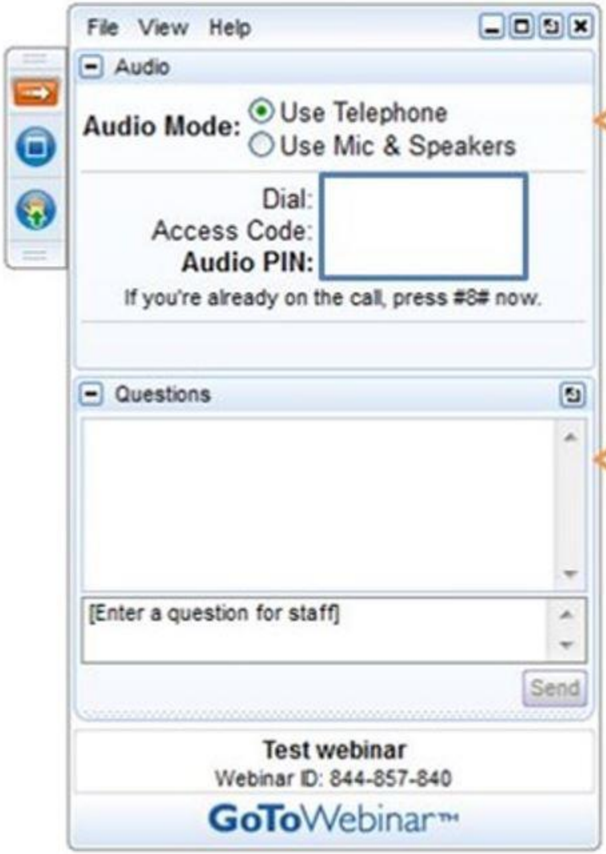
Energy Storage Technology Advancement Partnership (ESTAP) Webinar:

Optimizing Energy Storage Sizing, Location and Operation: Current R&D Efforts at Sandia National Laboratories

February 25, 2016

Hosted by Todd Olinsky-Paul
ESTAP Project Director
Clean Energy States Alliance

Housekeeping



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Submit your questions at any time by typing in the Question Box and hitting Send.

This webinar is being recorded.

You will find a recording of this webinar, as well as all previous CESA webcasts, archived on the CESA website at

www.cesa.org/webinars

State & Federal Energy Storage Technology Advancement Partnership (ESTAP)

Todd Olinsky-Paul

Project Director

Clean Energy States Alliance (CESA)

Thank You:

Dr. Imre Gyuk
U.S. Department of Energy,
Office of Electricity Delivery and
Energy Reliability

Dan Borneo
Sandia National Laboratories

CleanEnergy States Alliance

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

ESTAP is a project of CESA

Clean Energy States Alliance (CESA) is a non-profit organization providing a forum for states to work together to implement effective clean energy policies & programs:

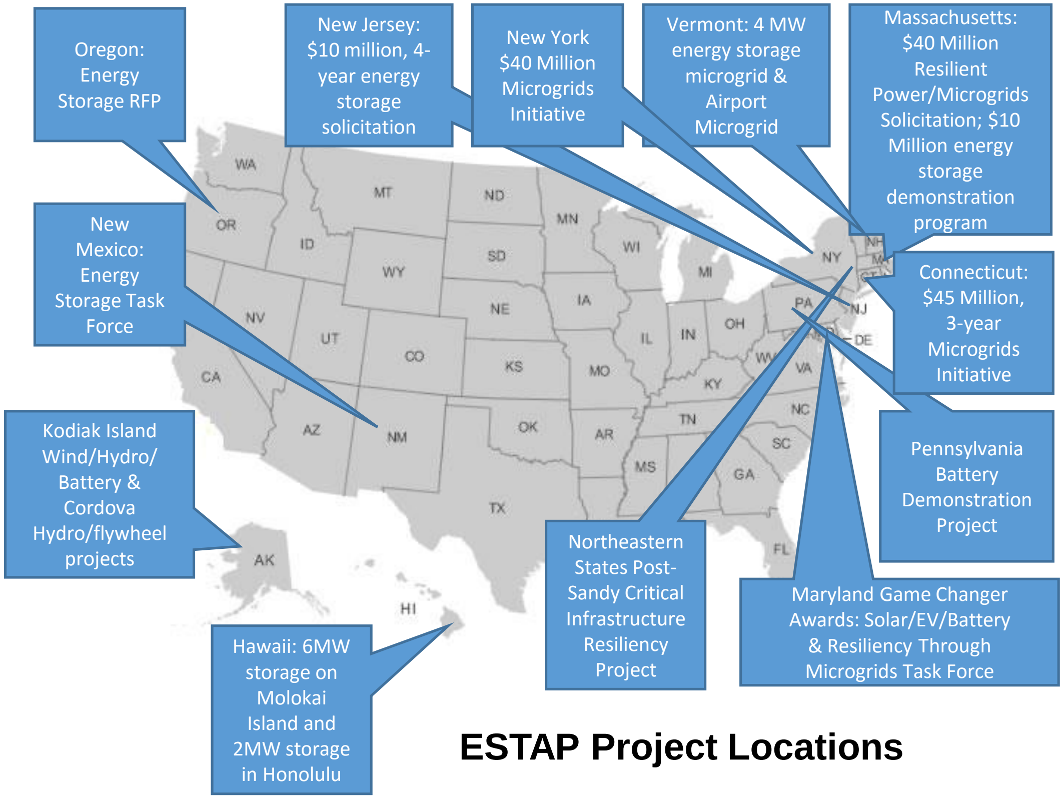
State & Federal Energy Storage Technology Advancement Partnership (ESTAP) is conducted under contract with Sandia National Laboratories, with funding from US DOE.

ESTAP Key Activities:

1. Disseminate information to stakeholders
    - ESTAP listserv >3,000 members
    - Webinars, conferences, information updates, surveys.

2. Facilitate public/private partnerships to support joint federal/state energy storage demonstration project deployment

3. Support state energy storage efforts with technical, policy and program assistance



Oregon: Energy Storage RFP

New Jersey: $10 million, 4-year energy storage solicitation

New York $40 Million Microgrids Initiative

Vermont: 4 MW energy storage microgrid & Airport Microgrid

Massachusetts: $40 Million Resilient Power/Microgrids Solicitation; $10 Million energy storage demonstration program

New Mexico: Energy Storage Task Force

Connecticut: $45 Million, 3-year Microgrids Initiative

Kodiak Island Wind/Hydro/ Battery & Cordova Hydro/flywheel projects

Pennsylvania Battery Demonstration Project

Northeastern States Post-Sandy Critical Infrastructure Resiliency Project

Maryland Game Changer Awards: Solar/EV/Battery & Resiliency Through Microgrids Task Force

