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Energy Storage Applications and Value Stacking

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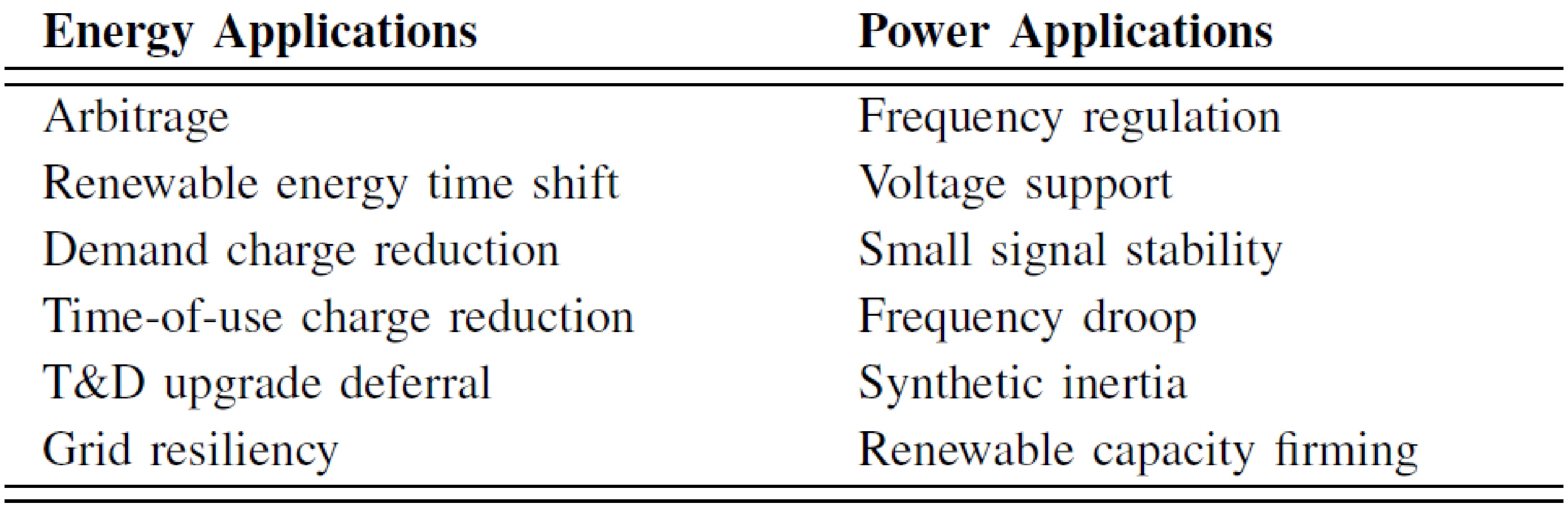
Energy Storage Applications

Power versus Energy Applications

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

R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala and I. Gyuk, "Energy Management and Optimization Methods for Grid Energy Storage Systems," in IEEE Access, vol. 6, pp. 13231-13260, 2018, doi: 10.1109/ACCESS.2017.2741578.

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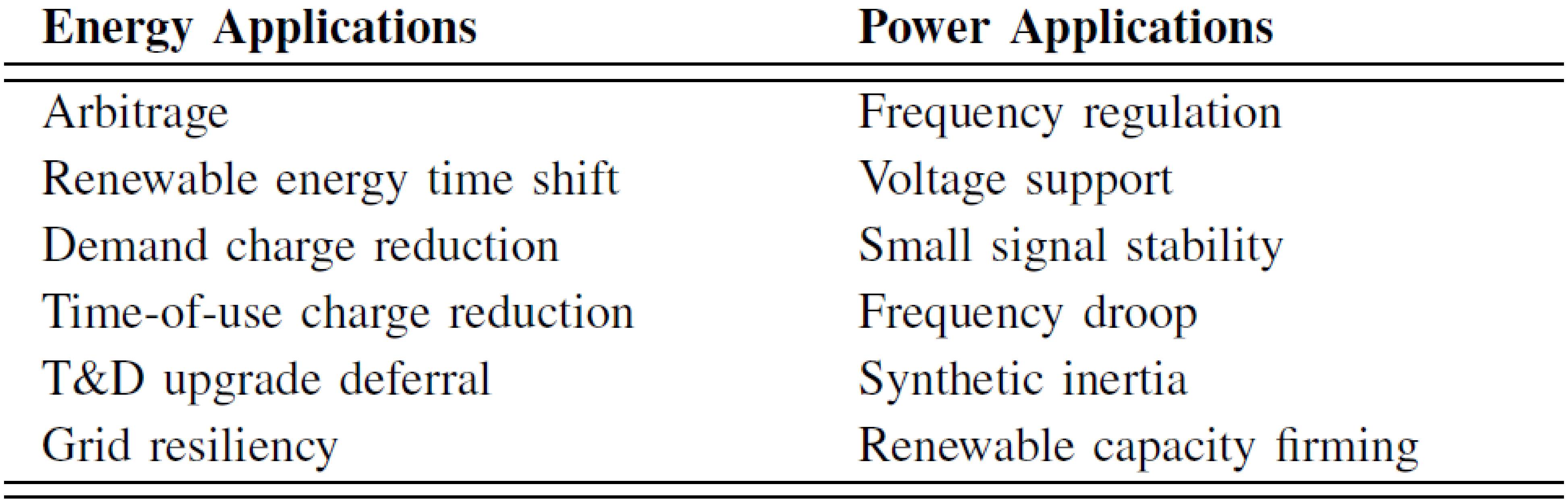

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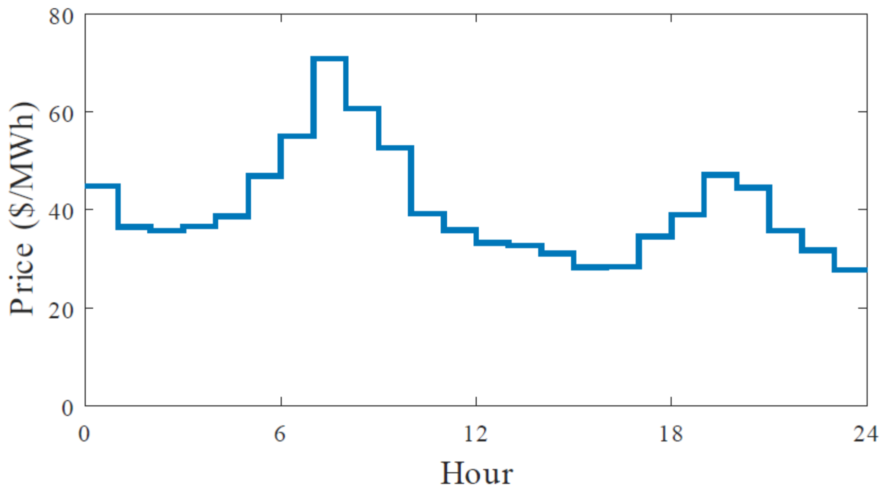
Energy Arbitrage

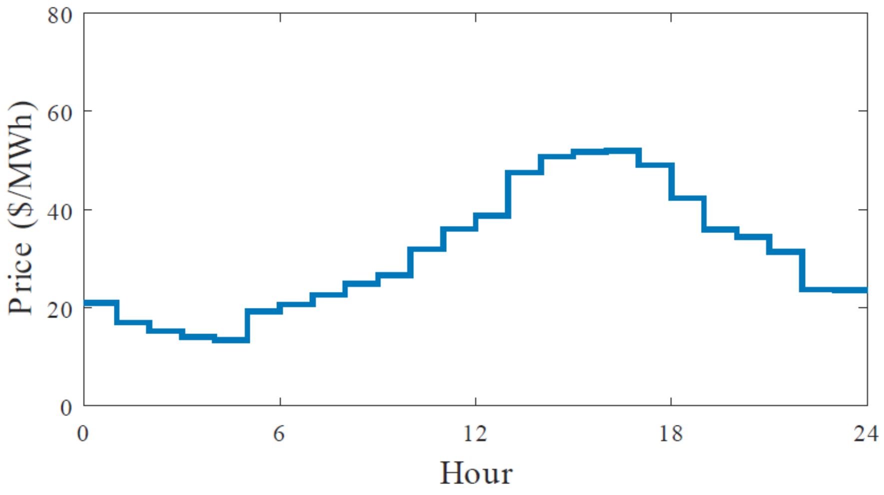
Buy low, sell high

- 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.

