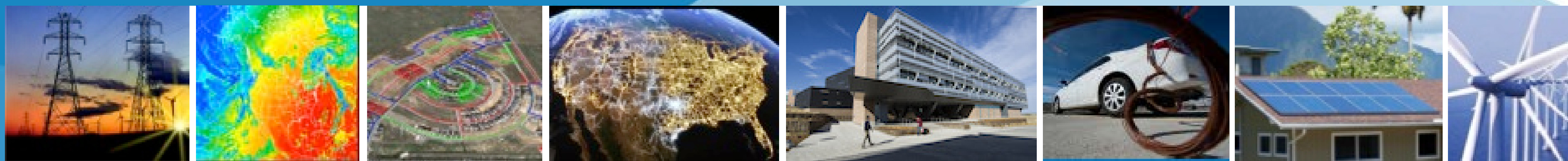
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Power Systems
Engineering Center



www.nrel.gov/grid

Integrating High Levels of Variable Renewable Energy into Electric Power Systems

Benjamin Kroposki, Ph.D., PE, FIEEE

Director, Power Systems Engineering Center

Revised December 2018

NREL/PR-5D00-68349

Errata

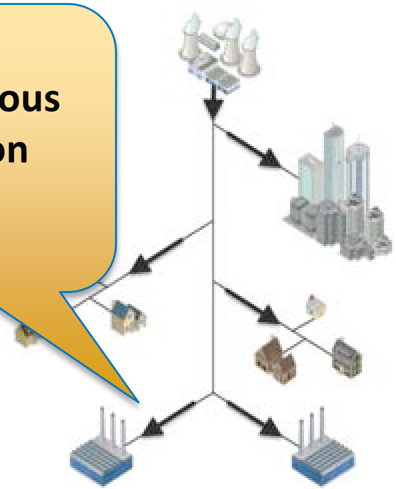
In December 2018, the following change was made to Slide 11: Alaska Village, 80%, has been corrected to state St. Paul Alaska, 55%. Additional data points have also been added.

Outline

- Understanding current and future power systems
- Current state of variable renewable energy (VRE): solar and wind
- Current power systems operating with VRE
- Challenges and solutions of operating power systems with very high levels of VRE
- Research needs

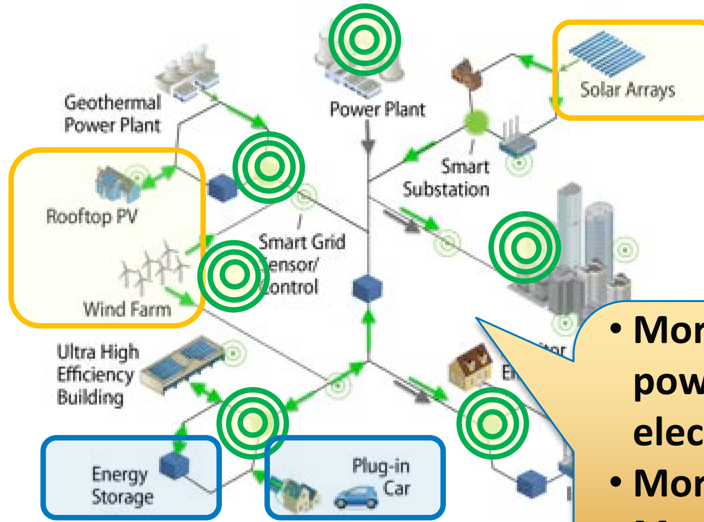
Evolution of the Power System

Current Power System



- **Large synchronous generation**
- **Central control.**

Future Power Systems



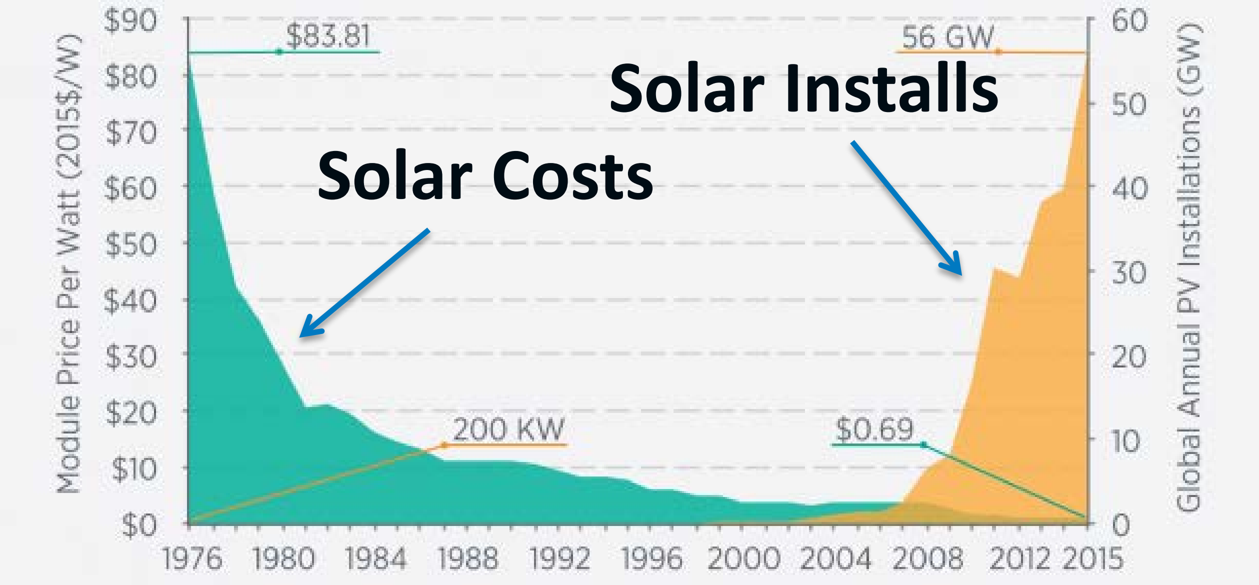
- **More VRE–power electronics**
- **More data**
- **More distributed resources**

New challenges in a modern grid:

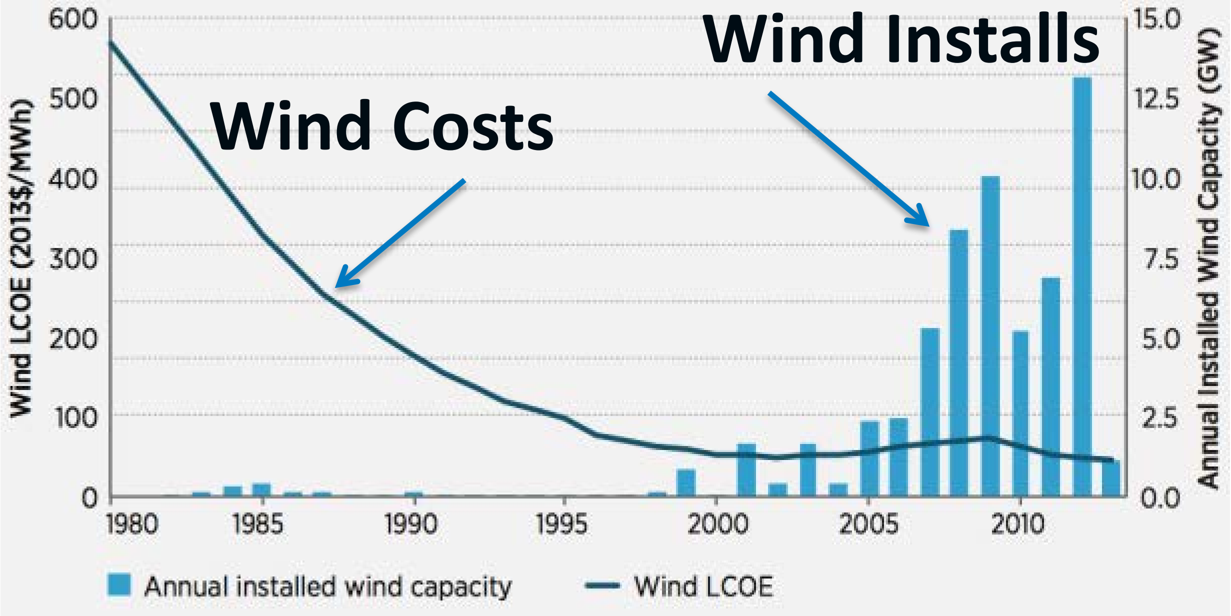
- Increasing levels of power electronics-based VRE: solar and wind
- More use of communications, controls, data, and information (e.g., smart grids)
- Other new technologies: electric vehicles (EVs), distributed storage, flexible loads
- Becoming highly distributed—more complex to control

Current State of Variable Renewable Energy: Solar and Wind

Significant Declines in Renewables Cost—Increase in Renewables Installations



Source**: U.S. Department of Energy (DOE), *On the Path to SunShot***, http://energy.gov/eere/sunshot/path-sunshot



Source: **DOE, *Wind Vision Report***, http://energy.gov/eere/wind/downloads/wind-vision-new-era-wind-power-united-states

Photovoltaic Systems in the United States

Solar Star

QUICK FACTS

Location:	Rosamond, California
Capacity:	579 MW
Owner:	MidAmerican Solar, a subsidiary of MidAmerican Renewables
Design/Construction:	SunPower
Power Purchaser:	Southern California Edison
Technology:	SunPower™ Oasis™ Power Plant
No. of Modules:	Approx. 1,720,000
Equivalent No. of Homes Powered:	Approx. 255,000
Acres:	Approx. 3,200

Source: Sunpower, https://us.sunpower.com/sites/sunpower/files/media-library/fact-sheets/fs-solar-star-projects-factsheet.pdf

Solar Subdivisions

Anatolia Subdivision, Rancho Cordova, CA. Source: © 2015 Google, Map Data

Wind Systems in the United States

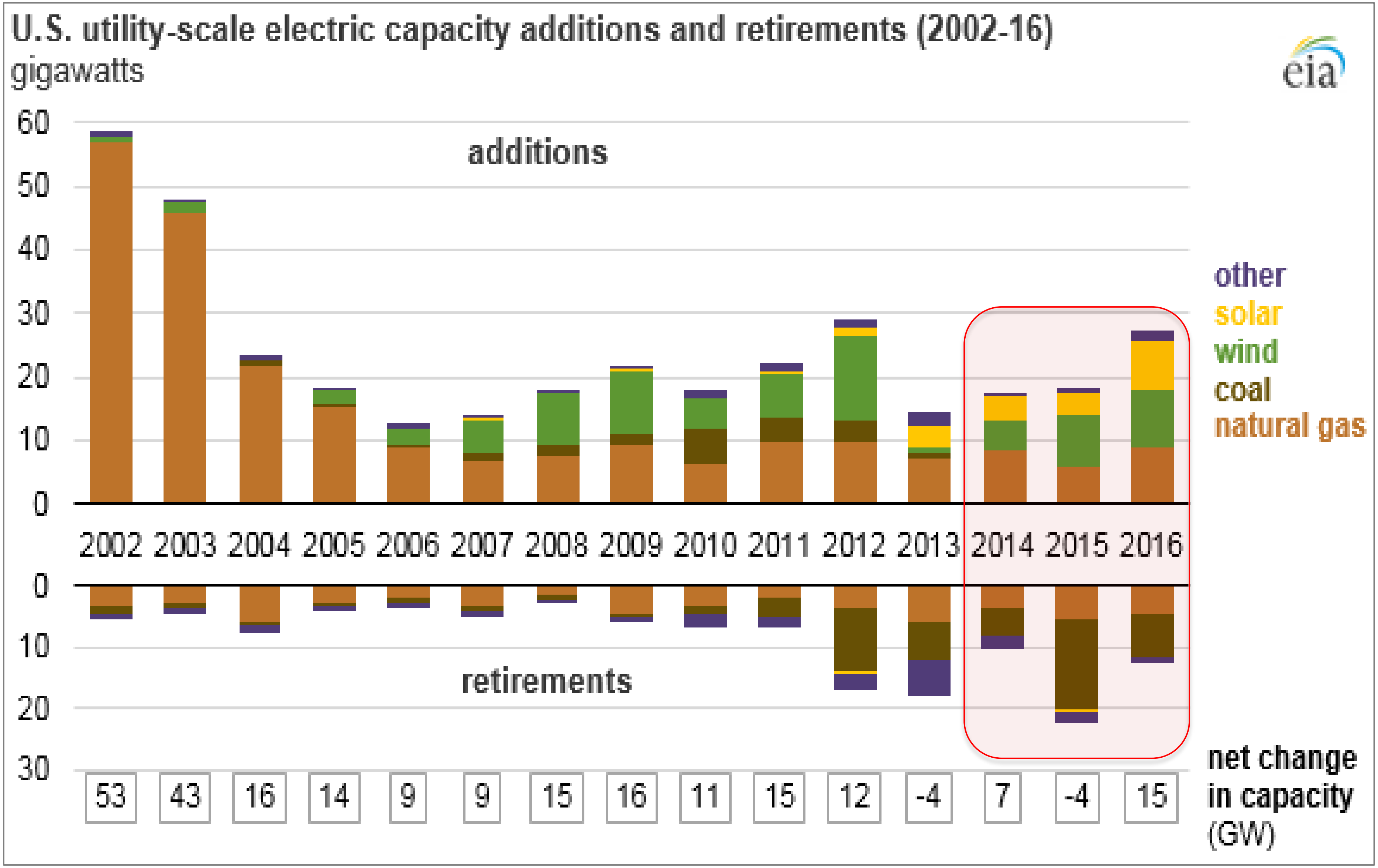
Alta Wind Energy Center, Tehachapi Pass, CA[1]
600 Vestas Wind Turbines
1,547 MW
2,680.6 GWh/yr

Capricorn Ridge Wind Farm, Sterling and Coke County, TX[2]
407 GE and Siemens Turbines
663 MW

Shepard's Flats, Arlington, OR[3]
338 GE Turbines
845 MW
2,000 GWh/yr

Sources:
[1] https://en.wikipedia.org/wiki/Alta_Wind_Energy_Center
[2] http://www.nexteraenergyresources.com/pdf_redesign/capricornridge.pdf
[3] https://en.wikipedia.org/wiki/Shepherds_Flat_Wind_Farm

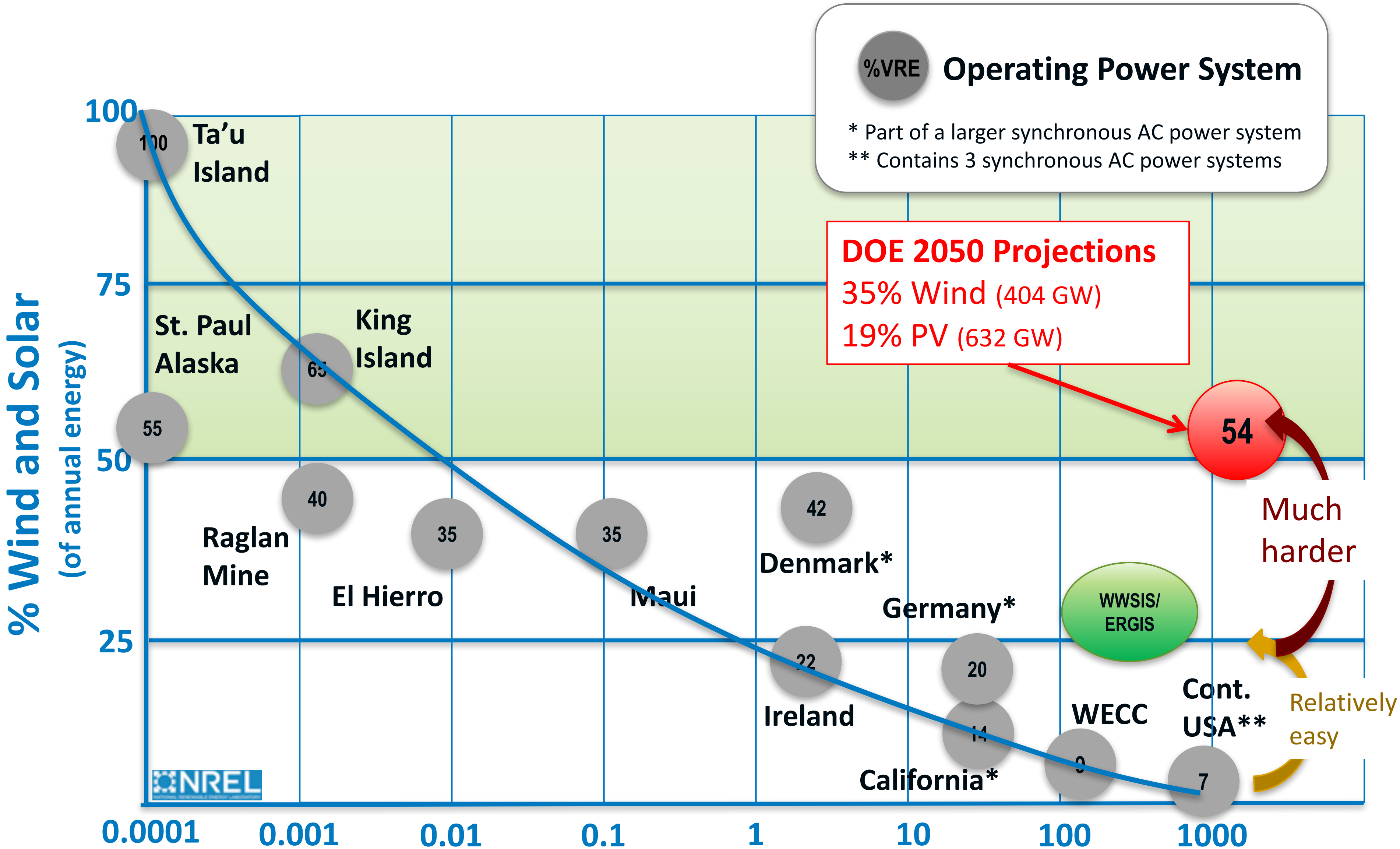
New Generation Additions in the United States Are Mostly Gas, Wind, and Solar



