NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Energy Systems Innovation

Martin Keller
Laboratory Director
October 2017

NREL at a glance

1,700

Employees,
plus more than
400
early-career researchers and visiting scientists

World-class
facilities, renowned technology experts

nearly 750

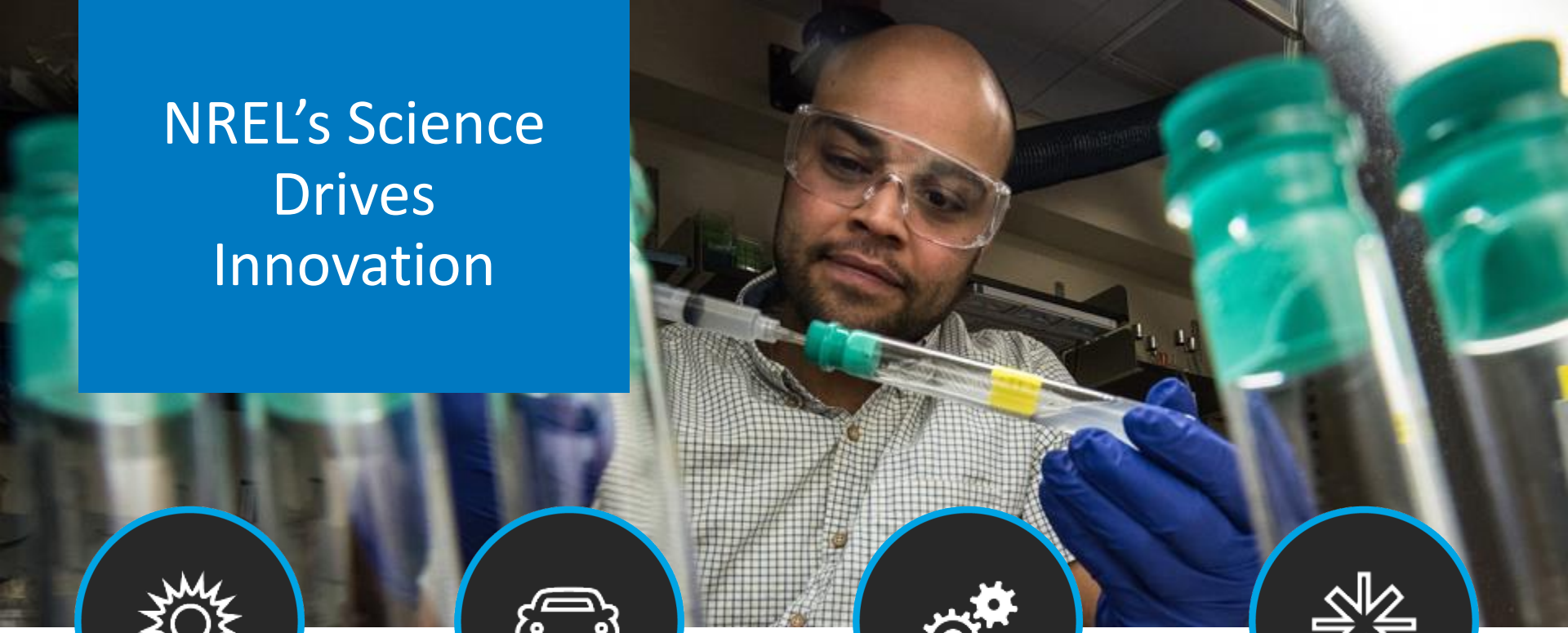
Partnerships
with industry, academia, and government

Campus
operates as a living laboratory

$872M annually

National economic impact

NREL's Science Drives Innovation



Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

Government Energy Management

Energy Systems Integration

High-Performance Computing

Data and Visualizations

NREL Innovations Yield Transformational Impacts

814
Technology innovation disclosures

147
U.S. patents since 2011

749
Active partnerships with industry, universities, local governments

Solar
Cost of solar energy **reduced 96%** to less than $1/watt; **nearly 374,000 jobs**

Wind
Wind energy **costs reduced** up to 90% to 4-7 cents/kWh; **more than 101,000 jobs**

Bioenergy
Cost of cellulosic ethanol **decreased 78%; more than 130,000 jobs**

Transportation
Alternative fuel vehicles employ **259,000**; **489,000** workers produce components

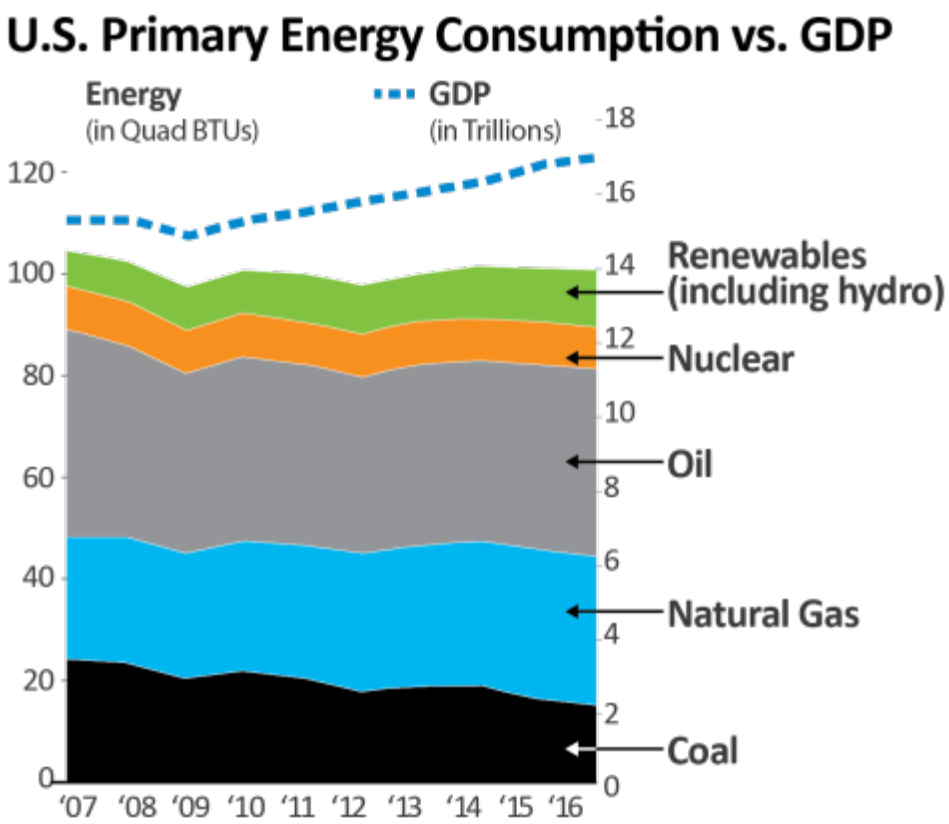
Buildings
Whole-house designs can reduce buildings-related energy use **by 50%**

Grid Integration
New domestic, distributed energy resources incorporated onto the grid at an increasing rate

$1.5 Trillion
in clean energy investment worldwide, 2012-2016

222 gigawatts
in renewable capacity, more than half of all new power generation

The U.S. Economy is Growing While Energy Use is Shrinking

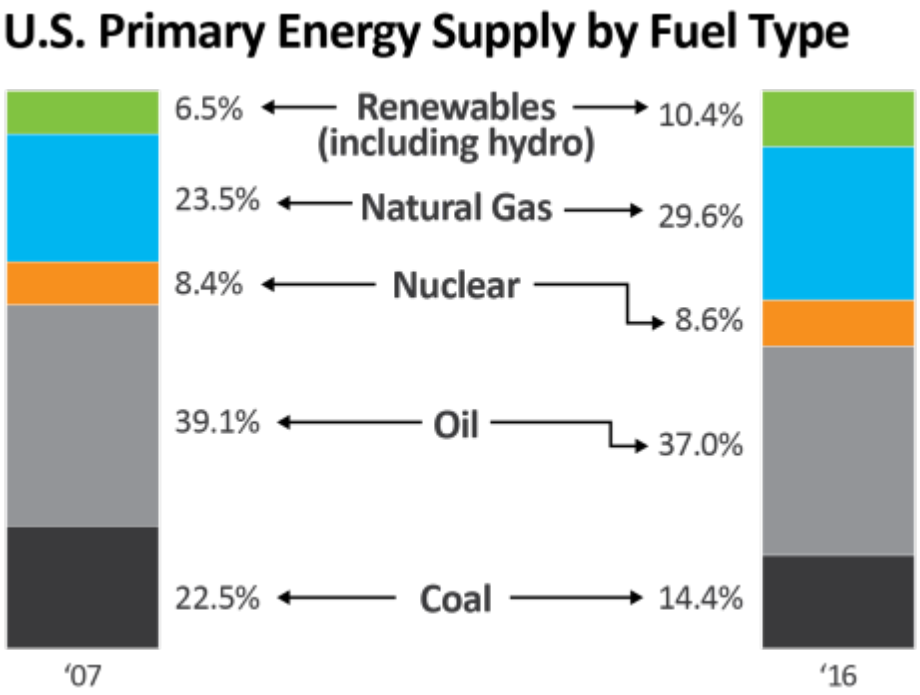


Gross domestic product (GDP) grew 12% since 2007, while total **energy use fell 3.6%**

