NREL
NATIONAL RENEWABLE ENERGY LABORATORY




Energy Systems Integration Facility

Creating the Future Clean Energy System….Today

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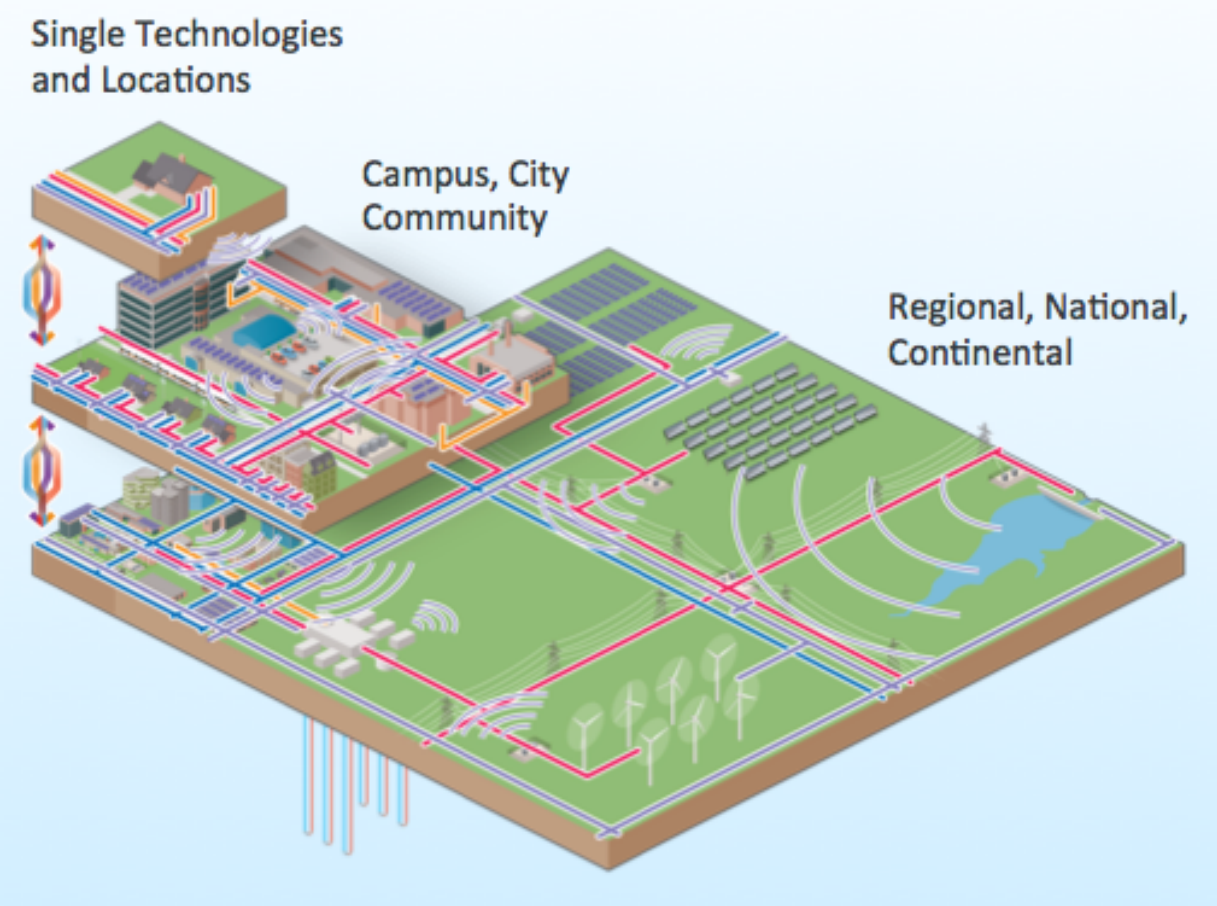
National Renewable Energy Laboratory

