**WIND ENERGY RESEARCH & DEVELOPMENT**
Grid Systems Integration

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Grid Systems Integration

Enabling integration of large amounts of wind power onto the nation's power grid by researching grid operations and planning, developing technological solutions for grid stability, optimizing wind-hybrid storage systems, and establishing principles to ensure cybersecurity and grid resilience.
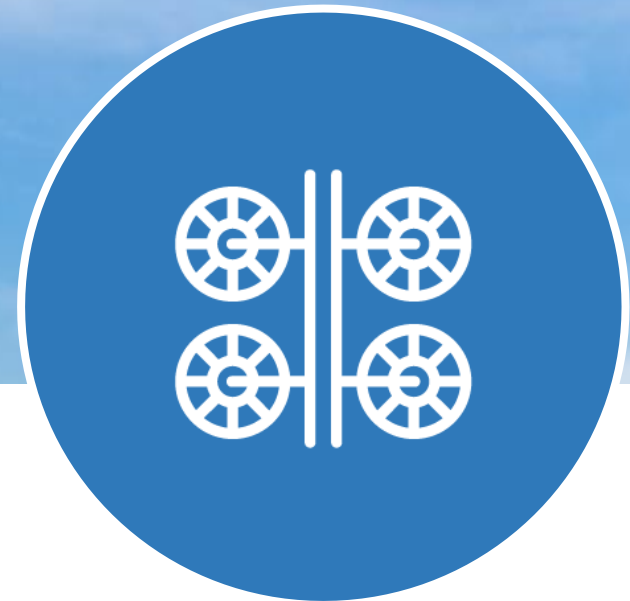
Optimal Grid Planning and Operation

Combining advanced research techniques with real-world operations and planning experience and market designs

Wind Plant Controls and Grid Stability Research

New technological solutions for improved grid stability and power system resilience

Wind Hybrid Systems

Optimized wind energy systems for high-penetration renewable energy grids, autonomous energy grids, and next-generation wind-hybrid systems coupled with energy storage

Cybersecurity and Resilience

Developing intrinsic security design principles for a future intelligent distributed grid that can automatically detect and respond to threats
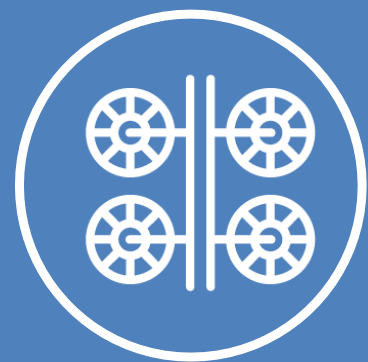
Optimal Grid Planning and Operation

- Enable seamless integration of large amounts of wind power into the nation's power grid through understanding the changes required to planning and operation.

- NREL works with university researchers, utilities, transmission system operators, and power system stakeholders to provide new solutions to integrate large penetrations of wind into the nation's power grid more efficiently.

Areas of Expertise
- Grid integration studies
- Probabilistic planning
- Solutions for operational challenges of weak grids
- Optimal infrastructure utilization.

Current Projects

North American Renewable Integration Study

### Optimal Grid Planning and Operation

CHALLENGE

Develop and publish tools for grid operators to plan an affordable, reliable, and sustainable grid.

APPROACH

- Develop a state-of-the-art analysis of the U.S., Canada, and Mexico power systems—from planning through operation
- Complete modeling and modeling visualization, make available resulting data sets
- Develop open-source tools and data-collection methods for grid stakeholders.

