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Sandia National Laboratories

Solar + Energy Storage Controls

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Solar + Storage Applications
  - Arbitrage
  - Renewable energy time shift
  - Demand charge reduction
  - Time of use charge reduction
  - T&D upgrade deferral
  - Grid resiliency/microgrids
  - Frequency regulation
  - Voltage support
  - Small signal stability
  - Synthetic inertia
  - Frequency droop
  - Renewable capacity firming
- Optimizing revenue in market areas

Energy Arbitrage

- Buy low, sell high

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

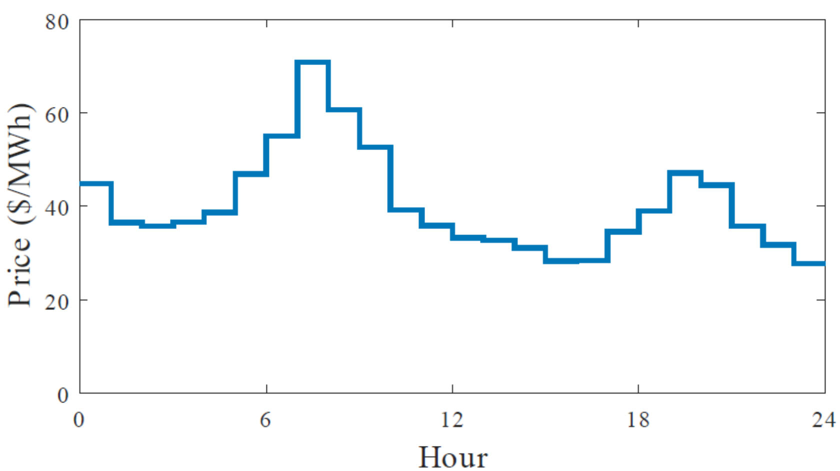
η_c= conversion efficiency

LMP_H = average high LMP, LMP_L = average low LMP

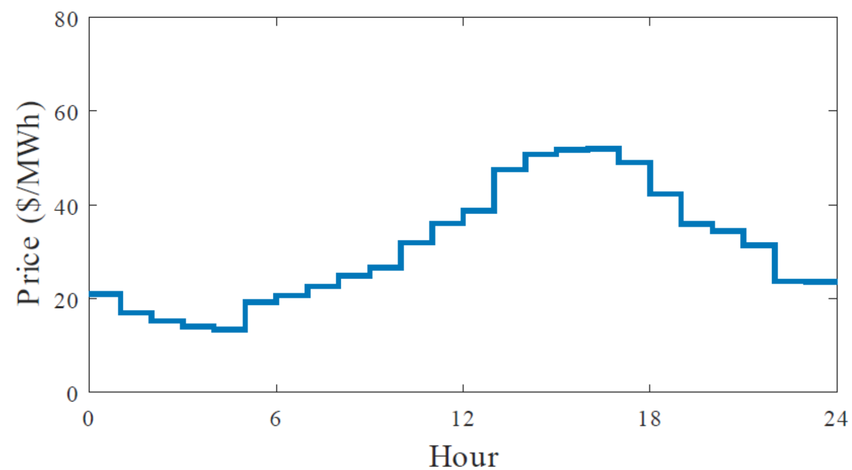
q = charge quantity

85% efficiency => 117.6% price difference

65% efficiency => 153.8% price difference



(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
- Different variants
  - Charge with inexpensive renewable energy
  - Arbitrage day ahead and real-time markets
  - Day ahead market only
- Rarely the highest potential revenue stream for storage alone
- With solar + storage, three options:
  - Sell solar immediately (LMP_1)
  - Store solar and sell later (LMP_2)

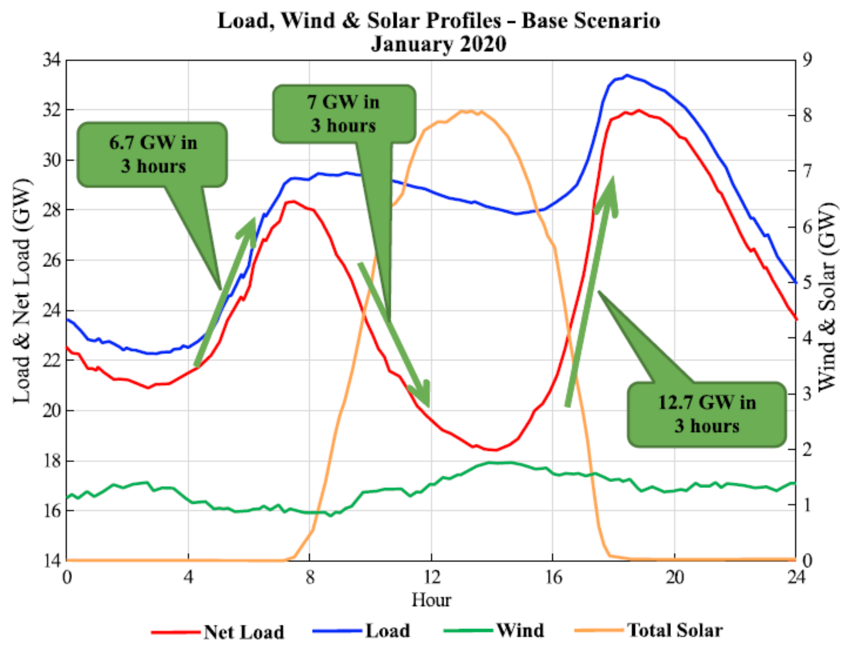
$$\eta_c LMP_2 > LMP_1$$

η_c= conversion efficiency

  - Curtail solar

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



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 for storage alone
- Solar + storage
  - Provides time-of-use charge reduction, plus
  - Inexpensive energy from solar

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
- Solar + storage
  - Provides demand charge reduction, plus
  - Inexpensive energy from solar