Source: EIA, https://www.eia.gov/todayinenergy/detail.php?id=30112

Current Power Systems Operating with Variable Renewable Energy

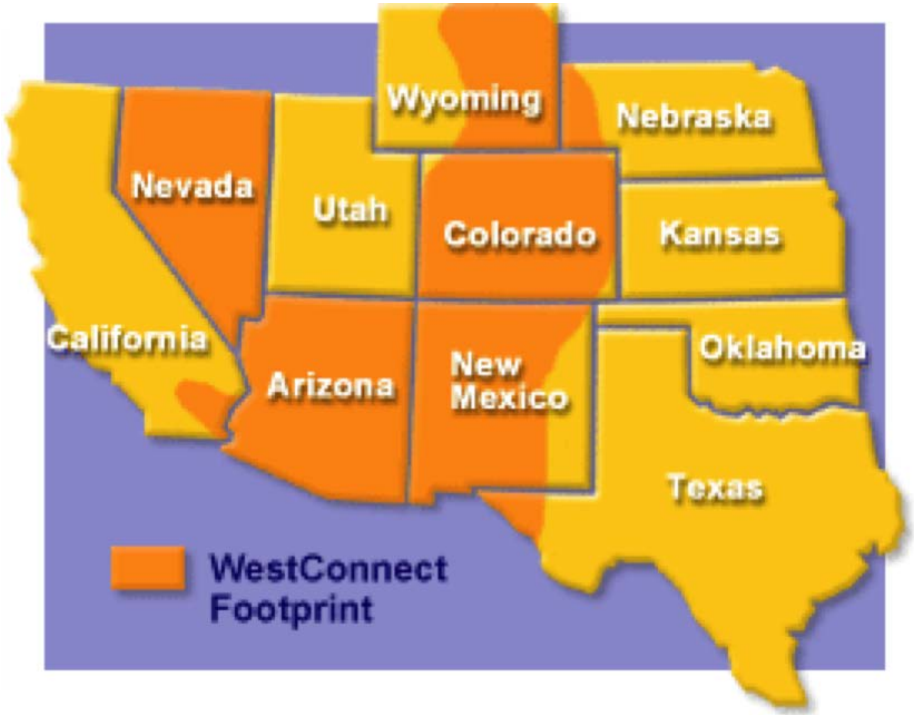
Moving toward Ultra-High Levels of Variable Renewable Energy



DOE Wind Vision Study : https://www.energy.gov/eere/wind/wind-vision
DOE Sunshot Vision Study: https://www.energy.gov/eere/solar/sunshot-vision-study

Western Wind and Solar Integration Study

- **Goal:**
  - To understand the costs and operating impacts due to the variability and uncertainty of wind, PV and concentrating solar power on the WestConnect grid.
- **Utilities:**
  - Arizona Public Service
  - El Paso Electric
  - NV Energy
  - Public Service Company of New Mexico
  - Salt River Project
  - Tri-State Generation & Transmission
  - Tucson Electric Power
  - Xcel Energy
  - Western Area Power Administration.

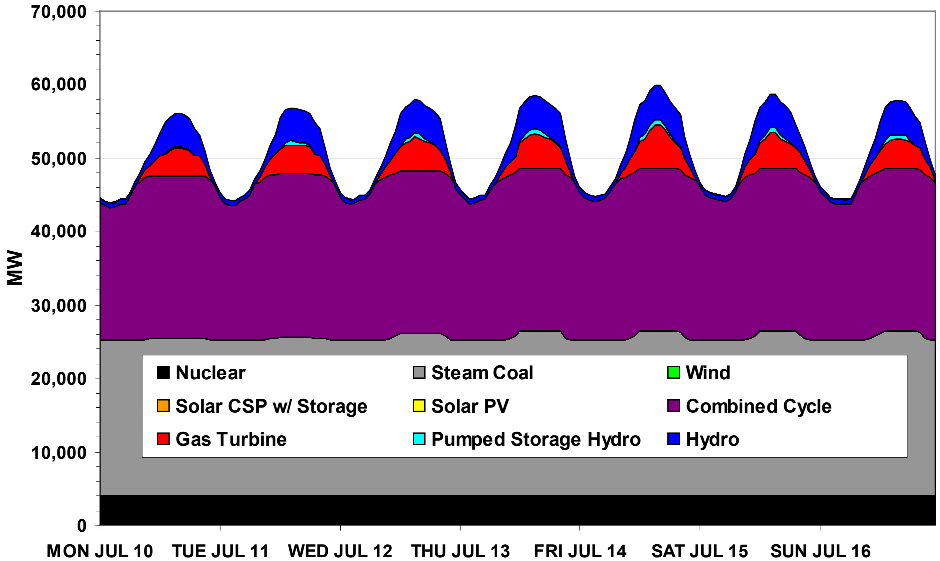


Can we integrate 35% renewables in the West?

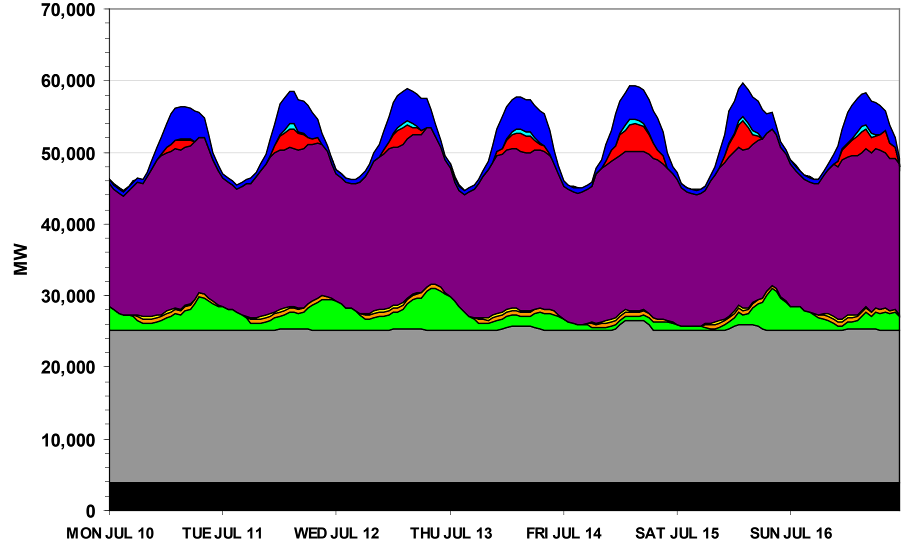
Source: NREL, Western Wind and Solar Integration Study (WWSIS) (2007–2015), http://www.nrel.gov/grid/wwsis.html

Dispatch During a Tame Week (July)

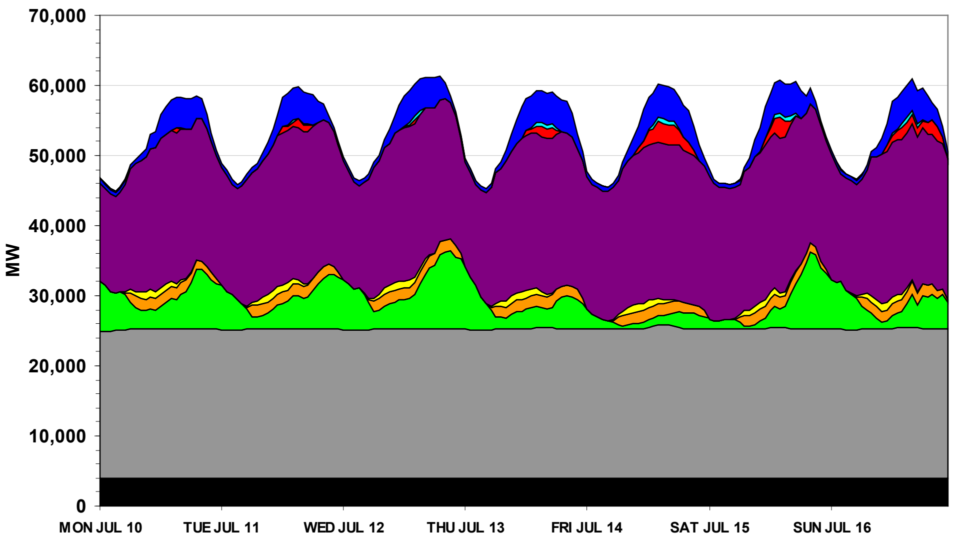
No wind



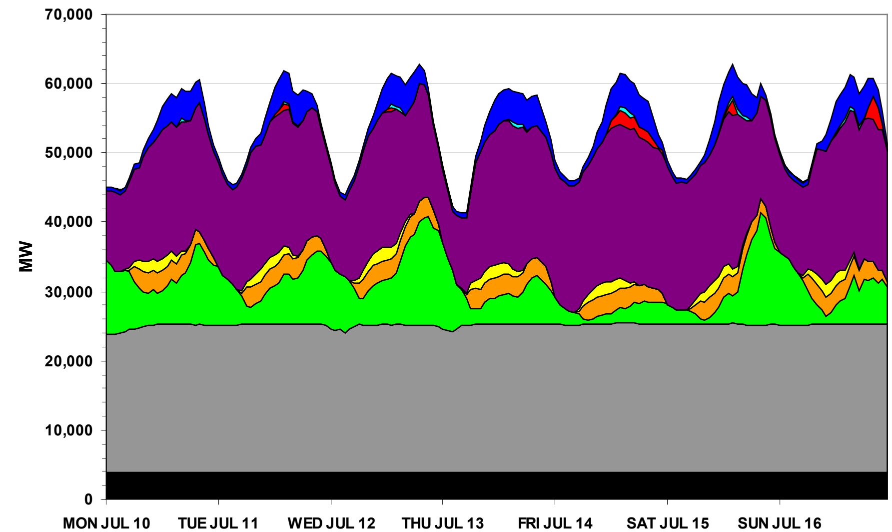
10% wind



20% wind

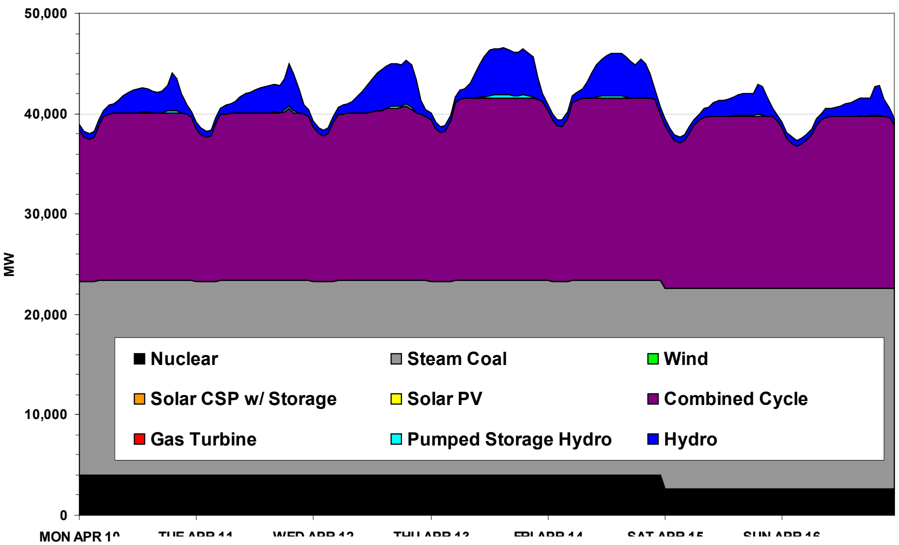


30% wind

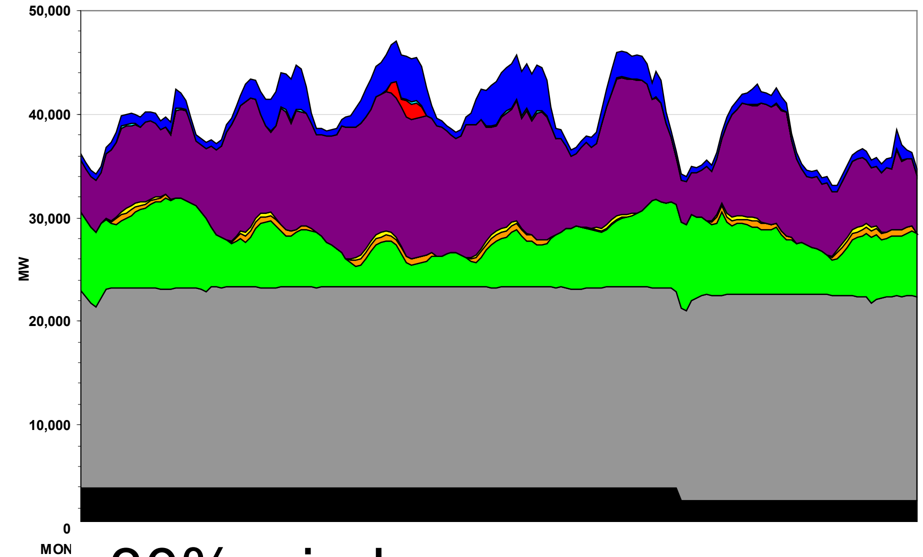


Dispatch During the Worst Week (April)

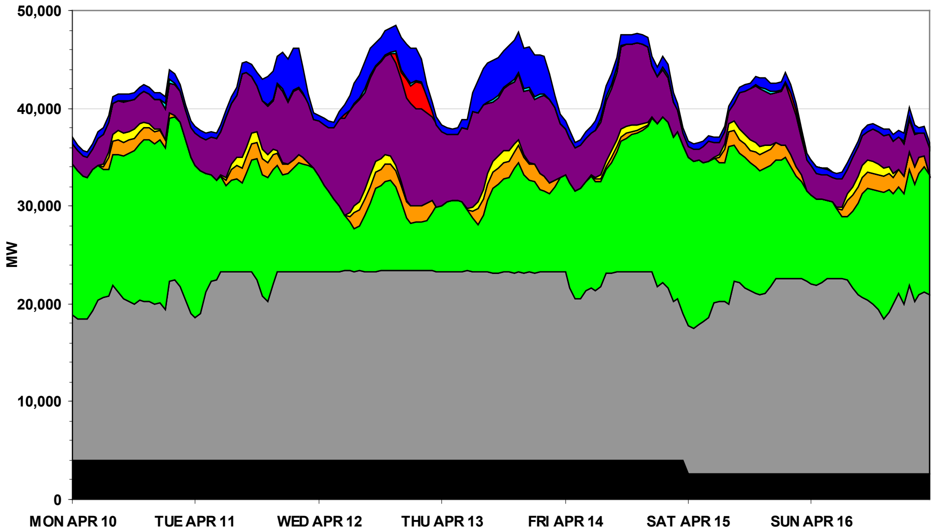
No wind



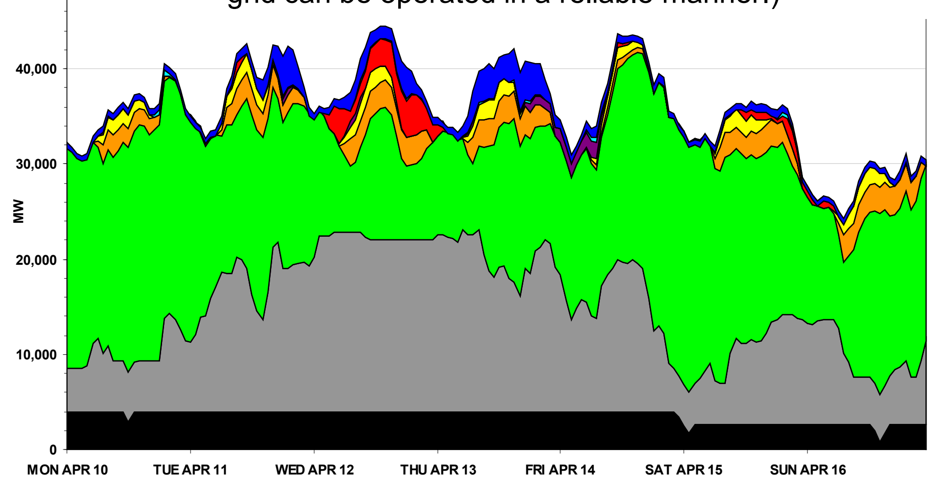
10% wind



20% wind



30% wind (Coal is cycling, and nuclear is being impacted; it is likely that wind will need to be curtailed. But the grid can be operated in a reliable manner.)