So, the **energy productivity** of the U.S. economy—the ratio of U.S. GDP to energy consumed—**grew 16%**

Source: *2017 Sustainable Energy in America Factbook*, Bloomberg New Energy Finance and the Business Council for Sustainable Energy, February 2017

U.S. Energy Supply is Shifting



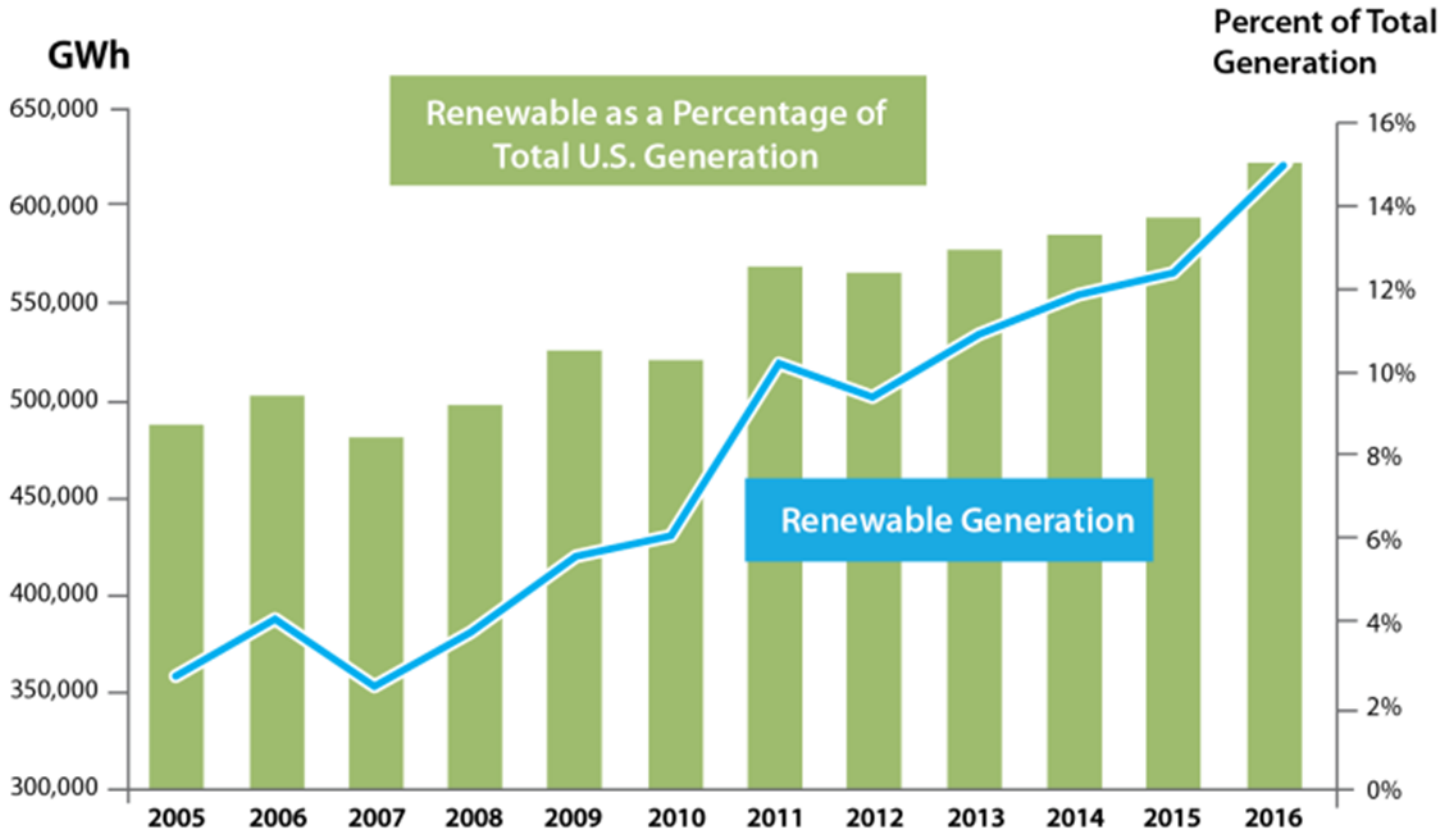
In 2016, the use of natural gas and **renewable energy increased** in the United States:

- Natural gas provided **29.6% of total energy supply**
- Renewable energy provided **10.4% of total energy supply**

Source: *2017 Sustainable Energy in America Factbook*, Bloomberg New Energy Finance and the Business Council for Sustainable Energy, February 2017

Renewables Represent Growing Share of U.S. Generation

Far from "alternative," **renewable energy is the new normal** in the United States

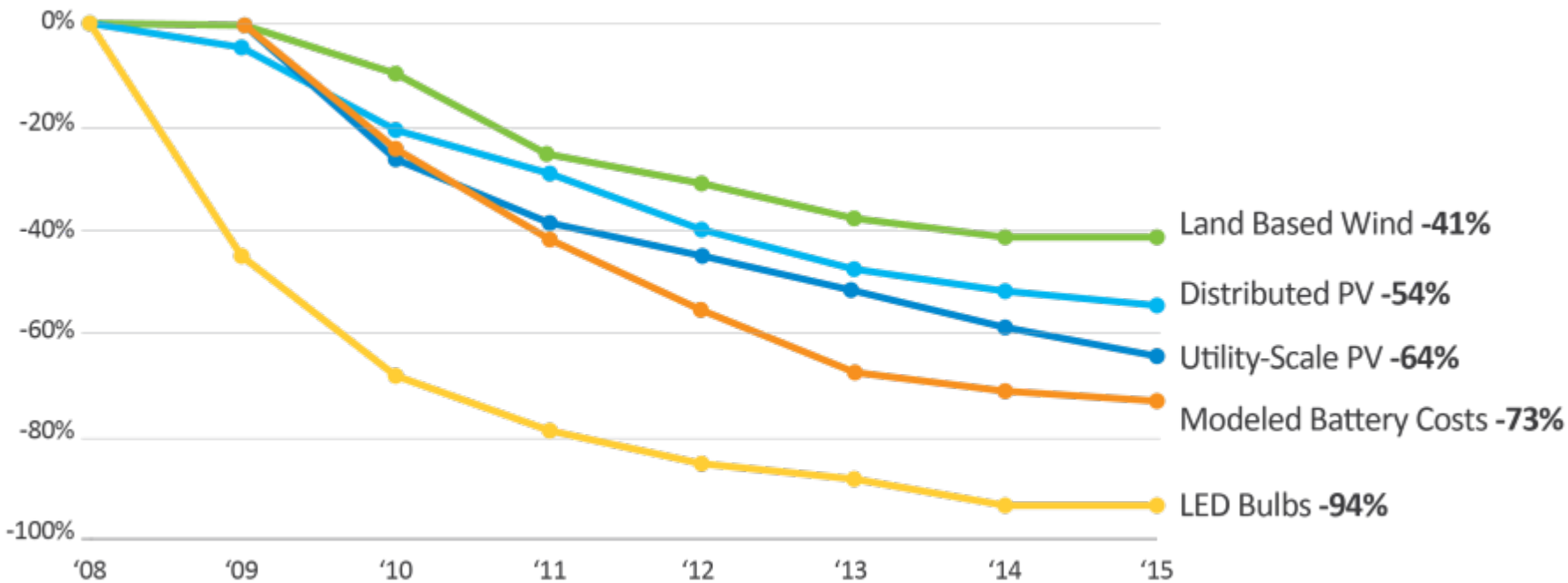


Source: U.S. Energy Information Administration (EIA)