Energy Arbitrage

Market area – market prices

Vertically integrated utility – efficiency savings

Different variants

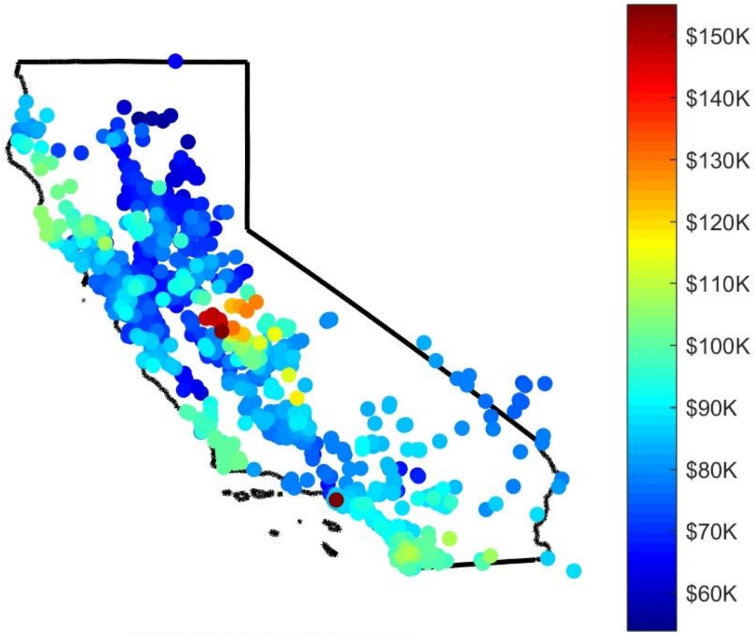
  - Charge with inexpensive renewable energy
  - Arbitrage day ahead and real-time markets
  - Day ahead market only

Rarely the highest potential revenue stream

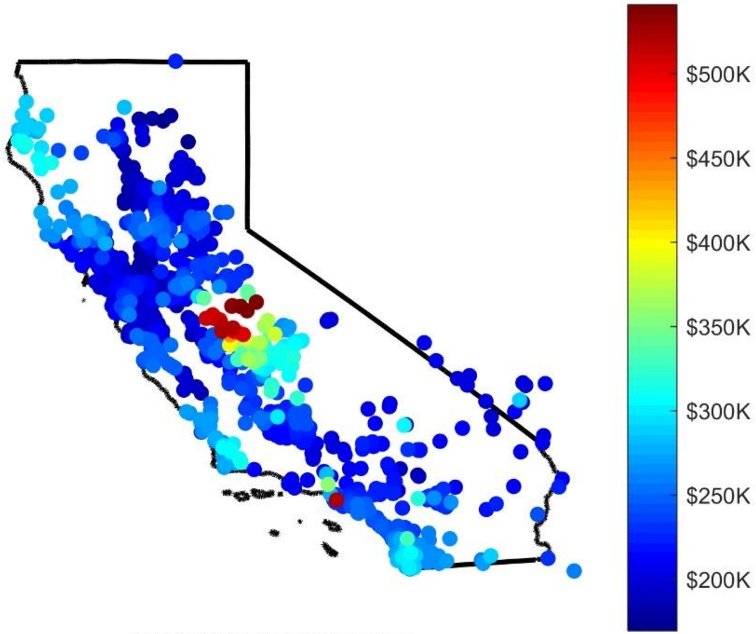
85% efficiency => 117.6% price difference

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)

R. H. Byrne, T. A. Nguyen, D. A. Copp, R. J. Concepcion, B. R. Chalamala and I. Gyuk, "Opportunities for Energy Storage in CAISO: Day-Ahead and Real-Time Market Arbitrage," *2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2018, pp. 63-68, doi: 10.1109/SPEEDAM.2018.8445408.

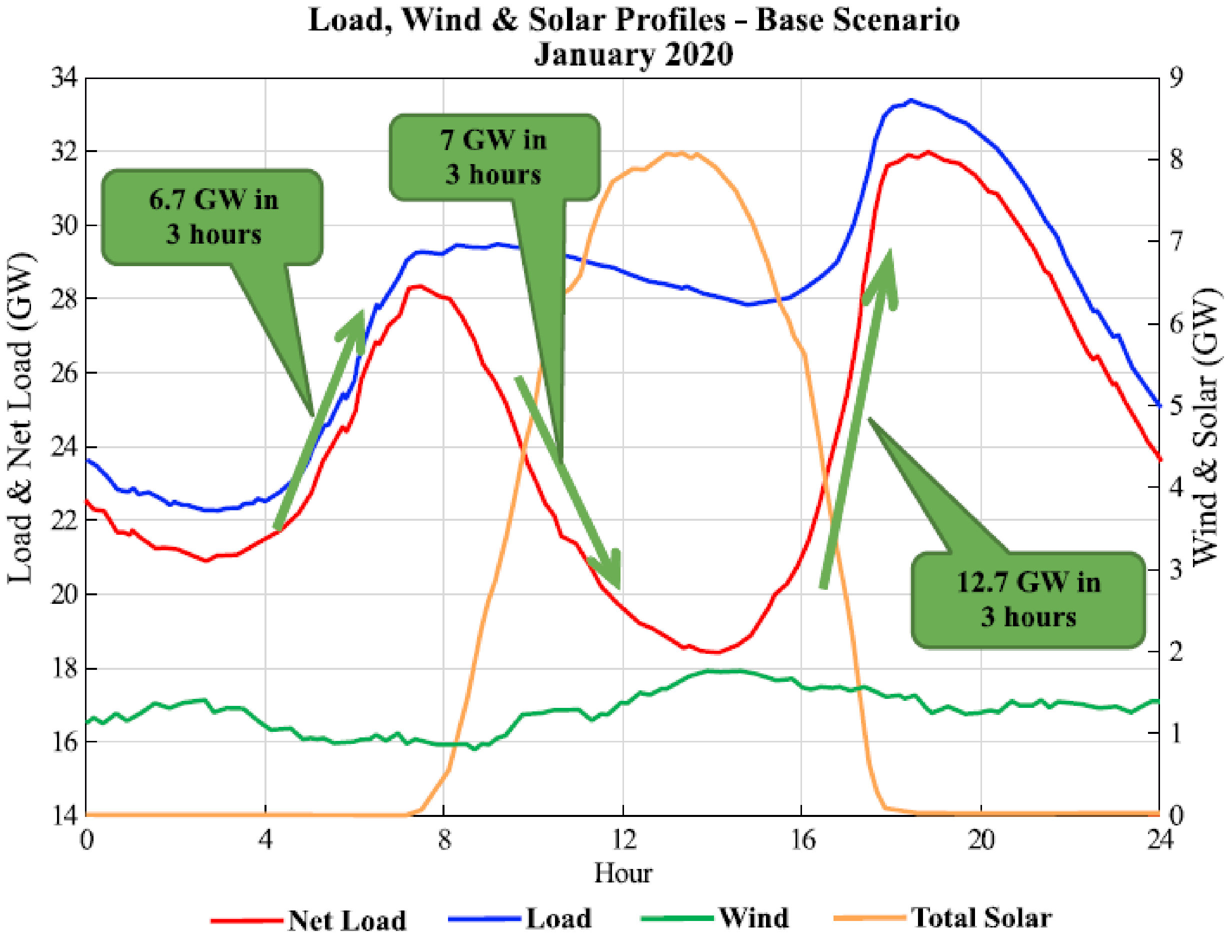
Renewable Energy Time Shift

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



6.7 GW in 3 hours

7 GW in 3 hours

12.7 GW in 3 hours

Renewable Energy Time Shift

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

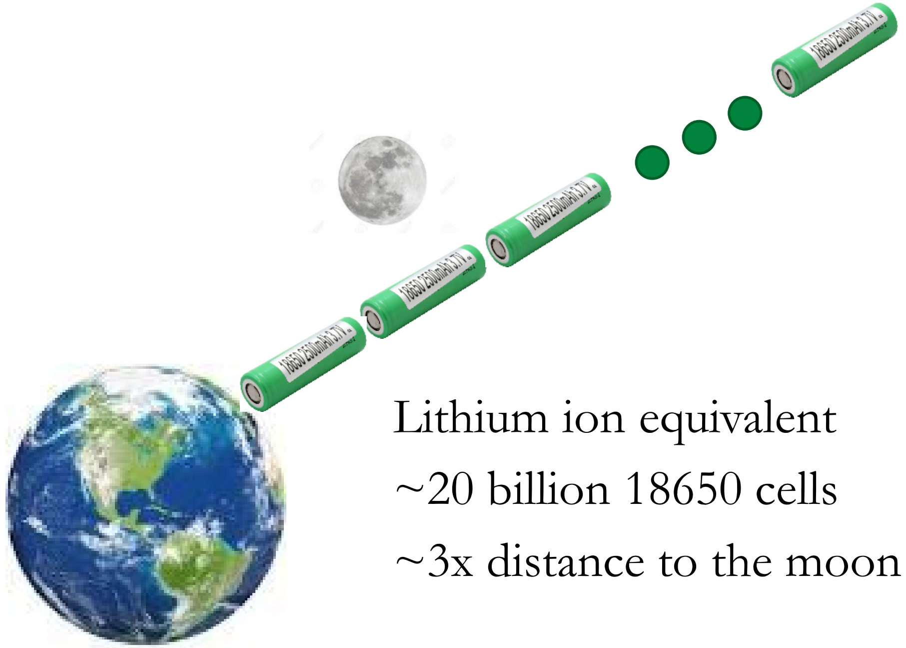
Tradeoffs between:

- 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

Renewable Energy Time Shift

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!