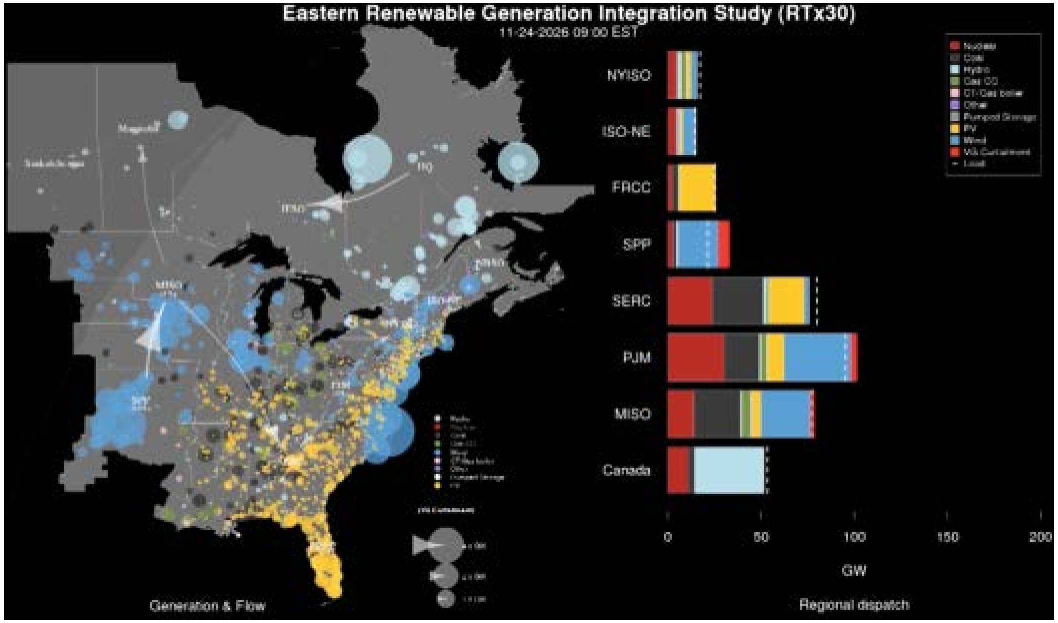


Eastern Renewable Generation Integration Study

- **Goals:**
  - Operational impact of 30% wind and solar penetration on the Eastern Interconnection at a 5-minute resolution
  - Efficacy of mitigation options in managing variability and uncertainty in the system.

Operational areas of interest:

- Reserves
  - Types
  - Quantities
  - Sharing.
- Commitment and dispatch:
  - Day-ahead
  - Four-hour-ahead
  - Real-time.
- Inter-regional transactions:
  - 1-hour
  - 15-minute
  - 5-minute.



Impact
Demonstrated that very large power systems can operate at a 5-min dispatch with 30% VRE.

Source: NREL, Eastern Renewable Energy Integration Study (ERGIS) (2016), http://www.nrel.gov/grid/ergis.html

We have done the research and demonstrated that achieving 30% VRE is possible with minimal system changes.

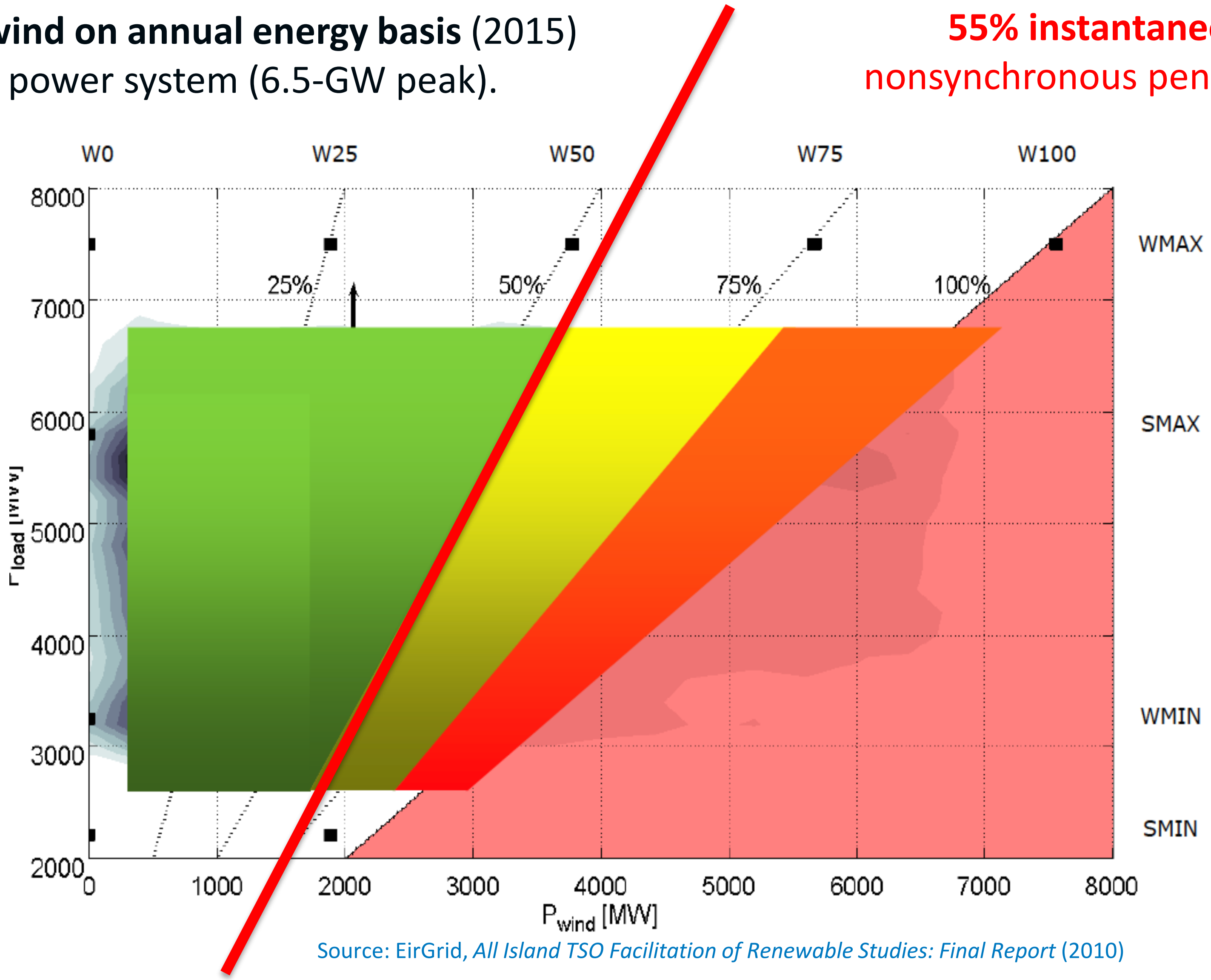
What do we need to do to achieve very high levels (more than 50%) of wind and solar integration?

Examples of High Levels of VRE: Case Study—Ireland

Ireland:

- **23% wind on annual energy basis** (2015)
- Island power system (6.5-GW peak).

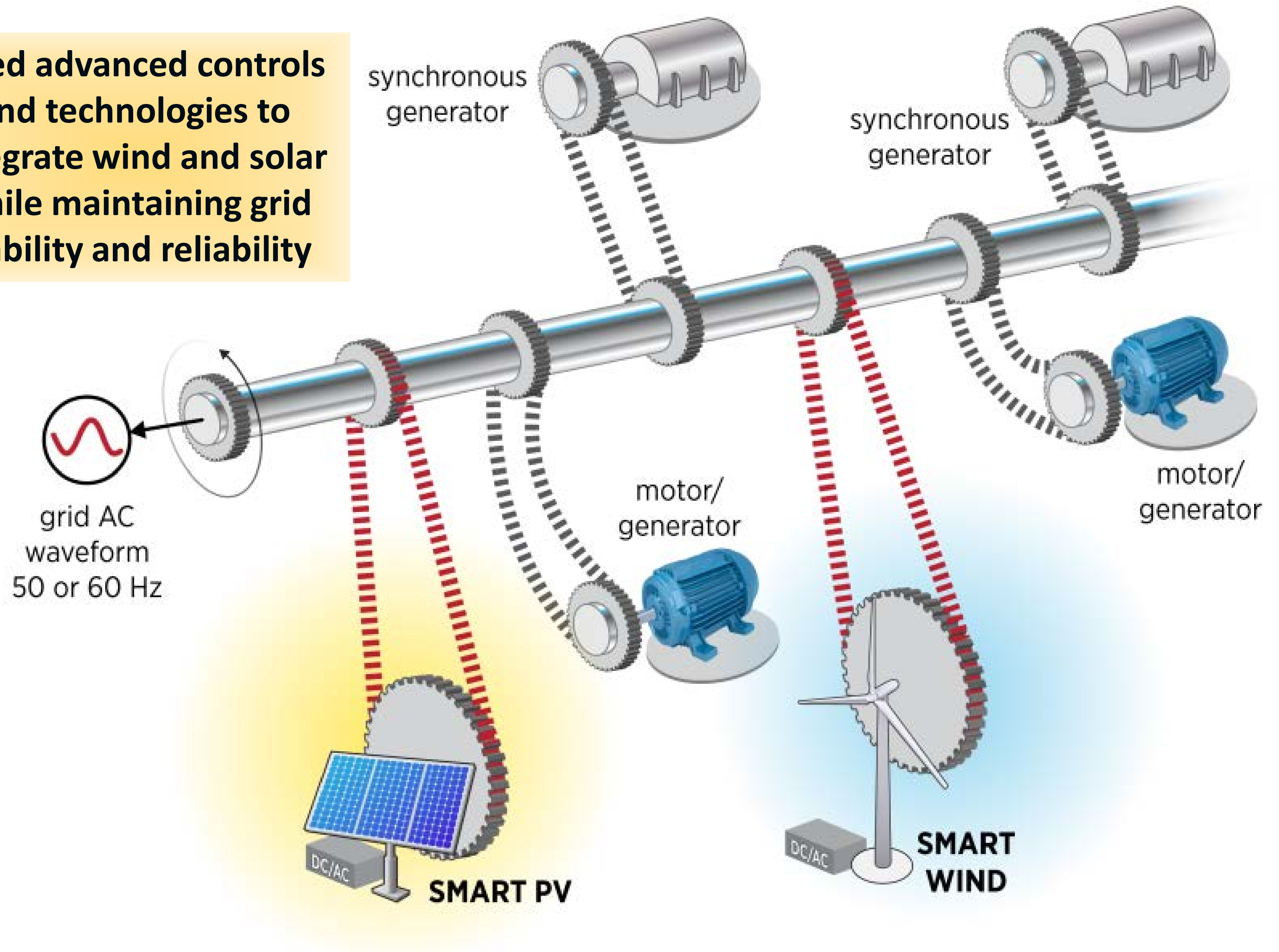
Currently limiting grid to **55% instantaneous** nonsynchronous penetration



Source: EirGrid, *All Island TSO Facilitation of Renewable Studies: Final Report* (2010)

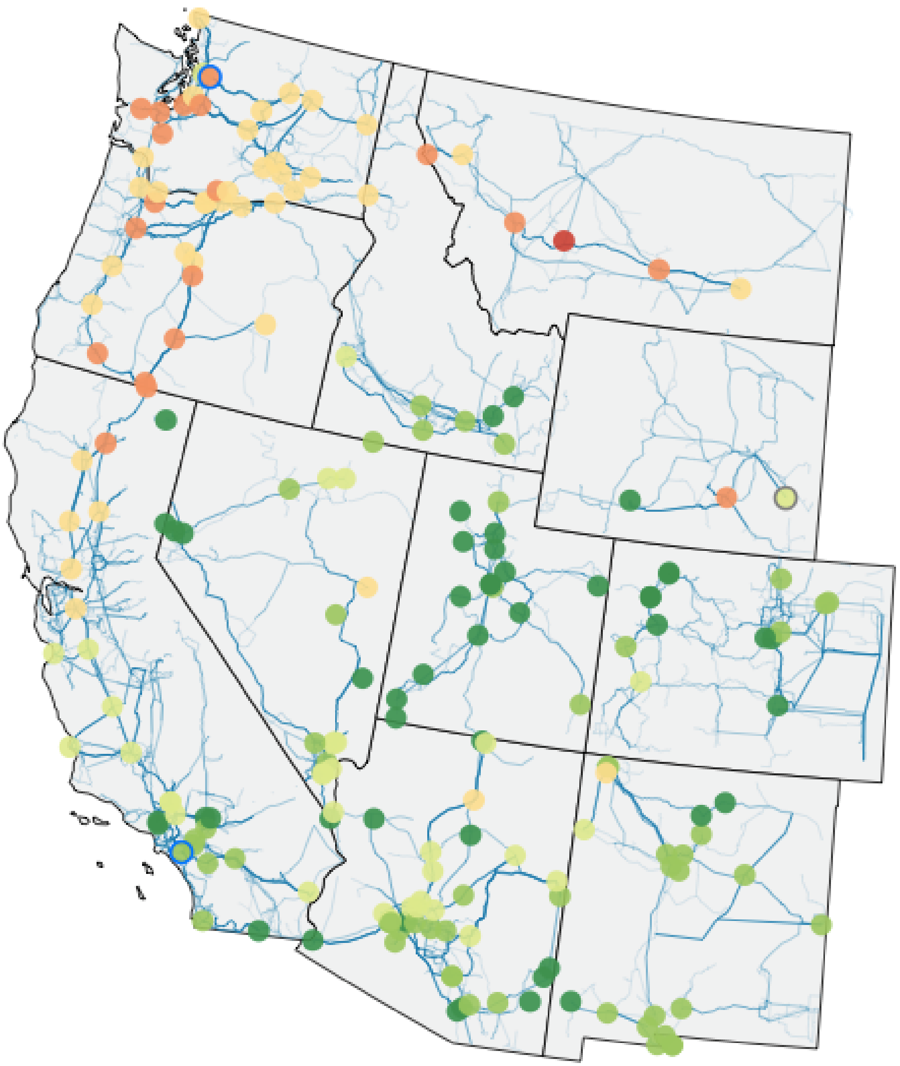
High Renewable Penetrations Require Paradigm Change in Power System Operation

Need advanced controls and technologies to integrate wind and solar while maintaining grid stability and reliability

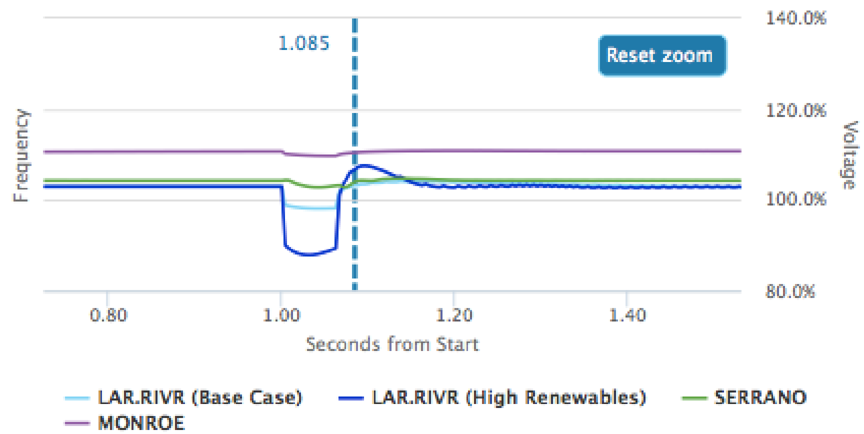


Western Wind and Solar Integration Study: Phase 3– Frequency Response

Western Wind and Solar Integration Study



- **Wind power plants:** voltage regulation and ride-through
- **Utility-scale PV:** voltage regulation and ride-through
- **Rooftop PV:** embedded in composite load model, no controls.