Costs for Renewable Technologies are Falling

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

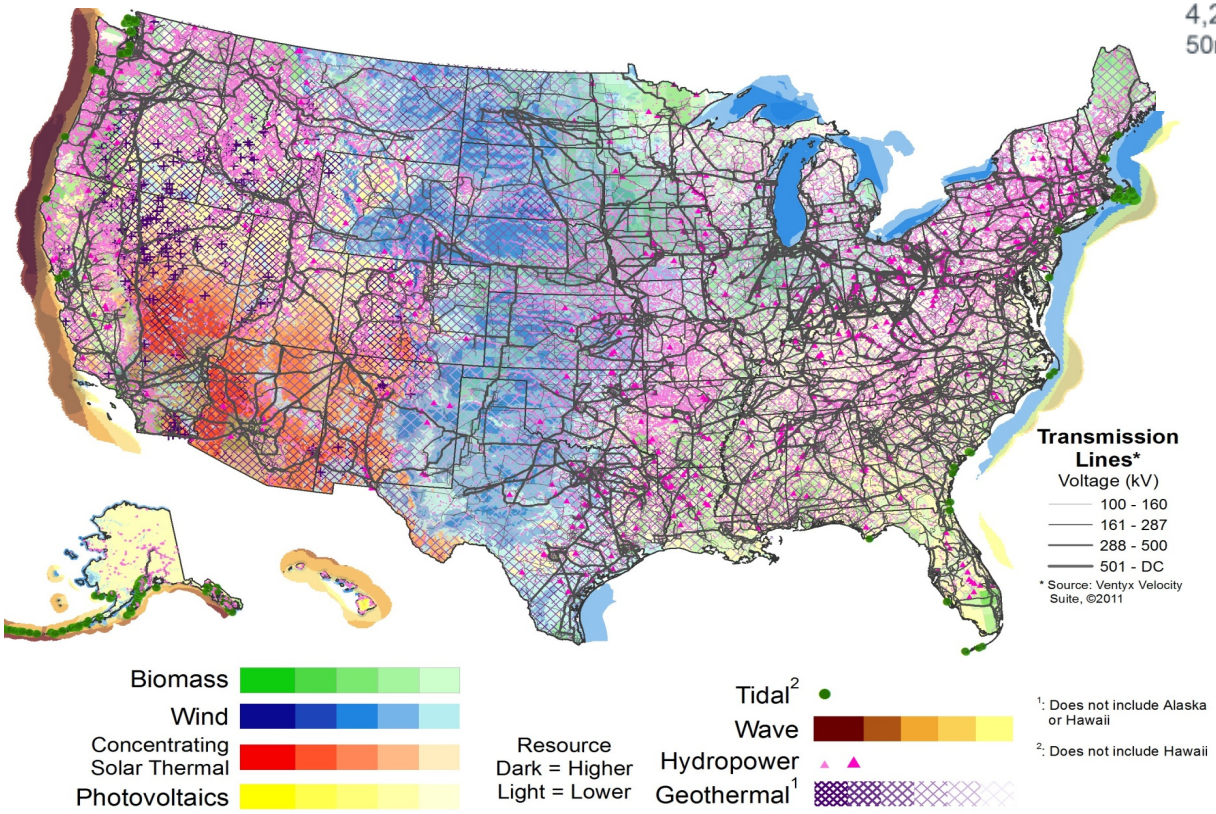
- They drive a domestic energy economy and are increasingly cost-competitive
- Energy manufacturing and installations provide major opportunities for American workers



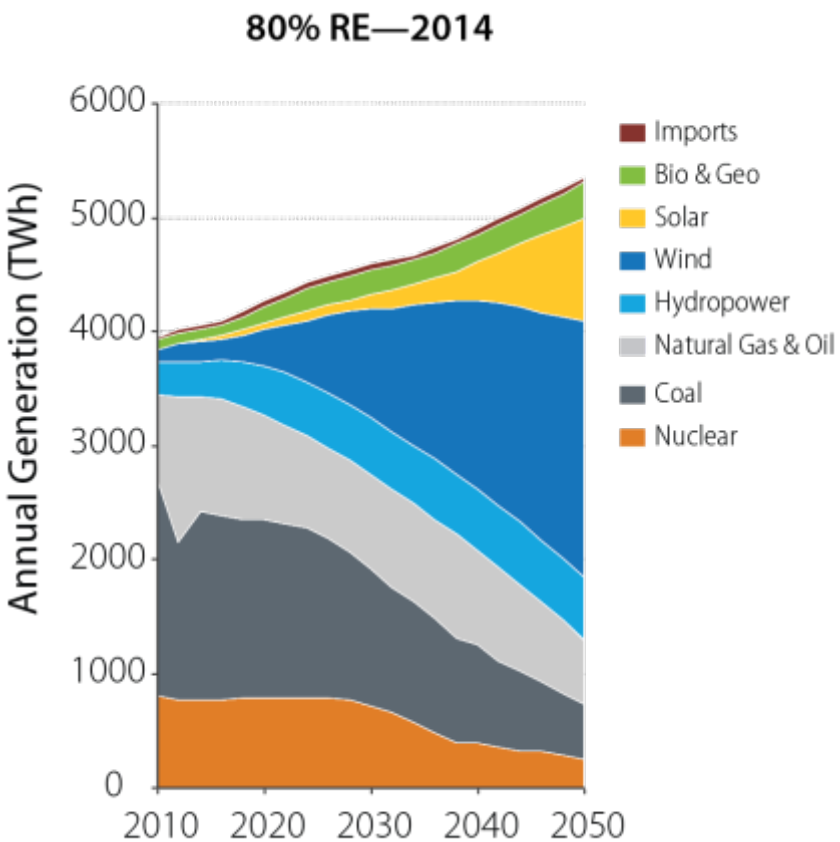
Source: *DOE Revolution Now* (2016)

U.S. Renewable Resources – We're Barely Scratching the Surface

Theoretical Potential of Resources	Percent of Theoretical Potential of Current Installed Capacity (2015)
Solar PV/CSP 155,000 GW (PV) 38,000 GW (CSP)	.0073%
Wind 11,000 GW (onshore) 4,200 GW (offshore to 50nm)	.48%



Much Higher Renewable Penetration is Possible



80% of total U.S. electricity generation in 2050 can be sourced from renewable technologies

- Commercially available today
- In combination with a more flexible electric system.

This scenario looks at very high renewable electricity penetrations.

2014 paper follow up to Renewable Energy Futures Study:

http://www.sciencedirect.com/science/article/pii/S0360544213009912

Renewable

Power

Impact of NREL's Solar Research

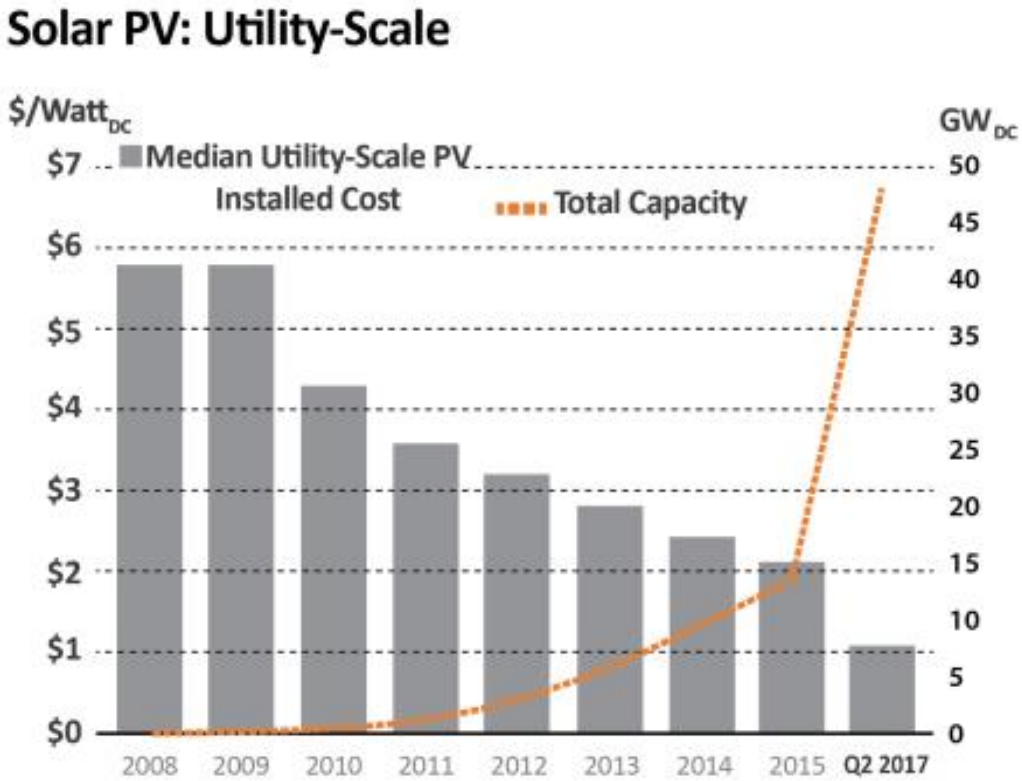
The **cost of solar energy has fallen 96%** and now stands at less than a dollar a watt for solar module, pre-installation.

Globally, solar energy **grew by more than 50%** each of the past five years (2010-2016).

Market Impact

- Costs: from less than **$1 to $6/W**
- Levelized cost of energy at **7-16 cents/kWhr**
- Solar provides nearly **1% of U.S. power generation**
- U.S. installed capacity at **45 GW**
- Solar power employs nearly **374,000 U.S. workers**
- U.S. forecast (through 2040) is for nearly **40 GW of photovoltaic (PV)** capacity in pipeline

Path to New Solar Materials, Manufacturing



Source: *DOE Revolution Now* (2016) and Solar Energy Industries Association

Key Research Areas

- **Providing rapid growth** – perovskite technology has provided new materials with an efficiency of more than **20%**
- **Boosting efficiency of modules** – high-efficiency thin films improve carrier lifetime of commercial products
- **Increasing cell efficiency** – research in silicon tandem cells improves the best cell efficiencies by **10%-30%**
- **Improving applications for high-efficiency technologies** – 1- and 2-junction III-V cells lower growth cost

Vision for Hybrid Perovskite Solar Cells (HPSCs)

HPSCs could be manufactured more than 50 times faster than current silicon cells

- Similar to newspaper production, HPSC manufacturing can use a roll-to-roll web printing method
- Considering the same speed as a newspaper line, it would take **~3 years** to manufacture 25 terawatts (TW) of 15%-efficient HPSCs vs. **~170 years** at current capacity, 35 years at current growth rate (~20%) to manufacture 25 TW of silicon PV

Benefits of HPSCs

- Low capex, high-volume manufacturing (for PV)
- On-demand manufacturing (for LEDs/displays)
- New technologies (e.g., quantum information processing, quantum computing)