T&D Upgrade Deferral

- Projected load growth requires a transmission or distribution upgrade
- Solar + energy storage can be deployed to defer the investment
- Deferment discharging might only occur a few hours a year
- Low cost energy from solar in the interim

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

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

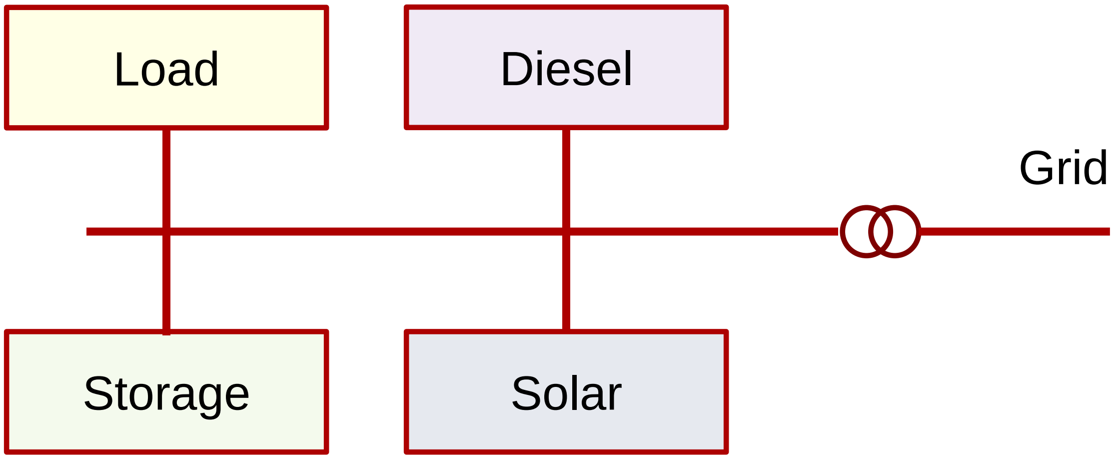
Grid Resiliency

- 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

Grid Resiliency – Backup Power

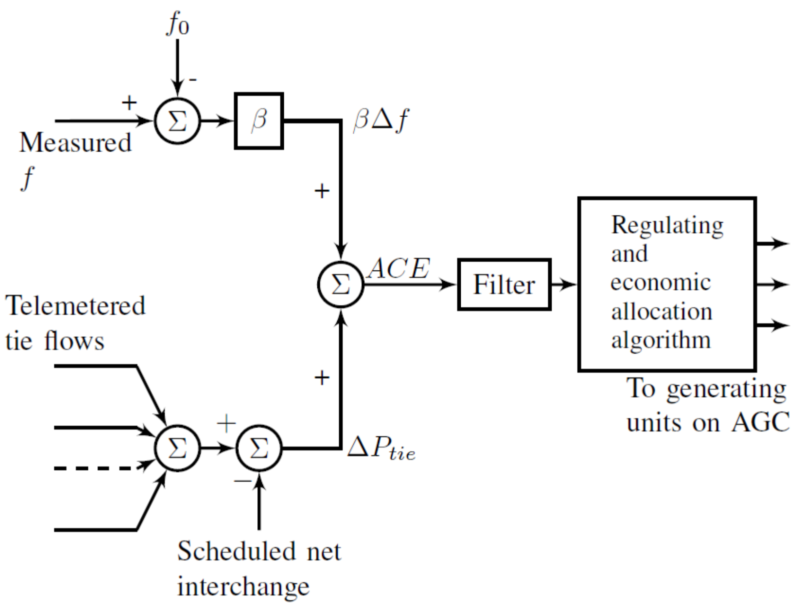
- Microgrids - hybrid renewable, storage and alternative backup solutions for critical load
  - Energy storage is a key component
  - Often paired with distributed generation
    - Solar
    - Wind
    - Diesel
    - Natural gas

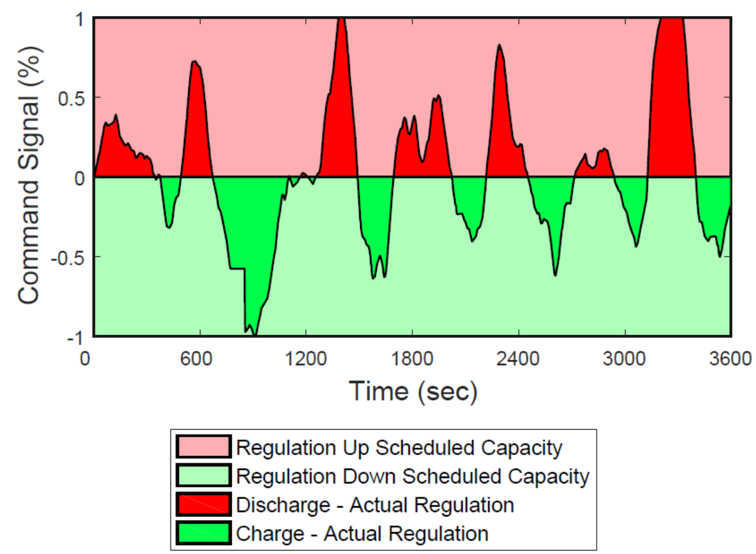


- Design and operation are optimization problems

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)

