Grid Integration of Variable Renewable Generation: Reliability Challenges and Solutions

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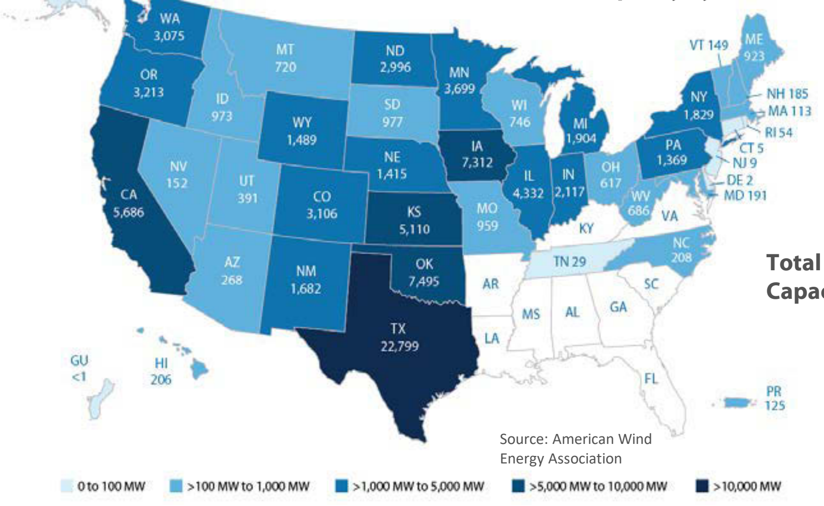
Status of Wind and Solar PV Capacity in U.S.

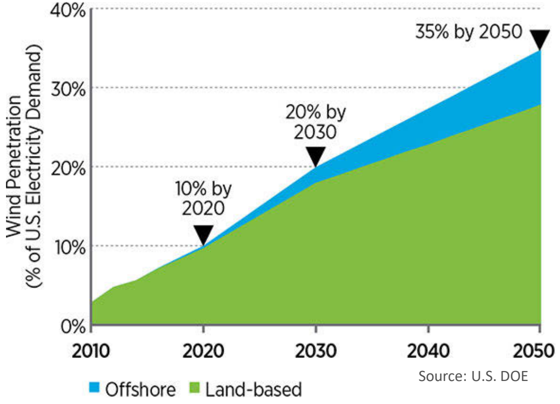
U.S. Wind Power Cumulative Installed Capacity by State



Source: American Wind Energy Association

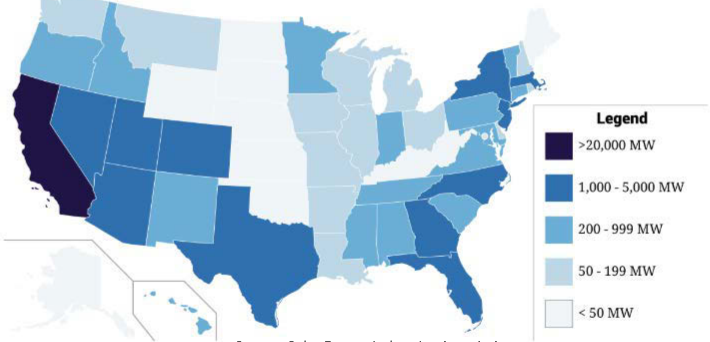
Total U.S. Wind Capacity: 90 GW

U.S. DOE Wind Vision Study Scenarios



Source: U.S. DOE

U.S. Solar Power Cumulative Installed Capacity by State



Source: Solar Energy Industries Association

Top 10 Solar States

1. California – 22,777 MW
2. North Carolina – 4,491 MW
3. Arizona – 3,613 MW
4. Nevada – 2,658 MW
5. Texas – 2,624 MW
6. New Jersey – 2,526 MW
7. Massachusetts – 2,226 MW
8. Florida – 1,943 MW
9. Utah – 1,627 MW
10. Georgia – 1,556 MW

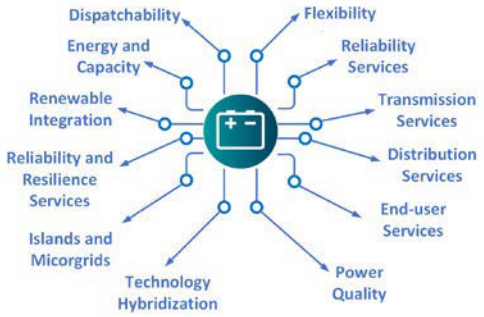
Source: Solar Energy Industries Association

Total U.S. Solar Capacity: 58.3 GW

Grid Integration Challenges for Variable Generation

Category	SOLUTIONS	VARIABILITY	UNCERTAINTY	LOCATION-SPECIFICITY	NON-SYNCHRONOUS NATURE	LOW CAPACITY FACTOR
Markets	Improved Market Design	•	•	•		
Markets	Joint Market Operation	•	•	•		
Markets	New Ancillary Service Markets	•			•	
Grids	Transmission Expansion	•		•		•
Grids	Transmission Reinforcement	•		•		
Grids	Advanced Network Management	•		•		
Flexibility	Coal, CT, CCGT and Hydro Ramping	•				
Operation	Balancing Areas Consolidation	•	•	•		
Operation	Sub-hourly Dispatch and Scheduling	•	•	•		
Operation	Improved Forecast		•			
Operation	Grid Services by Renewables				•	
Operation	New Grid Codes				•	
Operation	RE Curtailment	•			•	
Load	Demand Response	•			•	
Storage	Energy Storage	•	•	•	•	•
Storage	Hybrid Renewable Plants	•	•	•	•	•

NREL Research



Challenges:

- **Transient and dynamic stability** (loss of system inertia could reduce ability to respond to disturbances—need ride-though capabilities in VRE)
- **Frequency regulation** (need primary, secondary, and tertiary response from VRE)
- **Volt/VAR regulation** (need ability to locally change voltage to stay within nominal limits)

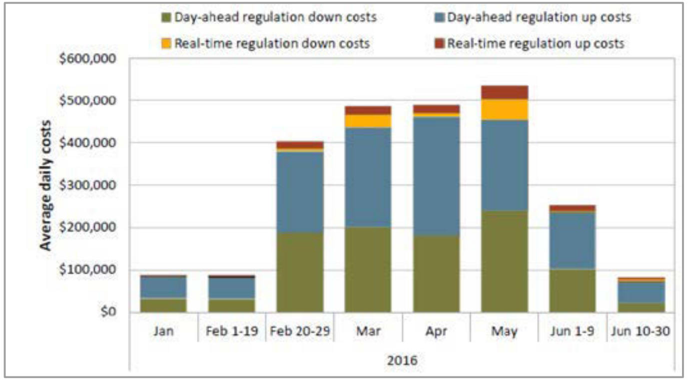
Solutions:

- Use smart inverters with advanced functionality.
- Mimic synchronous generator characteristics.
- Provide active power, reactive power, voltage, and frequency control.

