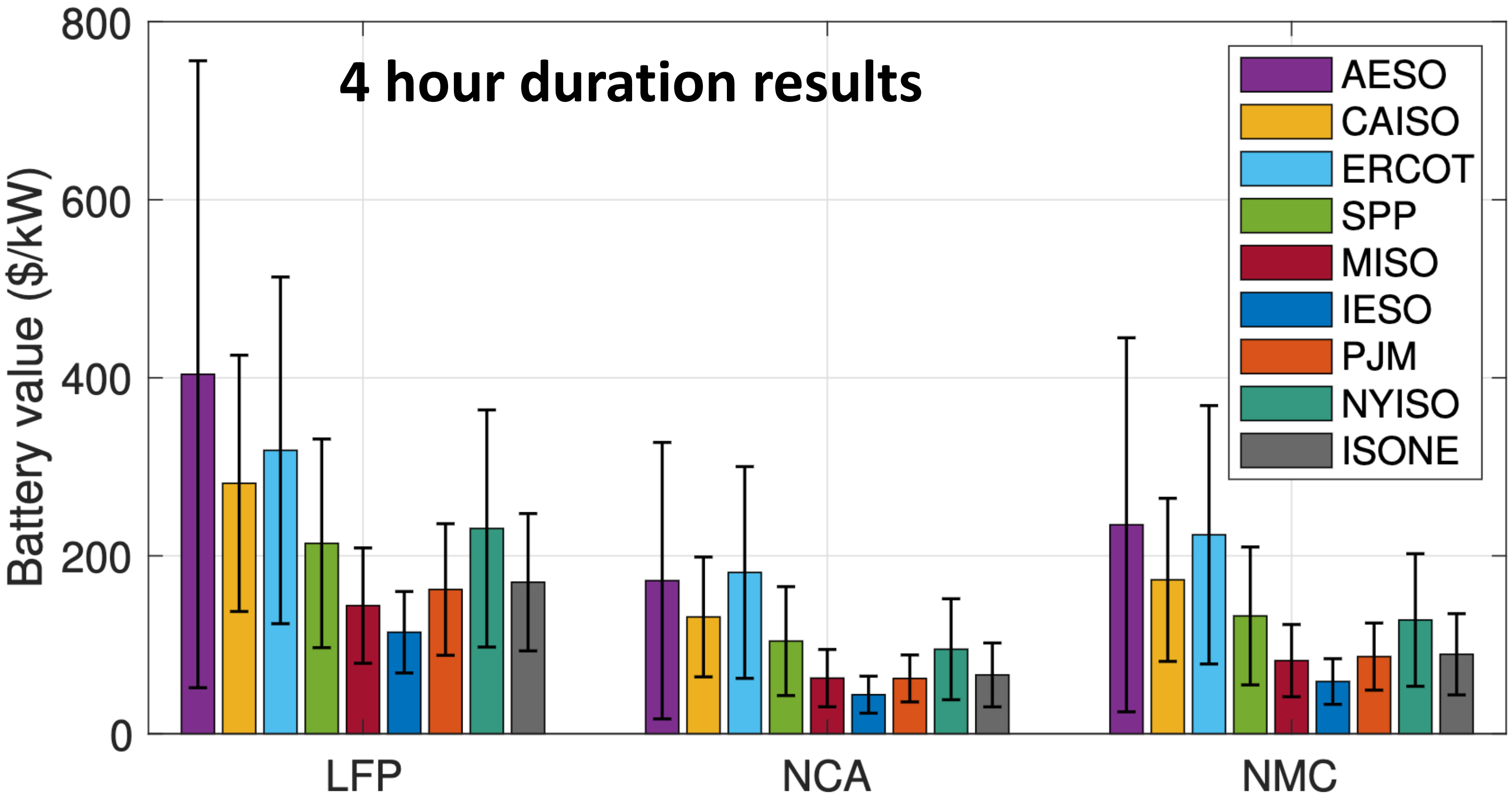




800
600
400
200
0
Battery value ($/kW)
LFP
NCA
NMC
AESO
CAISO
ERCOT
SPP
MISO
IESO
PJM
NYISO
ISONE

# Location Comparison

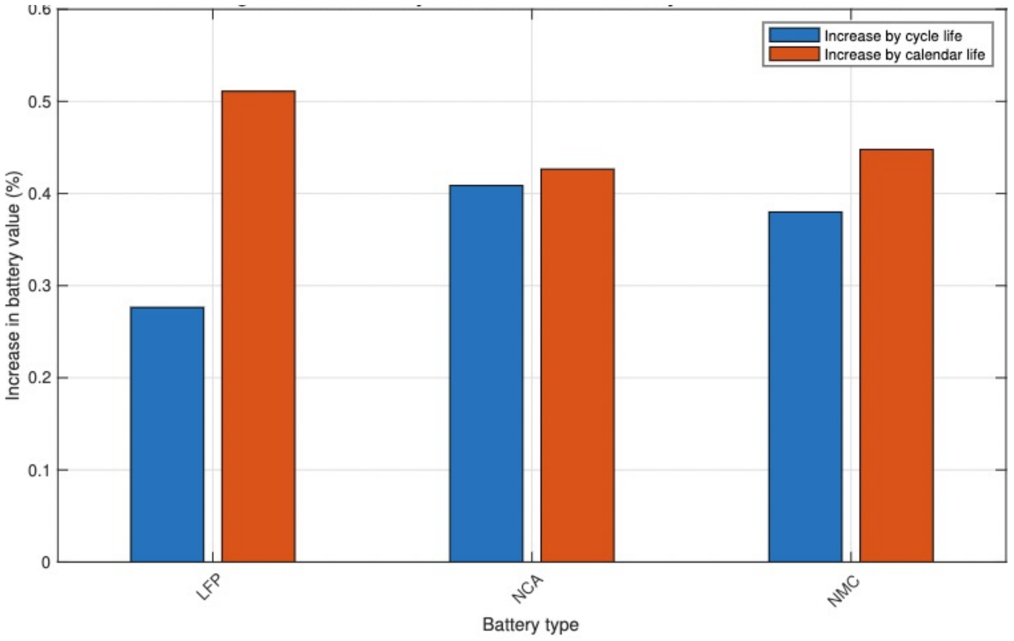
- Markets with higher renewable share provides higher storage value
- AESO provides highest battery value, followed by ERCOT, CAISO, and SPP

| ISO | Energy type/percentage share | | | | | |
|---|---|---|---|---|---|---|
| | Wind | Solar | Hydro | Nuclear | NG/ Oil | Coal |
| CAISO | 8 | 15 | 10 | 9 | 48 | 0 |
| AESO | 13 | 4 | 6 | 0 | 46 | 16 |
| SPP | 29 | 0 | 4 | 2 | 39 | 24 |
| ERCOT | 23 | 4 | 0 | 11 | 43 | 18 |
| MISO | 3 | 0 | 3 | 9 | 45 | 36 |
| IESO | 9 | 2 | 24 | 57 | 6 | 0 |
| PJM | 3 | 1 | 2 | 34 | 38 | 38 |
| NYISO | 5 | 1 | 23 | 29 | 43 | 0 |
| ISONE | 3 | 3 | 7 | 27 | 46 | 1 |



