Economic Analysis and Optimal Sizing for Behind-the-meter Battery Storage

DI WU

Pacific Northwest National Laboratory

Interagency Sustainability Working Group Webinar

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U.S. DEPARTMENT OF ENERGY

Grid Applications/Services using Energy Storage

- Transmission level
  - energy arbitrage
  - frequency regulation
  - spin and non-spin reserve
  - primary frequency response
  - resource adequacy
- Distribution level
  - distribution upgrade deferral
  - outage mitigation
  - volt/var support
- Behind-the-meter and customer domain
  - energy charge reduction (load shaping charge or energy imbalance charge)
  - demand charge reduction

Department of Commerce
BONNEVILLE POWER ADMINISTRATION
Sandia National Laboratories
CleanEnergy States Alliance
AVISTA
PSE PUGET SOUND ENERGY
SNOHOMISH COUNTY PUD PUBLIC UTILITY DISTRICT NO. 1
Portland General Electric
ORCAS POWER & LIGHT CO-OP
ENERGY NORTHWEST
EWEB
UET UniEnergy Technologies
PRIMUS POWER
BYD
Mitsubishi International Corporation
LG Chem

Washington State Clean Energy Funds Energy Storage Projects

2MW/1 MWh Li-ion system
2MW/8.8 MWh UET vanadium-flow
Everett, WA

2 MW/4.4 MWh lithium-ion/phosphate battery
Glacier, WA

1 MW/3.2 MWh UET vanadium-flow battery
Pullman, WA

Total—7 MW/15 MWh;
$14.3 million state investment and $43 million total investment for energy storage systems

Battery Storage for Behind-the-meter Applications

- Energy charge is based on the amount and time when energy is consumed.
  - Load shaping charge and energy imbalance charge are very similar as energy charge and can be modeled using the same mathematic formulation.
- Demand charge is based on the highest power consumption in different time periods.
- Separate charges for energy and demand more fairly distributed power system's operation and investment cost to customers.
- Example of electric utility rate tariff

		Summer	Winter (Oct.-May)
Energy ($/kWh)	On	0.145	NA
	Mid	0.092	0.096
	Off	0.067	0.073
Demand ($/kW/month)		30	

Battery Optimal Dispatch

$$\min_{p_k, e_k^{\text{batt}}} \quad \underbrace{\sum_{k=1}^{K} \lambda_k \overbrace{(L_k - p_k)}^{\text{net load}} \Delta T}_{\text{energy cost}} + \underbrace{\sum_{j=1}^{J} \beta_j \overbrace{\max\left(\{L_k - p_k : k \in \mathcal{N}_j\}\right)}^{\text{peak demand over time period } j}}_{\text{demand cost}} \qquad (1a)$$

subject to:

Charging/discharging limit: $-p_{\max} \le p_k \le p_{\max}, \quad \forall k = 1, \cdots, K \qquad (1b)$

ROC of energy in batt.: $p_k^{\text{batt}} = \begin{cases} p_k/\eta^+ & \text{if } p_k \ge 0 \\ p_k\eta^- & \text{if } p_k < 0 \end{cases}, \quad \forall k = 1, \cdots, K \qquad (1c)$

Dynamics of energy in batt.: $e_k^{\text{batt}} = e_{k-1}^{\text{batt}} - p_k^{\text{batt}}, \quad \forall k = 1, \cdots, K \qquad (1d)$

Energy limits: $0 \le e_k^{\text{batt}} \le E_s/\eta^+, \quad \forall k = 1, \cdots, K \qquad (1e)$

L_k: Load without battery at time step k (e.g., 15-minute or hour).

p_k: Battery charging/discharging power (measured at AC side) at time step k, which is positive when discharging, i.e., using generator convention.

