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Sandia National Laboratories

ENERGY STORAGE APPLICATIONS AND VALUE STACKING

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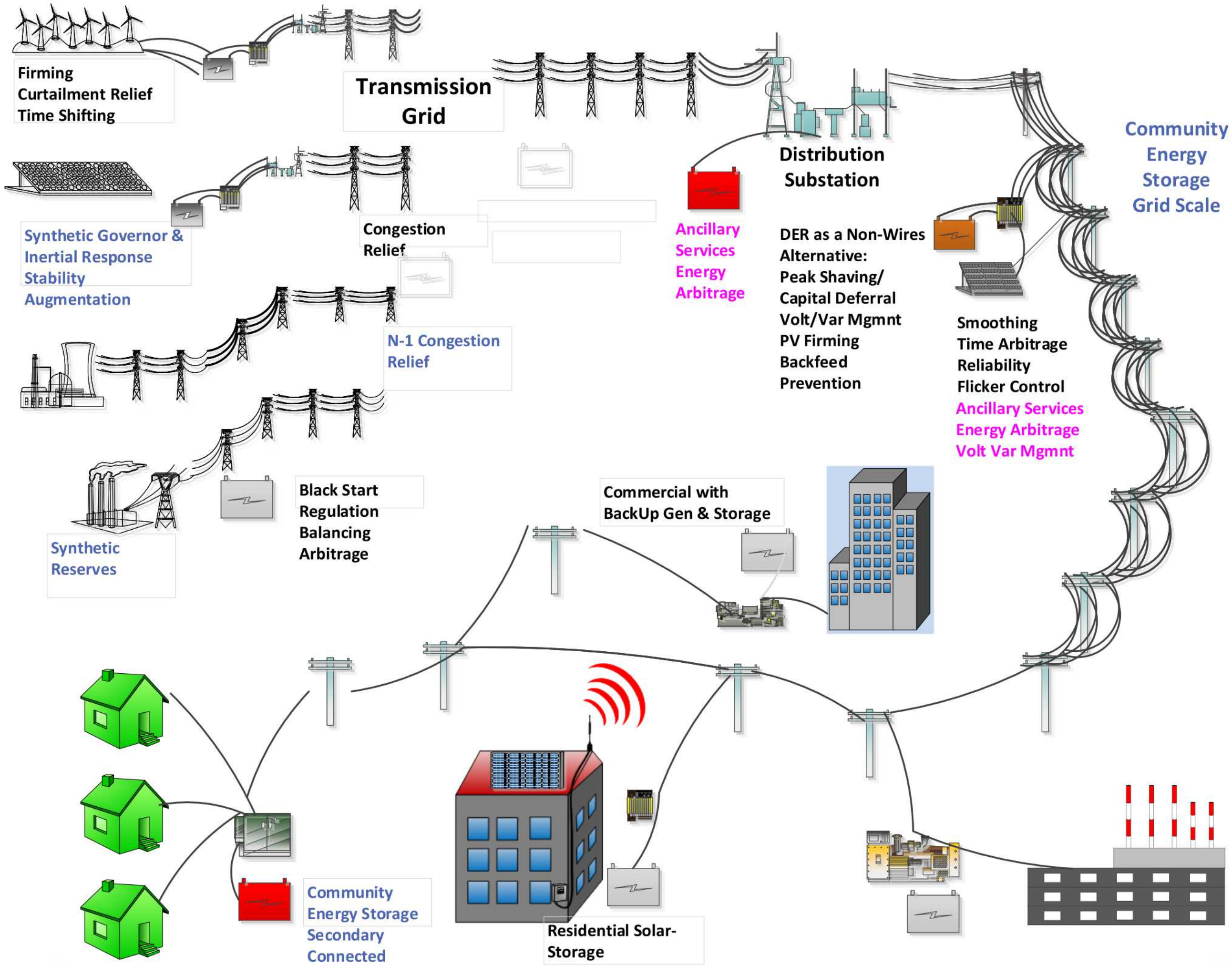
Energy Storage Applications – Location, Location, Location



IEEE PES Power & Energy Society®

IEEE

Energy Storage Applications

- Energy storage application time scale
  - "Energy" applications – longer times scale, large amounts of energy
  - "Power" applications – shorter 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

Critical Performance Characteristics

- Duration – Ratio of Energy Capacity (MWh) to Power Rating (MW)
- Efficiency - net of losses in charge-discharge cycle
- Self-Discharge – rate of internal discharge with no external power discharge
- Degradation – Loss of Energy Capacity with Discharge Cycles (not a simple single value)

Energy Storage Applications & “Duration”

DURATION

Days | Hours | Minutes | Seconds | Cycles

- Hydro-Thermal Coordination

- Resiliency

- DA & HA Energy Markets
- Time Arbitrage
- Curtailment Relief
- Demand Charge Reduction
- TOU Charge Reduction
- T&D Capacity Deferral
- Black Start
- Local Distribution Reliability

- Spinning Reserve
- Fast Ramping
- N-1 Congestion Relief
- Balancing (RT) Energy
- Voltage Support

- Frequency Regulation
- PV Flicker Mgmnt
- Renewable Smoothing

- Governor Response
- Synthetic Inertia
- Small Signal Stability

- Transient Stability

- Pumped Hydro
- CAES (cavern)

- NaS
- Va Redox
- Li Ion
- CAES (pipe)

- Flywheel
- Va Redox
- Li Ion
- CAES (pipe)

- Flywheel
- Li Ion

- Li Ion
- Super Caps

Duration (Hours) = Energy (MWh) / Power (MW)

