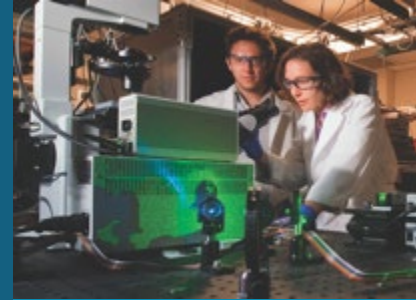


Energy Storage Applications and Value Stacking



PRESENTED BY

Ray Byrne, Ph.D.



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



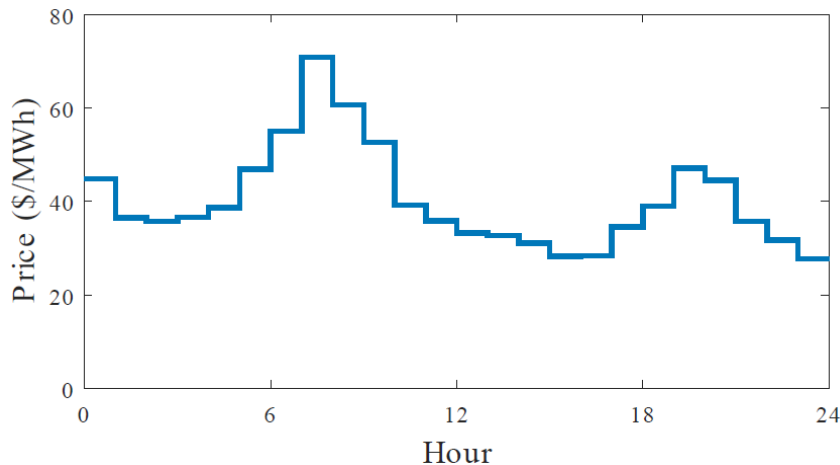
Buy low, sell high

η_c = conversion efficiency

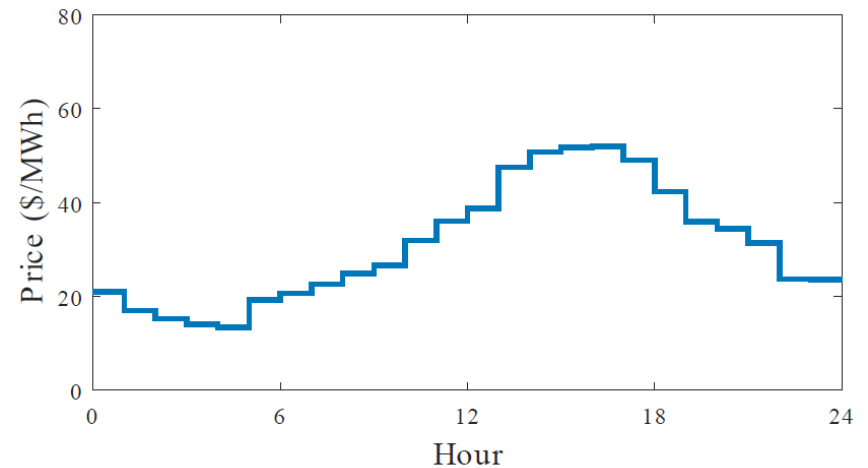
LMP_H = average high LMP, LMP_L = average low LMP

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.



Market area – market prices

Vertically integrated utility – efficiency savings

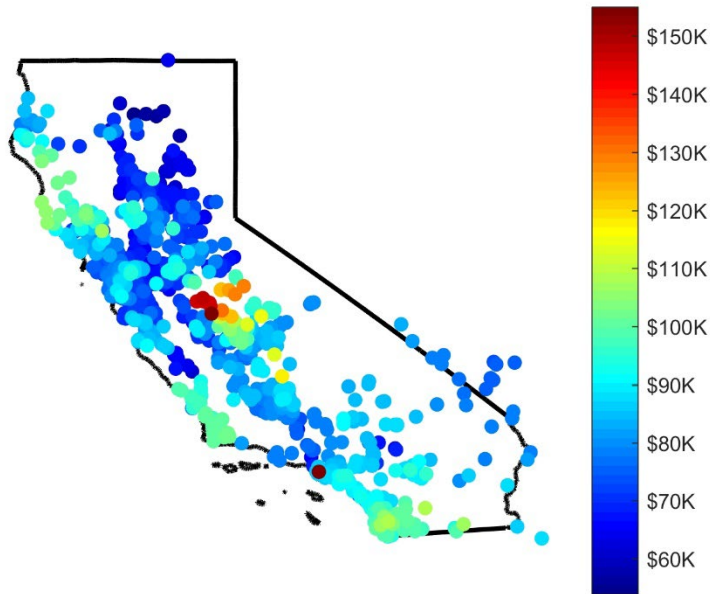
Different variants

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

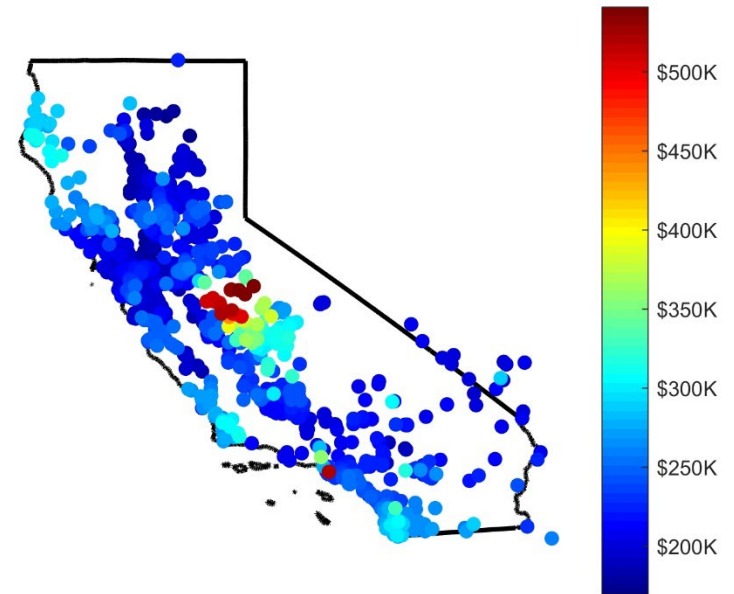
Rarely the highest potential revenue stream