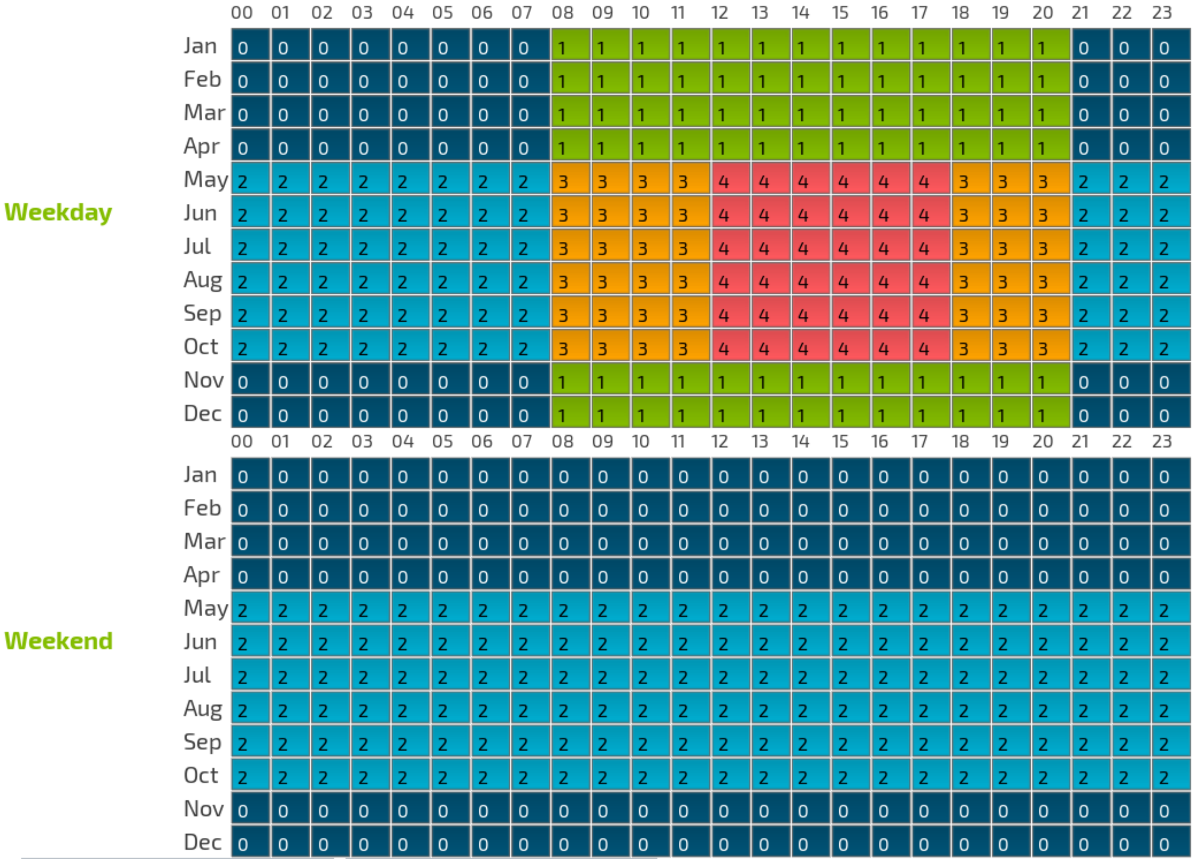
Time-of-Use Charge Reduction

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

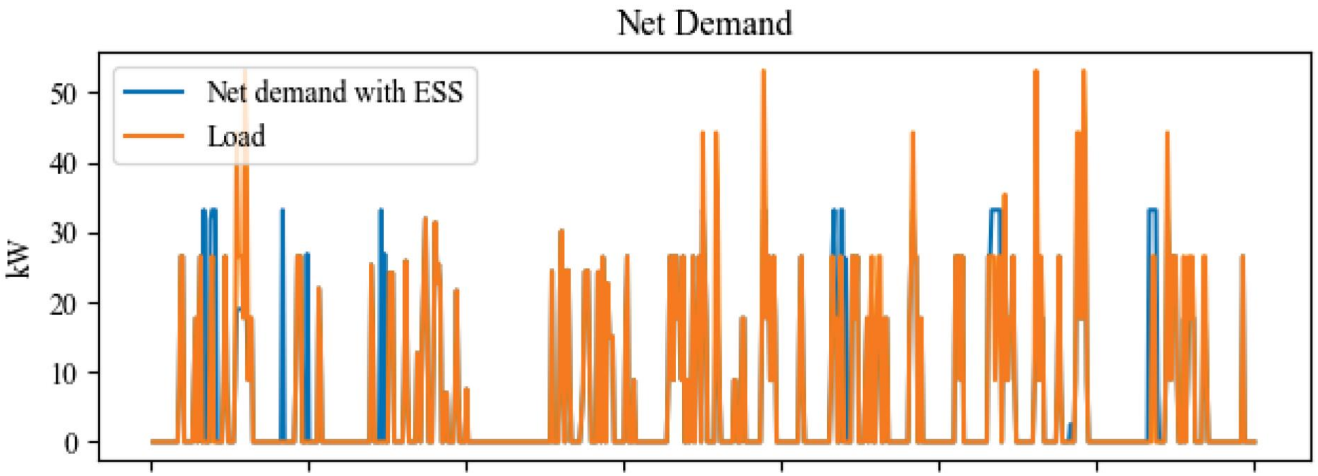
Demand Charge Reduction

Behind-the-meter application (mostly)

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



R. D. Trevizan, T. A. Nguyen and R. H. Byrne, "Sizing Behind-the-Meter Energy Storage and Solar for Electric Vehicle Fast-Charging Stations," 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2020, pp. 583-588, doi: 10.1109/SPEEDAM48782.2020.9161848.

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

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

Best case scenario: defer a very large investment for a very long time with a small energy storage system
Often a significant benefit, but highly dependent on the location/scenario

Grid Resilience

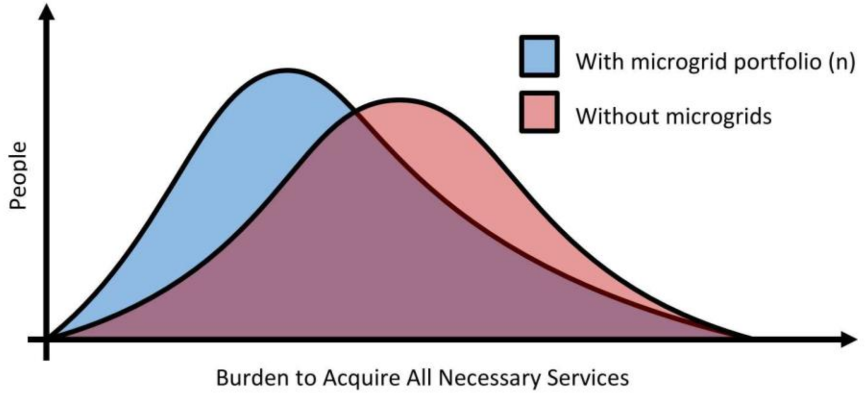
Events like Hurricane Sandy and Hurricane Katrina have increased the interest in grid resiliency applications

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

- Market prices
- Surveys

Data for public administration likely under estimates the value

Social burden metric - measures the burden on members of the community to satisfy their basic needs



Robert F. Jeffers, Michael J. Baca, Amanda M. Wachtel, Sean DeRosa, Andrea Staid, William Fogleman, Alexander Outkin, Frank Currie, “Analysis of Microgrid Locations Benefitting Community Resilience for Puerto Rico”, Technical Report, SAND2018-11145, Sandia National Laboratories, Albuquerque, NM, September 2018.