Energy Arbitrage

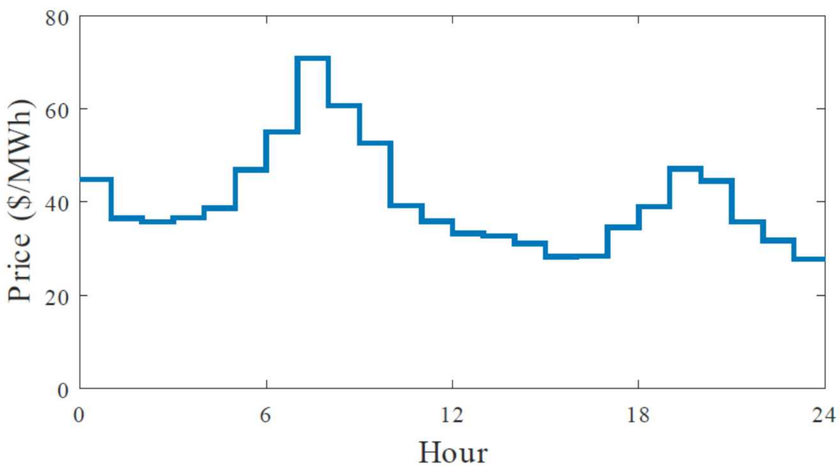
- Buy low, sell high

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

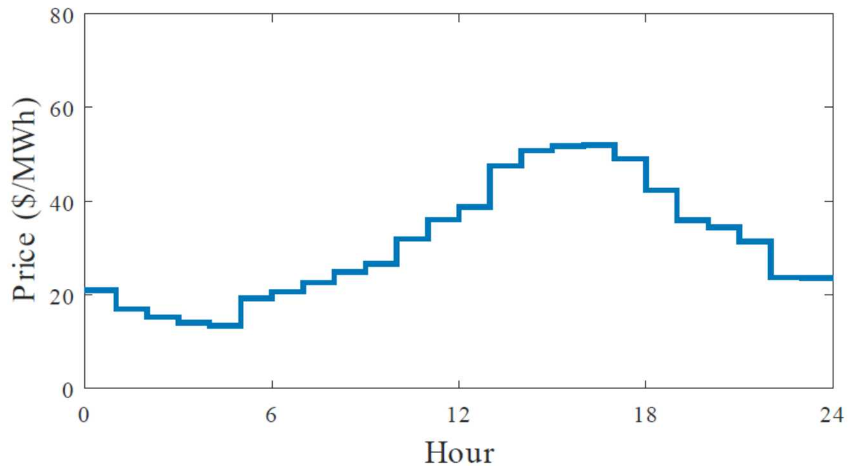
η_c= conversion efficiency

LMP_H = average high LMP, LMP_L = average low LMP

q = charge quantity



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

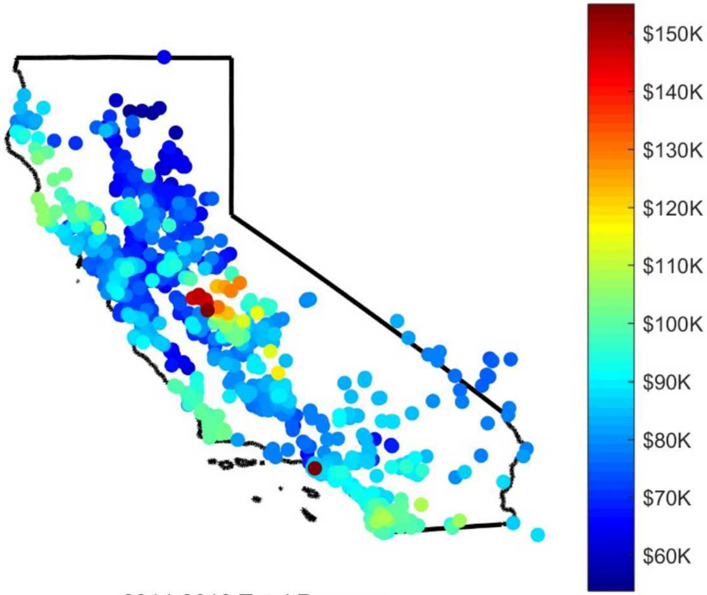


(b) Day ahead LMP for ISO-NE node 4476 (LD.STERLING13.8), July 14, 2016.

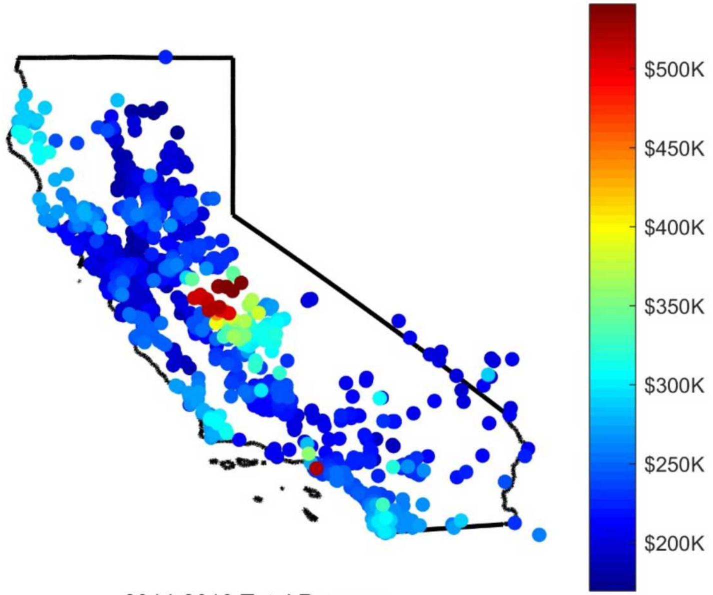
Energy Arbitrage

- 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



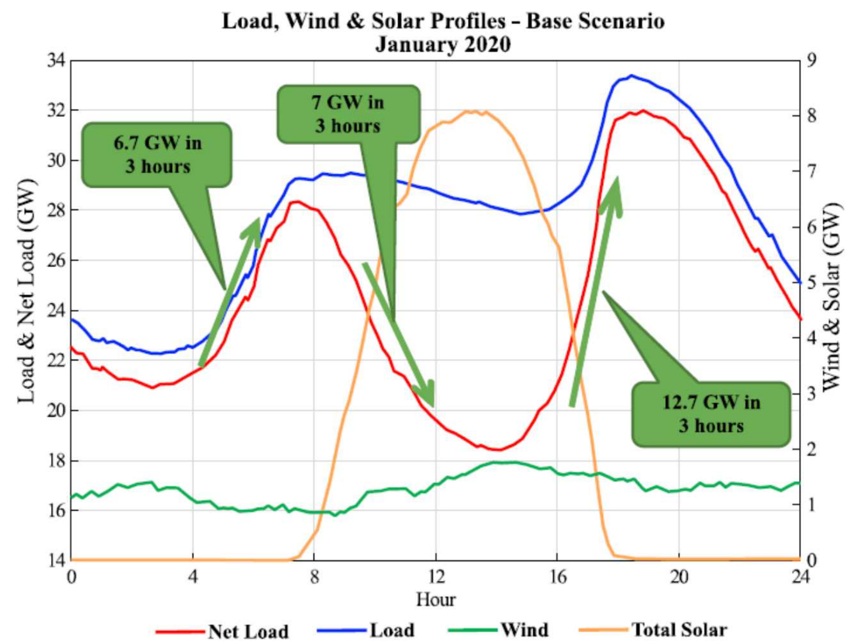
2014-2016 Total Revenue
DA+RT Arbitrage

- 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, I. Gyuk, “Opportunities for energy storage in CAISO: Day-ahead and real-time market arbitrage,” in proceedings of the 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi, Italy, June 20-22, 2019, pp. 1-6.

