NREL
Transforming ENERGY

Integrating Massive Amounts of Wind and Solar in Electric Power Systems

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Director – Power Systems Engineering Center
National Renewable Energy Laboratory

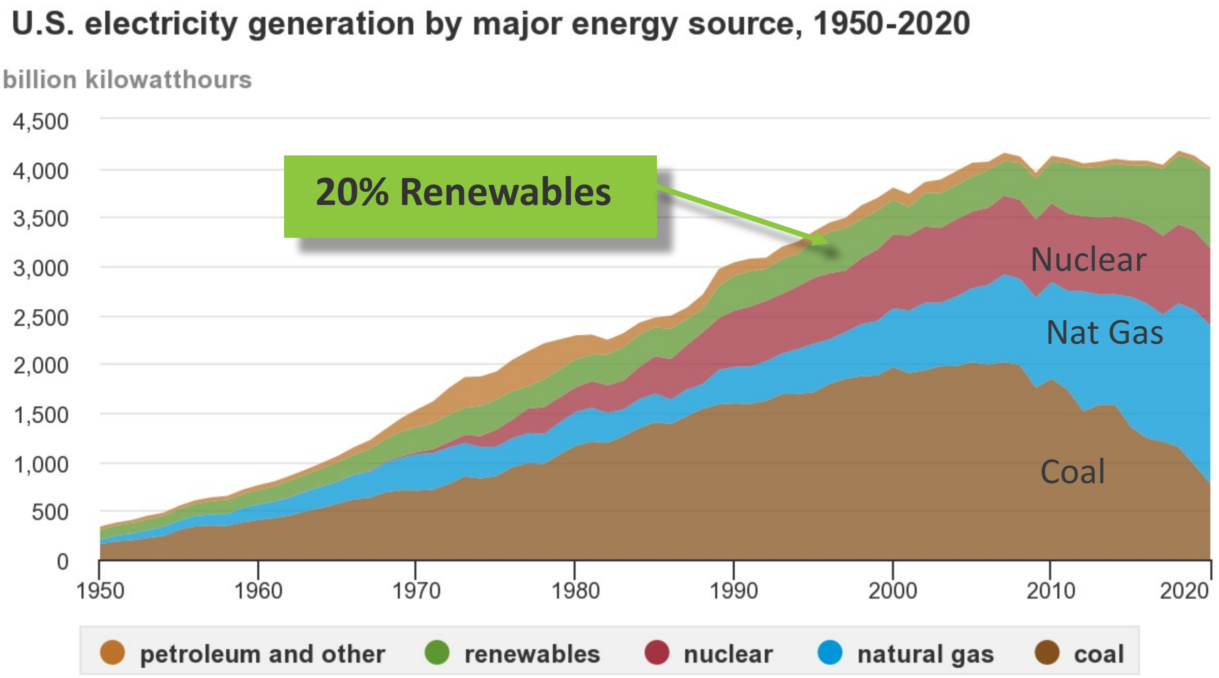
Photo: NREL

The US Energy Supply is Shifting

Since 2010:

- Coal has declined
- Gas and Renewables have increased
- Nuclear and Hydro have remained steady

2020 was the first year that Renewables surpassed either Nuclear or Coal in energy generation in the US.



Note: Electricity generation from utility-scale facilities.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.2a, January 2021 and *Electric Power Monthly*, February 2021, preliminary data for 2020

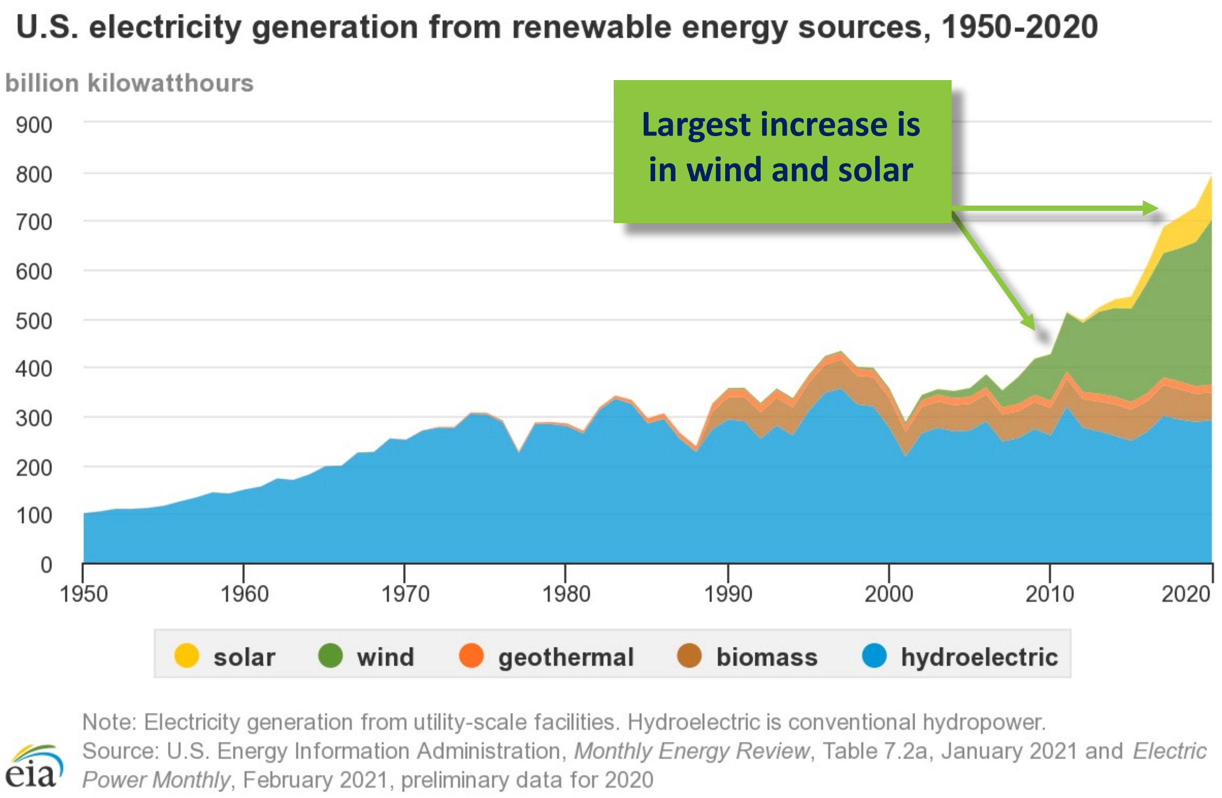
The US Energy Supply is Shifting

Renewable Energy

In 2020, 20% of annual electricity was from renewable sources.

- 8.5% Wind
- 7.3% Hydro
- 2.3% Solar
- 1.4% Biomass
- 0.4% Geothermal

In 2020, wind produces more energy than hydro

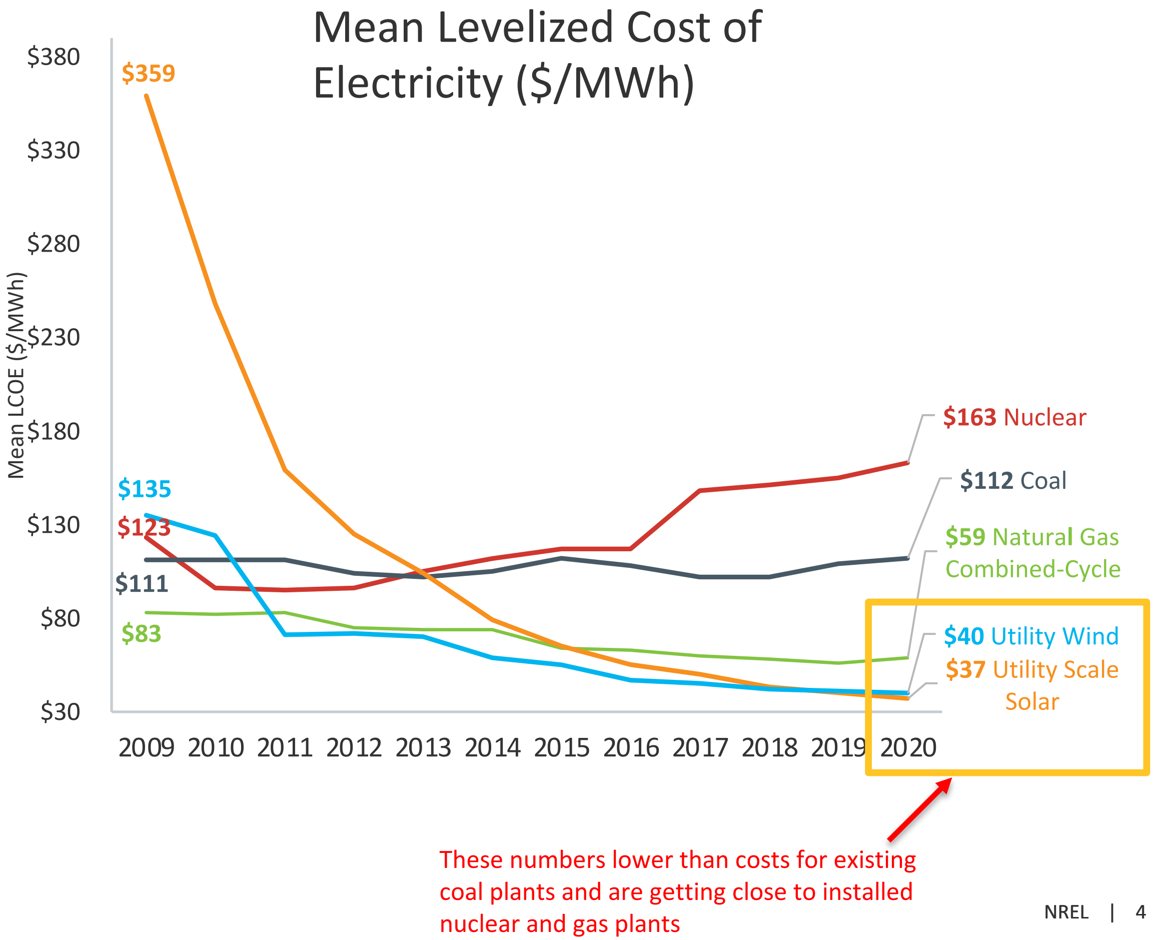


Note: Electricity generation from utility-scale facilities. Hydroelectric is conventional hydropower.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.2a, January 2021 and *Electric Power Monthly*, February 2021, preliminary data for 2020

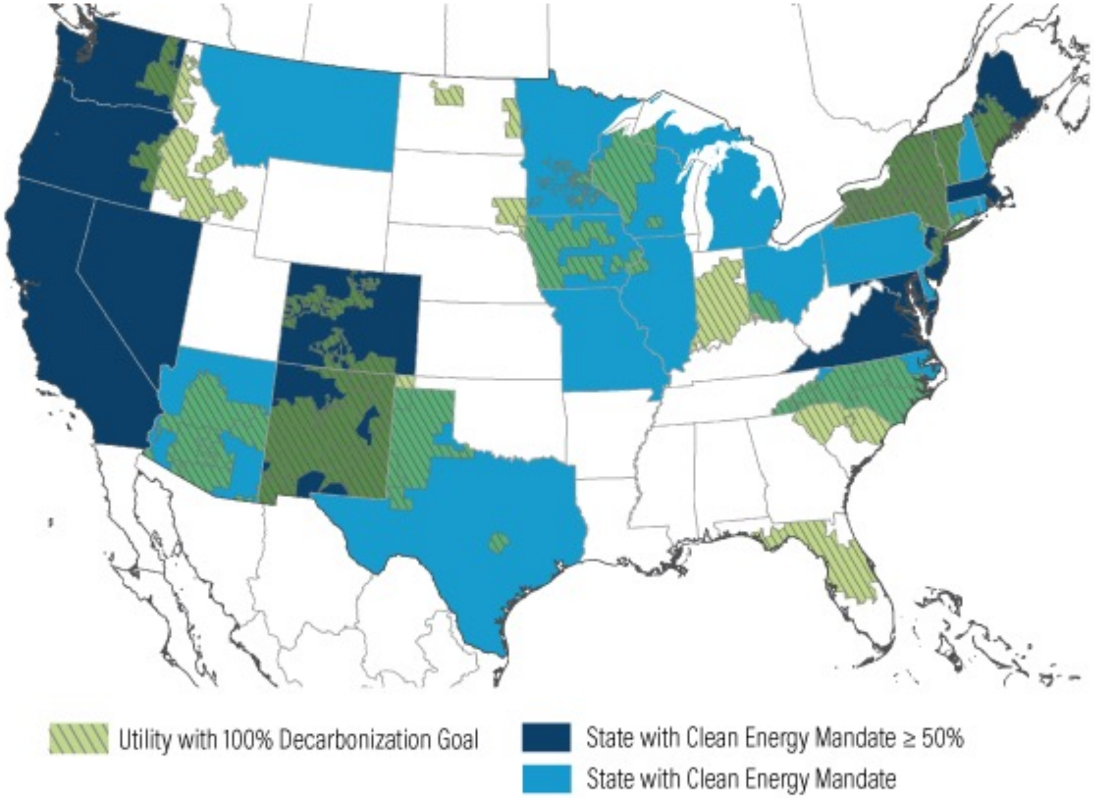
Cost of Renewables Continues to Fall

Utility-scale wind and solar are the most cost-competitive forms of new energy

Wind costs have decrease 70% and Solar costs have decreased 90% since 2009

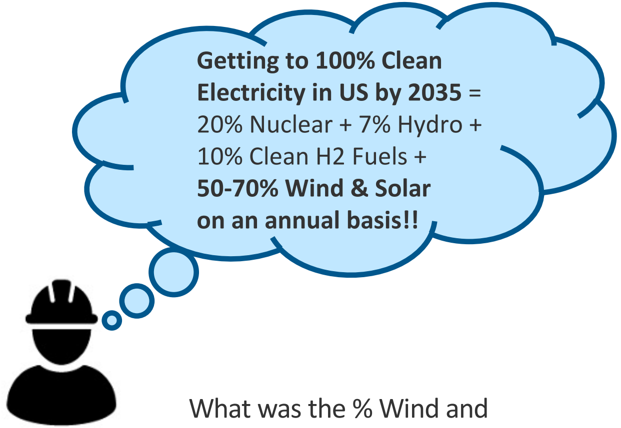


States and Utilities with Significant Clean Energy Targets



Source: WRI and Smart Electric Power Alliance.
Updated on April 17, 2020.

