NREL
Transforming ENERGY

Integrated Energy Systems at Scale

Enabling more Renewable Energy

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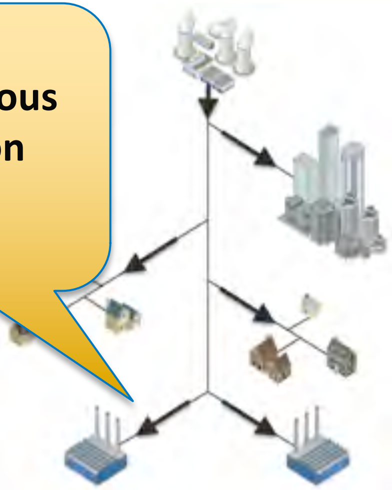
Driving innovation in Energy Systems Integration

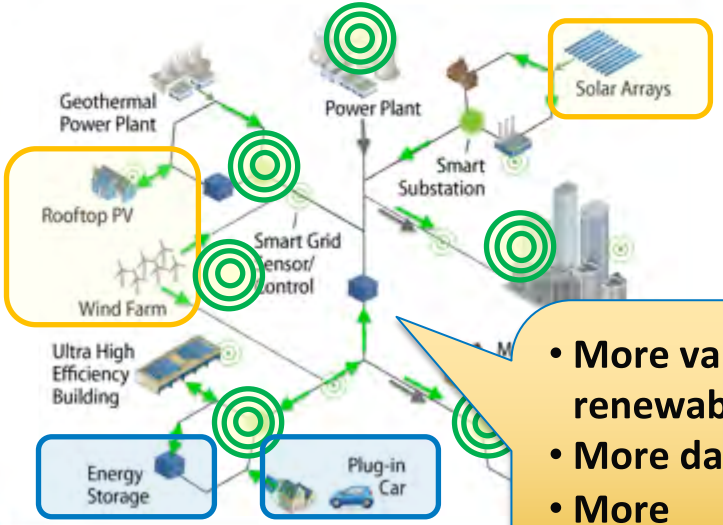
Evolution of the Power System

Current Power System

- Large synchronous generation
- Central control.



Future Power Systems

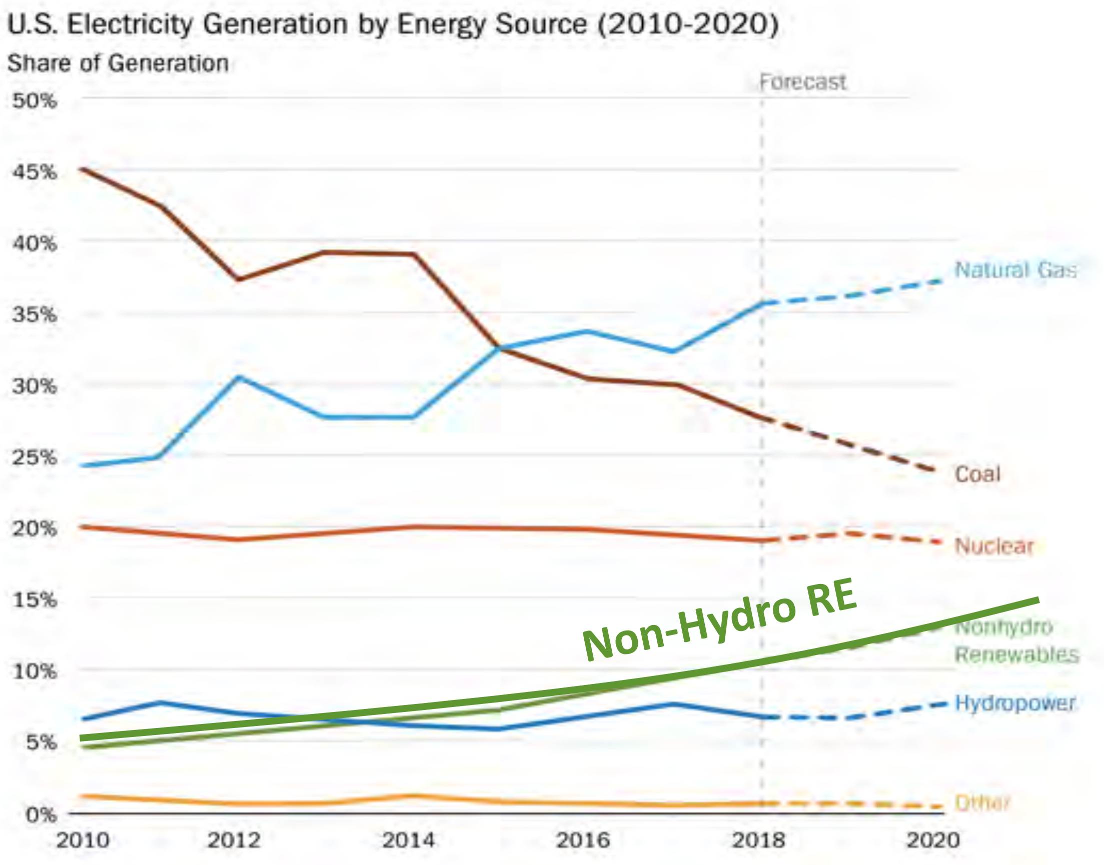


- More variable renewables
- More data
- More distributed resources

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

The US Energy supply is Shifting



Source: United States Energy Information Agency, *Today in Energy,* 18 January 2019

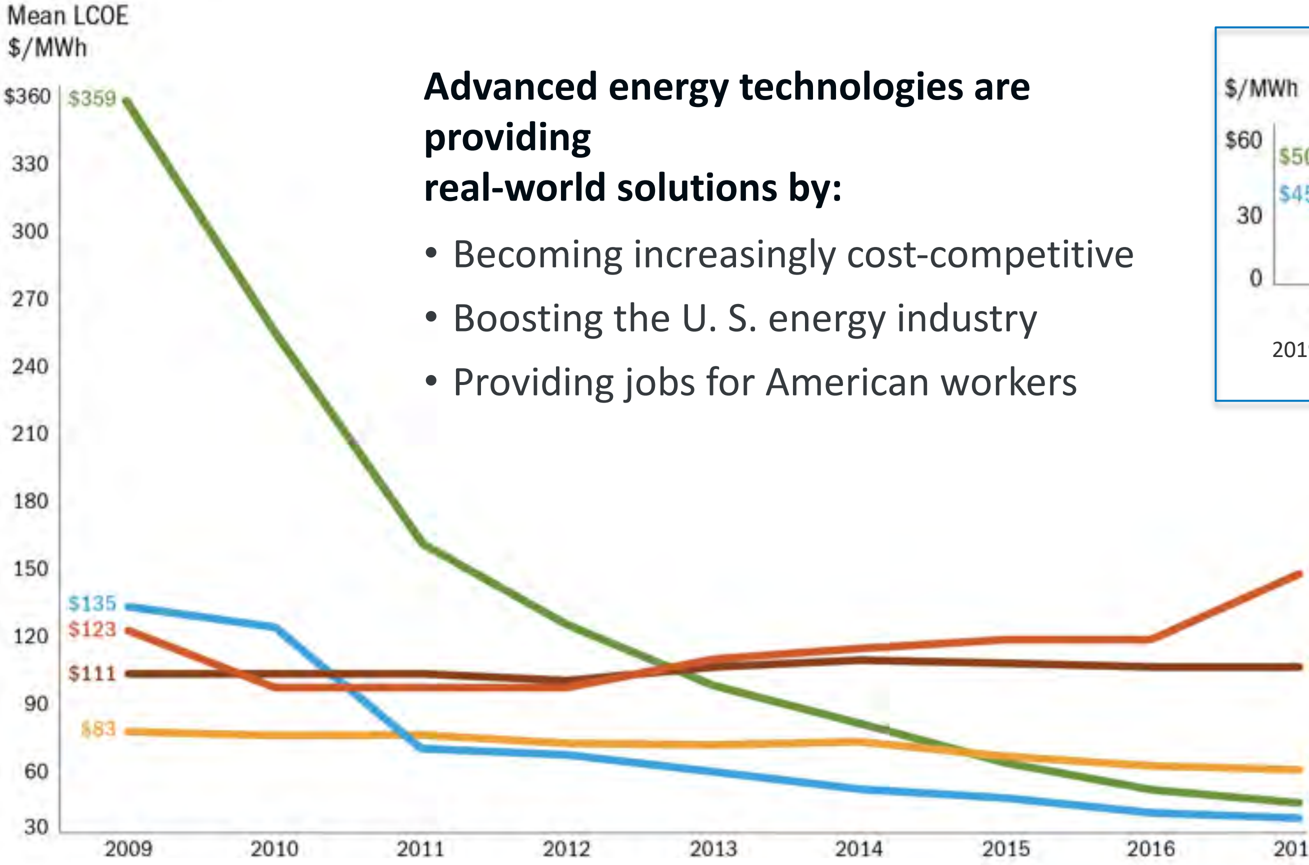
Renewable Energy—

not including hydropower—currently produces 10% of the total U.S. electricity generation. Within the next two years, this is expected to grow to 13%.