Hawaii: 6MW storage on Molokai Island and 2MW storage in Honolulu

ESTAP Project Locations

CleanEnergy States Alliance

Sandia National Laboratories

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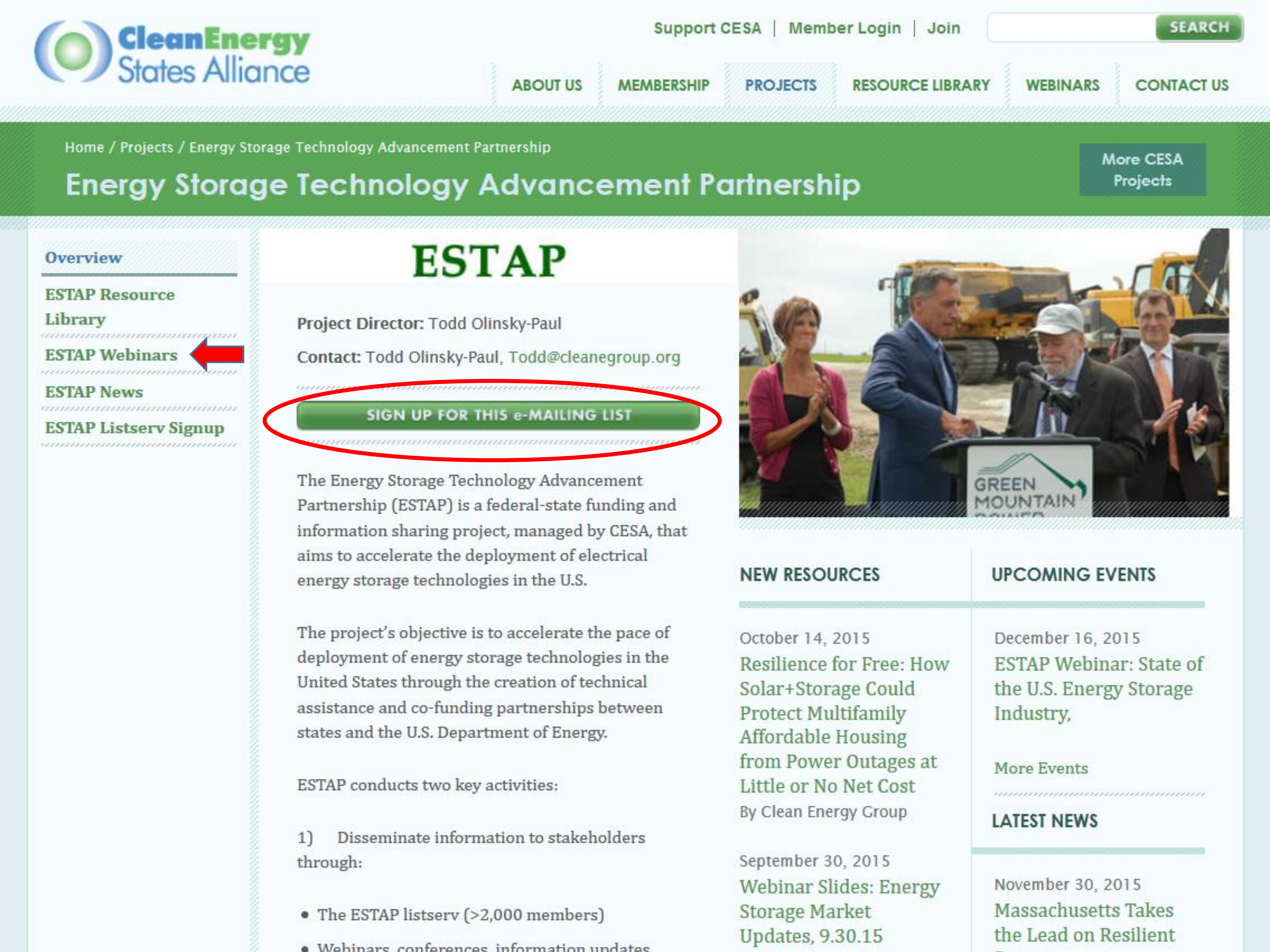

Energy Storage Technology Advancement Partnership

ESTAP

Project Director: Todd Olinsky-Paul

Contact: Todd Olinsky-Paul, Todd@cleanegroup.org

The Energy Storage Technology Advancement Partnership (ESTAP) is a federal-state funding and information sharing project, managed by CESA, that aims to accelerate the deployment of electrical energy storage technologies in the U.S.

The project's objective is to accelerate the pace of deployment of energy storage technologies in the United States through the creation of technical assistance and co-funding partnerships between states and the U.S. Department of Energy.

ESTAP conducts two key activities:

1) Disseminate information to stakeholders through:

- The ESTAP listserv (>2,000 members)
- Webinars, conferences, information updates

NEW RESOURCES

October 14, 2015

Resilience for Free: How Solar+Storage Could Protect Multifamily Affordable Housing from Power Outages at Little or No Net Cost

By Clean Energy Group

September 30, 2015

Webinar Slides: Energy Storage Market Updates, 9.30.15

UPCOMING EVENTS

December 16, 2015

ESTAP Webinar: State of the U.S. Energy Storage Industry,

More Events

LATEST NEWS

November 30, 2015

Massachusetts Takes the Lead on Resilient

Today's Guest Speakers

- **Dr. Cesar Silva-Monroy**, Senior Member of Technical Staff, Electric Power Systems Research Group, Sandia National Laboratories

- **Dr. Raymond Byrne**, Distinguished Member of Technical Staff, Energy Storage and Transmission Analysis Department, Sandia National Laboratories

- **Daniel Kirschen**, Close Professor of Electrical Engineering, University of Washington Graduate Research Assistant, University of Washington

- **Yury Dvorkin**, Graduate Research Assistant, University of Washington

- **Dan Borneo**, Senior Electrical Engineer, Sandia National Laboratories

Sandia National Laboratories

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Optimal Sizing/Siting of Energy Storage

Cesar A. Silva-Monroy, Ph.D.
casilv@sandia.gov

Feb. 26, 2015

Acknowledgment: this research was funded by Dr. Imre Gyuk from the DOE Energy Storage Program.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Optimize What?

- Find the size (MW/MWh) and location (electrical bus) at which the *value* of energy storage is maximized.

- “*Value* is in the eye of the beholder”

- Regulated markets – utilities seek to minimize their costs
- Deregulated markets – system operators seek to maximize social welfare and support/improve reliability
- Merchant energy storage plants – owners seek to maximize their profits

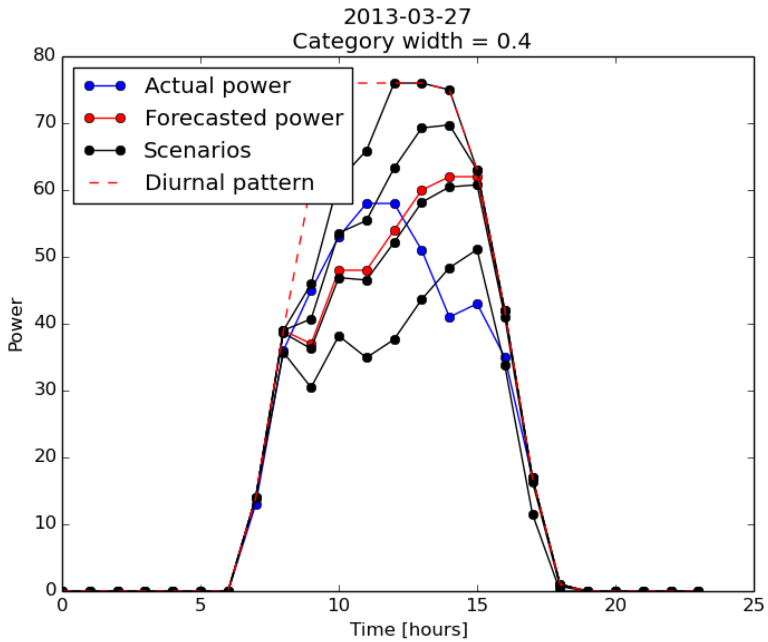
Optimization Approaches

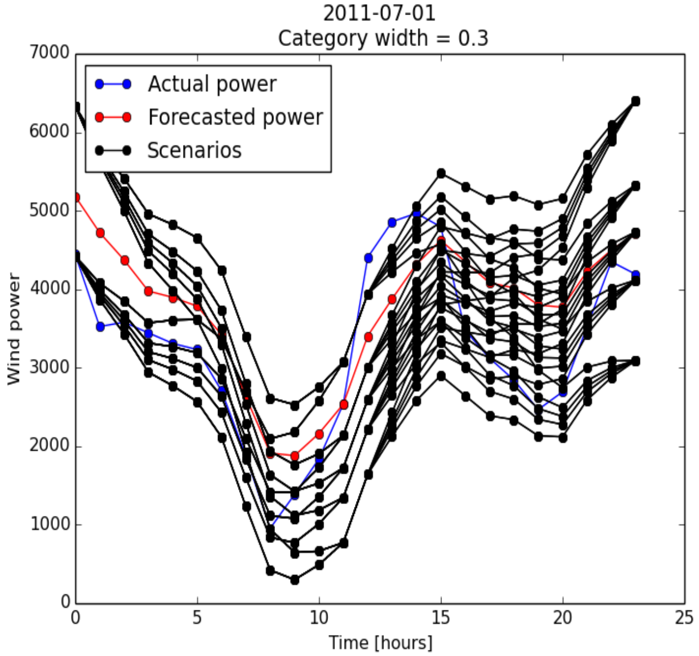
- Simulation-based approaches
  - Heuristic rule for operation of energy storage or optimize daily operations
  - Use historical load/price data (to create projections)
  - Perform rolling horizon simulations (e.g., production cost model)
- Mathematical programming
  - Formulate optimal size/location as a mathematical program
  - Use historical load/price data (to create projections) as inputs
  - Solve using power computer/algorithms – wait for a few days
  - Information about the quality of the solution is available
- Hybrid
  - Formulate optimal location for single day horizon, solve for multiple days
  - Use historical load/price data (to create projections) as inputs
  - Use results as input to optimal sizing problem, solve for multiple days
  - Use results as input to optimal operation problem, solve for multiple days