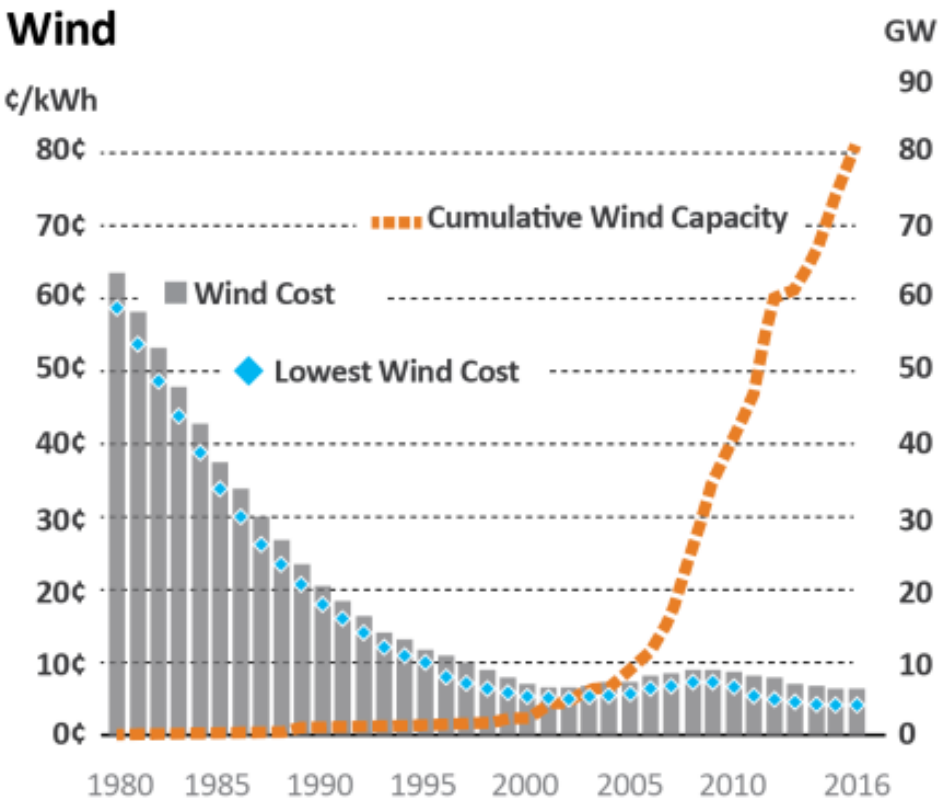
Impact of NREL's Wind Research

Innovations have **driven down the cost of wind energy as much as 90%** between 2009 and 2016, enabling industry success.

Market Impact

- Installed capital cost between **$1,300 and $1,900/kW**
- Costs: **4-7 cents/kWh**
- U.S. ranks second in world for installed capacity at **82 GW**
- Wind provides about **6.2% of U.S. electricity**
- Wind power **employs more than 101,000 U.S. workers**
- More than **500 wind-related manufacturing facilities** in the United States

Path to Performance Improvement, Cost Reduction for Wind



Source: *DOE Revolution Now* and *2016 Wind Technologies Market Report*

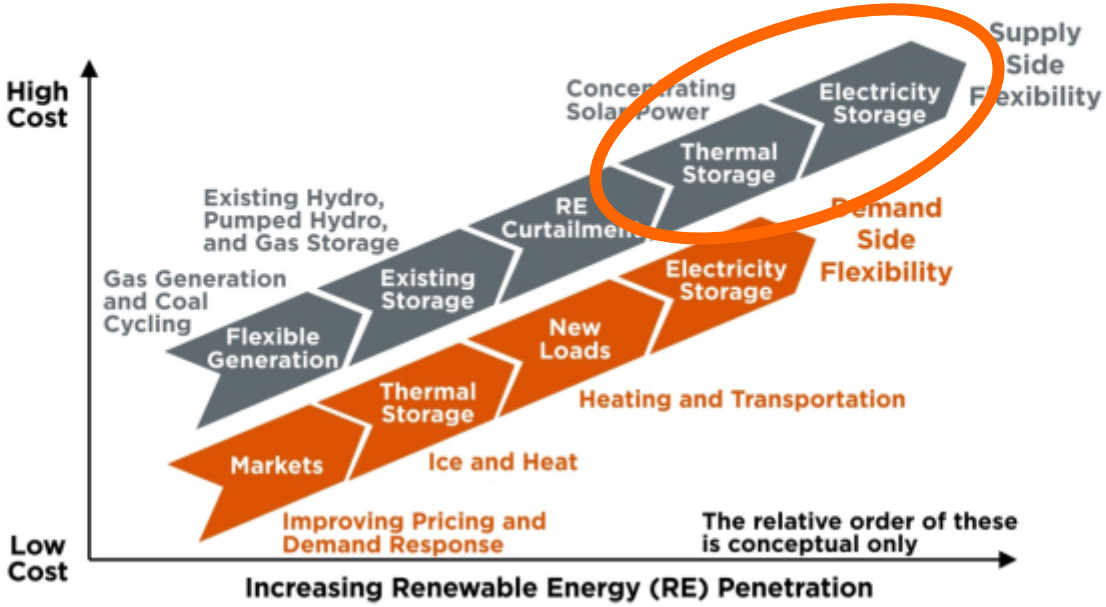
Key Research Areas

- **Optimizing wind plants** – individual wind turbine controls for improved performance
- **Eliminating transportation constraints** – process for on-site production of turbine blades
- **Integrating with the grid** – insights on higher wind generation in power grid through high-performance computing
- **Improving operations and reliability** – modeling wake effects from wind turbines and their impact
- **Increasing offshore and distributed wind technologies** – focus on new concepts, materials, and components
- **Accelerating market impacts** – lightweight carbon fiber materials for turbine blades

High Penetration of Renewables on Grid Requires Storage Options

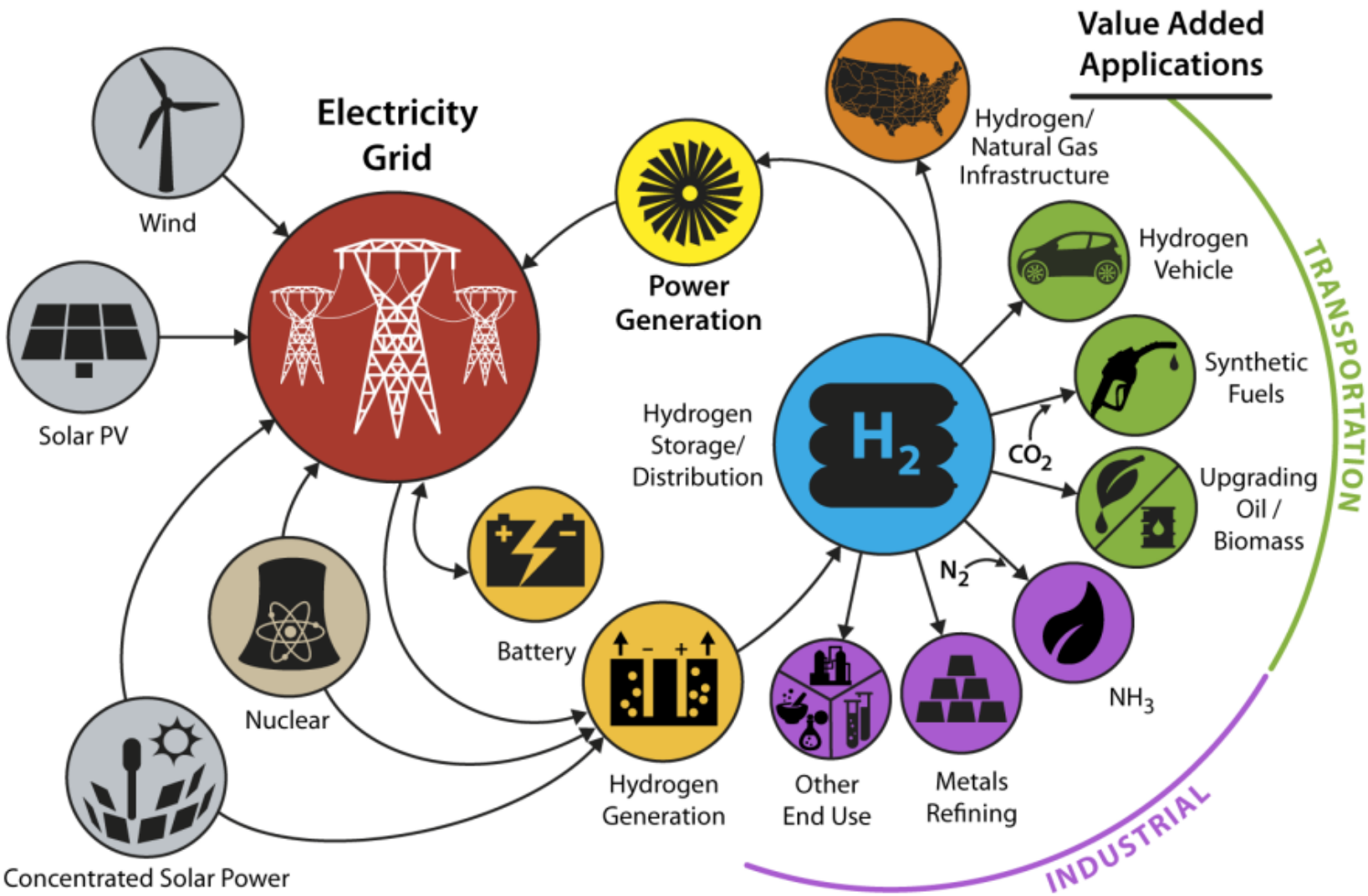
- Photovoltaic (and wind) power generation is variable
- Grid operators need generation that is dispatchable

- Storage can make renewables dispatchable
  - Thermal storage
  - Hydrogen storage
  - Other options



Denholm, "The Role of Energy Storage in the Modern Low-Carbon Grid," presentation (2008)

Future H2@Scale Energy System



Five Facts of Modern Energy Systems

- **Fact one:** The grid can handle more renewable generation than previously thought.
- **Fact two:** Geographic and resource diversity provide additional reliability to the system.
- **Fact three:** Wind and solar forecasting provide significant value.
- **Fact four:** Our electric power markets were not originally designed for variable renewables—but they could be adapted.
- **Fact five:** Modern power electronics are creating new sources of essential reliability services.