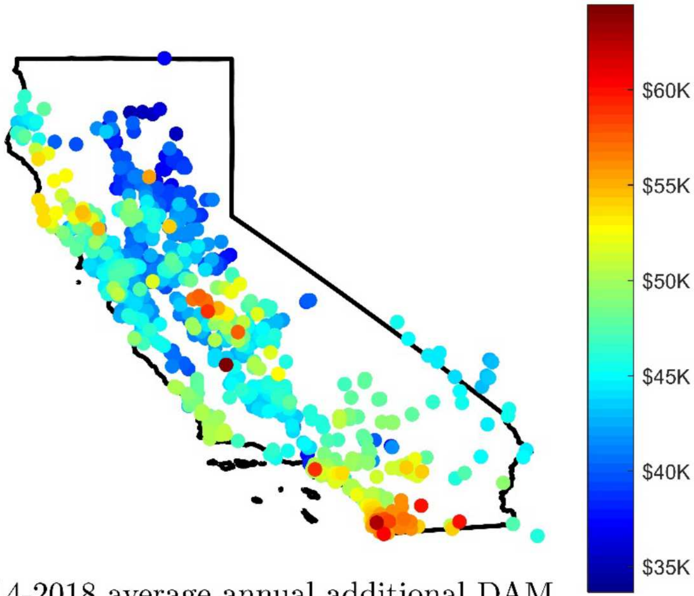
Renewable Energy Time Shift

- Goal – shift renewable generation from off-peak to on-peak hours
- Example – CAISO "duck curve"
- In some regions, also curtailment relief

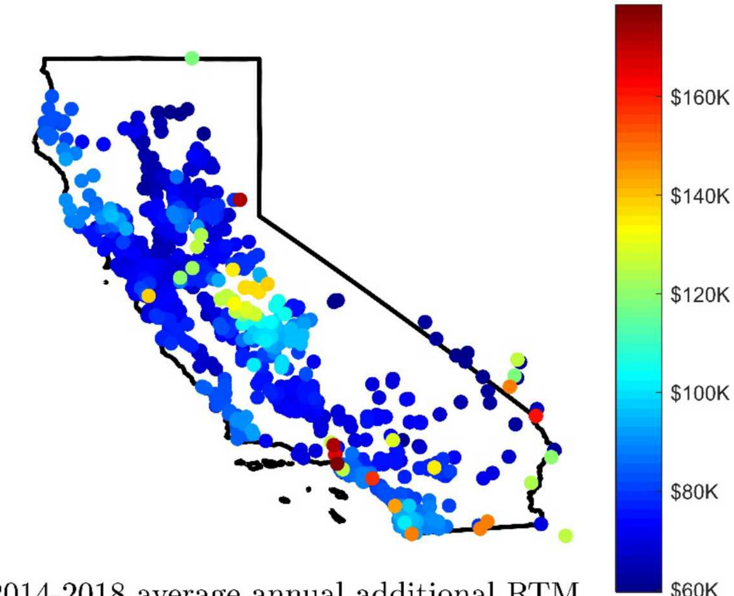


- CAISO has implemented a ramping product
- Other areas, arbitrage is your only option

Renewable Energy Time Shift – CAISO Example



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



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

- 1 MW, 4 MWh system, 85% efficiency
- Three year total revenue by LMP node, 2014-2016
- Assumes perfect foresight (best you can do)

R. H. Byrne, T. A. Nguyen, A. Headley, F. Wilches-Bernal, R. Concepcion, R. Trevizan, “Opportunities and trends for energy storage plus solar in CAISO: 2014-2018,” accepted for publication in the 2020 IEEE Power and Energy Society General Meeting, Montreal, Canada, August 2-6, 2020, pp.1-4.
R. H. Byrne, T. A. Nguyen, A. Headley, F. Wilches-Bernal, R. Concepcion, R. Trevizan, “Opportunities and trends for energy storage plus solar in CAISO: 2014-2018,” submitted to the 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Sorrento, Italy, June 24-26, 2020.