- They all follow the universal principle: “*Garbage in, garbage out*”

Stochastic Production Cost Modeling

- We have developed a stochastic production cost model (PRESCIENT) and added energy storage models.
- Stochastic Unit Commitment - schedule generation resources (ON/OFF) such that ***expected*** generation costs are minimized *under several load and renewable generation scenarios*





Future Work

- Comparing benefits of stochastic unit commitment with deterministic + storage
- Modifying the code to directly calculate optimal size/location of energy storage for a given budget.
- PRESCIENT code to be released as open source (working through copyright now)

- **We are always happy to discuss potential uses of our computational tools with utilities, ISOs, industry, and other researchers!**

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Optimal Operation of Energy Storage

Acknowledgment: this research was funded by Dr. Imre Gyuk from the DOE Energy Storage Program.

Ray Byrne, Ph.D.
Cesar A. Silva-Monroy, Ph.D.
Ricky Concepcion

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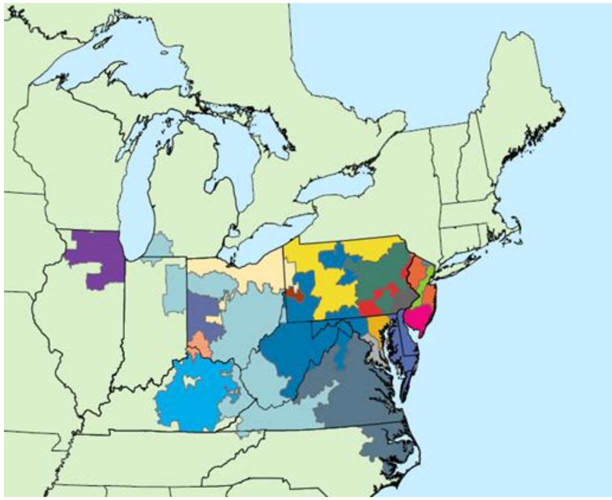
Optimal Operation of Energy Storage

- Two prevalent "goals" with energy storage
  - Maximize revenue or return-on-investment
  - Maximize benefit to the grid
  - Often, these do not align ….

    but that is a policy issue
- Two different use cases or applications
  - Vertically integrated utility
  - Market area
- This portion of the webinar will focus on:
  - Maximizing revenue in a market area

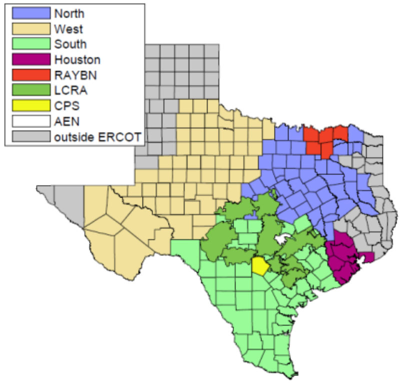


Maximizing Revenue - Market Area

- Linear Program Optimization
  - MATLAB
  - Python/Cooper
- Typically look at the following revenue streams
  - Arbitrage
  - Arbitrage + Regulation
  - Allocate charge to avoid double counting
- Typically look at maximizing revenue
- Can incorporate cost data (if available)
  - Penalty for charge/discharge
  - Variable O&M costs
- Optimization assumes perfect knowledge – best you can do
  - Serves as a benchmark for other trading algorithms

ERCOT Results

- Looked at every load zone
  - Arbitrage
  - Arbitrage + frequency regulation
  - 2011, 2012, 2013 data



ARBITRAGE OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, 2011-2013.

Load Zone	Year	Revenue	% Discharging	% Charging
North	2011	$1,063,599.54	18.90%	23.62%
	2012	$382,066.41	18.00%	22.50%
	2013	$254,605.18	18.81%	23.52%
South	2011	$1,076,180.49	18.78%	23.47%
	2012	$426,627.76	17.69%	22.11%
	2013	$289,562.01	18.62%	23.28%
West	2011	$1,182,502.88	20.00%	25.00%
	2012	$733,646.82	17.95%	22.44%
	2013	$517,344.45	18.49%	23.11%
Houston	2011	$1,063,385.41	18.84%	23.56%
	2012	$381,959.28	17.91%	22.38%
	2013	$280,054.47	18.78%	23.48%
RAYBN	2011	$1,057,443.51	18.91%	23.63%
	2012	$373,162.63	17.96%	22.45%
	2013	$250,356.83	18.78%	23.48%
LCRA	2011	$1,055,417.81	18.89%	23.62%
	2012	$449,793.75	17.97%	22.46%
	2013	$276,481.46	18.84%	23.55%
CPS	2011	$1,061,561.72	18.82%	23.53%
	2012	$391,876.86	17.99%	22.48%
	2013	$287,515.07	18.89%	23.62%
AEN	2011	$1,043,716.52	18.76%	23.45%
	2012	$368,224.91	17.92%	22.40%
	2013	$289,537.70	18.84%	23.56%

ENERGY STORAGE SYSTEM PARAMETERS.

Parameter	Value
$\bar{q}^D$	8 MWh
$\bar{q}^R$	8 MWh
$\bar{S}$	32 MWh
γ_S	1.0
γ_C	0.8
γ_{ru}	0.5
γ_{rd}	0.5

- Regulation -> more $$$
- Not location dependent (1 market)

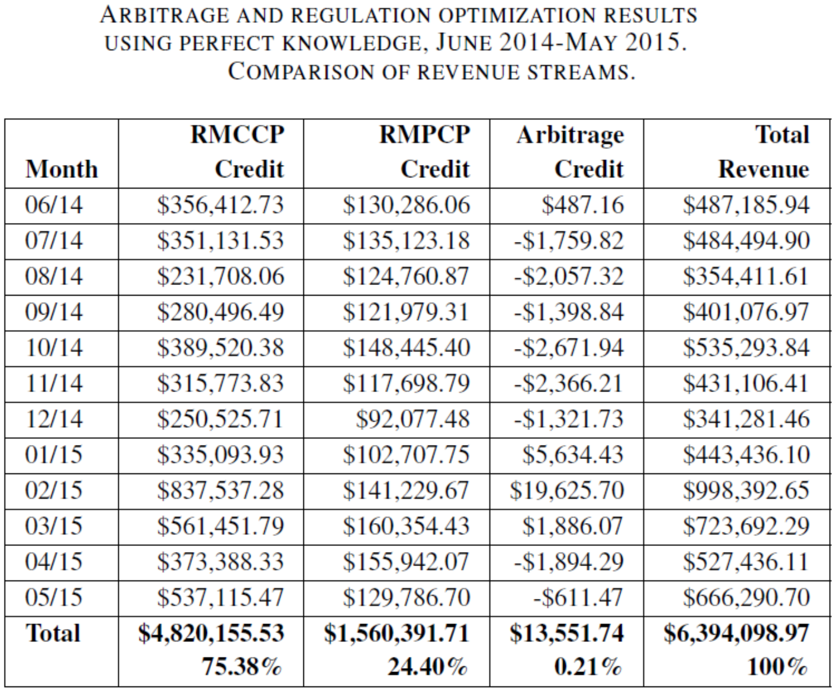
ARBITRAGE AND REGULATION OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, 2011-2013.