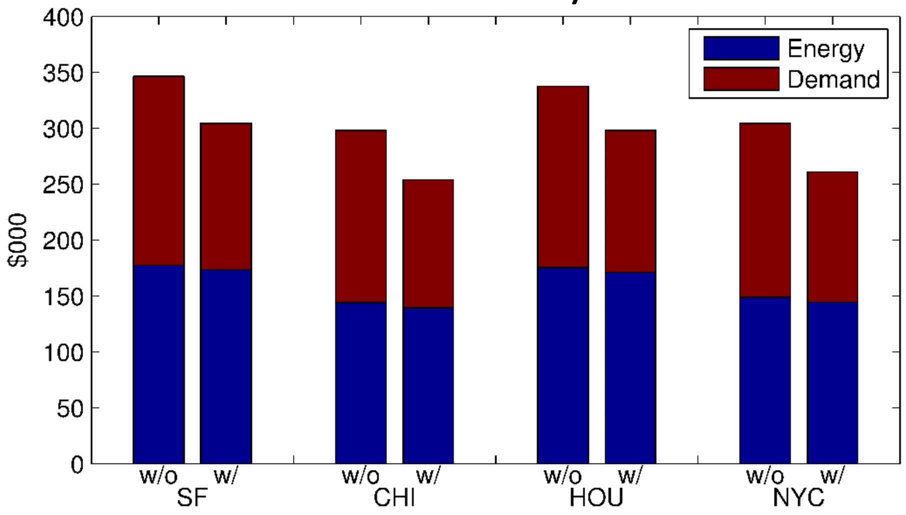
- D. Wu, C. Jin, P. Balducci, and M. Kintner-Meyer, “An energy storage assessment: Using optimal control strategies to capture multiple services,” *IEEE Power and Energy General Meeting*, Denver, CO, Jul. 2015.
- D. Wu, M. Kintner-Meyer, T. Yang, and P. Balducci, “Economic analysis and optimal sizing for behind-the-meter battery storage,” *IEEE Power and Energy General Meeting*, Boston, MA, Jul. 2016.
- D. Wu, M. Kintner-Meyer, T. Yang, and P. Balducci, “Analytical sizing methods for behind-the-meter battery storage,” *Journal of Energy Storage*, Aug. 2017.
- D. Wu, P. Balducci, A. Crawford, V. Viswanathan, and M. Kintner-Meyer, “Optimal control for battery storage using nonlinear models” *Electrical Energy Storage Applications and Technologies Conference,* San Diego, CA, Oct. 2017.

Annual Electricity Cost and Saving

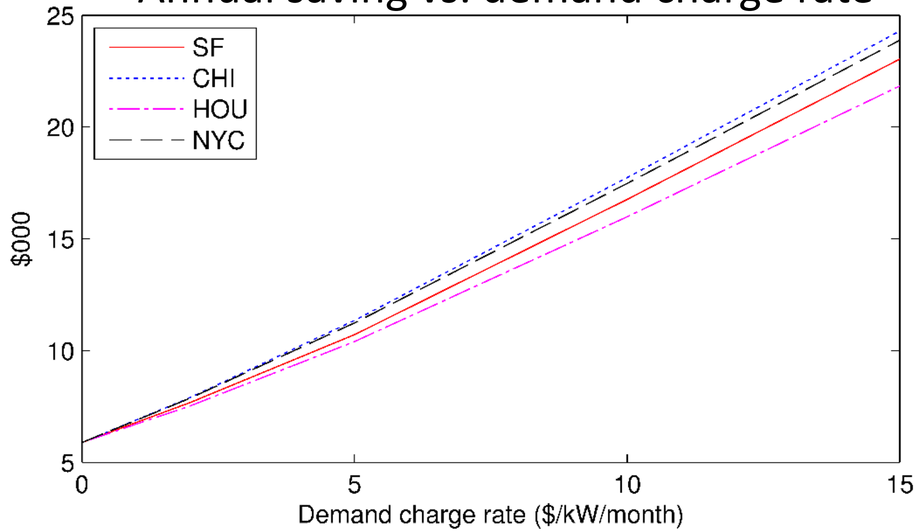
Battery rating: 0.2 MW/0.8 MWh
Efficiency: 0.868 (charging) and 0.887 (discharging)

- Demand charge account for half of total electricity bill. The capability of lowering peak from battery provides a great opportunity to cut electricity bill.
- Saving in energy charge is marginal comparing with demand charge due to losses.
- Total saving in electricity bill do not vary significantly with office load patterns.
- Energy charge reduction is independent of load profiles.
- Annual saving in electricity bill is quite linear to demand charge rate.