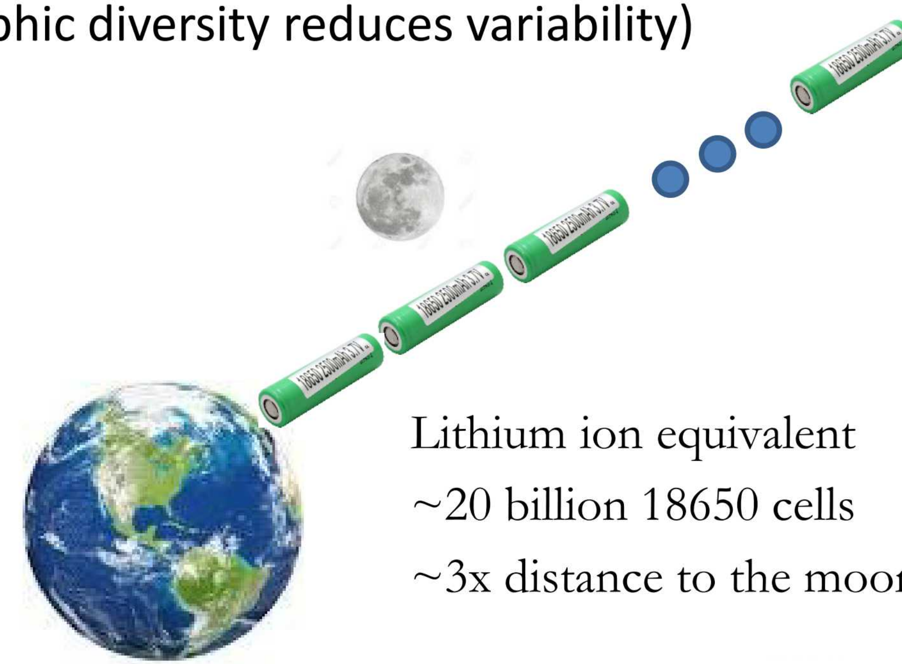
Renewable Energy Time Shift

- 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



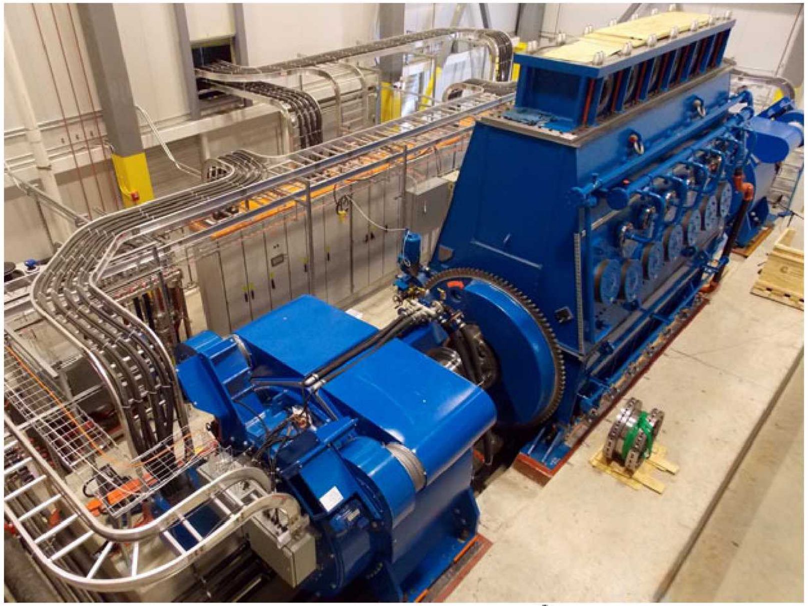
Lithium ion equivalent

~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
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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
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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
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Weekend

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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
  - *First pass estimate:*

ES_0 = energy storage cost

T_0 =

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

r = interest rate

K = number of deferral years

Real World typically quite complex

examples later

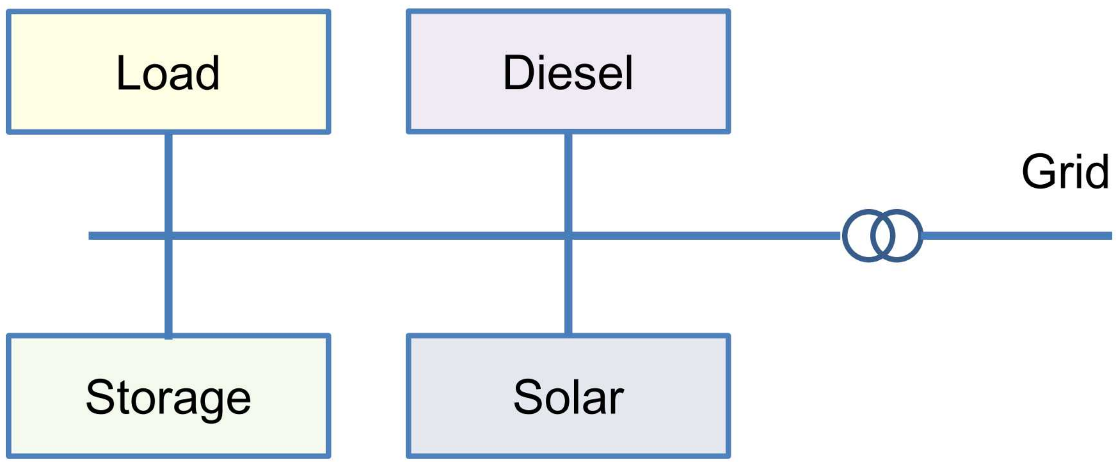
Grid Resiliency

- 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
- Storage plus DG (esp. PV) a viable customer alternative

Sterling Municipal Light Department
2 MW, 3.9 MWh system

Grid Resiliency – Backup Power

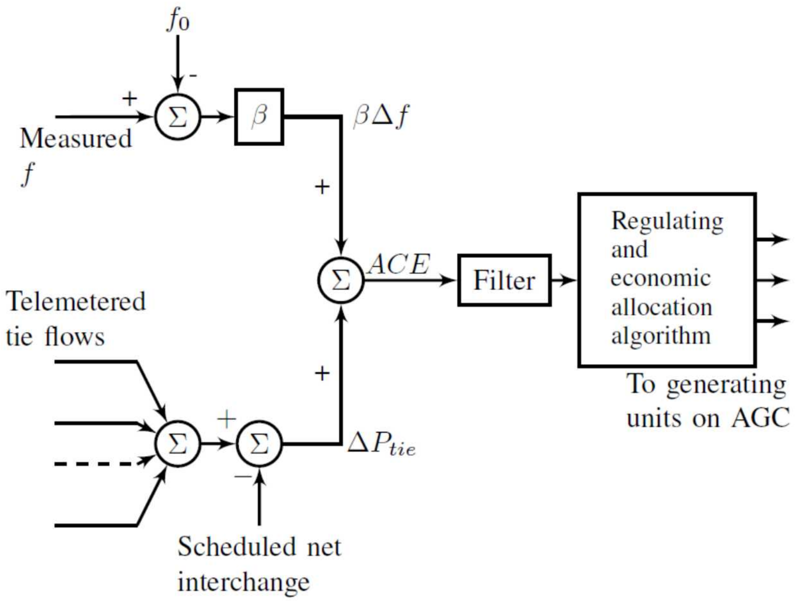
- Microgrids - hybrid renewable, storage and alternative backup solutions for critical load
  - Energy storage is a key component
  - Often paired with distributed generation
    - Solar
    - Wind
    - Diesel
    - Natural gas