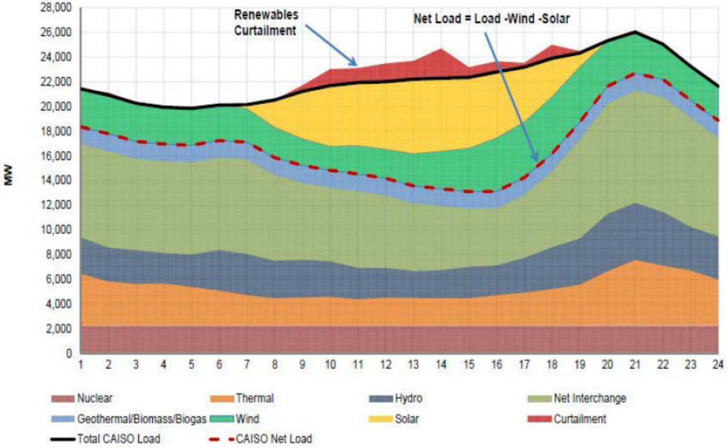
Essential Reliability Services

- Active Power Control capabilities include:
  - Ramp-rate-limiting controls
  - Active power response to bulk power system contingencies
  - Inertial response
  - Primary frequency response (PFR)
  - Secondary frequency response, or participation in automatic generation control (AGC)
  - Ability to follow security-constrained economic dispatch set points that are sent every 5 minutes through its real-time economic dispatch market software.
- Performance during and after disturbances
  - Fault ride-through
  - Short-circuit current contribution.
- Voltage, reactive, and power factor control and regulation (both dynamic and steady state).

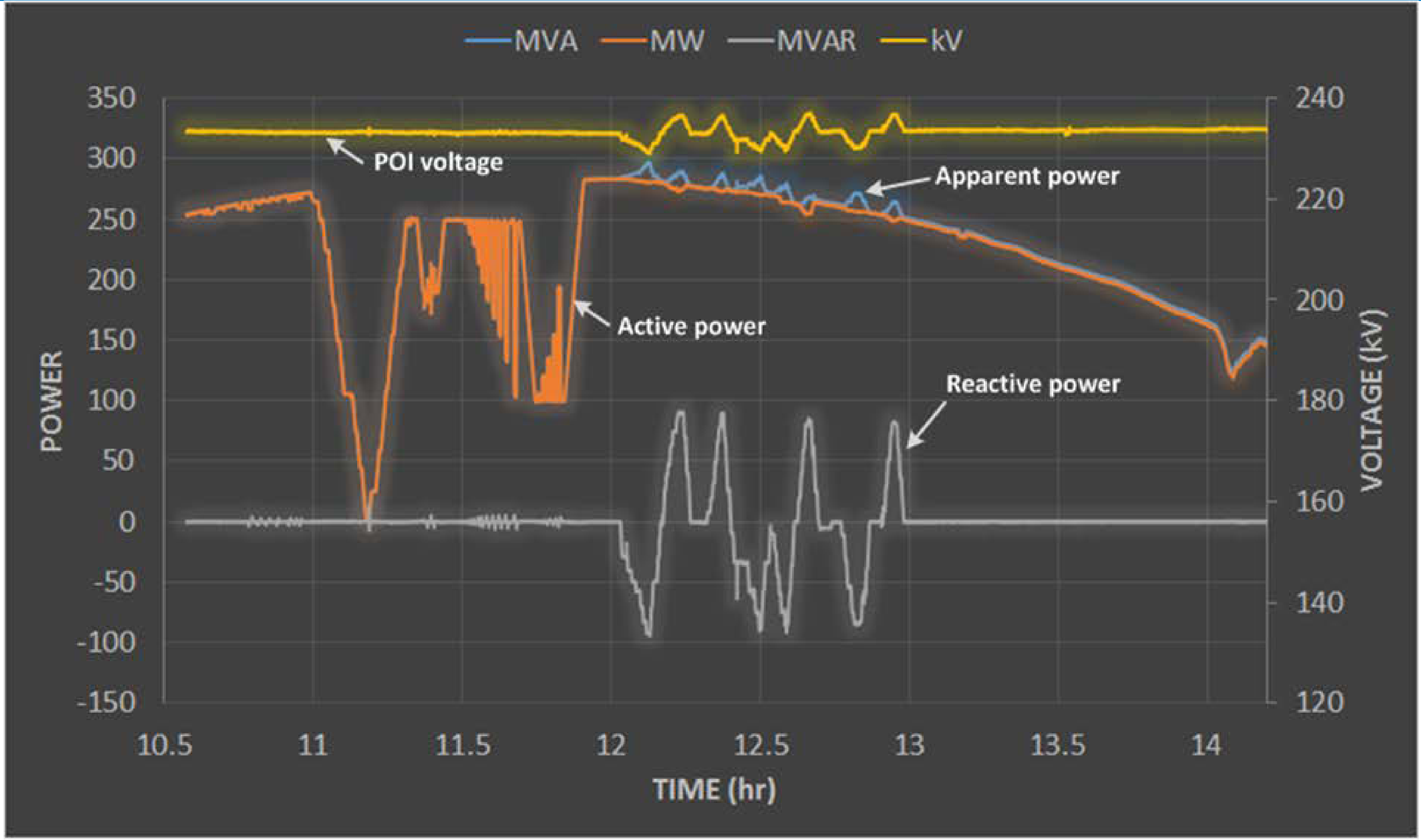
CAISO's average daily regulation procurement costs from January–June 2016



CAISO's generation breakdown for April 24, 2016

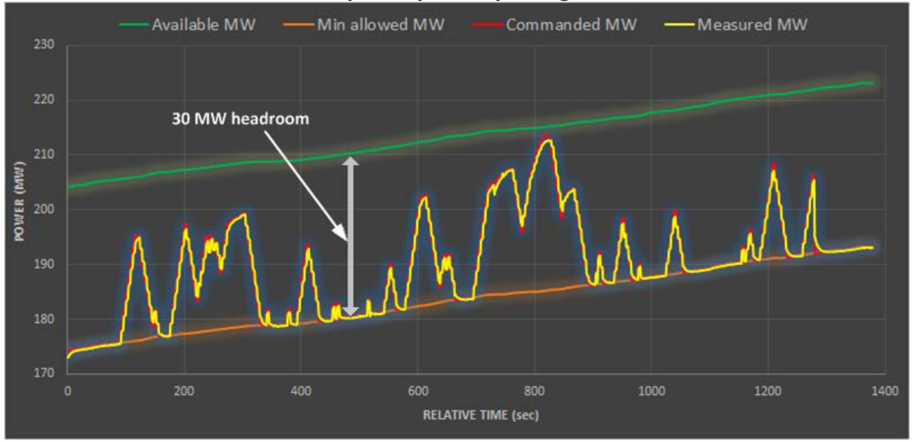


Testing 300-MW PV Plant in CAISO's Service Territory

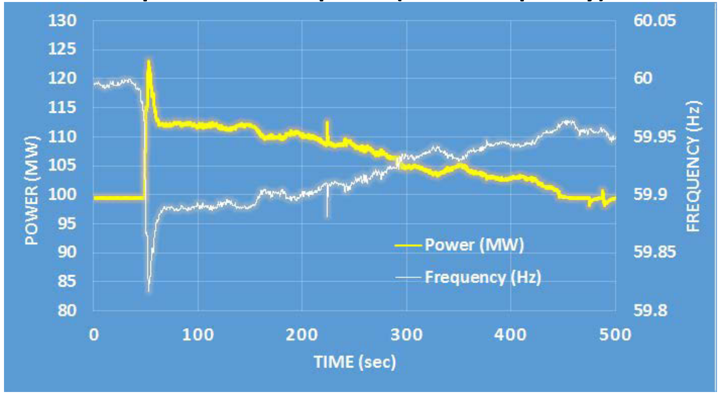


Testing 300-MW PV Plant in CA

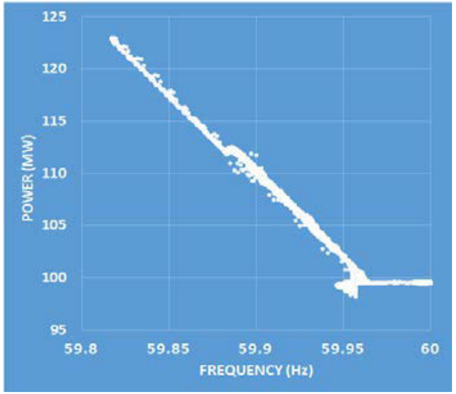
300-MW PV plant participating in AGC



Example of 3% droop test (underfrequency)



