Energy Storage Technology Advancement Partnership (ESTAP) Webinar

# Energy Storage 101:
## Part 3 – Applications and Economics

*Hosted by*
Todd Olinsky-Paul
Clean Energy States Alliance

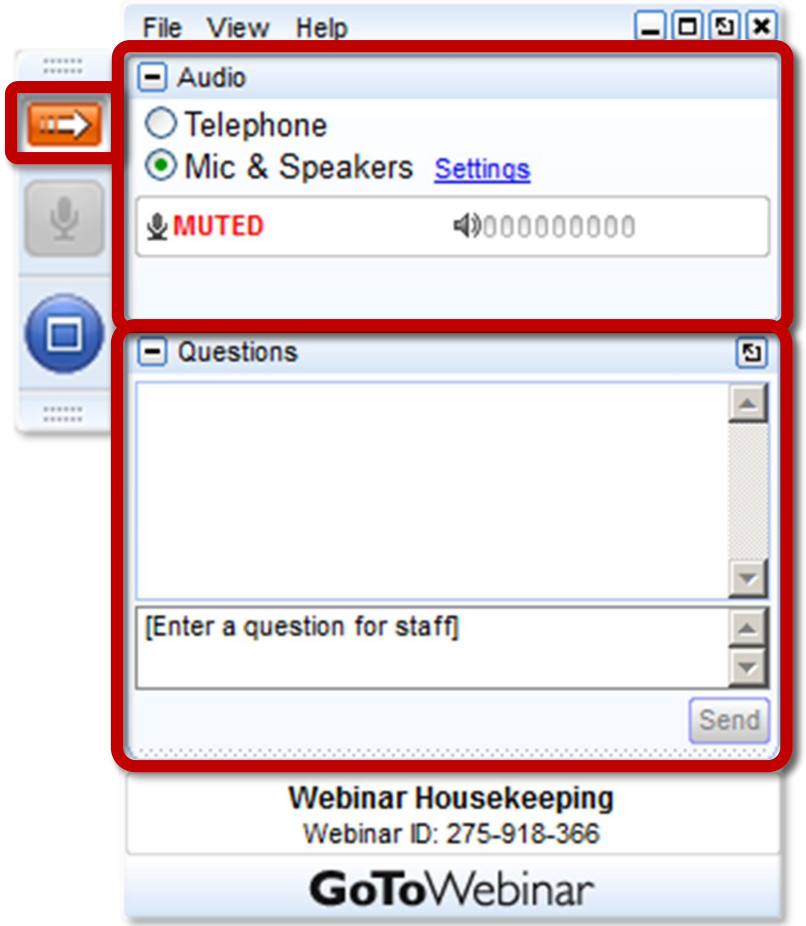
November 19, 2019

U.S. DEPARTMENT OF ENERGY

CleanEnergy States Alliance

Sandia National Laboratories

# Housekeeping



**Webinar Housekeeping**
Webinar ID: 275-918-366

**Join audio**

- Choose Mic & Speakers to use VoIP
- Choose Telephone and dial in PIN using the information provided

Click on the orange box with the arrow to open and close your control panel

Submit questions and comments via the Questions panel

This webinar is being recorded. We will email you a webinar recording within 48 hours. This webinar will be posted on CESA's website at [www.cesa.org/webinars](http://www.cesa.org/webinars)

# Clean Energy States Alliance

ALASKA ENERGY AUTHORITY

STATE OF CALIFORNIA ENERGY COMMISSION

DEPARTMENT OF ENERGY & ENVIRONMENT

Energy Trust of Oregon

IOWA economic development

MASSACHUSETTS CLEAN ENERGY CENTER®

IPA ILLINOIS POWER AGENCY

NEW MEXICO emnrd Energy, Minerals and Natural Resources Department

OEI Wisconsin Office of Energy Innovation

NEW YORK STATE OF OPPORTUNITY. | NYSERDA

BPU New Jersey's cleanenergy program™ njcleanenergy.com

CONNECTICUT GREEN BANK℠

New Hampshire Public Utilities Commission

MICHIGAN Energy Office

Maryland Energy Administration

State of Washington Department of Commerce Innovation is in our nature.

State of Rhode Island Office of Energy Resources

VERMONT CLEAN ENERGY DEVELOPMENT FUND PUBLIC SERVICE DEPARTMENT

SMUD™ Powering forward. Together.

mn COMMERCE DEPARTMENT

MassDEP

Prairie Island Indian Community

DOER Massachusetts Department of Energy Resources

OREGON DEPARTMENT OF ENERGY

Connecticut Energy Environment

Illinois Commerce Commission ICC

RHODE ISLAND COMMERCE CORPORATION

OPC-DC Office of the People's Counsel ADVOCACY | EDUCATION | PROTECTION

Smart Electric Power Alliance

NREL NATIONAL RENEWABLE ENERGY LABORATORY

ACEP Alaska Center for Energy and Power

www.cesa.org

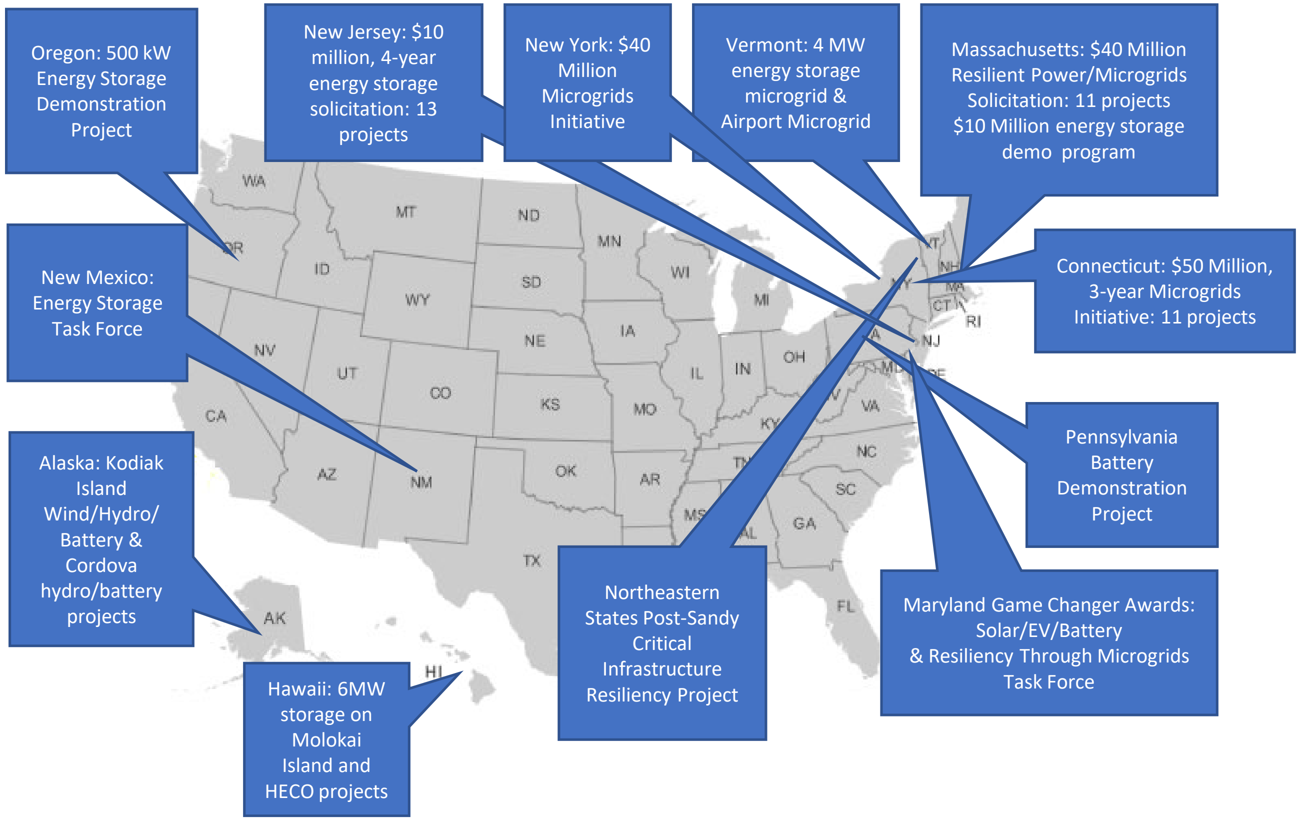
# Energy Storage Technology Advancement Partnership (ESTAP) (bit.ly/ESTAP)

ESTAP is supported by the U.S. Department of Energy Office of Electricity and Sandia National Laboratories, and is managed by CESA.

**ESTAP Key Activities:**

1. Disseminate information to stakeholders
    - ESTAP listserv >5,000 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

**ESTAP Project Locations:**



Oregon: 500 kW Energy Storage Demonstration Project

New Jersey: $10 million, 4-year energy storage solicitation: 13 projects

New York: $40 Million Microgrids Initiative

Vermont: 4 MW energy storage microgrid & Airport Microgrid

Massachusetts: $40 Million Resilient Power/Microgrids Solicitation: 11 projects $10 Million energy storage demo program

New Mexico: Energy Storage Task Force

Connecticut: $50 Million, 3-year Microgrids Initiative: 11 projects

Alaska: Kodiak Island Wind/Hydro/ Battery & Cordova hydro/battery 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 HECO projects

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

Clean Energy States Alliance

This webinar:

## Energy Storage 101, Part 3 – Applications and Economics

Previous webinars in this series:

- Energy Storage 101, Part 1 – Battery Storage Technology Systems and Cost Trends – March 26, 2019
- Energy Storage 101, Part 2 – Best Practices in State Policy – July 23, 2019

**Recordings at www.cesa.org/webinars/show/2019**

# Webinar Speakers

**Ray Byrne**
Sandia National
Laboratories

Sandia National Laboratories

**Todd Olinsky-Paul**
Clean Energy States
Alliance (moderator)

Clean Energy States Alliance

# Thank you for attending our webinar

Todd Olinsky-Paul
Project Director, CESA
Todd@cleanegroup.org

www.cesa.org/projects/energy-storage-technology-advancement-partnership/

Find us online:

www.cesa.org

facebook.com/cleanenergystates

# Upcoming Webinar

**SMUD’s Carbon-Reduction Strategies: Smart Homes, Strategic Electrification, and Energy Storage**

*Thursday, Dec. 5th at 1-2 pm ET*

This webinar is a follow-on to CESA's ESTAP webinars on energy storage projects and implementation at municipal utilities. The Sacramento Municipal Utility District (SMUD) is focused on deep carbon reduction via two key strategies: increasing renewable energy and strategic electrification. Rachel Huang, SMUD’s Director of Energy Strategy, Research & Development, will discuss SMUD's strategic electrification, storage, and carbon reduction efforts, and the programs benefits to the utility and ratepayer impacts.