85% efficiency \Rightarrow 117.6% price difference

65% efficiency \Rightarrow 153.8% price difference



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)

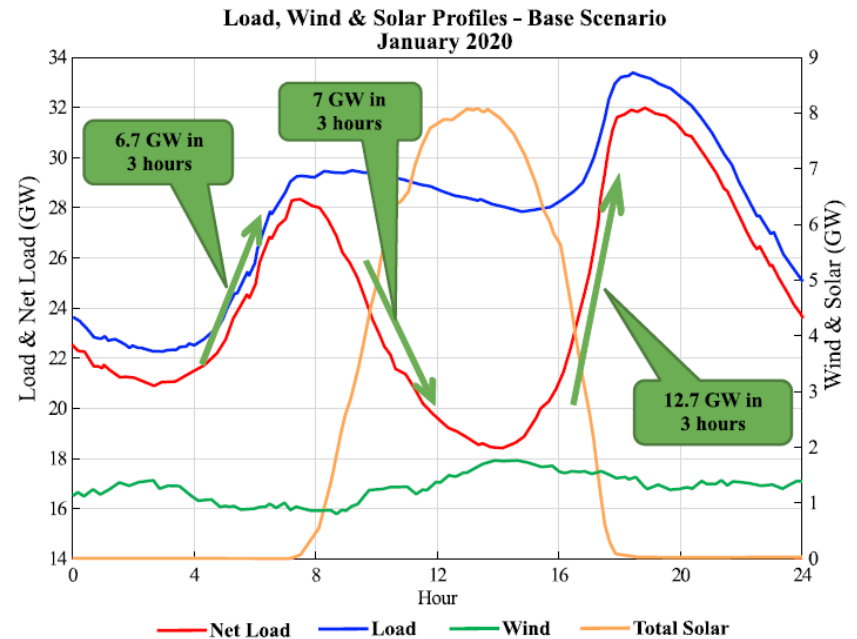


Goal – shift renewable generation from off-peak to on-peak hours

Example – CAISO “duck curve”

CAISO has implemented a ramping product

Other areas, arbitrage is your only option





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

Tradeoffs between:

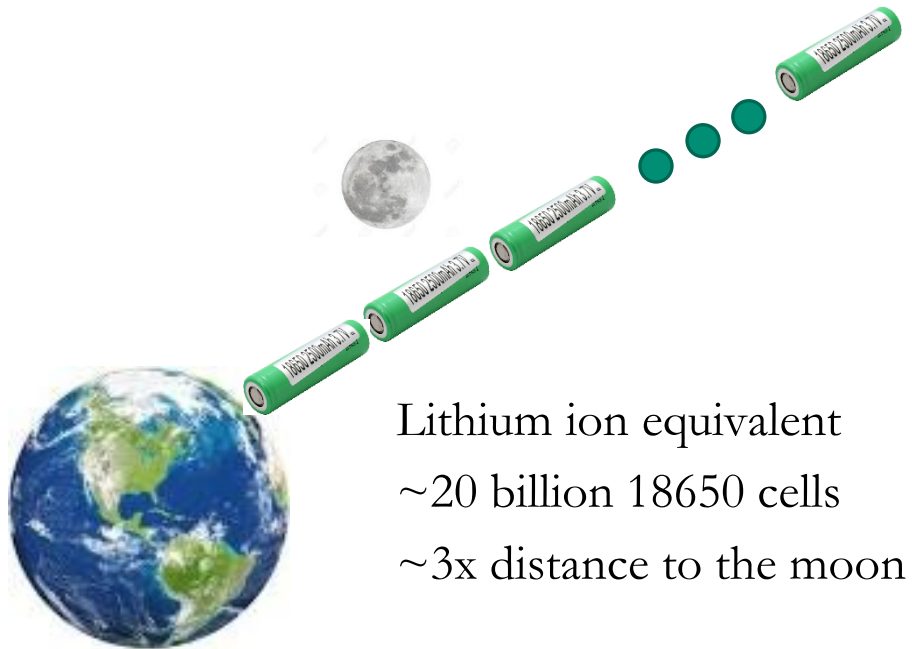
- Amount of storage
- Additional transmission (geographic diversity reduces variability)
- Renewable curtailment