Measured droop response



Measured Regulation Accuracy by 300-MW PV Plant

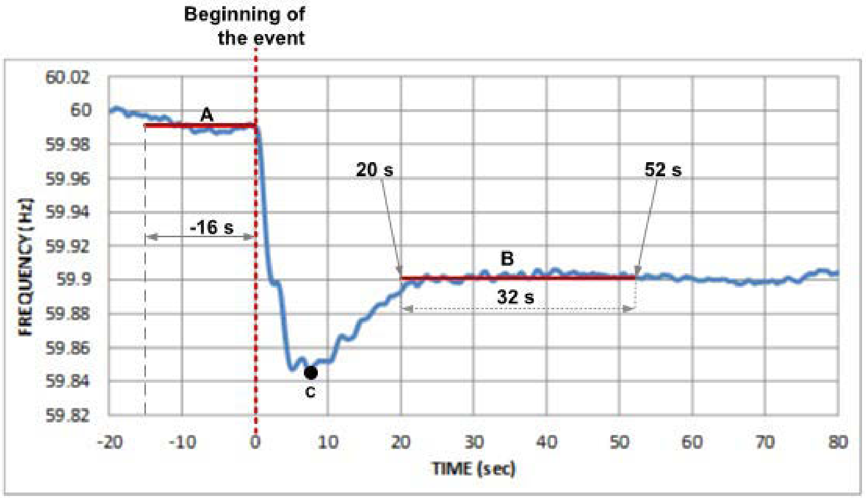
Time Frame	Solar PV Plant Test Results
Sunrise	93.7%
Middle of the day	87.1%
Sunset	87.4%

Typical Regulation-Up Accuracy of CAISO Conventional Generation

	Combined Cycle	Gas Turbine	Hydro	Limited Energy Battery Resource	Pump Storage Turbine	Steam Turbine
Regulation-Up Accuracy	46.88%	63.08%	46.67%	61.35%	45.31%	40%

Regulation accuracy by this PV plant is 24%–30% better than fast gas turbine technologies.

Frequency Response Metrics

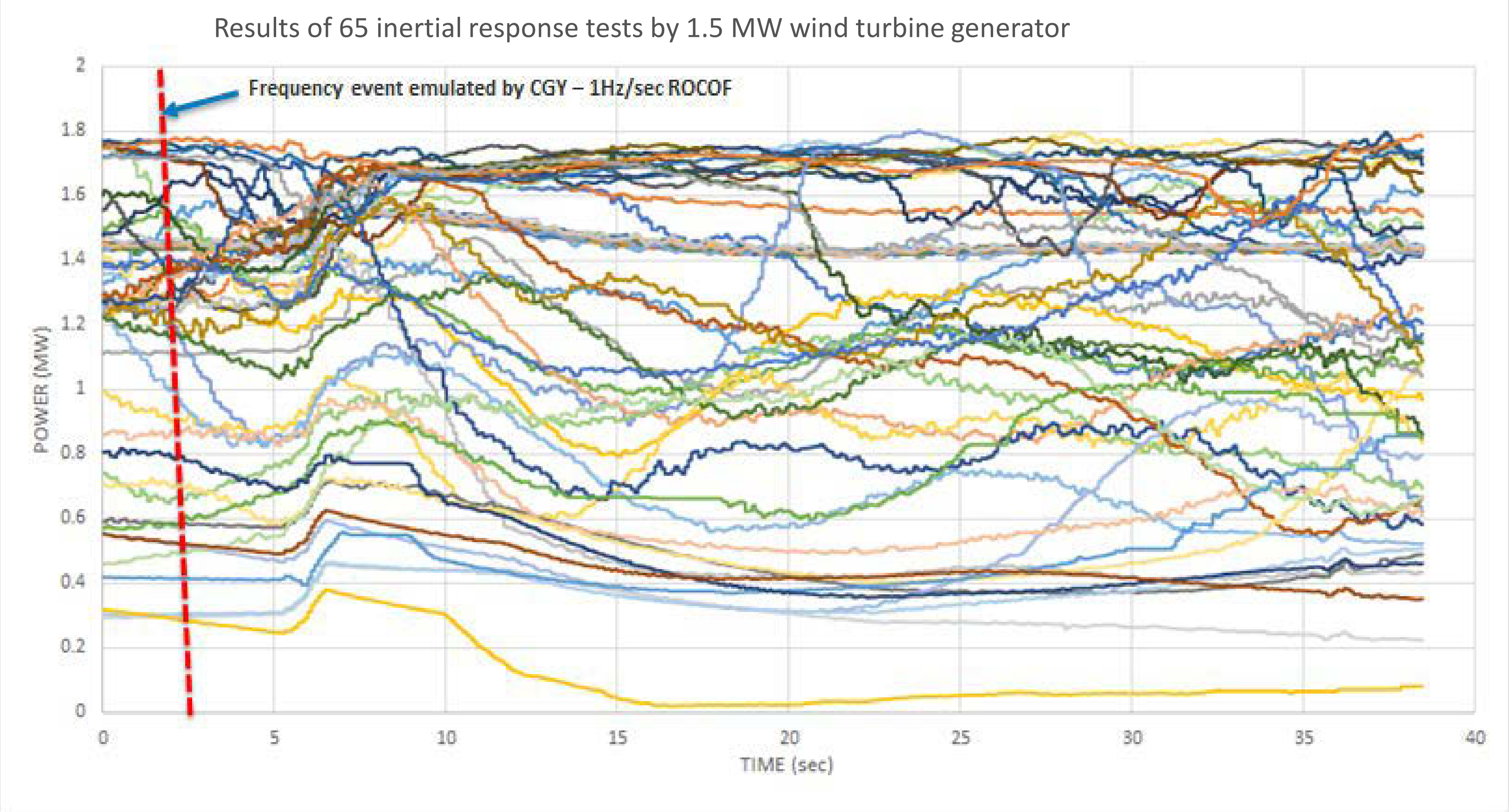


- Initial rate if decline of frequency (ROCOF)
- Value of frequency nadir (Point C)
- A-to-C transition time
- Value of settling frequency (Point B)
- C-to-B transition time
- C/B ratio.