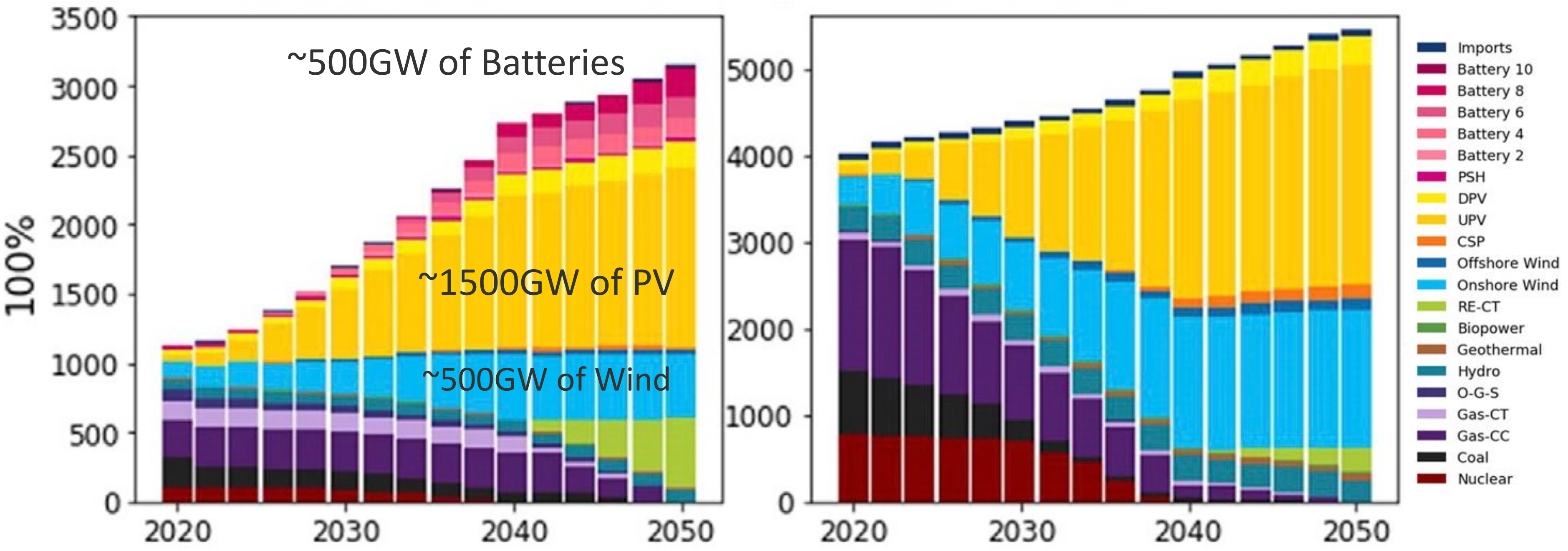
WORLD RESOURCES INSTITUTE



What was the % Wind and Solar in 2020? **11%**

What was the % Wind and Solar in 2021? **13%**

The U.S. is looking at how to get to 100% Clean Electricity



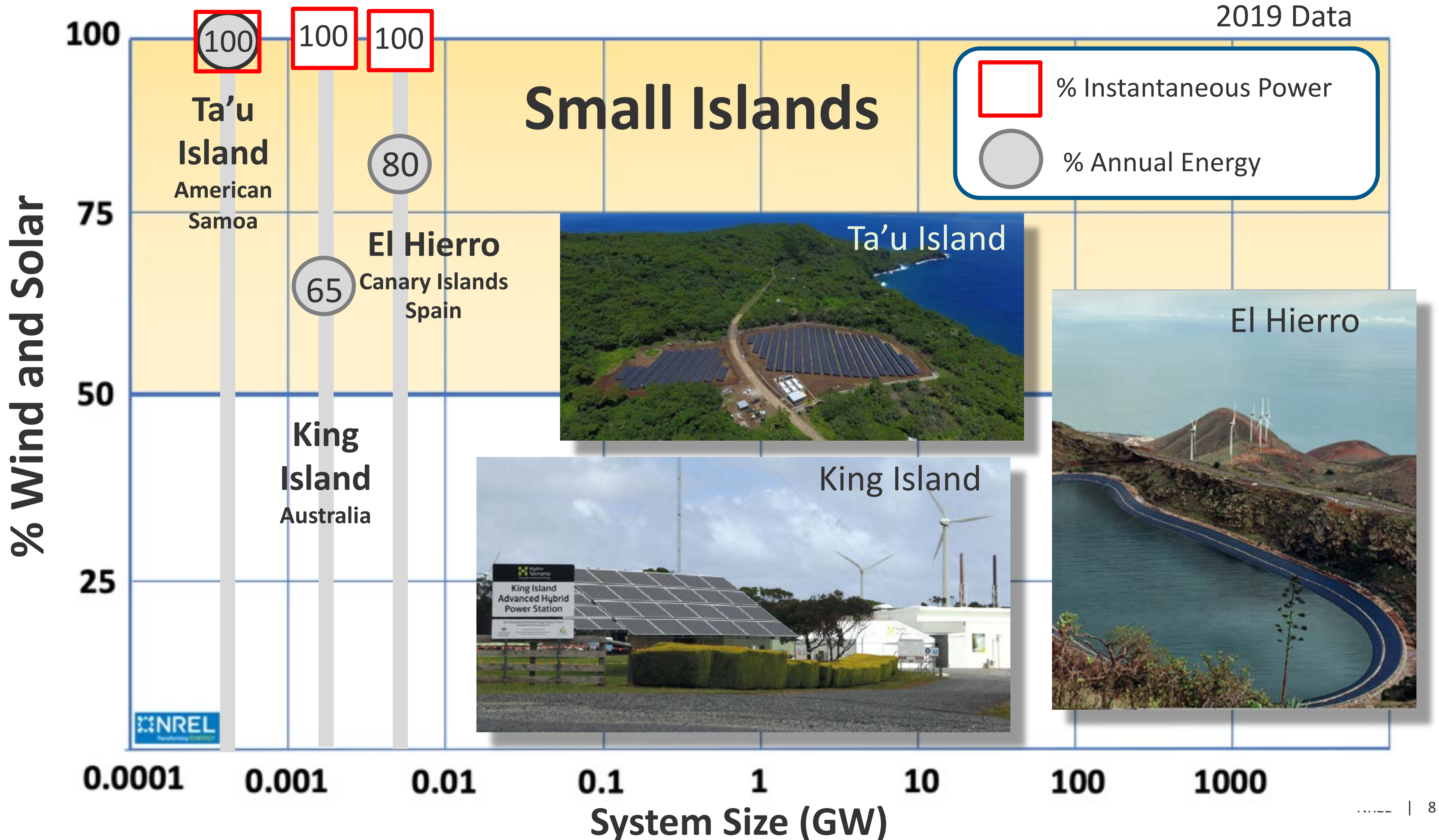
For more than 25% of the year, the system needs to operate at over 80% inverter-based resources

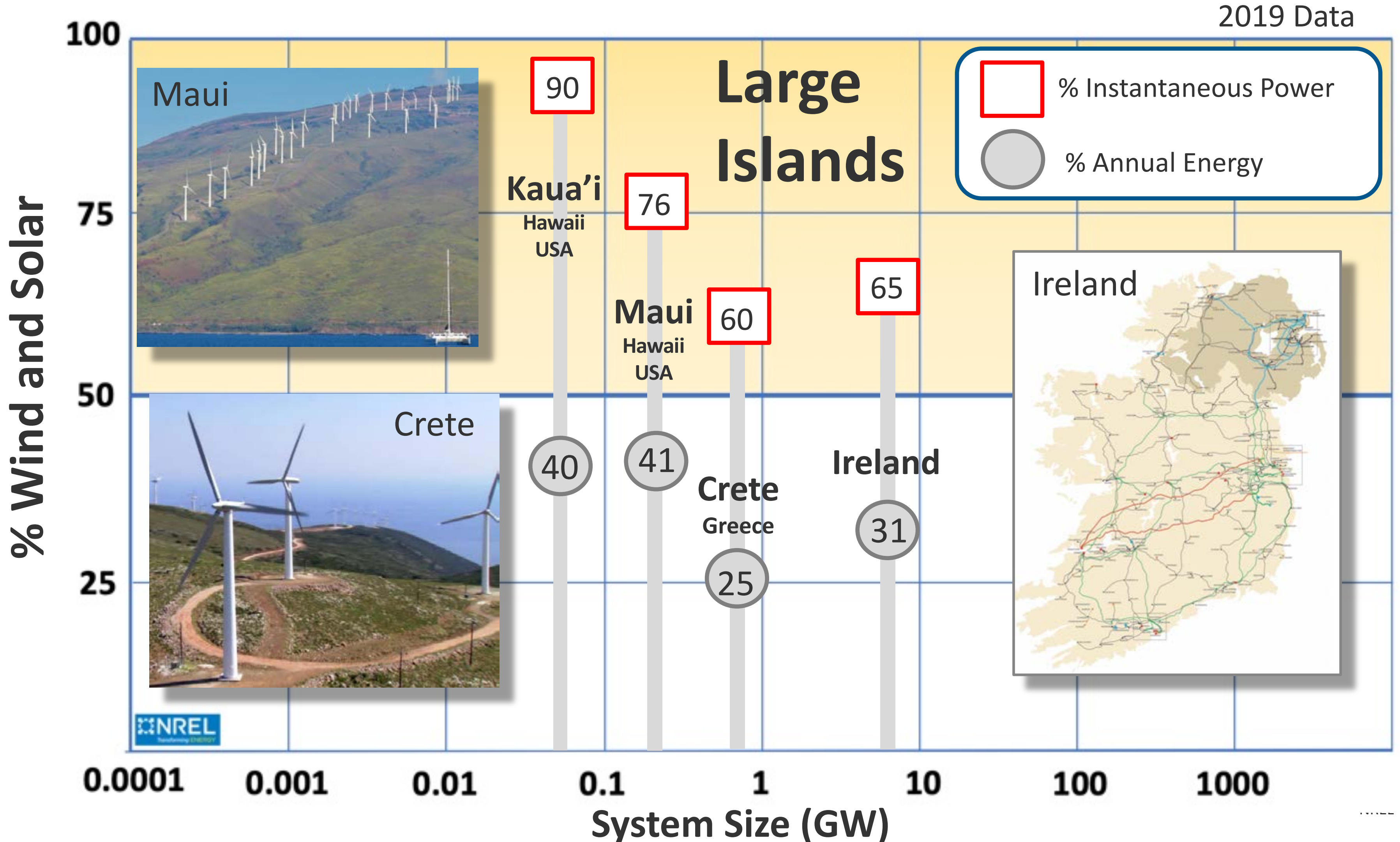
Source: Cole et al., Quantifying the challenge of reaching a 100% renewable energy power system for the United States, Joule (2021), https://doi.org/10.1016/j.joule.2021.05.011

Current Power Systems Operating with Variable Renewable Energy

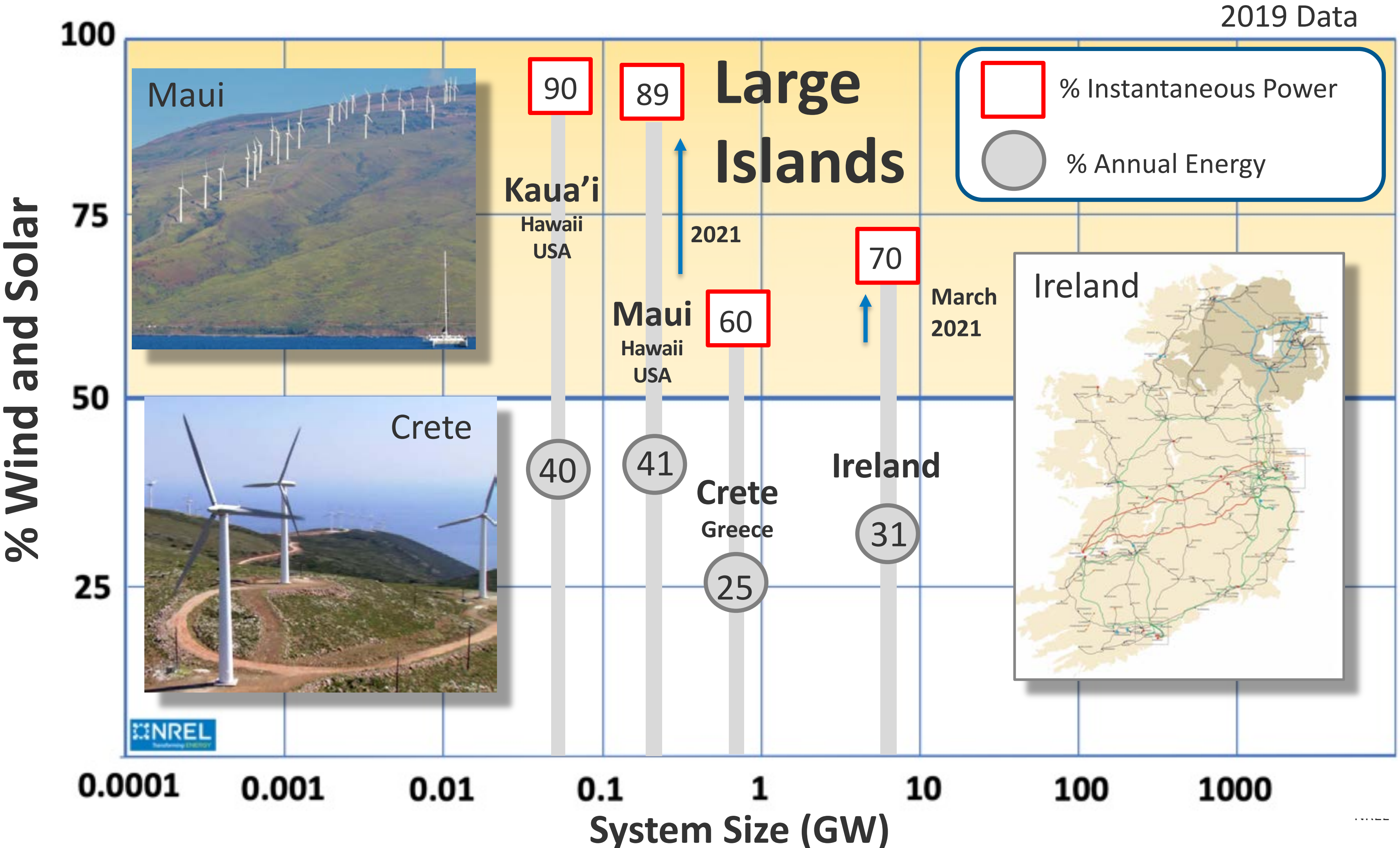
(what do we know)