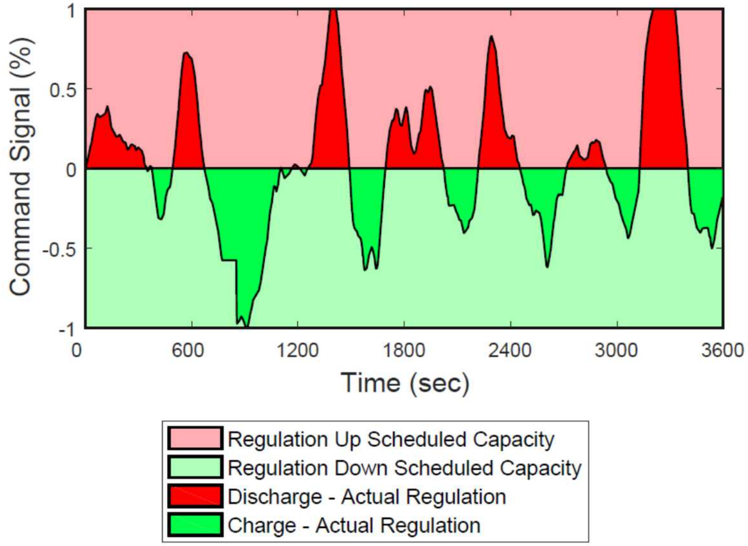


- Design and operation are optimization problems

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

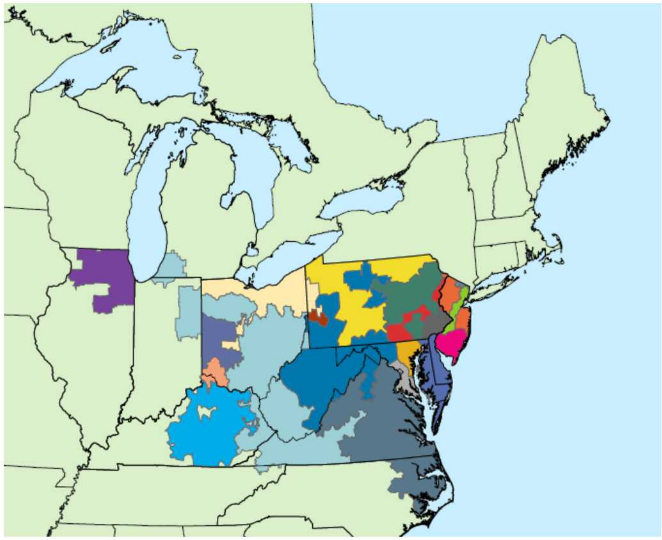
- Implementation varies by independent system operator
  - Bidirectional signal – PJM
  - Regulation Up, Regulation down – CAISO, ERCOT
  - Some ISOs allow specified SOC targets
- Pay-for-performance
  - Performance score (how well did you track command signal)
  - Mileage payment
- Some ISOs have storage-tuned “fast reg” service and separate AGC algorithm
  - Some are zero net energy over 5 – 15 minutes

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

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

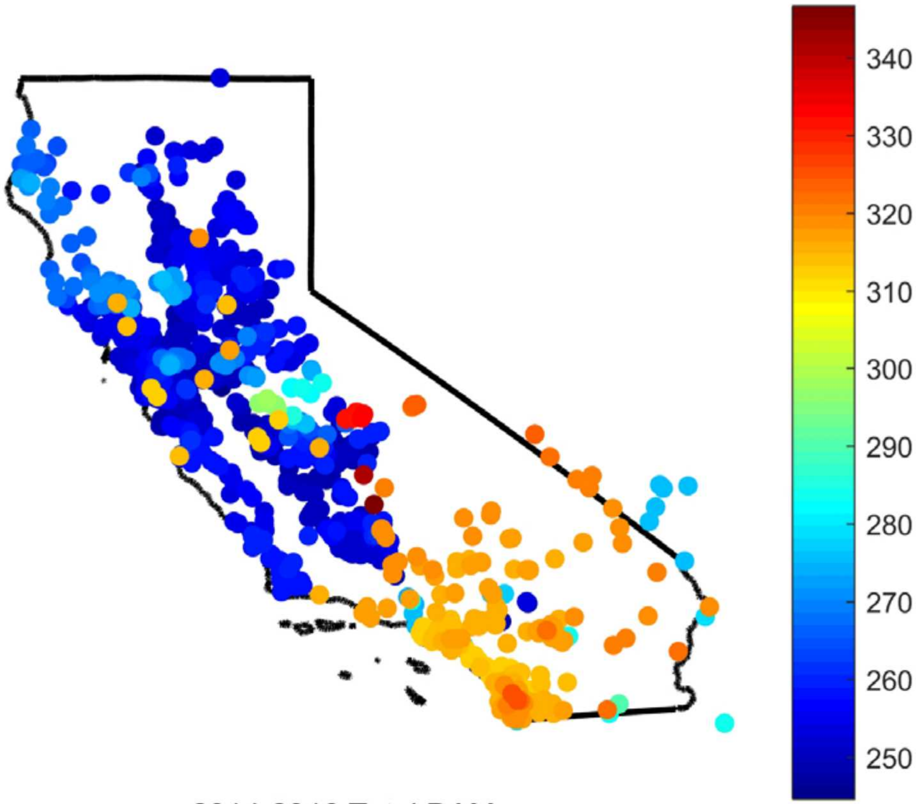


PJM results, 20MW, 5MWh 200-flywheel system

Beacon Power Flywheel

Market is "thin" and vulnerable to price crashes

Frequency Regulation



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

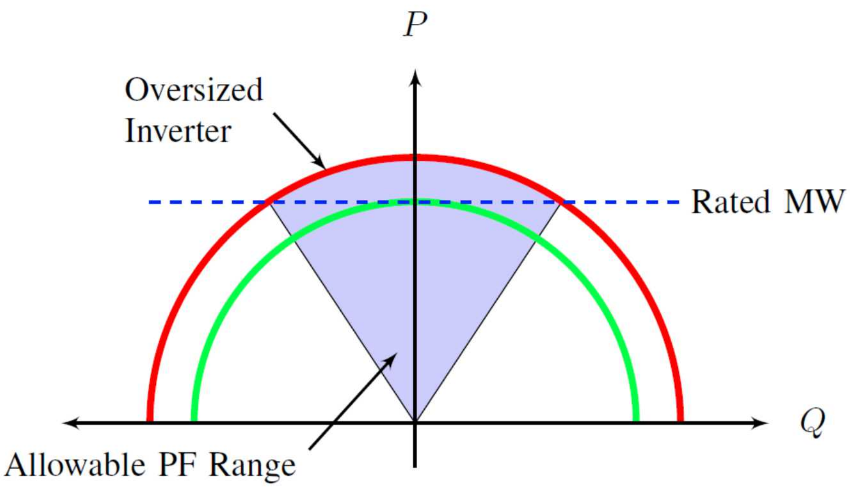
ENERGY STORAGE SYSTEM PARAMETERS

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

R. H. Byrne, T. A. Nguyen and R. J. Concepcion, "Opportunities for energy storage in CAISO," proceedings of the 2018 IEEE Power and Energy Society (PES) General Meeting, Portland, OR, August 5-9, 2018, pp. 1-5.