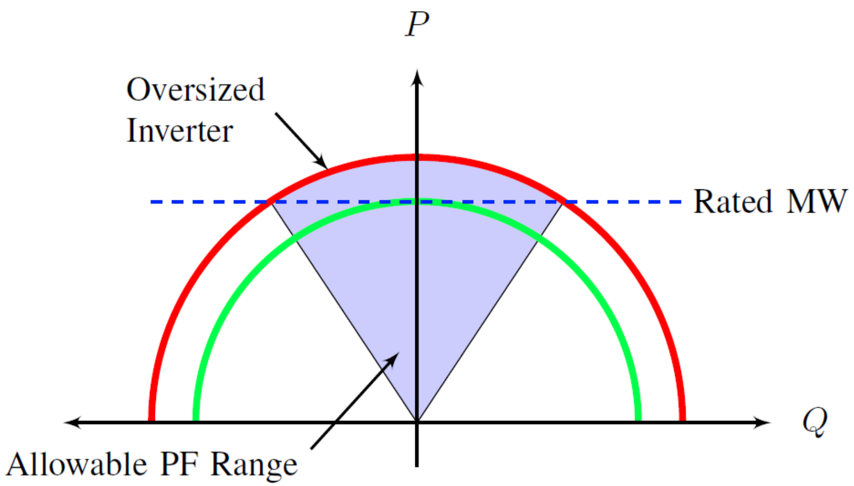
Frequency Regulation

- Implementation varies by independent system operator
  - Bidirectional signal – PJM
  - Regulation Up, Regulation down – CAISO, ERCOT
- Pay-for-performance
  - Performance score (how well did you track command signal)
  - Mileage payment
- Solar + storage possible configurations
  - Storage addresses all power modulation (e.g., no curtailment)
  - Both provide power modulation (e.g., some curtailment)

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

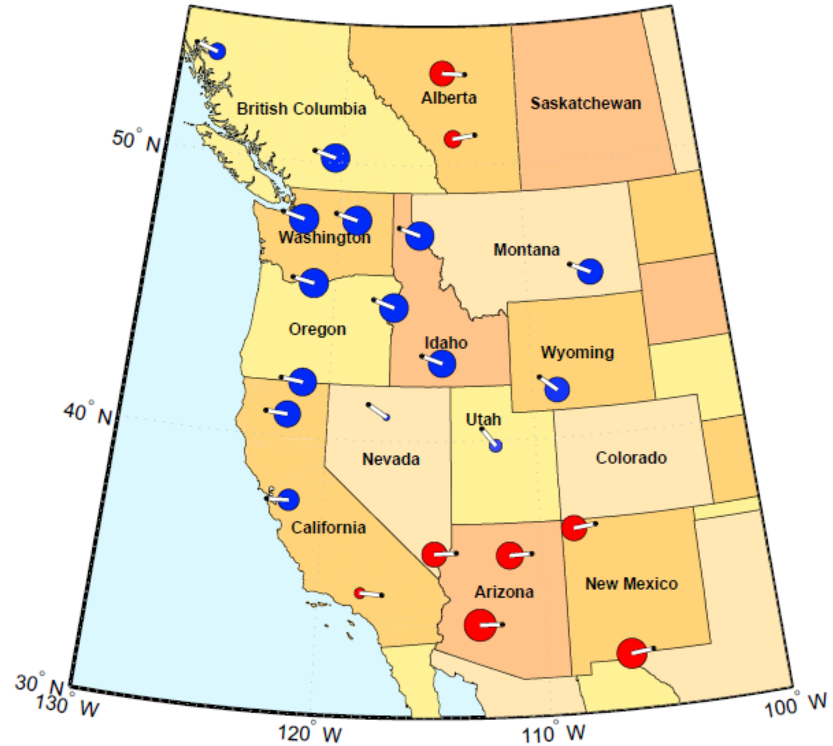
Voltage Support

- 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
- Solar + storage
  - Small amount of storage required for 24/7 operation
  - Might have to increase the size/cost of PV inverters



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
- Solar + storage configurations
  - Storage provides the modulated signal
  - Storage + solar provides the modulated signal (e.g., curtailment)