Energy Systems Integration – The Concept

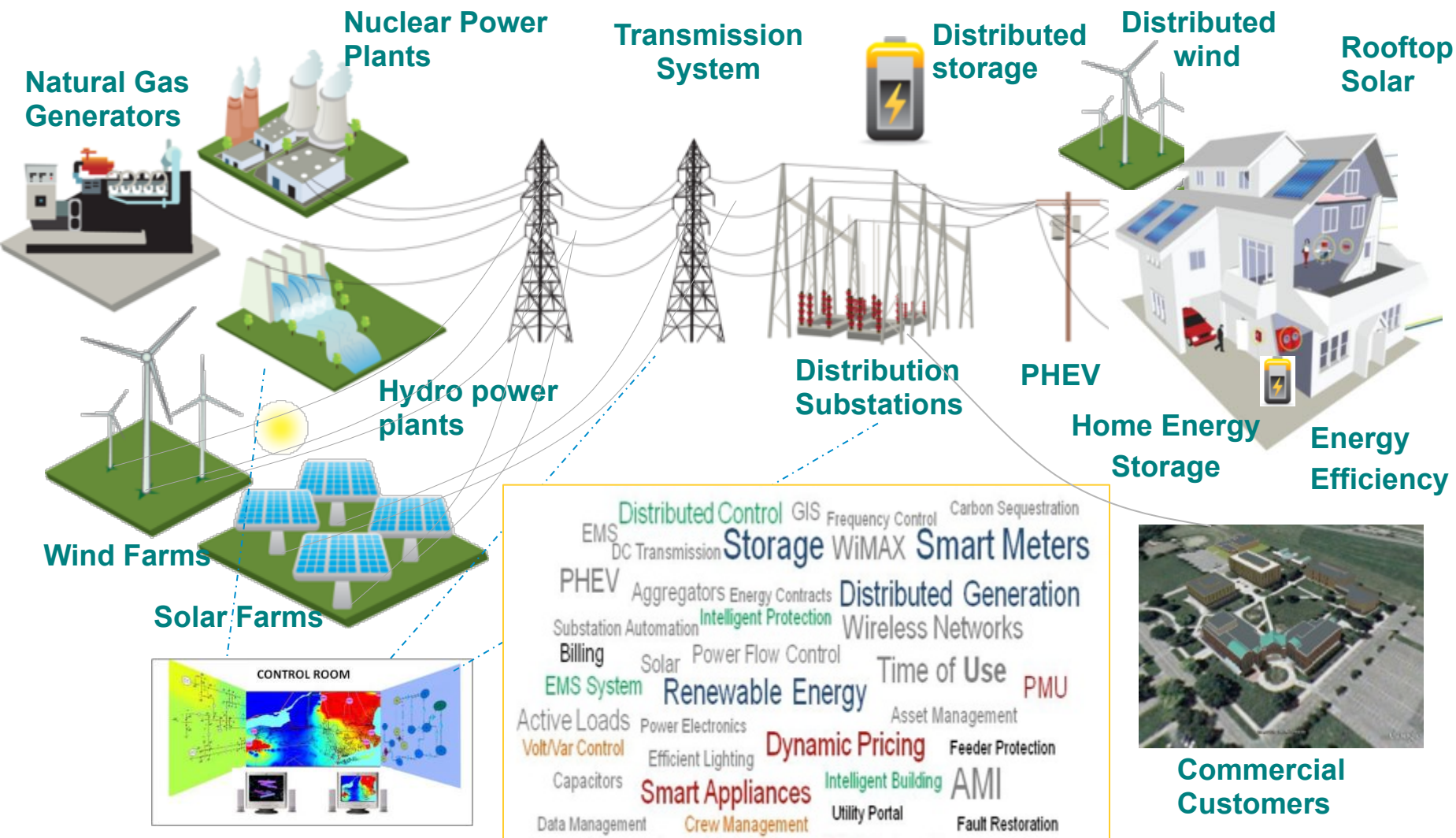
Energy Systems Integration

ESI Vision: Highly integrated, flexible, and efficient systems that enable utilization of clean energy sources while maintaining reliability at an affordable cost