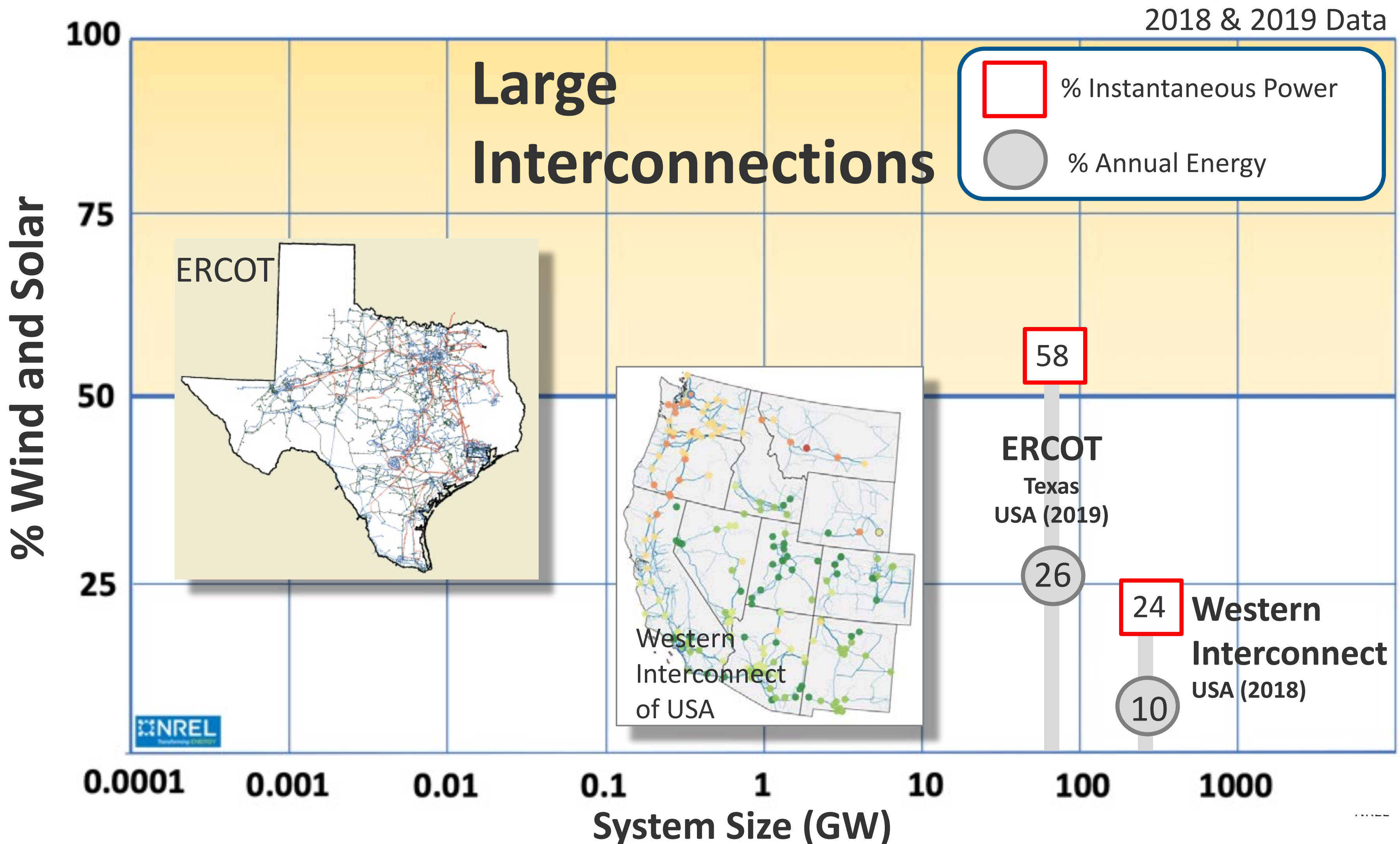
Photo: 550MW Desert Sunlight Plant
Courtesy: NextEra Energy Resources


2019 Data
Small Islands
% Instantaneous Power
% Annual Energy
100
Ta'u
Island
American
Samoa
100
65
King
Island
Australia
100
80
El Hierro
Canary Islands
Spain
Ta'u Island
King Island
King Island
Advanced Hybrid
Power Station
El Hierro
% Wind and Solar
100
75
50
25
0.0001
0.001
0.01
0.1
1
10
100
1000
System Size (GW)
NREL

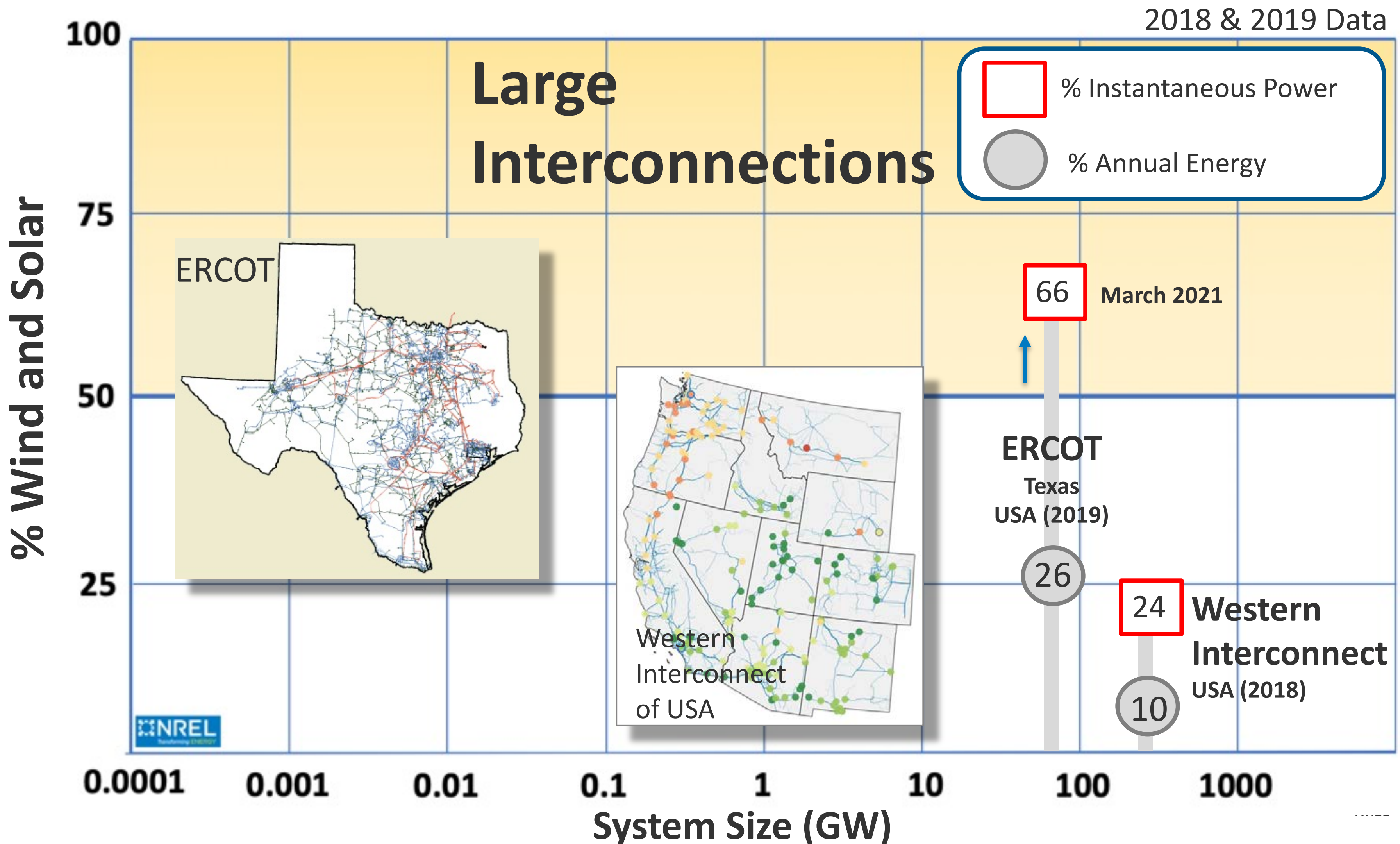


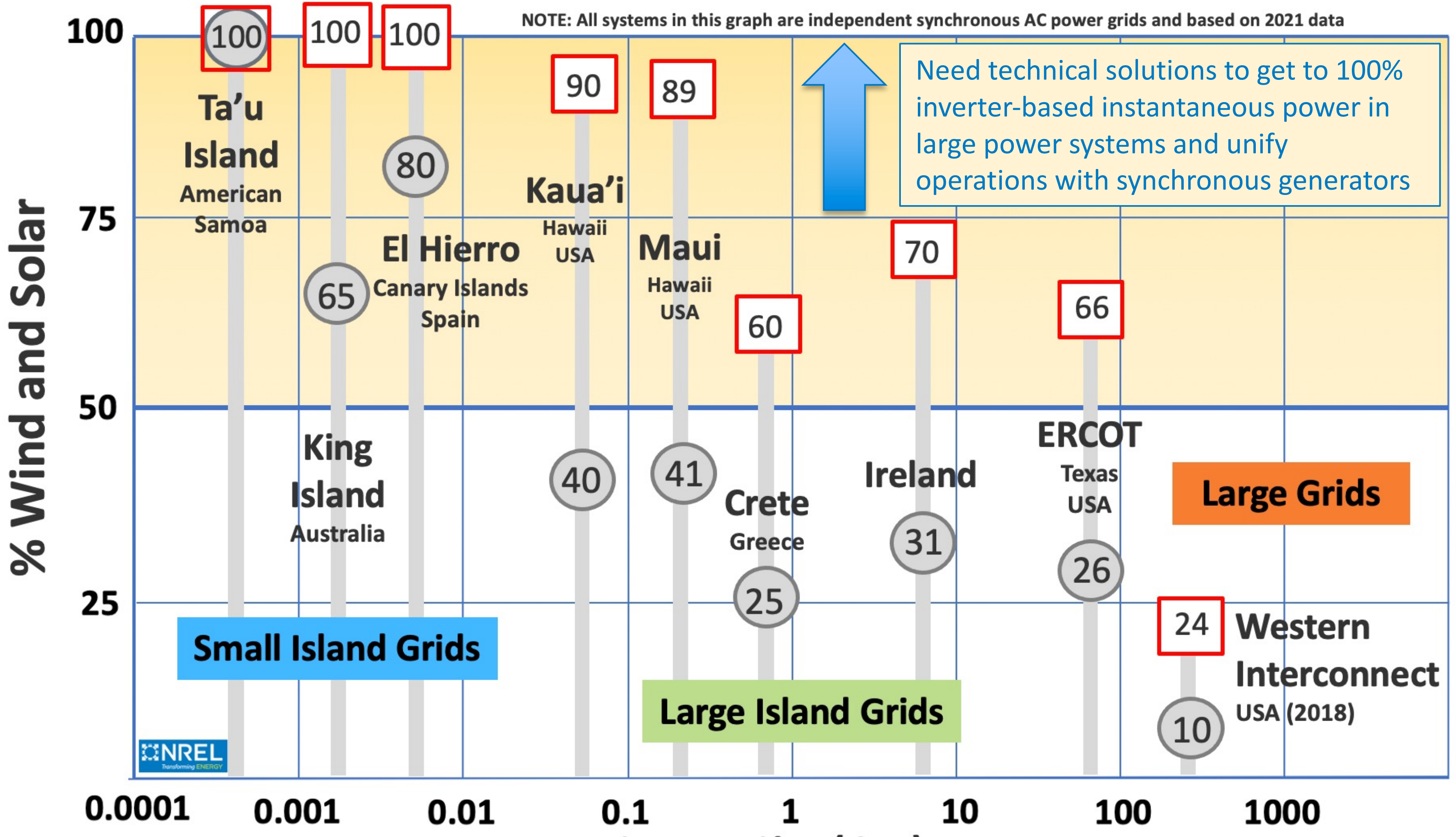
2019 Data
Large Islands
% Instantaneous Power
% Annual Energy
Maui
Crete
Ireland
90
Kaua'i
Hawaii
USA
40
76
Maui
Hawaii
USA
41
60
Crete
Greece
25
65
Ireland
31
% Wind and Solar
100
75
50
25
0.0001
0.001
0.01
0.1
1
10
100
1000
System Size (GW)
NREL


2019 Data
100
75
50
25
% Wind and Solar
Maui
90
Kaua'i
Hawaii
USA
89
2021
Large
Islands
% Instantaneous Power
% Annual Energy
70
March
2021
60
Maui
Hawaii
USA
Ireland
Crete
40
41
Crete
Greece
25
Ireland
31
NREL
0.0001
0.001
0.01
0.1
1
10
100
1000
System Size (GW)



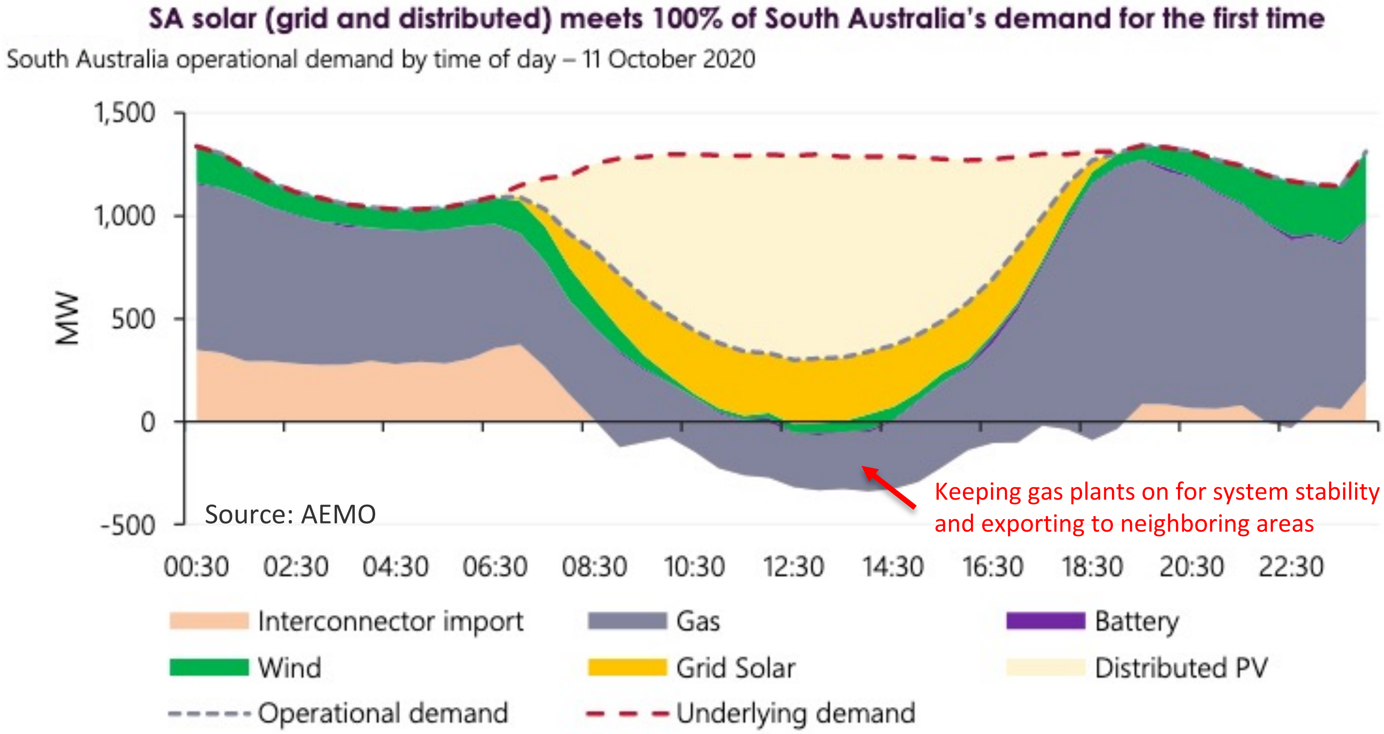
2018 & 2019 Data
Large Interconnections
% Instantaneous Power
% Annual Energy
ERCOT
58
ERCOT
Texas
USA (2019)
26
24
Western Interconnect
USA (2018)
10
Western Interconnect of USA
NREL
% Wind and Solar
100
75
50
25
0.0001
0.001
0.01
0.1
1
10
100
1000
System Size (GW)


2018 & 2019 Data
Large Interconnections
% Instantaneous Power
% Annual Energy
ERCOT
66
March 2021
ERCOT
Texas
USA (2019)
26
24
Western Interconnect
USA (2018)
10
Western Interconnect of USA
% Wind and Solar
100
75
50
25
0.0001
0.001
0.01
0.1
1
10
100
1000
System Size (GW)