Impact:
Western Interconnection can survive a major contingency outage with 30% variable generation (inverter-based).

Source: N.W. Miller et al., *WWSIS: Phase 3A*, http://www.nrel.gov/docs/fy16osti/64822.pdf

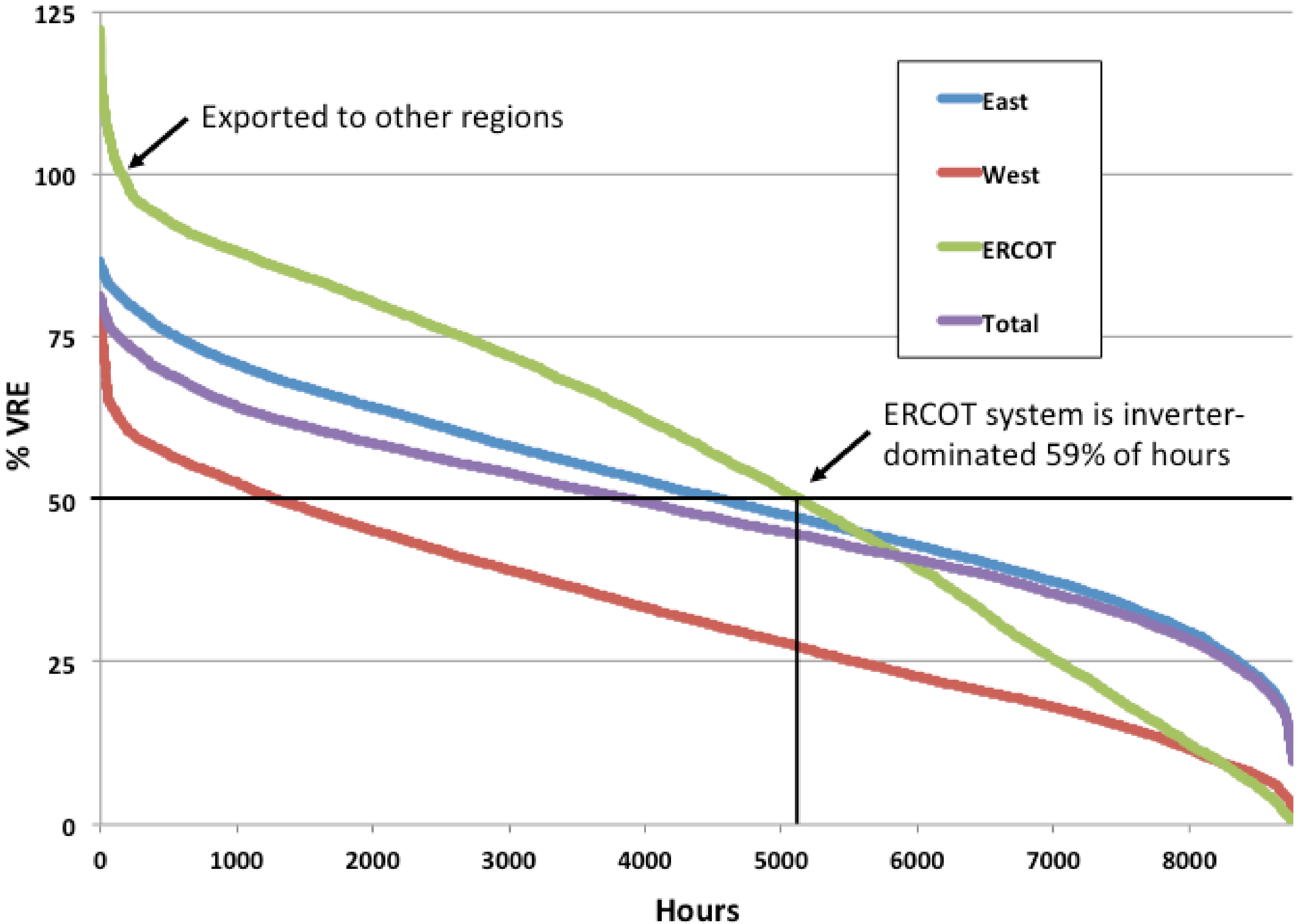
Let’s Look at Really High Levels of VRE

Renewable Electricity Futures (REF) Study

REF examined renewable penetrations from 30%–90% across entire United States.

All renewables were considered.

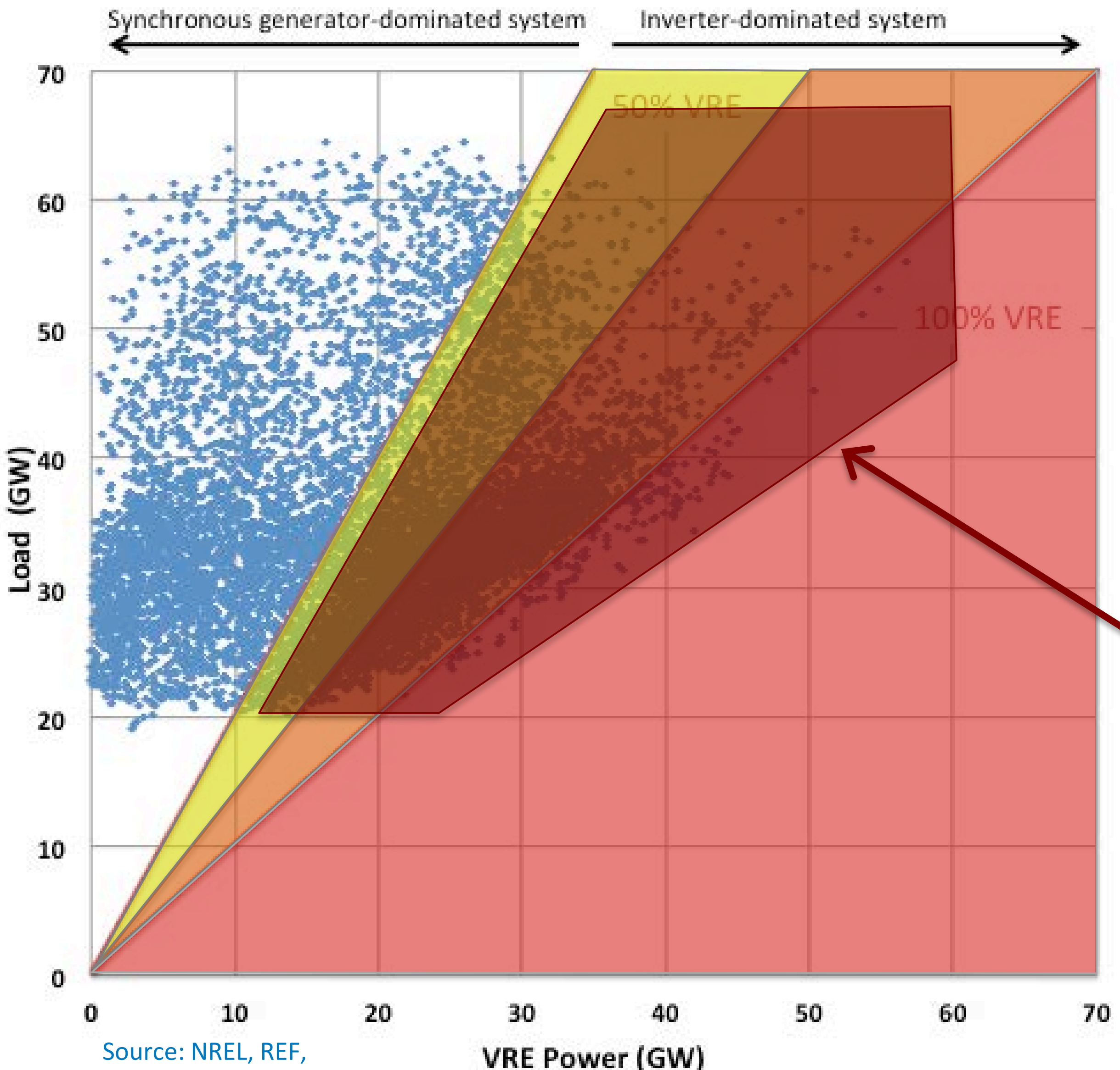
Various transmission scenarios were explored.



VRE penetration curve for three interconnects and total REF study at 80% VRE transmission constrained scenario

Source: NREL, REF, http://www.nrel.gov/analysis/re_futures/

Renewable Electricity Futures Study: 80%—ERCOT



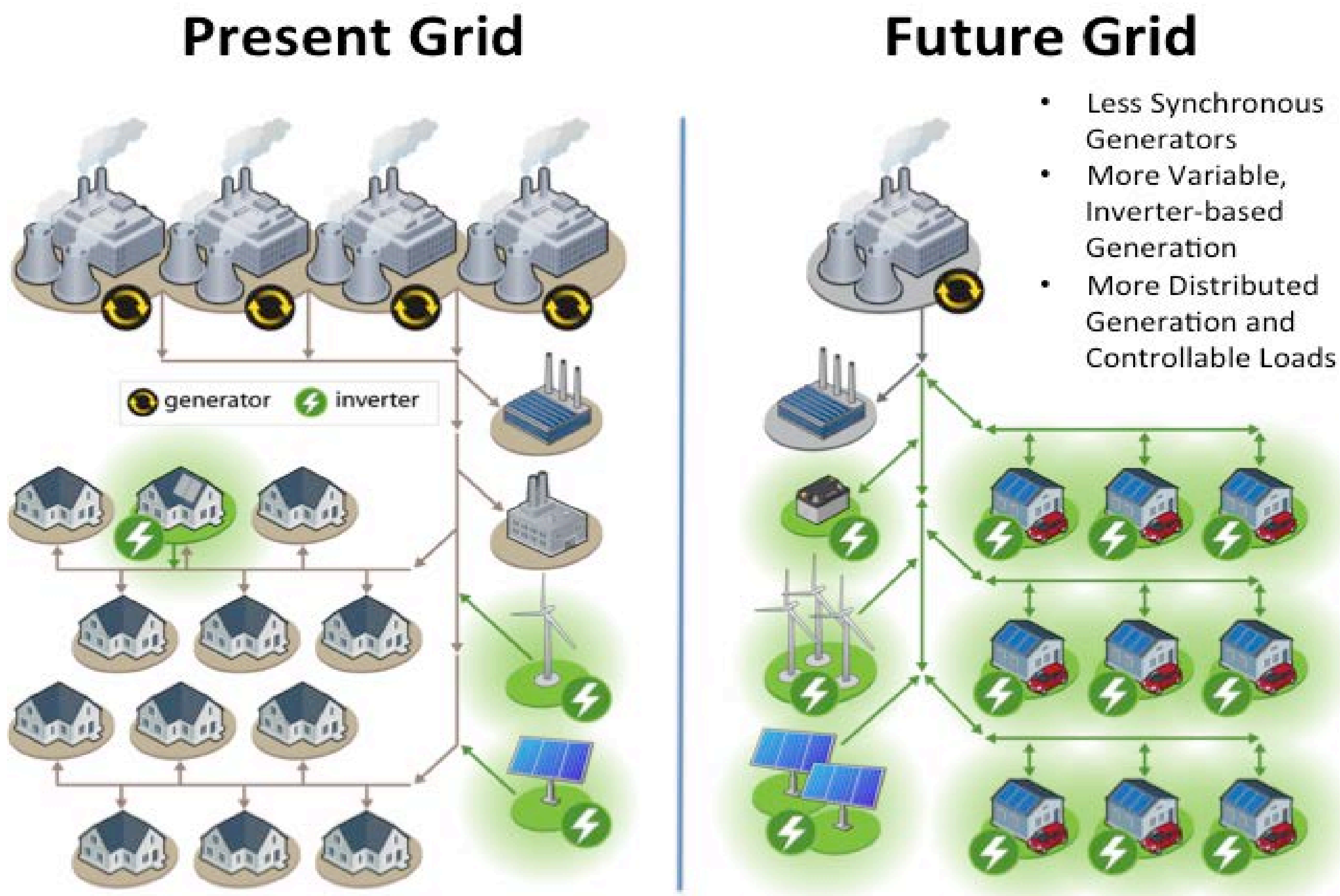
Source: NREL, REF, http://www.nrel.gov/analysis/re_futures/

VRE vs. load for only the Electric Reliability Council of Texas (ERCOT) system at the 80% VRE transmission constrained scenario

To operate AC power grids in this region, the dependence on the physical characteristics of synchronous generator grid operation needs to change: smart inverters need to provide grid services.

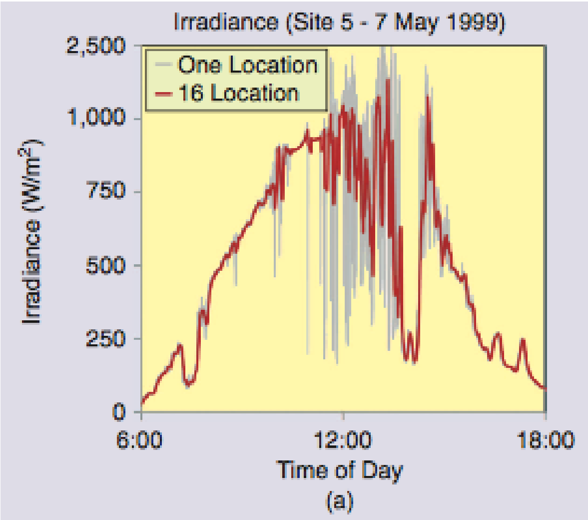
Challenges and Solutions of Operating Power Systems with Very High Levels of Variable Renewable Energy

Technical Challenges with High Levels of VRE

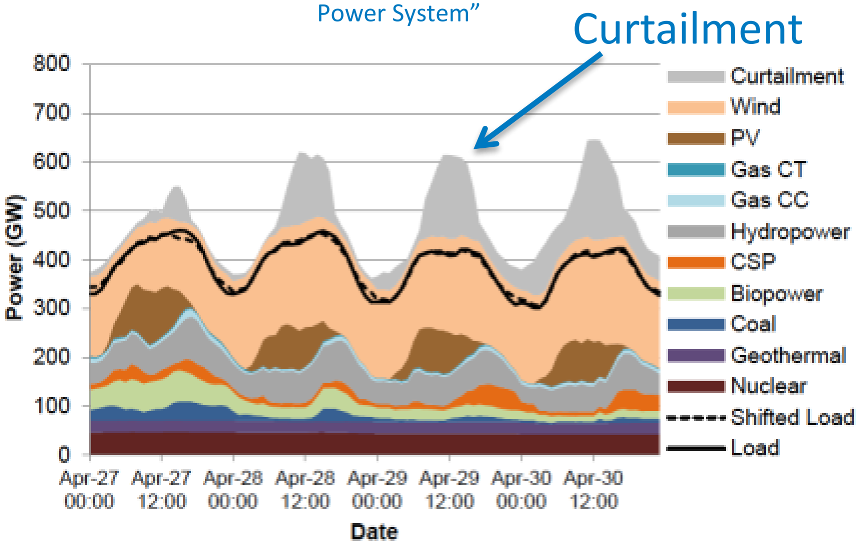


- Variability and uncertainty of VRE
- Power system stability.
- Protection coordination
- Unintentional islanding
- Black-start capability.