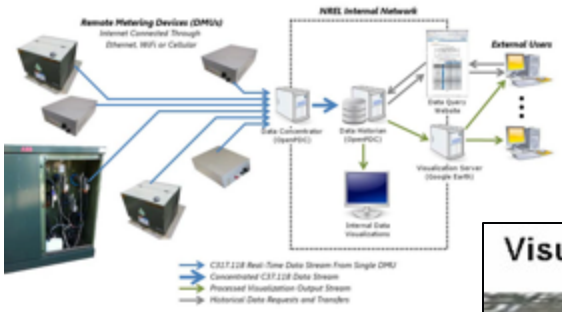
The Emerging Grid

Energy Systems Integration

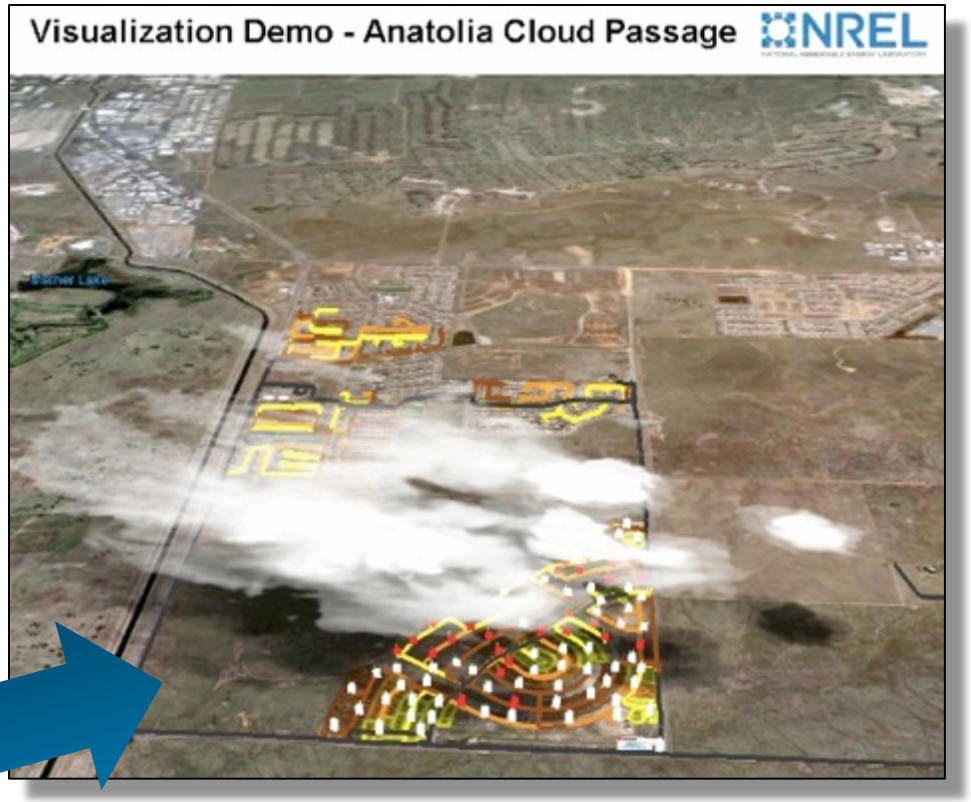


What types of problems are we solving?

Energy Systems Integration

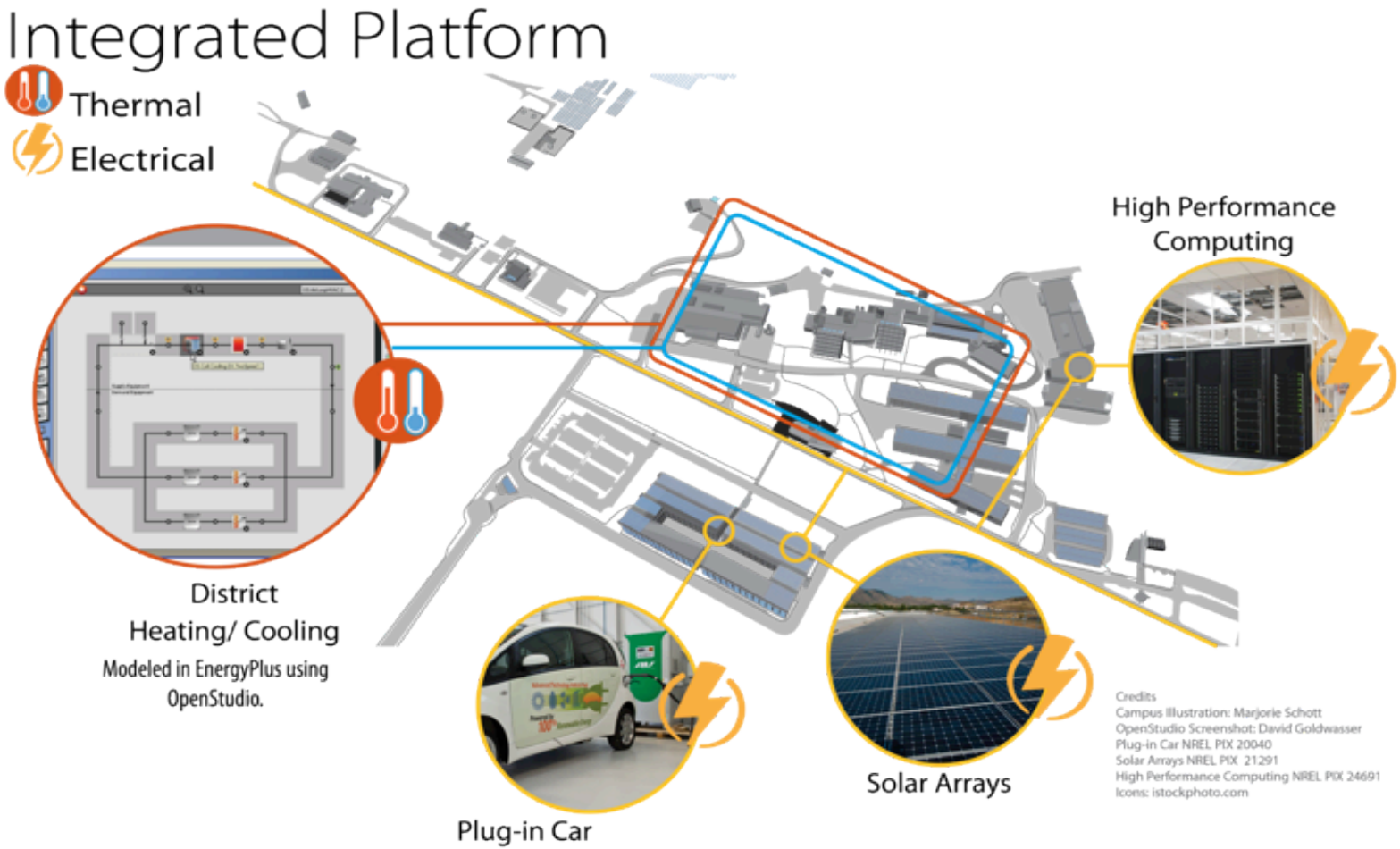


Understand and solving issues with high penetrations of variable renewables, distributed generation, electric vehicles, and controllable loads.