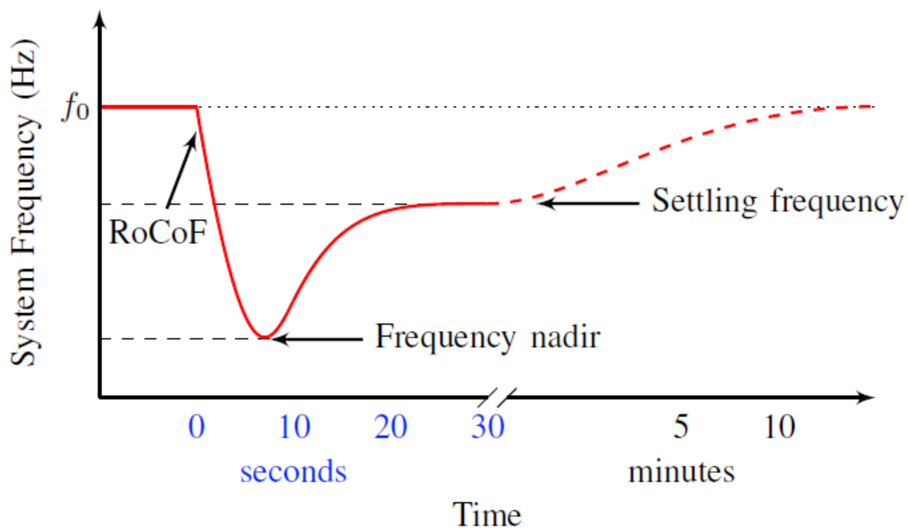


North-South Mode B (0.37 Hz) from a 2015 heavy summer WECC base case simulation

Frequency Droop

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

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

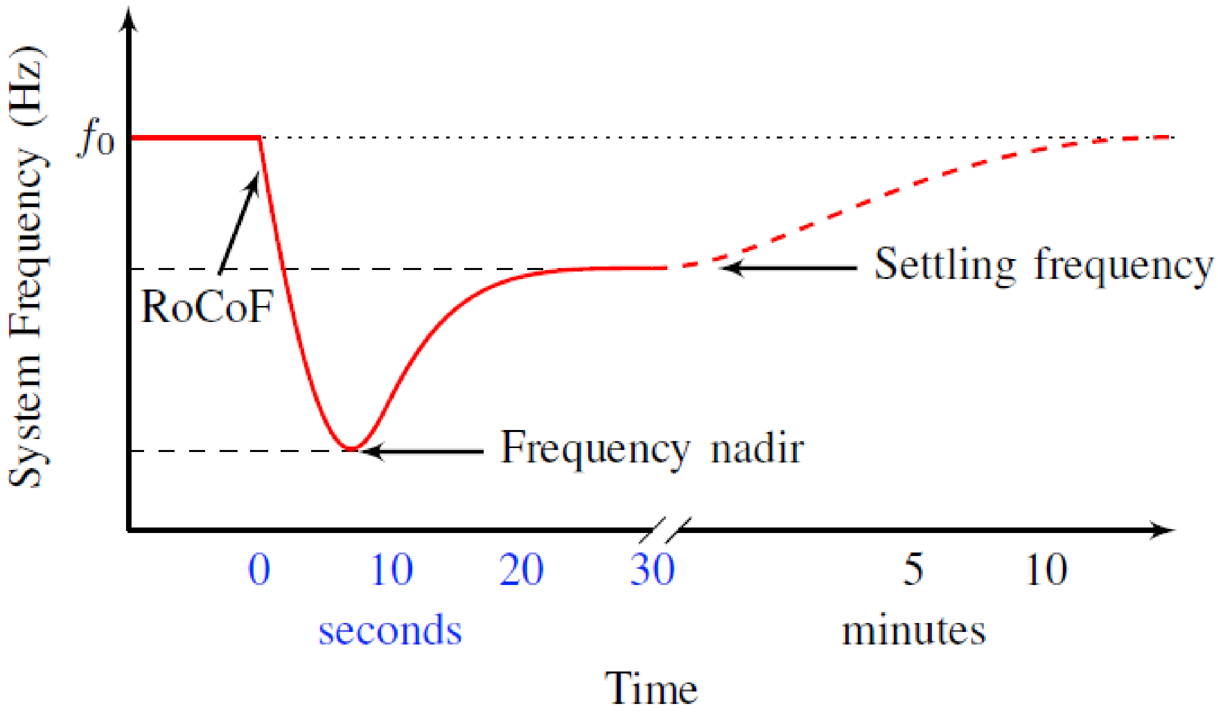


Frequency Droop

- 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
- Solar + storage configurations
  - Storage provides the response
  - Solar plus storage respond (e.g., curtailment)

Synthetic Inertia

- Large rotating machines provide inertia
- Rate of Change of Frequency (RoCoF) is proportional to the inertia in the system



Synthetic Inertia

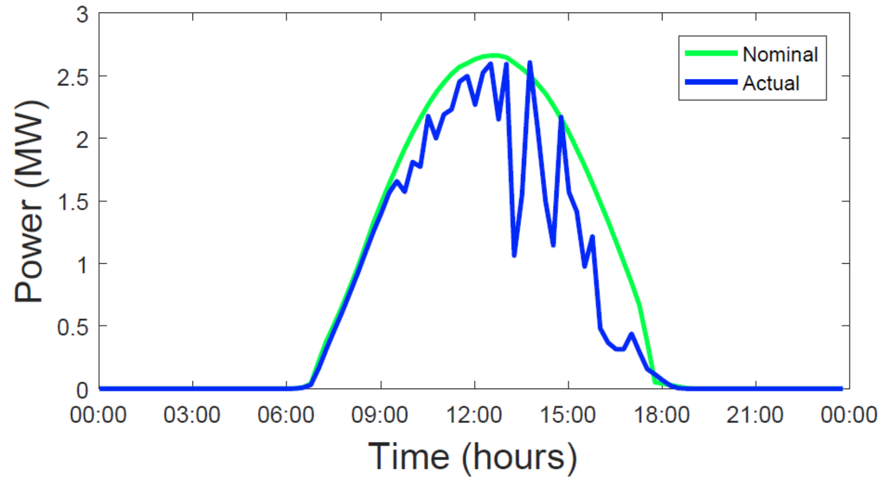
- Increased inverter-based generation displaces inertia
- Energy storage can provide synthetic inertia via a control law

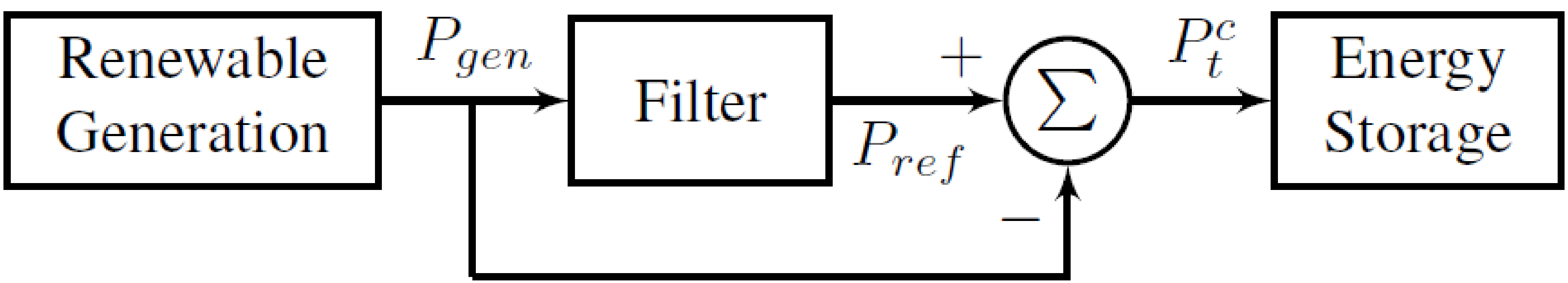
- No mechanisms for compensating resources that provide inertia

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

Renewable Capacity Firming

- Some areas are placing ramp rate limitations on renewable generation
  - Puerto Rico
  - Hawaii