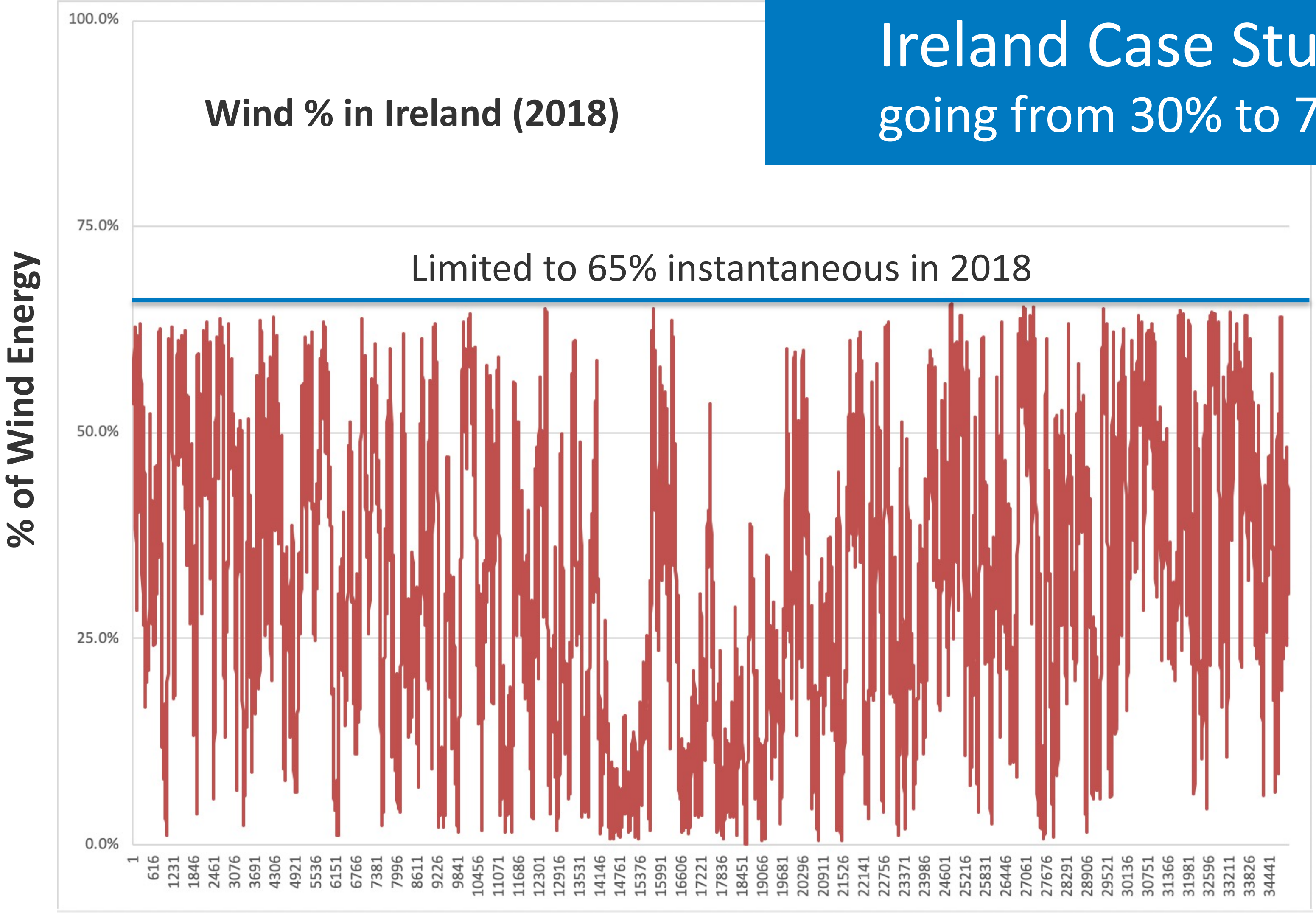


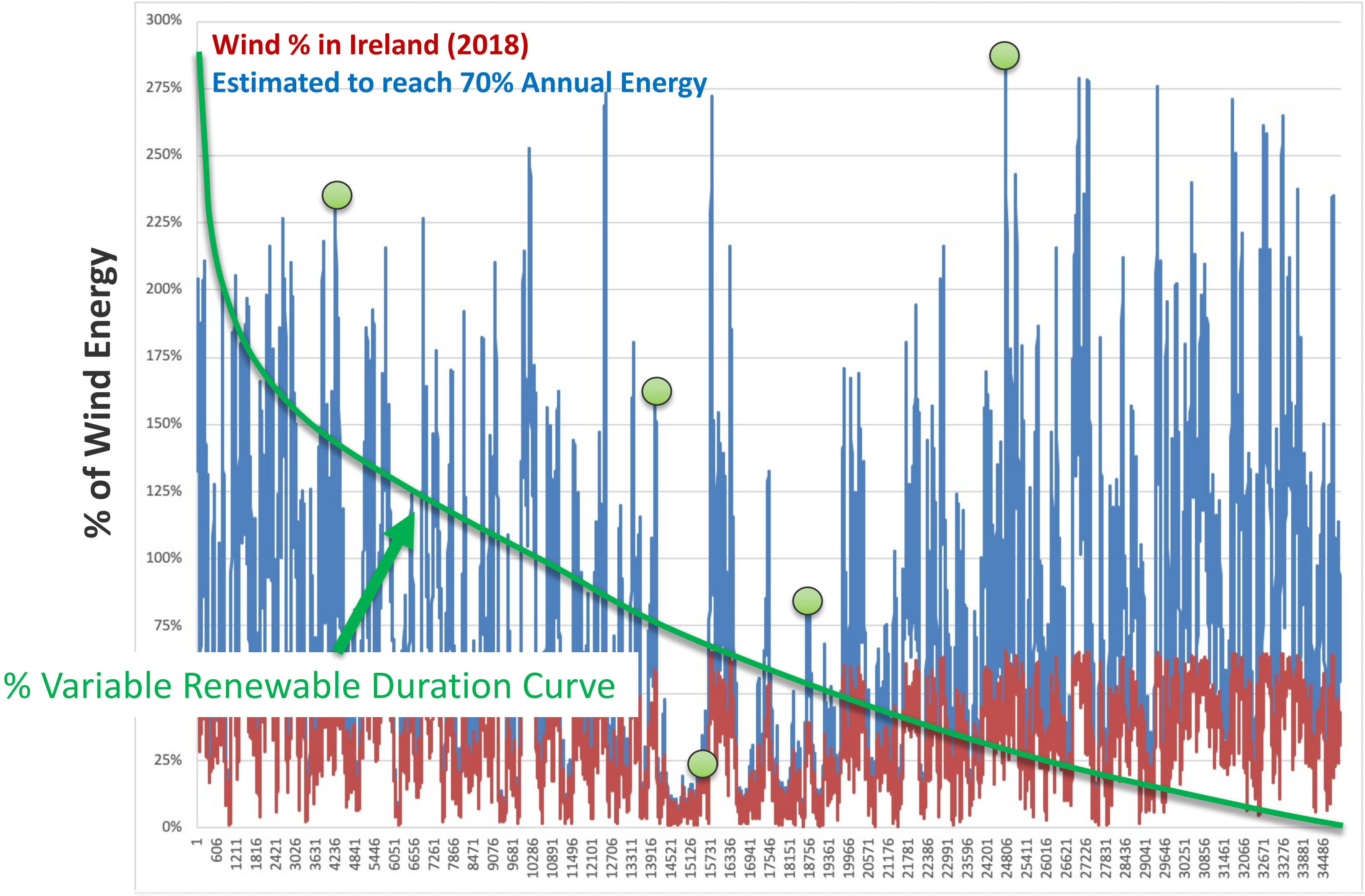
Source: Island Power Systems with High Levels of Inverter-Based Resources: Stability and Reliability Challenges, A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. Kenyon, B. Kroposki, IEEE Electrification Magazine, March 2021

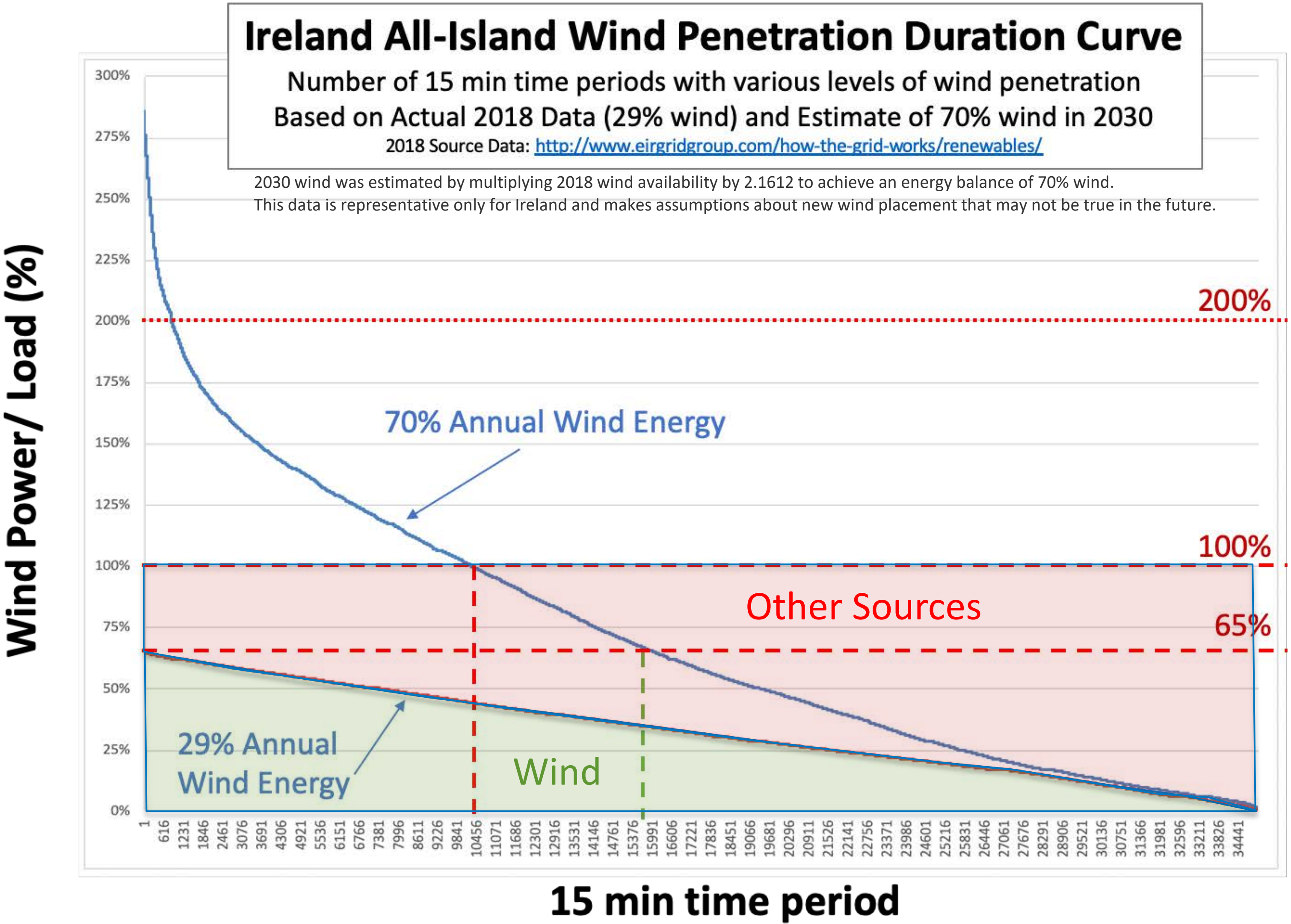
South Australia – Seeing large amounts of PV



Ireland Case Study
going from 30% to 70%




Wind % in Ireland (2018)
Estimated to reach 70% Annual Energy
% of Wind Energy
300%
275%
250%
225%
200%
175%
150%
125%
100%
75%
25%
0%
1
606
1211
1816
2421
3026
3631
4236
4841
5446
6051
6656
7261
7866
8471
9076
9681
10286
10891
11496
12101
12706
13311
13916
14521
15126
15731
16336
16941
17546
18151
18756
19361
19966
20571
21176
21781
22386
22991
23596
24201
24806
25411
26016
26621
27226
27831
28436
29041
29646
30251
30856
31461
32066
32671
33276
33881
34486
% Variable Renewable Duration Curve

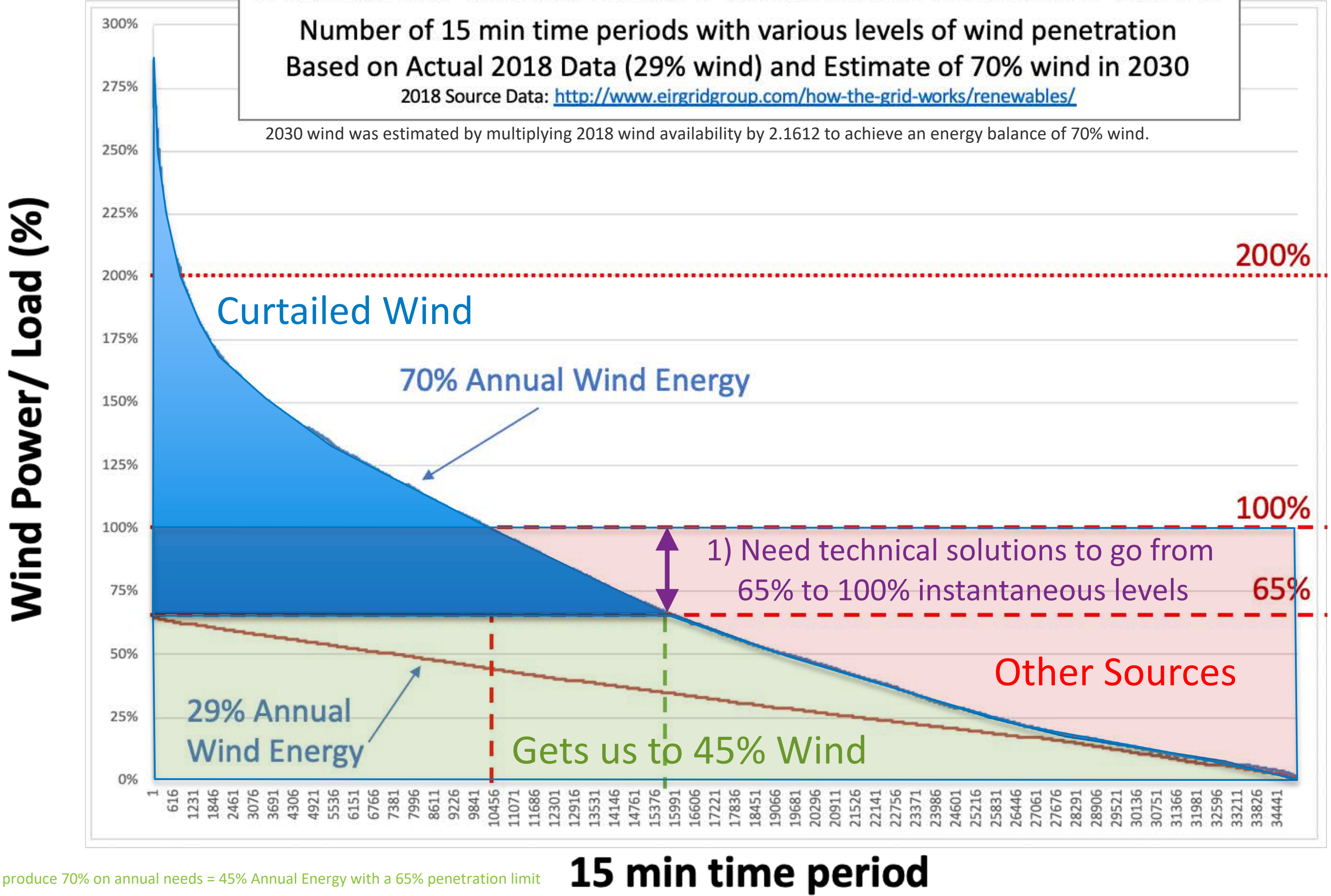


Currently limited to 65% (2018) for a variety of reasons including system inertia and minimum loading of existing on-line generation.