The Cost of Renewables is Falling

**Advanced energy technologies are providing
real-world solutions by:**

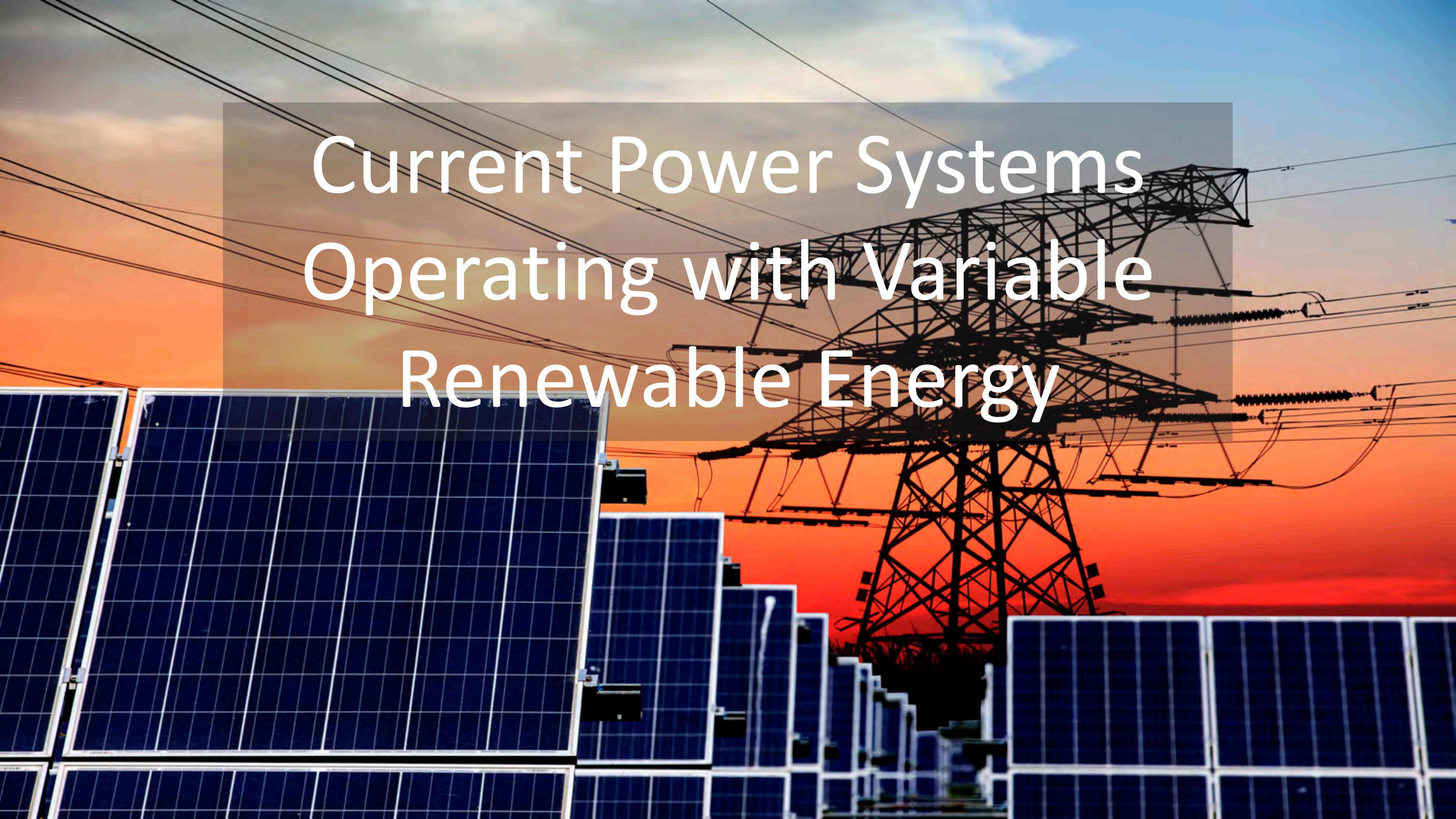
- Becoming increasingly cost-competitive
- Boosting the U. S. energy industry
- Providing jobs for American workers

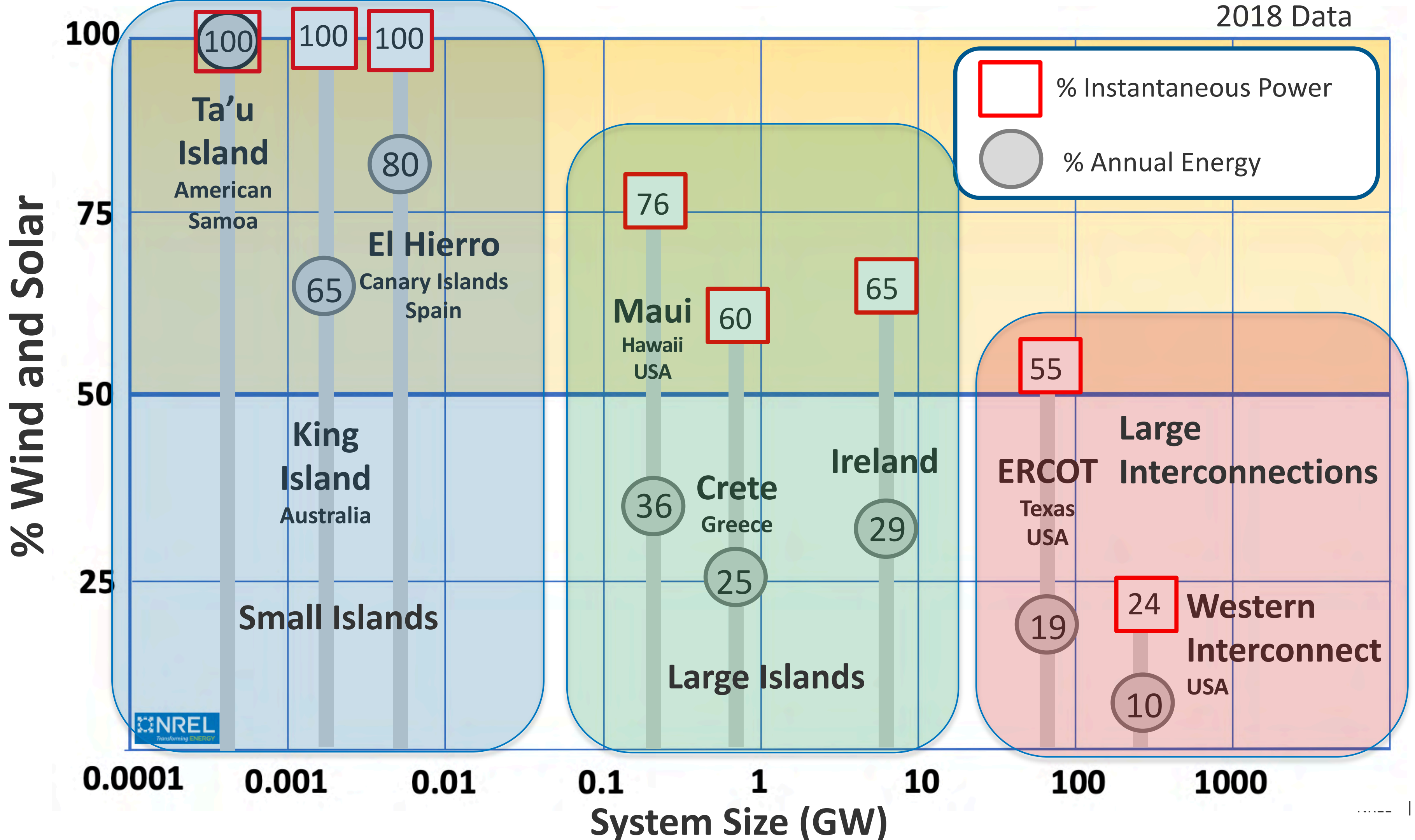


Source: *Lazard's 2017 Levelized Cost of Energy Analysis,* Version 11, 2 November 2017