How do we effectively interconnect renewable resources with the grid?

Our research is addressing this challenge.

ESI: Optimizing Energy Systems Across Multiple Pathways and Scales

1MWs

Island, Village

Today

10MWs

Campus

2020

100MWs

Community

2025

1GWs

City

2030

Energy Systems Integration Facility (ESIF)

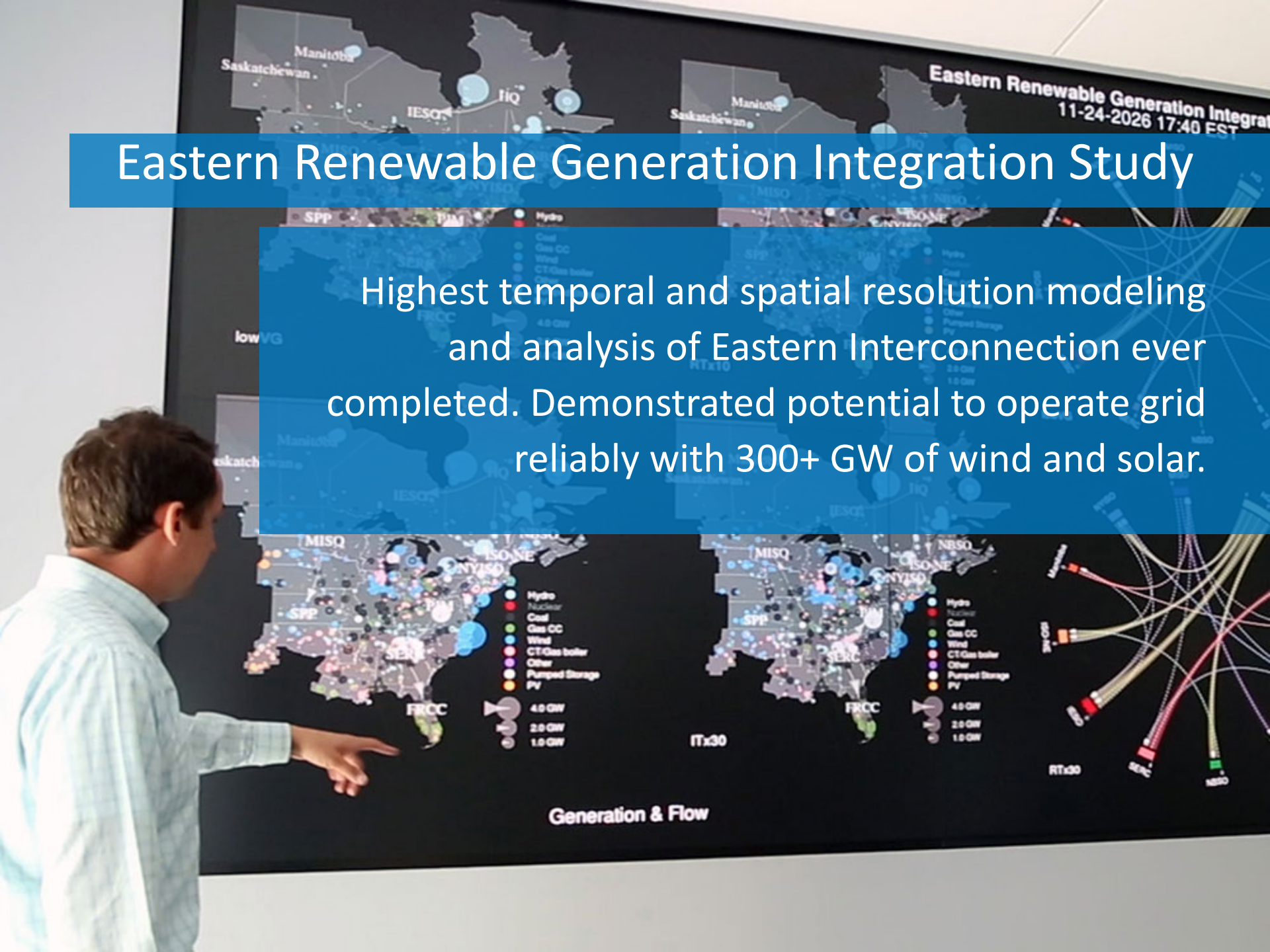
- NREL's largest R&D facility (182,500 ft^2/20,000 m^2)
- NREL's first DOE-designated User Facility
- Space for ~200 NREL staff and research partners
- Petascale HPC and data center supports the entire DOE mission
- Labs focus on R&D of integrated energy systems
- Integrated electrical, thermal, fuel, water, and data infrastructure