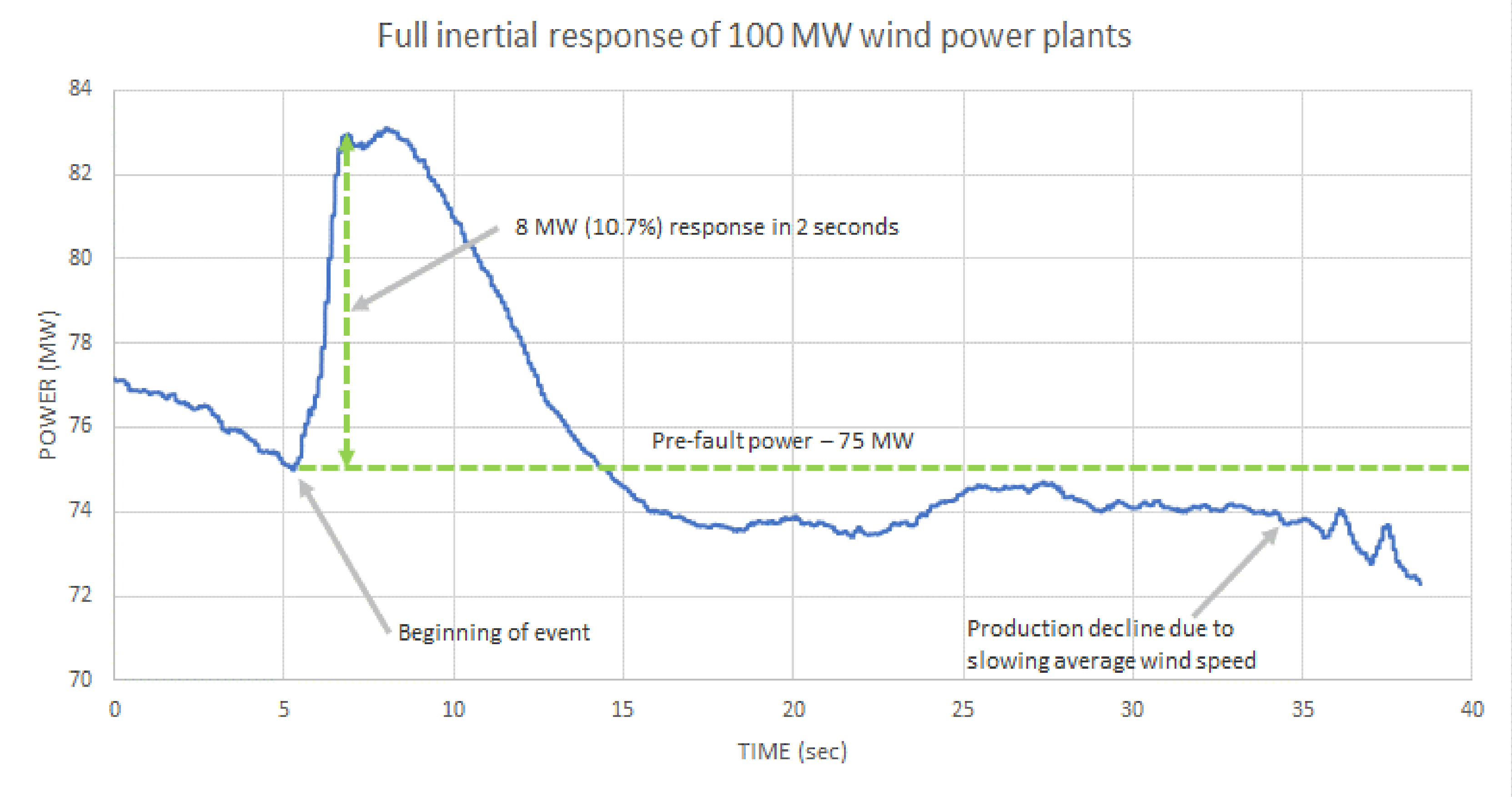
Interconnection Frequency Response Obligation

- **Calculated using statistical observations from many similar events**
- **Depends on:**
  - Initial frequency
  - First step of underfrequency load shedding
  - Contingency criteria
  - Governor withdrawal adjustment
  - C/B ratio
  - Demand response credit.
- **Western Interconnection frequency response obligation = -906 MW/0.1 Hz**
- **BAL-003-1 standard also sets frequency response obligations for all balancing authorities within interconnections.**

Inertial Response by Large Wind Power Plant



Aggregate Inertial Response

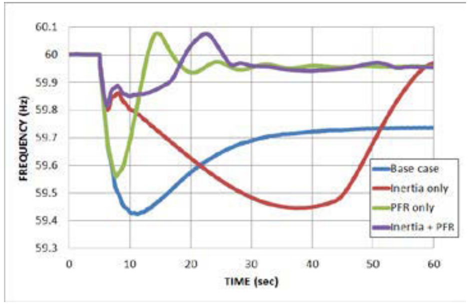


80% Wind Penetration Study for U.S. Western Interconnection

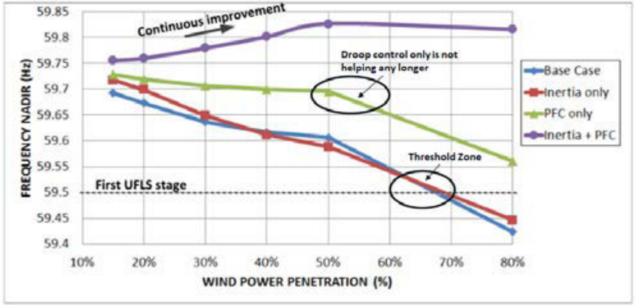
Studied Cases

Case	Wind Controls Scenarios			
15% 20% 30% 40% 50% 80%	No inertia, no PFR	Inertia only	PFR only (5% headroom; 5% droop)	Inertia + PFR (5% headroom; 5% droop)