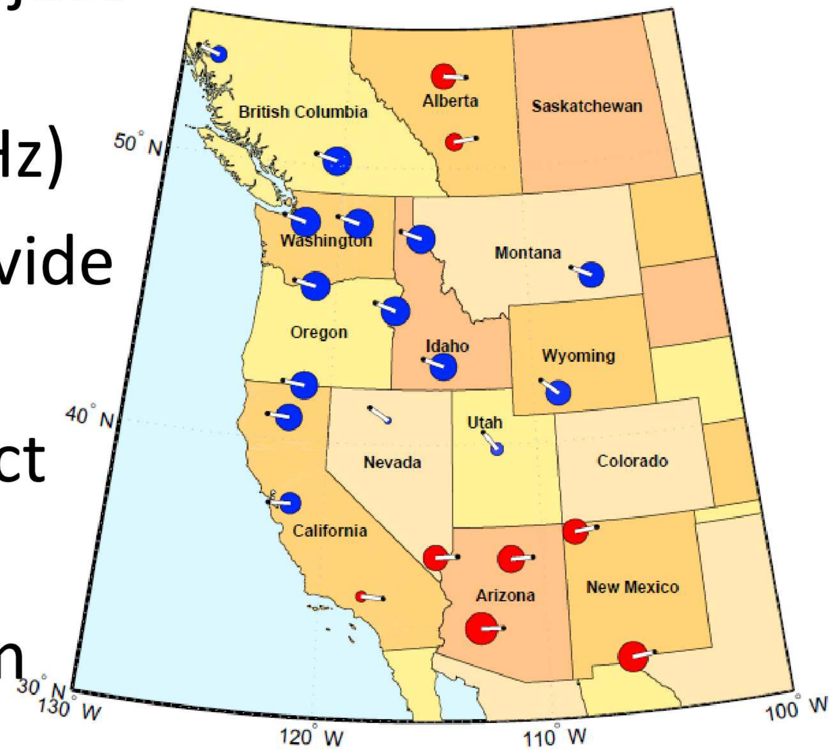
Voltage Support

- 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
- At distribution can increase PV hosting



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

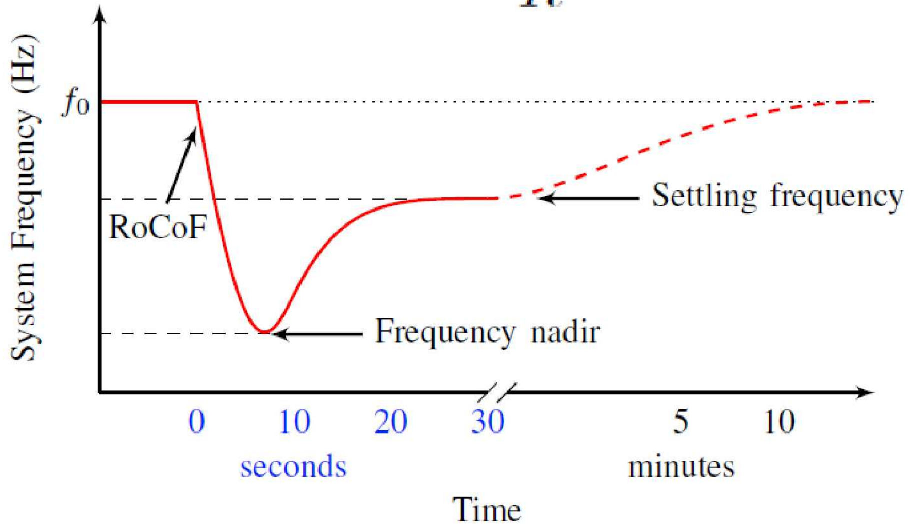


North-South Mode B (0.37 Hz) from a 2015 heavy summer WECC base case simulation

Frequency Droop

- Frequency droop: generator speed control proportional to the speed (frequency) error
- Energy storage can provide frequency droop via a control law

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

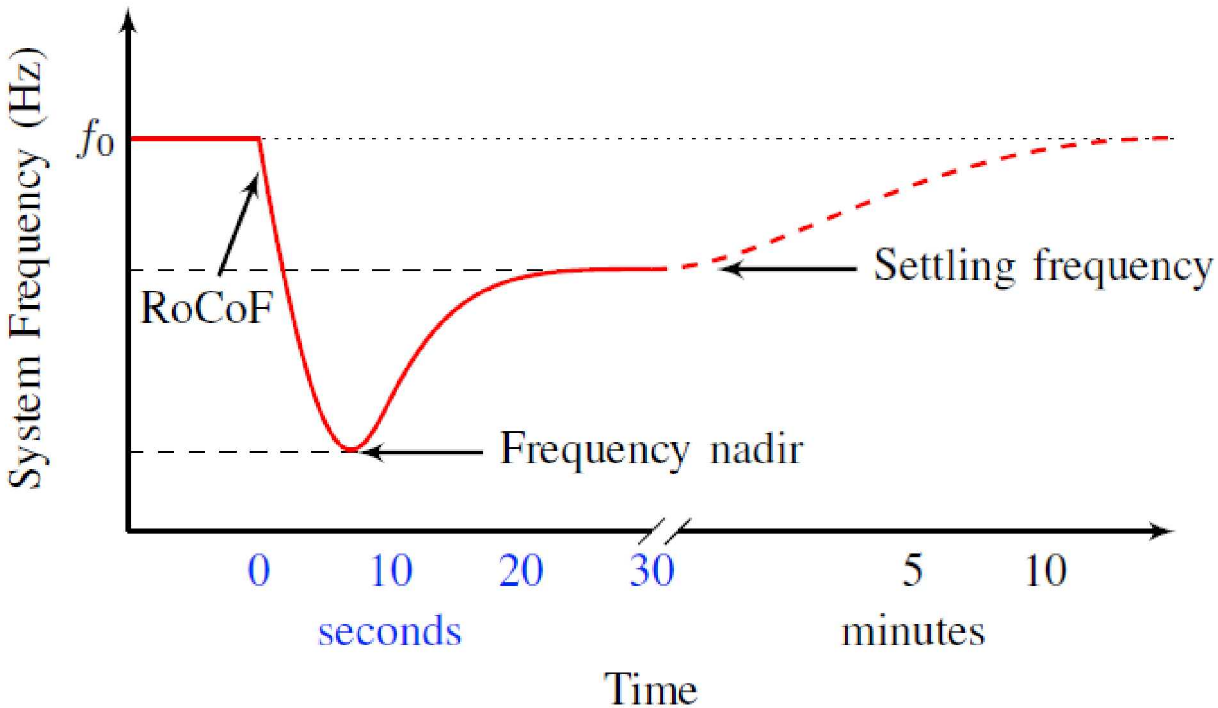


Frequency Droop

- In the U.S., generators were 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 (ignoring inter-generator transient effects and "local" frequency)