Annual Electricity Cost

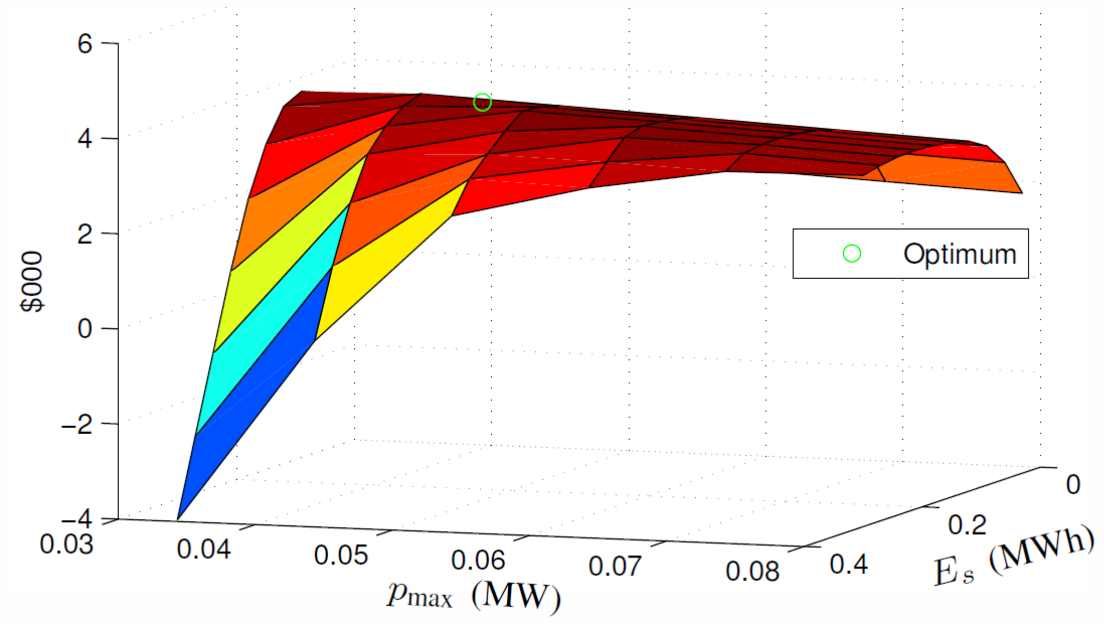


Annual saving vs. demand charge rate

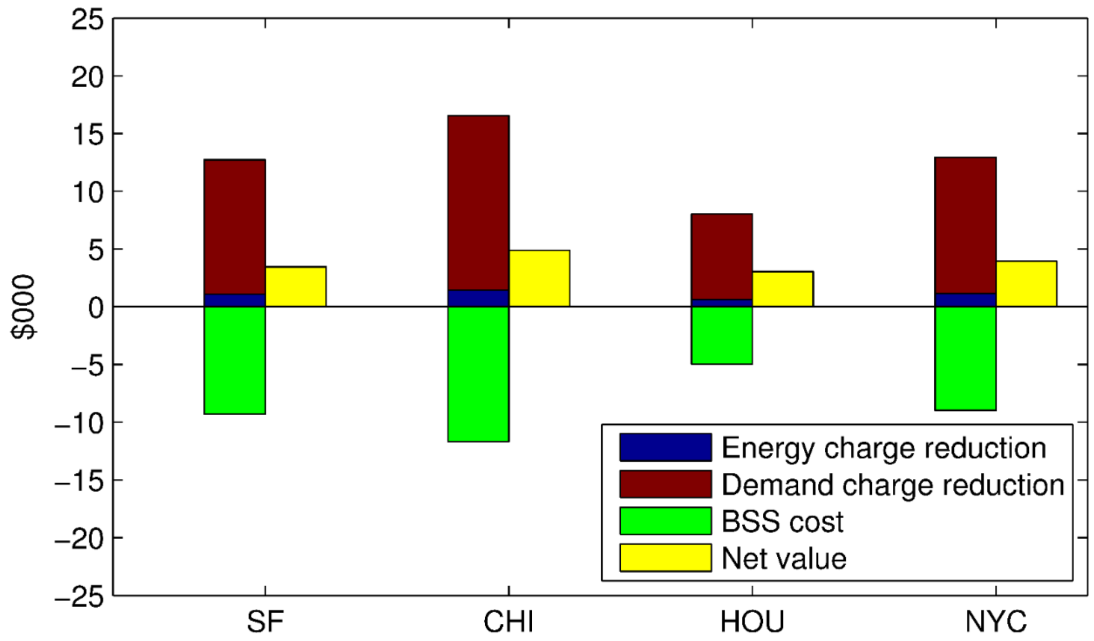


Optimal Sizing

Sensitivity of net value on battery sizes with Chicago office building load profile



Annual benefits vs. levelized cost with optimal size



Los Alamitos Microgrid with Energy Storage

- Background
- Key questions
  - What are the potential benefits from different investment candidates?
  - What is the optimal scale in terms of power and energy capacity for the energy storage systems?
  - How can we evaluate tradeoffs between benefits accruing to end-user and utility?