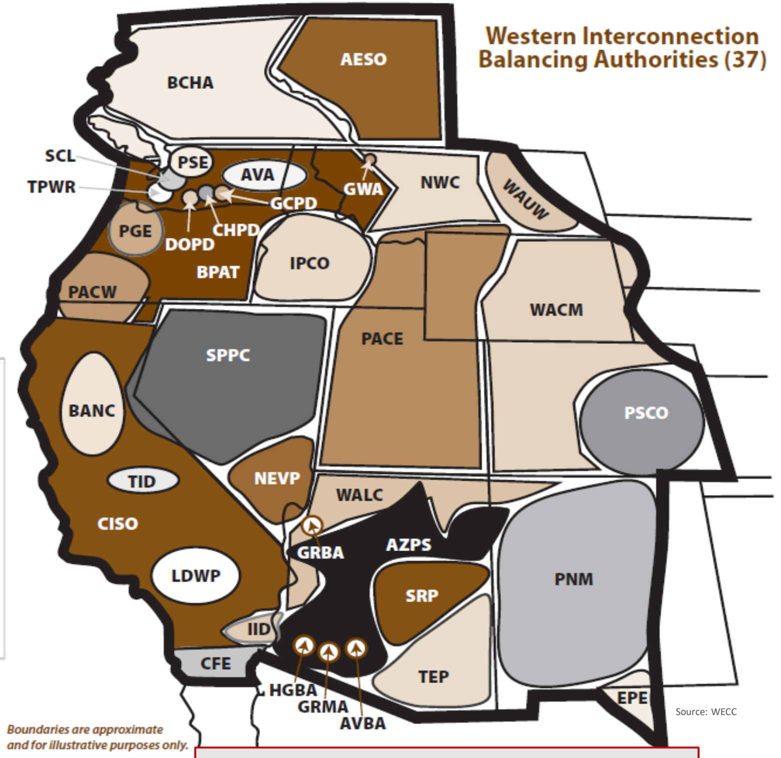
80% wind penetration



Impact of wind controls



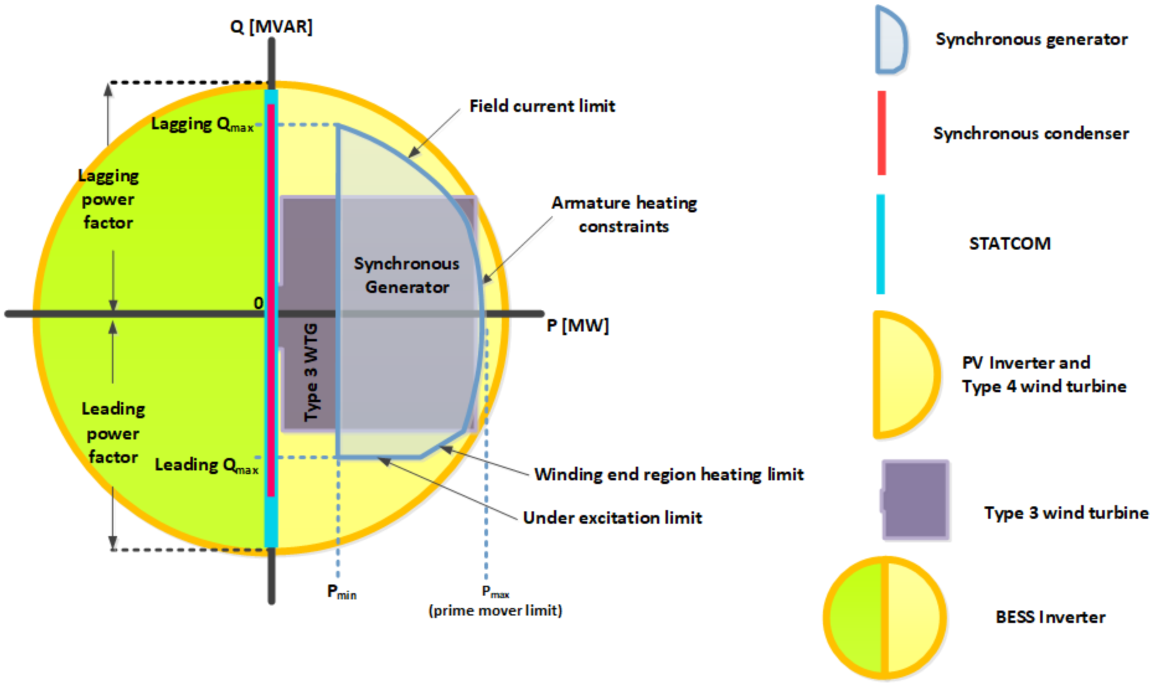
Combining inertial and primary frequency controls by wind results in nadir improvement with increasing penetration.



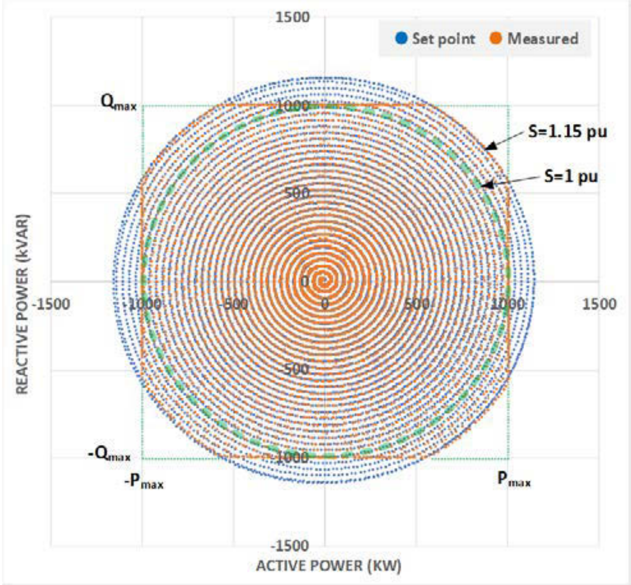
Largest Western Interconnection N-1 contingency: loss of two Palo Verde nuclear units (2.6 GW)

Reactive Power Capability

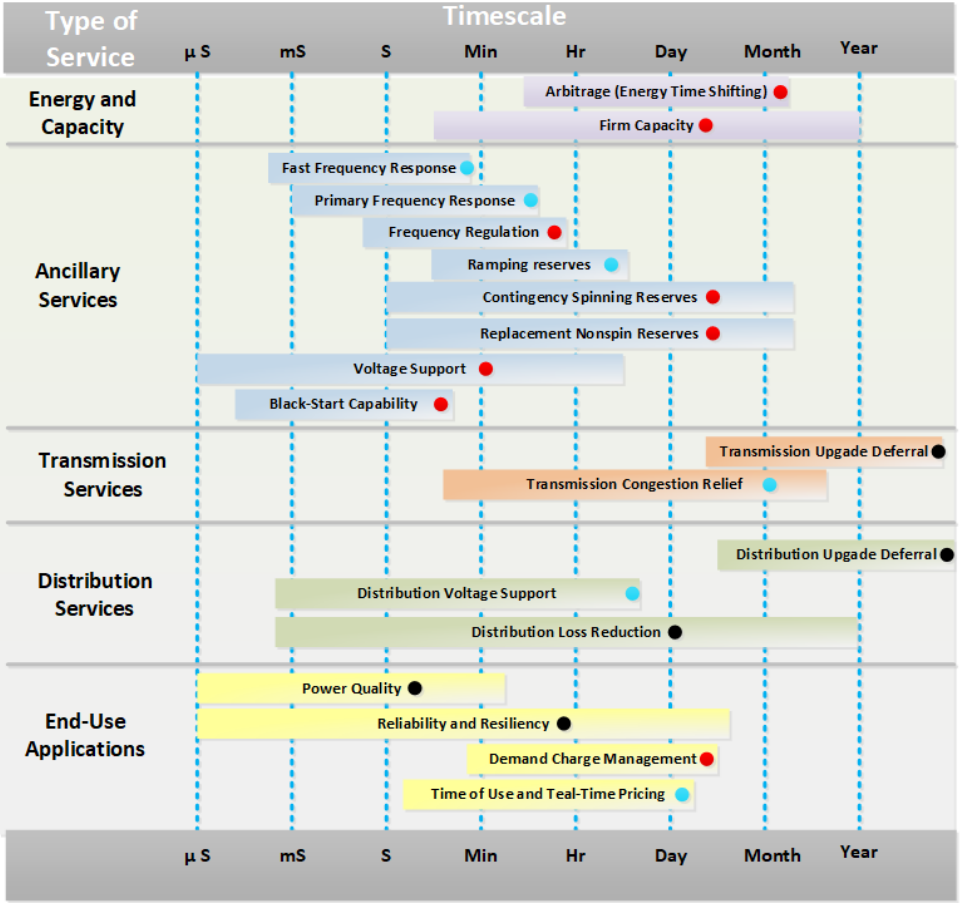
Comparison of Reactive Power Capabilities