Learn more and register at: [www.cesa.org/webinars](http://www.cesa.org/webinars)

Sandia National Laboratories

# Energy Storage Applications and Value Stacking

**Acknowledgment:** This work was funded by the Energy Storage program at the US Department of Energy under the guidance of Dr. Imre Gyuk.

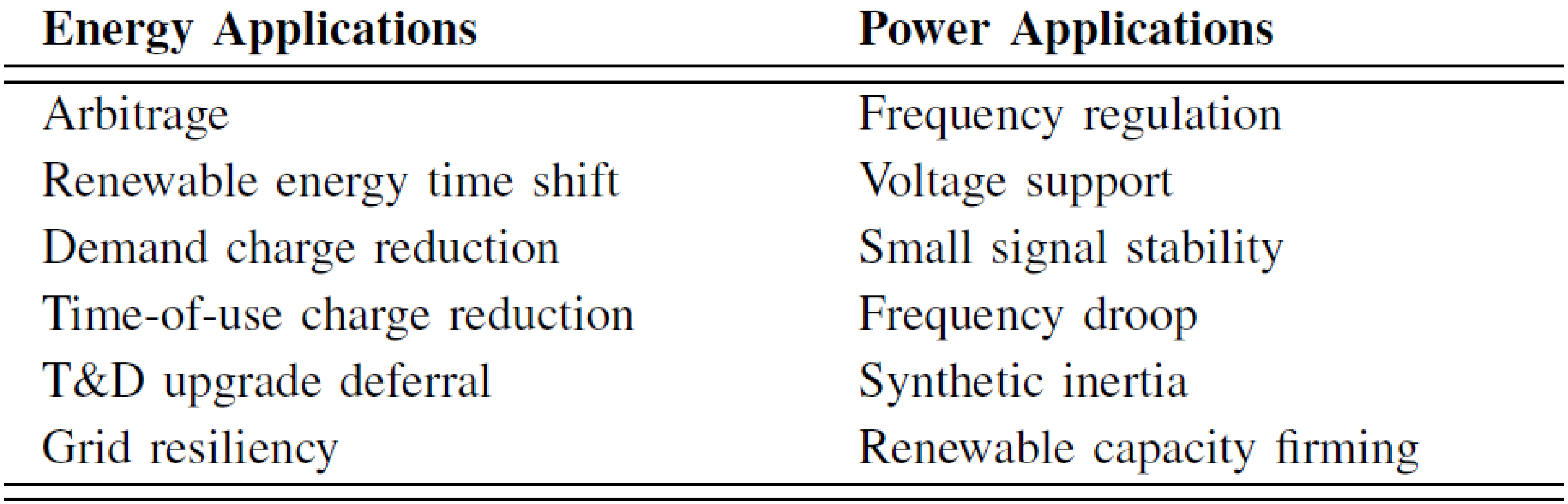
PRESENTED BY

Ray Byrne, Ph.D.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

# Energy storage application time scale

- "Energy" applications – slower times scale, large amounts of energy
- "Power" applications – faster time scale, real-time control of the electric grid



| **Energy Applications** | **Power Applications** |
|---|---|
| Arbitrage | Frequency regulation |
| Renewable energy time shift | Voltage support |
| Demand charge reduction | Small signal stability |
| Time-of-use charge reduction | Frequency droop |
| T&D upgrade deferral | Synthetic inertia |
| Grid resiliency | Renewable capacity firming |

# Energy Arbitrage

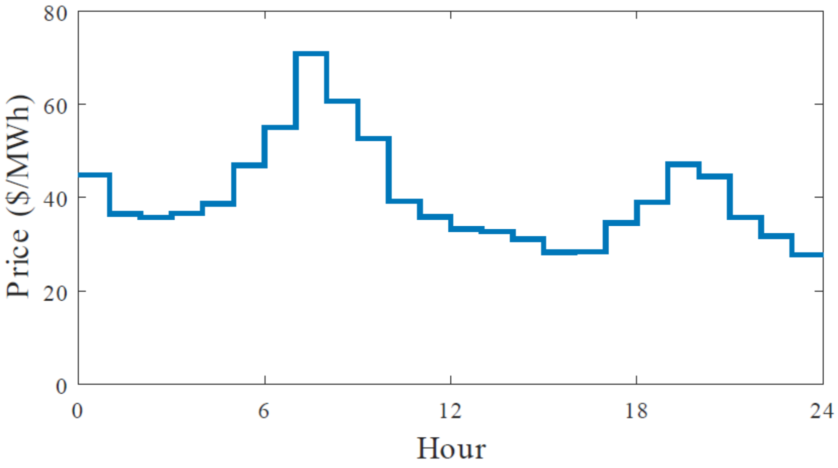
Buy low, sell high

$\eta_c$= conversion efficiency

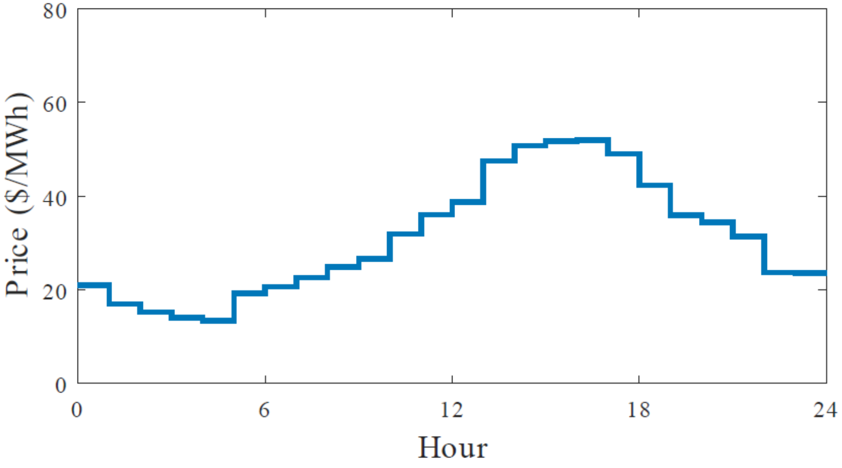
$LMP_H$ = average high LMP, $LMP_L$ = average low LMP

$q$ = charge quantity

$$\text{arbitrage opportunity} = q\eta_c LMP_H - qLMP_L$$



(a) Day ahead LMP for ISO-NE node 4476 (LD.STERLING13.8), March 23, 2017.



(b) Day ahead LMP for ISO-NE node 4476 (LD.STERLING13.8), July 14, 2016.

# Energy Arbitrage

Market area – market prices

Vertically integrated utility – efficiency savings

Different variants

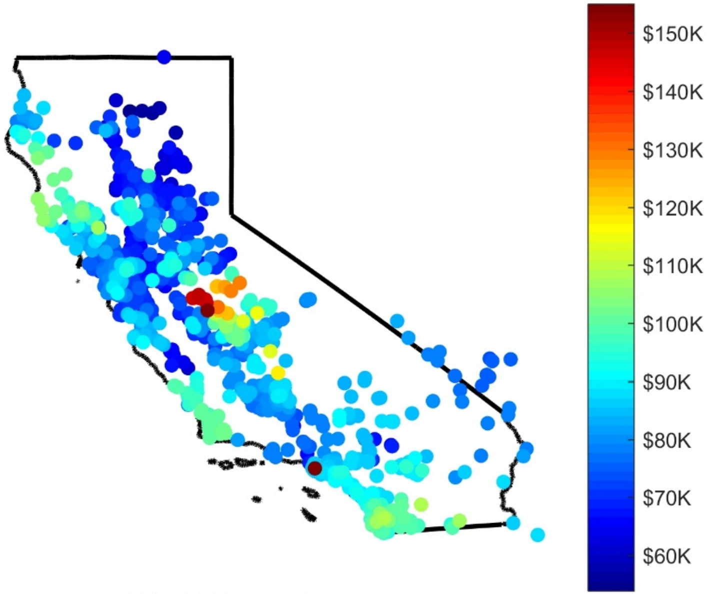
- Charge with inexpensive renewable energy
- Arbitrage day ahead and real-time markets
- Day ahead market only

Rarely the highest potential revenue stream

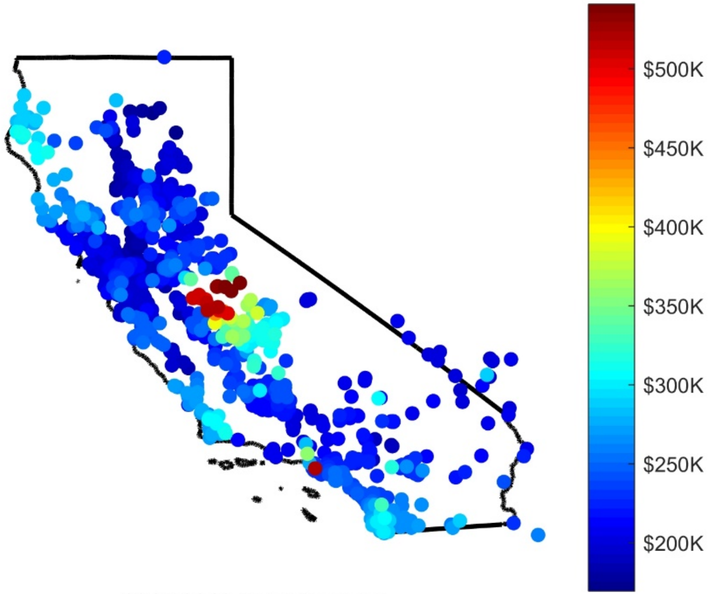
85% efficiency => 117.6% price difference