Year	Revenue	% q^D	% q^R	% q^{RU}	% q^{RD}
North Load Zone					
2011	$2,370,777.09	0.11%	0.87%	69.63%	85.62%
2012	$933,260.45	0.11%	0.83%	63.59%	78.12%
2013	$843,543.43	0.10%	1.38%	62.77%	75.98%
South Load Zone					
2011	$2,369,779.67	0.26%	0.99%	69.32%	85.36%
2012	$955,300.23	0.44%	0.94%	61.95%	76.67%
2013	$858,726.34	0.10%	1.35%	61.23%	74.11%
West Load Zone					
2011	$2,438,594.42	0.010%	2.23%	69.01%	82.16%
2012	$1,163,443.68	1.86%	2.57%	51.25%	63.61%
2013	$1,007,779.09	0.98%	2.57%	54.16%	65.03%
Houston Load Zone					
2011	$2,363,966.11	0.15%	0.85%	69.31%	85.37%
2012	$931,141.19	0.089%	0.78%	63.53%	78.09%
2013	$854,588.16	0.089%	1.30%	61.09%	73.99%
RAYBN Load Zone					
2011	$2,367,663.02	0.11%	0.84%	69.71%	85.78%
2012	$928,295.59	0.11%	0.83%	63.73%	78.31%
2013	$840,455.24	0.10%	1.44%	62.92%	76.02%
LCRA Load Zone					
2011	$2,362,665.58	0.17%	0.88%	69.24%	85.23%
2012	$982,249.28	0.61%	0.81%	61.34%	76.59%
2013	$853,824.74	0.10%	1.23%	61.40%	74.55%
CPS Load Zone					
2011	$2,359,793.64	0.14%	0.87%	69.32%	85.31%
2012	$938,393.86	0.23%	0.84%	63.38%	78.14%
2013	$856,761.94	0.17%	1.43%	60.95%	73.77%
AEN Load Zone					
2011	$2,355,535.66	0.14%	0.85%	69.73%	85.86%
2012	$925,236.23	0.10%	0.87%	64.26%	78.86%
2013	$862,277.62	0.12%	1.26%	60.38%	73.28%

R. H. Byrne and C. A. Silva-Monroy, "Potential revenue from electrical energy storage in ERCOT: The impact of location and recent trends," in *Proceedings of the 2015 IEEE Power and Energy Society (PES) General Meeting*, Denver, CO, July 2015, pp. 1–5.

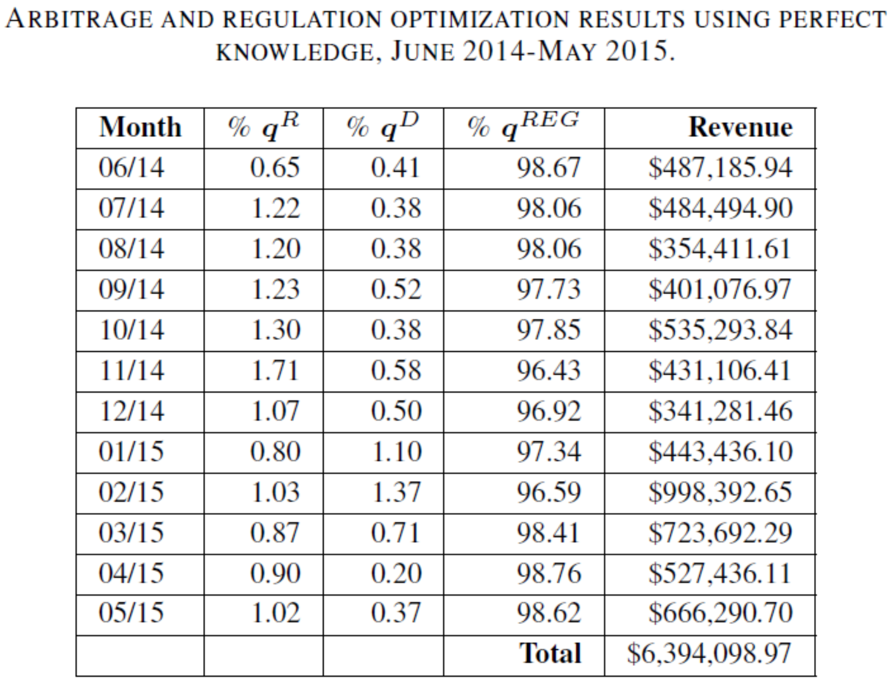
PJM Results

- Looked at 1-year of PJM data (June 2014-May 2015)
- Plant modeled on Beacon Flywheel
- Incorporated pay for performance in model
    - Regulation data on PJM website -> calculate $\gamma_t^{RD}, \gamma_t^{RU}$



ARBITRAGE AND REGULATION OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, JUNE 2014-MAY 2015. COMPARISON OF REVENUE STREAMS.

Month	RMCCP Credit	RMPCP Credit	Arbitrage Credit	Total Revenue
06/14	\$356,412.73	\$130,286.06	\$487.16	\$487,185.94
07/14	\$351,131.53	\$135,123.18	-\$1,759.82	\$484,494.90
08/14	\$231,708.06	\$124,760.87	-\$2,057.32	\$354,411.61
09/14	\$280,496.49	\$121,979.31	-\$1,398.84	\$401,076.97
10/14	\$389,520.38	\$148,445.40	-\$2,671.94	\$535,293.84
11/14	\$315,773.83	\$117,698.79	-\$2,366.21	\$431,106.41
12/14	\$250,525.71	\$92,077.48	-\$1,321.73	\$341,281.46
01/15	\$335,093.93	\$102,707.75	\$5,634.43	\$443,436.10
02/15	\$837,537.28	\$141,229.67	\$19,625.70	\$998,392.65
03/15	\$561,451.79	\$160,354.43	\$1,886.07	\$723,692.29
04/15	\$373,388.33	\$155,942.07	-\$1,894.29	\$527,436.11
05/15	\$537,115.47	\$129,786.70	-\$611.47	\$666,290.70
Total	**\$4,820,155.53** **75.38%**	**\$1,560,391.71** **24.40%**	**\$13,551.74** **0.21%**	**\$6,394,098.97** **100%**



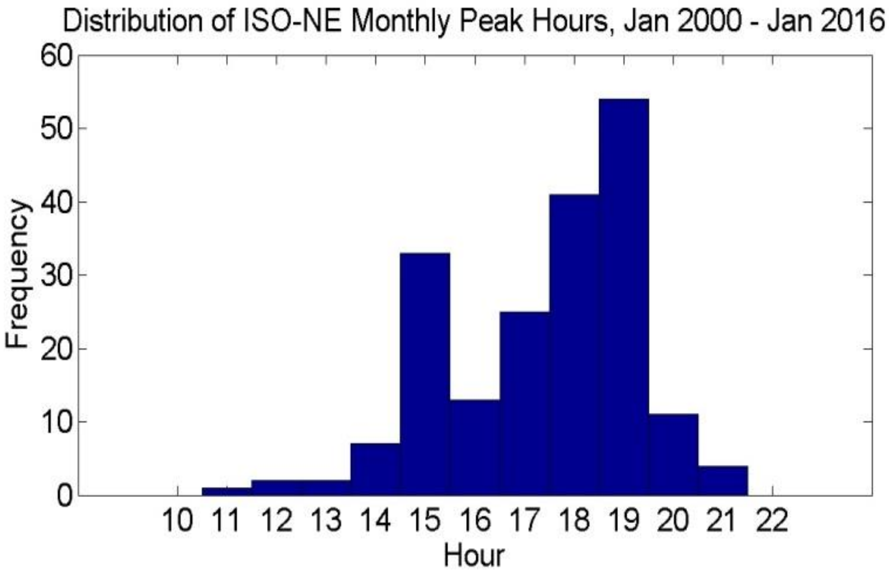
ARBITRAGE AND REGULATION OPTIMIZATION RESULTS USING PERFECT KNOWLEDGE, JUNE 2014-MAY 2015.