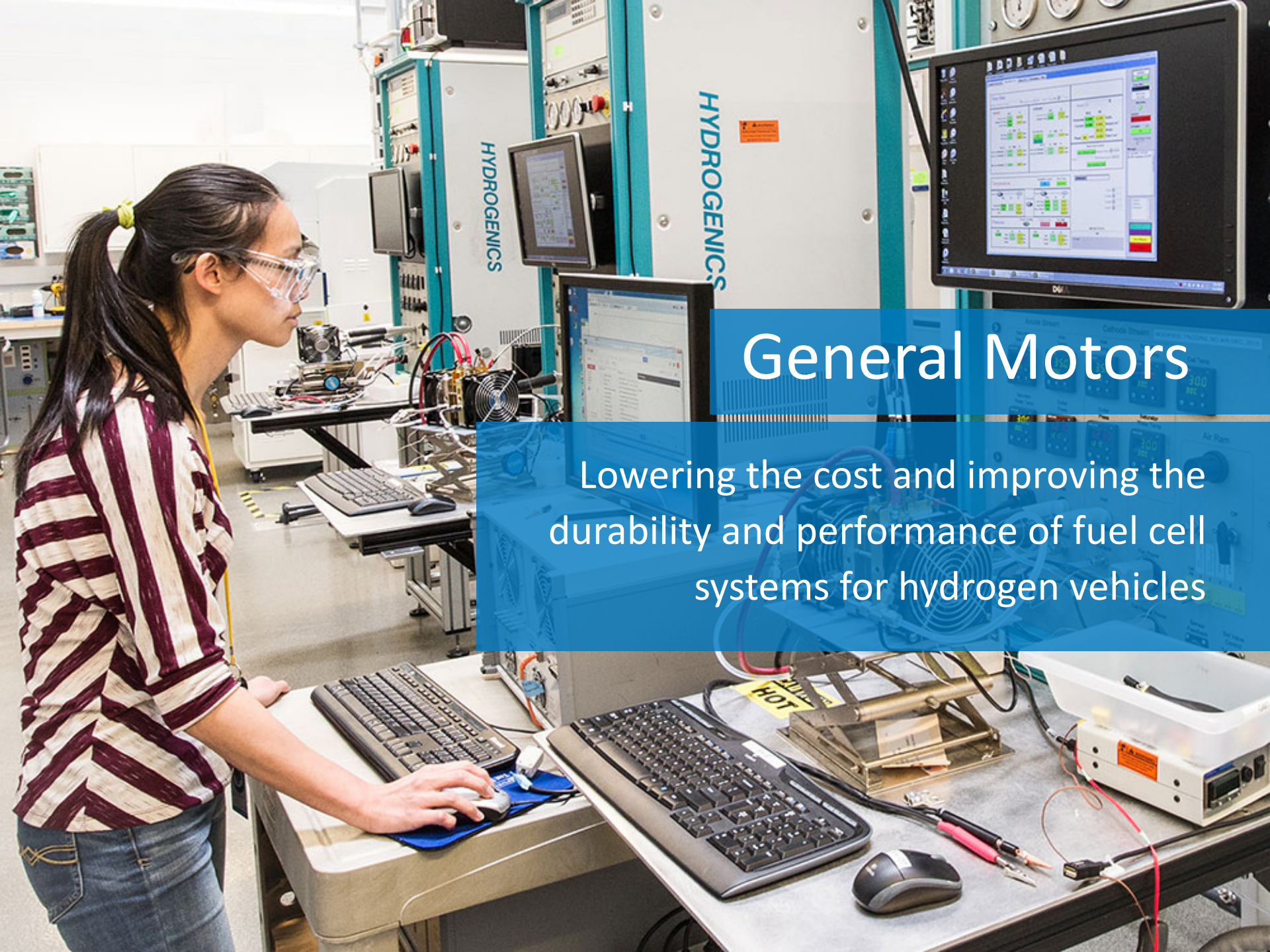
Duke Energy, GE Grid Solutions

Finding the best solution to control voltage for large-scale solar plants

Eastern Renewable Generation Integration Study

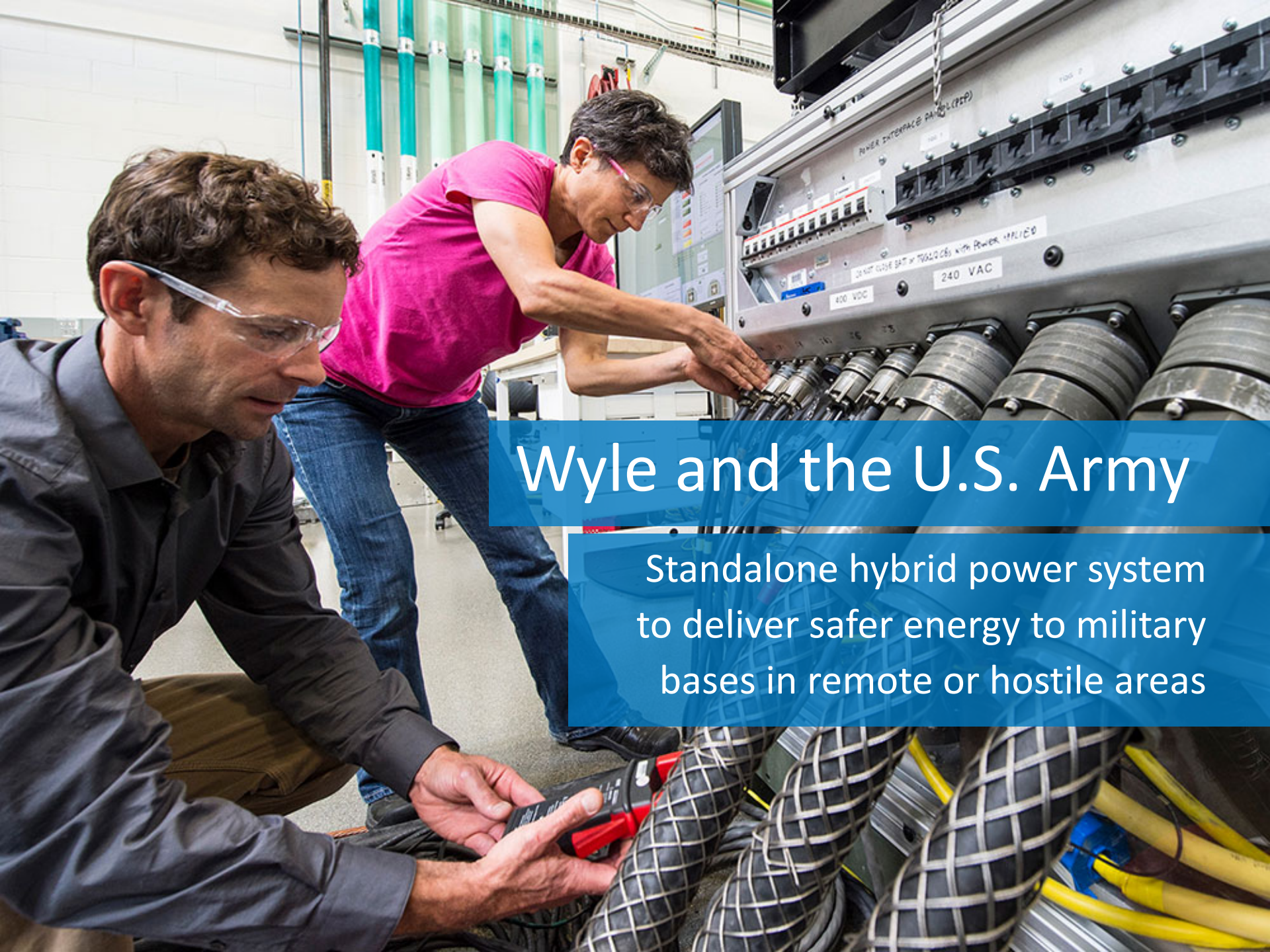
Highest temporal and spatial resolution modeling and analysis of Eastern Interconnection ever completed. Demonstrated potential to operate grid reliably with 300+ GW of wind and solar.





General Motors

Lowering the cost and improving the durability and performance of fuel cell systems for hydrogen vehicles



Wyle and the U.S. Army

Standalone hybrid power system to deliver safer energy to military bases in remote or hostile areas

Hawaiian Electric Companies

Advanced inverter research that guided inverter standards and allowed the connection of 2,500 rooftop solar customers in Hawaii

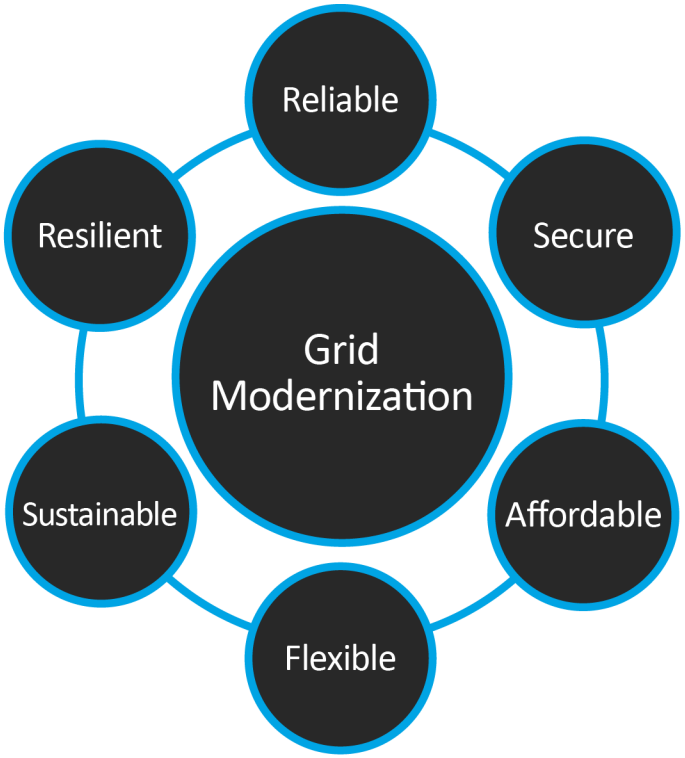
Panasonic and Xcel Energy Developing Zero Energy Communities

- Creating the planned zero energy and transit-oriented campus, Peña Station NEXT, near the Denver International Airport in Denver, Colorado.
- NREL is demonstrating its URBANopt software to analyze the projected dynamic energy consumption of corporate office space, retail space, multifamily dwellings, a hotel, parking, and street lighting within the planned development.

IMPACT

This project will result in tools that can be applied across the country for utility business models. It will also demonstrate the use of multiple distributed energy resources, and create a proven model for smart city design.

Grid Modernization Vision



The grid is a critical platform for U.S. prosperity, competitiveness, and innovation in a global clean energy economy.

A modern grid will solve the challenges of seamlessly integrating conventional and renewable energy sources, storage, and central and distributed generation.

Grid Modernization Laboratory Consortium

- Institutional Support
- Devices and Integrated Systems
- Sensing and Measurement
- System Operations and Control
- Planning and Design Tools
- Security and Resilience

87 projects,
$220M over 3 years

Security and Resilience

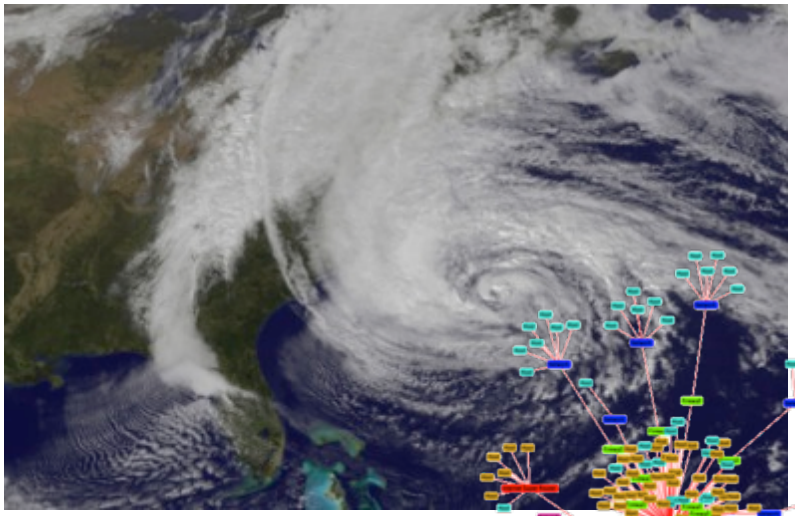
Improve ability to identify, protect, respond and recover from all hazards and threats potentially impacting grid function