Ireland All-Island Wind Penetration Duration Curve

Number of 15 min time periods with various levels of wind penetration
Based on Actual 2018 Data (29% wind) and Estimate of 70% wind in 2030
2018 Source Data: http://www.eirgridgroup.com/how-the-grid-works/renewables/

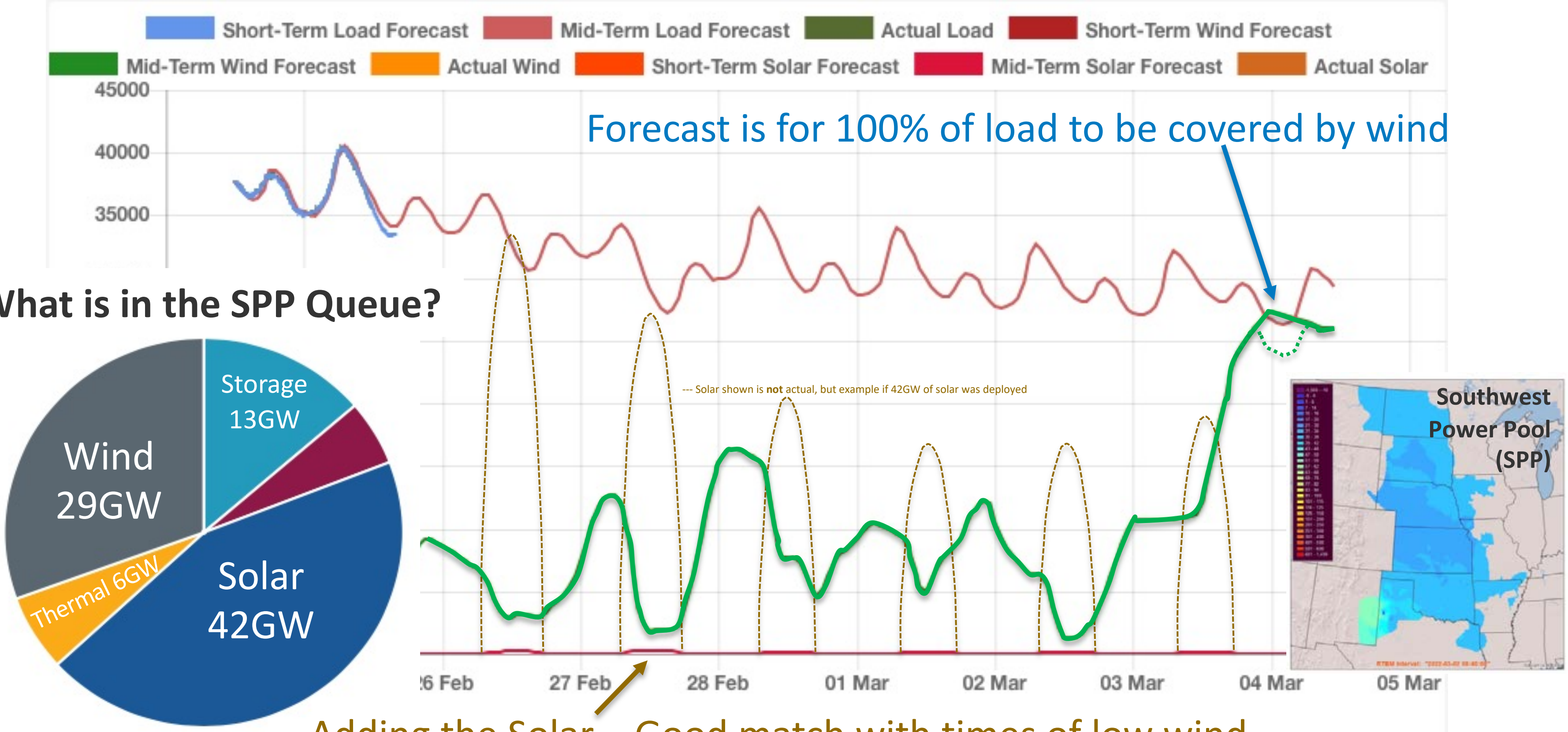
2030 wind was estimated by multiplying 2018 wind availability by 2.1612 to achieve an energy balance of 70% wind.



Installed capacity to produce 70% on annual needs = 45% Annual Energy with a 65% penetration limit

SPP Forecast vs. Actual for 2022-02-25 12:50:00 (Central Time)

https://marketplace.spp.org/pages/forecast-vs-actual



What is in the SPP Queue?

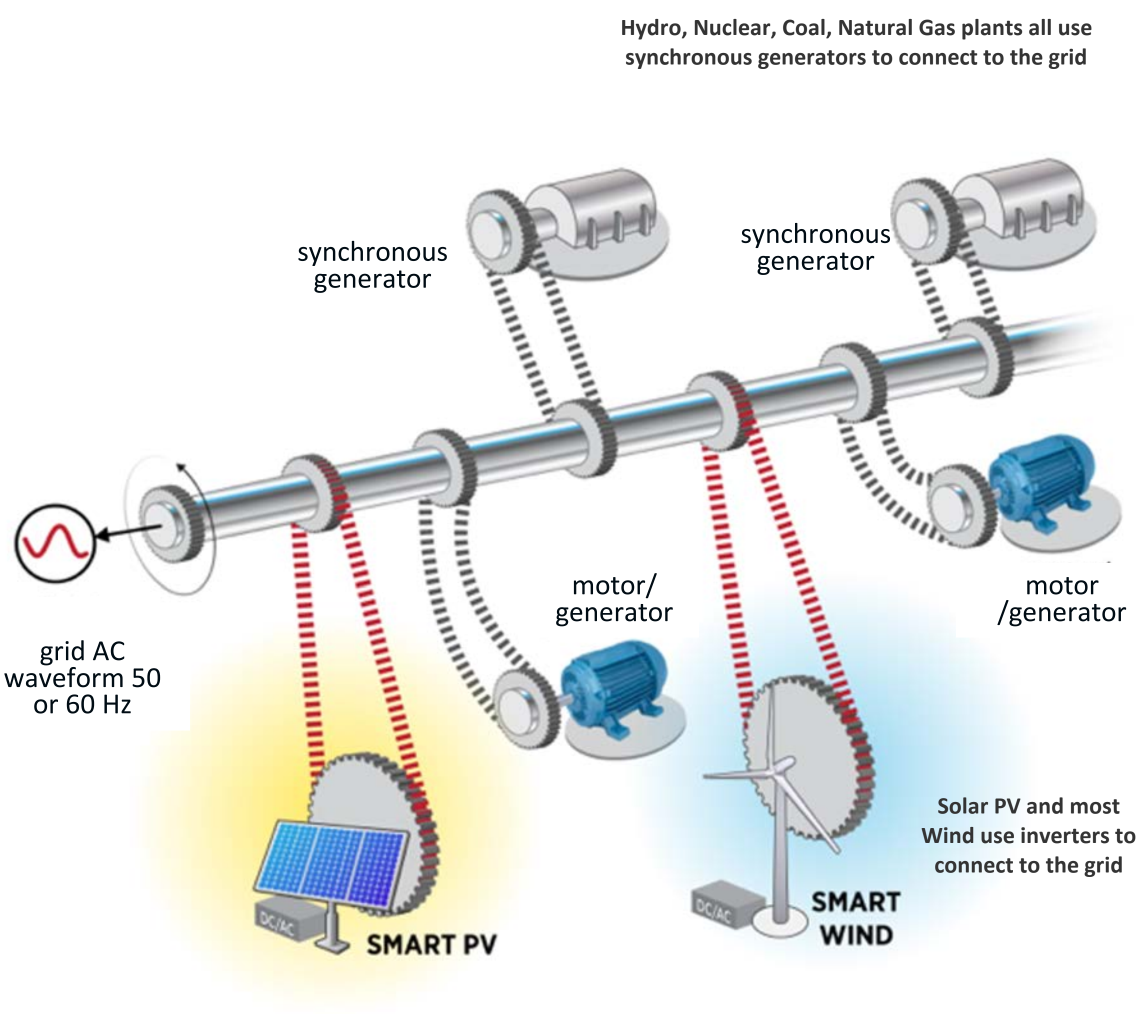
Adding the Solar – Good match with times of low wind
and Adding the Wind…

Getting to very high instantaneous levels of inverter-based resources

(Balance at very fast time scales (<10s)

Integrating Synchronous Generators with Inverters

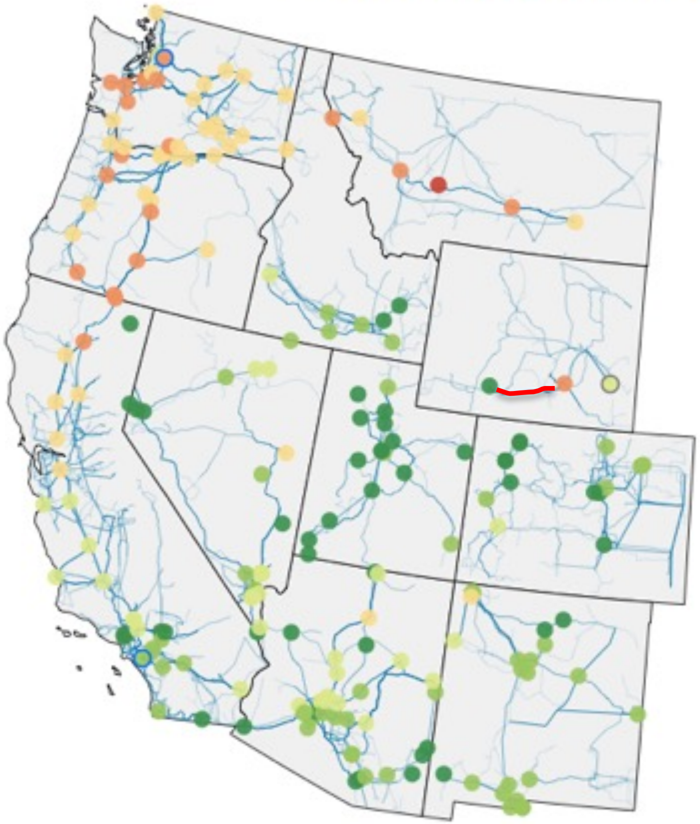
Need to unify the operation of synchronous machines and inverter-based resources at any scale



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/

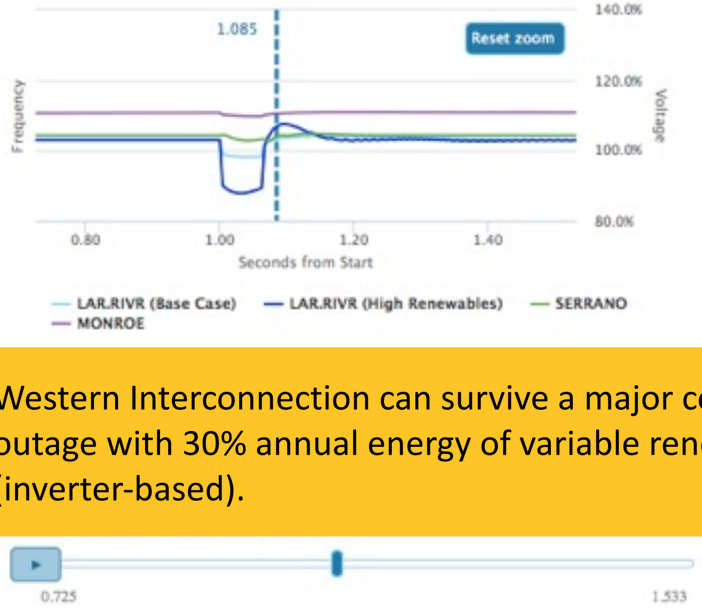
Understanding Inertia Video
https://www.youtube.com/watch?v=b9JN7kj1tso

System Stability



Western Wind and Solar Integration Study

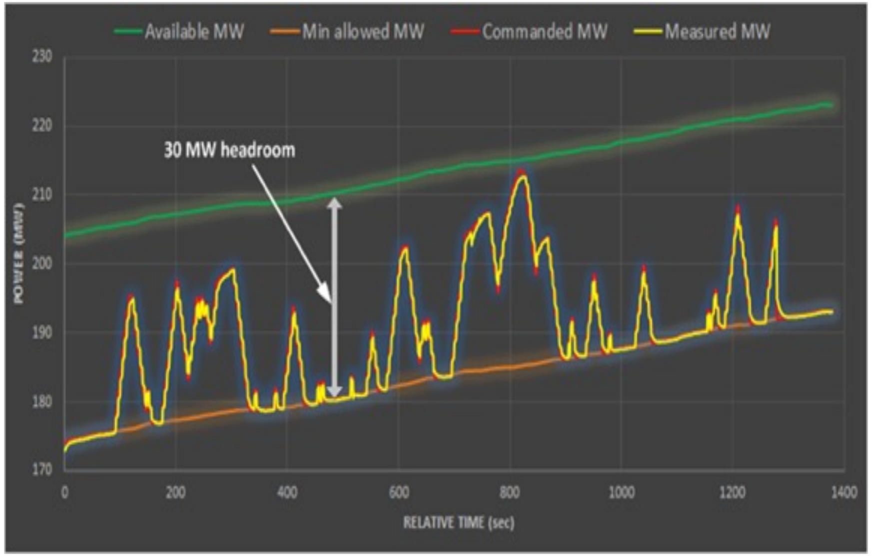
- **Wind power plants:** voltage regulation and ride-through
- **Utility-scale PV:** voltage regulation and ride-through
- **Rooftop PV:** embedded in composite load model, no controls.



Western Interconnection can survive a major contingency outage with 30% annual energy of variable renewable energy (inverter-based).

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

Inverter Based Resources can Provide Grid Services



NREL/FirstSolar/CAISO experiment: 300-MW plant following Automatic Generator Control (AGC) signal

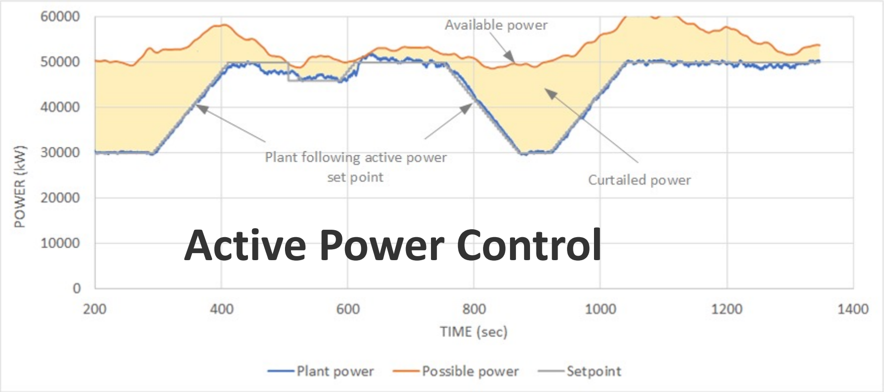
300-MW PV Plant in California *(Photo from First Solar)*

Demonstrated that PV plants (and wind power plants on next slide) can deliver essential grid services.