65% efficiency => 153.8% price difference

# Energy Arbitrage Example - CAISO



2014-2016 Total Revenue
DA Arbitrage



2014-2016 Total Revenue
DA+RT Arbitrage

- 1 MW, 4 MWh system, 80% efficiency
- Three year total revenue by LMP node, 2014-2016
- Assumes perfect foresight (best you can do)

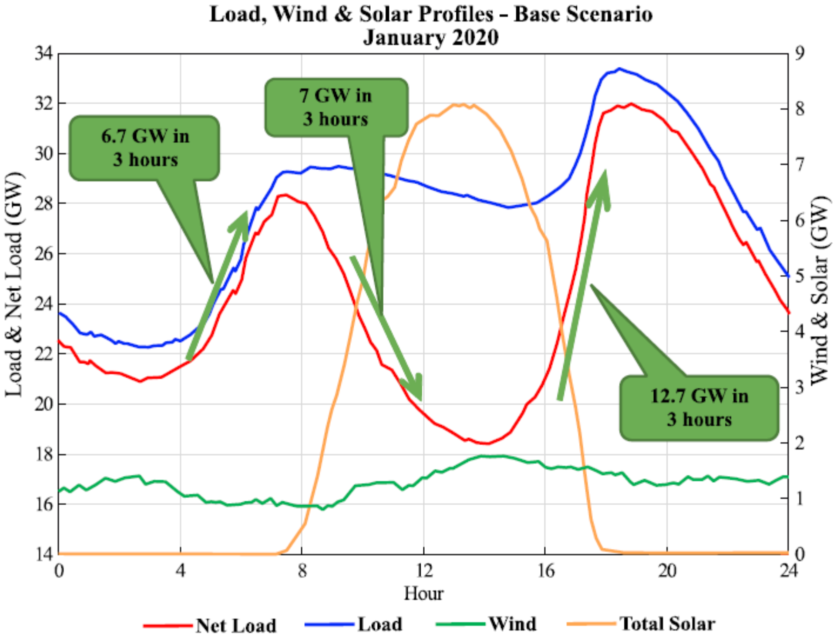
# Renewable Energy Time Shift

Goal – shift renewable generation from off-peak to on-peak hours

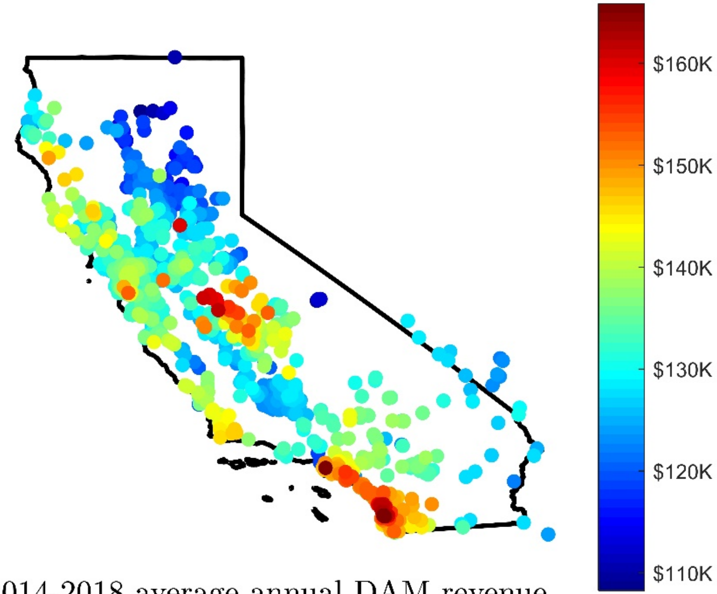
Example – CAISO "duck curve"

CAISO has implemented a ramping product

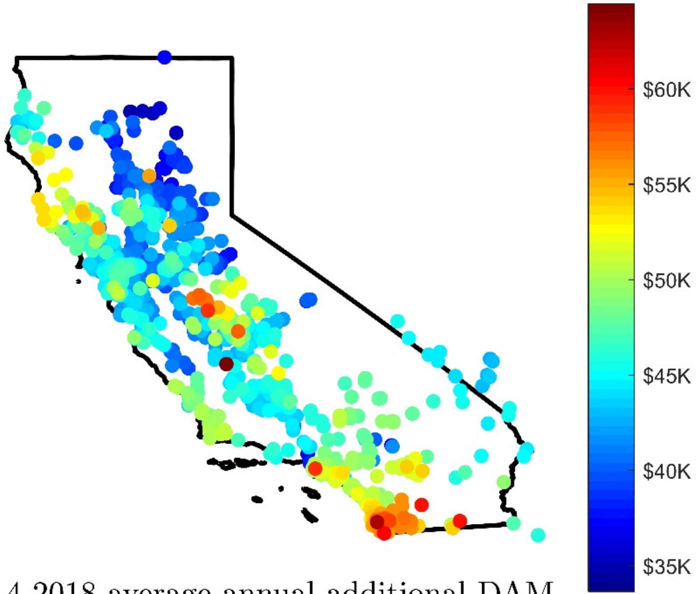
Other areas, arbitrage is your only option



# Solar + Storage Example - CAISO



2014-2018 average annual DAM revenue from solar + storage ($K)



2014-2018 average annual additional DAM revenue from storage ($K)

- 1 MW, 4 MWh system, 80% efficiency
- 1 MW solar plant
- Five year average revenue by LMP node, 2014-2018
- Assumes perfect foresight (best you can do)

# Renewable Energy Time Shift

To attain the goal of 100% renewable generation, massive amounts of longer-term storage will be needed

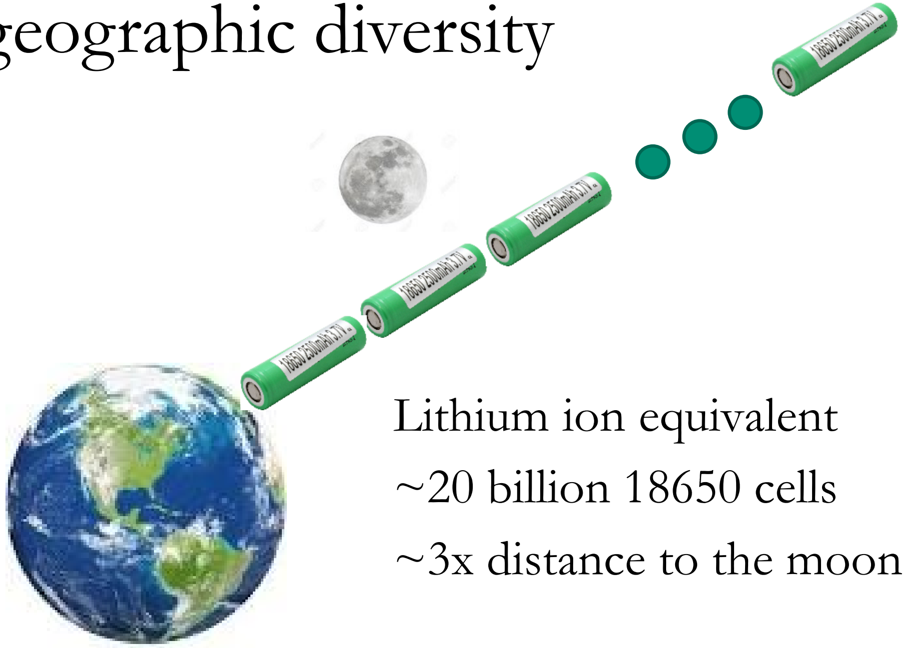
Tradeoffs between:

- Amount of storage
- Additional transmission (geographic diversity reduces variability)
- Renewable curtailment

Racoon Mountain pumped hydro

1,652 MW

22 hours



Lithium ion equivalent

~20 billion 18650 cells

~3x distance to the moon

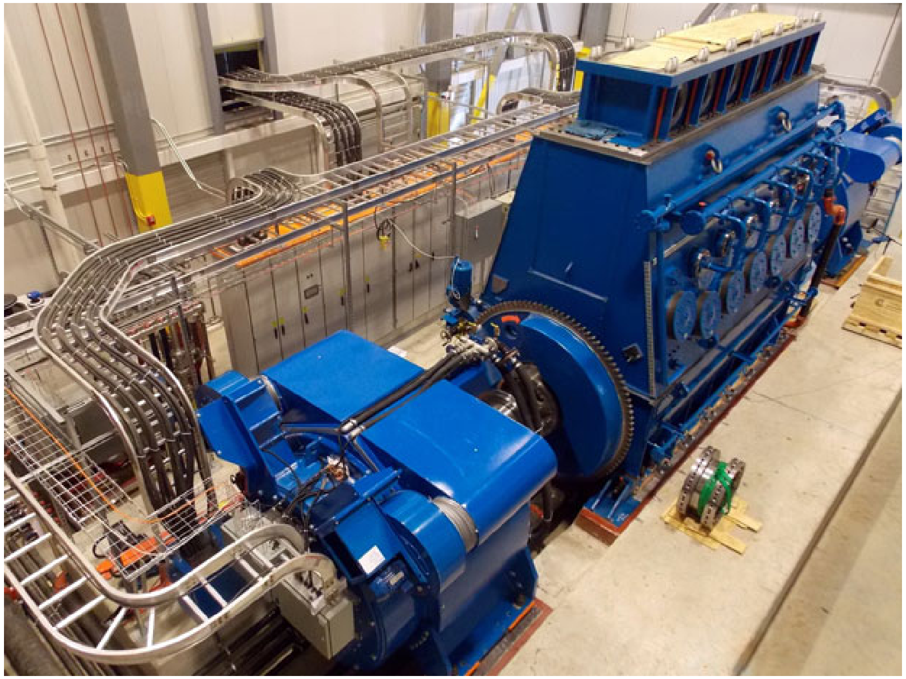
## Mature Long-Term Storage Technologies