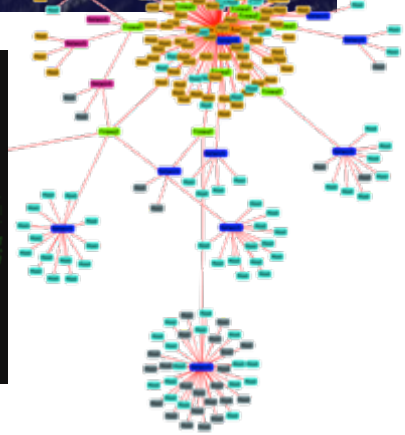
Expected Outcomes

- Holistic grid security and resilience, from devices to micro-grids to systems
- Inherent security designed into components and systems, not security as an afterthought
- Security and resilience addressed throughout system lifecycle including legacy and emerging technologies

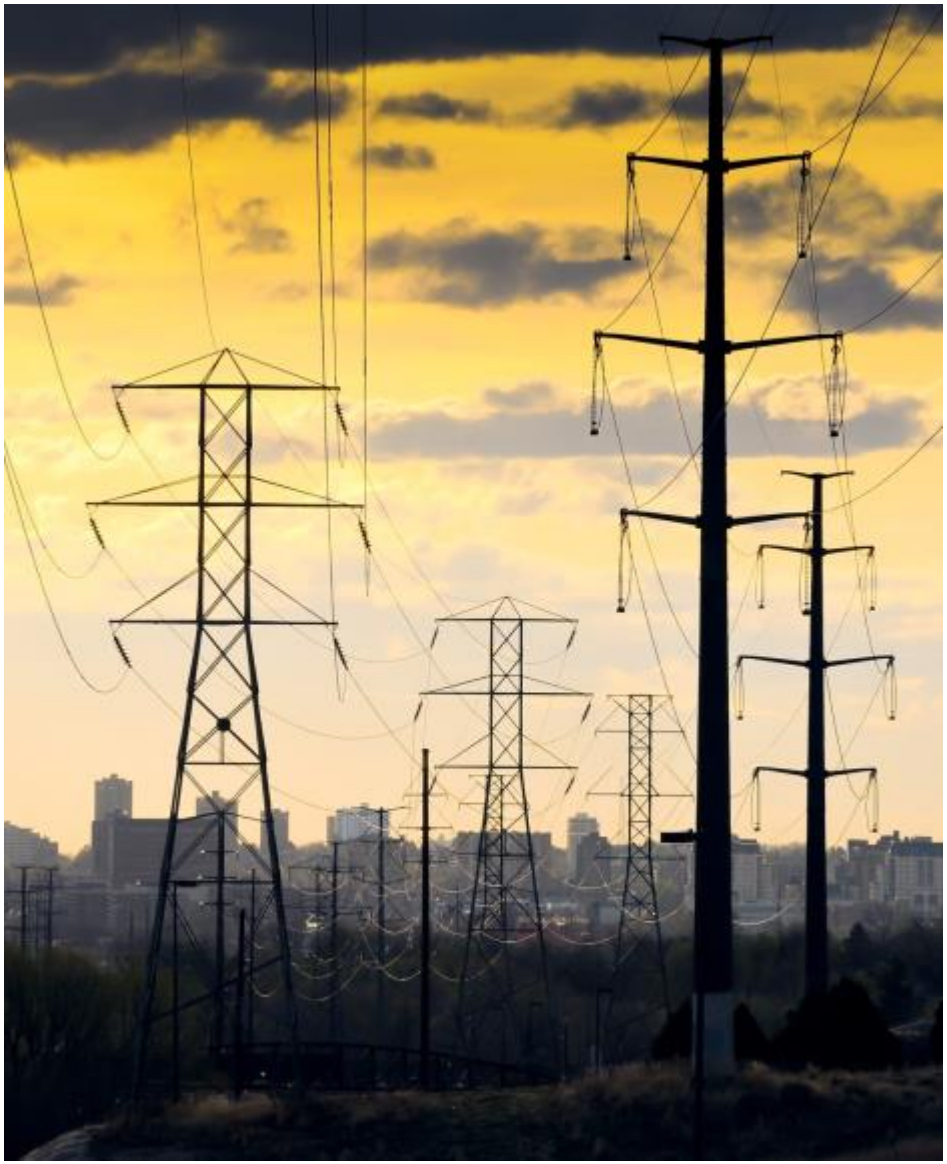
Current Projects

- Threat detection and response with data analytics;
- Cyber security approaches for renewables, DER and smart inverters;
- Distribution system restoration tools for natural disaster recovery; and
- Tools for improved outage forecasting from tropical cyclones and other weather events.





Cyber-Challenge With Distributed Generation



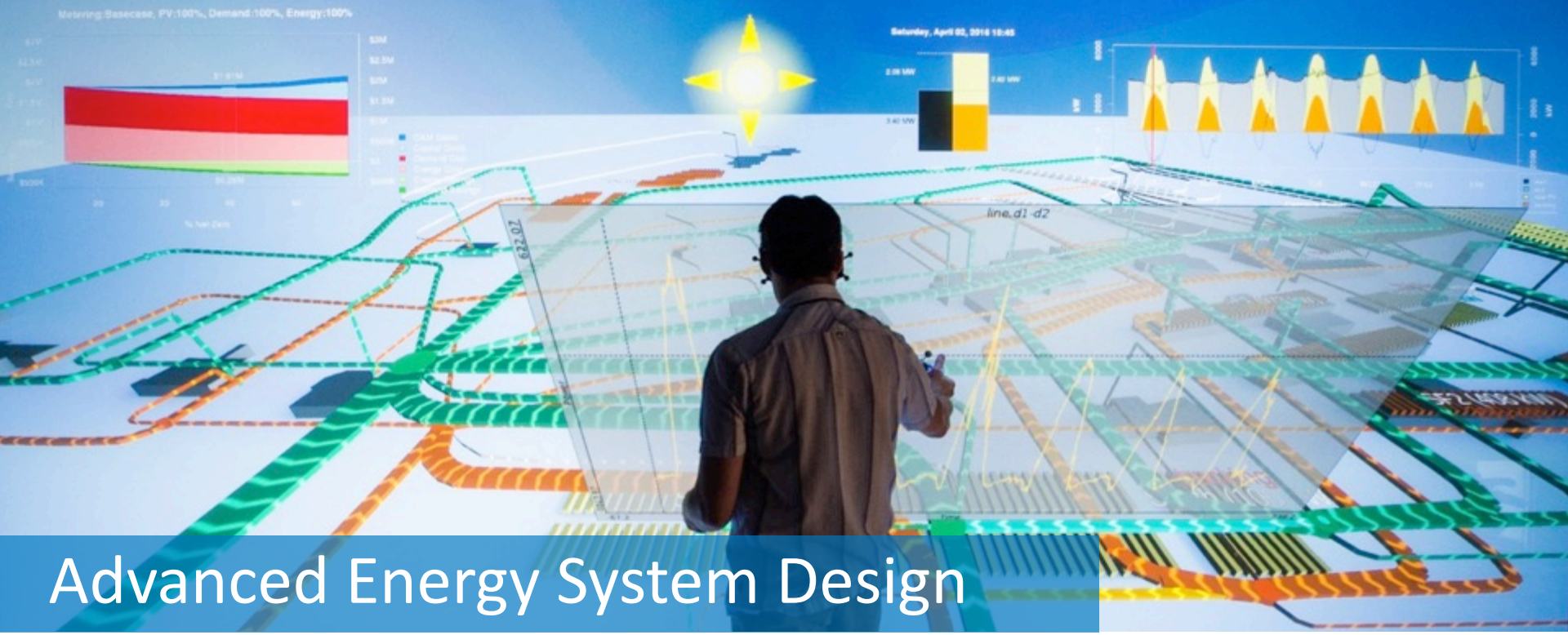
NREL, 18979

CHALLENGE:

Distributed intelligence creates new cybersecurity vulnerabilities on the electric grid.