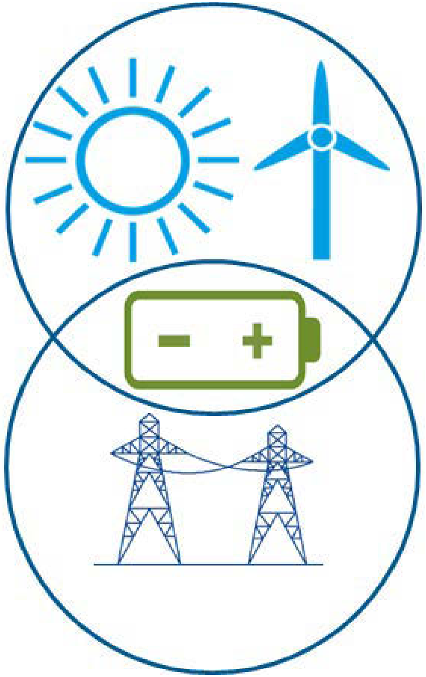


Measured P-Q Capability of 1-MW/1-MWh Li-ion BESS



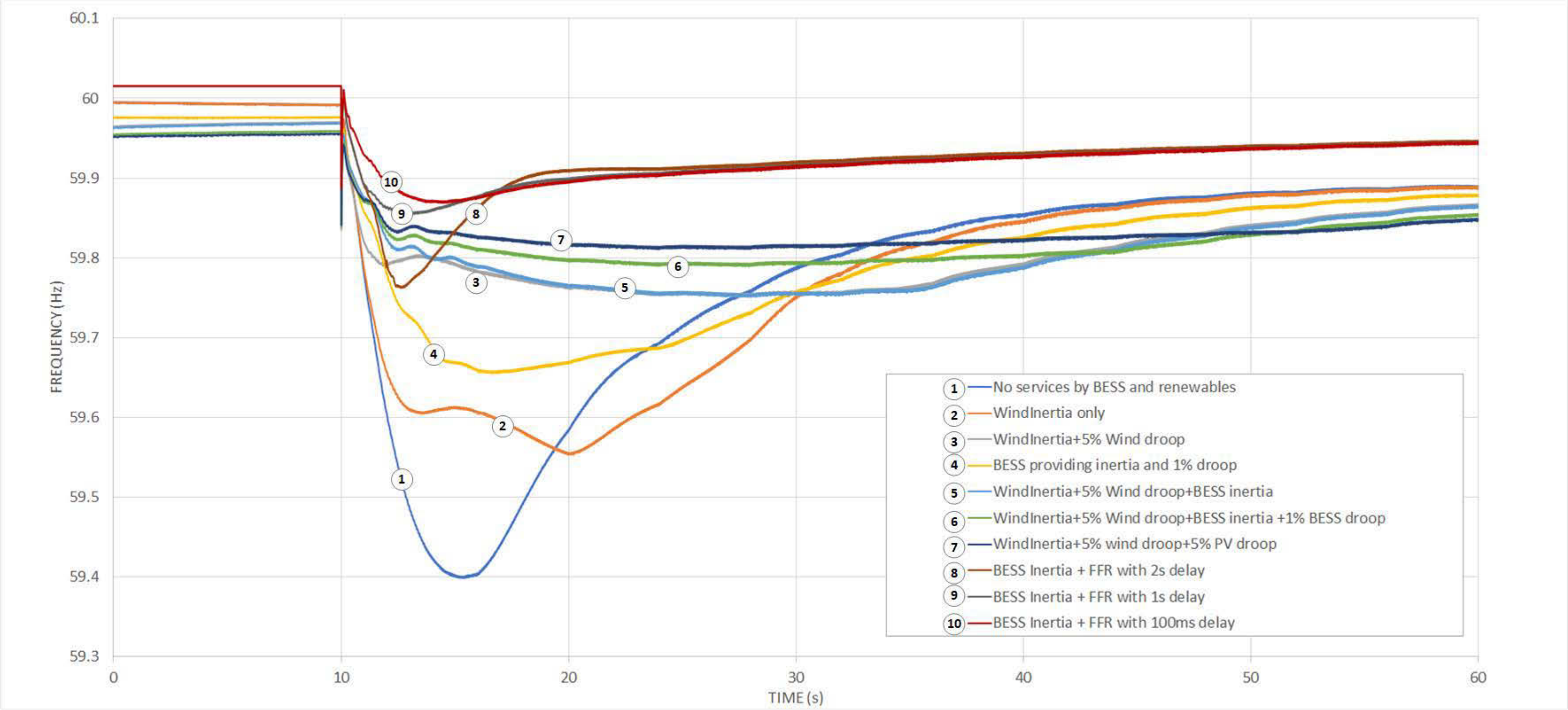
Value Streams of Battery Energy Storage



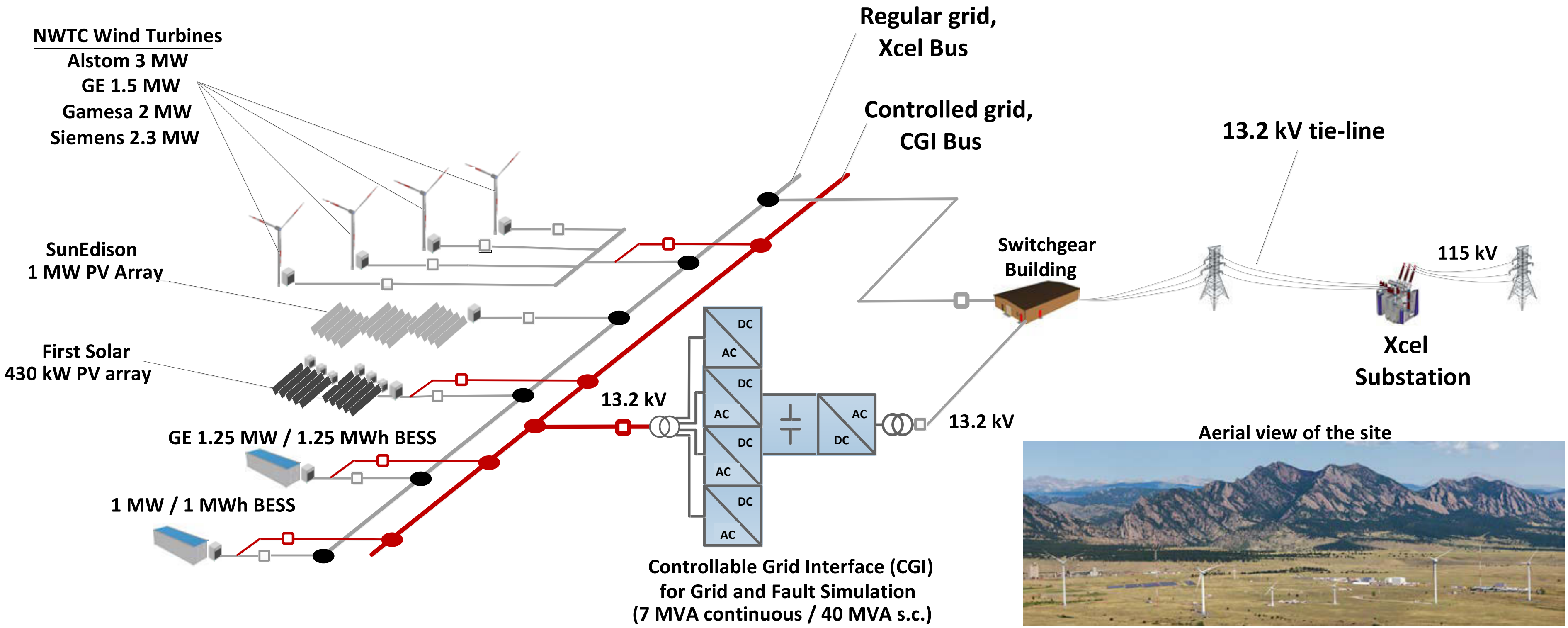


- Services currently valued in some markets (red)
- Proposed or early adoption services (blue)
- Currently not valued services (black)