- Pumped hydro
- Compressed air energy storage
- Thermal storage (e.g., concentrated solar)

## Promising Long-Term Storage Technologies

- Flow batteries
- Hydrogen electrolysis

## More Research is Needed



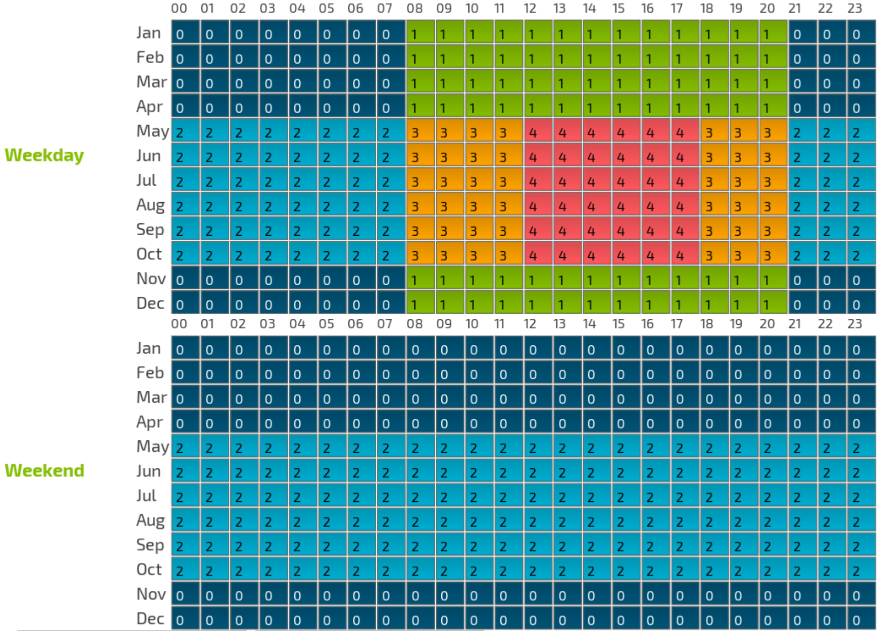
# Time-of-Use Charge Reduction

Behind-the-meter application

Arbitrage based on the rate structure

- Rates for each time period
- On-peak/off-peak pricing

Often not a significant benefit



**Weekday**

| | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Feb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Mar | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Apr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| May | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |
| Jun | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |
| Jul | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |
| Aug | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |
| Sep | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |
| Oct | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |
| Nov | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Dec | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |

**Weekend**

| | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mar | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Apr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| May | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Jun | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Jul | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Aug | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Sep | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Oct | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Nov | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dec | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

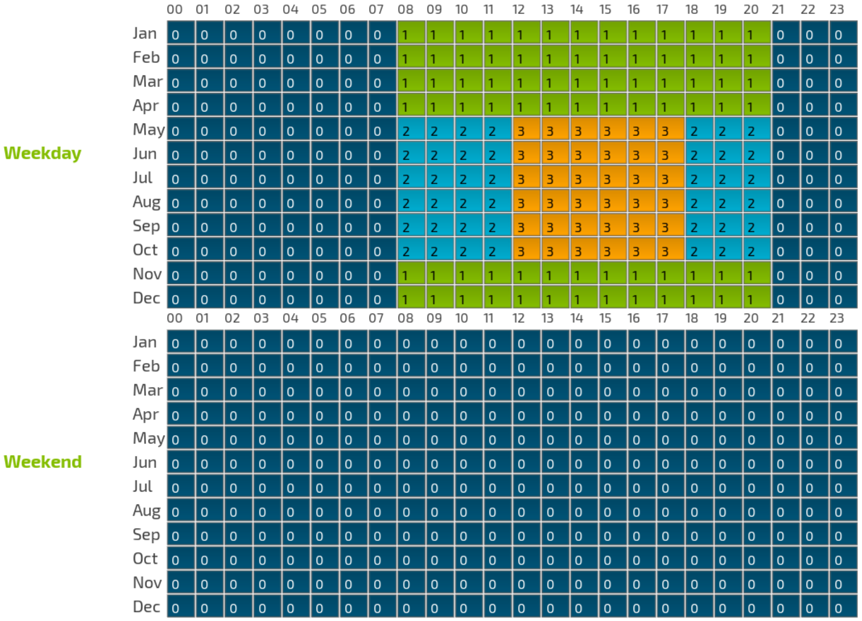
# Demand Charge Reduction

Behind-the-meter application

Demand charge typically based on the maximum rate of consumption ($/kW) over the billing period

Narrow spikes can significantly increase the electricity bill

Often results in a significant benefit



**Weekday**

| | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Feb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Mar | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Apr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| May | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 0 | 0 | 0 |
| Jun | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 0 | 0 | 0 |
| Jul | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 0 | 0 | 0 |
| Aug | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 0 | 0 | 0 |
| Sep | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 0 | 0 | 0 |
| Oct | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 0 | 0 | 0 |
| Nov | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Dec | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |

**Weekend**

| | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Feb | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mar | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Apr | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| May | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Jun | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Jul | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Aug | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sep | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oct | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Nov | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dec | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# T&D Upgrade Deferral

Projected load growth requires a transmission or distribution upgrade

Energy storage can be deployed to defer the investment

$ES_0$ = energy storage cost
$T_0$ = deferred transmission investment
$r$ = interest rate
$K$ = number of deferral years

$$ES_0 \leq T_0 \left(1 - e^{-rK}\right)$$

# Grid Resiliency

Events like Hurricane Sandy and Hurricane Katrina have increased the interest in grid resiliency applications

Value of Lost Load (VOLL) – typically estimated based on

- Market prices
- Surveys

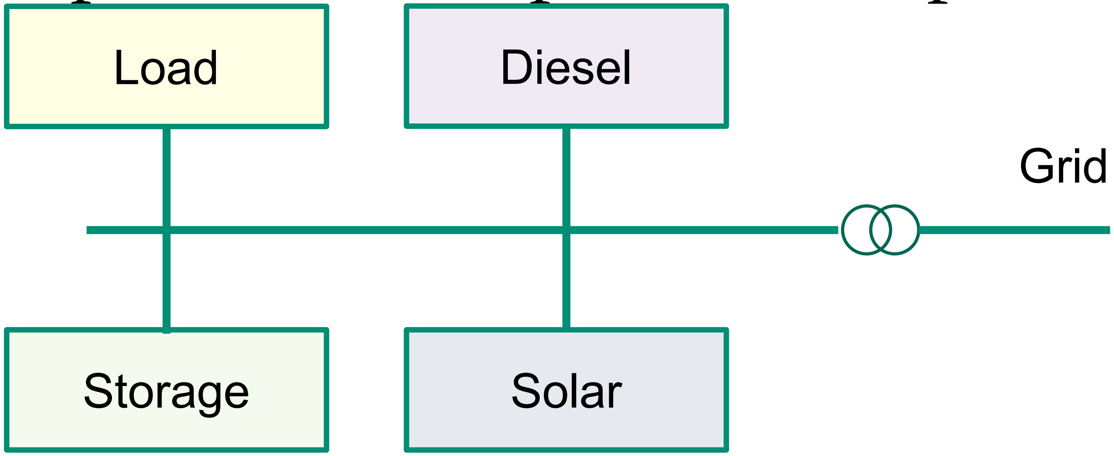
Data for public administration likely under-estimates the value

Sterling Municipal Light Department
2 MW, 3.9 MWh system

# Microgrids - hybrid renewable, storage and alternative backup solutions for critical load

- Energy storage is a key component
- Often paired with distributed generation
  - Solar
  - Wind
  - Diesel
  - Natural gas

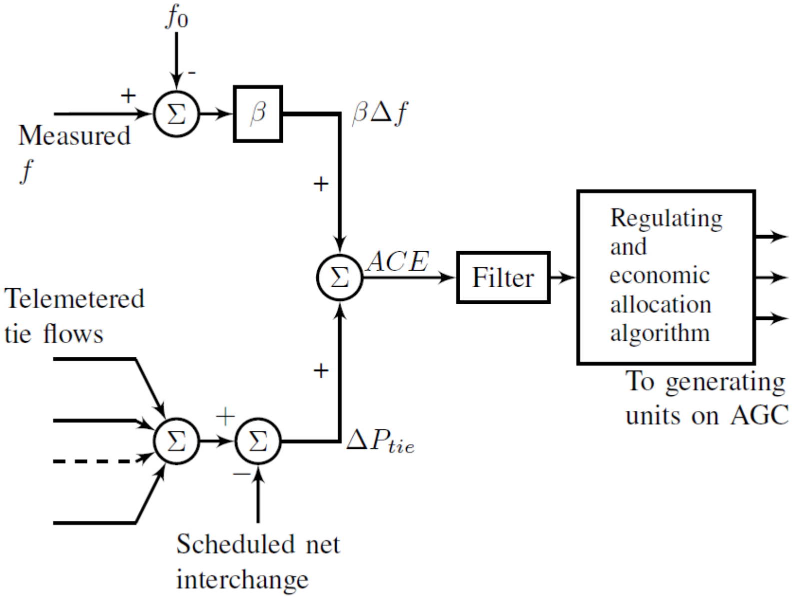
Design and operation are optimization problems