IMPACTS

- Informing grid planners, operators, market participants and regulators about challenges and opportunities for the grid
- Enabling stakeholders to deepen and extend their understanding of renewable energy and modern power systems
- Creating a framework for future analysis.
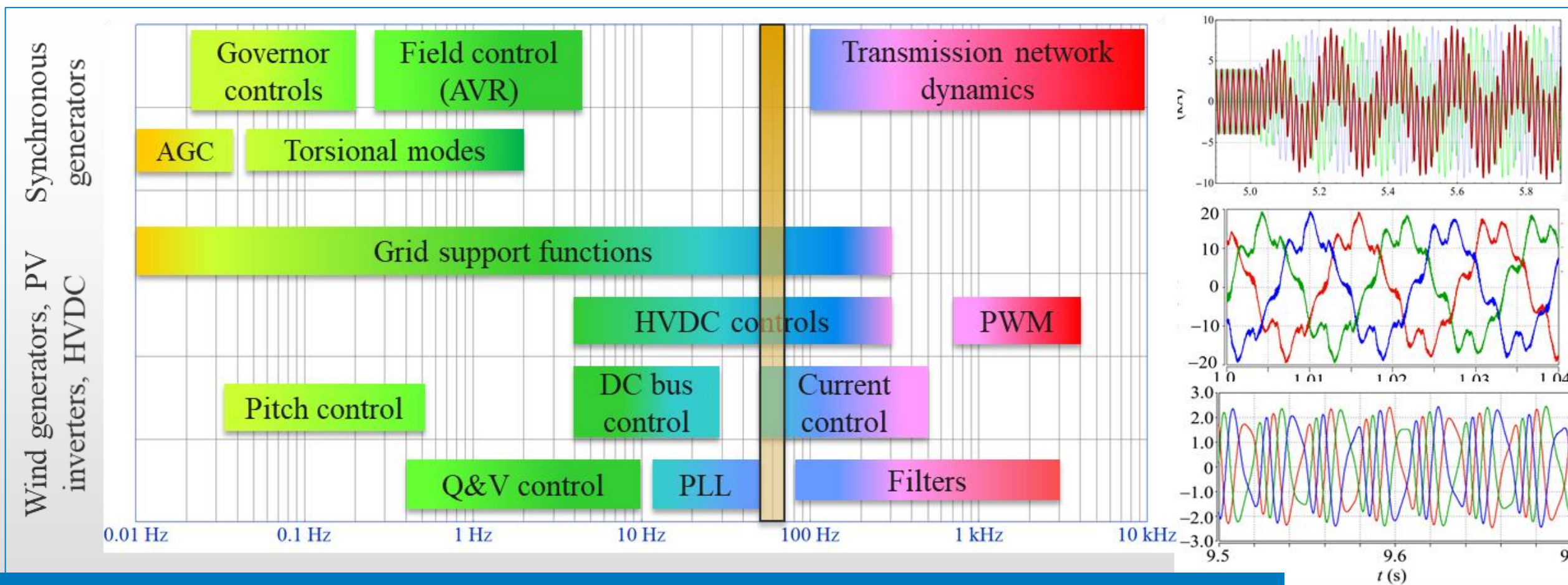
Wind Plant Controls and Grid Stability Research

- Increase capability of wind plants and increase wind's contribution to grid resiliency.

- NREL provides new analytical tools and testing methods at scale to evaluate stability impacts of wind power plants and develops advanced control functions to improve grid flexibility to absorb very high amounts of wind energy while also lowering the cost of grid integration.

Areas of Expertise

- Power systems and advanced controls
- Dynamic behaviors of power grids with high penetrations of wind
- Technological solutions for improved grid stability
- Testing methods for utility-scale applications
- Short-circuit currents and impacts on grid protection.

Current Projects

Advanced Modeling, Dynamic Stability Analysis, and Mitigation of Control Interactions in Wind Power Plants (WindStability)