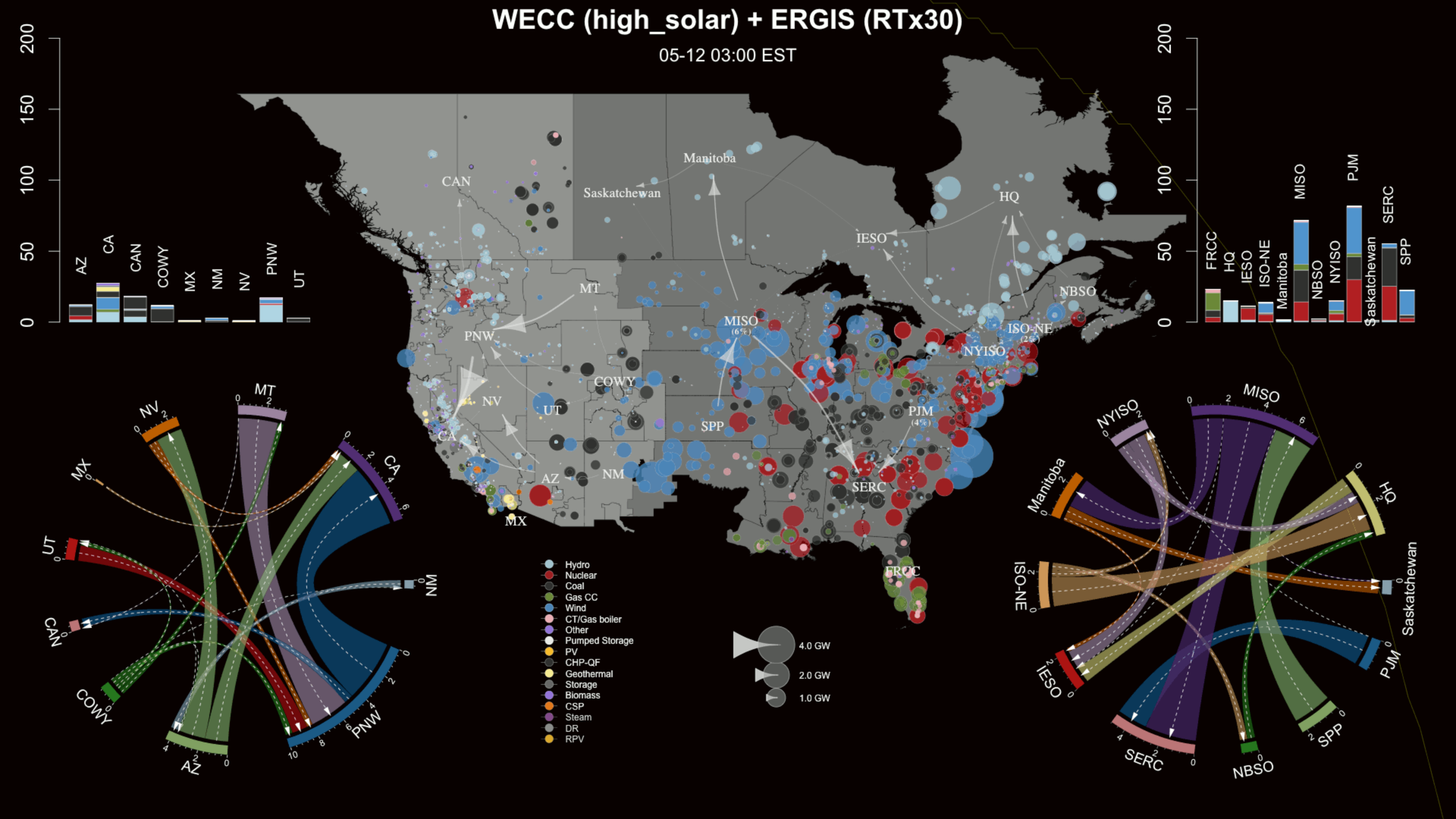
2019 Xcel pricing for projects due to go online in 2023.

Current Power Systems Operating with Variable Renewable Energy





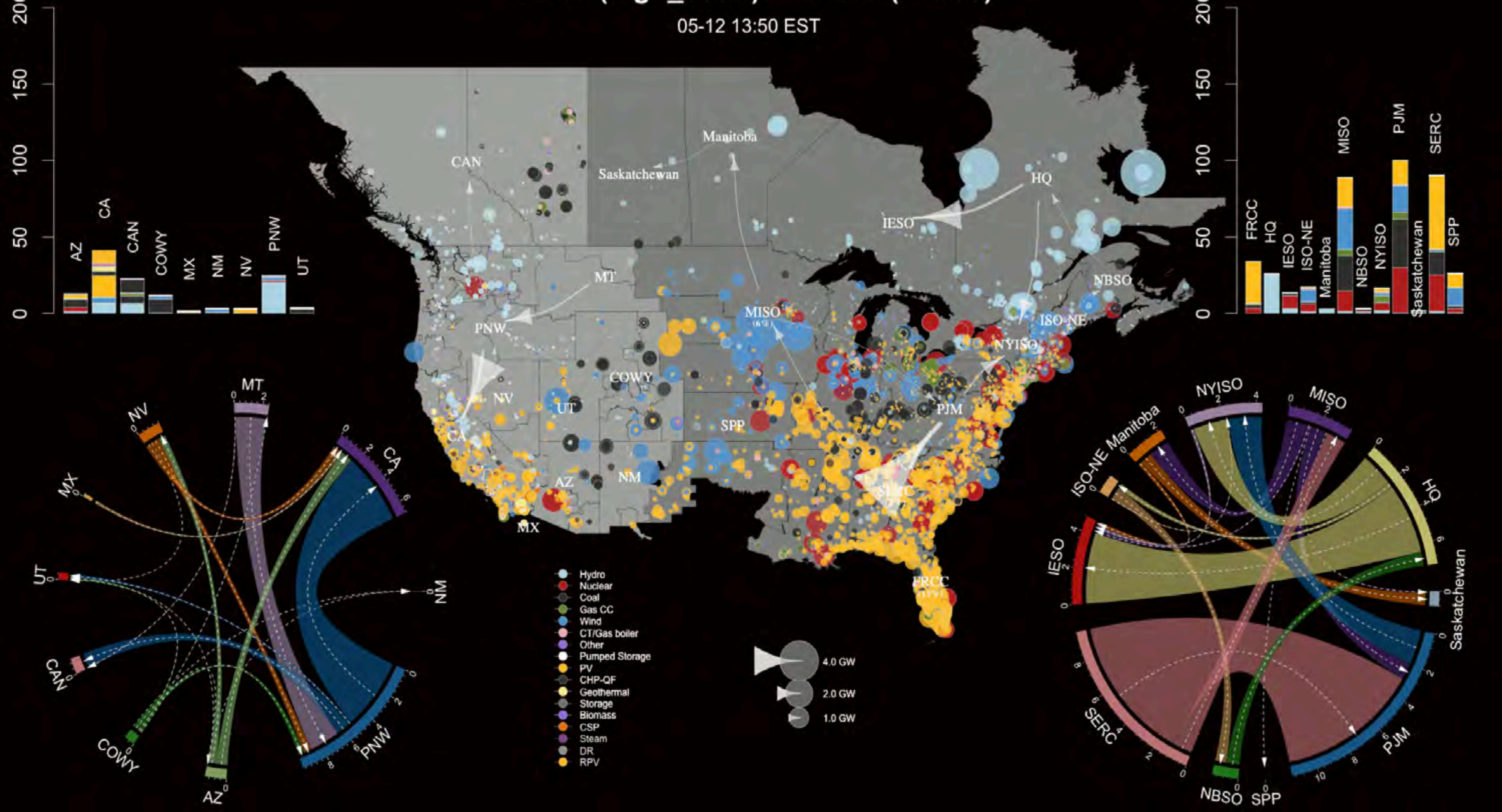
2018 Data
% Instantaneous Power
% Annual Energy
% Wind and Solar
100
75
50
25
100
Ta'u
Island
American
Samoa
100
100
80
El Hierro
Canary Islands
Spain
65
King
Island
Australia
Small Islands
76
Maui
Hawaii
USA
60
65
36
Crete
Greece
25
Ireland
29
Large Islands
55
ERCOT
Texas
USA
Large
Interconnections
19
24
Western
Interconnect
USA
10
NREL
Transforming ENERGY
0.0001
0.001
0.01
0.1
1
10
100
1000
System Size (GW)



WECC (high_solar) + ERGIS (RTx30)
05-12 03:00 EST
AZ
CA
CAN
COWY
MX
NM
NV
PNW
UT
FRCC
HQ
IESO
ISO-NE
Manitoba
MISO
NBSO
NYISO
PJM
Saskatchewan
SERC
SPP
Manitoba
Saskatchewan
CAN
HQ
IESO
MT
PNW
MISO (6%)
ISO-NE (2%)
NBSO
NYISO
COWY
NV
UT
SPP
PJM (4%)
CA
AZ
NM
SERC
MX
FRCC
Hydro
Nuclear
Coal
Gas CC
Wind
CT/Gas boiler
Other
Pumped Storage
PV
CHP-QF
Geothermal
Storage
Biomass
CSP
Steam
DR
RPV
4.0 GW
2.0 GW
1.0 GW

WECC (high_solar) + ERGIS (RTx30)