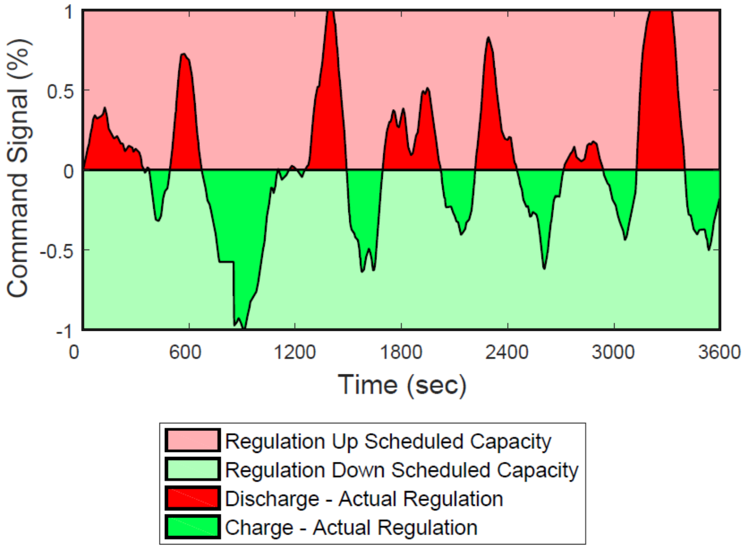


# Frequency Regulation

Second by second adjustment in output power to maintain grid frequency

Follow automatic generation control (AGC) signal





Representative regulation command signal (RegD from PJM)

# Frequency Regulation

Implementation varies by independent system operator

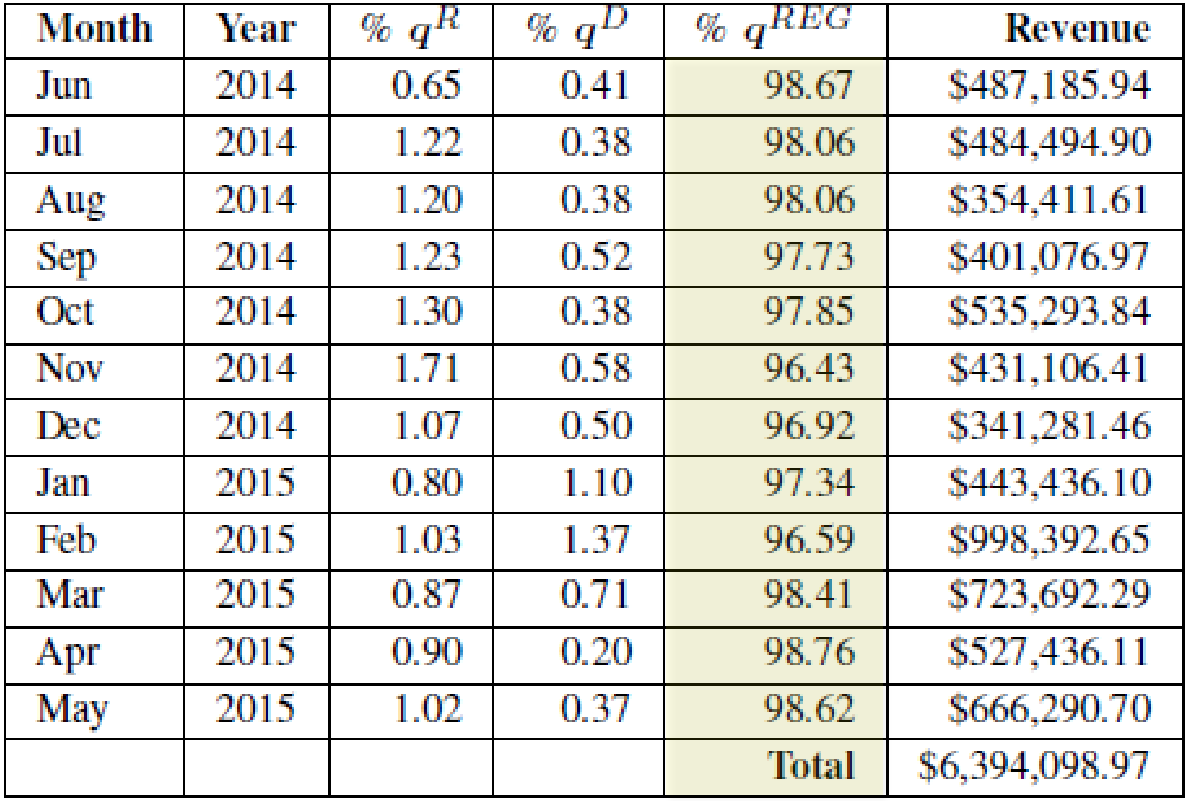
- Bidirectional signal – PJM
- Regulation Up, Regulation down – CAISO, ERCOT

Pay-for-performance

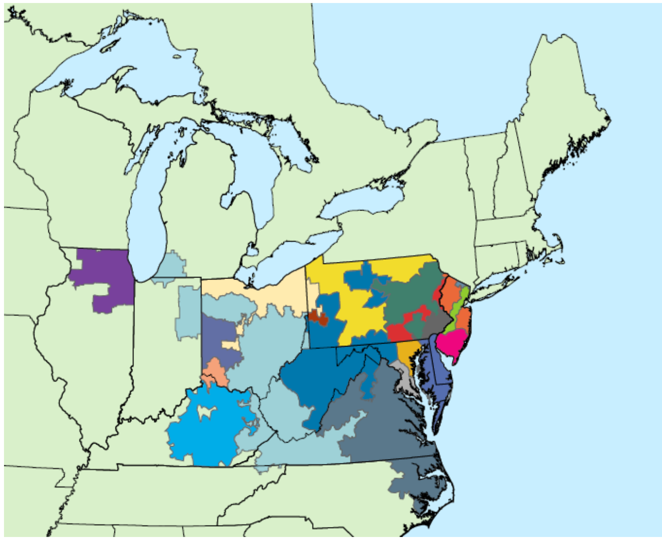
- Performance score (how well did you track command signal)
- Mileage payment

20 MW, 5 MWh Beacon flywheel plant at Hazle Township, Pennsylvania

# Often the highest potential revenue stream



| Month | Year | % $q^R$ | % $q^D$ | % $q^{REG}$ | Revenue |
|---|---|---|---|---|---|
| Jun | 2014 | 0.65 | 0.41 | 98.67 | $487,185.94 |
| Jul | 2014 | 1.22 | 0.38 | 98.06 | $484,494.90 |
| Aug | 2014 | 1.20 | 0.38 | 98.06 | $354,411.61 |
| Sep | 2014 | 1.23 | 0.52 | 97.73 | $401,076.97 |
| Oct | 2014 | 1.30 | 0.38 | 97.85 | $535,293.84 |
| Nov | 2014 | 1.71 | 0.58 | 96.43 | $431,106.41 |
| Dec | 2014 | 1.07 | 0.50 | 96.92 | $341,281.46 |
| Jan | 2015 | 0.80 | 1.10 | 97.34 | $443,436.10 |
| Feb | 2015 | 1.03 | 1.37 | 96.59 | $998,392.65 |
| Mar | 2015 | 0.87 | 0.71 | 98.41 | $723,692.29 |
| Apr | 2015 | 0.90 | 0.20 | 98.76 | $527,436.11 |
| May | 2015 | 1.02 | 0.37 | 98.62 | $666,290.70 |
|  |  |  |  | Total | $6,394,098.97 |



PJM results, 20MW, 5MWh 200-flywheel system

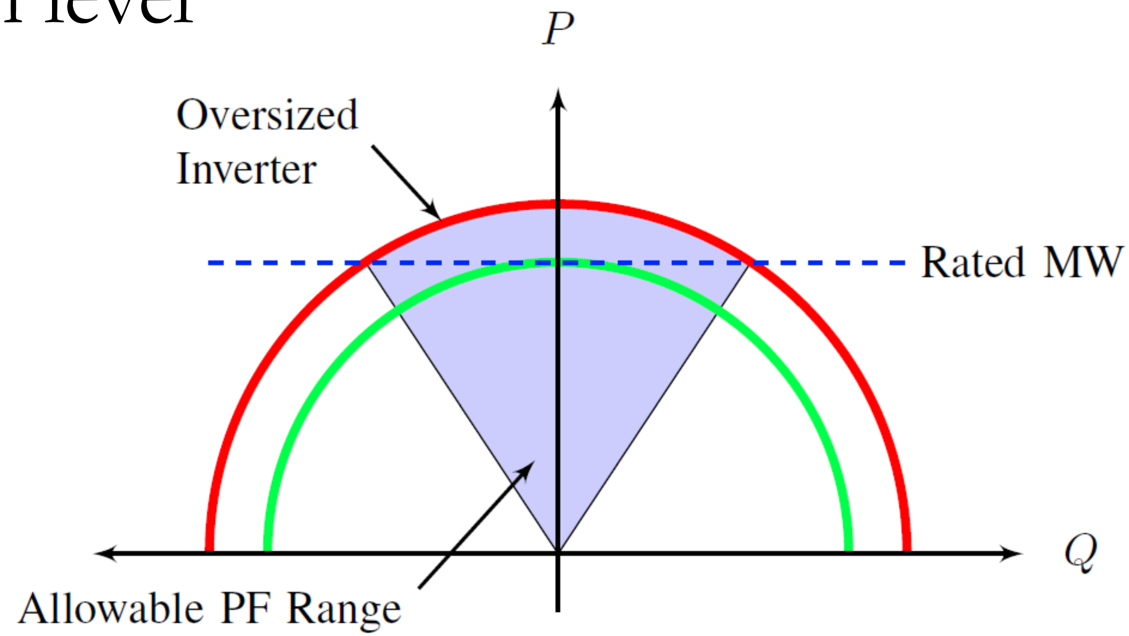
Beacon Power Flywheel

# Voltage Support

Inject real/reactive power to control voltage

Can support reactive power over a wide state-of-charge range, limited by inverter rating