Integrated Energy Systems – Campus Scale

Energy Systems Integration



1. Develop control strategies for Electric Vehicle (EV) car charging stations and PV Panels on the Parking Garage to respond to sunny and cloudy skies and reduce site variability.

2. Demand management for the ESIF high performance computer. This essentially enables another 1 MW of demand response capability at NREL. The ESI Campus Modeling LDRD will incorporate these capabilities into the campus wide simulation.

3. Optimize the thermal capacity in the district heating and cooling systems adjusting setpoints as a demand response event and still maintain proper building operational and comfort levels.

Energy Systems Integration Facility

Energy Systems Integration

NREL NATIONAL RENEWABLE ENERGY LABORATORY | ENERGY SYSTEMS INTEGRATION FACILITY

U.S. DEPARTMENT OF ENERGY

- NREL's largest R&D facility (182,500 ft^2 /20,000 m^2)
- Space for ~200 NREL staff and research partners
- Petascale HPC and Data Center supports all research at NREL
- Labs focus on R&D of integrated energy systems
  - Electricity
  - Fuels
  - Transportation
  - Buildings & Campus
- Integrated electrical, thermal, fuel, and data infrastructure

Addressing the challenges of large-scale integration of clean energy technologies into the energy systems infrastructure

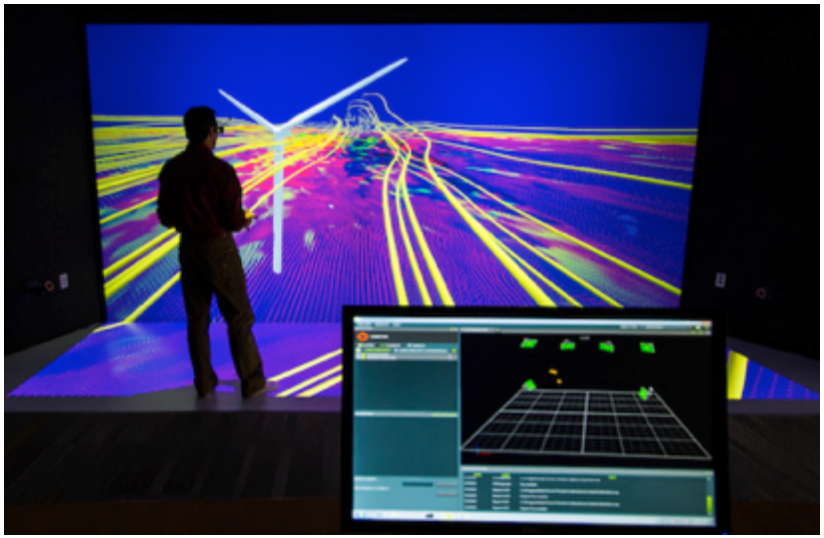
http://www.nrel.gov/eis/facilities_esif.html

"This new facility will allow for an even stronger partnership with manufacturers, utilities and researchers to help integrate more clean, renewable energy into a smarter, more reliable and more resilient power grid." *- Energy Secretary Ernest Moniz*