Racoon Mountain pumped hydro

1,652 MW

22 hours



Lithium ion equivalent
~20 billion 18650 cells
~3x distance to the moon



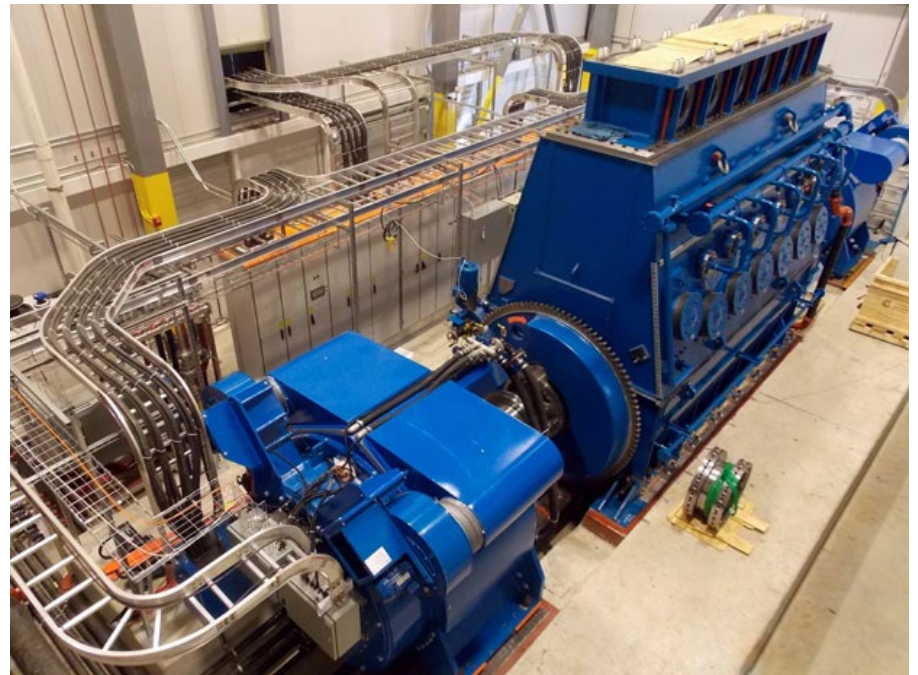
Mature Long-Term Storage Technologies

- 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





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



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



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 underestimates the value



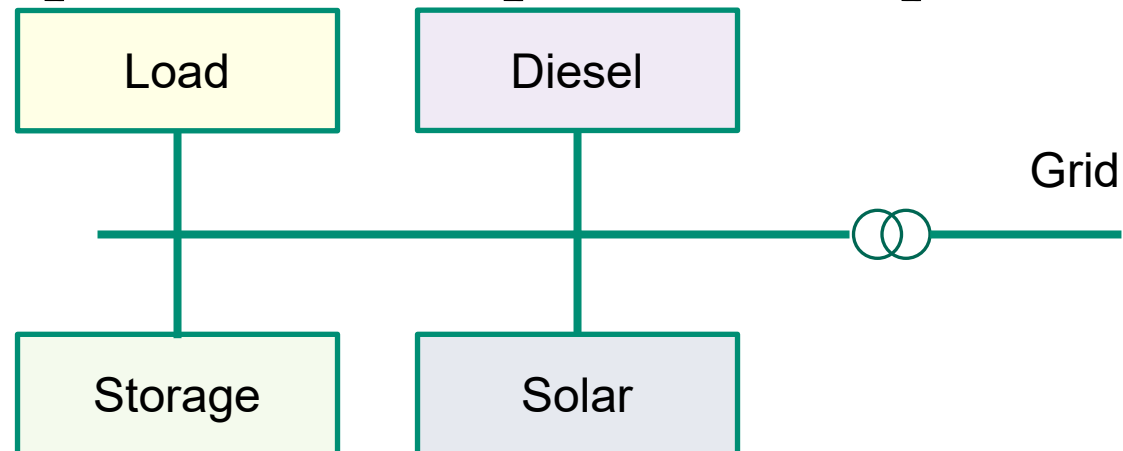
Sterling Municipal Light Department
2 MW, 3.9 MWh system



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

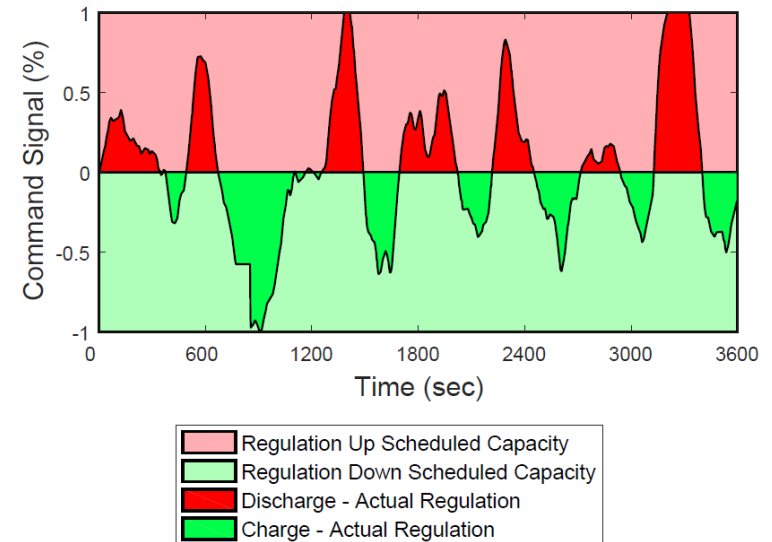
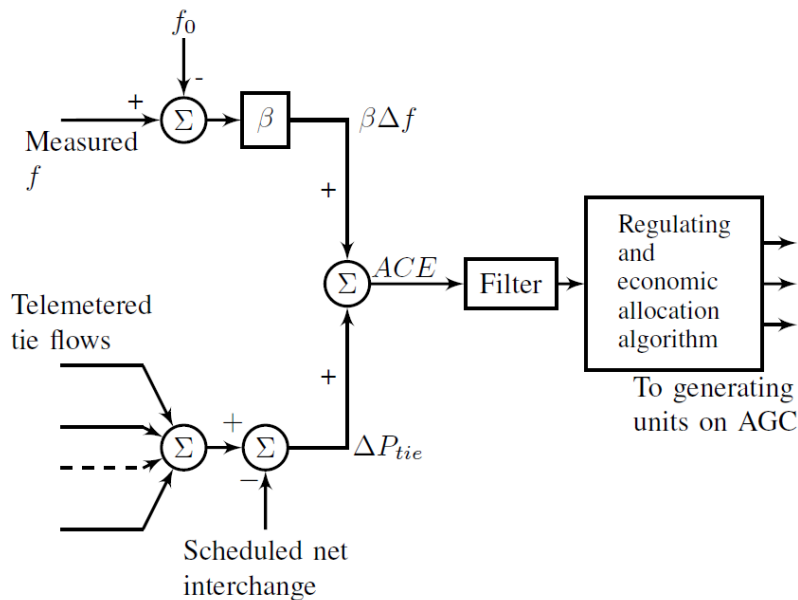
Design and operation are optimization problems





Second by second adjustment in output power to maintain grid frequency

Follow automatic generation control (AGC) signal



Representative regulation command signal (RegD from PJM)