Optimizing Revenue

- In a market area, optimizing storage + solar operation is a Linear Program (LP) optimization problem
- Constraints:
  - Energy storage model (power rating, max state-of-charge)
  - Solar model (max power rating)
- Inputs
  - Market prices for services
  - Solar irradiance/solar power output
- Typical scenarios
  - Historical data and perfect foresight to evaluate maximum potential revenue
  - Plant operation using forecasts and a sliding time horizon

Optimizing Revenue

- Storage model

$$S_t = \eta_s S_{t-1} + \eta_c(q_t^R + q_t^S) - q_t^D$$

S_t = State of charge at time period t (MWh)

η_s = Storage efficiency (%)

η_c = Conversion efficiency (%)

q_t^R = Market charge energy at time period t (MWh)

q_t^S = Solar charge energy at time period t (MWh)

q_t^D = Market discharge energy at time period t (MWh)

- Solar model

P_t^{gen} = Potential solar energy generated at time period t (MWh)

P_t^{curt} = Solar energy curtailed at time period t (MWh)

P_t^{SM} = Solar energy sold at time period t (MWh)

$$P_t^{SM} = P_t^{gen} - q_t^S - P_t^{curt}$$

Optimizing Revenue

- Decision variables

q_t^R = Market charge energy at time period t (MWh)

q_t^S = Solar charge energy at time period t (MWh)

q_t^D = Market discharge energy at time period t (MWh)

P_t^{curt} = Solar energy curtailed at time period t (MWh)

P_t^{SM} is calculated $(P_t^{SM} = P_t^{gen} - q_t^S - P_t^{curt})$

- Cost function

$$J = \sum_i \left(q_t^D + P_t^{SM} - q_t^R\right) LMP\_i$$

- Constraints

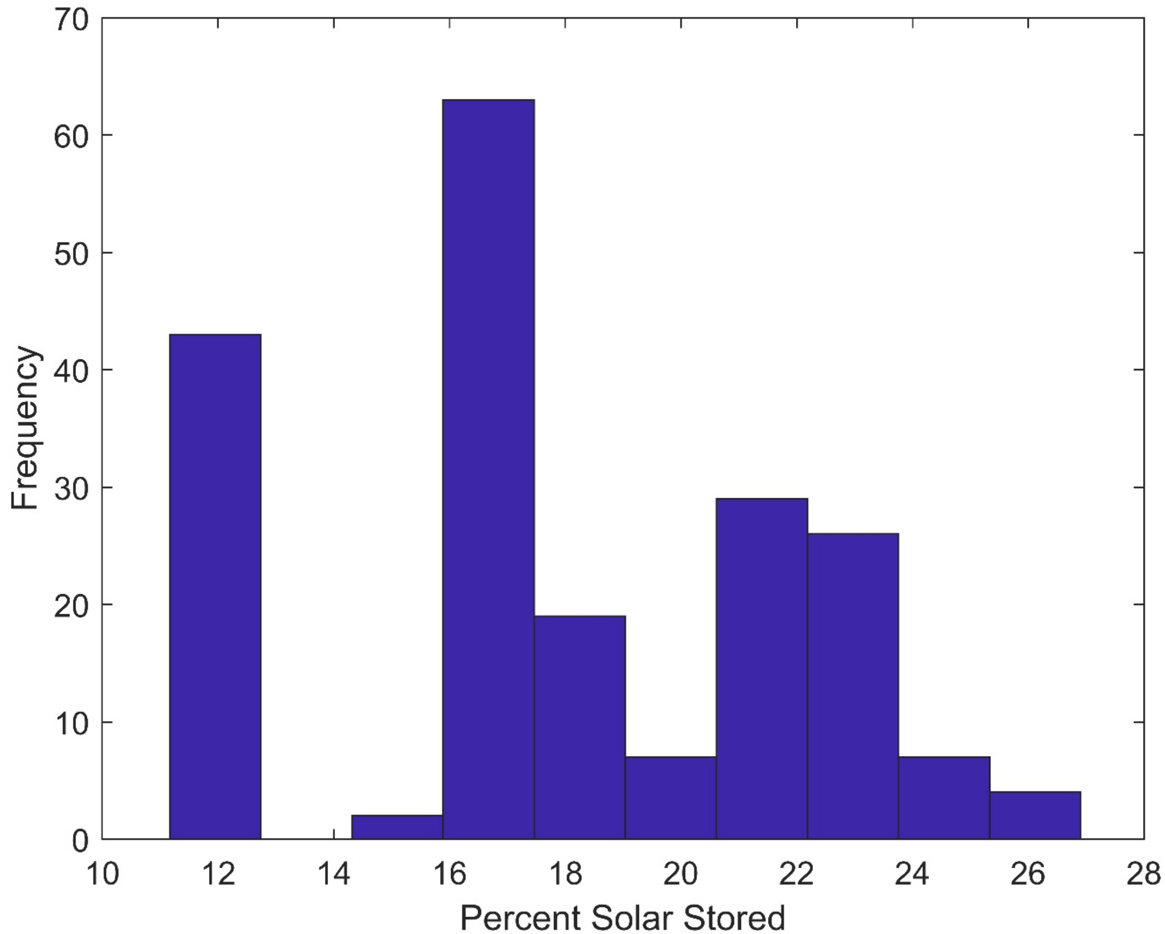
$\bar{q}$ = maximum charge/discharge quantity per period