Impacts of Wind and Energy Storage Controls on Frequency Response

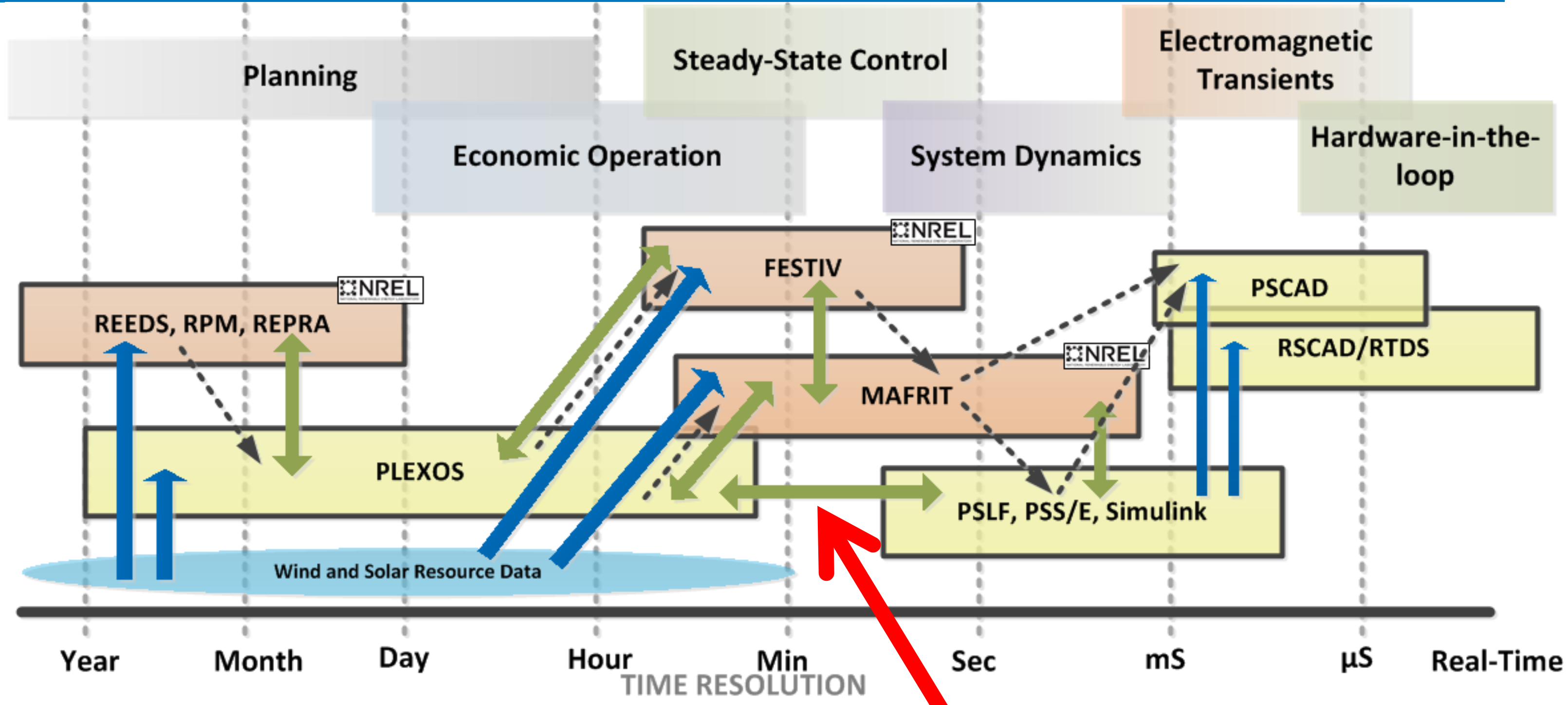


NWTC Controllable Grid Platform



Aerial view of the site

NREL Software Tools for Grid Integration

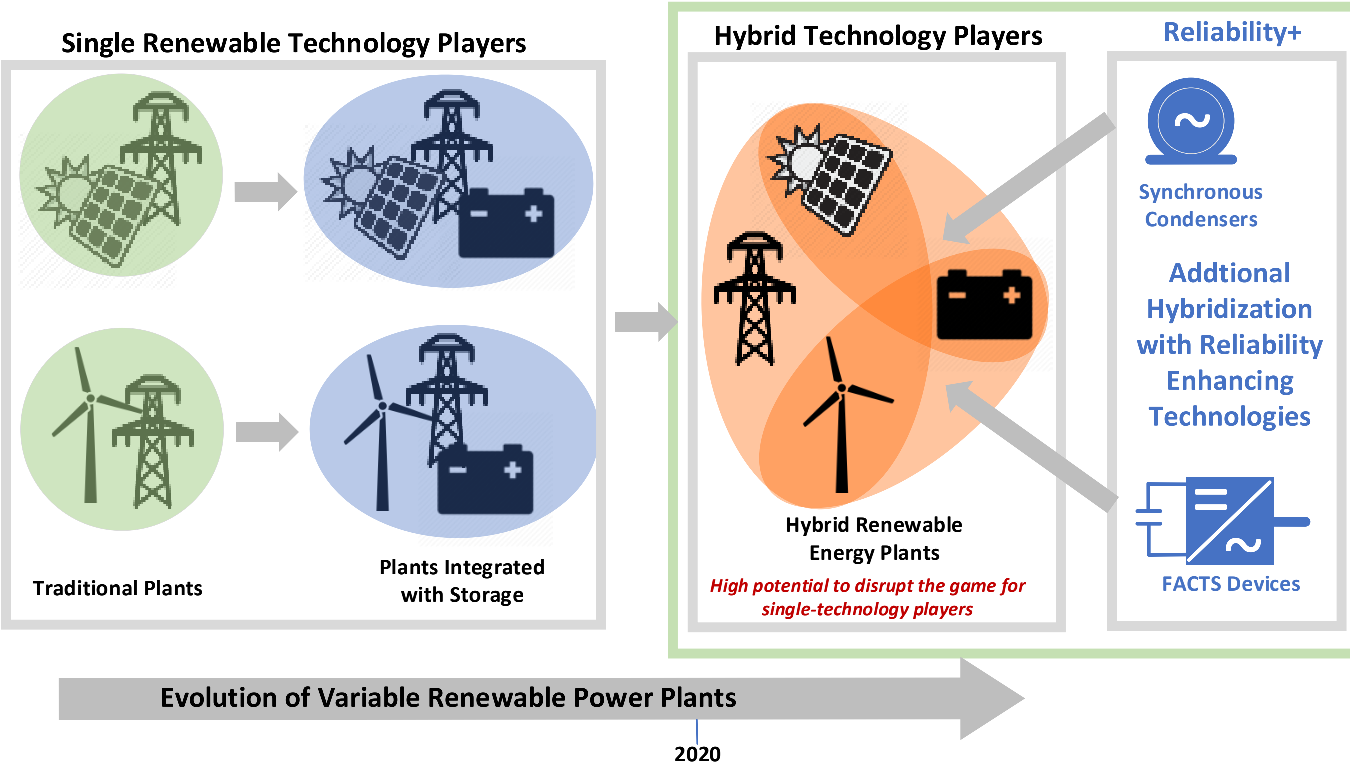


<u>NREL in-house modelling tools</u>

REEDS – Regional Energy Deployment System model
RPM – Resource Planning Model tool
REPRA – Renewable Energy Probabilistic Resource Assessment tool
FESTIV – Flexible Energy Scheduling Tool for Integrating Renewables
MAFRIT – Multi-area Frequency Response Integration Tool

Thinking Beyond Traditional Variable Generation Plants

Flexible, Dispatchable and Reliable Renewable Generation Plants

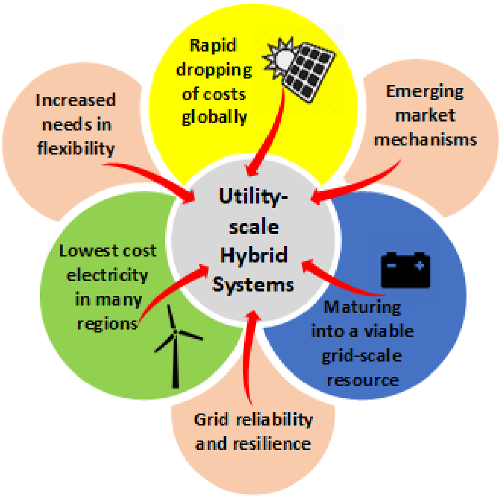


- Dispatchability
- Energy shifiting
- Flexibility
- Scalability
- All essential reliability services
- Advanced reliability services
- All forms of APC and RPC
- Short circuit currents
- Grid strength reinforcement
- Real and synthetic inertias
- Synchronizing torque
- Grid forming/black start
- Fast response, ultra-wide dynamic ranges
- Resiliency, robustness
- Grid-connected and islanded operation