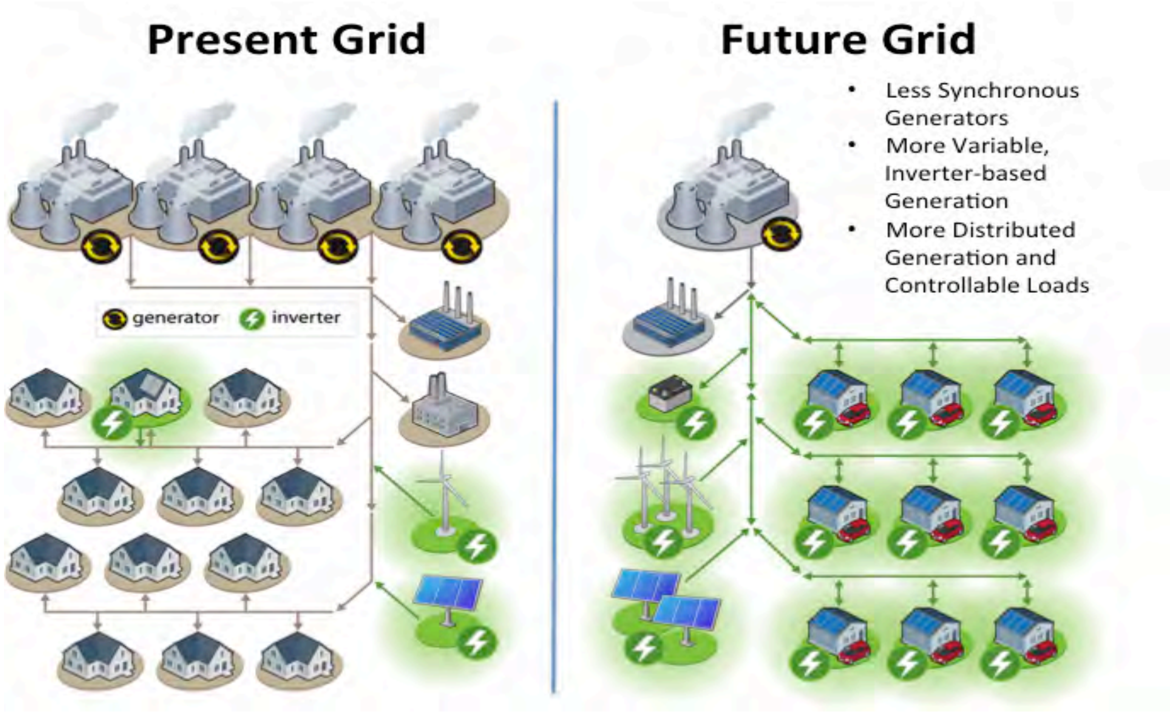
05-12 13:50 EST



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?

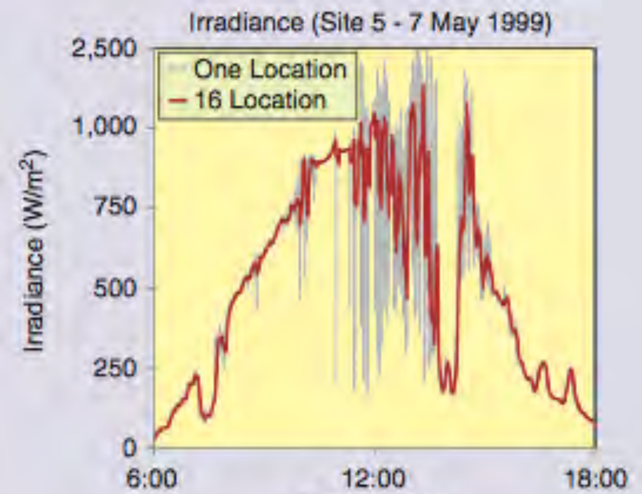
Technical Challenges with Ultra-high Levels of VRE



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

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

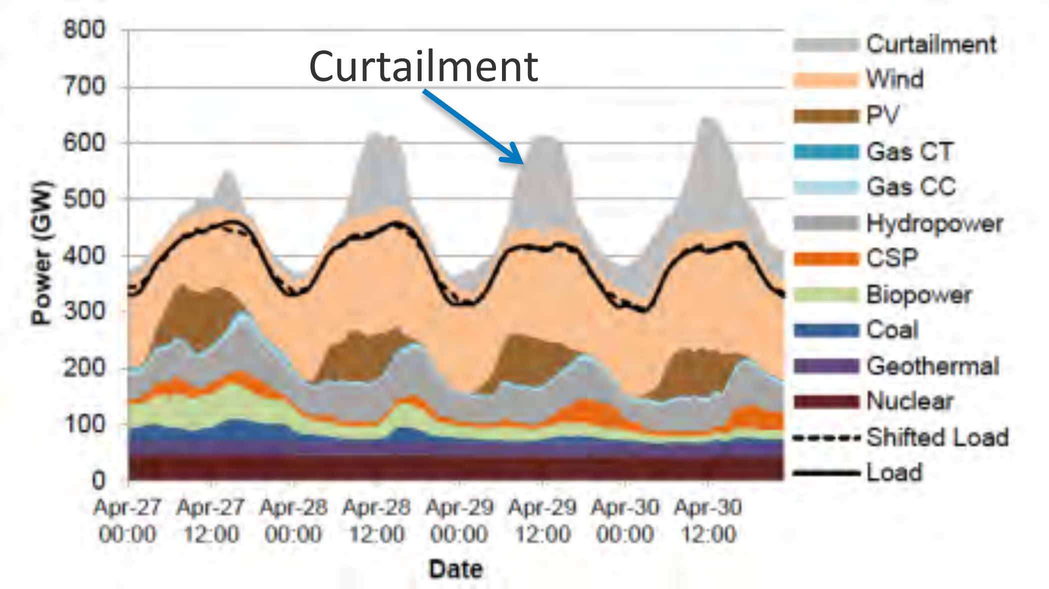
Variability and Uncertainty



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

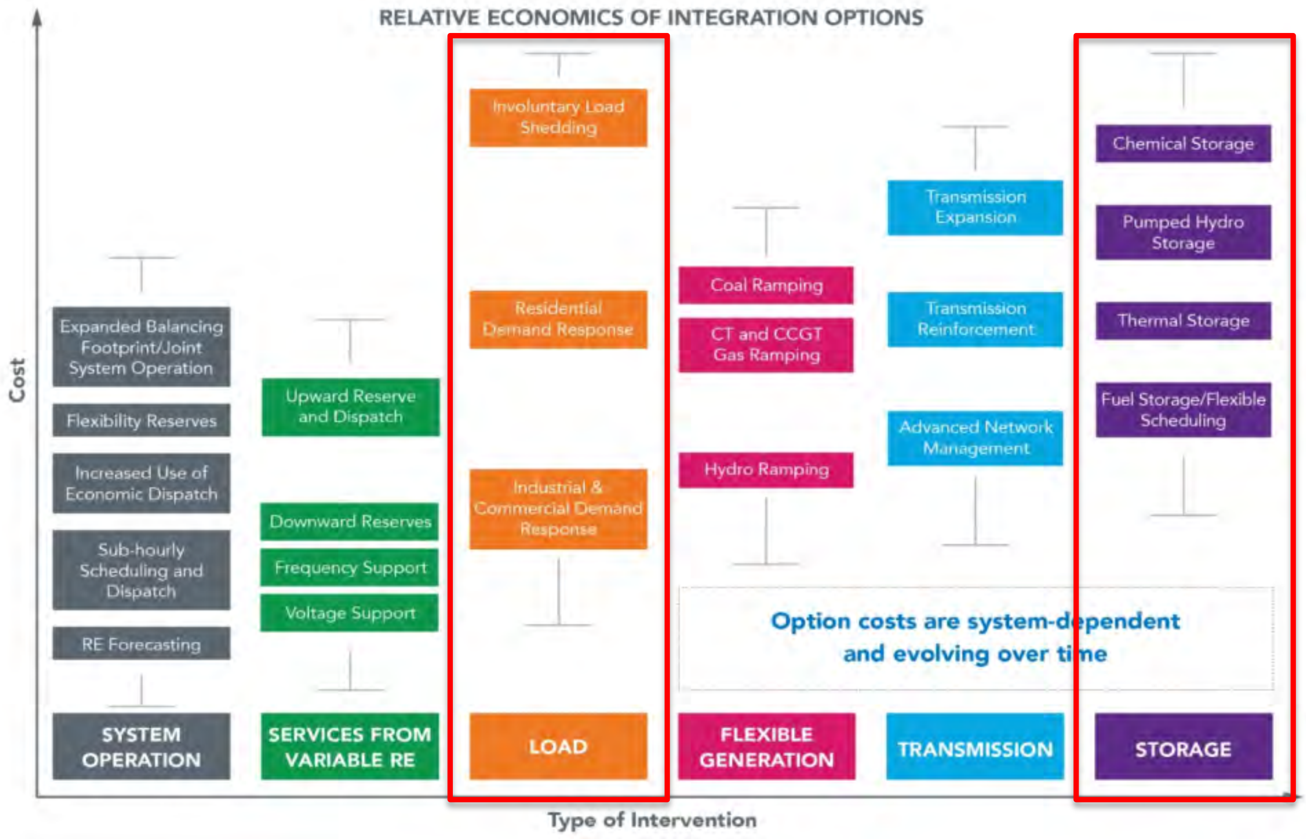
Challenges:

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



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

Options for Dealing with Variability and Uncertainty

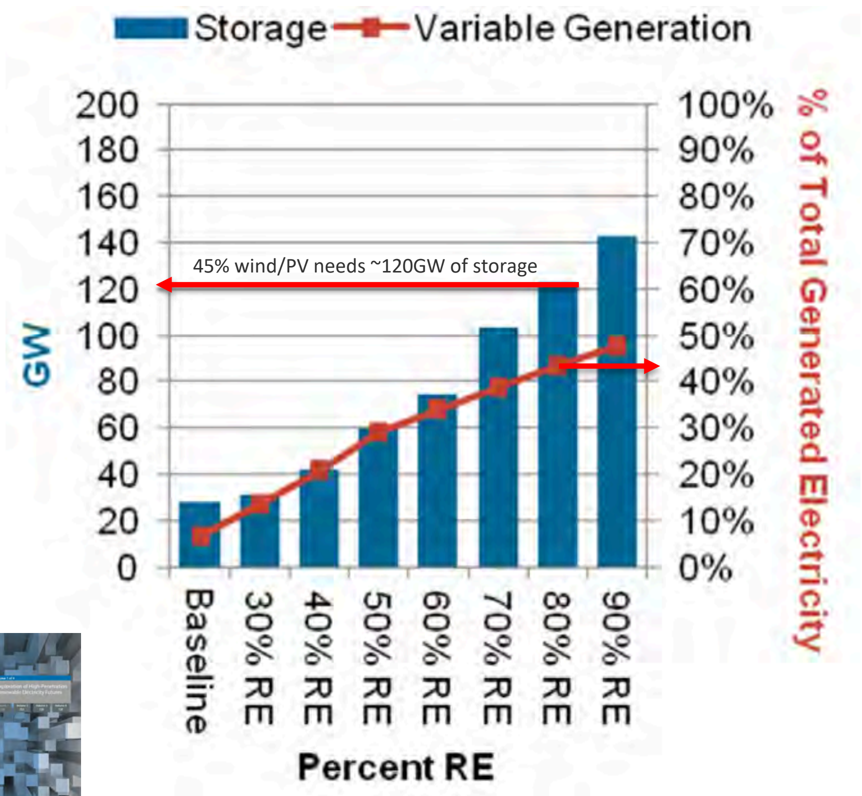


Solutions:

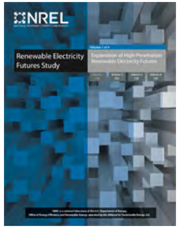
- Utilize geographic diversity.
- Utilize flexible conventional generation.
- Increase sharing among balancing authority areas.
- Expand the transmission system.
- Curtail excess VRE production.
- Enhance VRE and load forecasting.
- **Coordinate flexible loads (active demand response).**
- **Add electrical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

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

Energy Storage – How Much do we Need?



- NREL's Renewable Electricity Futures Study (2012) estimated the amount of energy storage needed for various penetrations of renewable energy (RE) for the continental US in 2050.
- RE included all types of renewables including hydro
- The figure on the left shows GW of storage capacity (Y1-axis), % variable generation (Y2-axis) and % total RE energy (x-axis)
- **For the 80% RE scenario (that has 45% wind and PV) the estimated storage need was ~120GW of 8hr storage.**
- For context, currently there is 22GW of pumped hydro and 1 GW of batteries installed in the US.
- The difference between current levels and 120GW could be made from a variety of new storage technologies, shiftable loads, hydrogen, etc.

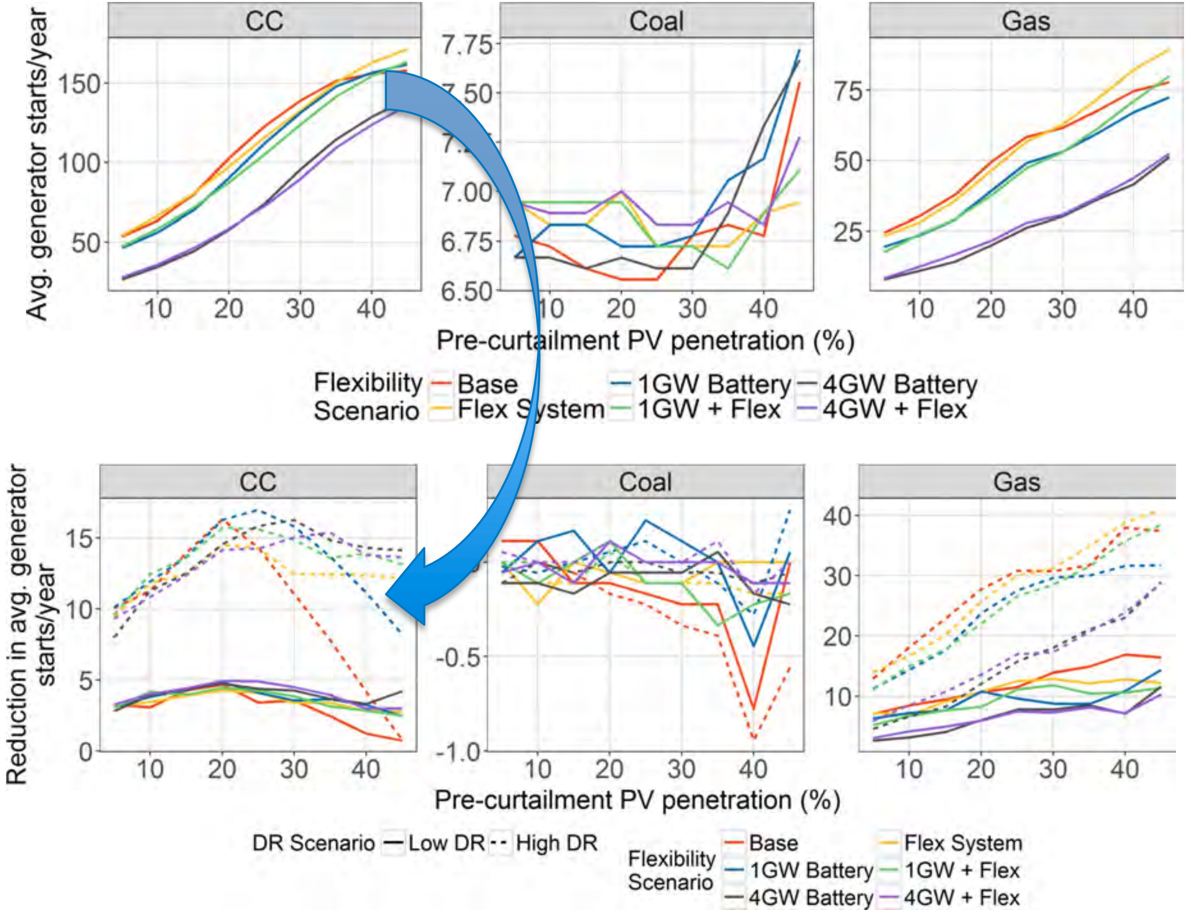


Source: Renewable Electricity Futures Study (Entire Report)
National Renewable Energy Laboratory. (2012). Renewable Electricity Futures Study. Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/analysis/re-futures.html

Tapping into Demand Response (DR)

No DR

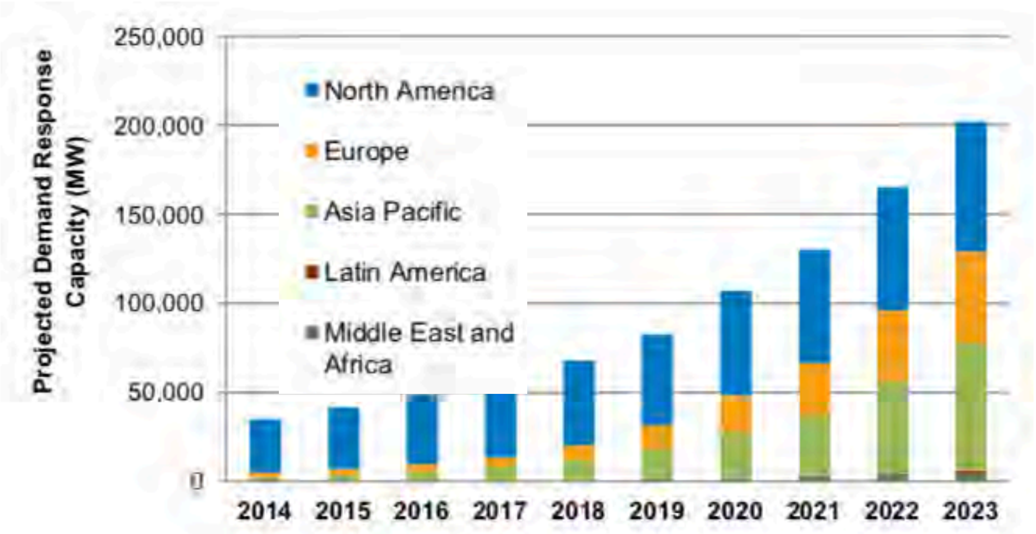
With DR



Reduced number of Combined Cycle and Gas Turbine Starts due to using demand response

Source: *"The value of demand response in Florida"*, Brady Stoll, Elizabeth Buechler, and Elaine Hale, https://www.sciencedirect.com/science/article/pii/S1040619017302609