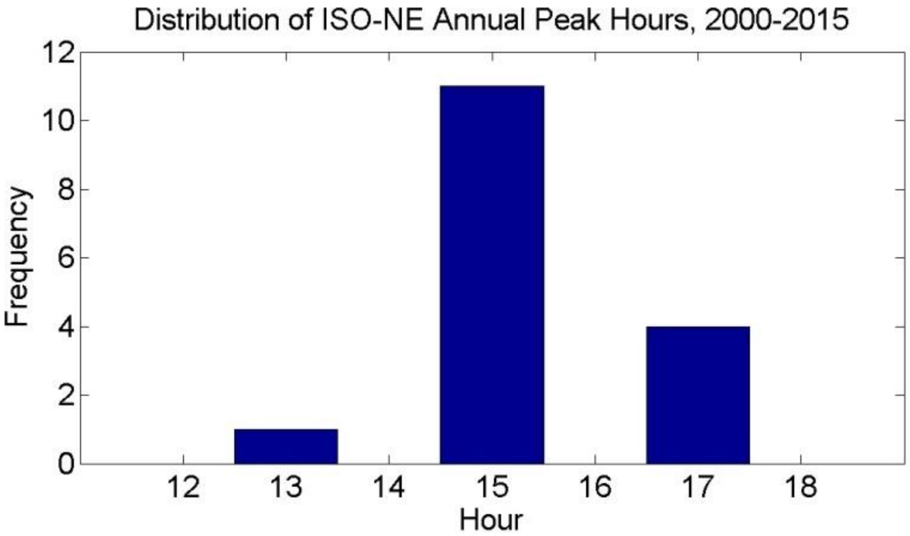
Month	% q^R	% q^D	% q^{REG}	Revenue
06/14	0.65	0.41	98.67	\$487,185.94
07/14	1.22	0.38	98.06	\$484,494.90
08/14	1.20	0.38	98.06	\$354,411.61
09/14	1.23	0.52	97.73	\$401,076.97
10/14	1.30	0.38	97.85	\$535,293.84
11/14	1.71	0.58	96.43	\$431,106.41
12/14	1.07	0.50	96.92	\$341,281.46
01/15	0.80	1.10	97.34	\$443,436.10
02/15	1.03	1.37	96.59	\$998,392.65
03/15	0.87	0.71	98.41	\$723,692.29
04/15	0.90	0.20	98.76	\$527,436.11
05/15	1.02	0.37	98.62	\$666,290.70
			Total	\$6,394,098.97

R. H. Byrne, R. Concepcion, and C. A. Silva-Monroy, "Estimating potential revenue from electrical energy storage in PJM," accepted for publication in the 2016 IEEE Power and Energy Society (PES) General Meeting, Boston, MA, July 2016.

ISO-NE

- We’ve been looking at several projects in ISO-NE
- Potential revenue streams
  - Arbitrage
  - Reduction in monthly network load (Regional Network Services – RNS)
  - Reduction in capacity payments to ISO-NE (annual peak)


Distribution of ISO-NE Monthly Peak Hours, Jan 2000 - Jan 2016


Distribution of ISO-NE Annual Peak Hours, 2000-2015

  - Additional capacity hours don’t increase max revenue -> increases your odds of hitting peak hours

Future Work

- Look at pay-for-performance models in other ISOs
- Incorporating cost of degradation based on charge/discharge profile
- Development of algorithms that do not rely on perfect knowledge
- Add additional revenue streams to the optimization
- Pyomo code published on SNL web site (working through copyright now)

Backup Slides

Maximizing Revenue - Market Area

- Assume price insensitive to supply (if not -> production cost modeling)
- Typically use 1 hour data
- Energy storage model – arbitrage

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D \ \forall t \in T$$

Decision Variables

q_t^D	quantity of energy sold (Discharged) at time t (MWh)
q_t^R	quantity of energy purchased (Recharged) at time t (MWh)

- Constraints on:
  - Total capacity
  - Maximum hourly charge/discharge quantity

$$0 \leq S_t \leq \bar{S}, \ \forall t \in T$$

$$0 \leq q_t^R \leq \bar{q}^R, \ \forall t \in T$$

$$0 \leq q_t^D \leq \bar{q}^D, \ \forall t \in T$$

$$\max \sum_{t=1}^{T} \left[(P_t - C_d) q_t^D - (P_t + C_r) q_t^R \right] e^{-rt}$$

Maximizing Revenue - Market Area

- Assume price insensitive to supply (if not -> production cost modeling)
- Typically use 1 hour data
- Energy storage model – arbitrage + regulation

$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU}$$

Decision Variables

q_t^D	quantity of energy sold (Discharged) at time t (MWh)
q_t^R	quantity of energy purchased (Recharged) at time t (MWh)
q_t^{RU}	quantity of energy offered into the regulation up market at time t (MWh)
q_t^{RD}	quantity of energy offered into the regulation up market at time t (MWh)

$$\max \sum_{t=1}^{T} [(P_t - C_d) q_t^D + (P_t^{RU} + \gamma_{ru}(P_t - C_d)) q_t^{RU} + (P_t^{RD} - \gamma_{rd}(P_t + C_r)) q_t^{RD} - (P_t + C_r) q_t^R] e^{-rt}$$

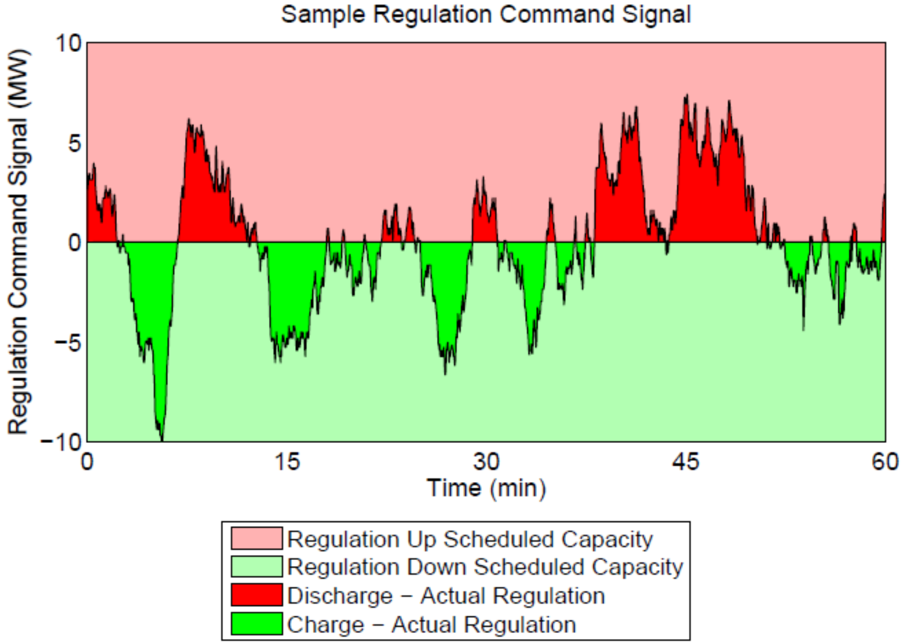
$$0 \leq S_t \leq \bar{S}, \ \forall t \in T$$

$$0 \leq q_t^R + q_t^{RD} \leq \bar{q}^R, \ \forall t \in T$$

$$0 \leq q_t^D + q_t^{RU} \leq \bar{q}^D, \ \forall t \in T$$

Maximizing Revenue - Market Area

- Modeling regulation – need to assume fraction that is assigned



$$S_t = \gamma_s S_{t-1} + \gamma_c q_t^R - q_t^D + \gamma_c \gamma_{rd} q_t^{RD} - \gamma_{ru} q_t^{RU}$$