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

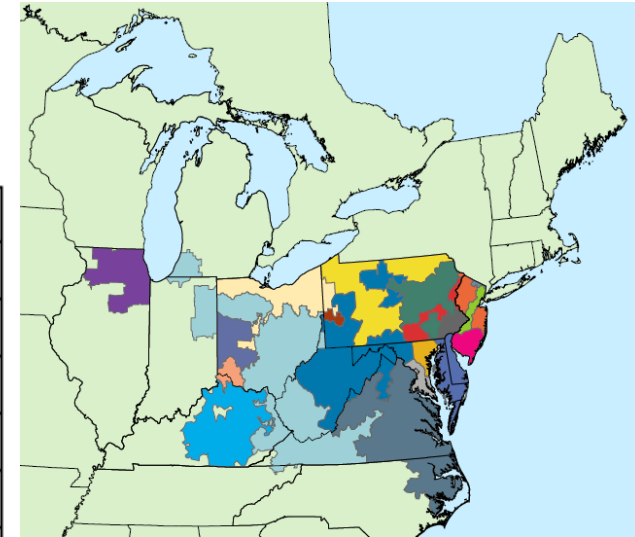


20 MW, 5 MWh Beacon flywheel plant at Hazle Township, Pennsylvania



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



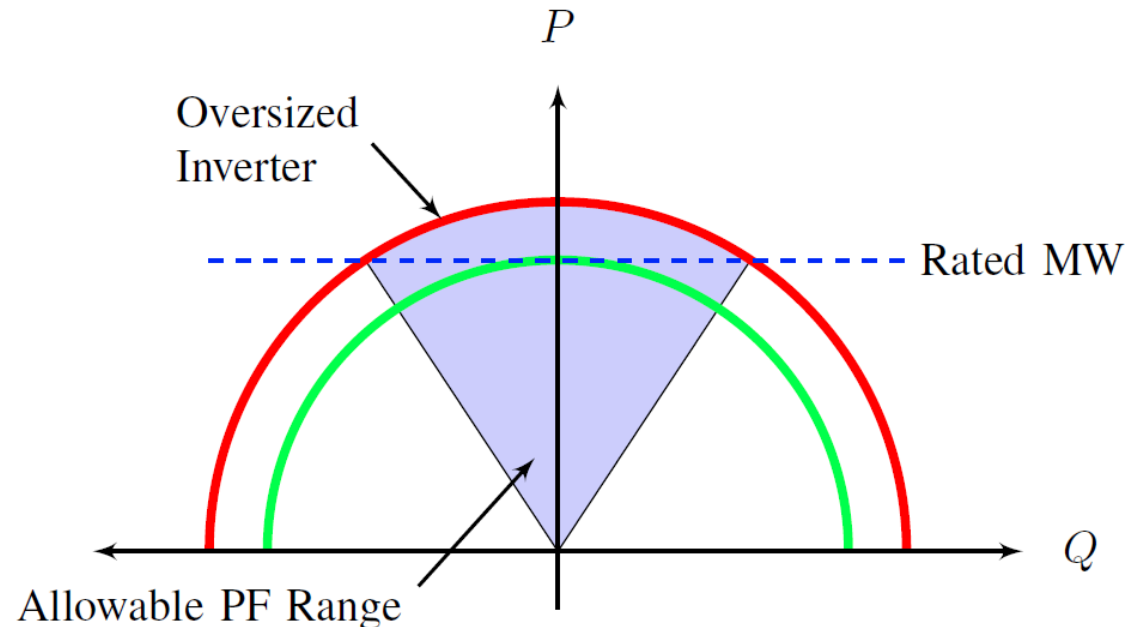
Beacon Power Flywheel



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



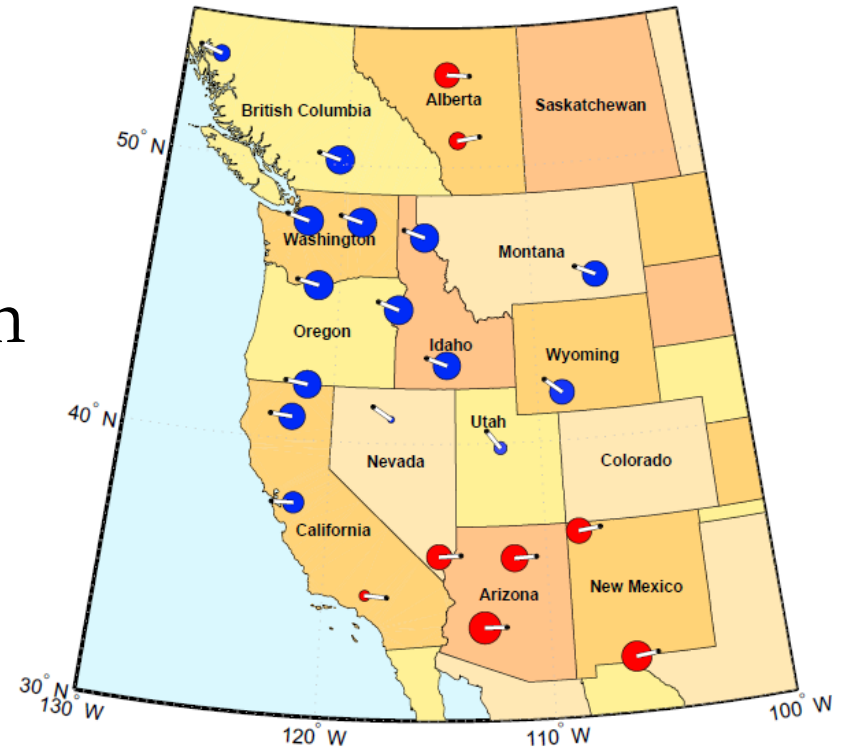


All large power systems are subject to low frequency electro-mechanical oscillations (0.2-1 Hz)

Injection of real power can provide damping

BPA has a demonstration project underway

Potential future revenue stream



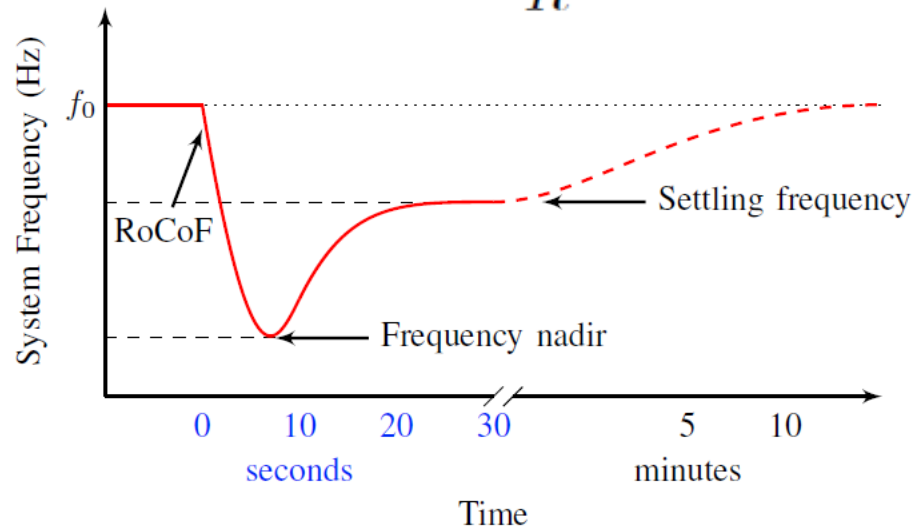
North-South Mode B (0.37 Hz) from a 2015 heavy summer WECC base case simulation