Some ISOs compensate for reactive power at the transmission level



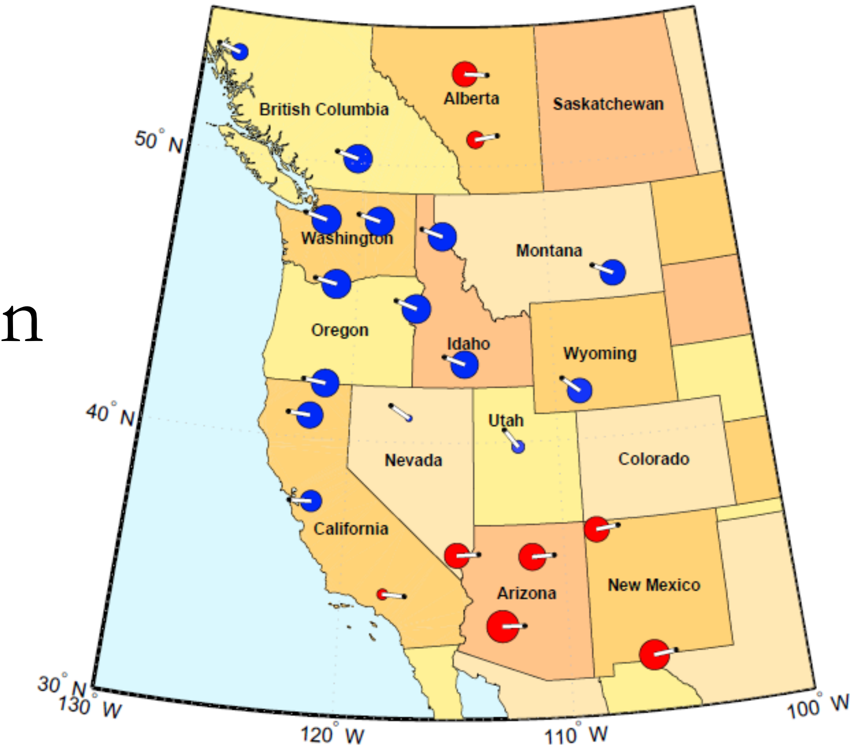
# Small Signal Stability

All large power systems are subject to low frequency electro-mechanical oscillations (0.2-1 Hz)

Injection of real power can provide damping

BPA has a demonstration project underway

Potential future revenue stream



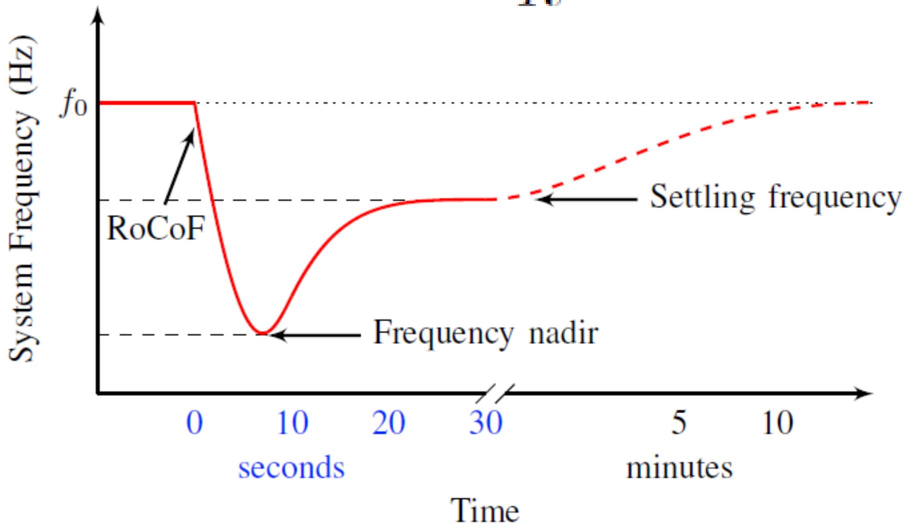
North-South Mode B (0.37 Hz) from a 2015 heavy summer WECC base case simulation

# Frequency Droop

Frequency droop: generator speed control proportional to the speed (frequency) error

Energy storage can provide frequency droop via a control law

$$\Delta P = -\frac{1}{R}\Delta f$$



# Frequency Droop

In the U.S., generators are not required to provide frequency responsive service

Nor are they compensated for providing the service

Eastern Interconnection suffers from a "Lazy L"

February 18, 2016, FERC issued a notice of inquiry to reform rules and regulations

- Required service, Mechanisms for compensating service

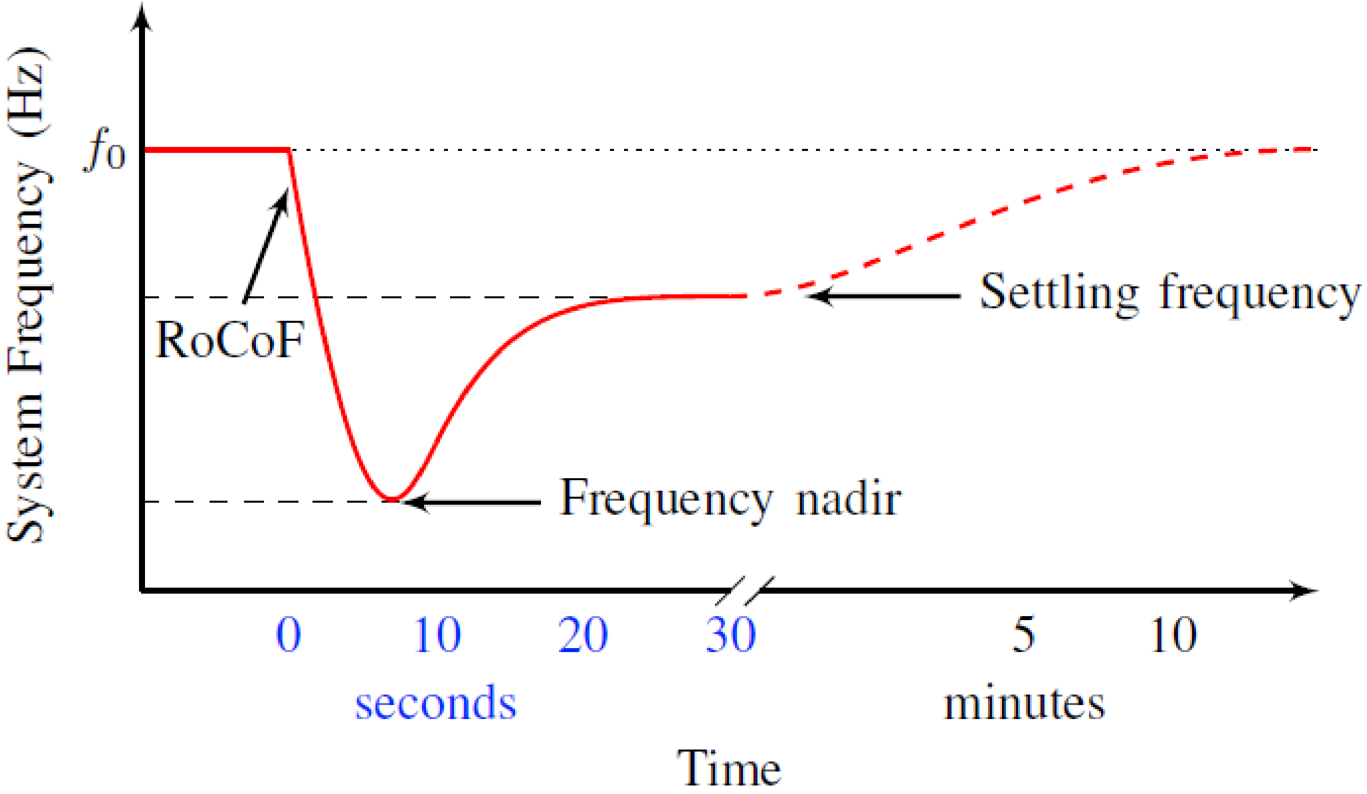
August 8, 2017 FERC requests supplemental comments

February 15, 2018 – FERC Order 842, all new generation must be capable of providing primary frequency response as a condition of interconnection