Source: C. Loutan, P. Klauer, S. Chowdhury, S. Hall, M. Morjaria, V. Chadliev, N. Milam, C. Milan, V. Gevorgian, *Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant*, http://www.nrel.gov/docs/fy17osti/67799.pdf

Wind Providing Grid Services

CAISO, in partnership with Avangrid Renewables, NREL, and General Electric, conducted tests on the energy company's Tule Wind Farm, located in eastern San Diego County, to demonstrate that a large, utility- scale wind plants can provide essential reliability services

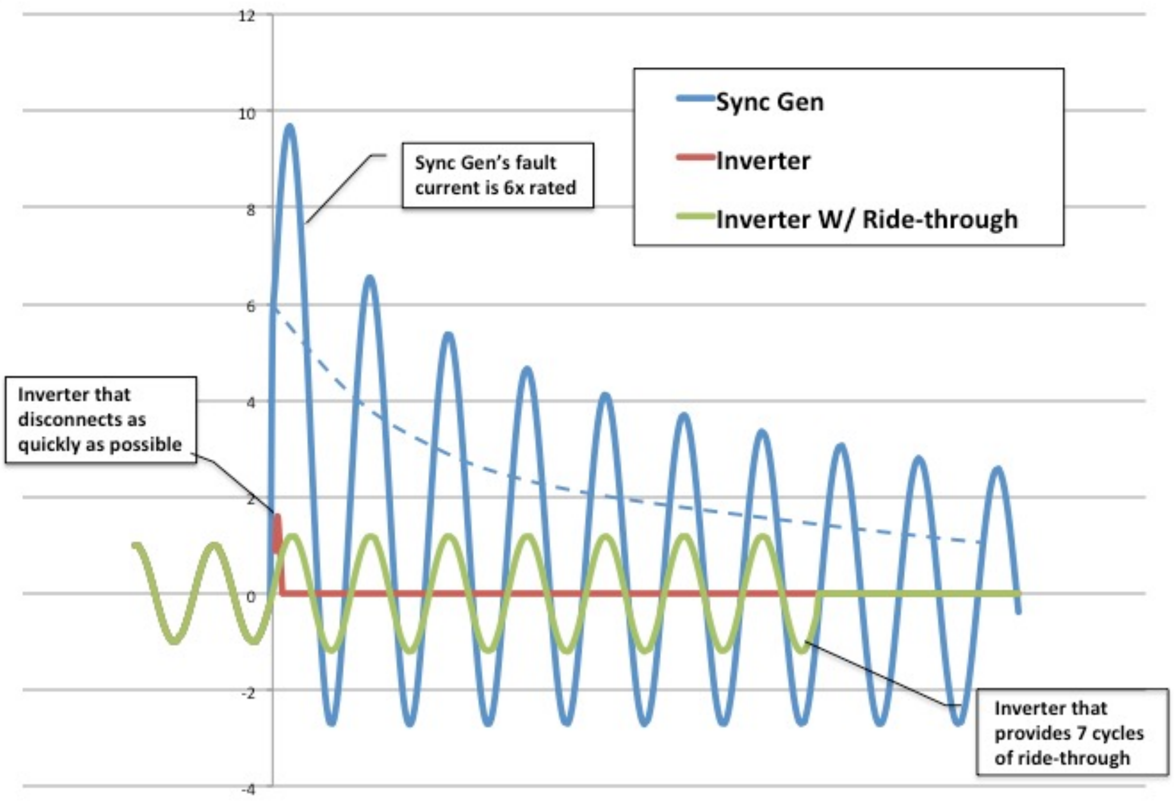


Avangrid Renewables Tule Wind Farm
Demonstration of Capability to Provide Essential Grid Services
http://www.caiso.com/Documents/WindPowerPlantTestResults.pdf

Technical challenges with higher Inverter-based resources

Challenges:

- Lower System Inertia (frequency stability)
- Voltage Stability and Regulation
- Grid Forming capability
- Black Start capability
- System Protection
- Control system interactions and resonances
- Cybersecurity



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/

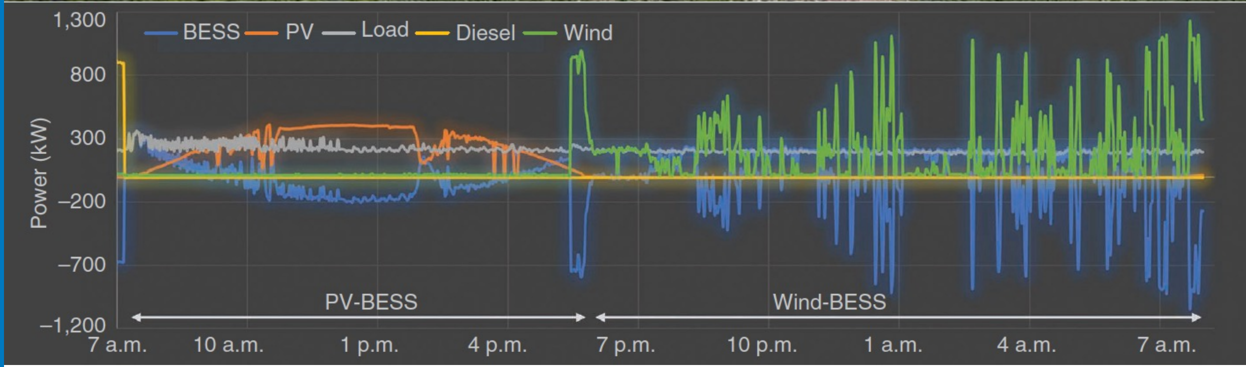
Running a 100% Inverter-based Grid

Operations of a 100% Wind-Solar-Battery Power Grid

including Blackstart

- 1.5MW Wind turbine, 450kW PV system, and 1MW/1MWh Battery
- NREL operated a 100% Wind-PV-Battery Grid for 72 Hours during a site outage
- Demonstrating new control techniques for these types of systems

Source: Island Power Systems with High Levels of Inverter-Based Resources: Stability and Reliability Challenges, A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. Kenyon, B. Kroposki, IEEE Electrification Magazine, March 2021



24-hour operation of Wind-PV-Battery System at NREL's Flatiron Campus

Working to unify the integration of inverters and synchronous machines

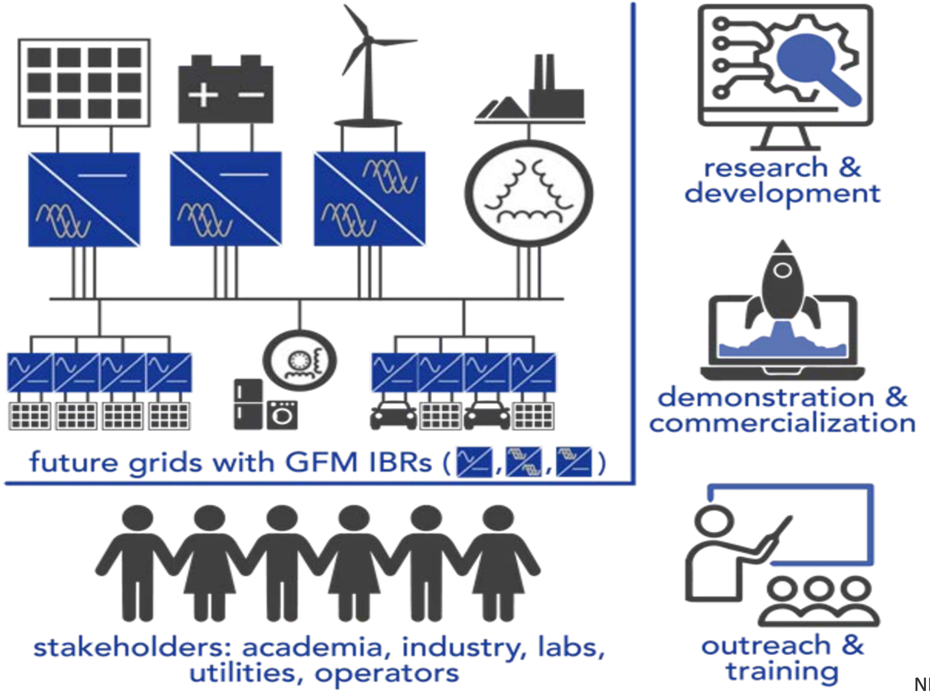
Co-led by NREL, Univ. of Washington, and EPRI

Forum to address fundamental challenges in seamless integration of GFM technologies into power systems of the future

Conduct research and development, demo concepts at scale, author best practices and standards, train next-generation workforce

unifi consortium

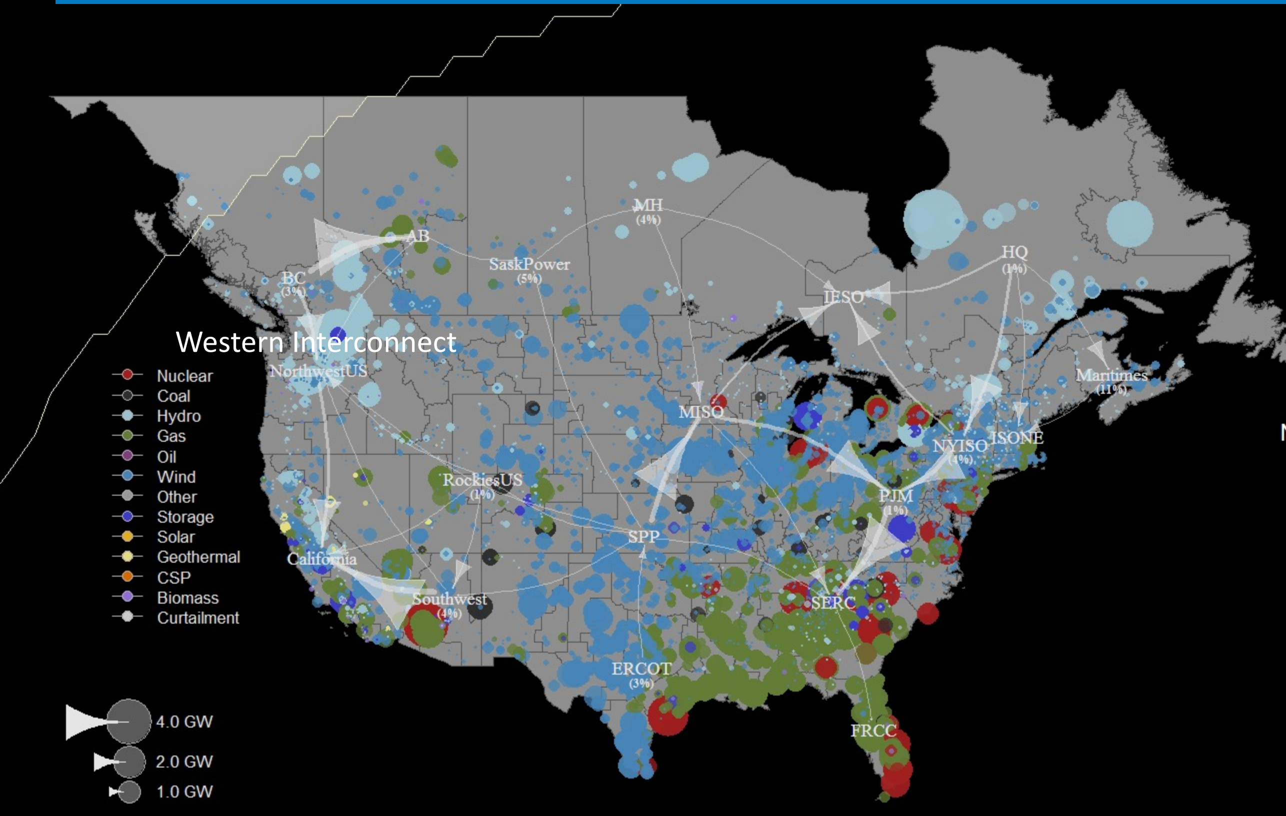
universal interoperability for grid-forming inverters



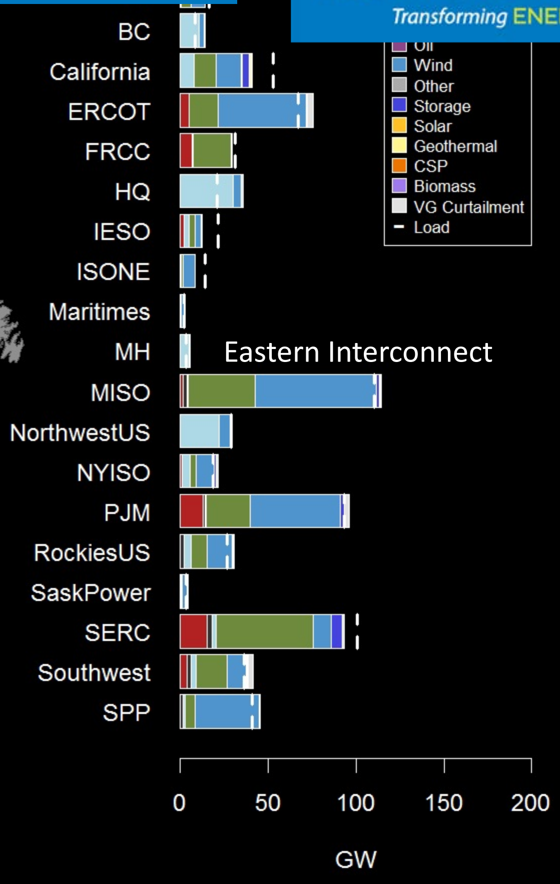
Dealing with Variability and Uncertainty of Solar and Wind

(Balancing at longer time scales >10sec)

Need to balance generation and load at every time period



Generation & Flow



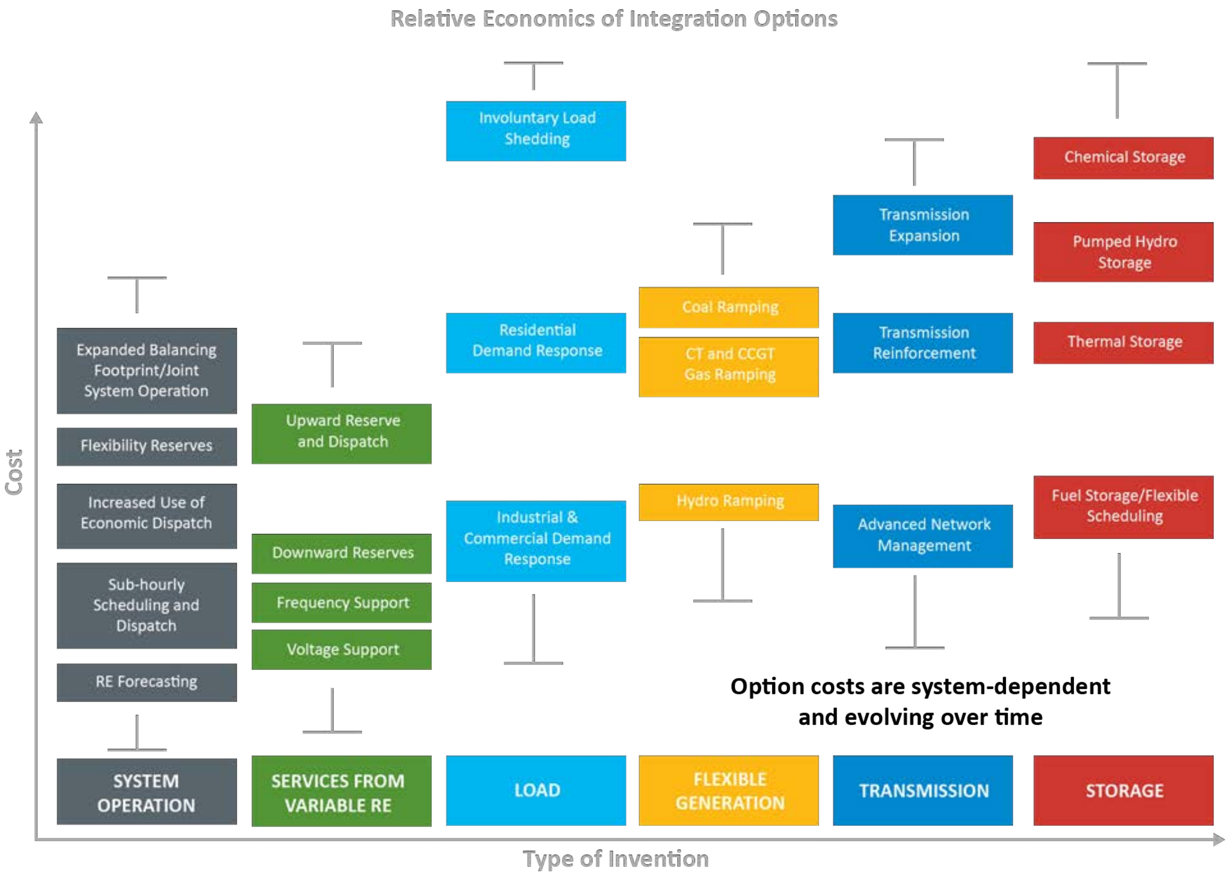
Regional dispatch

Options for Dealing with Variability and Uncertainty

-Creating System Flexibility

Solutions:

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



Option costs are system-dependent and evolving over time

Source: *Impact of Flexibility Options on Grid Economic Carrying Capacity of Solar and Wind: Three Case Studies*
P. Denholm, J. Novacheck, J. Jorgenson, and M. O'Connell, National Renewable Energy Laboratory, NREL/TP-6A20-66854, December 2016, https://www.nrel.gov/docs/fy17osti/66854.pdf

Using Generation to Address Integration Issues

Upward Reserve and Dispatch

Downward Reserves

Frequency Support

Voltage Support

SERVICES FROM VARIABLE RE

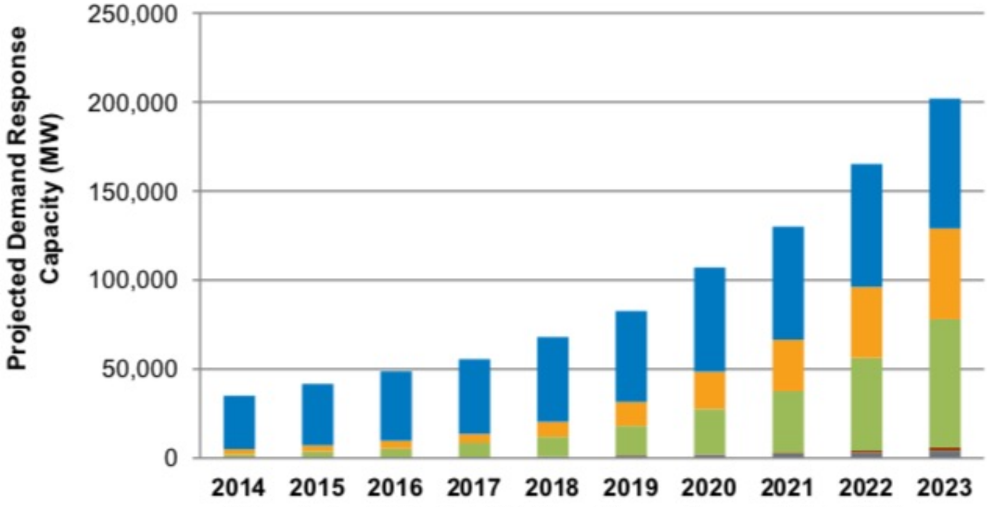
Coal Ramping

CT and CCGT Gas Ramping

Hydro Ramping

FLEXIBLE GENERATION

Demand Response



Feldman, Brett, and Bob Lockhart. 2014. "Demand Response: Commercial & Industrial DR, Residential DR, and DR Management Systems: Global Market Analysis and Forecasts." Navigant Research.

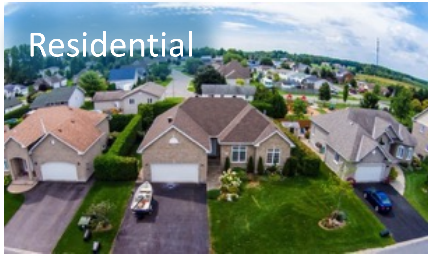
How do you control millions of generators, storage, loads?

Involuntary Load Shedding

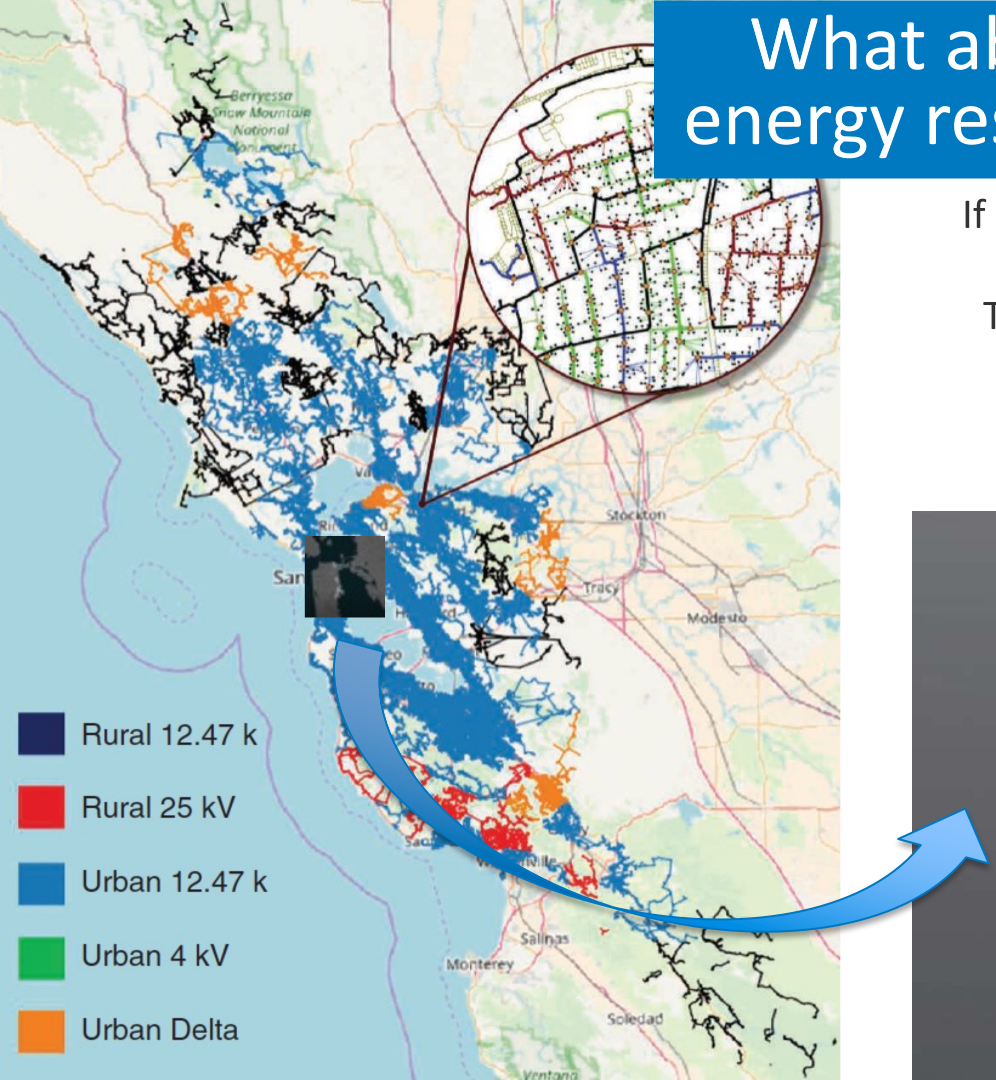
Residential Demand Response

Industrial & Commercial Demand Response

LOAD

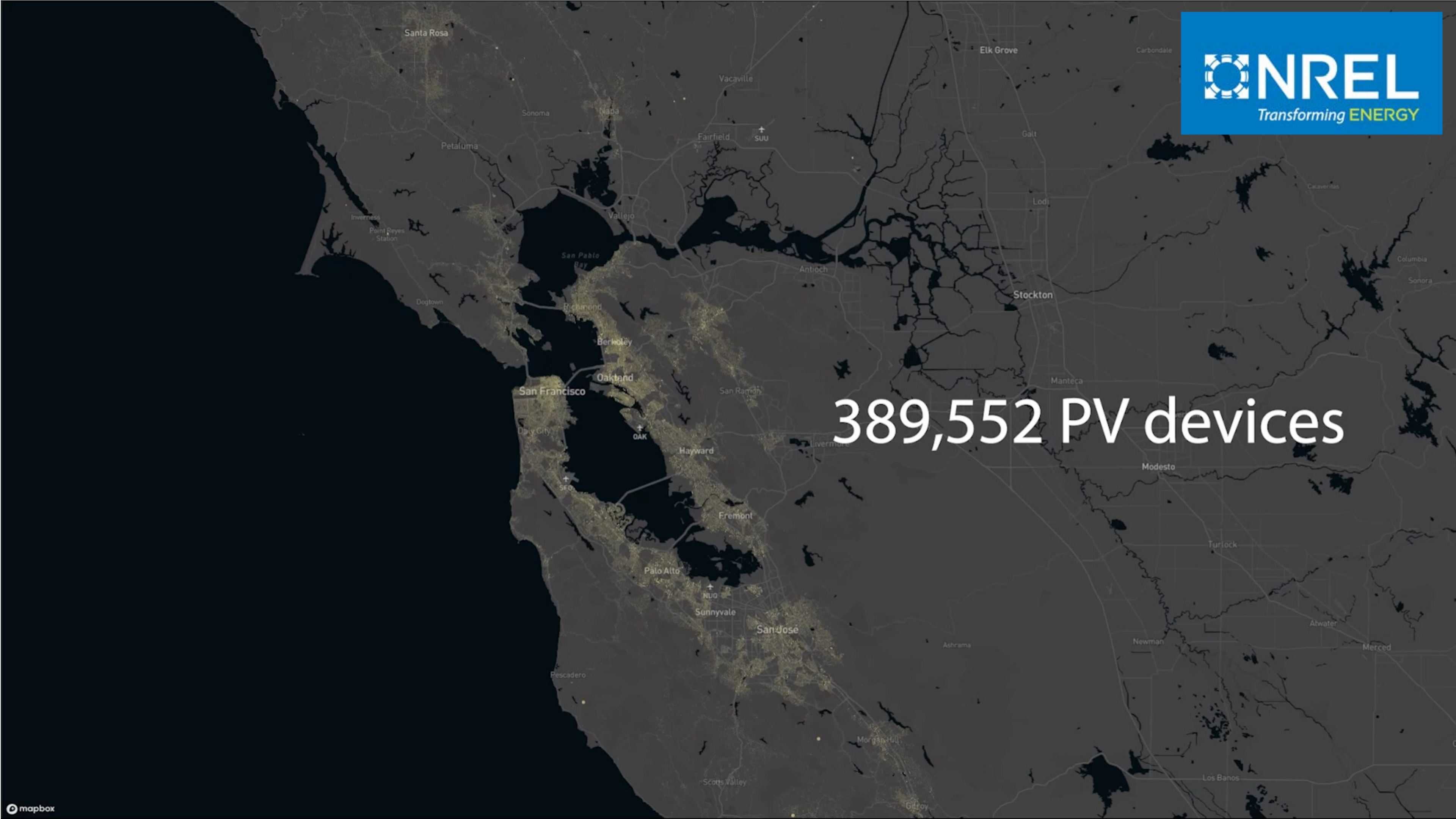


What about massive distributed energy resource (DER) deployment?

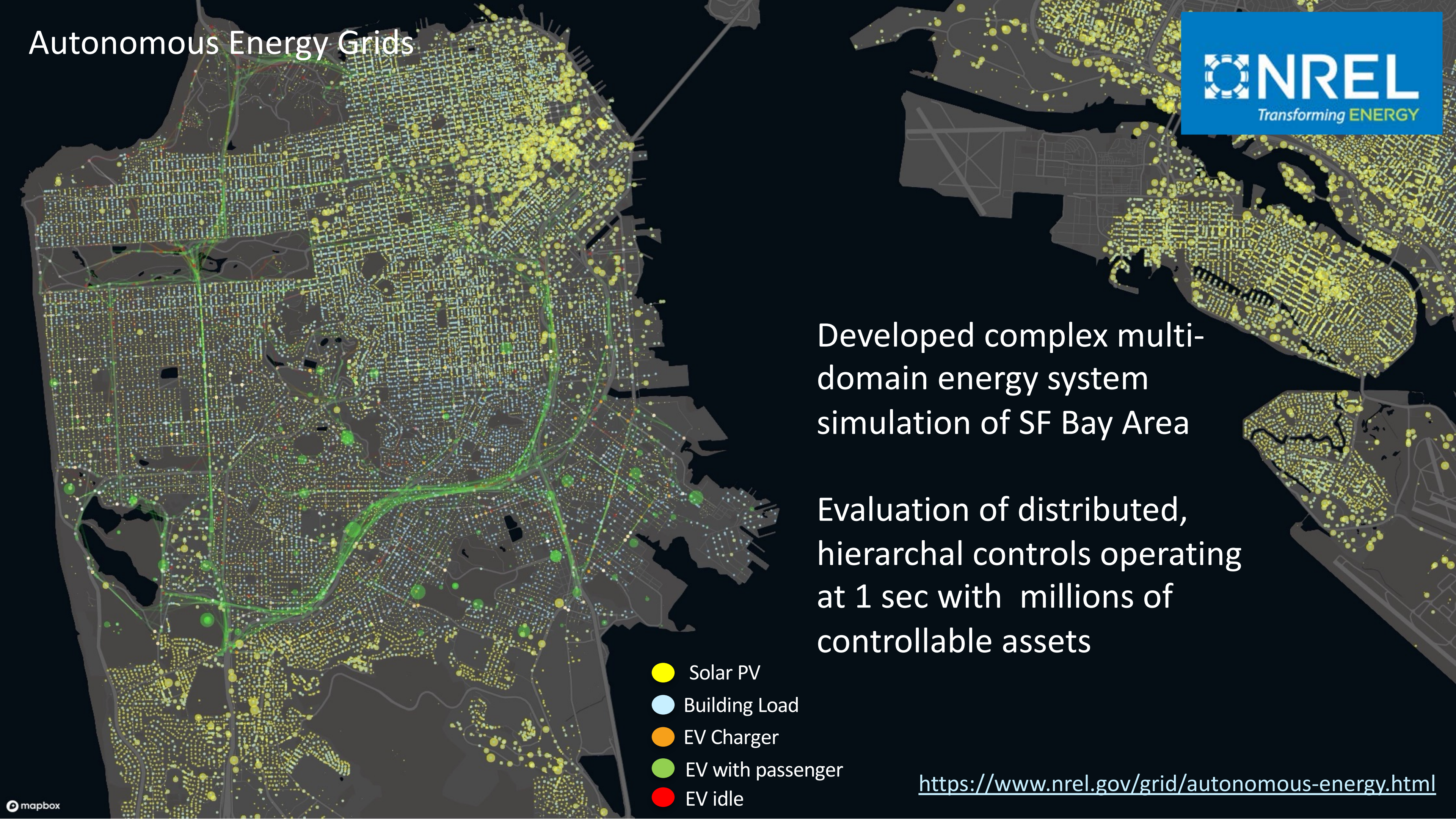


If every customer in the San Francisco Bay Area had PV, storage batteries, Electric Vehicles, Smart Thermostats and Smart Appliances you may have 10-20 Million controllable devices in this area.