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

Energy storage can provide frequency droop via a control law

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





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

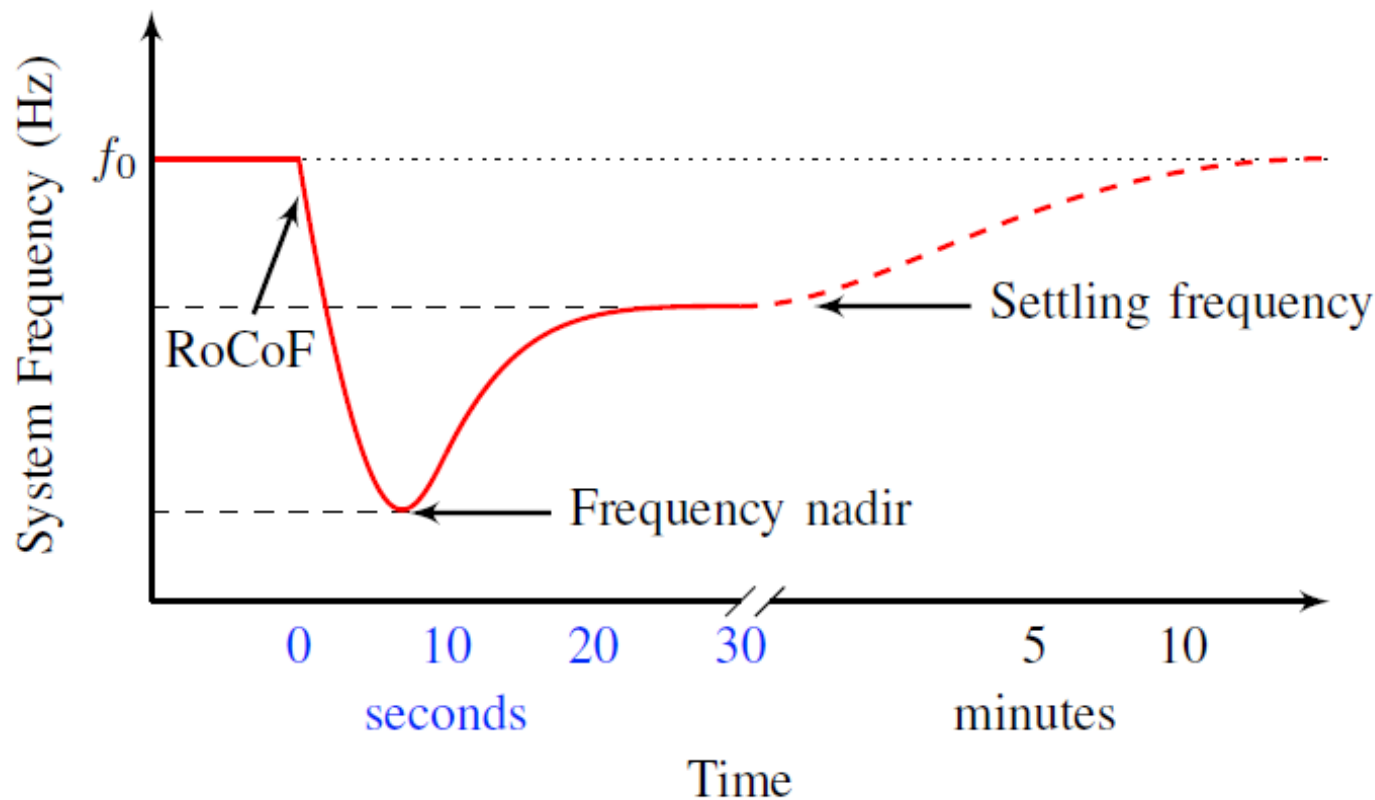
August 8, 2017 FERC requests supplemental comments