# Sensitivity Studies - Lifetime

Percentage increase in battery value due to 1% increase cycle or calendar life

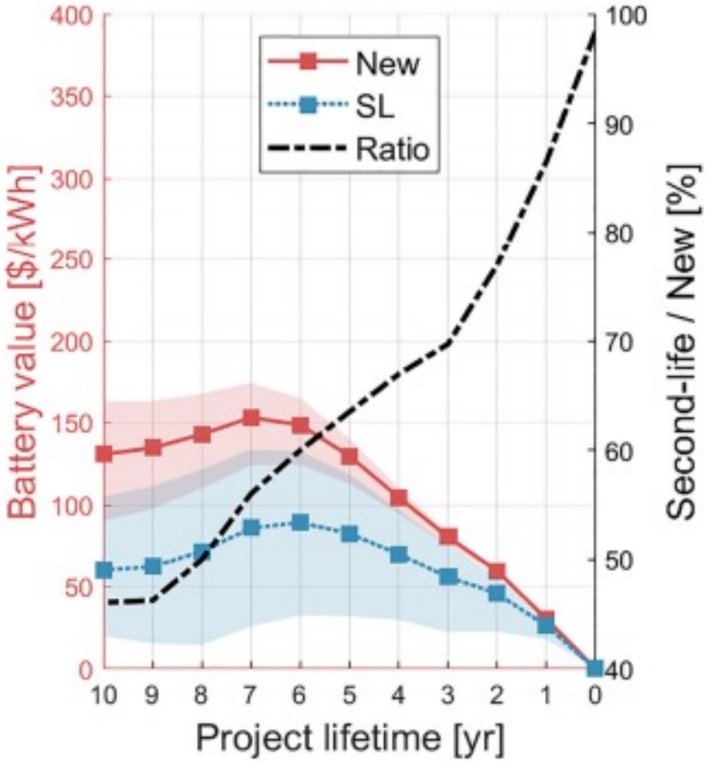



- Calendar life more significant, especially in long cycle life batteries

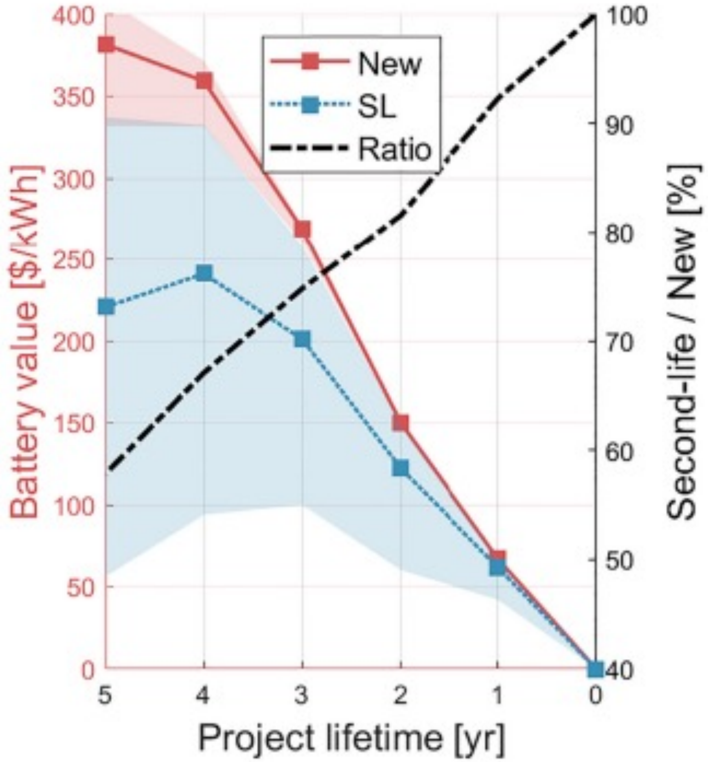
# Second-life Battery Value

**New battery value vs. Second life (80% SoH), End-of-life ranges between 75% to 50%**

**Price Arbitrage**
**(NYISO - WEST)**




**Frequency Regulation**
**(PJM - RegD)**



# Conclusions

Storage technology valuation using dynamic programming

- A framework for battery technology valuation
- LFP provides best value for grid-scale storage
- Regional value high correlates with renewables
- Calendar life is more important for existing storage technologies
- Second-life batteries still provide considerable economic value