$$q_t^R + q_t^S + q_t^D < \bar{q}, \qquad 0 \leq SOC_t \leq \overline{SOC}$$

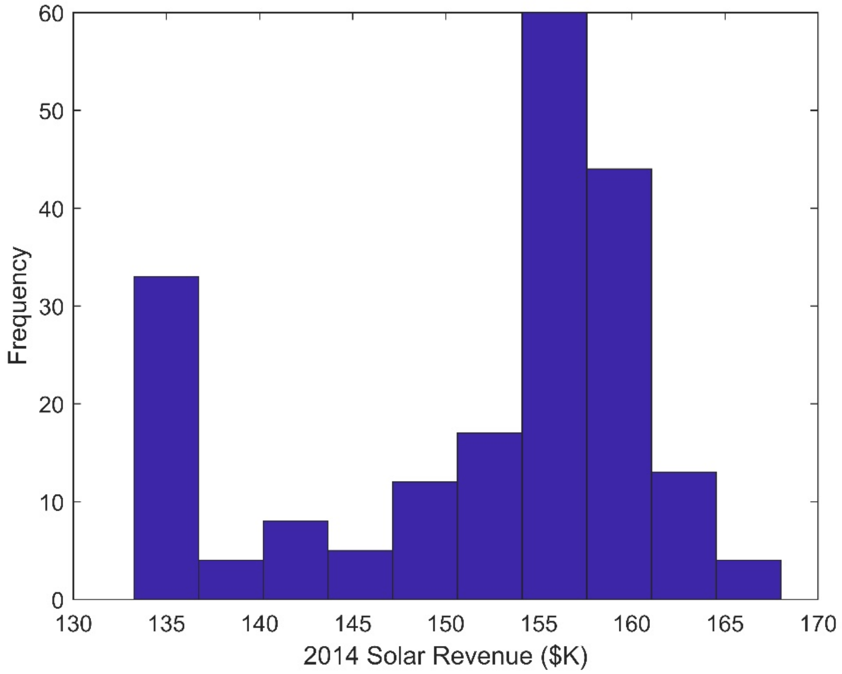
Example 1 – CASIO DA Market

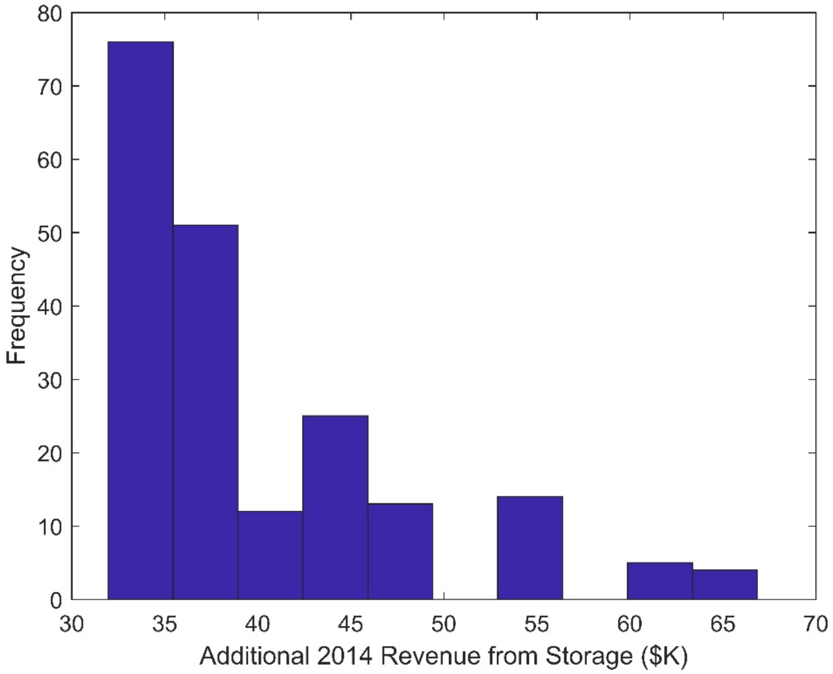
- Model
  - 1 MW, 4MWh storage, 85% conversion efficiency
  - 1 MW solar plant
  - Participate in the CAISO DA energy market
- Data
  - Solar irradiance data from NERL (lat/lon)
  - CAISO day ahead market data from 2014 (~2200 nodes with lat/lon data)
- Results for 200 nodes so far