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



Large rotating machines provide inertia

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





Increased inverter-based generation displaces inertia

Energy storage can provide synthetic inertia via a control law

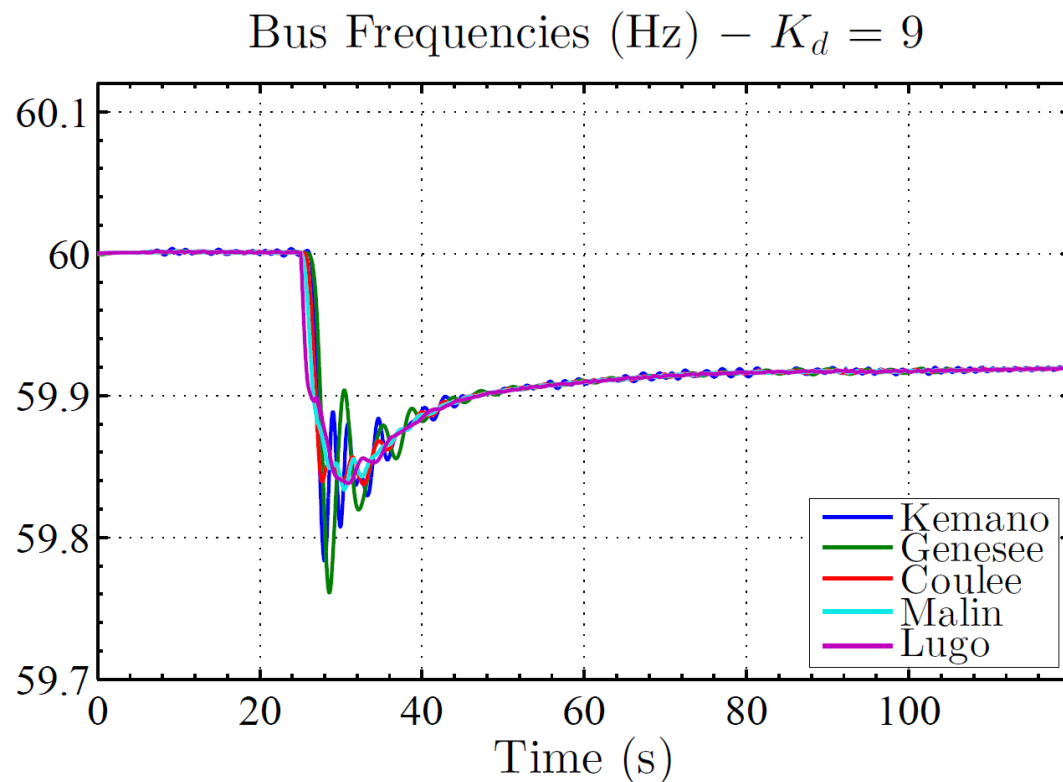
$$\Delta P = -k_{in} \frac{df}{dt}$$

No mechanisms for compensating resources that provide inertia



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

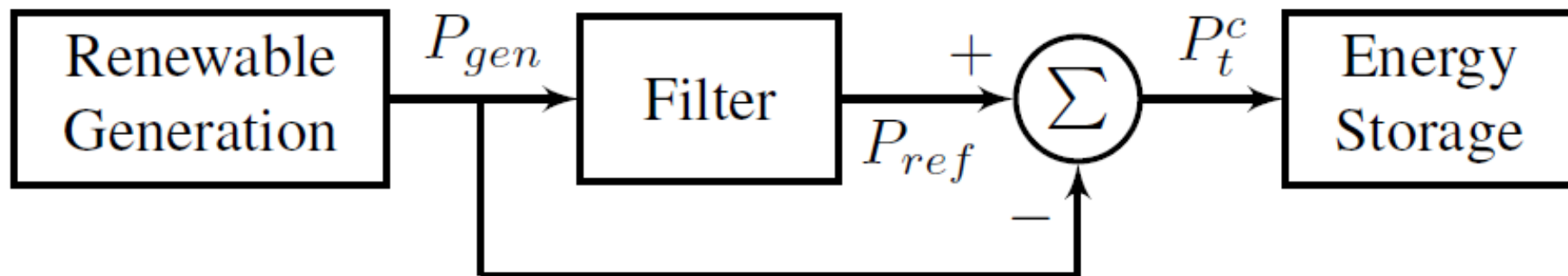
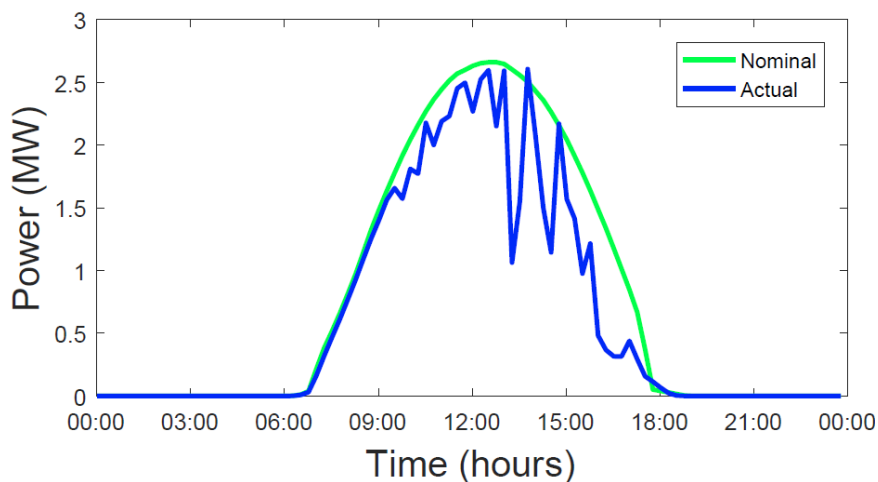
There are advantages to responding to a system frequency





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 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)

γ_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{S} minimum storage capacity (MWh)

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

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



Objective function

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

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

Energy storage model parameters

ENERGY STORAGE SYSTEM PARAMETERS

parameter	value
γ_c	0.80
γ_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



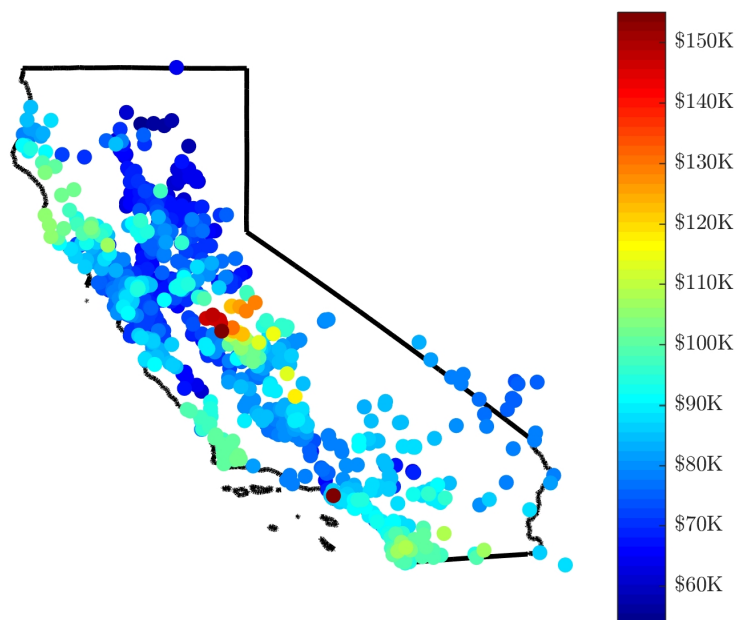
Analyzed ~2200 LMP nodes in CAISO

- Day ahead market arbitrage
- Day ahead and real time market arbitrage

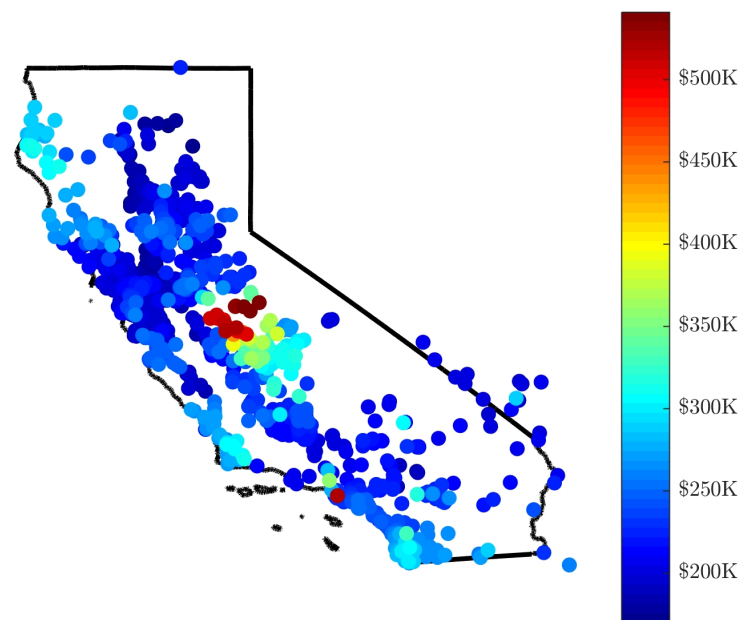
Key takeaways

- Revenue opportunity is highly location dependent
- Significantly more potential revenue if the real time market is included