SOLUTION:

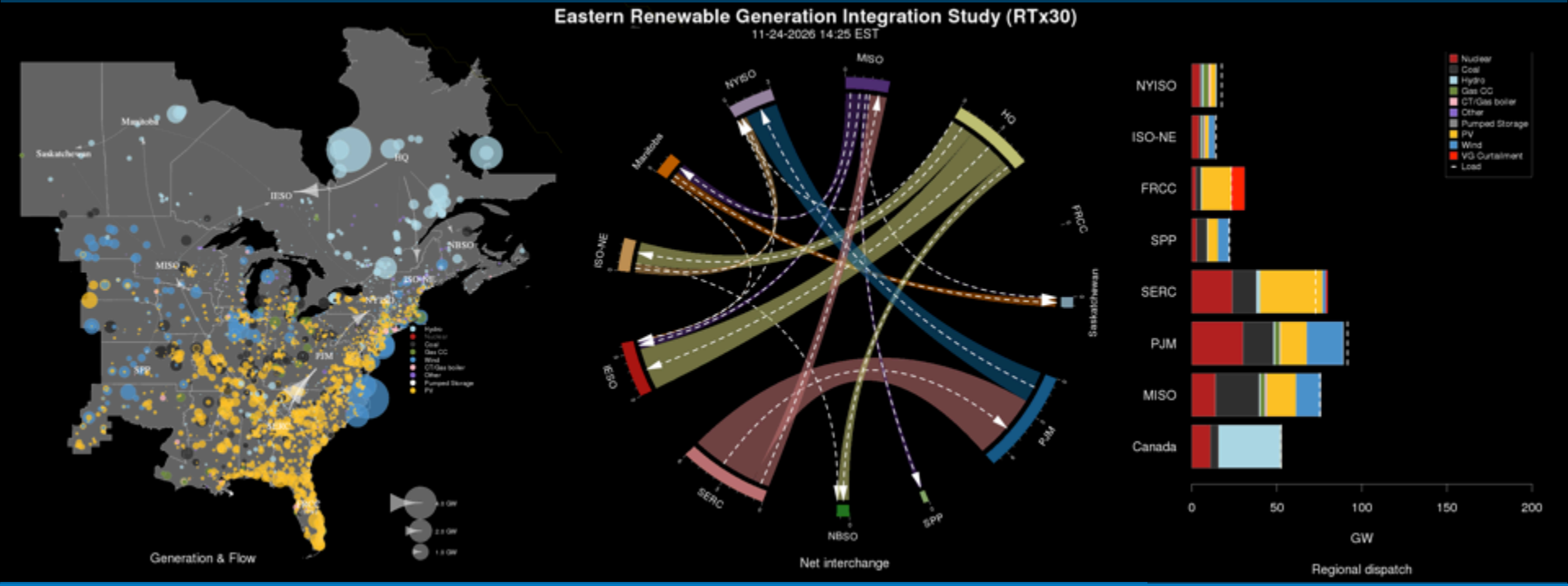
A new, disruptive approach to system security based on nine layers.



Advanced Energy System Design

Enabling Rapid Exploration of Infrastructure Options

- HPC models enable **interactive** evaluation of potential power system design choices -wide variety of technology, infrastructure, operation, economic and policy possibilities.
- Additional integration opportunities: heating/cooling, hydrogen, natural gas, liquid transportation fuels, water and wastewater systems, and communications networks.
- **IMPACT:** Optimized energy system designs with higher reliability, security and resilience, affordability, and use of advanced technologies.



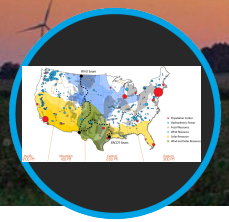
Multi-Scale Power System Modeling

Grid Modernization

Incorporate Emerging Technologies into Existing Grid Models

- Dramatically reduce the time required to analyze larger ensembles of future power system scenarios to find optimal grid infrastructure design and operations.
- Significantly increase the fidelity of the grid system being modeled, allowing direct incorporation of variable generation and loads, and distributed energy resources.
- New computational science approaches allow for accurate decomposition of large power system planning problems to allow for greater application of parallel computing
- **IMPACT:** Improved confidence in long-term grid planning studies, reducing economic and operational risk for future grid infrastructure investments.

NREL's Advanced Analysis Enables Cost-Effective, Reliable, and Clean Energy Systems



Interconnections Seam Study

What happens if the east joins the west?

December 2017

North American Renewable Integration Study

What if North America works together?

October 2019

Electrification Futures Study

What if the energy economy electrifies?

October 2019

Multi-scale Production Cost Modeling

Can we make models more detailed and faster?

October 2018

Los Angeles 100%

Can LA operate on 100% renewable energy?

January 2020

Questions?

www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Publication Number

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL Partnerships Advance Energy Technologies

NREL is unique among the 17 national laboratories in its focus on commercializing and deploying energy efficiency and advanced energy technologies.

Some current partners include:

- U.S. Navy
- Statoil
- The Port of Long Beach
- Air Force
- Children's Investment Fund Foundation
- Department of the Interior
- SolarWindow Technologies
- Bonneville Power Administration
- Hawaiian Electric Industries
- Toyota

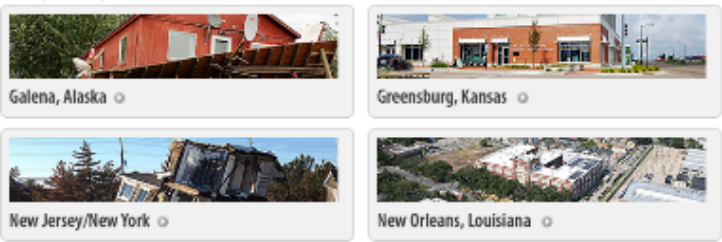
Energy Systems Integration Facility

Research Focus Areas

- Renewable electricity to grid integration
- Vehicle-to-grid integration
- Renewable fuels to grid integration
- Battery and thermal energy storage
- Microgrids
- Large-scale numerical simulation
- Cybersecurity and resilience
- Smart home and building systems
- Energy-water nexus
- High-performance computing, analytics, and visualization

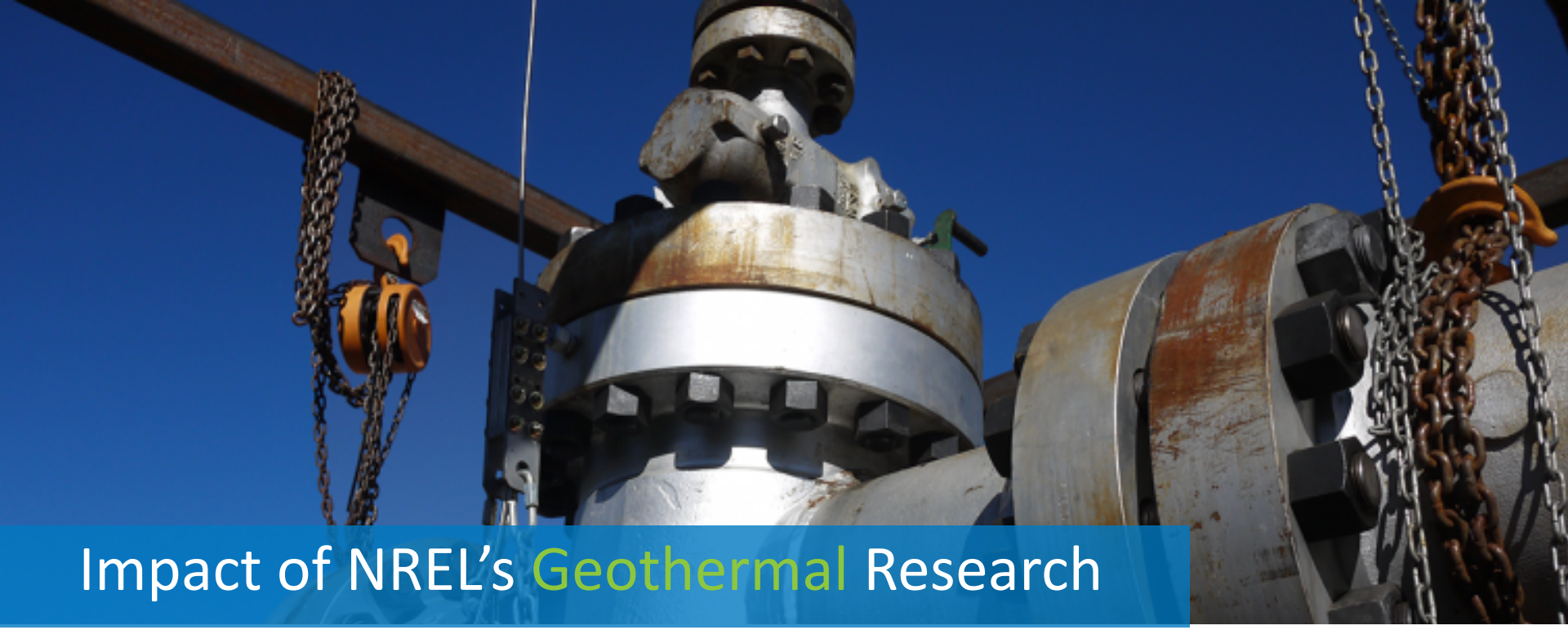
Disaster Recovery

- NREL's disaster recovery work has led to a deeper understanding of resilience and how it can be built into nearly every project.
- DOE, DHS (FEMA) and other agencies
- More than 30 projects "resilience" projects from grid stability, cyber-security, transportation and development codes
- Pilot project to create a resilience roadmap: www.nrel.gov/tech_deployment/resilience-planning-roadmap



Example Recovery Projects

- 2005: New Orleans, Louisiana after Hurricanes Rita and Katrina (DOE funded)
- 2007: Greensburg, Kansas after an EF5 tornado (DOE funded)
- 2010: Haiti after a 7.0 magnitude earthquake
- 2012-2013: New York and New Jersey after Hurricane Sandy
- 2013-2014: Galena, Alaska after a flood on the Yukon River
- 2013-2017: State of Colorado after wildfires and floods
- 2016: Oglala Sioux Tribe on the Pine Ridge Reservation in South Dakota after extreme storms
- 2017: West Virginia after flooding



Impact of NREL's Geothermal Research

The U.S. geothermal industry has 4 GW of installed nameplate capacity—and is developing another 1 GW of geothermal power.

Market Impact

Leading the Geothermal Vision Study **(GeoVision)** to:

- Establish geothermal growth potential
- Position the sector to play a key role in national energy priorities