Variability and Uncertainty of VRE



Source: A Mills et al., "Dark Shadows: Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System"



Source: NREL, REF:
80% Renewables Case, http://www.nrel.gov/analysis/re_futures/

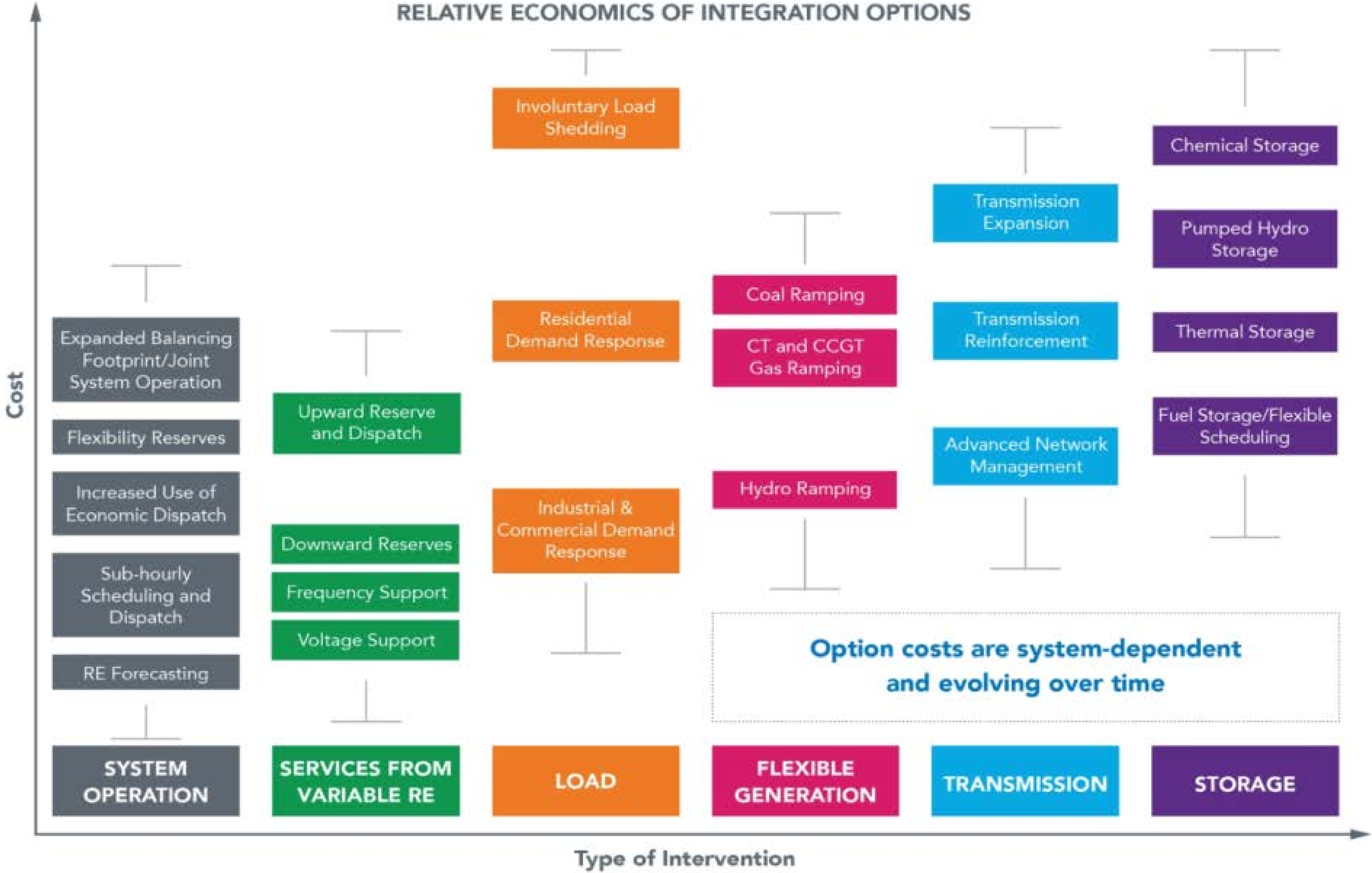
Challenges:

- **Energy shifting** (VRE produces energy when resources are available—variable and uncertain)
- **Forecasting** (renewable resources and load).

Solutions:

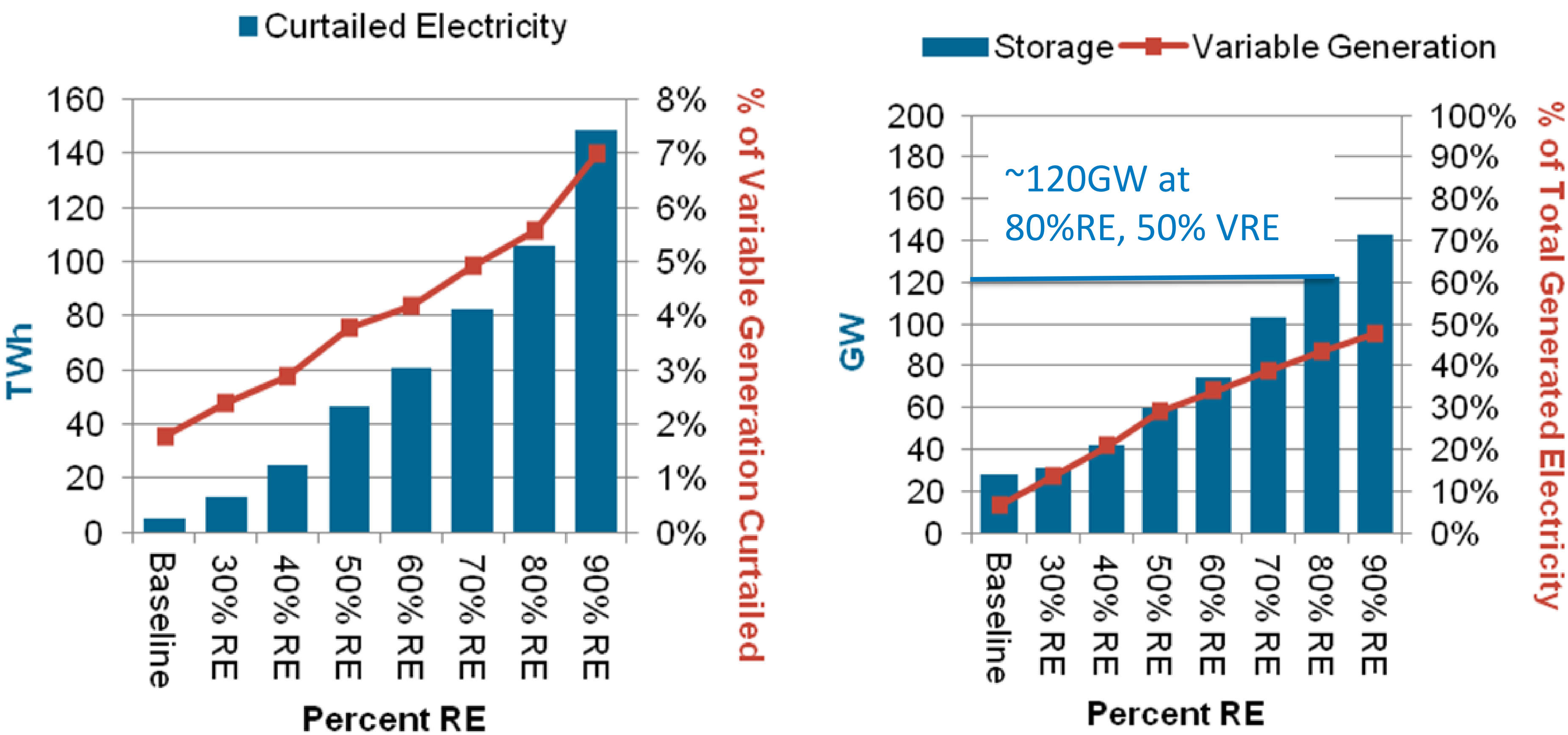
- Utilize geographic diversity.
- Utilize flexible conventional generation.
- Increase sharing among balancing authority areas.
- Expand the transmission system.
- Curtail excess VRE production.
- Coordinate flexible loads (active demand response).
- Enhance VRE and load forecasting.
- Add electrical storage.
- Interact with other energy carriers.

Grid Flexibility Options



Source: J. Cochran et al., *Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy*, http://www.nrel.gov/docs/fy15osti/62607.pdf

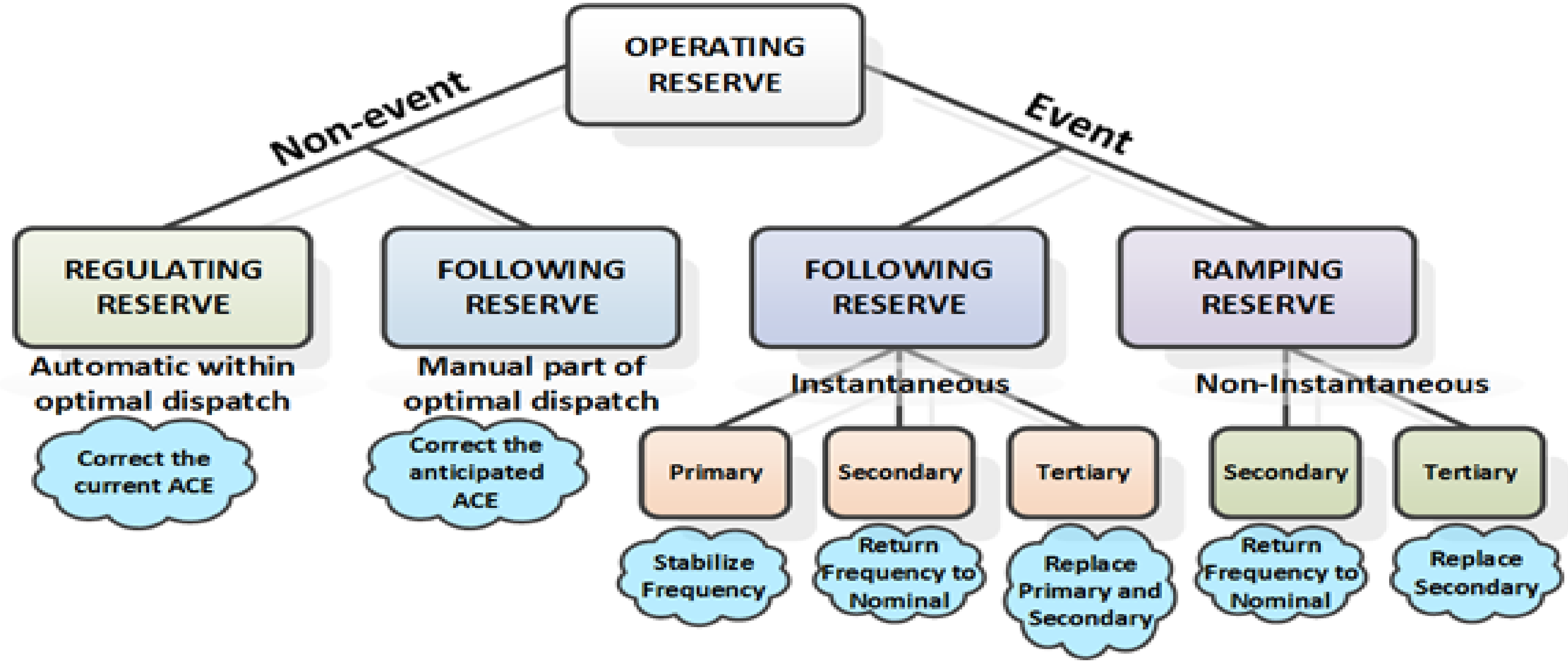
VRE Curtailment and Energy Storage: Renewable Electricity Futures Study



By 2050, storage capacity was estimated at 28 GW in the Low-Demand Baseline scenario, 31 GW in the 30% RE scenario, 74 GW in the 60% RE scenario, **and 142 GW in the 90% RE scenario.** Currently, there is 21 GW of pumped hydro in the United States.

Source: NREL, REF, http://www.nrel.gov/analysis/re_futures/

Power System Stability



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)

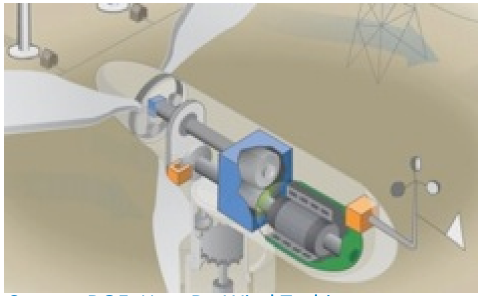
Solutions:

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

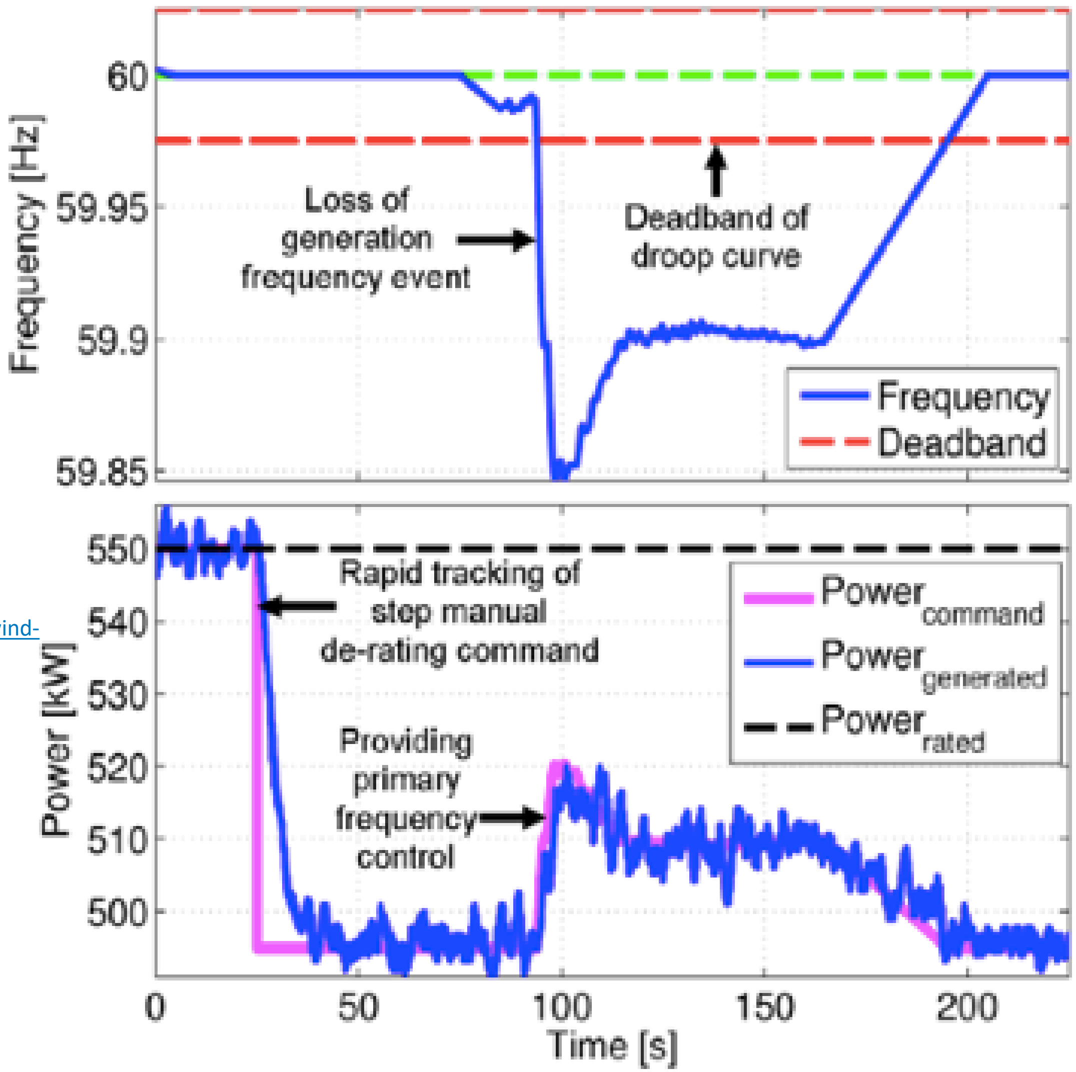
Active Power Control from Wind and Solar Inverters

Technology addressed:

- Understanding how variable generation (wind and solar) can provide primary and secondary reserves



Source: DOE, How Do Wind Turbines Work?, https://energy.gov/eere/wind/how-do-wind-turbines-work



Source: E. Ela et al., *Active Power Controls from Wind Power: Bridging the Gaps*, http://www.nrel.gov/docs/fy14osti/60574.pdf

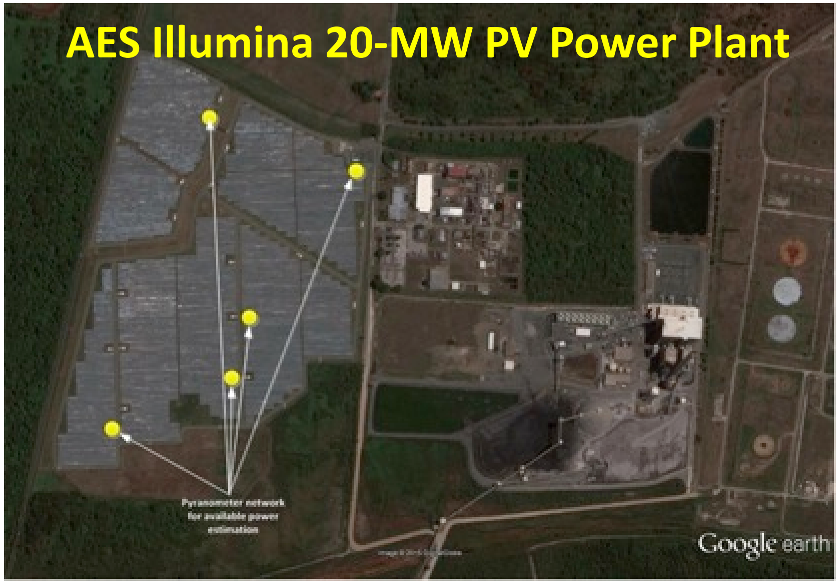
Impact:

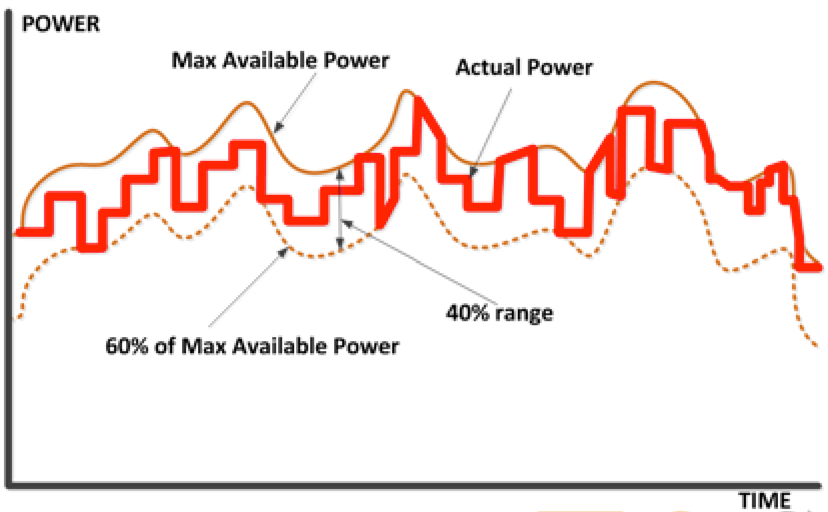
- Inertial control, primary frequency control, and automatic generation control (AGC) from wind and solar are feasible with negligible impacts on loading.