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# Thank You

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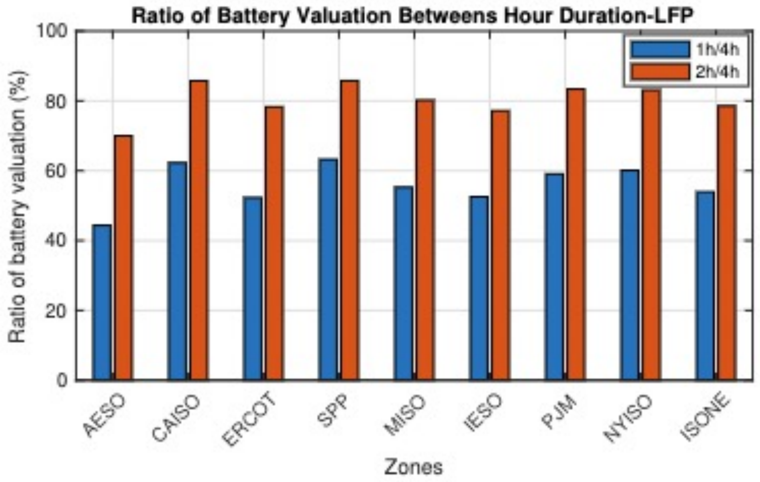
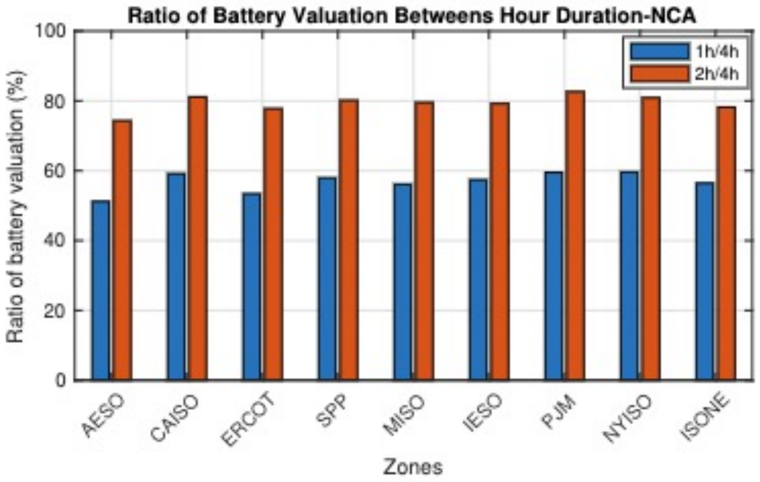
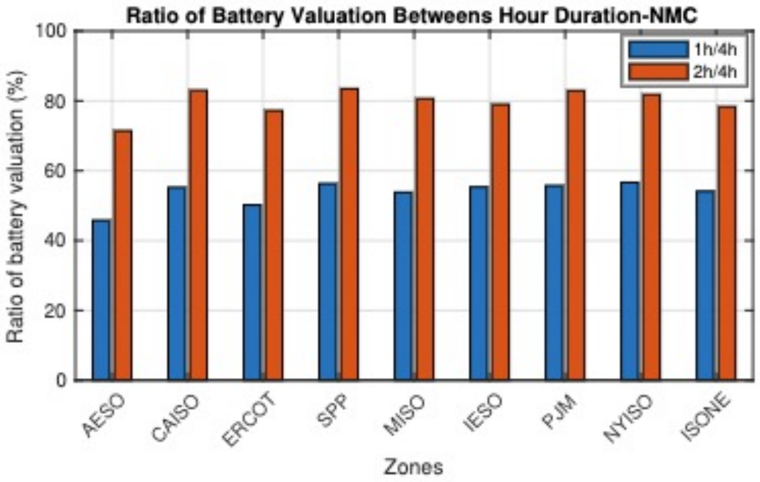
# Sensitivity Studies - Duration




- Consistent value ratio with different battery durations across locations and technologies