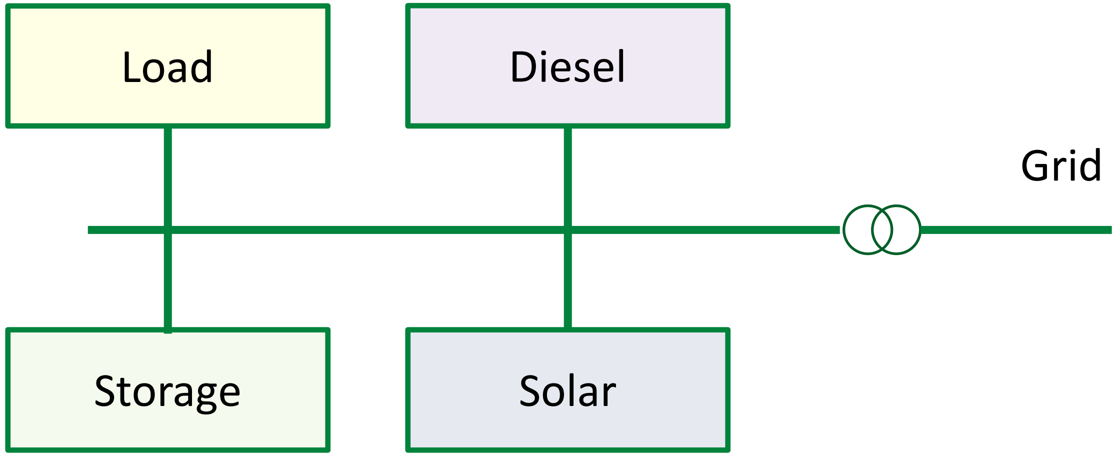
Grid Resilience

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

The definition of resilience can have a significant effect on the design and value of the system


Load

Diesel

Grid

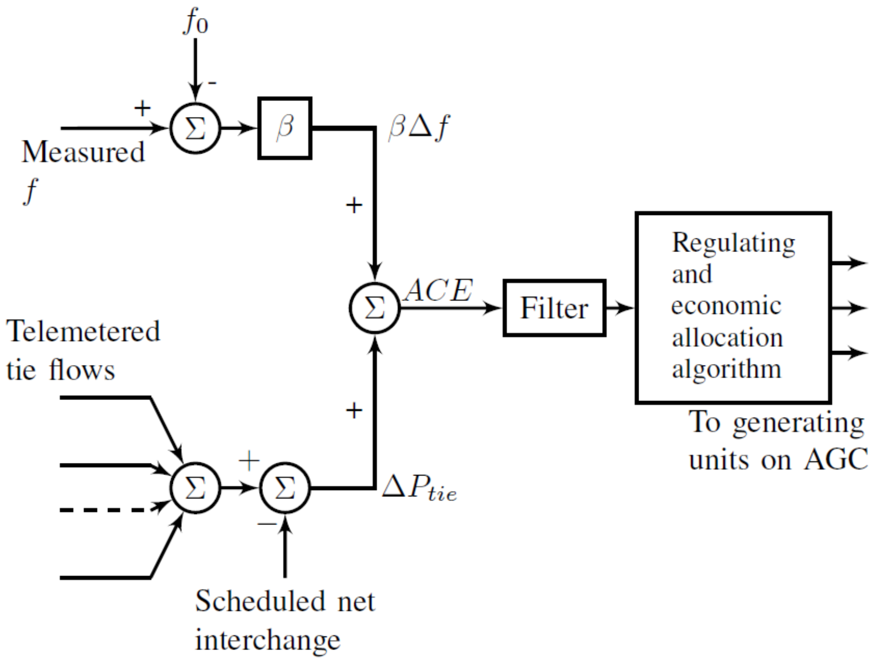
Storage

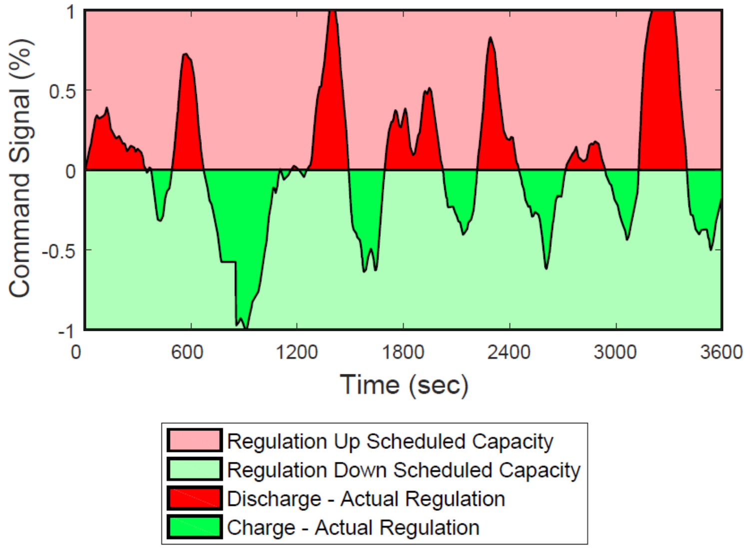
Solar

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

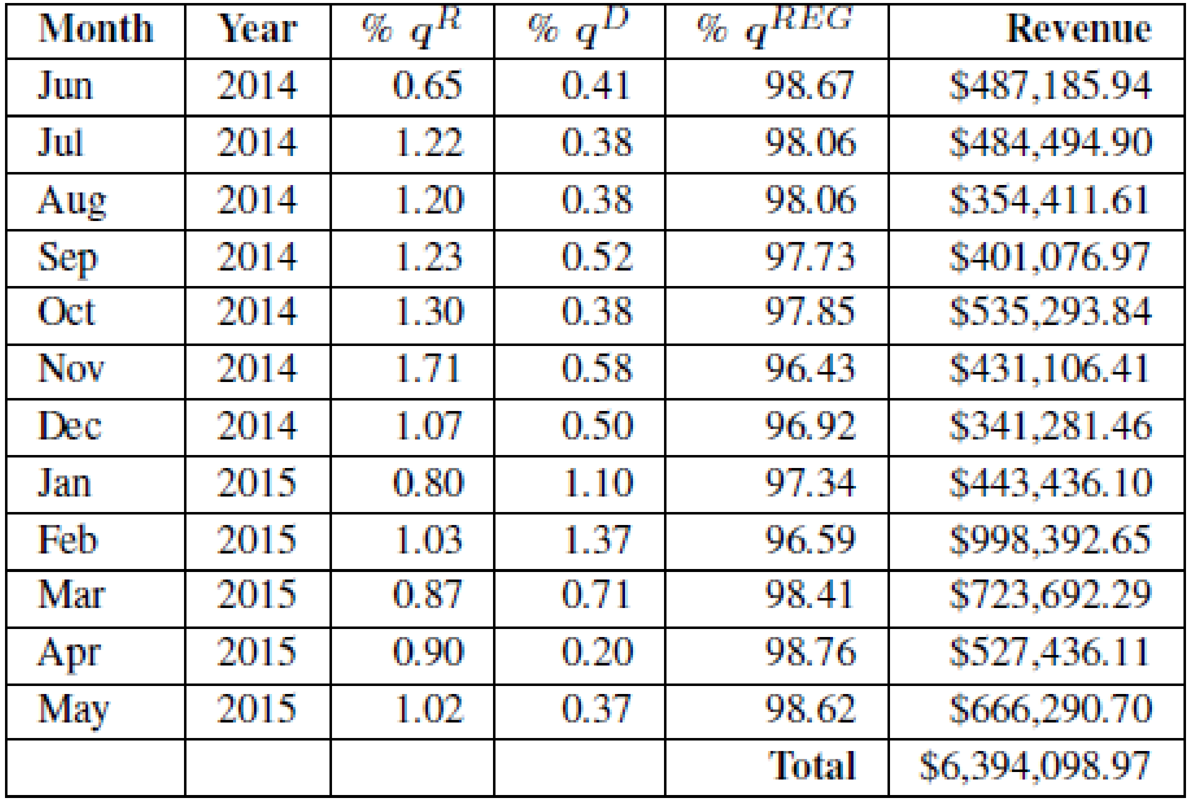
Pay-for-performance

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

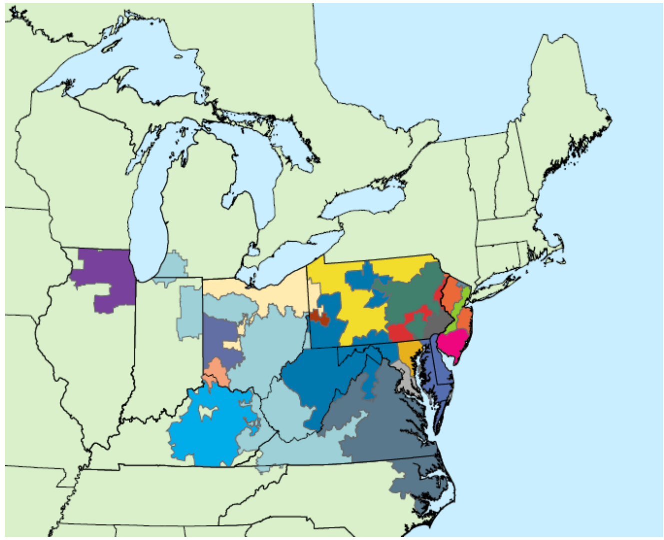
AES 32MW/8MWh grid energy storage solution at the Laurel Mountain facility, Belington, WV
Source: https://energystorage.org/

Frequency Regulation

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

But … regulation markets are small relative to energy…

R. H. Byrne, R. J. Concepcion and C. A. Silva-Monroy, "Estimating potential revenue from electrical energy storage in PJM," *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 2016, pp. 1-5, doi: 10.1109/PESGM.2016.7741915.