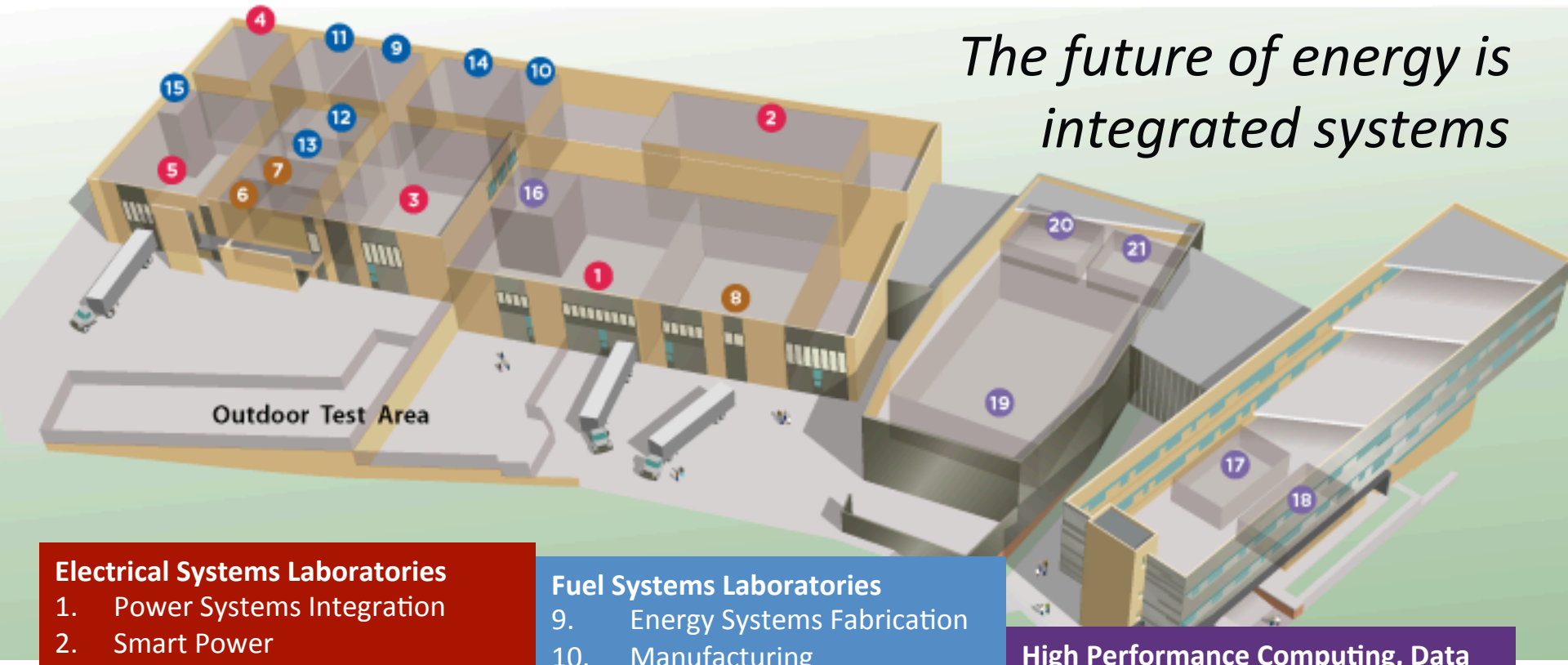
ESIF's Unique Advanced Capabilities

Energy Systems Integration

- Multiple parallel AC and DC experimental busses (MW power level) with grid simulation
- Flexible interconnection points for electricity, thermal, and fuels
- Medium voltage (15kV) microgrid test bed
- Virtual utility operations center and visualization rooms
- Smart grid testing lab for advanced communications and control
- Interconnectivity to external field sites for data feeds and model validation
- Petascale HPC and data mgmt system in showcase energy efficient data center
- Hardware-in-the-loop (HIL) simulation capability to test grid scenarios with high penetration of renewables



ESIF Laboratories



The future of energy is integrated systems

Electrical Systems Laboratories
1. Power Systems Integration
2. Smart Power
3. Energy Storage
4. Electrical Characterization
5. Energy Systems Integration

Thermal Systems Laboratories
6. Thermal Storage Process and Components
7. Thermal Storage Materials
8. Optical Characterization

Fuel Systems Laboratories
9. Energy Systems Fabrication
10. Manufacturing
11. Materials Characterization
12. Electrochemical Characterization
13. Energy Systems Sensor
14. Fuel Cell Development & Test
15. Energy Systems High Pressure Test

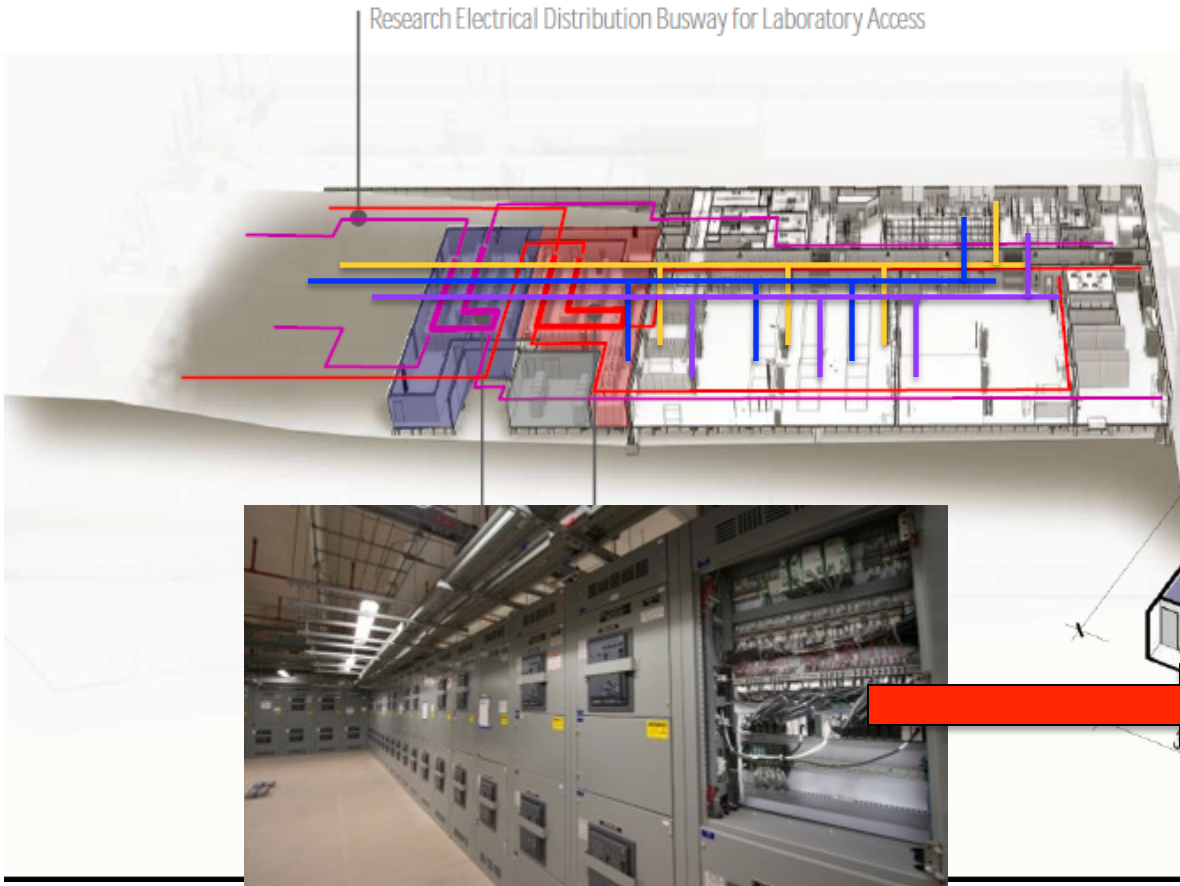
High Performance Computing, Data Analysis, and Visualization
16. ESIF Control Room
17. Energy Integration Visualization
18. Secure Data Center
19. High Performance Computing Data Center
20. Insight Center Visualization
21. Insight Center Collaboration