Account for fraction called

Optimizing Energy Storage Sizing, Location and Operation

Prof. Daniel Kirschen

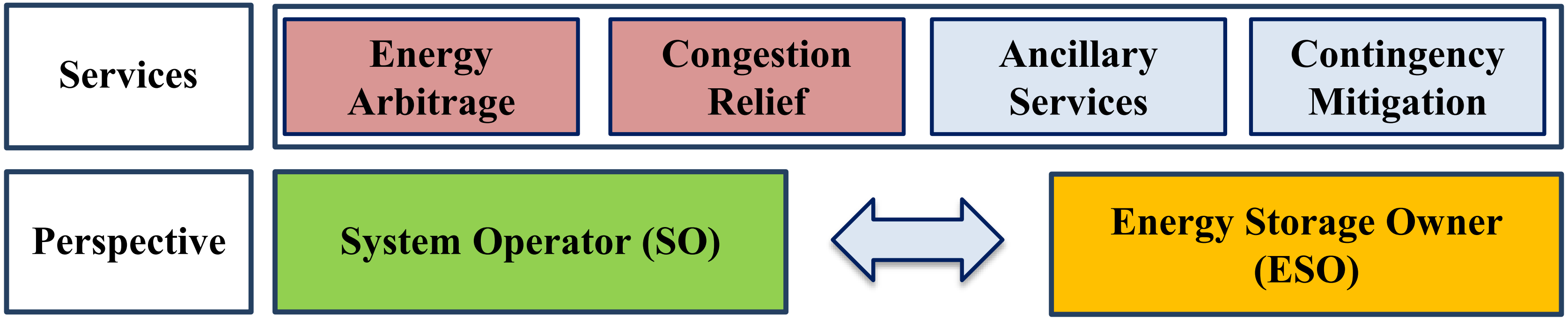
Yury Dvorkin

Energy Storage for Electrical Grids

Services

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

Energy Storage for Electrical Grids



Services

Energy Arbitrage

Congestion Relief

Ancillary Services

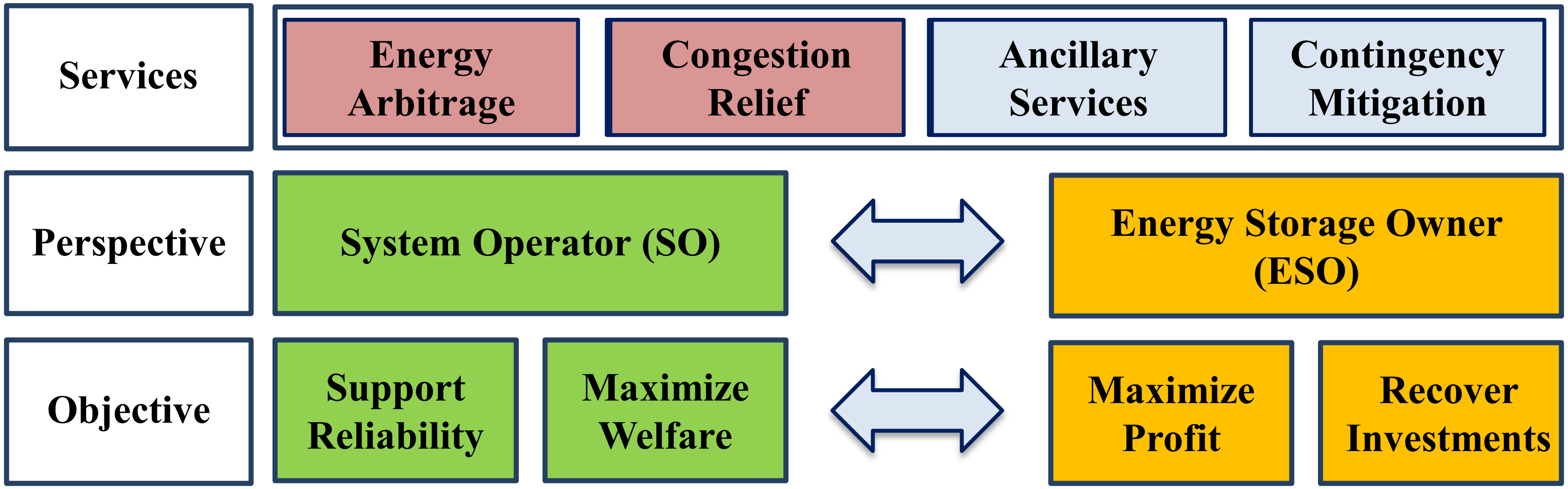
Contingency Mitigation

Perspective

System Operator (SO)

Energy Storage Owner (ESO)

Energy Storage for Electrical Grids

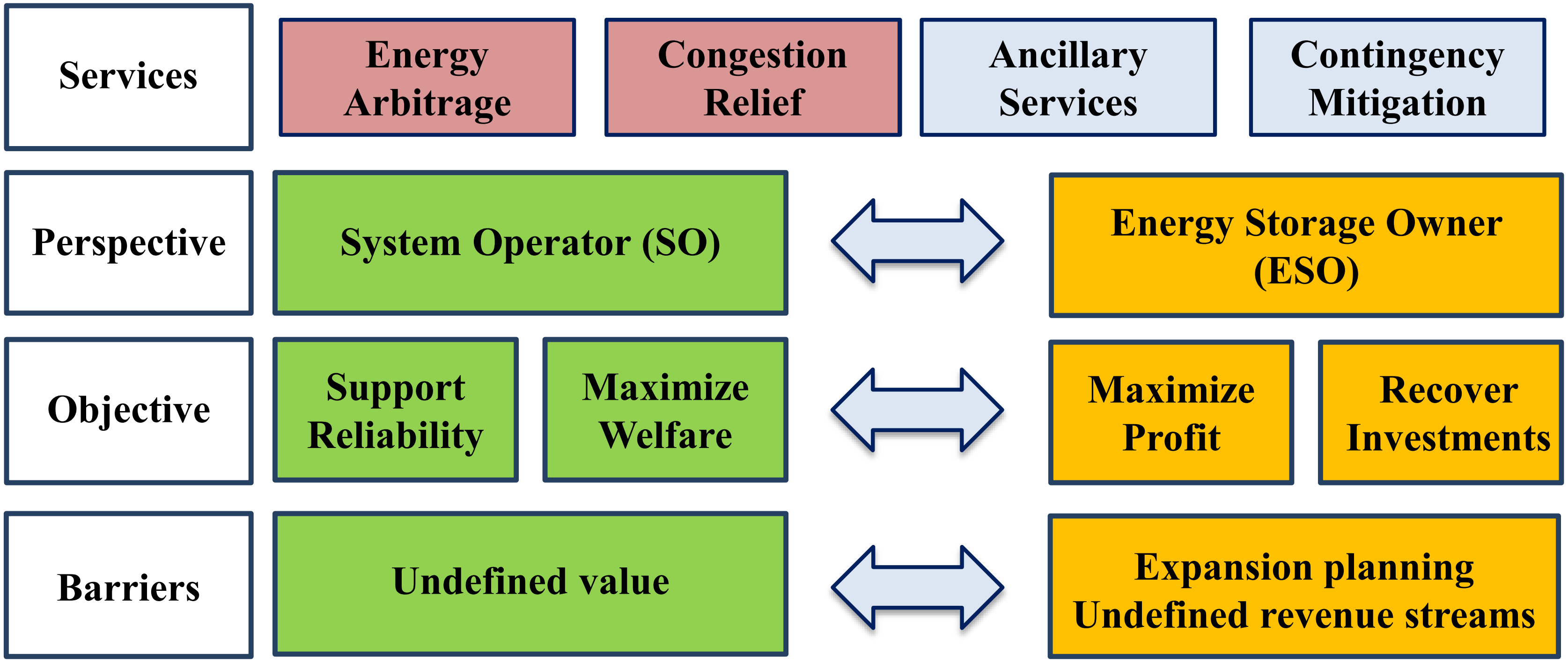


Services
- Energy Arbitrage
- Congestion Relief
- Ancillary Services
- Contingency Mitigation

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

Objective
- Support Reliability
- Maximize Welfare
- ⟷
- Maximize Profit
- Recover Investments

Energy Storage for Electrical Grids



Services

Energy Arbitrage

Congestion Relief

Ancillary Services

Contingency Mitigation

Perspective

System Operator (SO)

Energy Storage Owner (ESO)