Voltage Support

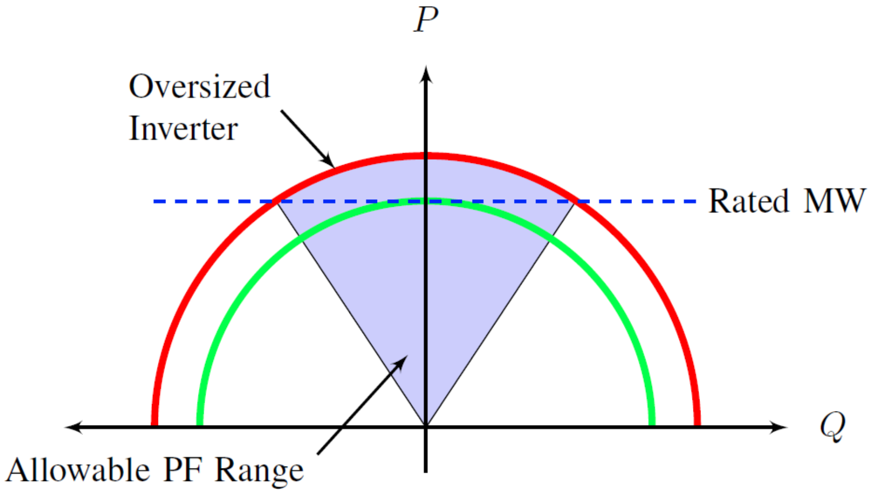
Inject real/reactive power to control voltage

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

Value is often not very high

- Alternatives (e.g., capacitors) are relatively low cost
- All inverter-based resources can also provide the same capability



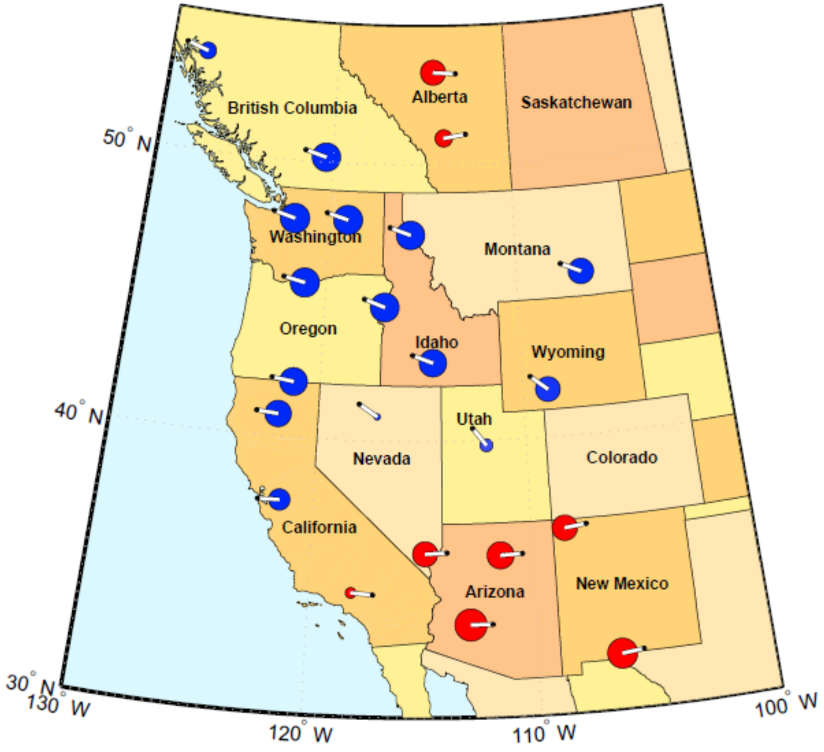
Small Signal Stability

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

Injection of real power can provide damping

BPA completed a PDCI demonstration project

Potential future revenue stream



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

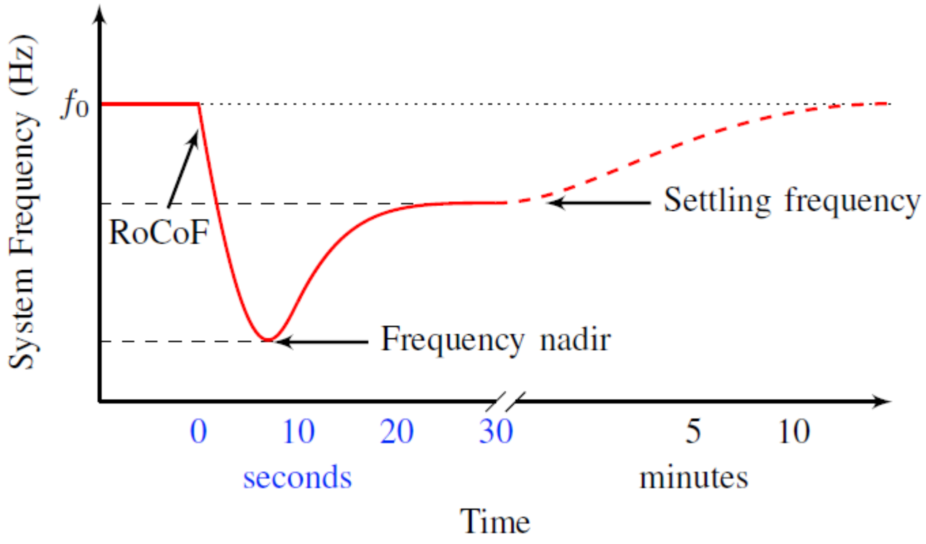
R. Elliott, R. Byrne, A. Ellis and L. Grant, "Impact of increased photovoltaic generation on inter-area oscillations in the Western North American power system," *2014 IEEE PES General Meeting, Conference & Exposition*, 2014, pp. 1-5, doi: 10.1109/PESGM.2014.6939889.

D. Trudnowski et al., "Initial closed-loop testing results for the pacific DC intertie wide area damping controller," 2017 IEEE Power & Energy Society General Meeting, 2017, pp. 1-5, doi: 10.1109/PESGM.2017.8274724.

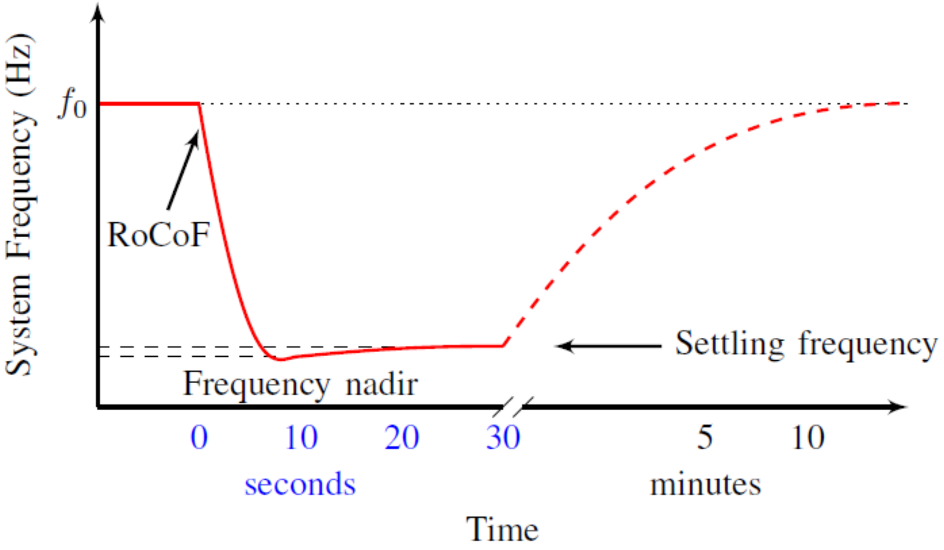
Frequency Droop

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

Energy storage can provide frequency droop via a control law: $\Delta P = -\frac{1}{R}\Delta f$



Adequate frequency droop, higher frequency nadir



Inadequate frequency droop, “Lazy L” response

Frequency Droop - History

In the U.S. prior to 2018, generators were not required to provide frequency responsive service, nor were 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