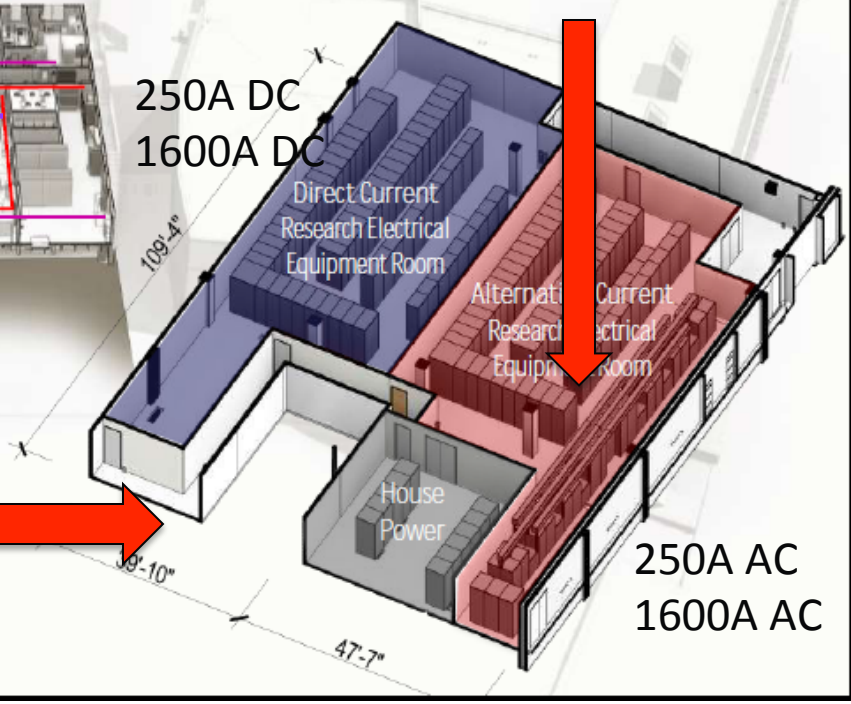
ESIF Research Infrastructure

Energy Systems Integration

- Research Electrical Distribution Bus – REDB (AC 3ph, 600V, 1200A and DC +/-500V, 1200A)
- Thermal Distribution Bus
- Fuel Distribution Bus
- Supervisory Control and Data Acquisition (SCADA)

1MW Grid Simulator

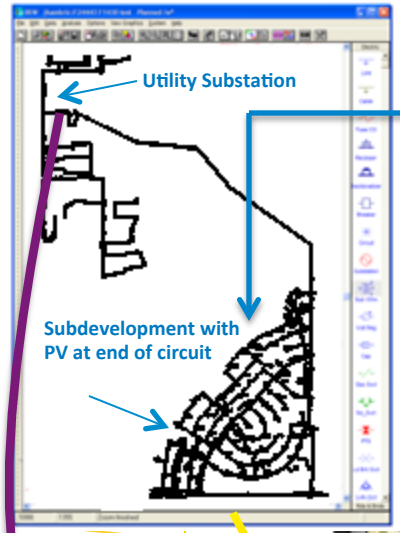




Hardware-in-the-Loop: Connecting Experiments to Simulations

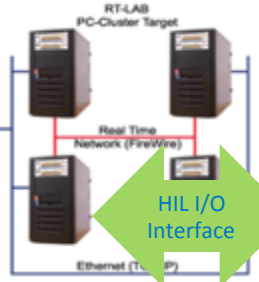
Energy Systems Integration

Simulation validated with real field data



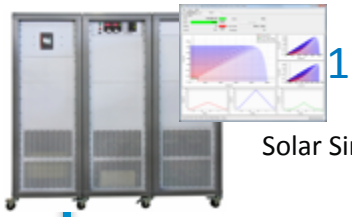
Simulation and Visualization at ESIF

Visualization Interface



HIL I/O Interface

Actual hardware at ESIF



1.5MW

Solar Simulator

Device Under Test (e.g. inverter, energy storage, EV, load, etc.)