# Synthetic Inertia

Large rotating machines provide inertia

Rate of Change of Frequency (RoCoF) is proportional to the inertia in the system



# Synthetic Inertia

Increased inverter-based generation displaces inertia

Energy storage can provide synthetic inertia via a control law

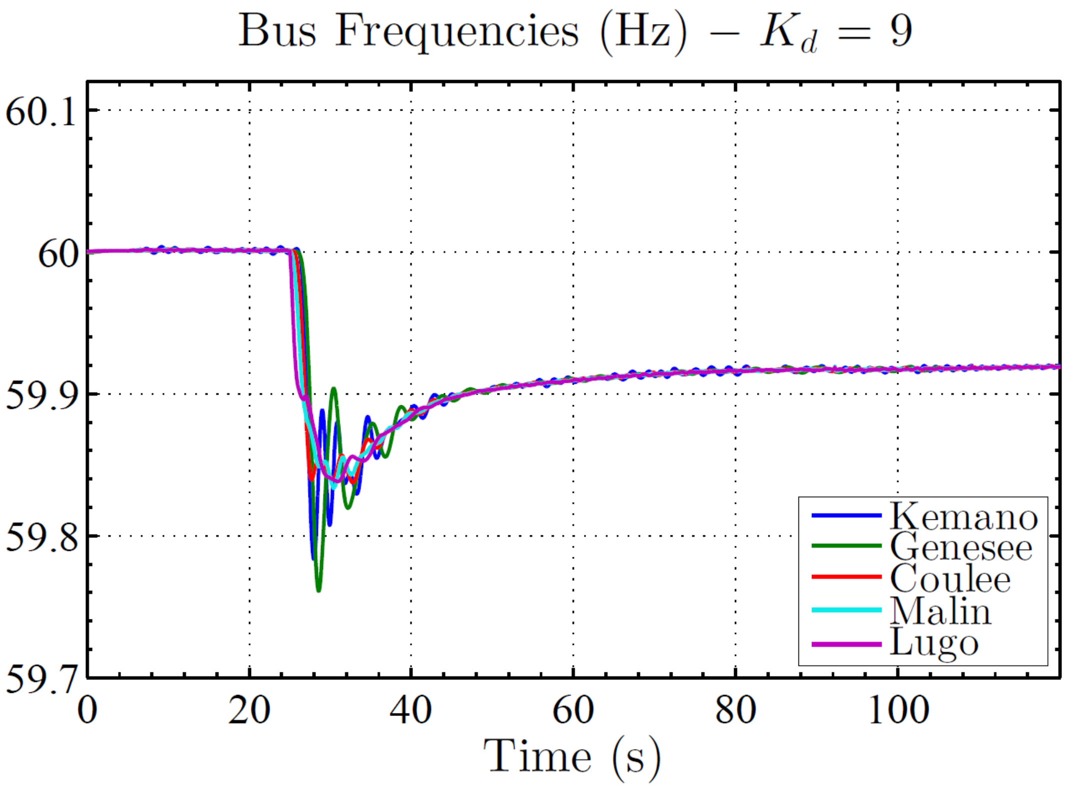
$$\Delta P = -k_{in}\frac{df}{dt}$$

No mechanisms for compensating resources that provide inertia

# Synthetic Inertia

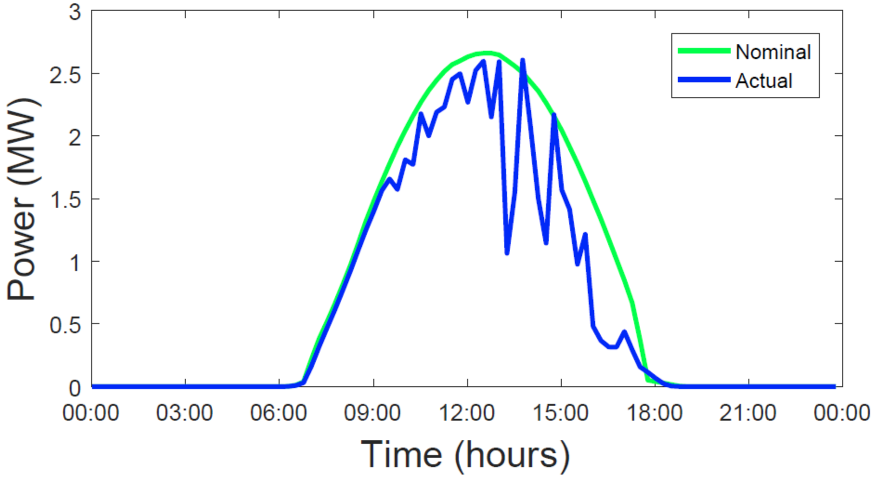
Local frequency measurement is often proposed – this can be problematic near faults

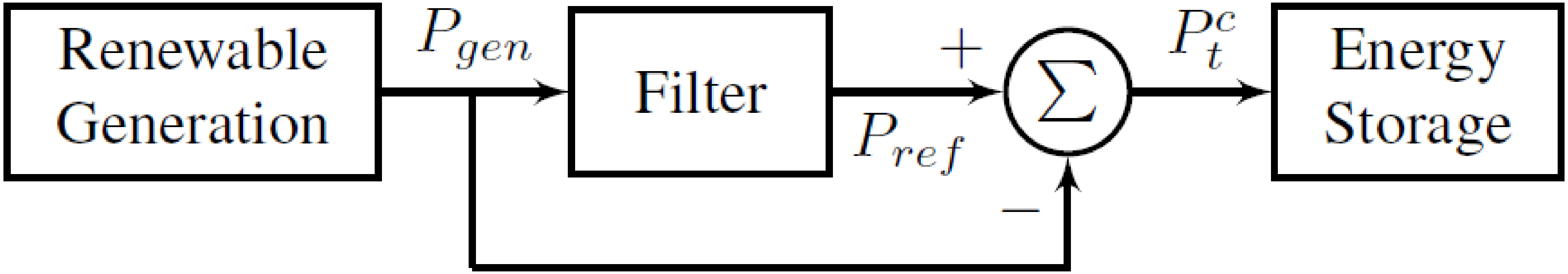
There are advantages to responding to a system frequency



# Some areas are placing ramp rate limitations on renewable generation

- Puerto Rico
- Hawaii





# Maximizing Revenue from Energy Storage

Revenue maximization can be formulated as an LP-optimization

First step – best possible scenario (perfect foresight)
- Gives insight into storage operation
- Starting point for developing operating strategy

In most market areas, frequency regulation is the optimum application

Exception – ISO NE
- Forward Capacity Market payments
- Regional Network Service payment

Grid resilience is a common goal
- VOLL from surveys does not yield a significant value
- Likely does not capture the value to first responders
- Definition of resilience is important

# Energy Storage Model

Energy flow model

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

$S_t$: state of charge at time step $t$ (MWh)

$\gamma_s$: storage efficiency (percent)

$q_t^R$: quantity of energy purchased for recharging at time step $t$ (MWh)

$q_t^D$: quantity of energy sold for discharging at time step $t$ (MWh)

Constraints:

| | |
|---|---|
| $\bar{q}$ | maximum discharged/recharged energy in one period (MWh) |
| $\bar{S}$ | maximum storage capacity (MWh) |
| $\underline{\mathrm{S}}$ | minimum storage capacity (MWh) |

$$\underline{\mathrm{S}} \leq S_t \leq \bar{S}, \forall t$$

$$0 \leq q_t^D + q_t^R \leq \bar{q}, \forall t$$

# CAISO MODEL – DA/RT Market Arbitrage

Objective function

$$\begin{aligned}\max \sum_{t=1}^{T} \quad & [(P_t^{DA} - C_d)q_t^{D-DA} + \\ & (P_t^{RT} - C_d)q_t^{D-RT} - \\ & (P_t^{DA} + C_r)q_t^{R-DA} - \\ & (P_t^{RT} + C_r)q_t^{R-RT}]\, e^{-rt}\end{aligned}$$

Analyzed 3 years for market data (2014-2016) for ~2200 CAISO nodes

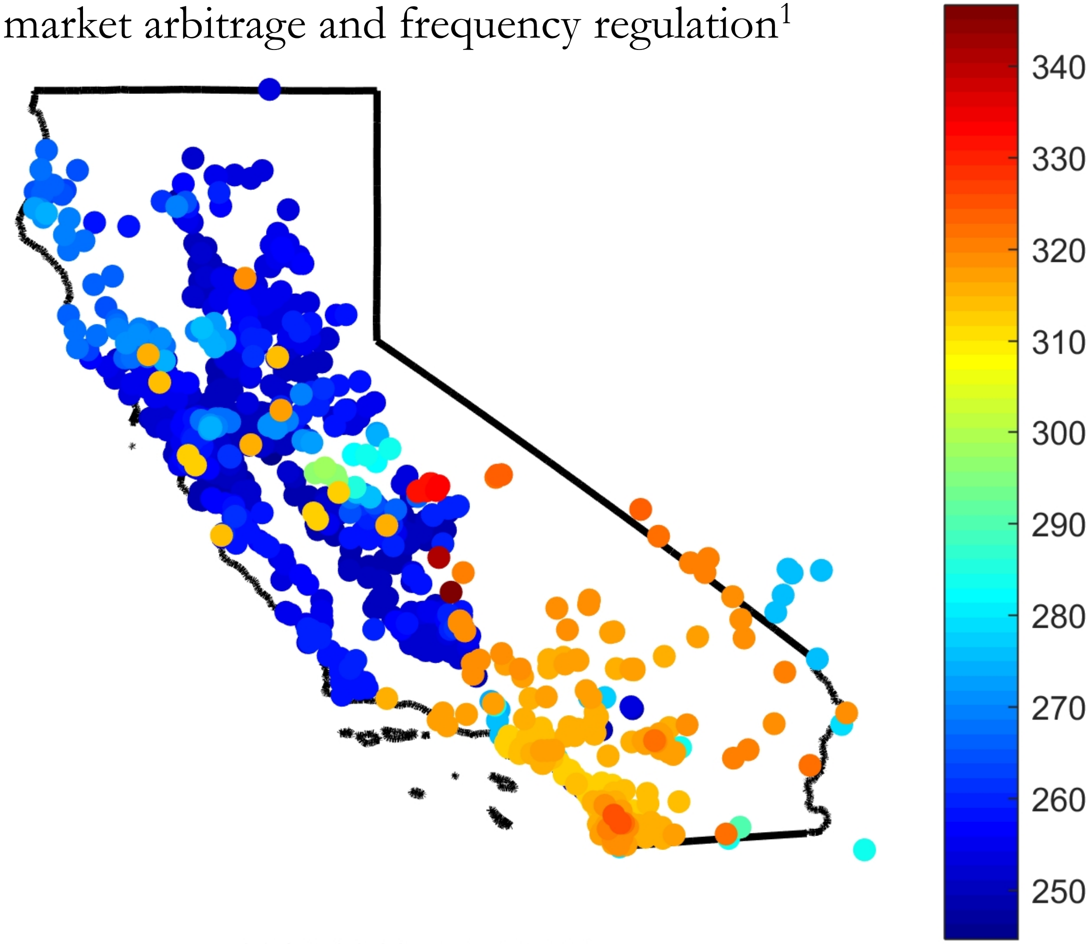
Energy storage model parameters

ENERGY STORAGE SYSTEM PARAMETERS

| **parameter** | **value** |
|---|---|
| $\gamma_c$ | 0.80 |
| $\gamma_s$ | 1.0 |
| $\bar{q}$ | 1.0 MWh |
| $\bar{S}$ | 4.0 MWh |
| $\underline{S}$ | 0.0 MWh |

# Estimating the Value of Energy Storage – CAISO Example

Results for DA market arbitrage and frequency regulation[1]



2014-2016 Total DAM
Arbitrage plus Regulation Revenue ($K)

---

[1] R. H. Byrne, T. A. Nguyen and R. J. Concepcion, “Opportunities for energy storage in CAISO," accepted for publication in the 2018 IEEE Power and Energy Society (PES) General Meeting, August 5-9, 2018.