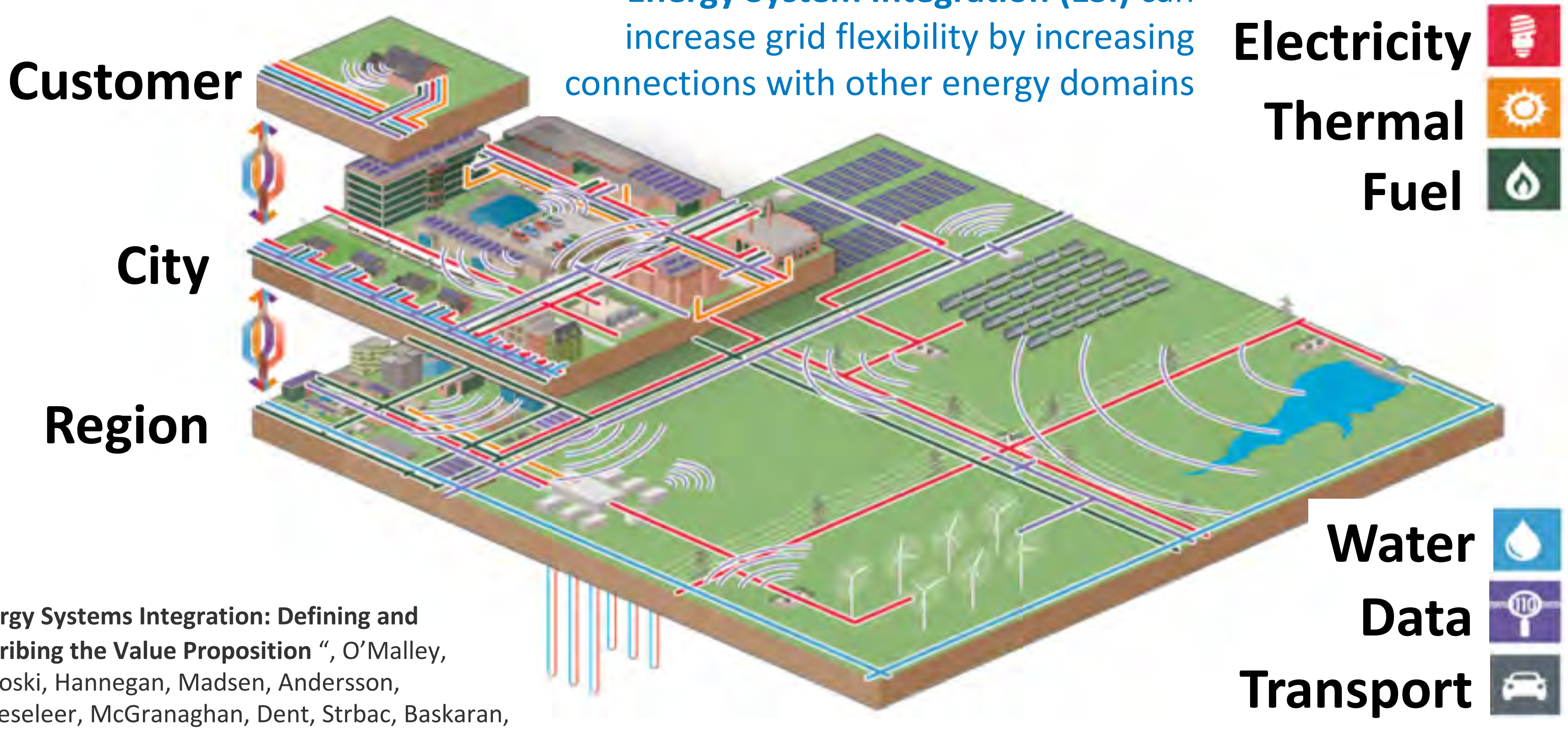
Tapping into Controllable Demand



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

Energy Systems Integration

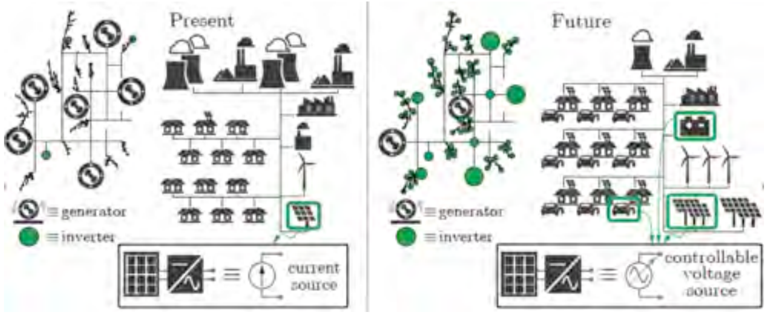
Energy System Integration (ESI) can increase grid flexibility by increasing connections with other energy domains



"Energy Systems Integration: Defining and Describing the Value Proposition ", O'Malley, Kroposki, Hannegan, Madsen, Andersson, D'haeseleer, McGranaghan, Dent, Strbac, Baskaran, Rinker., NREL/TP-5D00-66616. June 2016

How to control millions of devices?

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



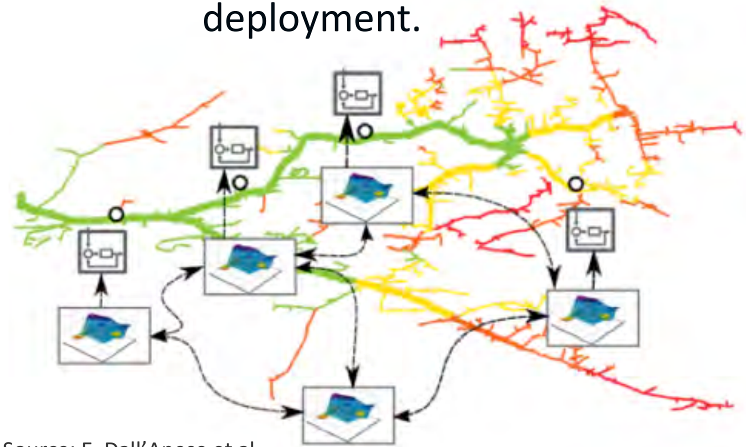
We need smart inverters with advanced functionality to maintain grid stability and…

Improved optimization for millions of controllable devices in the grid.

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

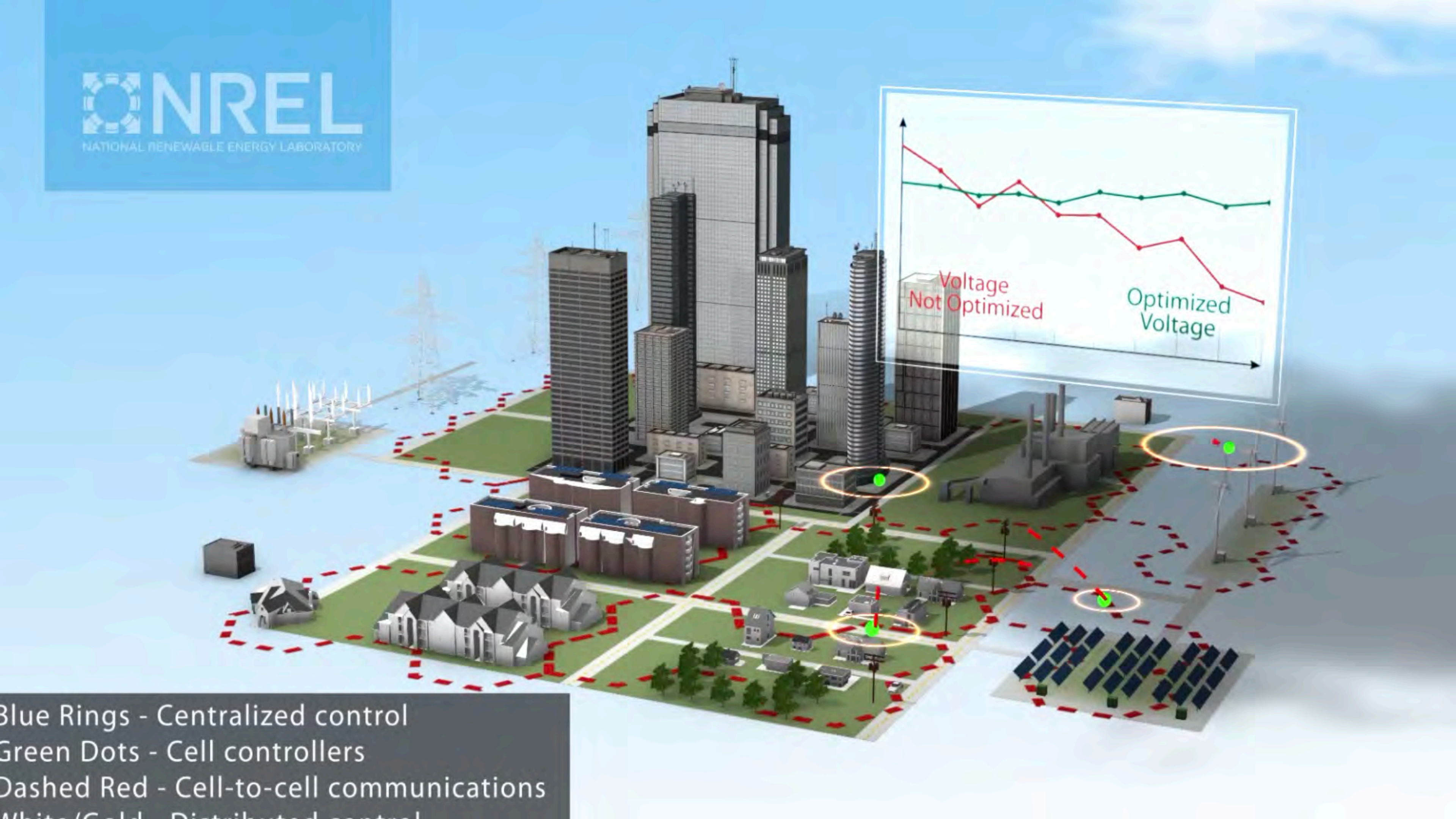
Research Needs

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



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

Autonomous Energy Grids


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Voltage Not Optimized
Optimized Voltage
Blue Rings - Centralized control
Green Dots - Cell controllers
Dashed Red - Cell-to-cell communications