Photovoltaic Solar Provides Grid Services for Puerto Rico

Technology addressed:

- **PV participated in AGC.**
  - Followed AGC signal within 40% of available power.
- **PV provided frequency droop response.**
  - Both up and down-regulation
  - 5% and 3% symmetric droop.
- **PV provided fast frequency response.**
  - Evaluated plant's ability to deploy all reserves within 500 ms
  - Three new controls were implemented and validated.



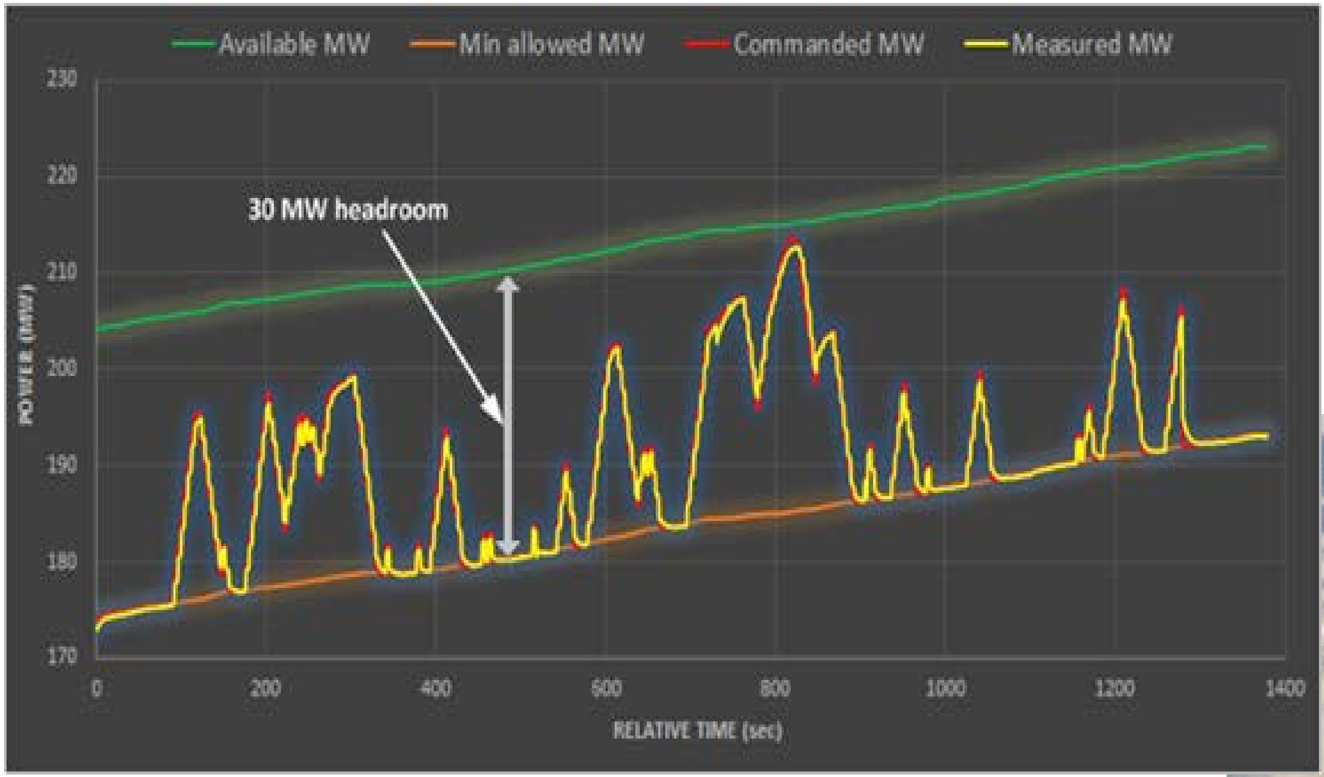


Impact:
First-of-a-kind real-world experiment using PV systems to maintain large grid stability.

Source: V. Gevorgian and B. O'Neill, *Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants*, http://www.nrel.gov/docs/fy16osti/65368.pdf

Large-Scale Photovoltaic Plant Regulation

NREL/FirstSolar/CAISO experiment: 300-MW plant following AGC signal



300-MW PV Plant in California

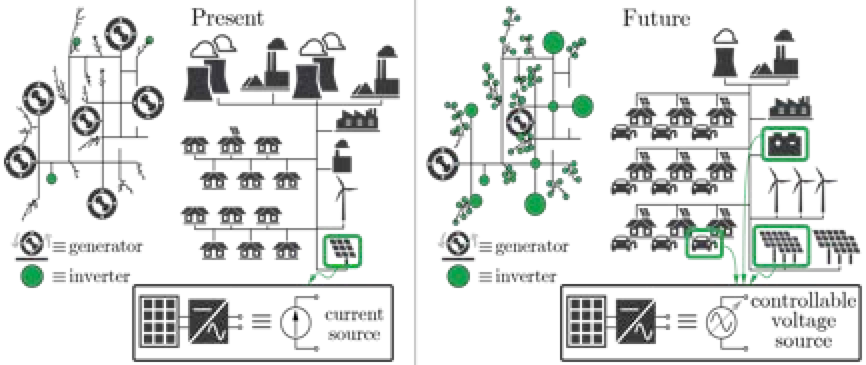
Photo from First Solar

Source: C. Loutan et al., *Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant*, http://www.nrel.gov/docs/fy17osti/67799.pdf

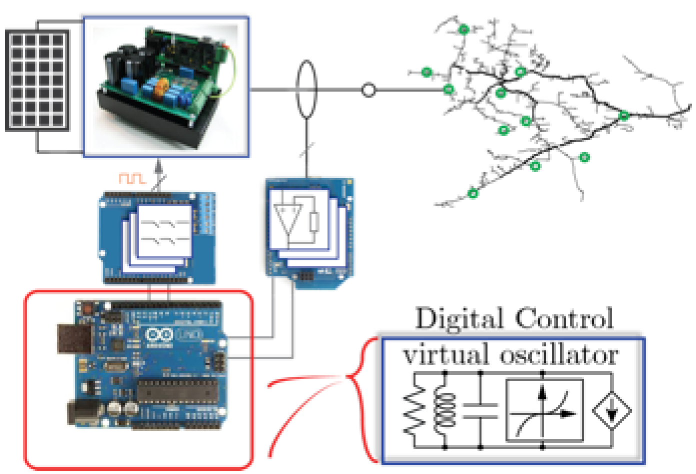
We demonstrated that PV plants (and wind power plants) can deliver essential grid services.

SunShot U.S. Department of Energy

SunShot: Stabilizing the Grid in 2035 and Beyond



From grid-following controls → To next-generation grid-forming controls



Project objective:

Develop distributed inverter controllers that provide a low-resistance path from the current inertia-dominated grid paradigm to a future grid paradigm dominated by low-inertia power systems with hundreds of GWs of PV integration.

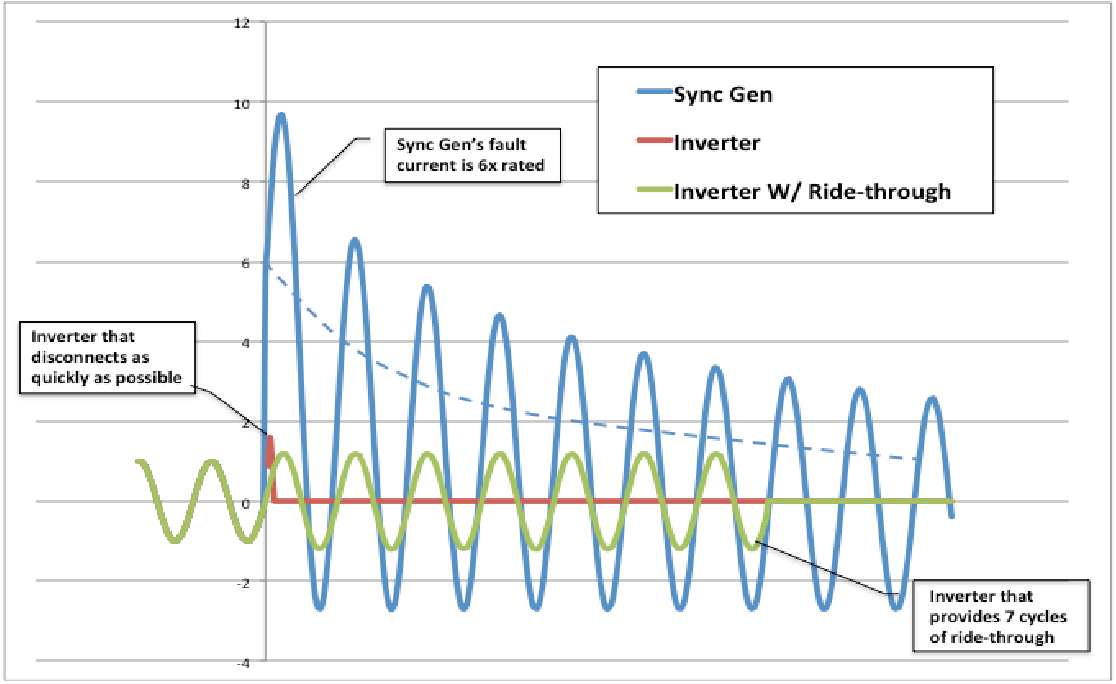
Technical approach:

- Model, analyze, and design framework for grid-stabilizing PV inverter controllers.
- Design, build, and prototype digital microcontrollers to implement proposed PV inverter controllers.

Project outcomes:

- Enable low-inertia and distributed infrastructures with massive PV and storage utilization.
- Perform demonstration on commercial microinverters.

Additional Technical Challenges



Source: B. Kroposki et al., "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," http://ieeexplore.ieee.org/document/7866938/

Challenges:

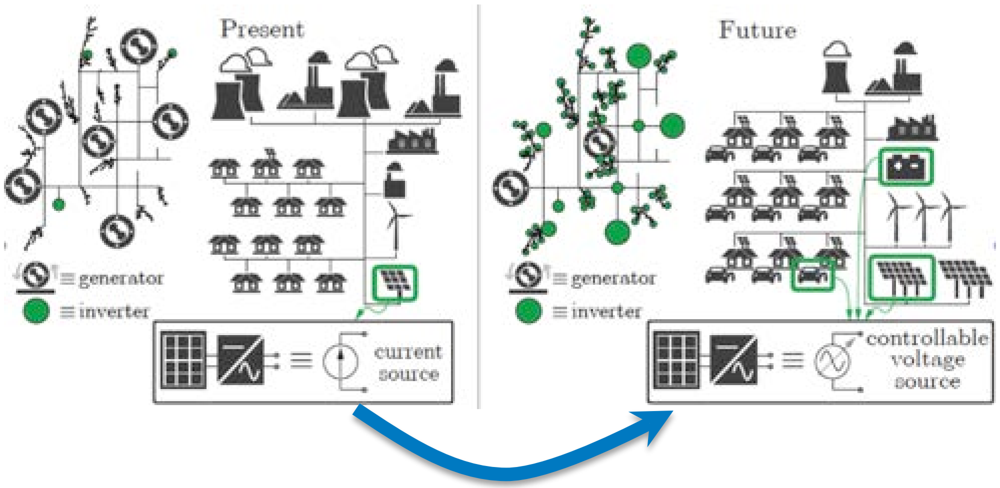
- **Protection coordination** (loss of high short-circuit current may effect protection schemes)
- **Unintentional islanding** (need methods to protect against unintentional islanding)
- **Black-start**—ability to restore system from outage
- **Distributed controls.**

Solutions:

- **Protection coordination**—synchronous condensers, new protection schemes
- **Unintentional islanding**—New artificial intelligence options
- **Black-start**—New system restoration methods
- **Distributed controls**—new control architectures and management systems.

Challenge: Control and Optimization of Millions of Devices

As we migrate from a centrally controlled, synchronous generator-based grid to a highly distributed, inverter-based system…

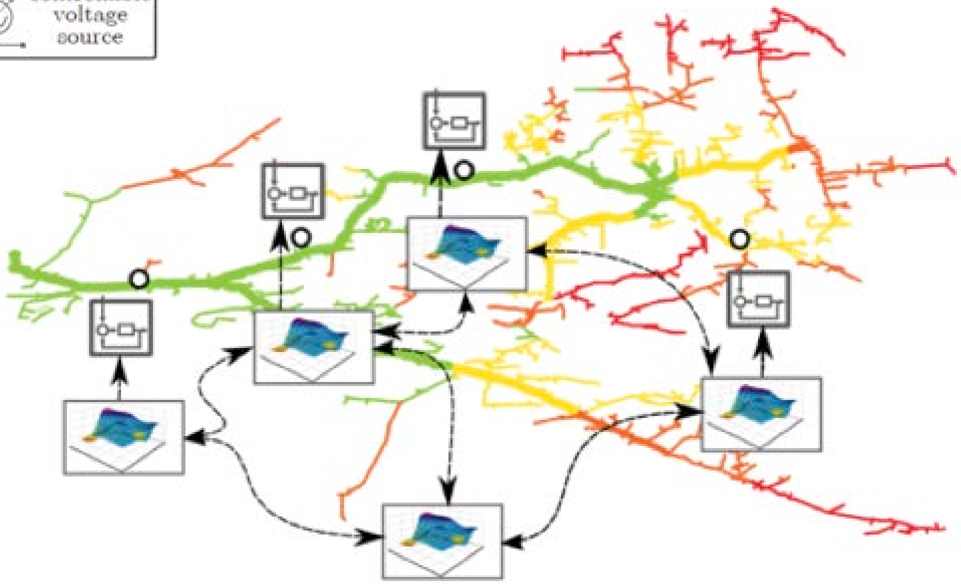


We need smart inverters with advanced functionality to maintain grid stability and…

Improved optimization for millions of controllable devices in the grid.

Research Needs

- Control theory
- Advanced control and optimization algorithms
- Imbedded controllers in devices
- Linkage to advanced distribution management systems (ADMS)
- Validation of concepts and deployment.