Wind Plant Controls and Grid Stability Research
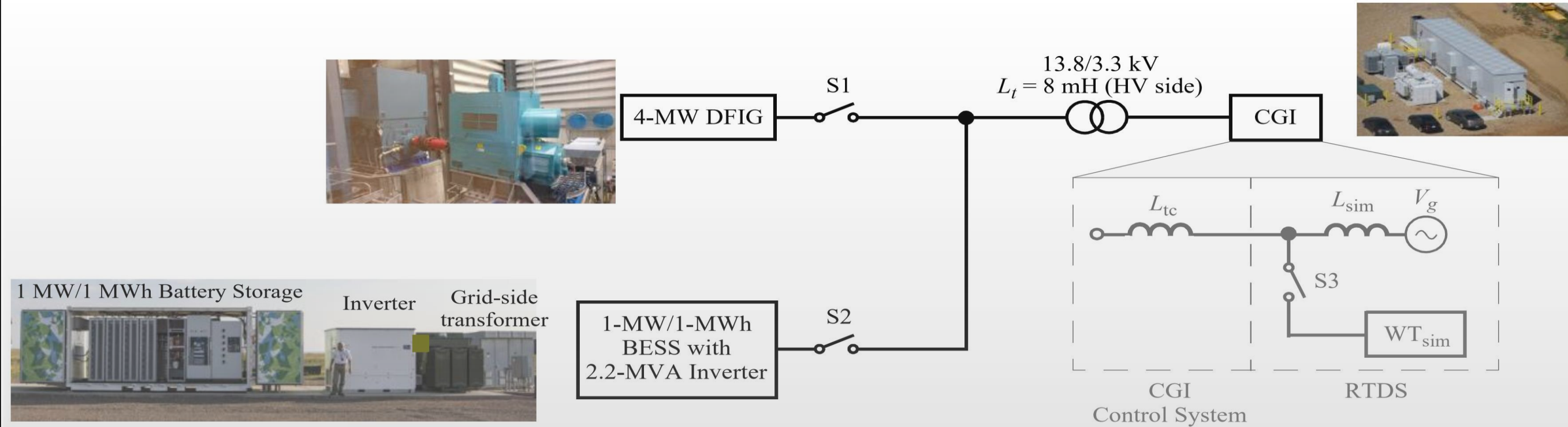
CHALLENGE

Fast and diverse controls of wind turbines from different manufacturers, unavailability of high-fidelity models, and complex dynamics result in stability problems for wind power plants and the grid.
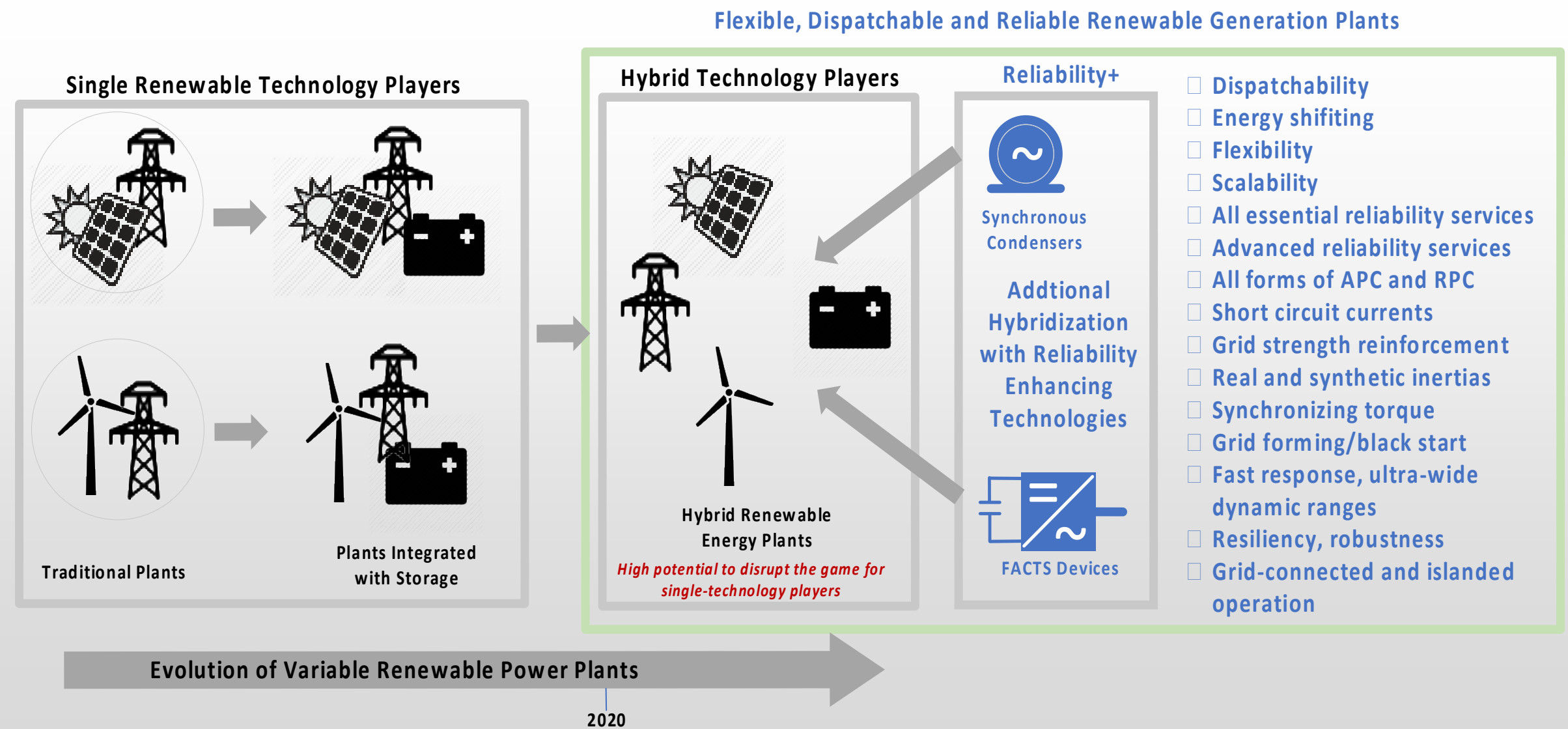
APPROACH