Example 1 – CAISO DA Market



Example 1 – CAISO DA Market

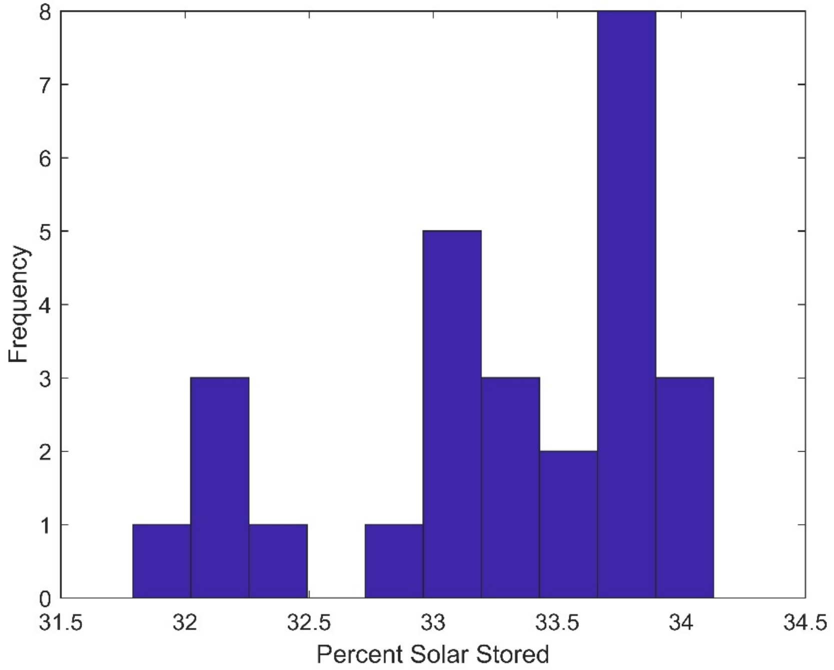


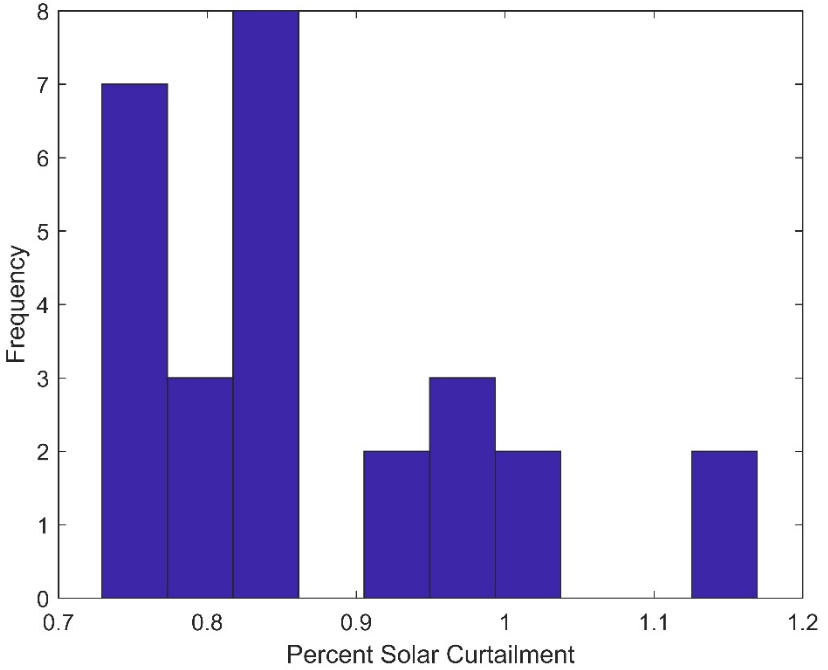


Example 2 – CASIO RT Market

- Model
  - 1 MW, 4MWh storage, 85% conversion efficiency
  - 1 MW solar plant
  - Participate in the CAISO RT energy market
- Data
  - Solar irradiance data from NERL (lat/lon)
  - CAISO day ahead market data from 2014 (~2200 nodes with lat/lon data)
- Results for 27 nodes (so far)

Example 2 – CAISO RT Market

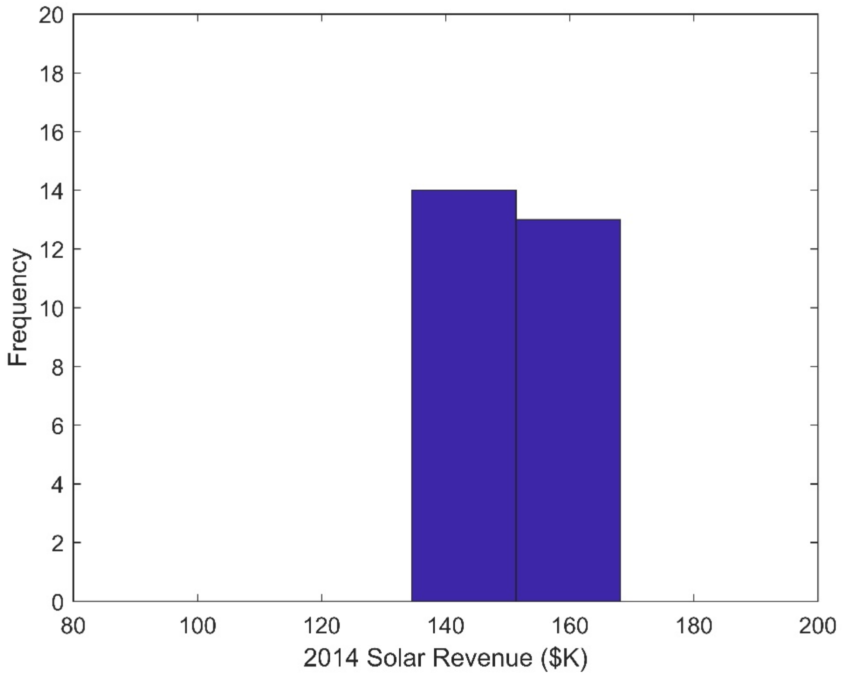


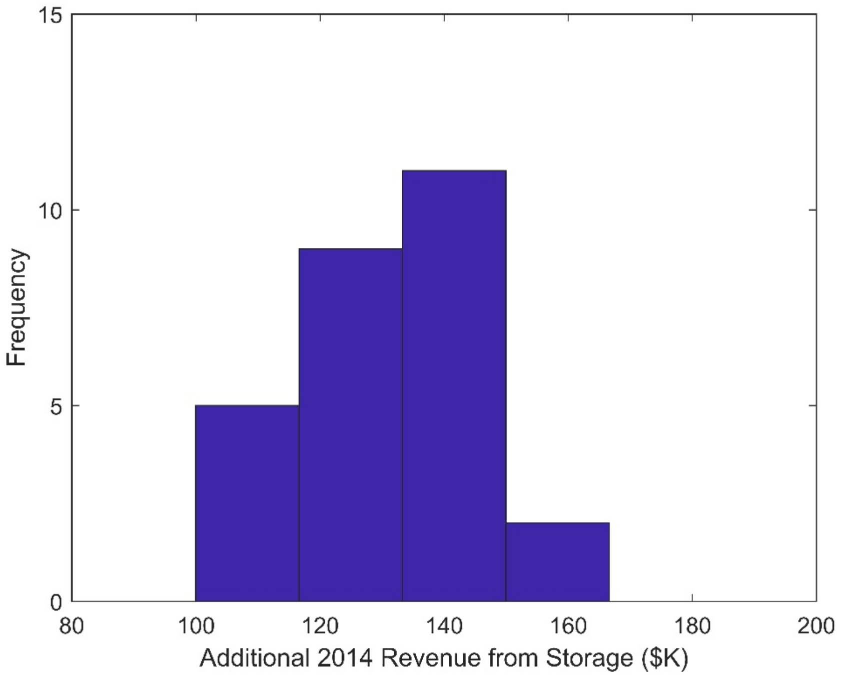


~1/3 of solar generation gets stored in the energy storage

Minimal curtailment (for these nodes)