# Sterling Municipal Light Department (SMLD)

Sterling Potential value streams:

- Energy arbitrage
- Reduction in monthly network load (based on monthly peak hour)
- Reduction in capacity payments (based on annual peak hour)
- Grid resilience
- Frequency Regulation

Grid Resilience was the primary goal – other applications help pay for the system

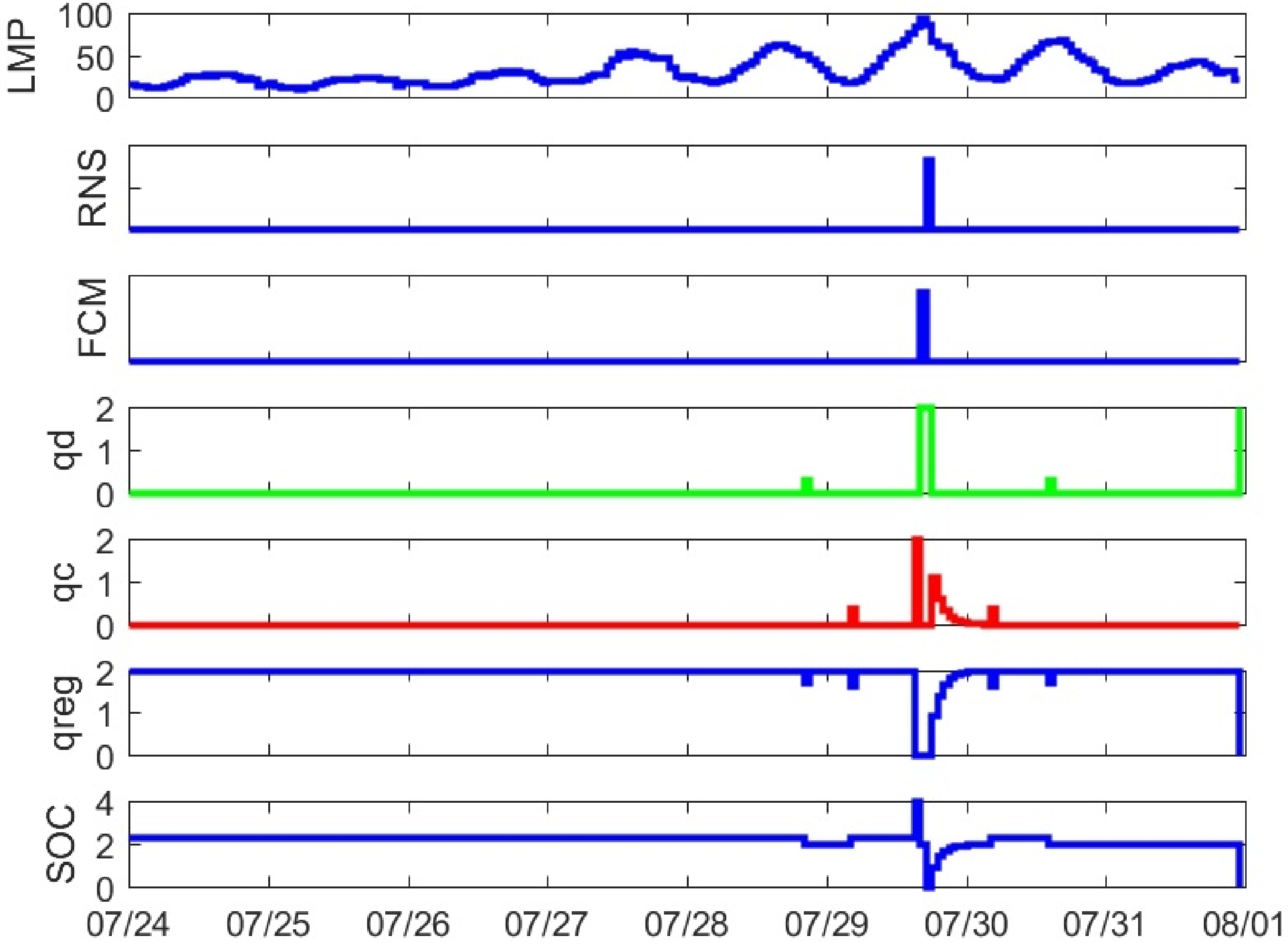
Several potential value streams (1MW, 1MWh 2017-18 data)

| Description | Total | Percent |
|---|---:|---:|
| Arbitrage | $40,738 | 16.0% |
| RNS payment | $98,707 | 38.7% |
| FCM obligation* | $115,572 | 45.3% |
| Total | $255,017 | 100% |

For more information, please refer to:

R. H. Byrne, S. Hamilton, D. R. Borneo, T. Olinsky-Paul, and I. Gyuk, "The value proposition for energy storage at the Sterling Municipal Light Department," proceedings of the 2017 IEEE Power and Energy Society General Meeting, Chicago, IL, July 16-20, 2017, pp. 1-5. DOI: 10.1109/PESGM.2017.8274631

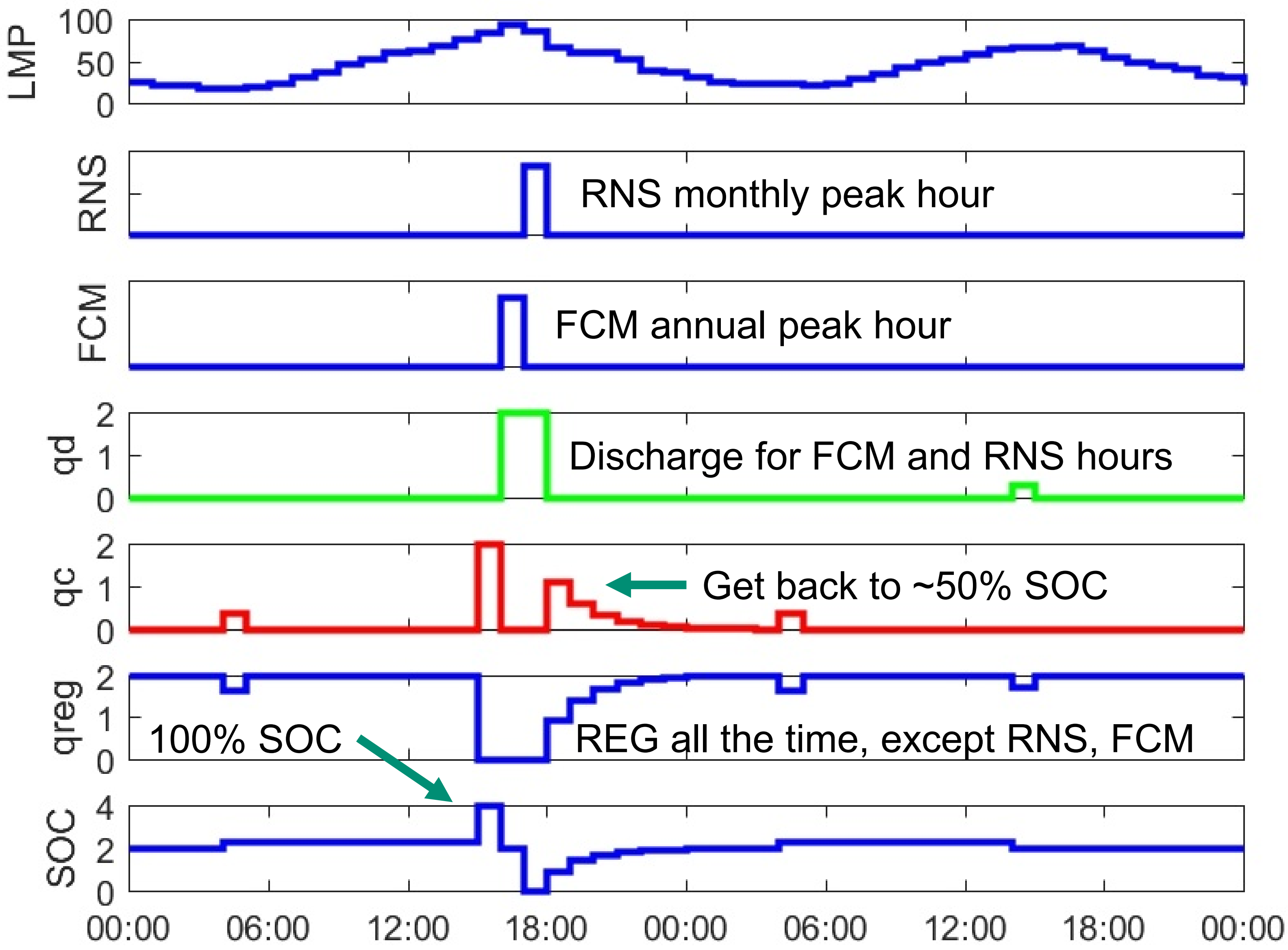
# Optimization Results – Typical Week SMLD



2 MW, 4 MWh system

- Last week of July 2015
- Annual and monthly peaks
- Spend the majority of the time at 50% SOC performing frequency regulation
- Charge up to 100% SOC in hour prior to FCM peak
- Discharge for two consecutive hours (FCM and RNS peak)
- Return to 50% SOC and continue performing frequency regulation
- Note minimal arbitrage (qc, qd)
- Assumes an energy neutral (with losses) regulation signal

# Optimization Results – Typical Day SMLD



RNS monthly peak hour

FCM annual peak hour

Discharge for FCM and RNS hours

Get back to ~50% SOC

100% SOC

REG all the time, except RNS, FCM

# Valuing Storage in a Vertically Integrated Utility

Production cost modeling is the gold standard for valuing storage in the Integrated Resource Planning Process

- Requires an accurate system mode
  - Transmission system
  - Load variability
  - Renewable variability
  - Generator models
- Primarily addresses arbitrage and reserve products

Other benefits require technical analysis & comparative economic analysis

- Primary frequency response/inertia – dynamic simulations
- Voltage support – power flow simulations
- Solar hosting capacity analysis of distribution networks
- T&D deferral – load modeling

# Stacking Benefits - Takeaways

Stacking benefits can increase potential revenue …

At the expense of:

- Potentially accelerated degradation of the energy storage system
- Potentially increased complexity of the forecasting and control algorithms

Modeling the degradation as a function of charge/discharge profile is still an active research area

# Summary

Energy storage is capable of providing a wide array of grid services

Regulatory structure is still evolving for many applications

Different technologies for energy versus power applications

Valuation of storage is highly location-specific

For further reading:

www.sandia.gov/ess