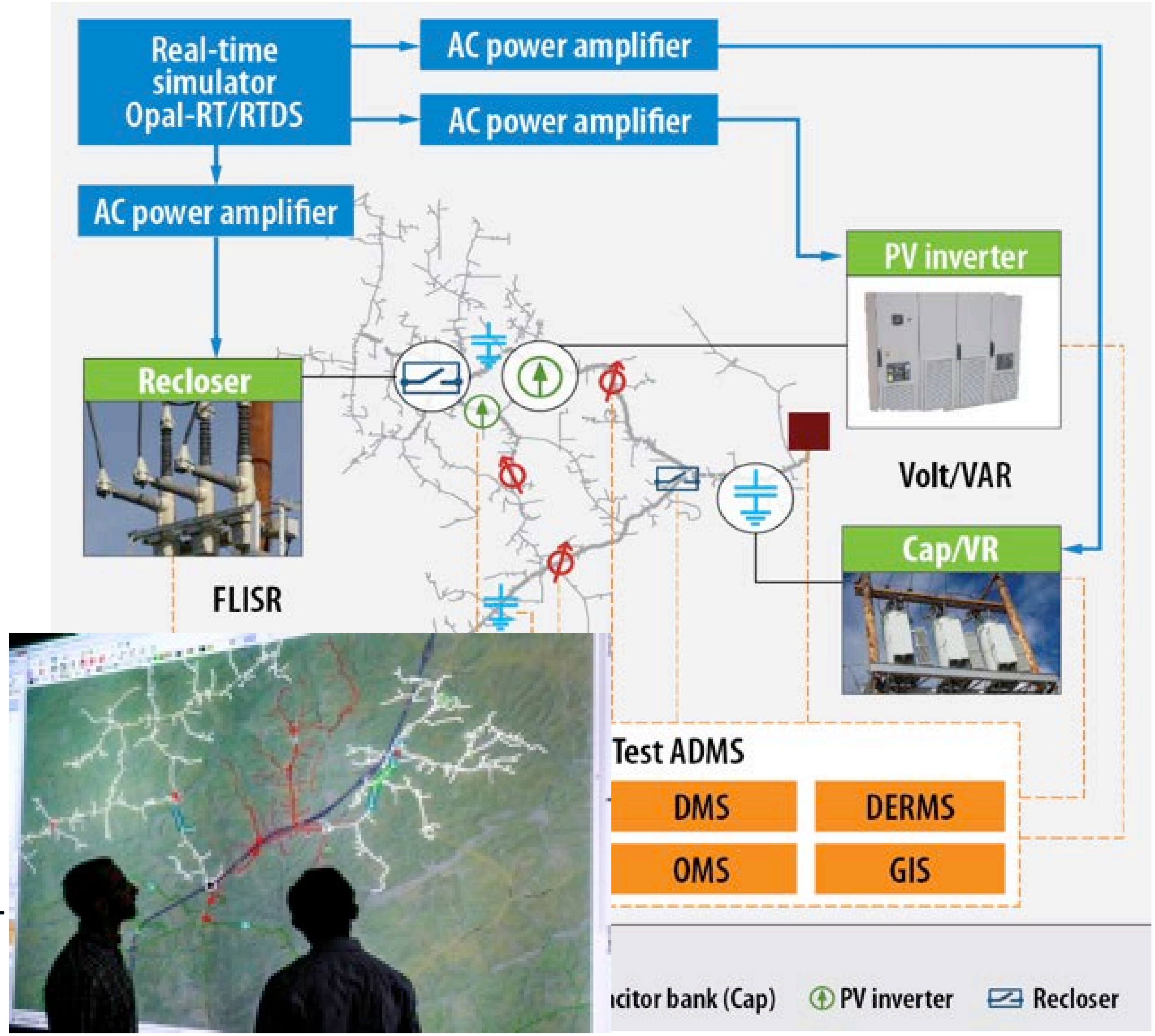


Source: ARPA-E, http://www.arpa-e.energy.gov/?q=arpa-e-programs/nodes

Source: E. Dall'Anese et al., http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6920041

Advanced Distribution Management System Test Bed

- NREL is establishing a **national, vendor-neutral** ADMS test bed to **accelerate industry development and adoption of ADMS capabilities.**
- This will enable utility partners, vendors, and researchers to evaluate existing and future ADMS use cases and integrate with hardware-in-the-loop (HIL) equipment.



Credit: NREL

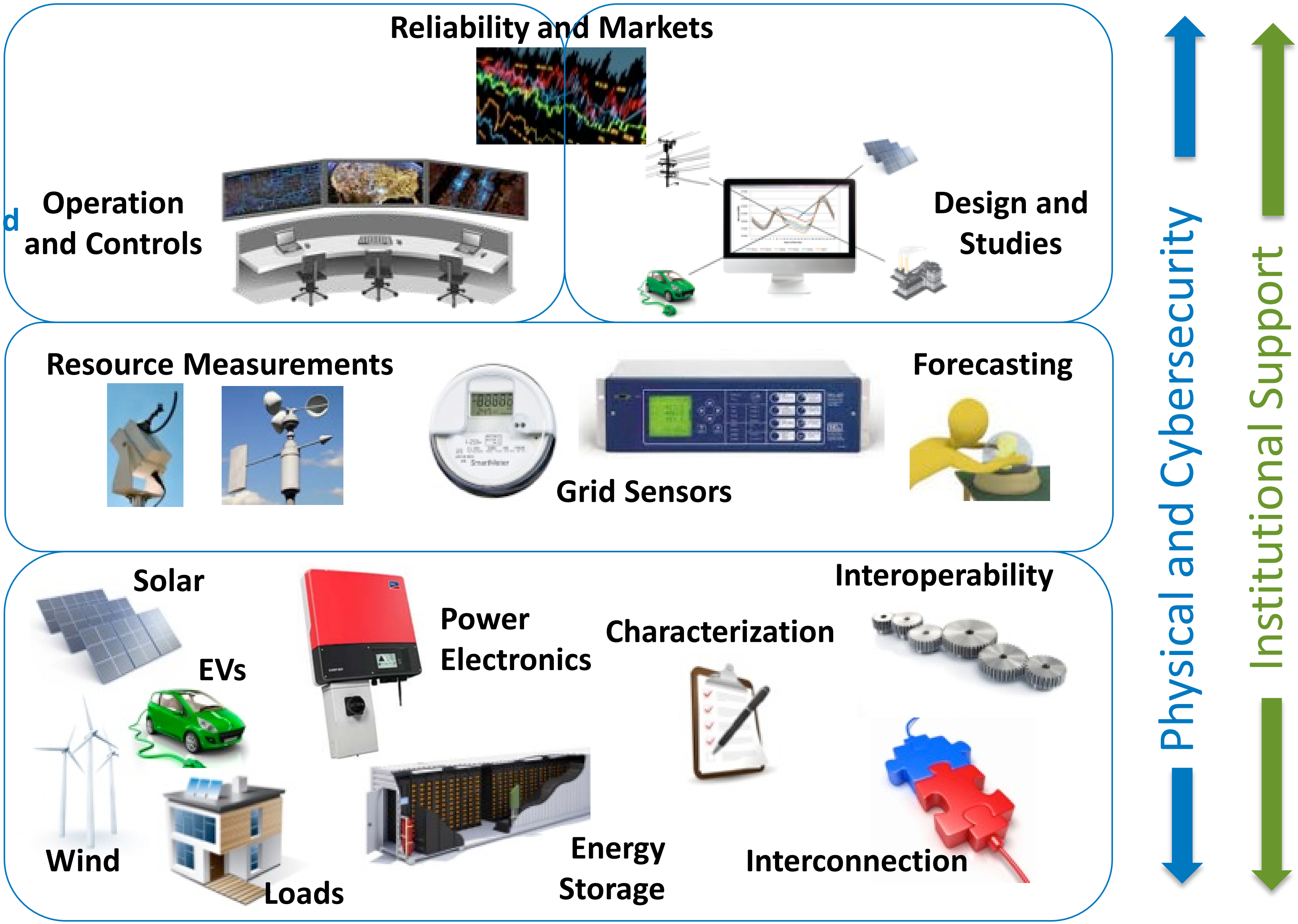
NREL Power Systems Research

Design and Studies

Operations and Controls

Sensing, Measurement, and Forecasting

Integrated Devices and Systems



Energy Systems Integration Facility

http://www.nrel.gov/esif

Credit: NREL

NREL NATIONAL RENEWABLE ENERGY LABORATORY | ENERGY SYSTEMS INTEGRATION FACILITY

U.S. DEPARTMENT OF ENERGY

Unique capabilities:

- Multiple parallel AC and DC experimental busses (MW power level) with grid simulation and loads
- Flexible interconnection points for electricity, thermal, and fuels
- Medium-voltage (15-kV) microgrid area
- Virtual utility operations center and visualization rooms
- Smart grid lab for advanced communications and control
- Interconnectivity to external field sites for data feeds and model validation
- Petascale high-performance computing (HPC) and data management system in showcase energy-efficient data center
- MW-scale power hardware-in-the-loop simulation capability to evaluate grid scenarios with high penetrations of clean energy technologies.

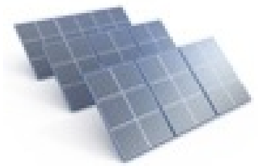
Credit: NREL

Shortening the time between innovation and practice

Credit: NREL

Energy Systems Integration Facility Cont.

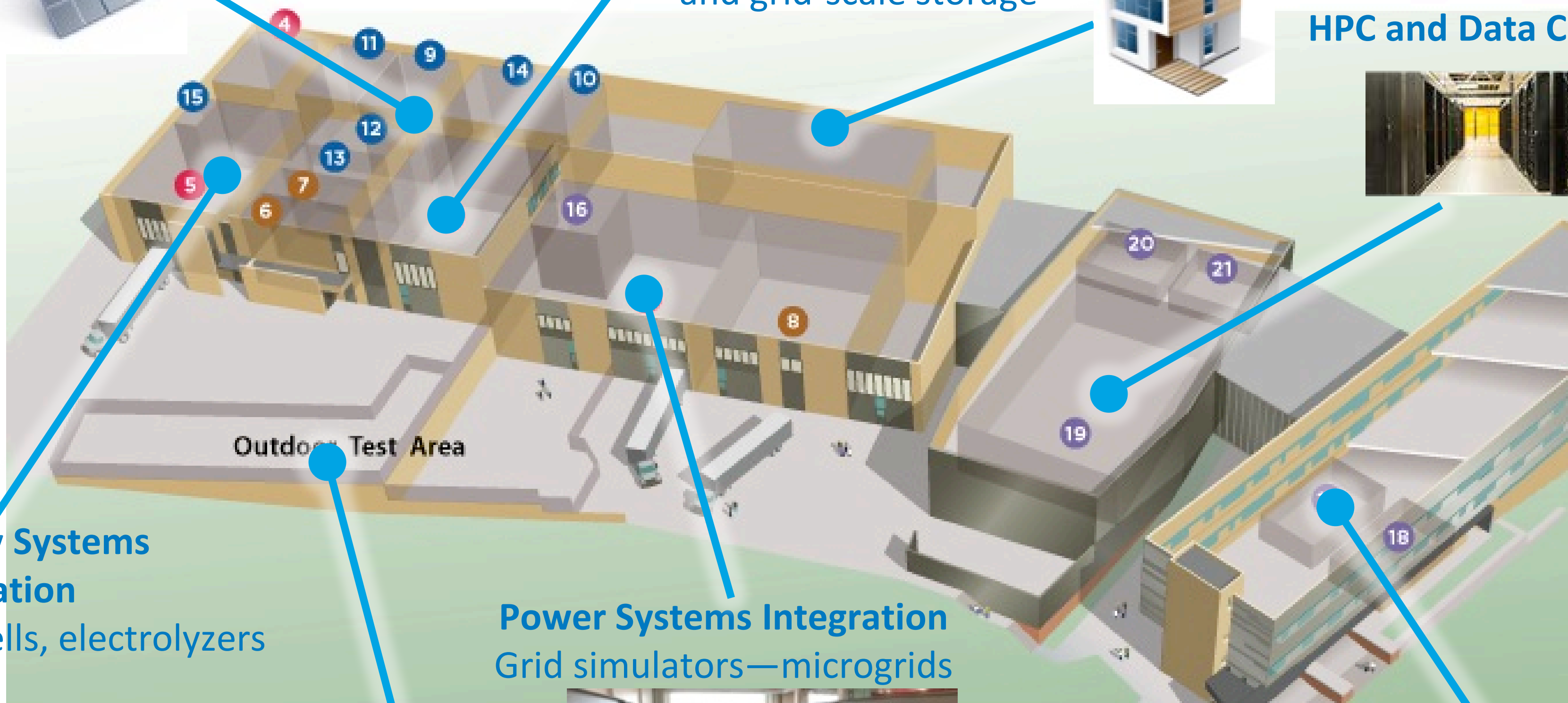
Rooftop PV



Energy Storage
Residential, community and grid-scale storage

Smart buildings and controllable loads

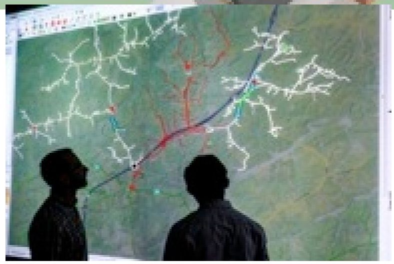
HPC and Data Center



Energy Systems Integration
Fuel cells, electrolyzers

Outdoor Areas
EVs, transformers, capacitor banks, voltage regulators

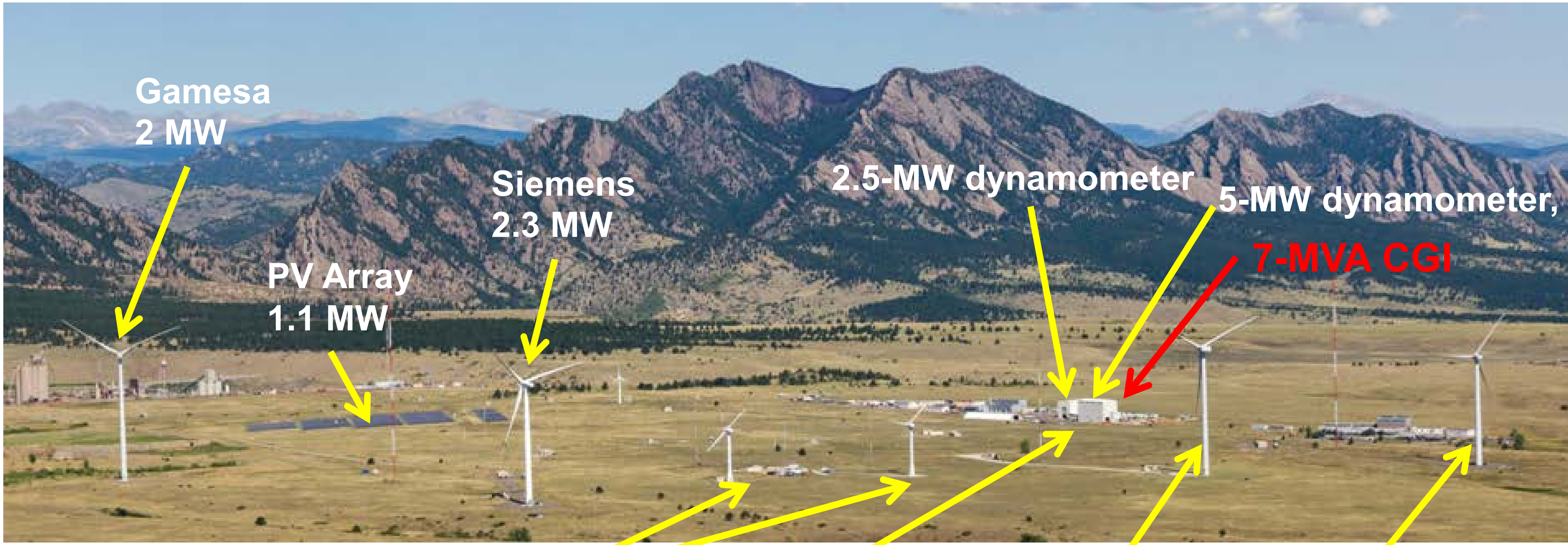
Power Systems Integration
Grid simulators—microgrids