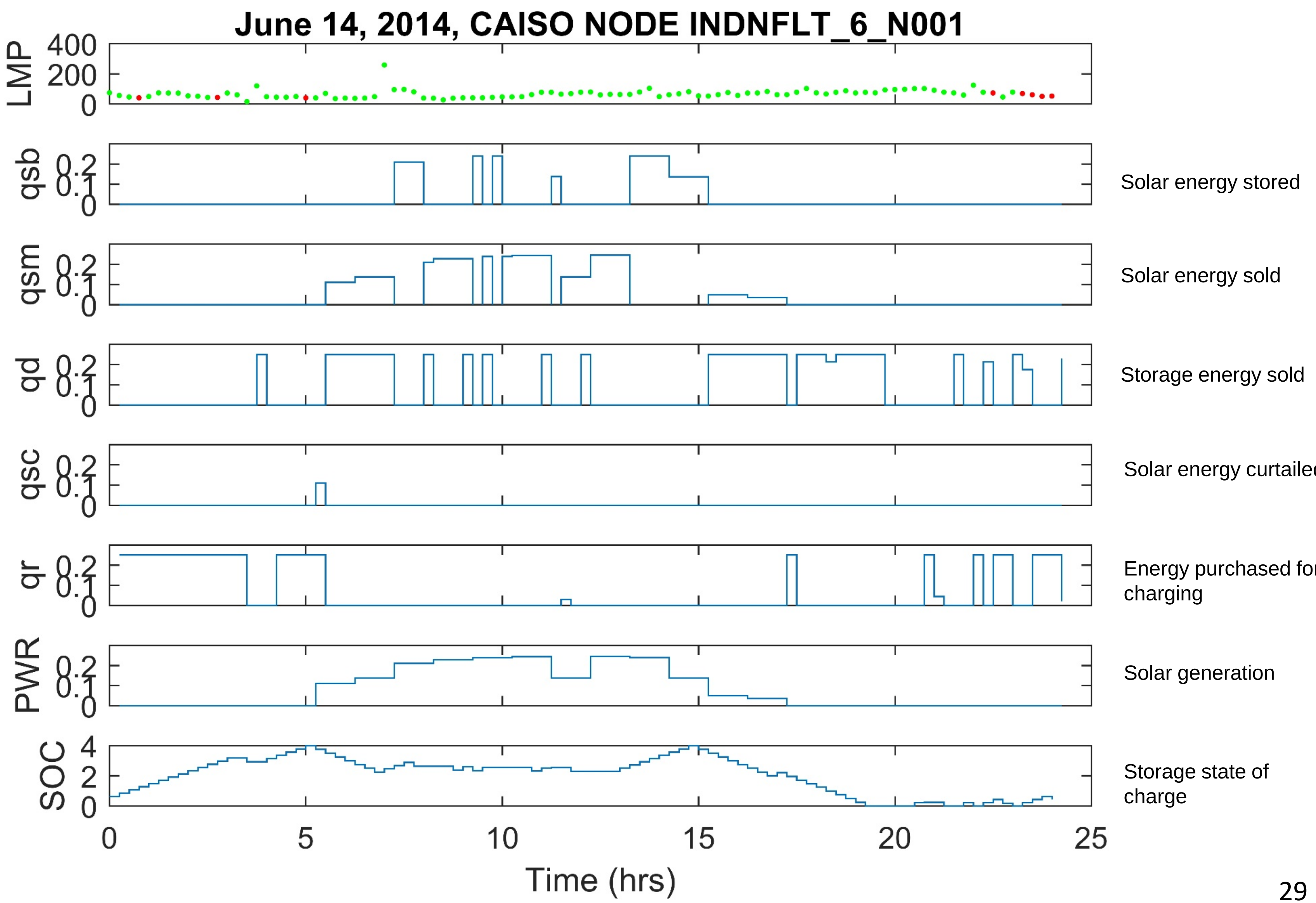
Example 2 – CAISO RT Markets





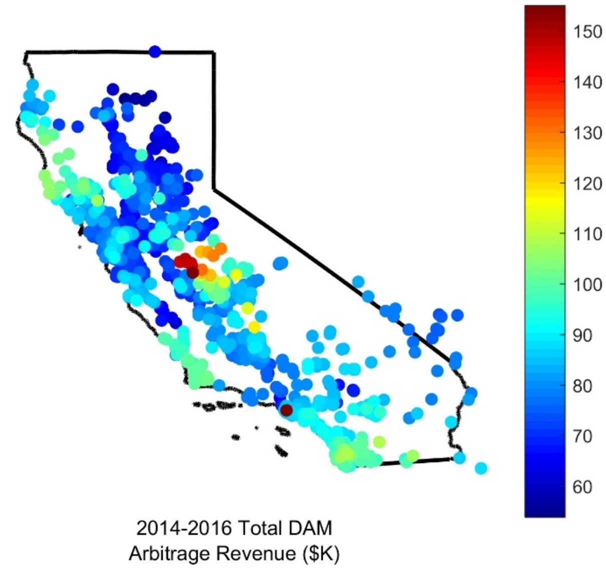
Adding 1MW/4MWh of storage to 1MW of solar roughly doubles the potential revenue (for these nodes)

Example 2 – CAISO RT Market



Conclusions

- Solar + energy storage is capable of providing a number of grid benefits
- Typical configurations:
  - Storage addresses all power modulation (e.g., no curtailment)
  - Both provide power modulation (e.g., some curtailment)
- Revenue maximization in market areas can be formulated as an LP optimization
- We are currently working on a publication that assess the value of storage + solar in CAISO
- More information on energy storage valuation: www.sandia.gov/ess



Example results for energy storage only