Objective

Support Reliability

Maximize Welfare

Maximize Profit

Recover Investments

Barriers

Undefined value

Expansion planning
Undefined revenue streams

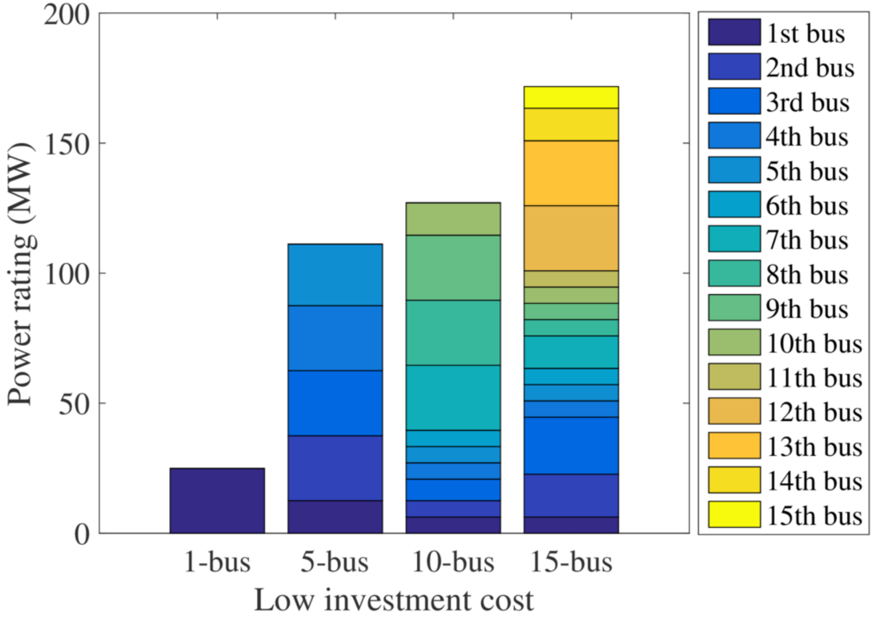
Case I: Centralized (SO) Perspective

- Site and size energy storage (ES) to reduce the operating cost
- Minimize:

  Operating cost

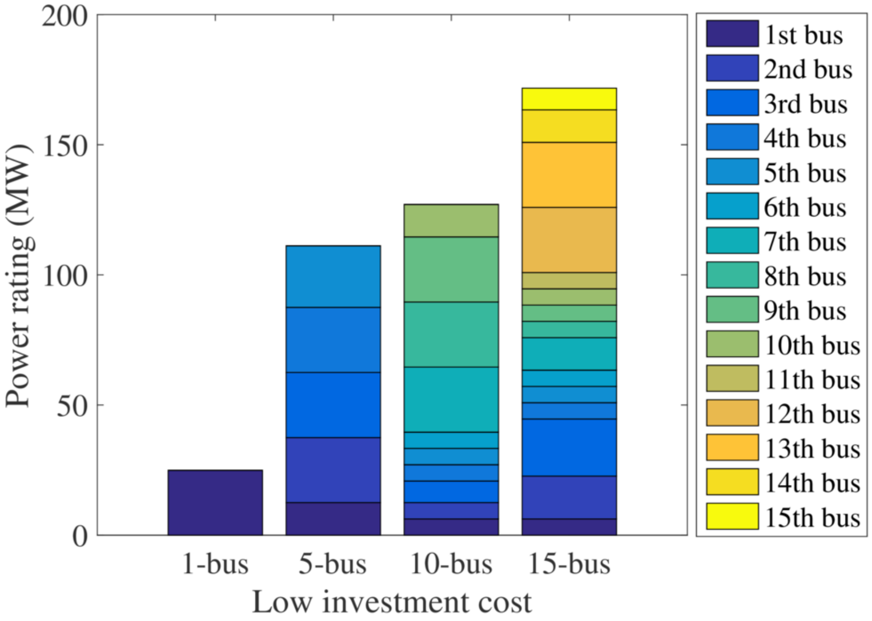
  \+ Investment cost in energy storage
- Subject to constraints:
  - System operation: generation and transmission
  - Operation of energy storage
  - Investment in energy storage
- Consider stochastic nature of renewable generation
- Tested on a model of the WECC system

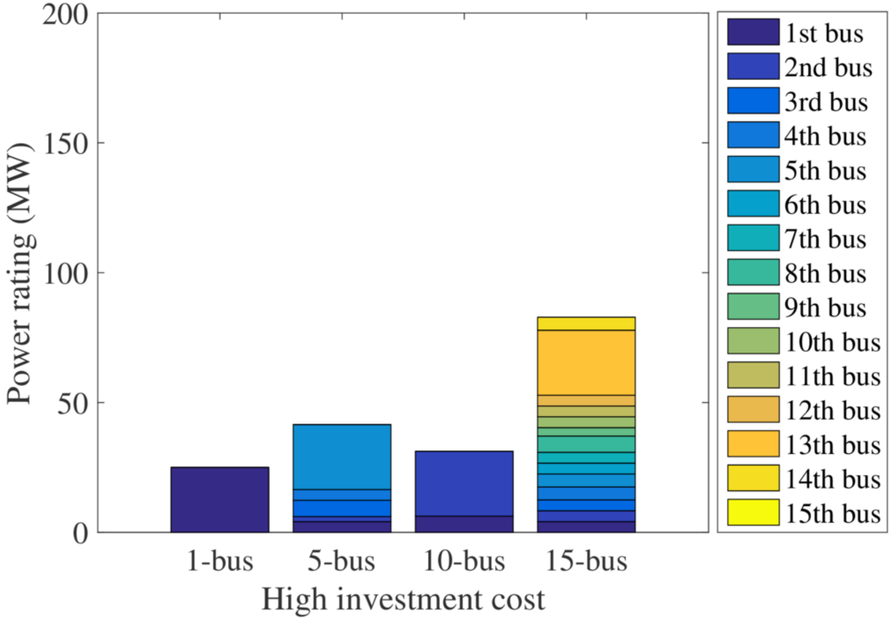
Case I: Key Results



- Installing ES at more buses affects power and energy ratings
- The total power rating gradually saturates

Case I: Key Results

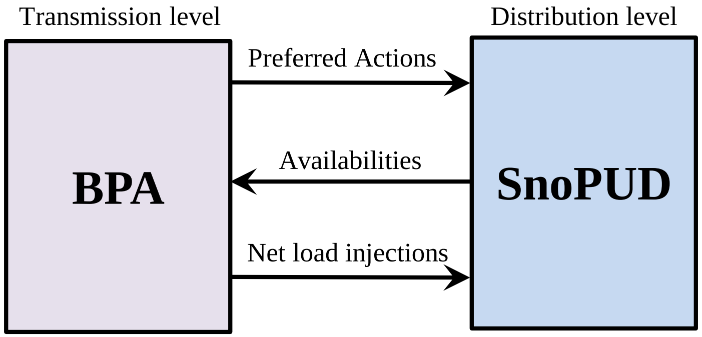




- The investment cost is the primary driver of sizing decisions
  - As the capital cost increases, the total rating of ES installed reduces

Case II: Mixed TSO+DSO Perspective

- Distribution System Operator (DSO)
  - Owns and operates batteries
  - Willing to “share” with the TSO
- Transmission System Operator (TSO)
  - Interested in using batteries for congestion relief
- How to structure the TSO-DSO coordination?



Case III: Mixed SO+ESO Perspective

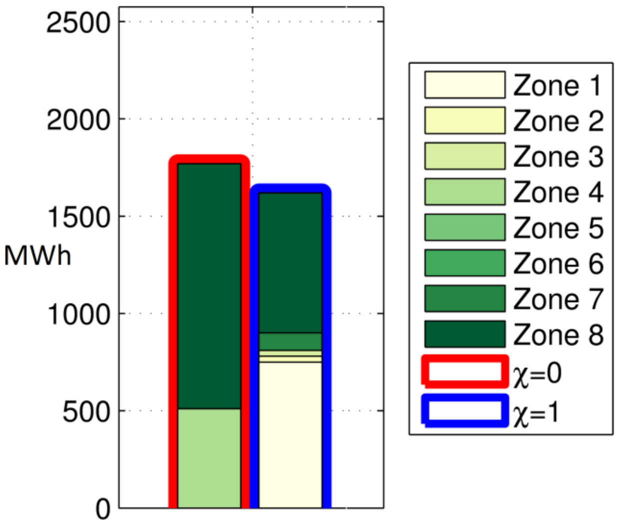
- How to site and size merchant-owned energy storage?
  - Energy Storage Owner (ESO) must make a profit on its investment
  - Balance SO's cost savings and ESO's profits
- Minimize