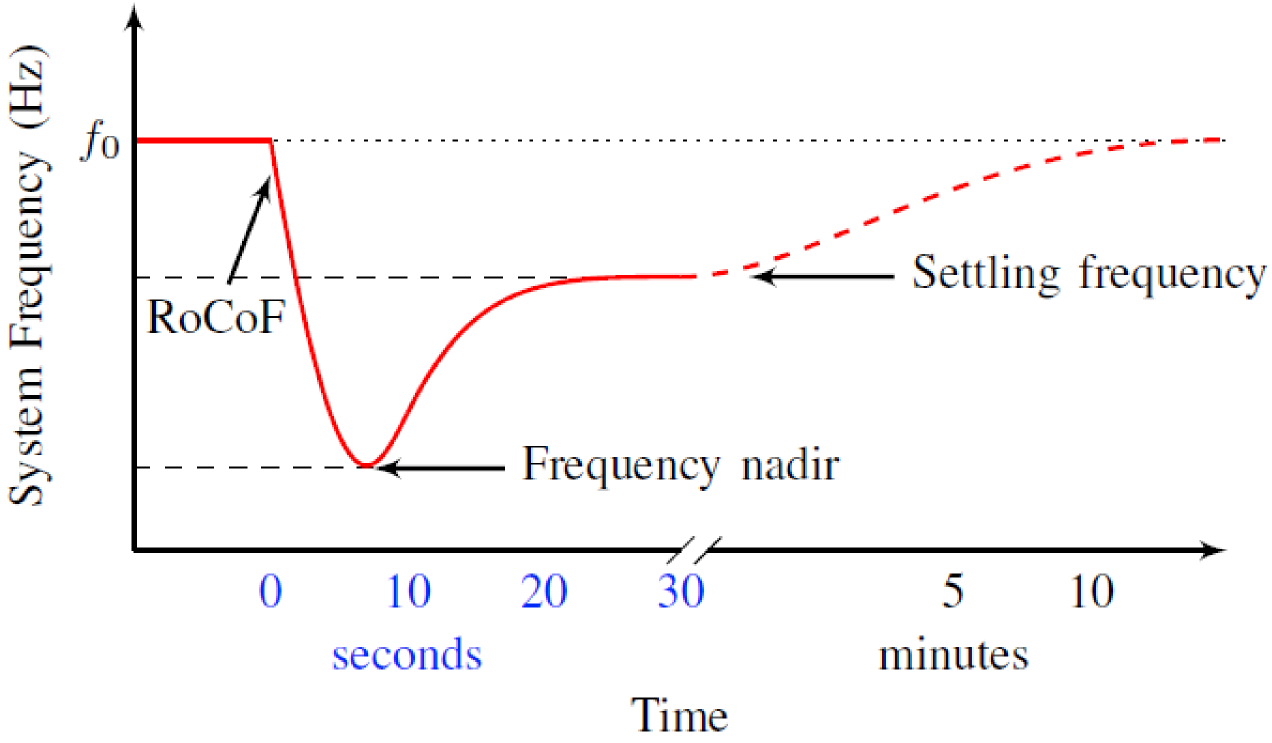
Did not address the compensation aspect

Energy storage is well suited to provide frequency droop because of its fast response

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

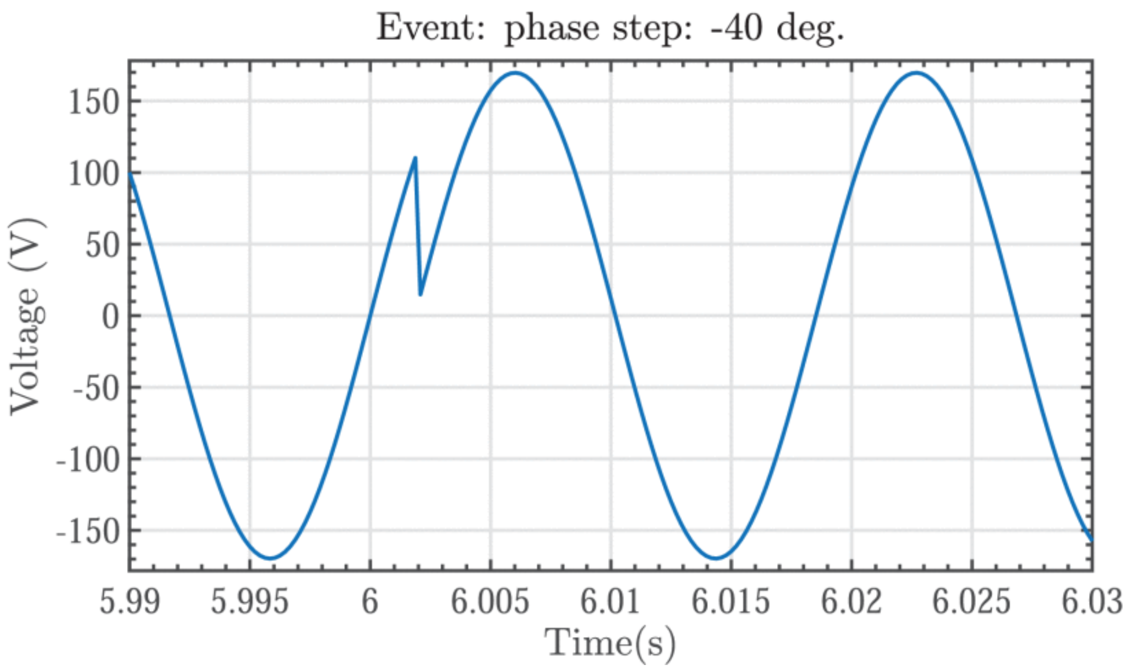
$$\Delta P = -k_{in}\frac{df}{dt}$$

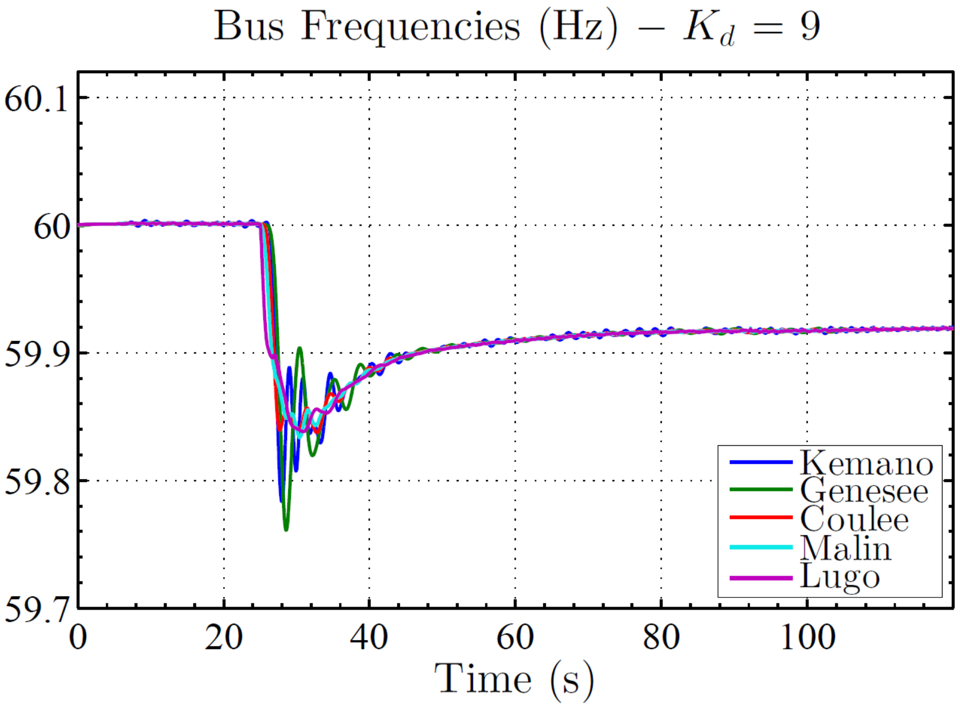
No mechanisms for compensating resources that provide inertia