Use cases

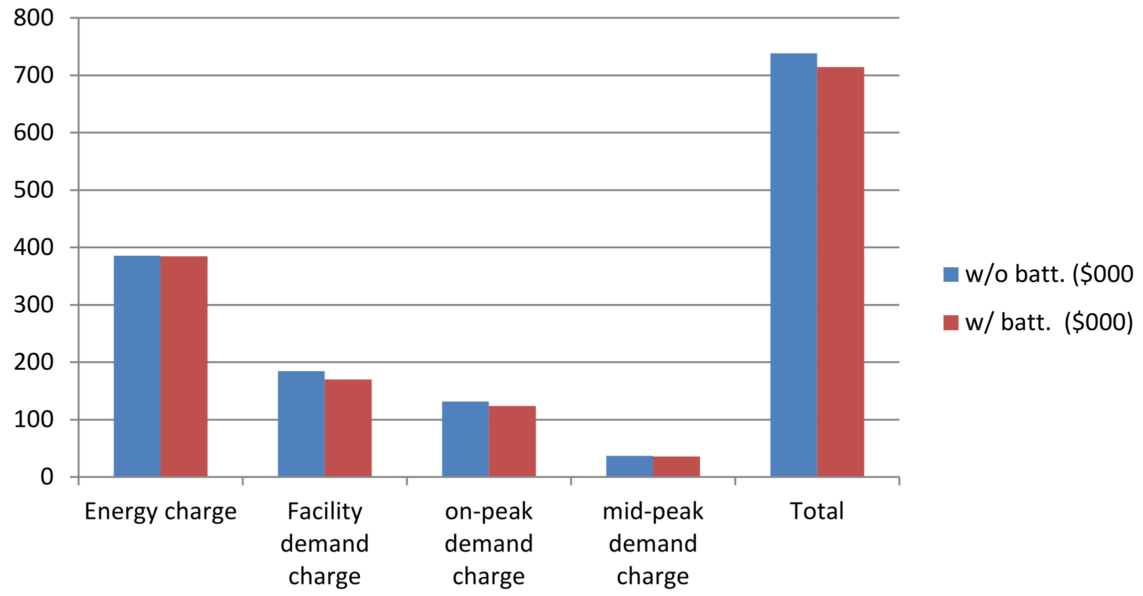
- Utility benefits
  - Capacity value
  - Energy time shifting
  - Regulation services
  - Spin and non-spinning reserves
  - Outage mitigation
  - Distribution investment deferral
  - Voltage support

- End-user benefits
  - Energy time shifting (reduce energy charge)
  - Peak demand reduction (reduce demand charge)
  - Outage mitigation

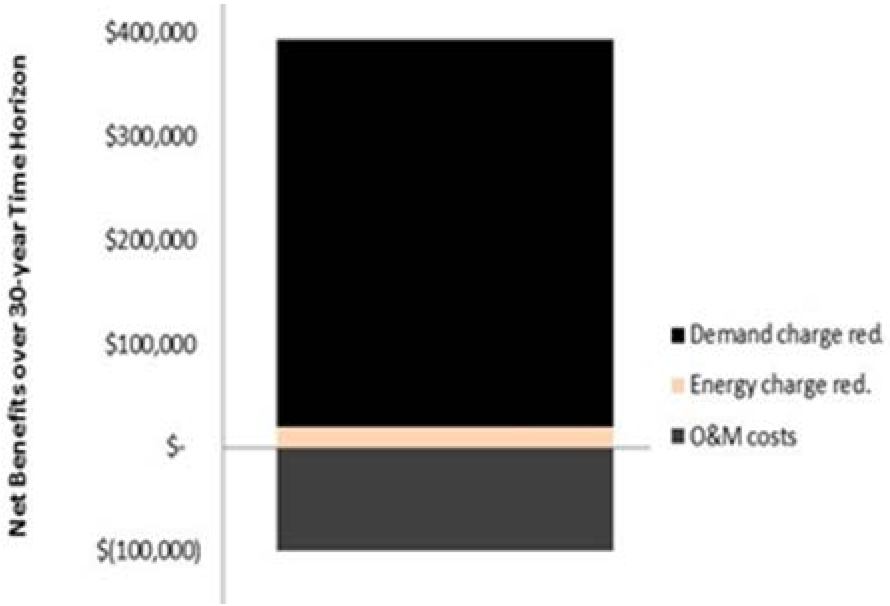
Results in Scenario a

175 kW/175 kWh (behind-the-meter, benefits to end-user)