1 MW

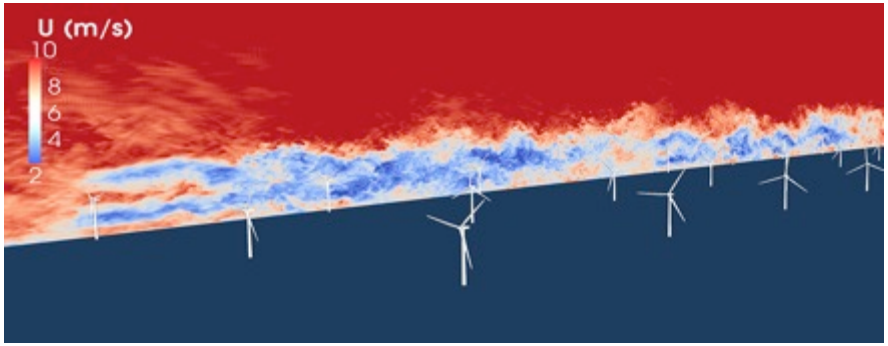
1 MW

Replicated into Larger Simulation

Simulation loop closed with actual hardware

High Performance and Highly Efficient Computing

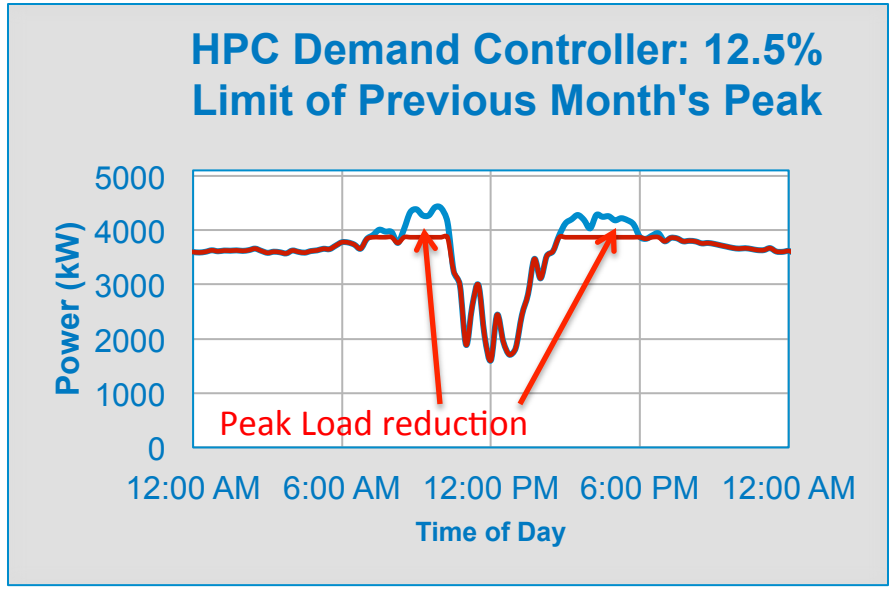
Energy Systems Integration



This computer-generated simulation shows the turbulent nature of wind turbine wakes. The simulation helped uncover potential differences in output between downstream 'waked' turbines and upstream turbines.

3D Simulation model of Polymeric organic nitroxide radical (PTMA) film for battery applications

- High performance computing (1.2 peteflops) provides a multi-faceted basis for simulating future integrated energy innovations that would otherwise be too expensive, too lengthy, too dangerous, or otherwise impossible to study by direct experimentation
- Highly Energy Efficient (PUE under 1.06)
- HPC also has integrated energy control (run scheduling) and waste heat capture

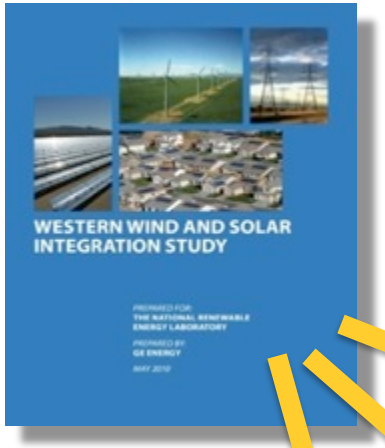


Energy System Operations

Energy Systems Integration

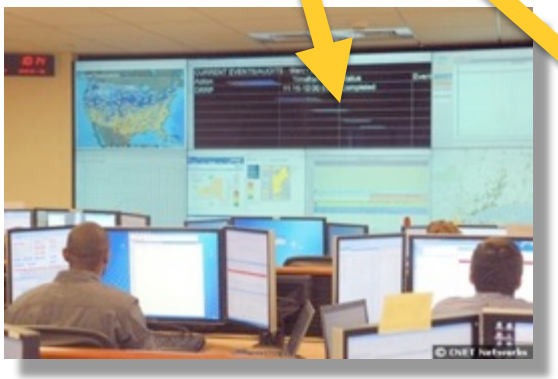
A Flight Simulator for Energy System Operators

"connecting integration studies to operations"