NREL's research on impedance-based modeling, wind turbine testing, and analysis identifies potential stability problems before commissioning, helps mitigate problems, and supports the development of advanced control functions, such as grid-forming turbines to improve reliability of wind power plants and the grid.

IMPACT

Impedance-based modeling, testing, and stability analysis tools developed by NREL serve as a template for OEMs and utilities to conduct grid stability studies for existing and incoming wind power plants and identify and mitigate potential stability problems. This enhances grid flexibility to absorb high amounts of wind energy and lower the cost of grid integration.

Wind Hybrid Systems

Single Renewable Technology Players

Traditional Plants

Plants Integrated with Storage

Hybrid Technology Players

Hybrid Renewable Energy Plants

High potential to disrupt the game for single-technology players

Reliability+

Synchronous Condensers

Addtional Hybridization with Reliability Enhancing Technologies

FACTS Devices

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

Evolution of Variable Renewable Power Plants

2020

- Enable seamless integration of wind with other types of power generation and thermal and fuel systems to provide a more flexible and efficient power system of the future.

- NREL conducts world-class research that spans different hybrid energy systems, combined with wind, from thermal to electric, that includes integration with advanced transportation systems, hydrogen-based power and fuel systems, and thermal management systems that integrate advanced energy storage options and provide for a more resilient, fully integrated, and advanced energy future.

Areas of Expertise

- Controls research for multiple technologies
- Integrated energy resource assessments and forecasting
- Microgrids and autonomous energy systems
- Optimal infrastructure utilization for integrated energy systems.

Current Projects

Integrated Design and Analysis of Hybrid Power Plants

Wind Hybrid Systems

CHALLENGE

Optimize the design of a hybrid power plant, at the component level, for any combination of technology and any revenue stream for future developers/owners/operators. This project focuses on integrating wind, solar (photovoltaic and concentrating solar power), storage, geothermal, and hydro resources.

APPROACH

Address two key pillars of designing and operating hybrid power plants:

- Modeling of different technologies and the interactions between technologies
- Large-scale optimization for component-level design and operation

IMPACT

Developed a hybrid optimization and performance platform that can design and operate utility-scale hybrid power plants, down to the component level, with timescales of one minute.

Current Projects

Autonomous Energy Systems

Wind Hybrid Systems

CHALLENGE

Optimize and control massively deployed distributed energy resources in real-time—integrating renewables, buildings, vehicles, and the grid.