Synthetic Inertia

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

There are advantages to responding to a system frequency



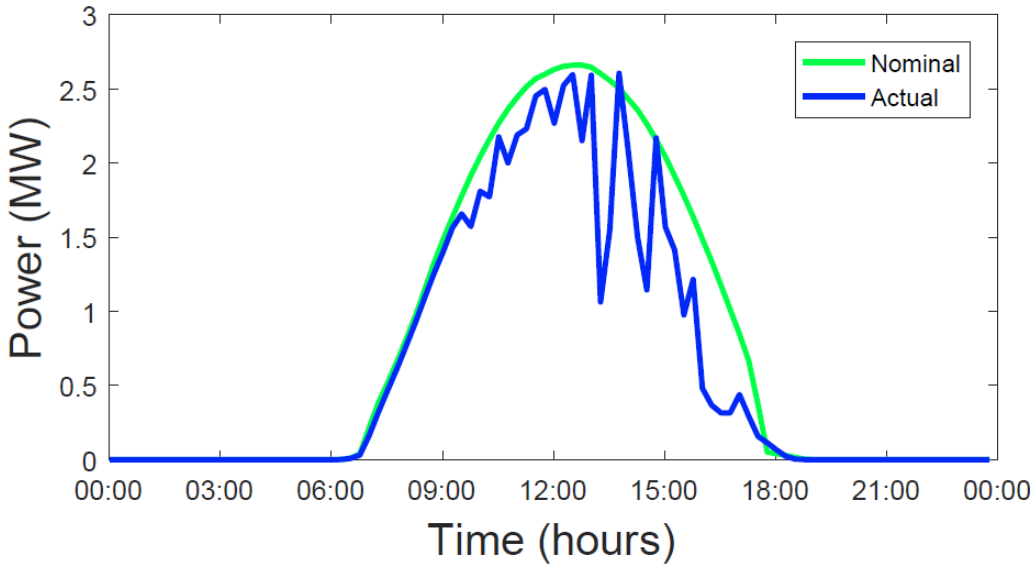


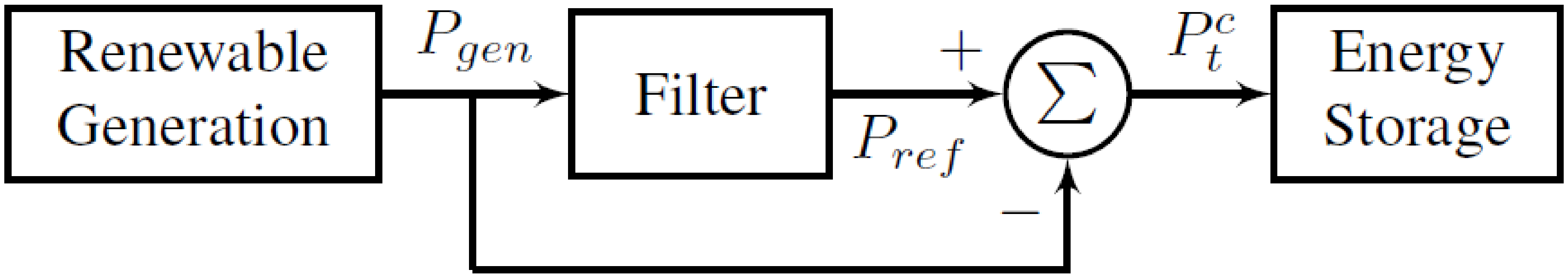
F. Wilches-Bernal, J. Wold and W. H. Balliet, "A Method for Correcting Frequency Estimates for Synthetic Inertia Control," in *IEEE Access*, vol. 8, pp. 229141-229151, 2020, doi: 10.1109/ACCESS.2020.3044583.

Renewable Capacity Firming

Some areas are placing ramp rate limitations on renewable generation

- Puerto Rico
- Hawaii





Energy Storage Applications - Takeaways

The value of energy storage is highly location specific

- Market area versus a vertically integrated
- Front of the meter versus behind the meter

Market areas – remuneration is well defined, but future revenue is uncertain

Vertically integrated utilities – valuation can be difficult (more on this later)

Highest value applications include:

- Frequency regulation
- Demand charge reduction
- T&D deferral

Value Stacking

Maximizing Revenue

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)
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)

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

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

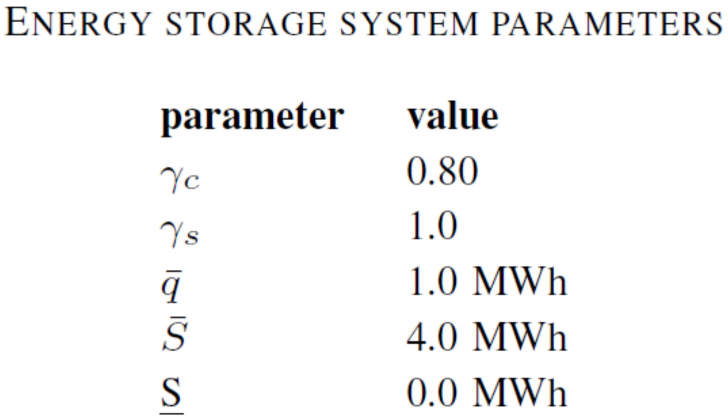
CAISO Model – DA/RT Arbitrage

Objective function

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

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

CAISO Example

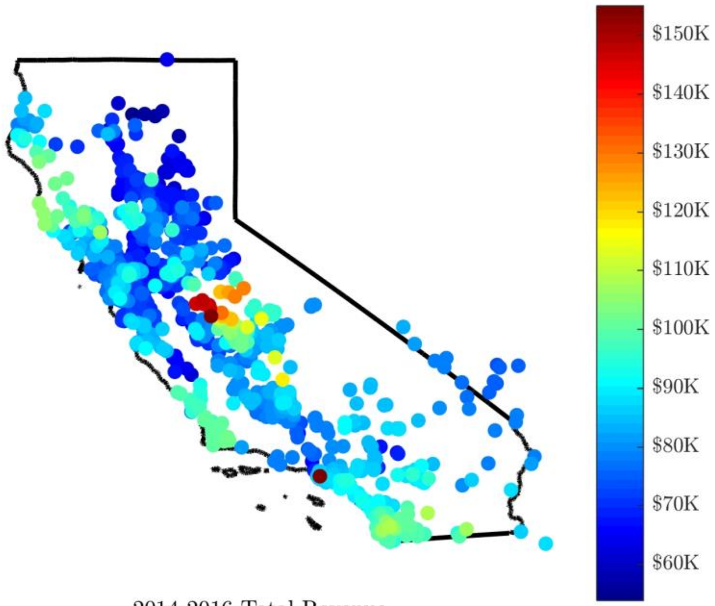
Analyzed ~2200 LMP nodes in CAISO

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

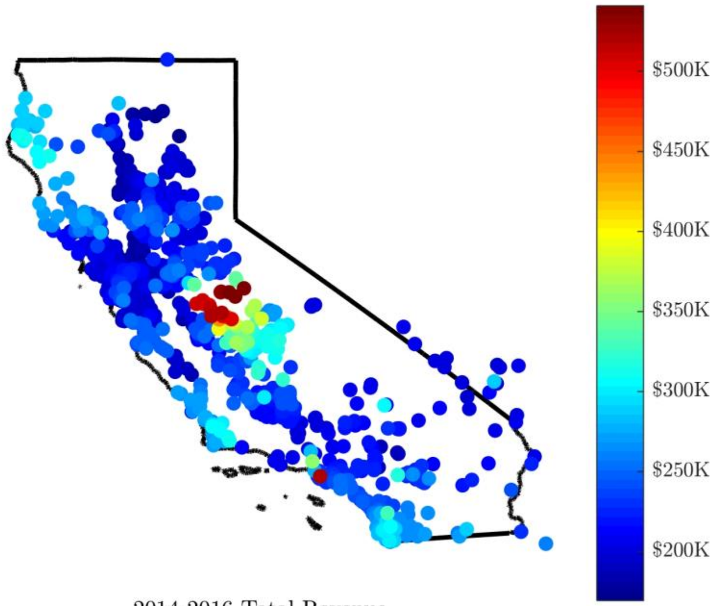
Key takeaways

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

<u>Storage model</u>
1 MW, 4 MWh
80% efficiency



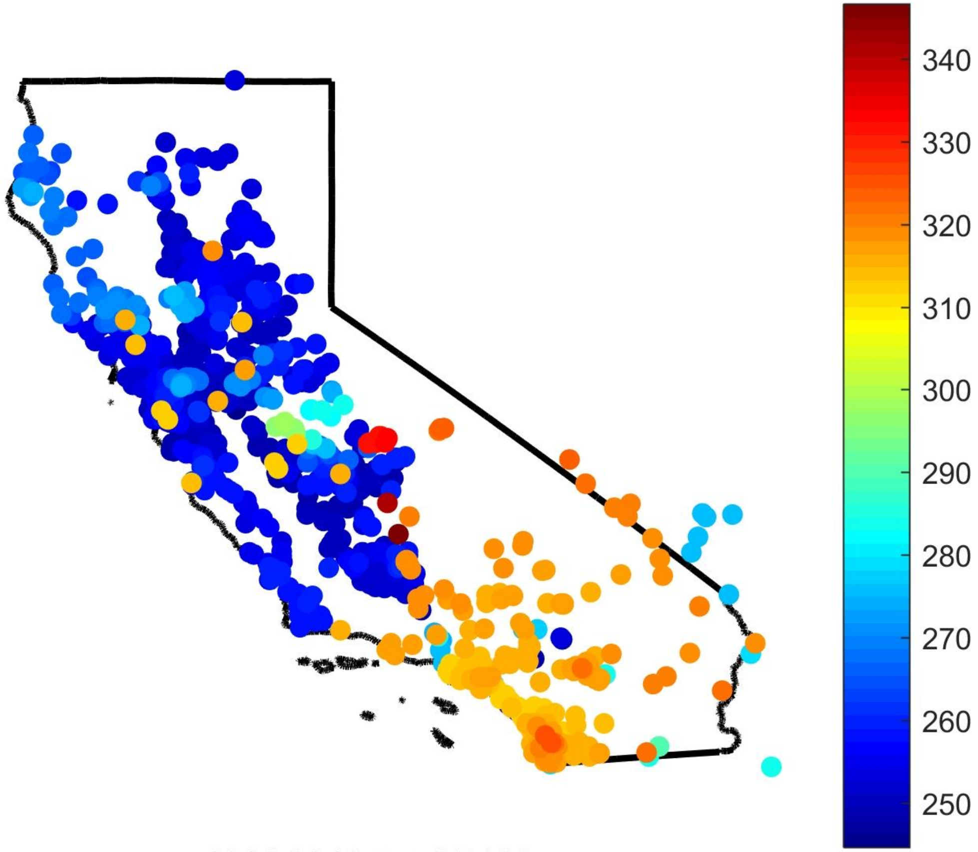
2014-2016 Total Revenue
DA Arbitrage



2014-2016 Total Revenue
DA+RT Arbitrage

CAISO Example

Results for DA market arbitrage and frequency regulation



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

R. H. Byrne, T. A. Nguyen and R. J. Concepcion, “Opportunities for energy storage in CAISO," 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