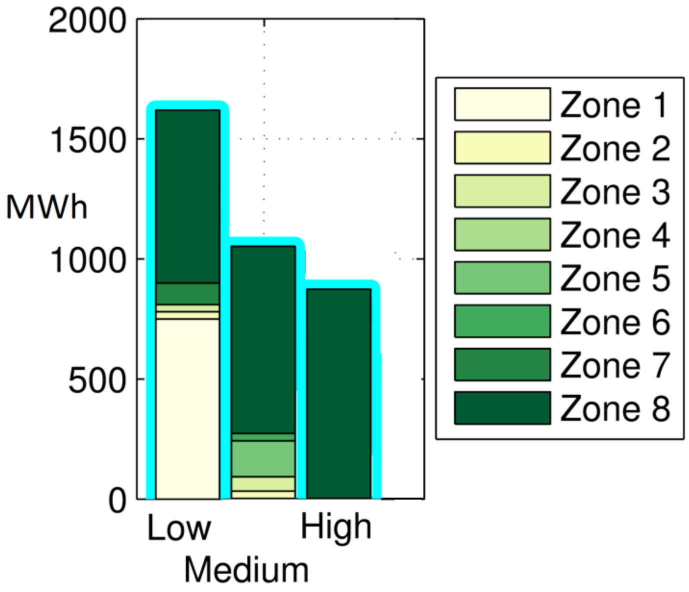
  Operating cost

  + Cost of investment in energy storage
- Subject to constraints:
  - System operation: generation and transmission
  - Operation of energy storage
  - Investment in energy storage
  - Minimum profit constraint
    - Lifetime Profit $\geq \chi \cdot$Investment Cost
    - χ is the rate of return

Case III: Key results

$$\text{Lifetime Profit} \geq \chi \cdot \text{Investment Cost}$$





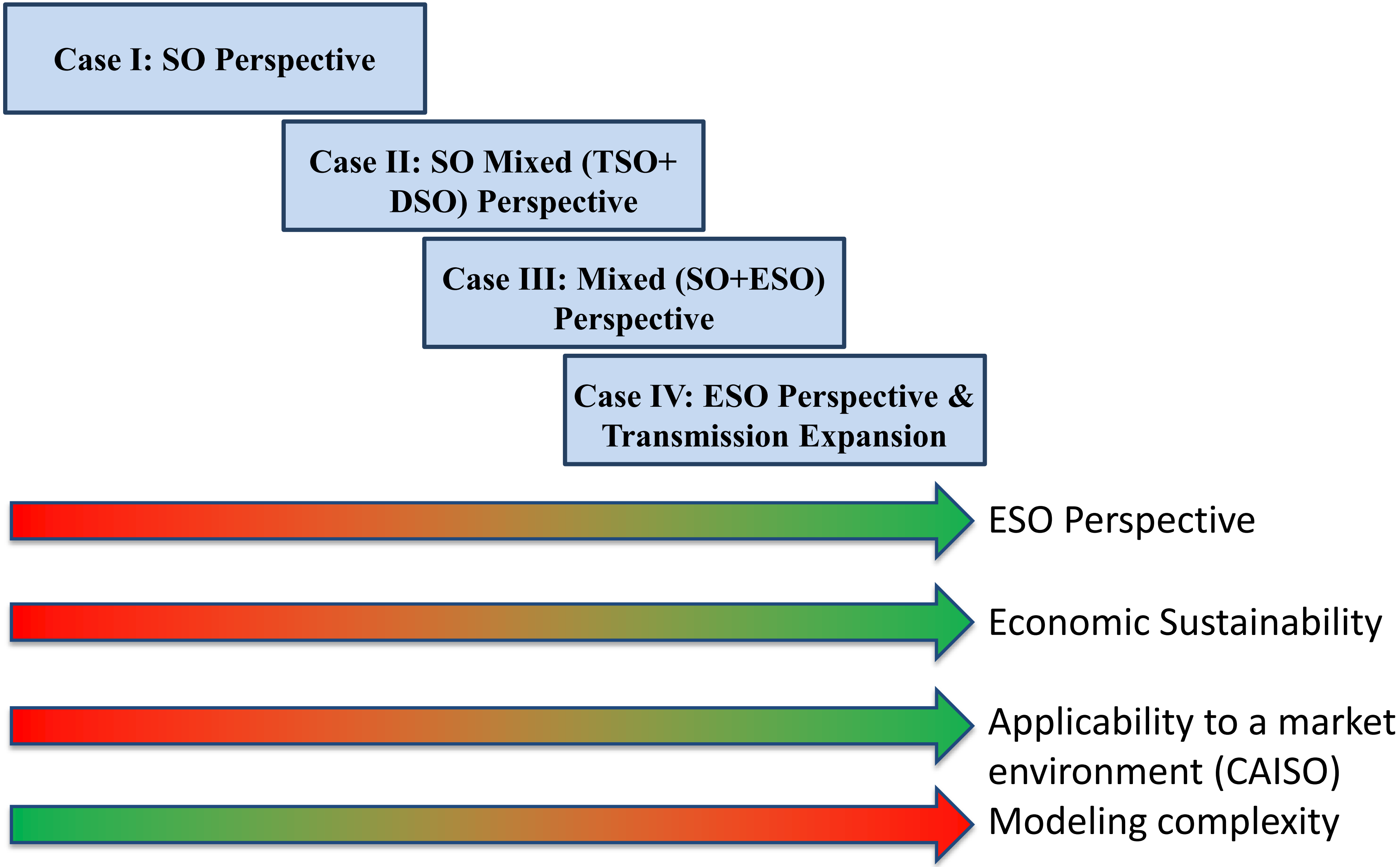
- Profit constraints drives both the siting and sizing decisions
  - Reduction in the cumulative rating
  - More diversity in locations
  - Results are strongly affected by the capital cost (Low, Medium, High)

Y. Dvorkin, R. Fernandez Blanco, D.S. Kirschen, H. Pandzic, J.P. Watson, and C.A. Silva Monroy, "Ensuring Profitability of Energy Storage ," *IEEE Transactions on Power Systems,* in review (available upon request), 2015.

Case IV: Merchant ESO Perspective

- How to site and size merchant-owned energy storage?
  - Energy storage owner aims to maximize its profit
  - System operator must minimize the overall cost
- Bi-level problem:
  - ESO maximizes (Lifetime net revenue of ES – Cost of investment in storage)
  - SO minimizes (Operating cost + Cost of investment in transmission expansion)
- Constraints
  - Minimum profit constraint, i.e. Lifetime Profit $\geq \chi \cdot$Investment Cost
  - System operation: generation and transmission
  - Operation of energy storage
  - Investment in energy storage
- Siting and sizing decisions for a profit-seeking ESO
  - Robust to transmission expansion decisions

Summary



Case I: SO Perspective

Case II: SO Mixed (TSO+ DSO) Perspective

Case III: Mixed (SO+ESO) Perspective

Case IV: ESO Perspective & Transmission Expansion

ESO Perspective

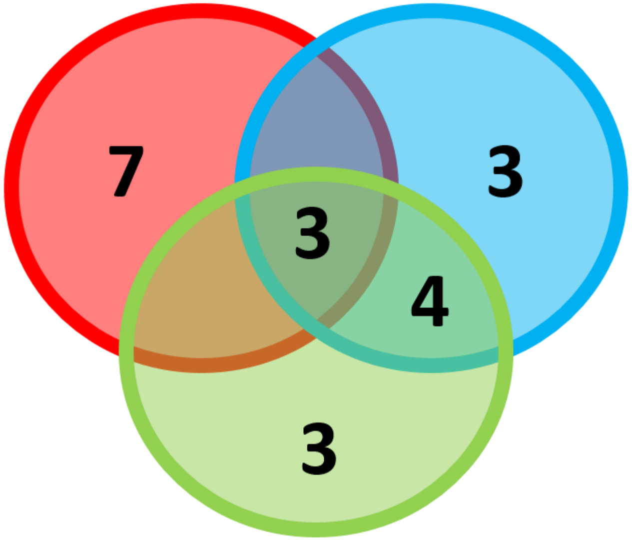
Economic Sustainability

Applicability to a market environment (CAISO)

Modeling complexity

Conclusion

- Compare siting of 10 batteries for cases I, III, and IV:



- Only 3 locations are the same for all three cases
- Cases III and IV have 7 out of 10 common locations
- It is thus essential to take the right perspective when exploring potential locations

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