APPROACH

NREL is developing distributed, scalable optimization and control algorithms that can operate millions of smart devices in real time. Our technical experts are creating a complex simulation framework to integrate buildings, renewables, vehicles, and the grid that can be deployed on high-performance computing resources.

IMPACT

This project represents a paradigm shift in how energy systems are integrated. Rather than a top-down approach, using centrally controlled assets, the grid of the future requires a bottom-up approach where distributed energy resources are controlled in real time with distributed, hierarchical controls.
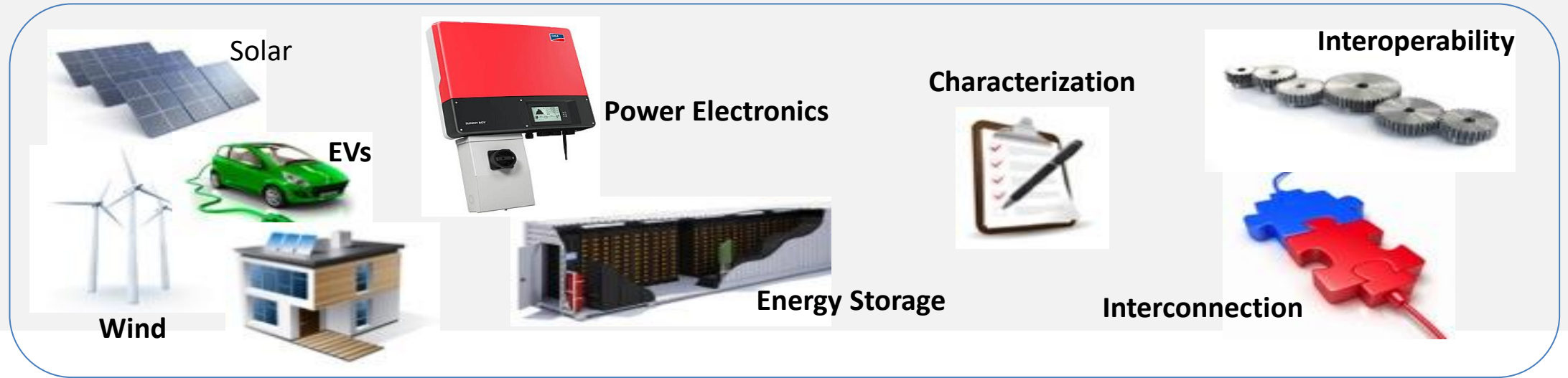
Current Projects

Clusters of Flexible PV-Wind-Storage Hybrid Generation (FlexPower)

Wind Hybrid Systems

Integrated Devices and Systems

Solar · Wind · EVs · Power Electronics · Energy Storage · Characterization · Interconnection · Interoperability

CHALLENGE

Emerging hybrid renewable energy systems offer new opportunities for the global renewable energy industry with disruptive market potential. This demands grid solutions that are cost effective, reliable and scalable, and that can function within energy systems ranging in size from large, continental- interconnected power systems, to islands, to microgrids.

APPROACH

NREL is building a fully operational, scalable, multi-MW FlexPower Wind-PV-energy storage hybrid power plant that provides a full set of reliability and resiliency services.

IMPACTS

- NREL will establish the ability of hybrid power plants to operate in grid-forming mode, and to provide reliability and resiliency services (e.g., black start, islanded operation) in a multi-MW-scale system
- Our technical experts will demonstrate the ability of hybrid systems to couple electrical energy with thermal management systems, resulting in an increased number of energy storage options that will enhance the resilience and efficiency of the grid.
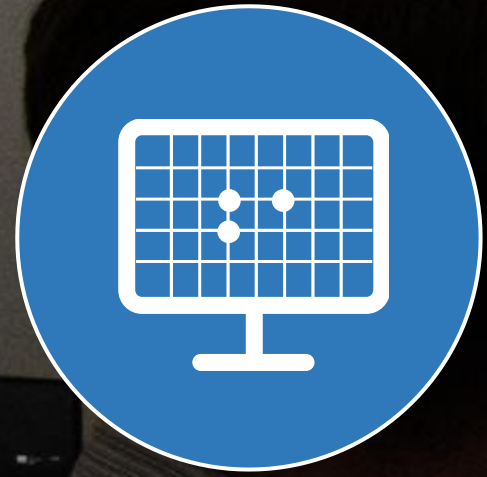
Cybersecurity and Resilience