Synthetic Inertia

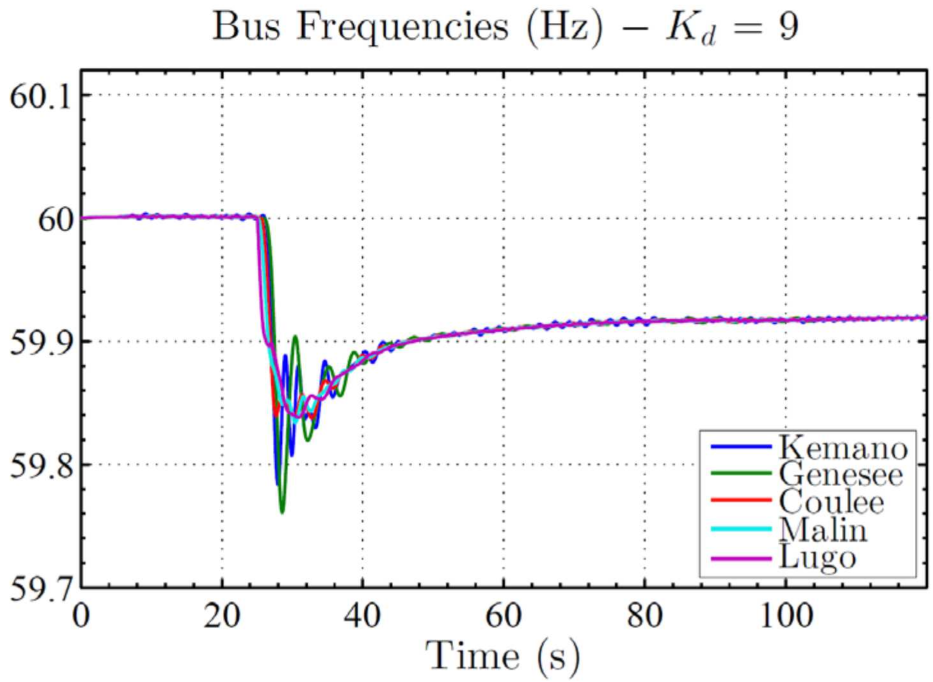
- Increased inverter-based generation displaces inertia
- Energy storage can provide synthetic inertia via a control law

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

- No mechanisms for compensating resources that provide inertia

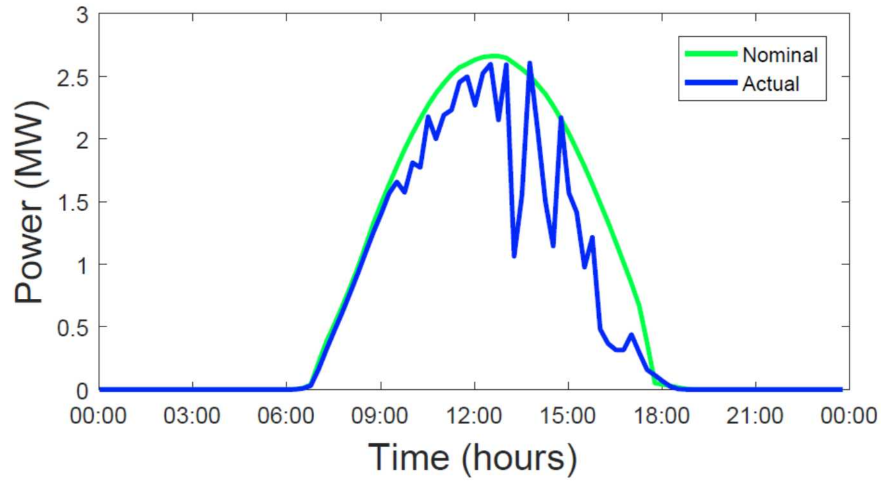
Synthetic Inertia

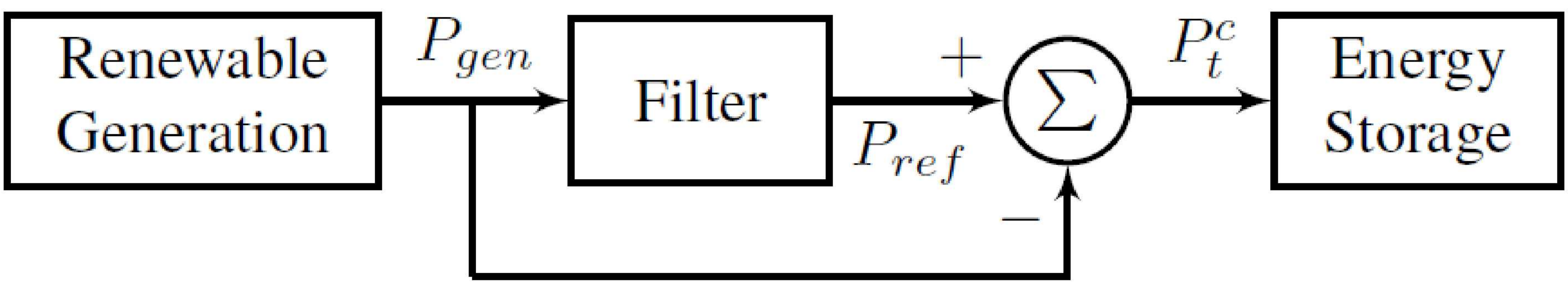
- Local frequency measurement is often proposed – this can be problematic near faults
- There are advantages to responding to a system frequency
- Logical PMU application



Renewable Capacity Firming

- 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)
- 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 Market Arbitrage

- 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

Sterling Municipal Light Department (SMLD)