Annual



Present value

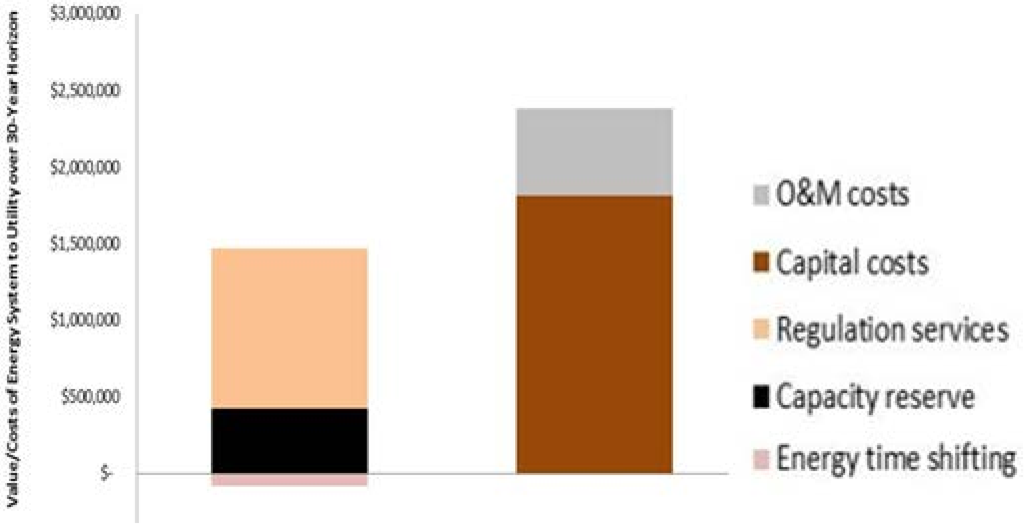


Key Point: BSET found optimal energy storage sizing at 204 kW/258 kWh when combined with 625 kW of PV.