Services by Multi-Technology (Hybrid) Plants

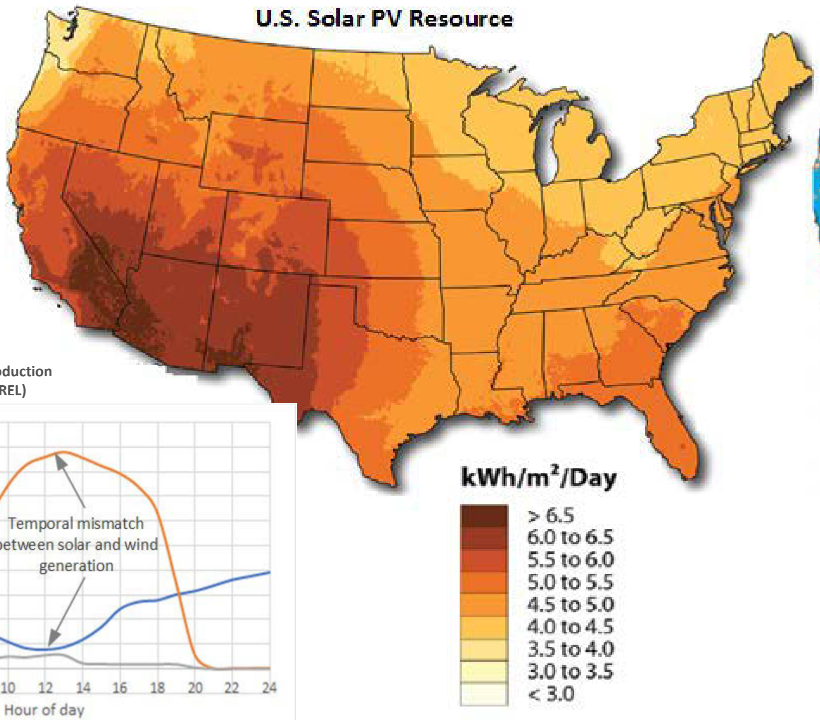
- Dispatchable renewable plant operation
  - Long-term and short-term production forecasts
  - Capability to bid into day-ahead and real-time energy markets like conventional generation
  - Flexibility services.
- Ramp limiting, variability smoothing, cloud-impact mitigation
- Provision of spinning and nonspinning reserves
- AGC functionality
- Primary frequency response (programmable droop control)
- Fast frequency response
- Inertial response:
  - Programmable synthetic inertia for a wide range of H constants emulated by wind generation
  - Selective inertial response strategies by wind turbines.
- Reactive power/voltage control
- Black start, resiliency services
- Advanced controls: power system oscillations damping, phasor measurement unit measurement-based controls, wide-area stability services
- Stacked services
- Plant electric loss reduction, annual energy production increase
- Battery state-of-charge management
- Optimization model-predictive control strategies
- Revenue optimization for transmission- and distribution-level applications.

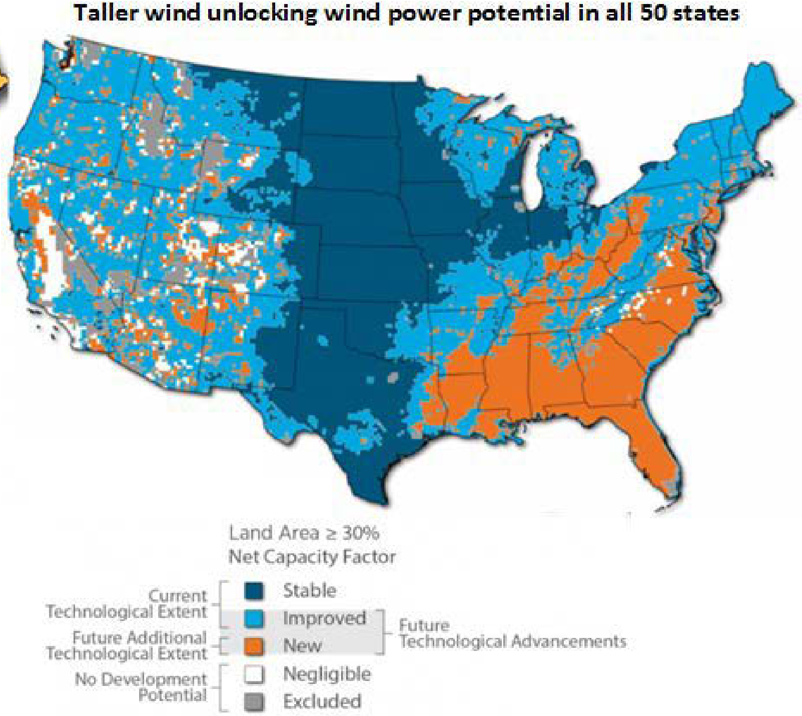
Hybridization Recipe



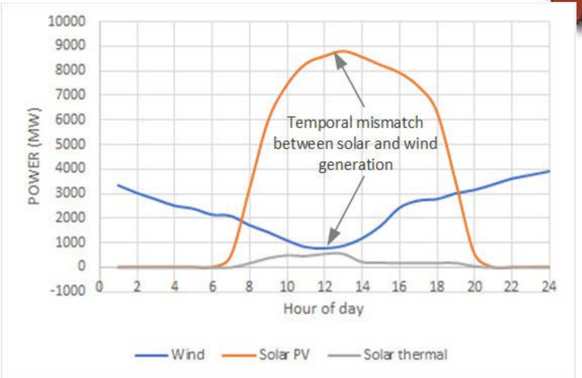
Potential for Hybridizing Solar and Taller Wind Resources in U.S.

Bringing "taller" economic wind power to areas rich in solar resource



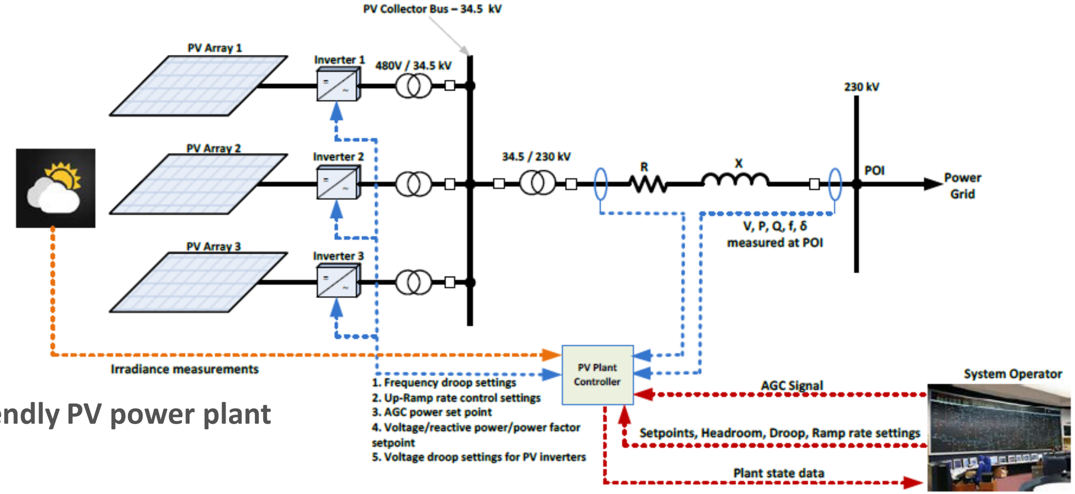


CAISO's typical wind and solar hourly production profiles; data for July 17, 2017 (source: NREL)



Conclusions

- Modern inverter-coupled variable generation and energy storage systems are capable of providing all types of reliability services to the grid.
- Adequate market design is essential for unleashing such capabilities as important tools in achieving the broader objective of a resilient, reliable, low-carbon grid.
- Explore economic and/or contractual incentives to maximize production and not hold back production to provide reliability services.
- Markets should incentivize faster and more accurate resources that provide such services.



Grid-friendly PV power plant

Thank you

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