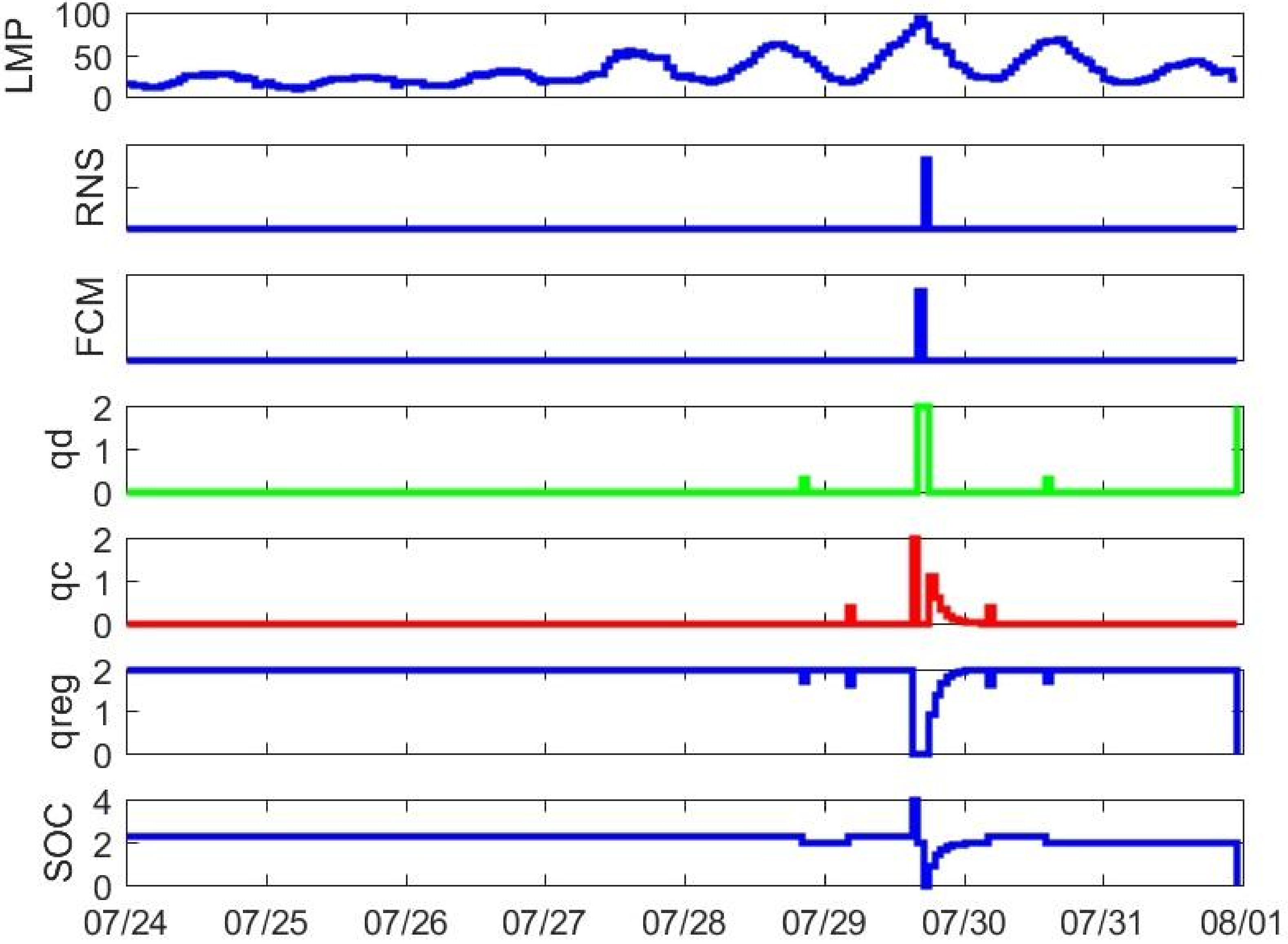
Grid Resilience was the primary goal – other applications help pay for the system

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%

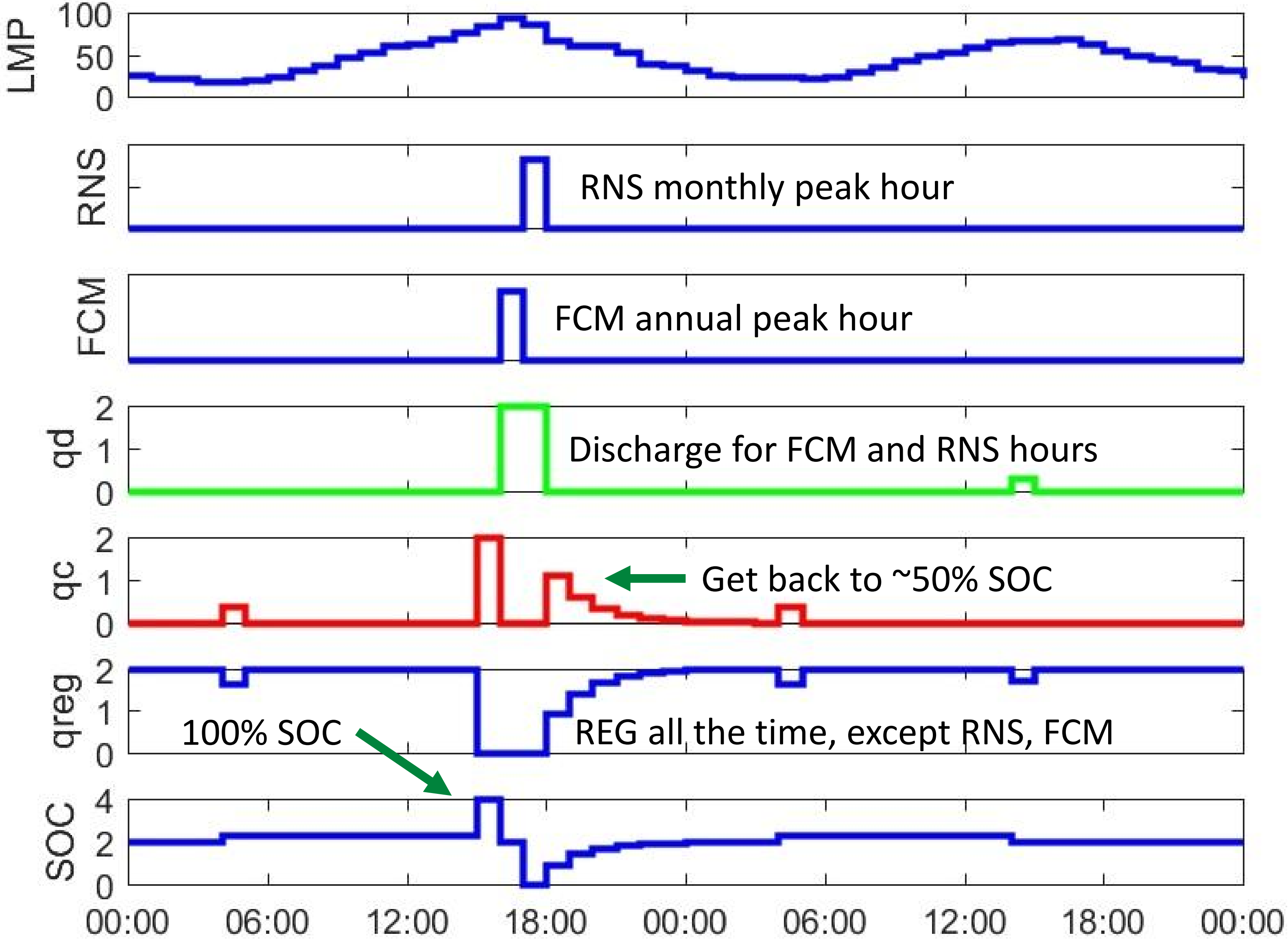
R. H. Byrne, S. Hamilton, D. R. Borneo, T. Olinsky-Paul, and I. Gyuk, “The value proposition for energy storage at the Sterling Municipal Light Department,” proceedings of the 2017 IEEE Power and Energy Society General Meeting, Chicago, IL, July 16-20, 2017, pp. 1-5. DOI: 10.1109/PESGM.2017.8274631

Optimization Results – Typical Week SMLD



- 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
- 2 MW, 4 MWh system

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 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 - 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