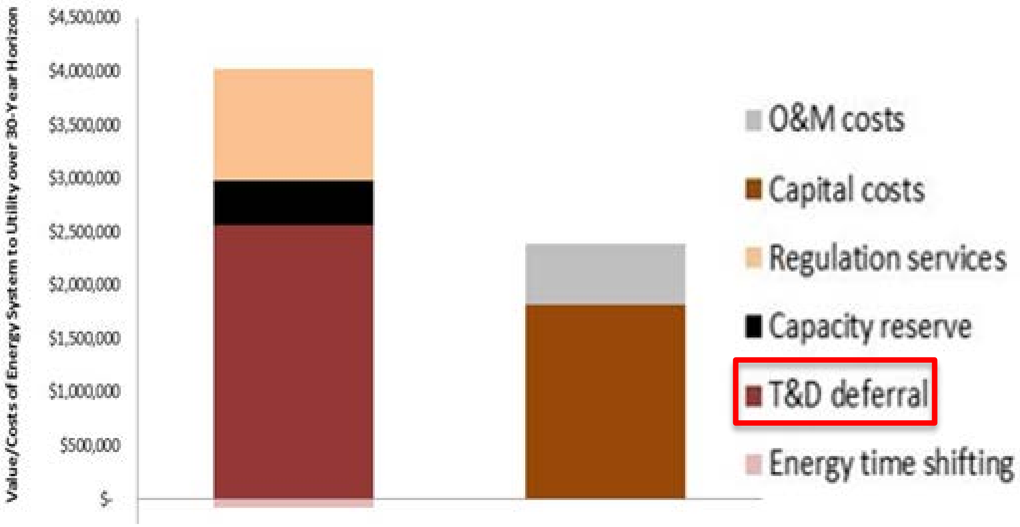
Results in Scenario b

1 MW/1 MWh (utility invested and owned)

Utility benefits without T&D deferral

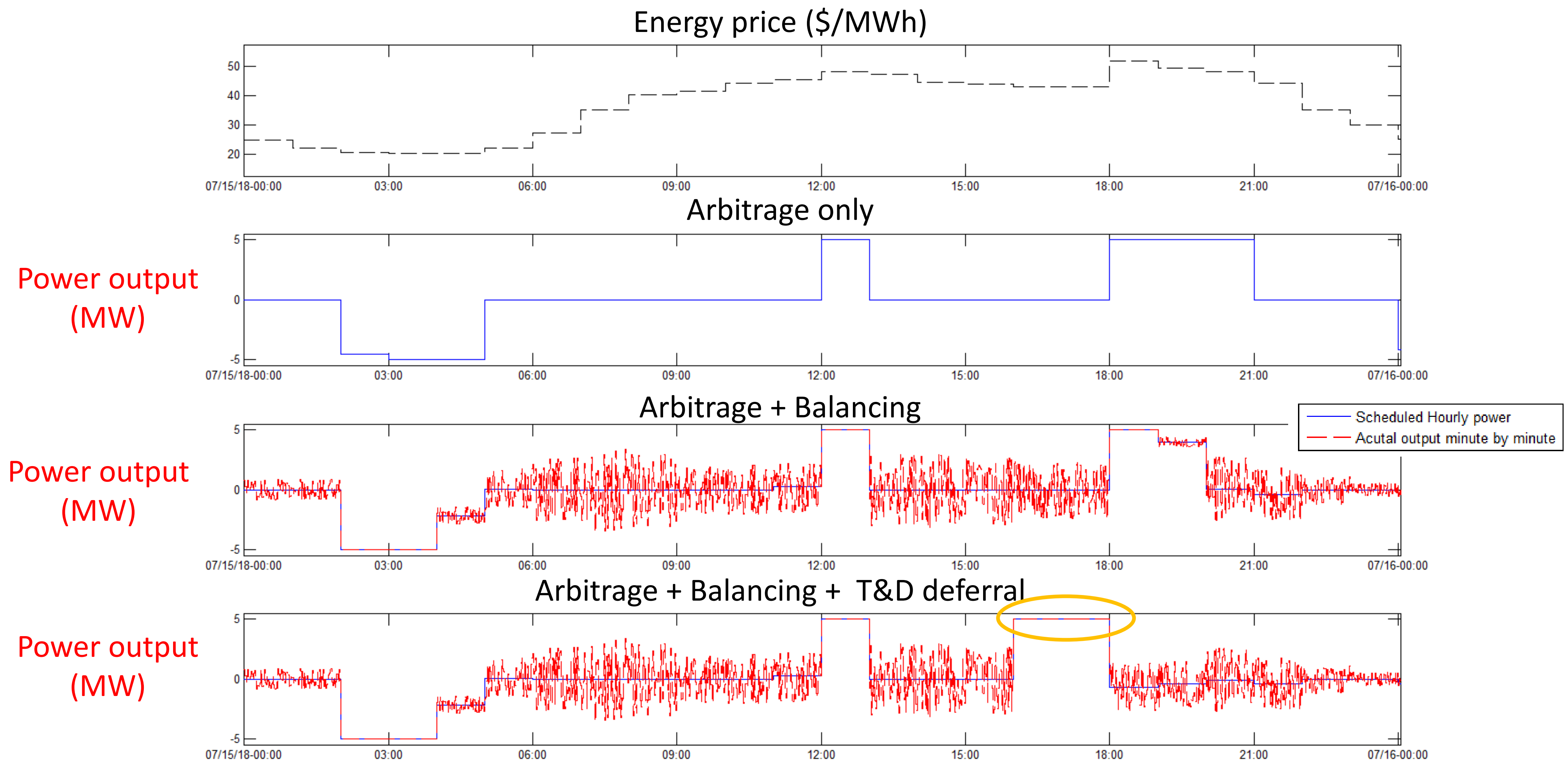


Utility benefits include T&D deferral ($156/kW-year)



Key Point: In base case, energy storage benefits are significant but fall short of costs. Adding transmission and distribution (T&D) system upgrade deferral could easily yield benefits that exceed costs.

Bundling Services: How To Do It Optimally?