NREL technical experts are working to:

- **Improve our** current understanding of potential energy service disruption and its consequences
- **Improve e**nergy security under different scenarios by continuing to provide energy services that protect energy systems from when human or natural disruptions occur
- Develop more resilient energy systems
- Develop intrinsic security design principles for a future intelligent, distributed grid in which millions of interconnected devices can automatically detect and respond to threats
- Close the system-level security gaps that inevitably emerge when so much hardware and software are brought into harmonious operation.

Areas of Expertise

- Malicious threats to wind turbines and power plants
- Cyber-energy emulation and visualization of wind systems
- Automated intrusion detection
- Automated threat response with autonomous energy systems.

Current Projects

Distributed Energy Resources Cybersecurity Framework

Cybersecurity and Resilience

CHALLENGE

Compared to traditional centralized generation, distributed energy resources (DERs) result in complex, data-driven communications networks. The growing number of smart devices that support DERs increases the number of access points outside of the utility's administrative domain.

APPROACH

Built upon previous cybersecurity frameworks, and with NREL's expertise in distributed energy systems, our researchers developed the Distributed Energy Resources Cybersecurity Framework (DERCF) to help federal agencies mitigate gaps in their cybersecurity posture for distributed energy systems.

IMPACT

The DERCF provides U.S. federal government sites with a tool to assess the cybersecurity posture of their DER systems, informing policies and controls for cyber governance, cyber-physical technical management, and physical security of distributed energy technologies.

Current Projects

Wind Cybersecurity Roadmap

Cybersecurity and Resilience

CHALLENGE

With new devices entering the wind energy market, there is a lack of standardization in communication protocols, software, and hardware. Varied ownership models and wind control network complexities make it difficult for utilities to identify and share allowable parameters across a given network.

APPROACH

NREL researchers are exploring consequence-driven and cyber-informed engineering solutions as well as consequence-based targeting for vulnerability analysis. The multilab team is evaluating best security practices for U.S. wind power plants, including network segmentation, zoning, monitoring, intrusion, detection, and prevention systems for supervisory control and data acquisition.

IMPACT

The roadmap will identify gaps, solutions, and opportunities in cybersecurity research and development for wind energy.

Current Projects

Cyber-Energy Emulation Platform

Cybersecurity and Resilience

CHALLENGE

Today's electric grid was designed before cyberattack was a potential threat to critical infrastructure. This has led to a patchwork culture that can't keep pace with the growth in cyber-related vulnerabilities.

APPROACH

NREL developed the Cyber-Energy Emulation (CEE) Platform that allows researchers to develop, emulate, and visualize interconnected power and communications systems. The platform can generate any number of energy system environments and connect to physical devices at NREL's Energy Systems Integration Facility. A strategic vision is for the CEE Platform to also connect to devices throughout NREL's Flatirons Campus, including wind turbines.

IMPACT

The CEE Platform helps improve the current understanding of potential energy service disruption and its consequences. With the platform's ability to generate grid environments for evaluation, researchers can safely explore vulnerabilities and mitigation effectiveness for current and future energy systems.

Accomplishments & Impacts

NREL's technical experts in grid systems integration are uniquely qualified to:

- Combine advanced research techniques with real-world operations and planning experience

- Provide technological solutions for improved grid stability and power system resilience

- Optimize wind energy systems for high-penetration renewable energy grids, autonomous energy grids, and next-generation wind-hybrid systems

- Conduct advanced research on integrated energy systems (ARIES), creating a platform for integrated hybrid plant control that includes operational modes for wind, solar, fuel cells/electrolyzer, and hydropower

- Identify, anticipate, detect, protect against, and respond to today's biggest threats to the energy grid—primarily, in the renewable energy sector.