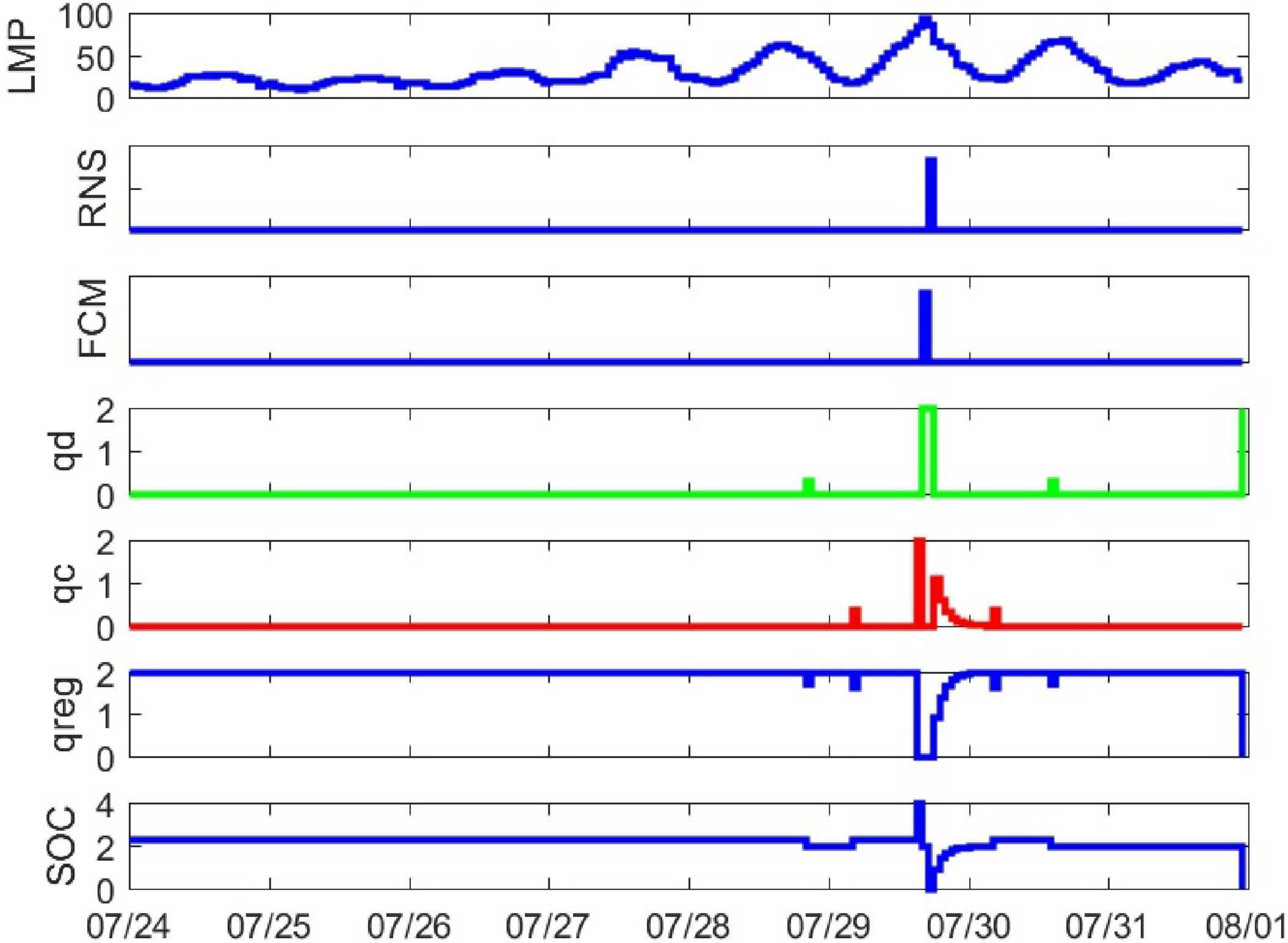
- Sterling Potential value streams:
  - Energy arbitrage
  - Reduction in monthly network load (based on monthly peak hour)
  - Reduction in capacity payments (based on annual peak hour)
  - Grid resilience
  - Frequency Regulation
- Grid Resilience was the primary goal – other applications help pay 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

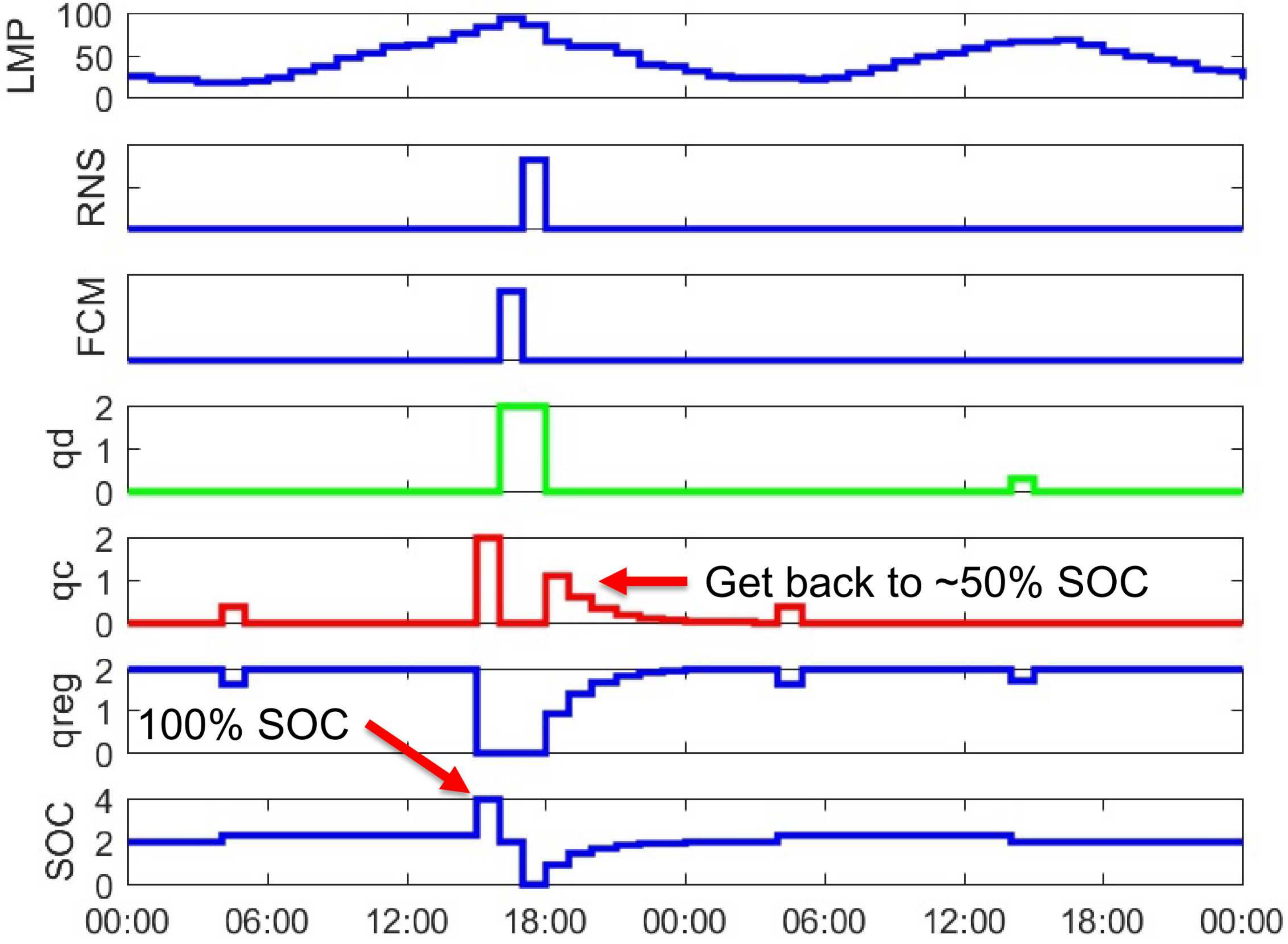
Optimization Results – Typical Week SMLD



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



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

Energy Storage Applications

- 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

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