Pareto Front for Multi-objective Optimization

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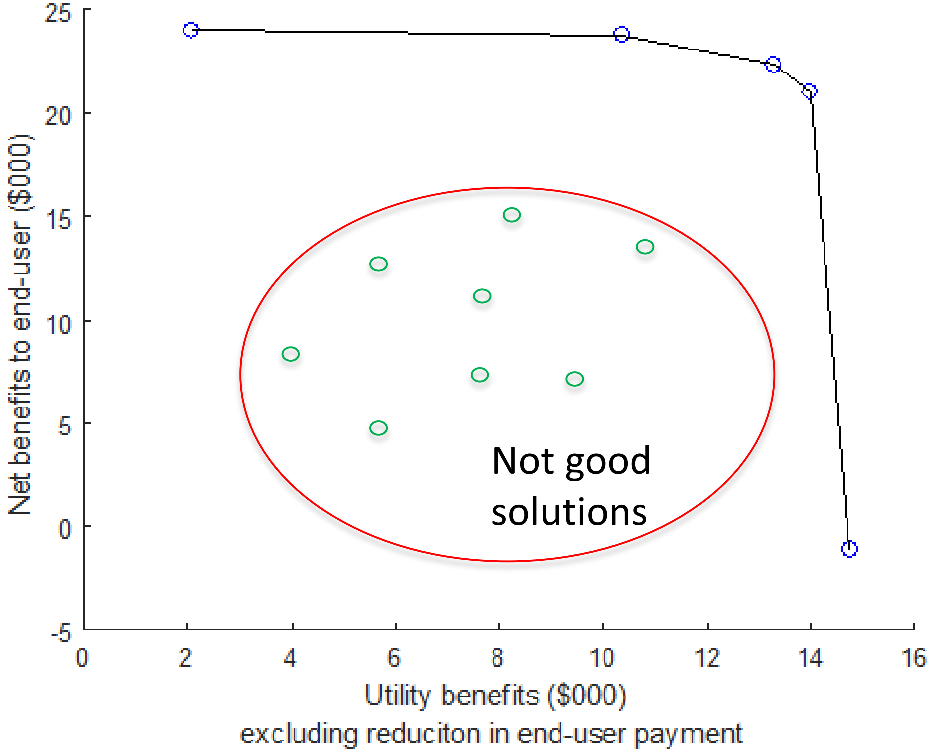
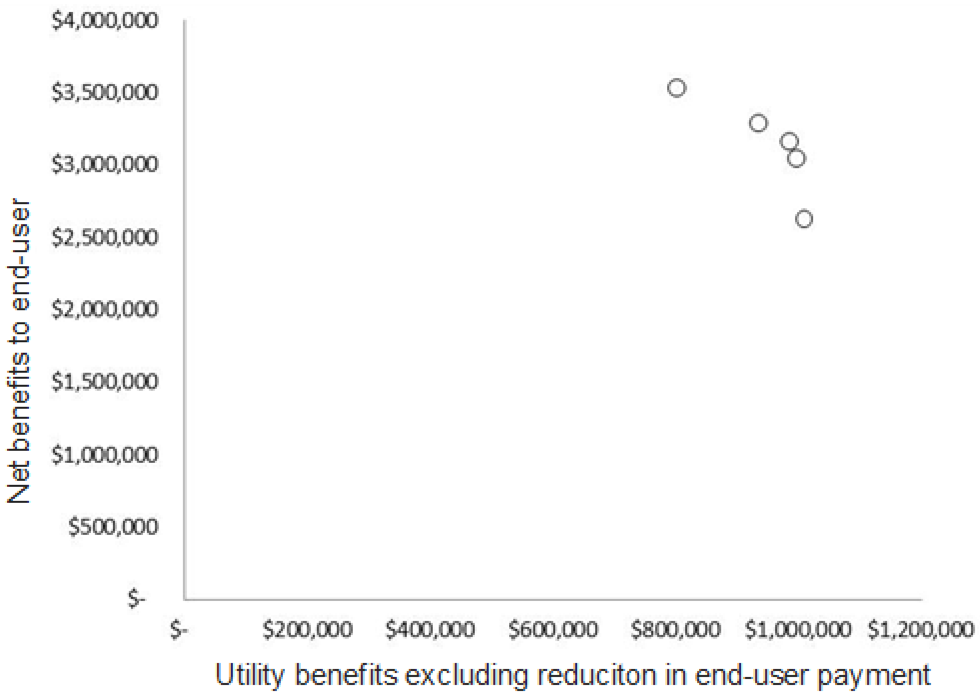
175kW /175kWh battery