--- **Autonomous Energy Grids**---


389,552 PV devices
Santa Rosa
Elk Grove
Vacaville
Sonoma
Petaluma
Fairfield
Galt
Lodi
Vallejo
Antioch
Stockton
Richmond
Berkeley
Oakland
San Francisco
San Ramon
Manteca
Hayward
Modesto
Fremont
Palo Alto
Sunnyvale
San Jose
Turlock
Atwater
Merced
Newman
Pescadero
Los Banos
mapbox

Autonomous Energy Grids



Developed complex multi-domain energy system simulation of SF Bay Area

Evaluation of distributed, hierarchal controls operating at 1 sec with millions of controllable assets

NREL Transforming ENERGY

https://www.nrel.gov/grid/autonomous-energy.html

Using System Operations and Assets to Address Integration Issues

Expanded Balancing Footprint/Joint System Operation

Flexibility Reserves

Increased Use of Economic Dispatch

Sub-hourly Scheduling and Dispatch

RE Forecasting

SYSTEM OPERATION

Interconnection Seam Study

Evaluated the benefits and costs of options for continental transmission across the U.S. electric grid.

No increase in transmission capacity between the interconnections

Increasing capacity at existing back-to-back ties

Increasing existing back-to-back capacity and add three long-distance HVDC ties

Nationwide HVDC

https://www.nrel.gov/analysis/seams.html

Transmission Expansion

Transmission Reinforcement

Advanced Network Management

TRANSMISSION

Energy Storage


Photo: LS Power

Gateway Energy Storage Project
San Diego, California, USA
250MW for 1hr (250MWh) Li-ion Battery

Since wind and solar have relatively low capacity factors (20-50%) there will be increasing needs for energy storage

- Chemical Storage
- Pumped Hydro Storage
- Thermal Storage
- Fuel Storage/Flexible Scheduling

STORAGE

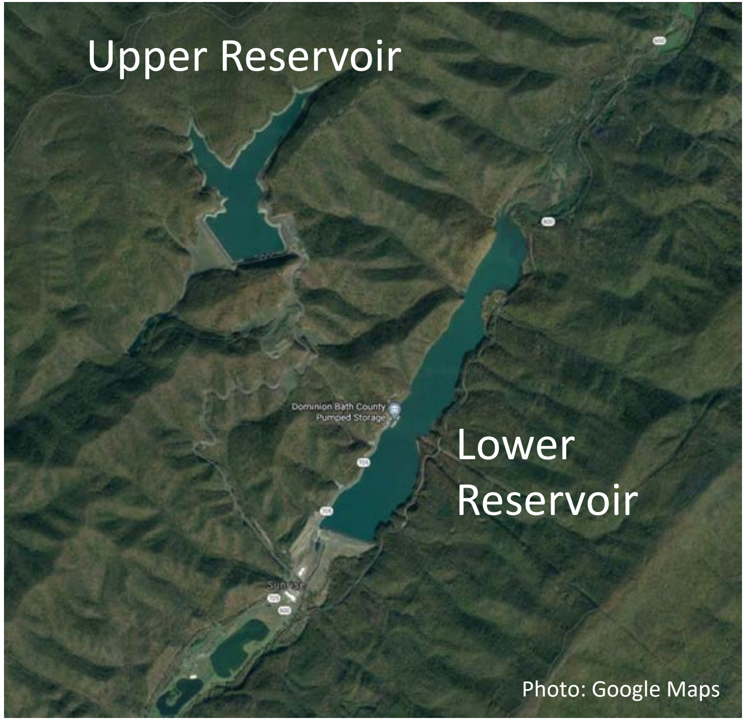


Photo: Google Maps

Pumped Hydro Storage Facility
Bath County, Virginia, USA
3GW for 11 Hrs (24-30GWh)

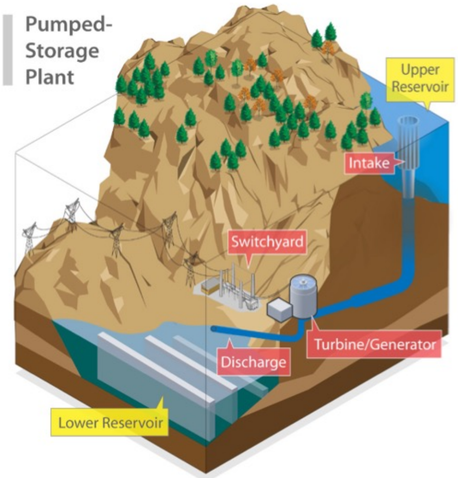
Informative video on this Pumped Hydro System
https://www.youtube.com/watch?v=ppPlUdBdvhU

Energy Storage

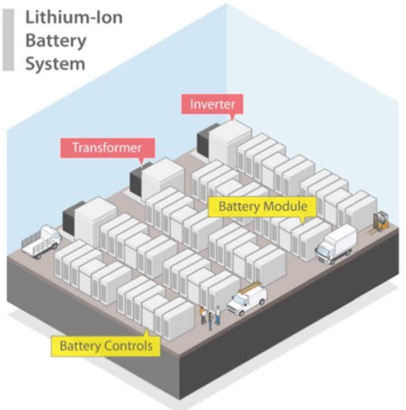
Summary of the Four Phases of Storage Deployment

Phase	Primary Services	National Deployment Potential (Capacity) in Each Phase	Duration	Response Speed
Deployment prior to 2010	Peaking capacity, energy time-shifting and operating reserves	23 gigawatts of pumped storage hydropower	Mostly 8–12 hr	Varies
1	Operating reserves	<30 gigawatts	<1 hr	Milliseconds to seconds
2	Peaking capacity	30–100 gigawatts, strongly linked to photovoltaics deployment	2–6 hr	Minutes
3	Diurnal capacity and energy time shifting	100+ gigawatts. Depends on both Phase 2 and deployment of variable renewable energy resources	4–12 hr	Minutes
4	Multiday to seasonal capacity and energy time-shifting	Zero to more than 250 gigawatts	>12 hr	Minutes

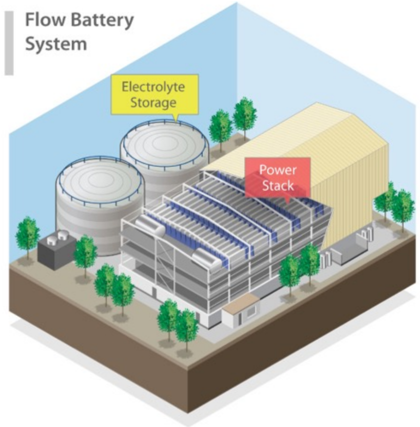
Source: P. Denholm, W. Cole, W. Frazier, K. Podkaminer, and N. Blair. 2021. *The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77480, https://www.nrel.gov/docs/fy21osti/77480.pdf



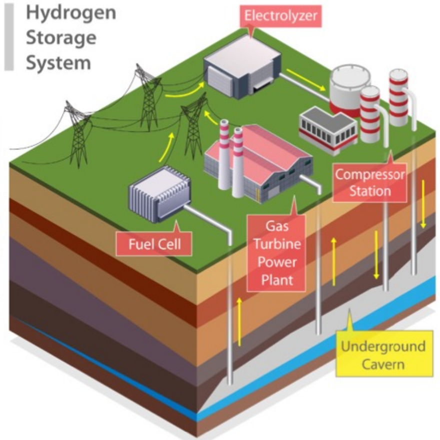
Pumped Hydro



Li-ion Battery

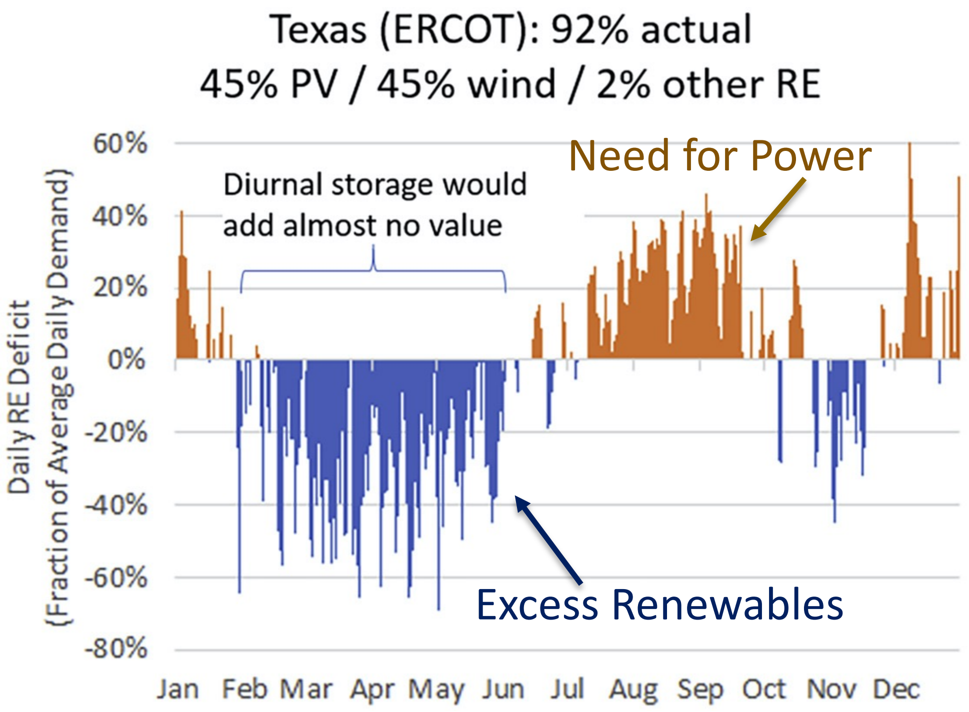


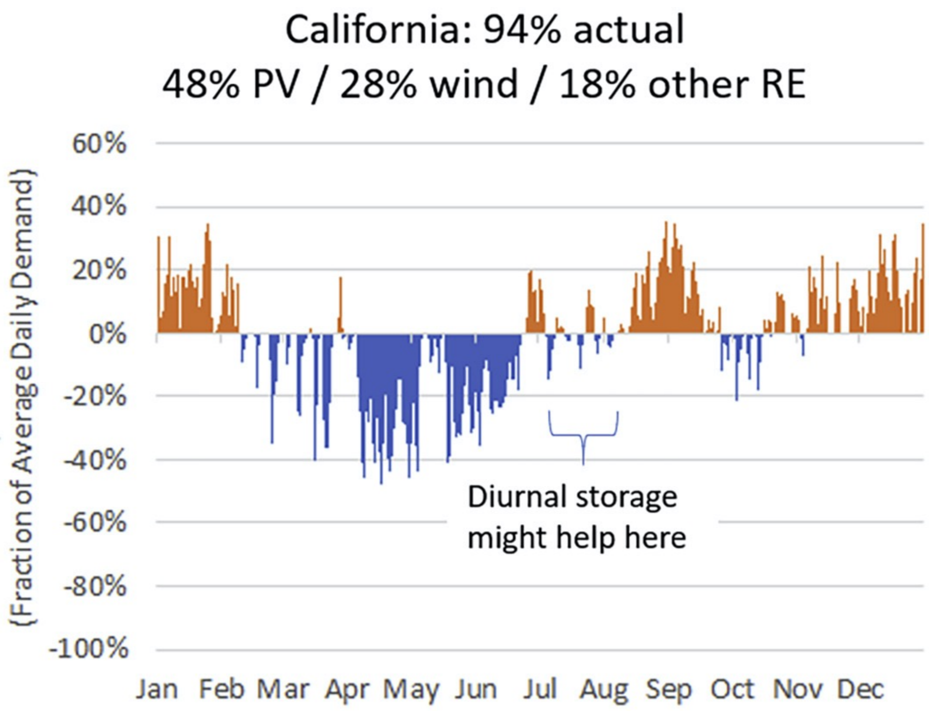
Flow Battery



Hydrogen Storage

The Need for Long-Term Energy Storage at Very High Levels of RE





Source: *"The challenges of achieving a 100% renewable electricity system in the United States"*, P. Denholm, D. Arent, S. Baldwin, D. Bilello, G. Brinkman, J. Cochran, W. Cole, B. Frew, V. Gevorgian, J. Heeter, B. Hodge, B. Kroposki, T. Mai, M. O'Malley, B.Palmintier, D. Steinberg, and Y. Zhang, Joule, May 2020, https://www.sciencedirect.com/science/article/pii/S2542435121001513

Summary

- The power industry is seeing a shift towards 100% clean energy goals and each region has a variety of resources to tap into to meet these goals
- One way to address these goals is increasing use of variable renewable energy like solar and wind
- The favorable economics of solar and wind are driving new installations and deployments
- There are two main challenges with integrating very high levels of solar and wind in power systems:
  - The inverter challenge of adding more power electronics-based technologies and removing synchronous generators
  - The balancing challenge of maintaining the supply/demand balance at all time scales by increasing system flexibility
- These are solvable challenges that will take working together to meet!

For More Information

- *Lazards's Levelized Cost of Energy Analysis-Version 14.0 – 2020* https://www.lazard.com/perspective/lcoe2020
- "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," B. Kroposki et al., IEEE Power & Energy Magazine, Nov/Dec 2017 http://ieeexplore.ieee.org/document/7866938/
- *"Addressing technical challenges in 100% variable inverter-based renewable energy power systems",* B. Hodge et al., WIREs Energy and Environment, April 2020, https://onlinelibrary.wiley.com/doi/full/10.1002/wene.376
- *"WWSIS: Phase 3A",* N.W. Miller et al., http://www.nrel.gov/docs/fy16osti/64822.pdf
- *"Autonomous Energy Grids: Controlling the Future Grid with Large Amounts of Distributed Energy Resources",* B. Kroposki, A. Bernstein, J. King, D. Vaidhynathan, X. Zhou, C. Chang, and E. Dall'Anese IEEE Power and Energy Magazine, November/December 2020, https://ieeexplore.ieee.org/document/9229208
- *"Impact of Flexibility Options on Grid Economic Carrying Capacity of Solar and Wind: Three Case Studies",* P. Denholm, J. Novacheck, J. Jorgenson, and M. O'Connell, National Renewable Energy Laboratory, NREL/TP-6A20-66854, December 2016, https://www.nrel.gov/docs/fy17osti/66854.pdf
- *"The challenges of achieving a 100% renewable electricity system in the United States",* P. Denholm, D. Arent, S. Baldwin, D. Bilello, G. Brinkman, J. Cochran, W. Cole, B. Frew, V. Gevorgian, J. Heeter, B. Hodge, B. Kroposki, T. Mai, M. O'Malley, B.Palmintier, D. Steinberg, and Y. Zhang, Joule, May 2020, https://www.sciencedirect.com/science/article/pii/S2542435121001513
- *"Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States",* Mai, Trieu, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson, 2018, NREL/TP-6A20-71500. https://www.nrel.gov/docs/fy18osti/71500.pdf
- *"Island Power Systems with High Levels of Inverter-Based Resources: Stability and Reliability Challenges",* A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. Kenyon, B. Kroposki, IEEE Electrification Magazine, March 2021 https://ieeexplore.ieee.org/document/9371251
- *"North American Renewable Integration Study"* Brinkman, Gregory, Dominique Bain, Grant Buster, Caroline Draxl, Paritosh Das, Jonathan Ho, Eduardo Ibanez, et al. 2021. https://www.nrel.gov/docs/fy21osti/79224.pdf

Thank you

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