Storage model
1 MW, 4 MWh
80% efficiency



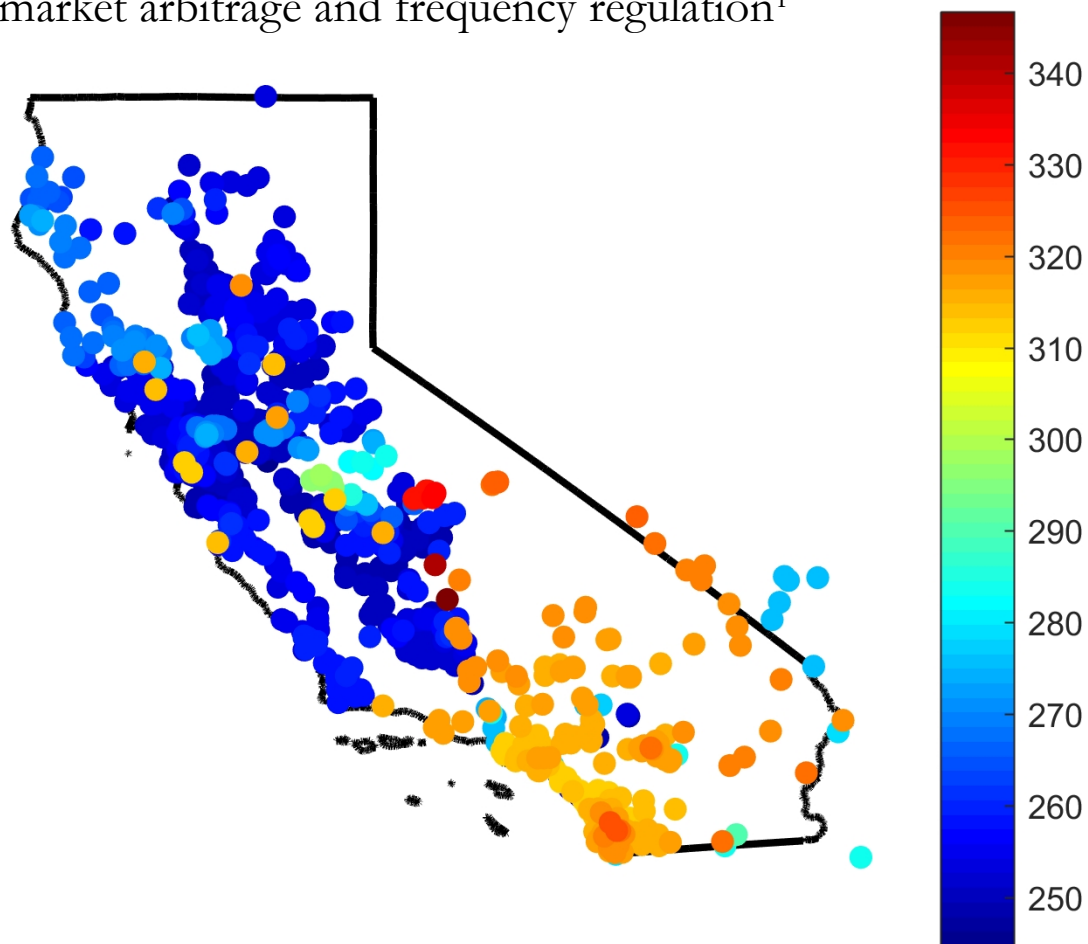
2014-2016 Total Revenue
DA Arbitrage



2014-2016 Total Revenue
DA+RT Arbitrage



Results for DA market arbitrage and frequency regulation¹



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

¹R. 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:

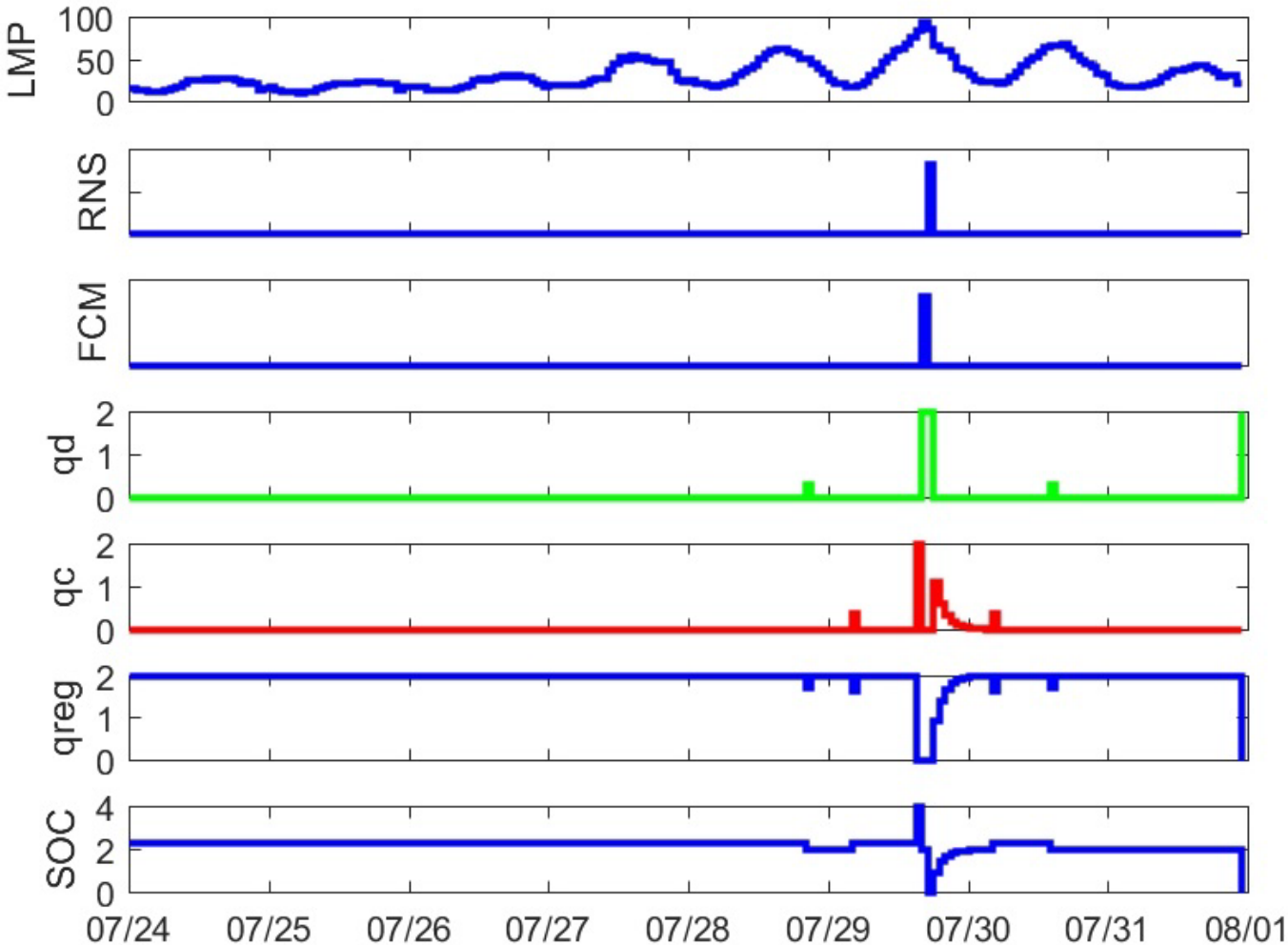
R. H. Byrne, S. Hamilton, D. R. Borneo, T. Olinsky-Paul, and I. Gyuk, “The value proposition for energy storage at the Sterling Municipal Light Department,” proceedings of the 2017 IEEE Power and Energy Society General Meeting, Chicago, IL, July 16-20, 2017, pp. 1-5. DOI: 10.1109/PESGM.2017.8274631



Optimization Results – Typical Week SMLD



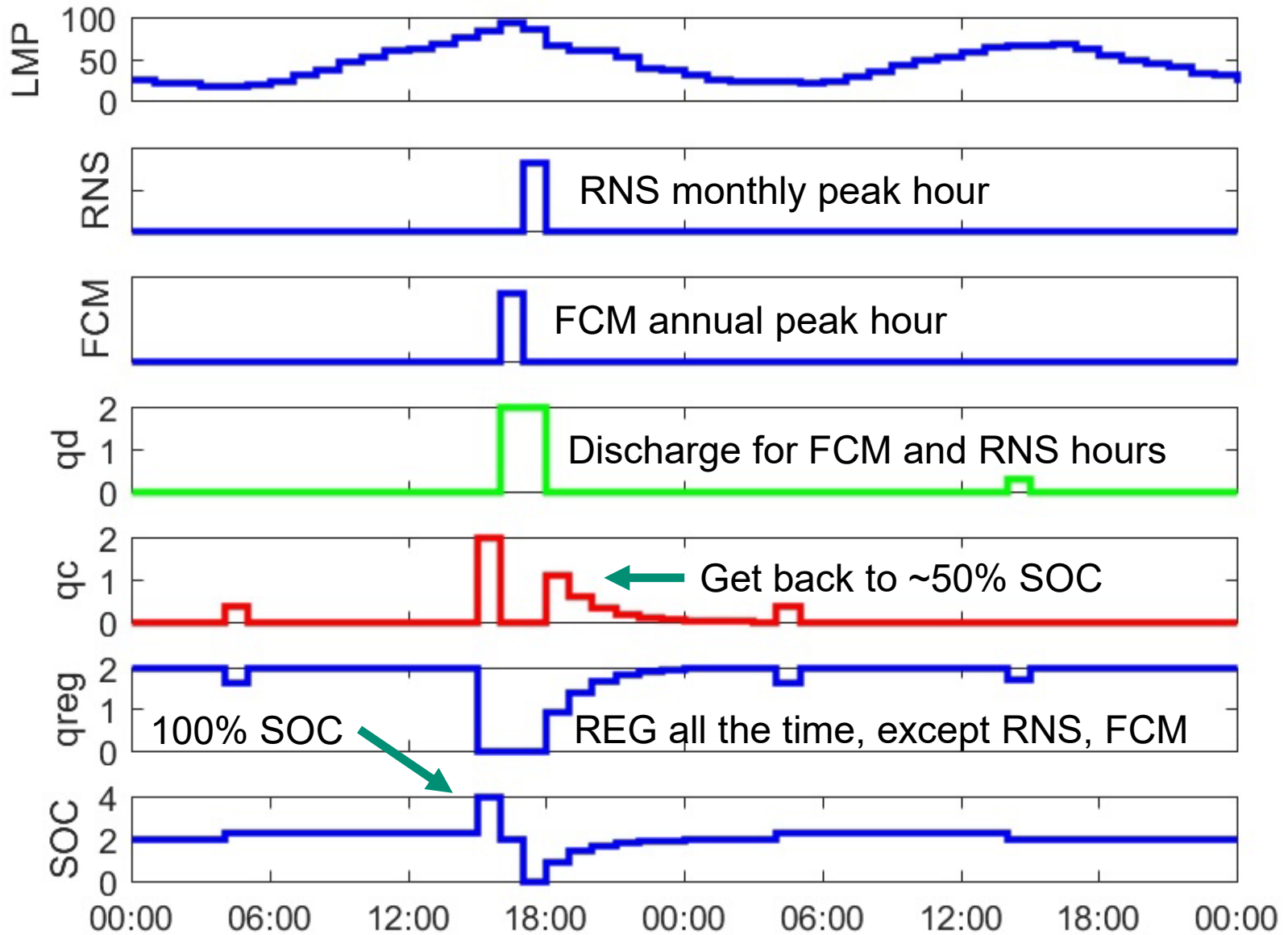
31



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





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

- Requires an accurate system model
 - 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 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



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