Annual



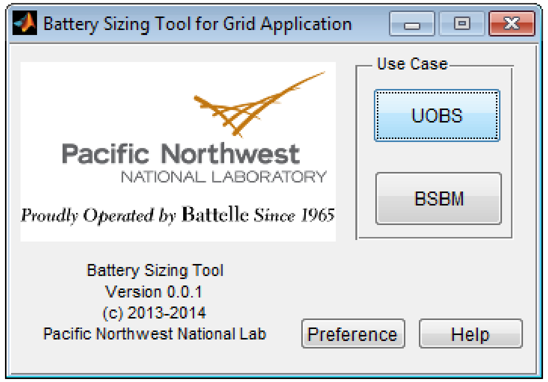
625 kW PV + 175kW /175kWh battery

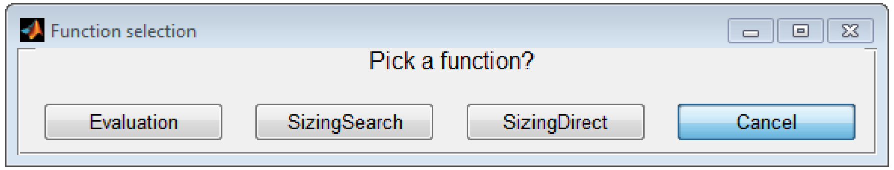
Present value

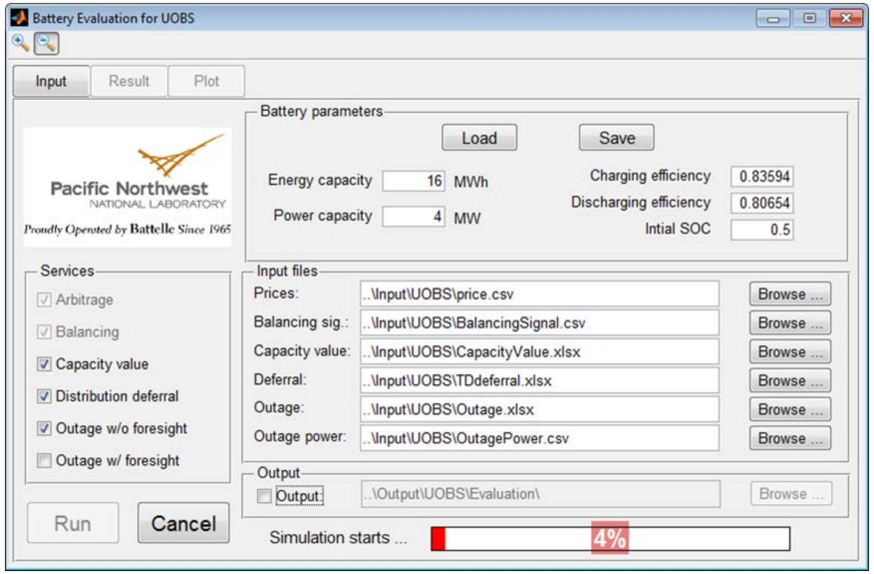


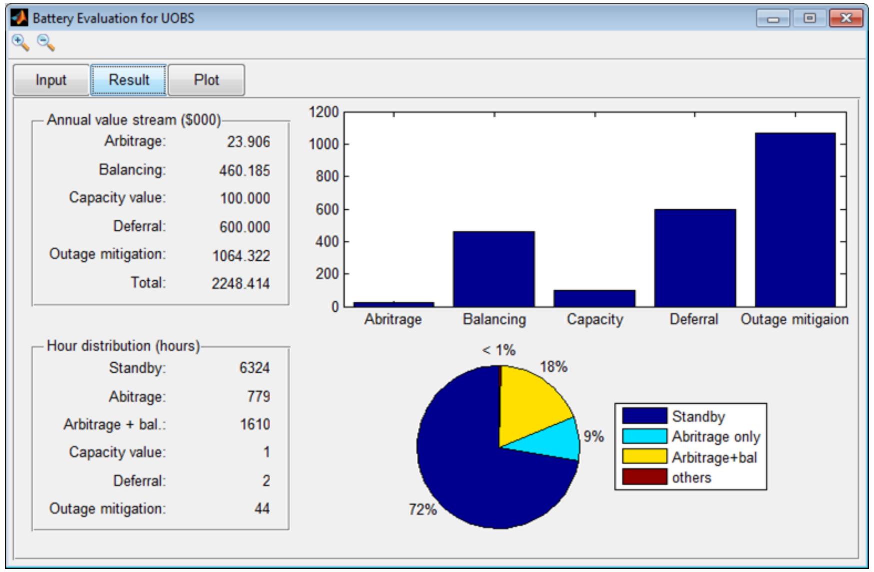
There does not exist a single solution that can simultaneously maximize both objectives; there exist Pareto optimal solutions

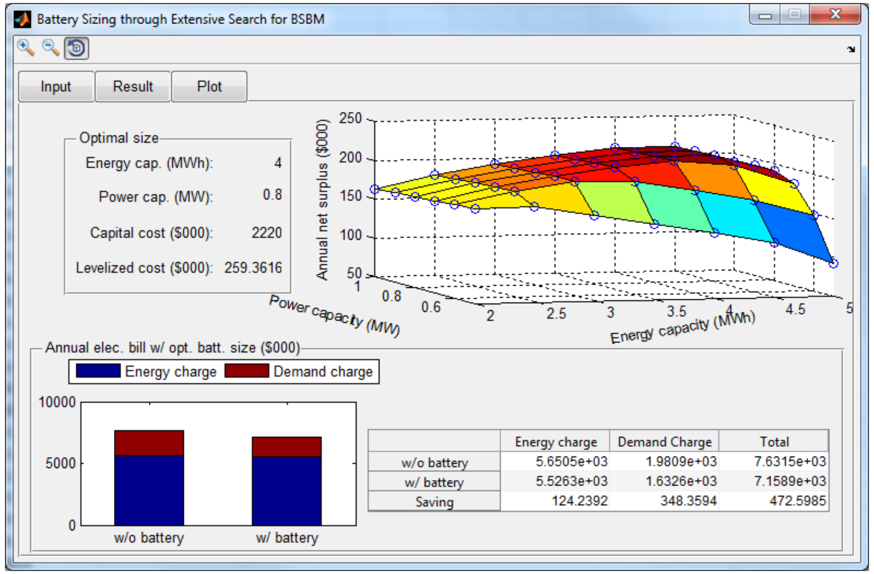
Evaluation and Sizing Tool











	Energy charge	Demand Charge	Total
w/o battery	5.6505e+03	1.9809e+03	7.6315e+03
w/ battery	5.5263e+03	1.6326e+03	7.1589e+03
Saving	124.2392	348.3594	472.5985

Thank you !

Questions?

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