Advancing Technologies through Grid Simulation and Experimentation

NREL Grid Simulation and Experimentation Capabilities

Grid Simulation and Data Capabilities

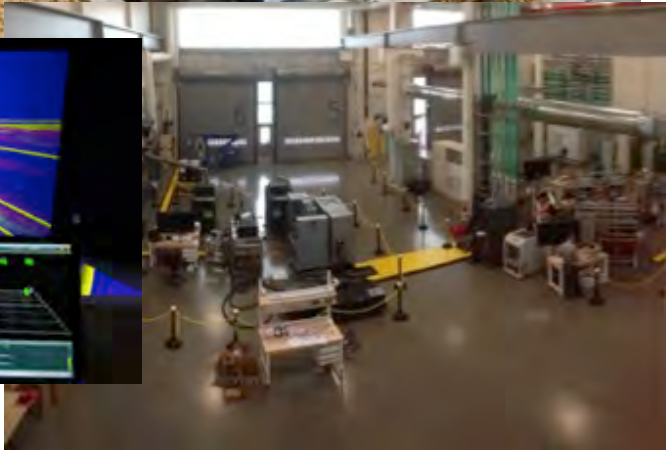
- High Performance Computing (Eagle)
- Large-scale Renewable Integration Studies
- Integrated Transmission, Distribution, Communications, and Markets Grid Co-simulation platform (HELICS)
- Synthetic Grid Datasets
- Renewable Resource Datasets

Grid Experimental Capabilities

- NREL Energy Systems Integration Facility
- Advanced Distribution Management System Testbed
- NREL Flatirons Campus
- Integrated Energy Systems at Scale (IESS) - Integrated multi-site integrated Power Hardware in the Loop Experiments

Energy Systems Integration Facility

Shortening the time between innovation and practice

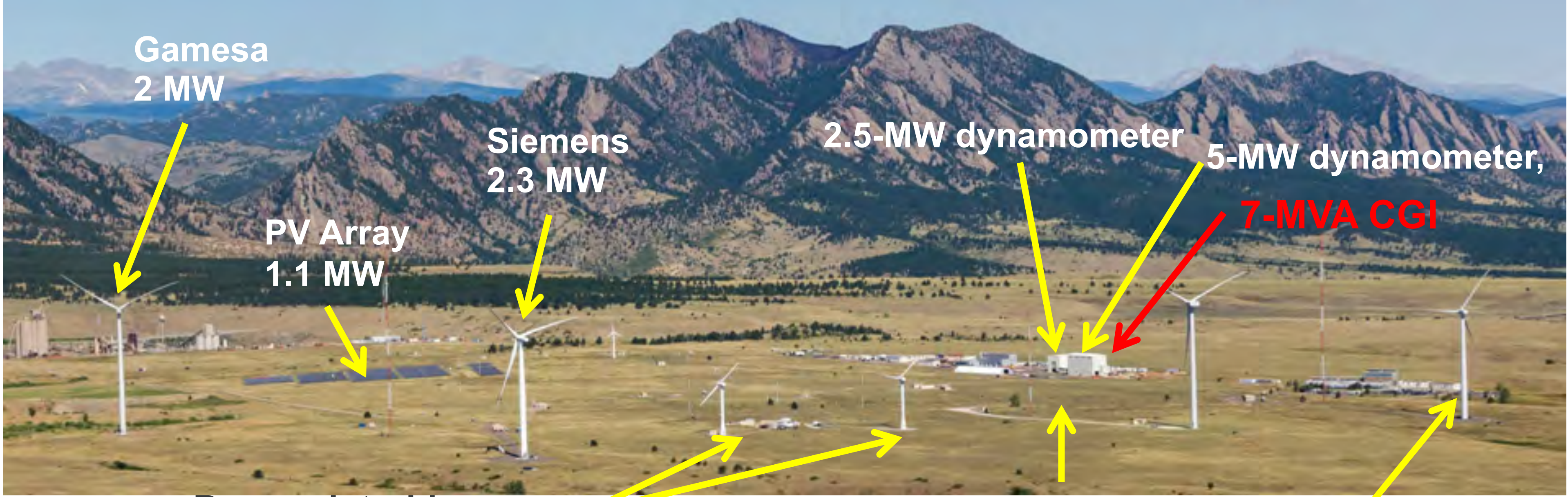


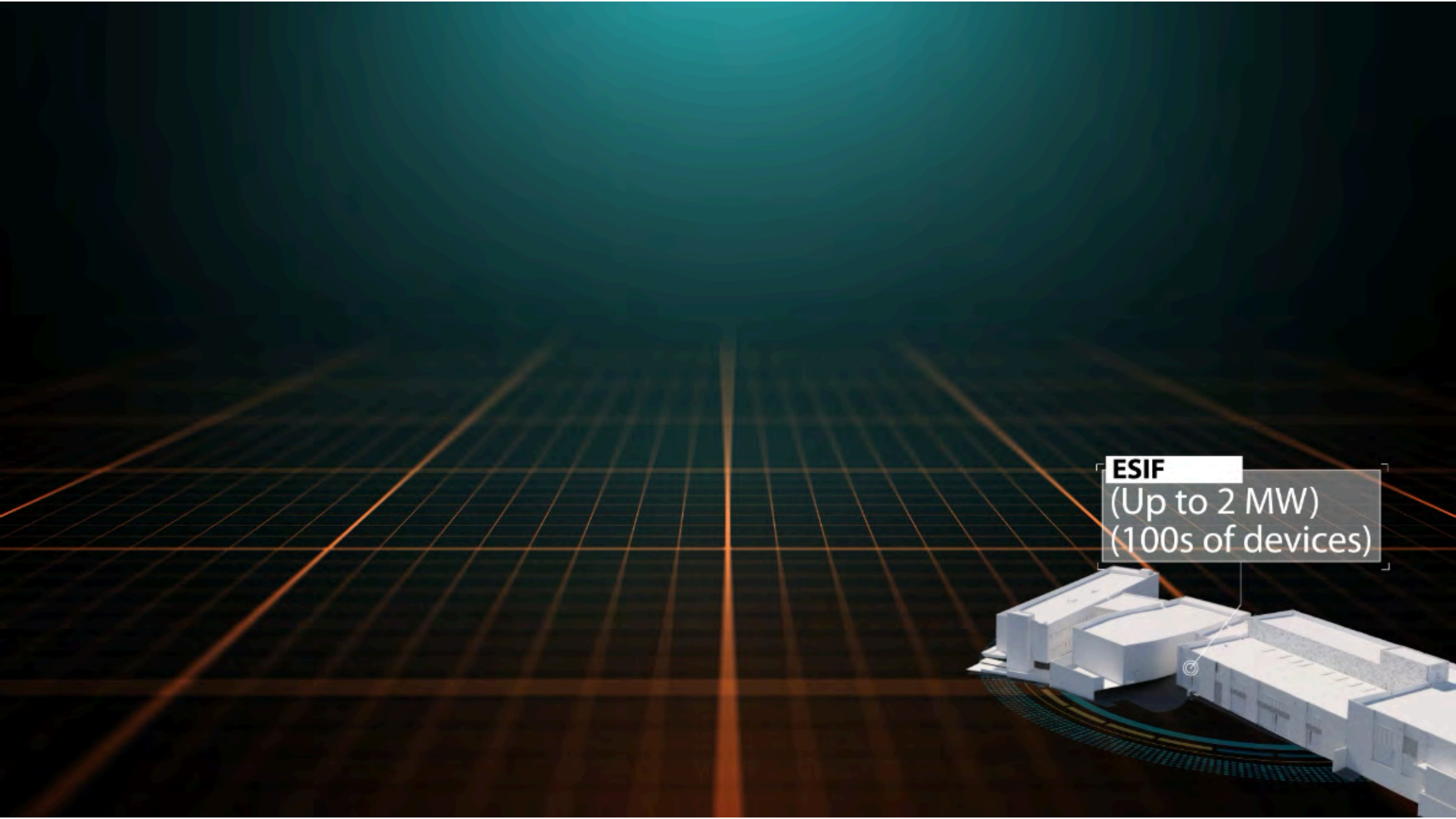
Unique capabilities:

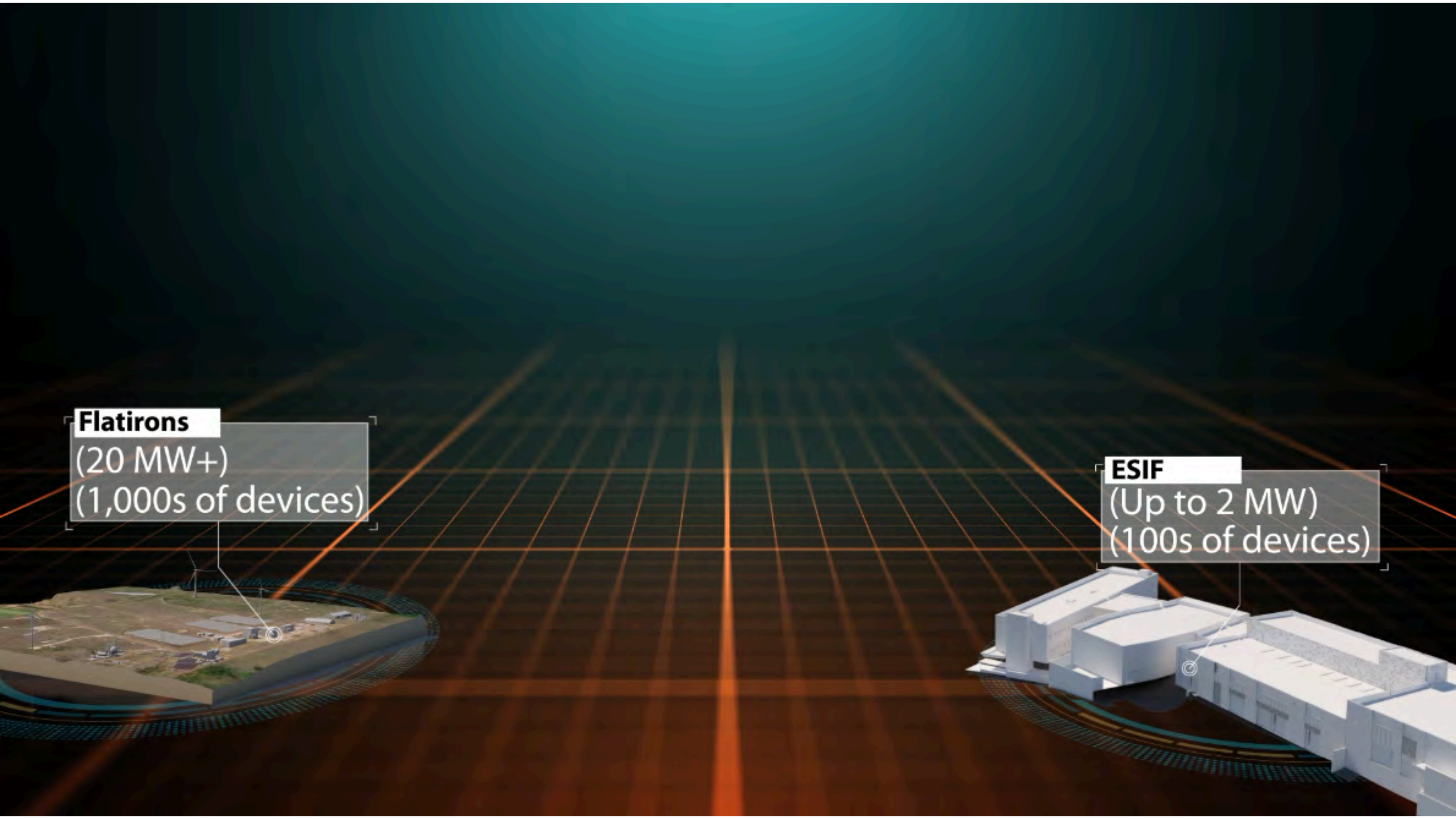
- Multiple parallel AC and DC experimental busses (MW power level) with grid simulation and loads
- Flexible interconnection points for electricity, thermal, and fuels
- Medium-voltage (15-kV) microgrid area
- Virtual utility operations center and visualization rooms
- Smart grid lab for advanced communications 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.

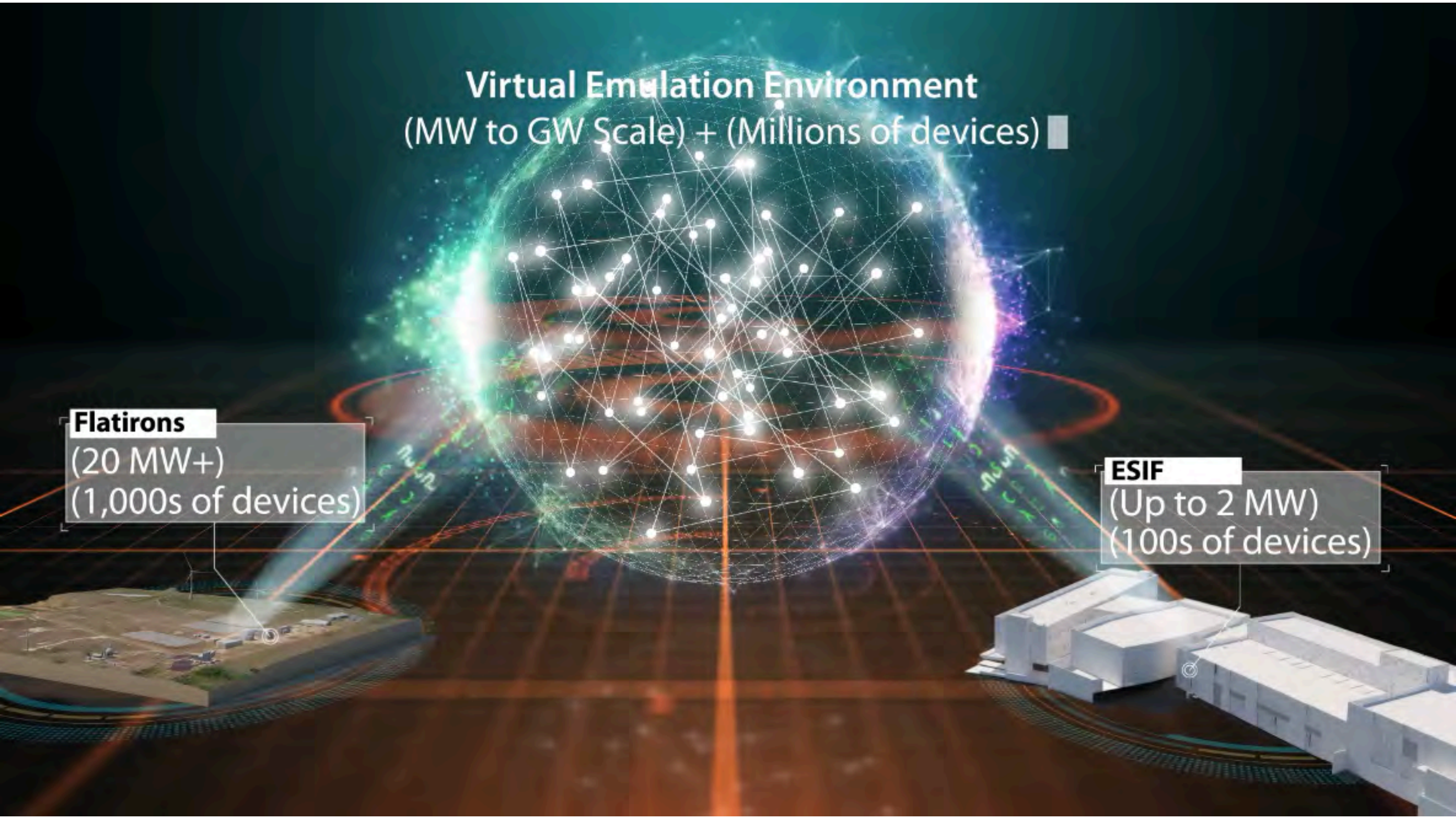
Flatirons Campus

- Total of 11 MW of variable renewable generation currently installed
- Many small wind turbines (less than 100 kW) are installed
- 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.




ESIF
(Up to 2 MW)
(100s of devices)


Flatirons
(20 MW+)
(1,000s of devices)
ESIF
(Up to 2 MW)
(100s of devices)


Virtual Emulation Environment
(MW to GW Scale) + (Millions of devices)
Flatirons
(20 MW+)
(1,000s of devices)
ESIF
(Up to 2 MW)
(100s of devices)


NREL Flatirons Campus

NREL Power Systems Engineering Center
www.nrel.gov/grid

NREL: Providing Solutions to Grid Integration Challenges

Thank You!