ADMS

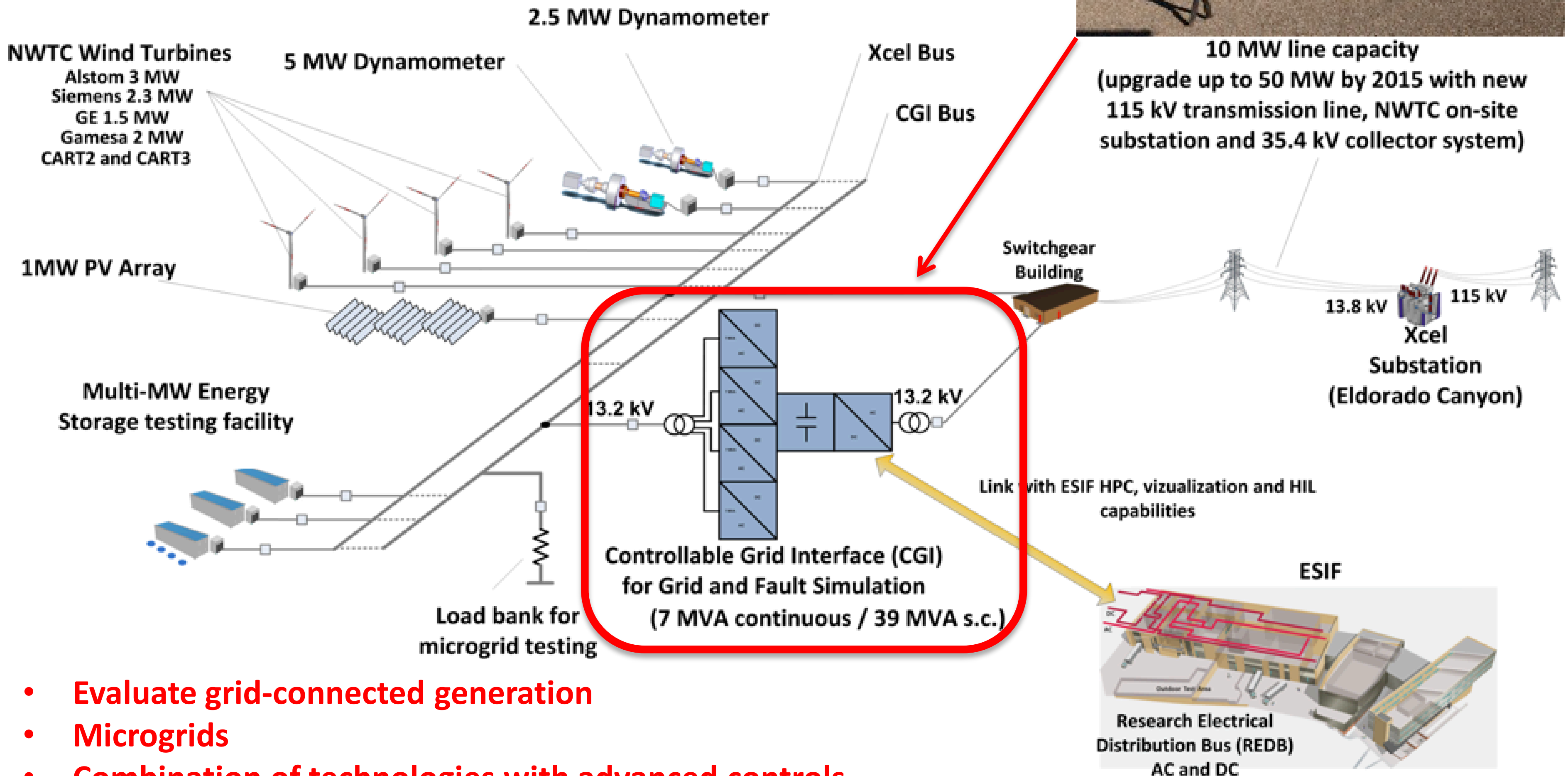
National Wind Technology Center: Large-Scale Grid Research

- **Total of 11 MW of variable renewable generation currently installed at the National Wind Technology Center (NWTC)**
- **Many small wind turbines (less than 100 kW) are installed as well**
- **2.5-MW and 5-MW dynamometers**
- **7-MVA controllable grid interface (CGI) for grid integration experiments**
- **Multi-megawatt energy storage evaluation capability ready for use.**



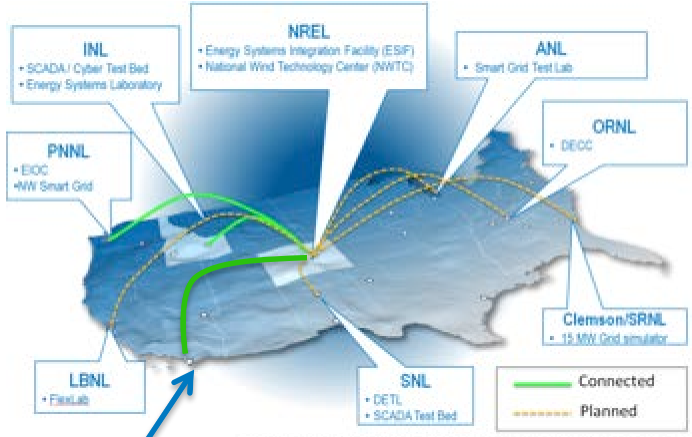
Controllable Grid Interface

Highly flexible and configurable system-level multi-megawatt evaluation platform

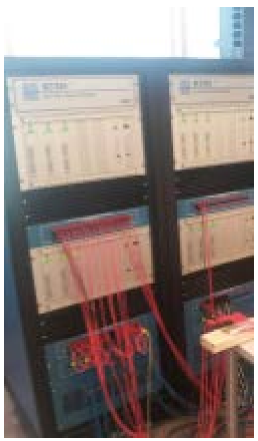


- **Evaluate grid-connected generation**
- **Microgrids**
- **Combination of technologies with advanced controls.**

Remote Hardware-in-the-Loop Capability

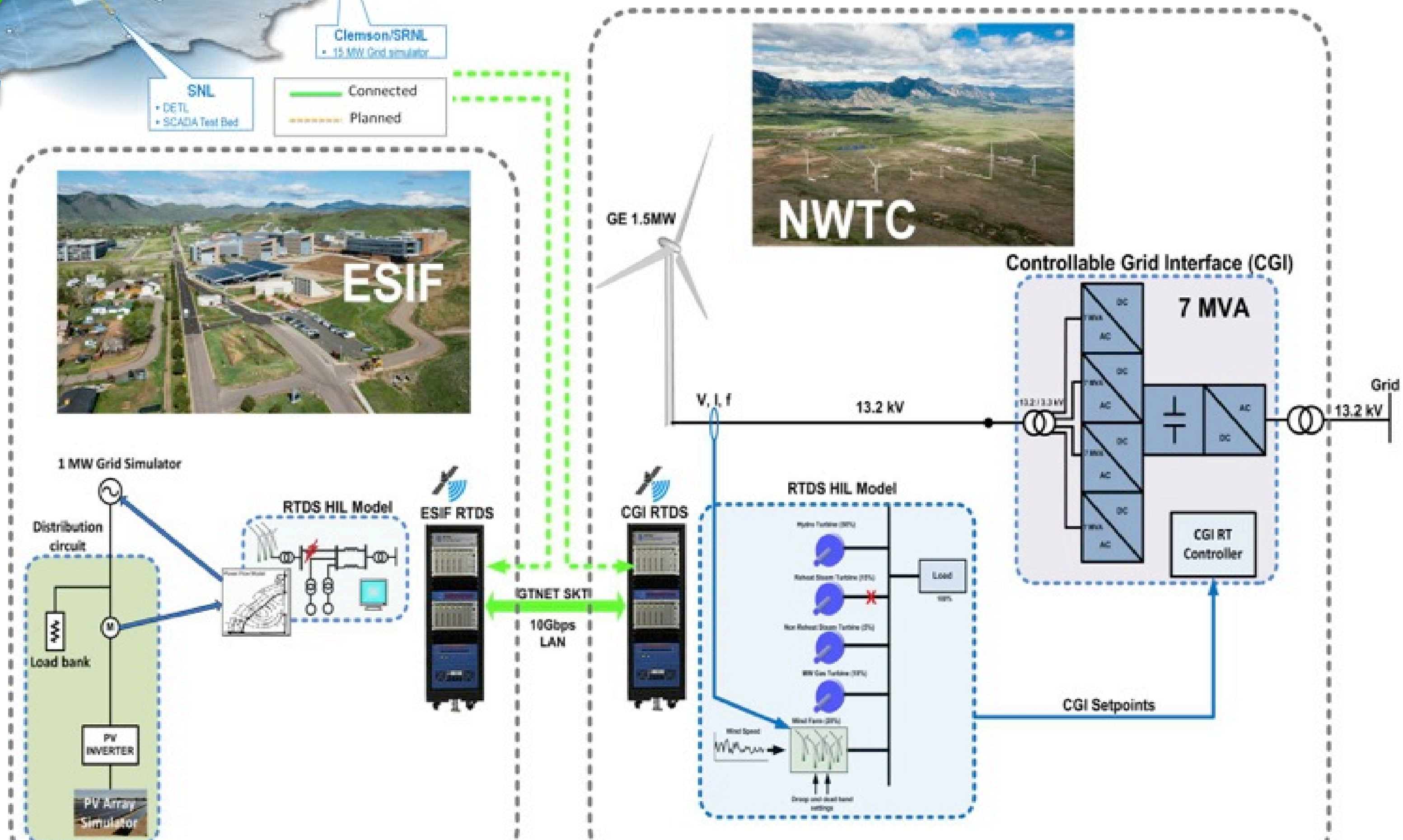


SDG&E



Source: SDG&E

IMPACT: First-of-a-kind remote HIL experiments increase capability without large investments in physical equipment at multiple sites.



Source: NREL

Research Needs in Power Systems to Achieve 100% VRE

Technology:

- Advanced functionality embedded in wind and PV inverters needs to **provide all grid services** and maintain stable grid operations (act like synchronous generators).
- Grid codes and standards are needed that enforce grid stability (updates to standards from the Institute of Electrical and Electronics Engineers and North American Electric Reliability Corporation)
- Need cost-effective energy storage methods (storage, flexible demand, power-to-gas).

Sensing, measurement, and forecasting:

- Improved solar, wind, and load forecasting
- Improved communications from measurements and data analytics to derive grid forecasts.

Power system operations and controls:

- Better algorithms and use of grid data to make decisions for power system operations and control
- Transmission and distribution energy management systems need to be able to control millions of distributed devices.

Power system design and studies:

- Need integrated transmission and distribution models to understand complexities and simulate both steady-state and dynamic conditions
- Need models that link electric power grid to other energy infrastructures
- Need models need to incorporate uncertainty and various market designs.

NREL Power Systems Engineering Center

www.nrel.gov/grid

NREL: Providing Solutions to Grid Integration Challenges

Thank You!

NATIONAL RENEWABLE ENERGY LABORATORY

For More Information: Integrated Devices and Systems

- Chakraborty, S., et al. 2014. "Examining System-Wide Impacts of Solar PV Control Systems with a Power Hardware-in-the-Loop Platform." In *Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*. Piscataway, NY: Institute of Electrical and Electronics Engineers.
- Chakraborty, S., et al. 2015. "Evaluation of Multiple Inverter Volt-VAR Control Interactions with Realistic Grid Impedances." In *Proceedings of the 2015 IEEE Power and Energy Society General Meeting*. Piscataway, NY: Institute of Electrical and Electronics Engineers.
- Gevorgian, V., et al. 2015. "Investigating the Impacts of Wind Generation Participation in Interconnection Frequency Response." *IEEE Transactions on Sustainable Energy* 6(3) July: 1,004–1,012.
- Gevorgian, V., et al. 2016. *Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants* (Technical Report NREL/TP-5D00-65368). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65368.pdf.
- Hoke, A., et al. 2013. "Steady-State Analysis of Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders." *IEEE Transactions on Sustainable Energy* 4(2): 350–357.
- Hoke, A., et al. 2016. *Experimental Evaluation of PV Inverter Anti-Islanding with Grid Support Functions in Multi-Inverter Island Scenarios* (Technical Report NREL/TP-5D00-66732). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/66732.pdf.
- Johnson, B., et al. 2014. "Oscillator-Based Inverter Control for Islanded Three-Phase Microgrids." *IEEE Journal of Photovoltaics* 4(1) January: 387–395.
- Kroposki, B. 2016. "Can Smarter Solar Inverters Save the Grid?" *IEEE Spectrum*. http://spectrum.ieee.org/energy/renewables/can-smarter-solar-inverters-save-the-grid.
- Kroposki, B., et al. 2017. "Achieving a 100% Renewable Grid—Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy." *IEEE Power and Energy Magazine*. http://ieeexplore.ieee.org/document/7866938/.
- Nagarajan, A., et al. 2016. "Advanced Inverter Functions and Communication Protocols for Distribution Management." In *Proceedings of the 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*. Piscataway, NY: Institute of Electrical and Electronics Engineers.
- Ropp, M., et al. 2016. "Ground Fault Overvoltage with Inverter-Interfaced Distributed Energy Resources." *IEEE Transactions on Power Delivery* 32(2): 890–899.

For More Information: Sensing, Measurement, and Forecasting

- Brancucci Martinez-Anido, C., et al. 2016. "Value of Day-Ahead Solar Power Forecasting Improvement." *Solar Energy* 129: 192–203.
- Cui, M., et al. 2015. "Wind Power Ramp Event Forecasting Using a Stochastic Scenario Generation Method." *IEEE Transactions on Sustainable Energy* 6(2): 422–433.
- Hodge, B.-M., et al. 2015. *The Value of Improved Short-Term Wind Power Forecasting* (Technical Report NREL/TP-5D00-63175). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy15osti/63175.pdf
- Sengupta, M., et al. 2015. *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications*. (Technical Report NREL/TP-5D00-63112). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy15osti/63112.pdf.
- Wang, Q., et al. 2016. "Quantifying the Economic and Grid Reliability Impacts of Improved Wind Power Forecasting." *IEEE Transactions on Sustainable Energy*.
- Yu, X. 2016. "Fast All-Sky Radiation Model for Solar Applications (FARMS): Algorithm and Performance Evaluation." *Solar Energy* 135: 435–445.
- Zhang, J., et al. 2015. "Suite of Metrics for Assessing the Performance of Solar Power Forecasting." *Solar Energy* 111: 157–175.

For More Information: Power System Operations and Control

- Dall'Anese, E. 2016. "Optimal Power Flow Pursuit." In *Proceedings of the 2016 American Control Conference (ACC)*. Red Hook, NY: Curran Associates.
- Dall'Anese, E., et al. 2014. "Decentralized Optimal Dispatch of Photovoltaic Inverters in Residential Distribution Systems." *IEEE Transactions on Energy Conversion* 29(4): 957–967.
- Dall'Anese, E., et al. 2015. "Optimal Dispatch of Residential Photovoltaic Inverters Under Forecasting Uncertainties." *IEEE Journal of Photovoltaics* 5(1): 350–359.
- Dall'Anese, E., et al. 2015. "Photovoltaic Inverter Controllers Seeking AC Optimal Power Flow Solutions." *IEEE Transactions on Power Systems* 31(4): 2,809–2,823.
- Jiang, H., et al. 2015. "Synchrophasor-Based Auxiliary Controller to Enhance the Voltage Stability of a Distribution System With High Renewable Energy Penetration." *IEEE Transactions on Smart Grid* 6(4): 2,107–2,115.
- Mittal, S., et al. 2015. "System-of-Systems Approach for Integrated Energy Systems Modeling and Simulation." Presented at the Society for Modeling & Simulation International Summer Simulation Multi-Conference, Chicago, Illinois, July 26–29.
- Wu, H., et al. 2015. "Stochastic Optimal Scheduling of Residential Appliances with Renewable Energy Sources." In *Proceedings of the 2015 IEEE Power and Energy Society General Meeting*. Piscataway, NY: Institute of Electrical and Electronics Engineers.
- Yang, R., and Y.C. Zhang. 2016. "Coordinated Optimization of Distributed Energy Resources and Smart Loads in Distribution Systems." In *Proceedings of the 2016 IEEE Power and Energy Society General Meeting*. Piscataway, NY: Institute of Electrical and Electronics Engineers.

For More Information: Power System Design and Studies

- Bloom, A., et al. 2016. *Eastern Renewable Generation Integration Study* (Technical Report NREL/TP-6A20-64472). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/64472.pdf.
- Cheng, D. 2016. “Photovoltaic (PV) Impact Assessment for Very High Penetration Levels.” *IEEE Journal of Photovoltaics* 6(1): 295–300.
- Denholm, P. 2016. *On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System* (Technical Report NREL/TP-6A20-65800). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65800.pdf.
- Mather, B., et al. 2015. “In Divergence There is Strength: Measuring and Mitigating Solar PV Impacts in Southern California Using Power Factors Other than One.” *IEEE Power and Energy Magazine* 13(2): 62–70.
- Miller, N.W, et al. 2015. *Western Wind and Solar Integration Study Phase 3A: Low Levels of Synchronous Generation* (Technical Report NREL/TP-5D00-64822). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/64822.pdf.
- Milligan, M., et al. 2015. “Alternatives No More: Wind and Solar Power Are Mainstays of a Clean, Reliable, Affordable Grid.” *IEEE Power and Energy Magazine* 13(6): 78–87.
- Palmintier, B., et al. 2016. *Final Technical Report: Integrated Distribution—Transmission Analysis for Very High Penetration Solar PV*. (Technical Report NREL/TP-5D00-65550). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65550.pdf.
- Palmintier, B., et al. 2016. *On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System* (Technical Report NREL/TP-5D00-65331). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65331.pdf.
- Sequin, R., et al. 2016. *High-Penetration PV Integration Handbook for Distribution Engineers* (Technical Report NREL/TP-5D00-63114). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/63114.pdf.