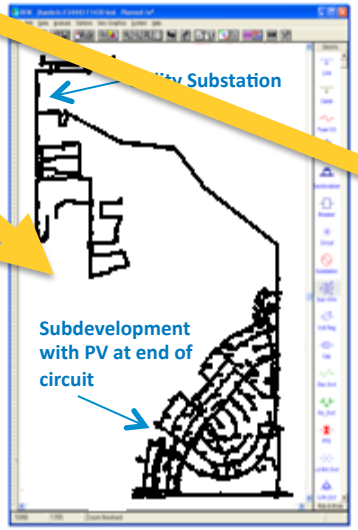


Operations techniques development for:

- High renewables and energy efficiency penetrations
- New systems configurations and contingency response
- High storage / DR penetrations
- Resource forecast integration



Transmission



Distribution

Campus Energy Dashboard

ESIF – Power Systems Integration Lab

Energy Systems Integration

Research in the Power Systems Integration Laboratory focuses on the development and testing of large-scale distributed energy systems for grid-connected, standalone, and microgrid applications. The laboratory can accommodate large power system components, such as inverters for PV and wind systems, diesel and natural gas generators, battery packs, microgrid interconnection switchgear, and vehicles.

Lab Functions

- Main test lab for conducting MW-scale electrical system integration activities.
- Research explores a variety of operating configurations including: grid connected stand-alone, microgrids, and hybrid power systems.
- House infrastructure for DG research (AC and DC power supplies for REDB, chiller and boiler)

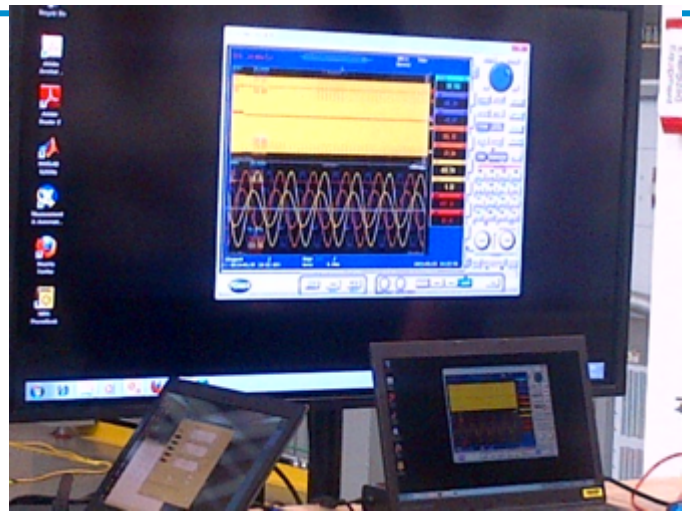
Major Lab Equipment

- 1 MW grid simulator
- 1.5MW PV Array Simulator
- 100kW PV Array Simulator
- Several 250kW DC power supplies
- 100 ton research chiller
- 750MBH research boiler
- Connections to Research Electrical, Thermal, Fuel Buses

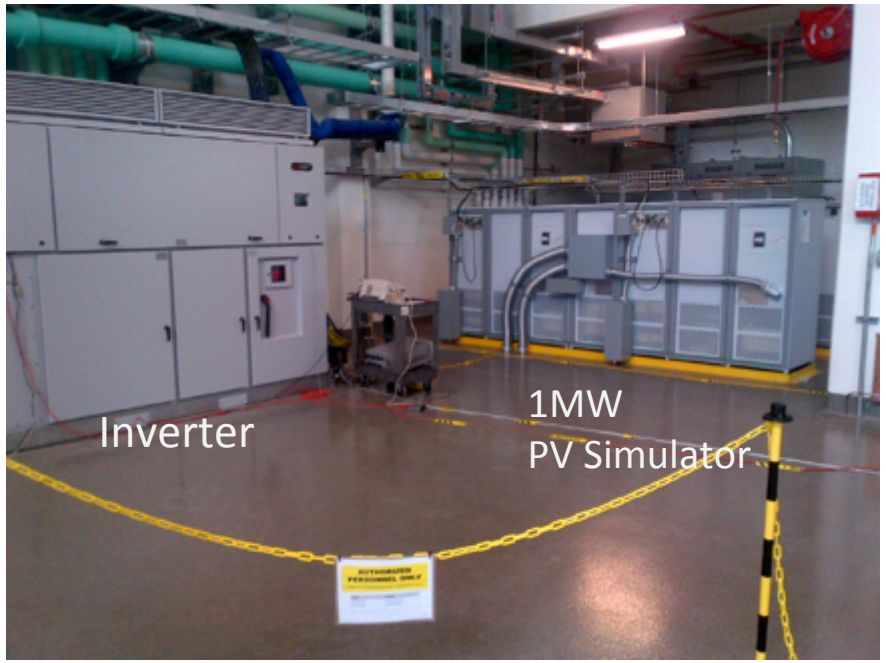
Smart Solar Systems

Energy Systems Integration

- ***Advanced Energy: 500 kW PV Inverter with Volt-VAR and Freq-Watt Control***
- **(DOE SEGIS-AC project to develop advanced Volt-VAR and Freq-Watt control that improves grid operations)**



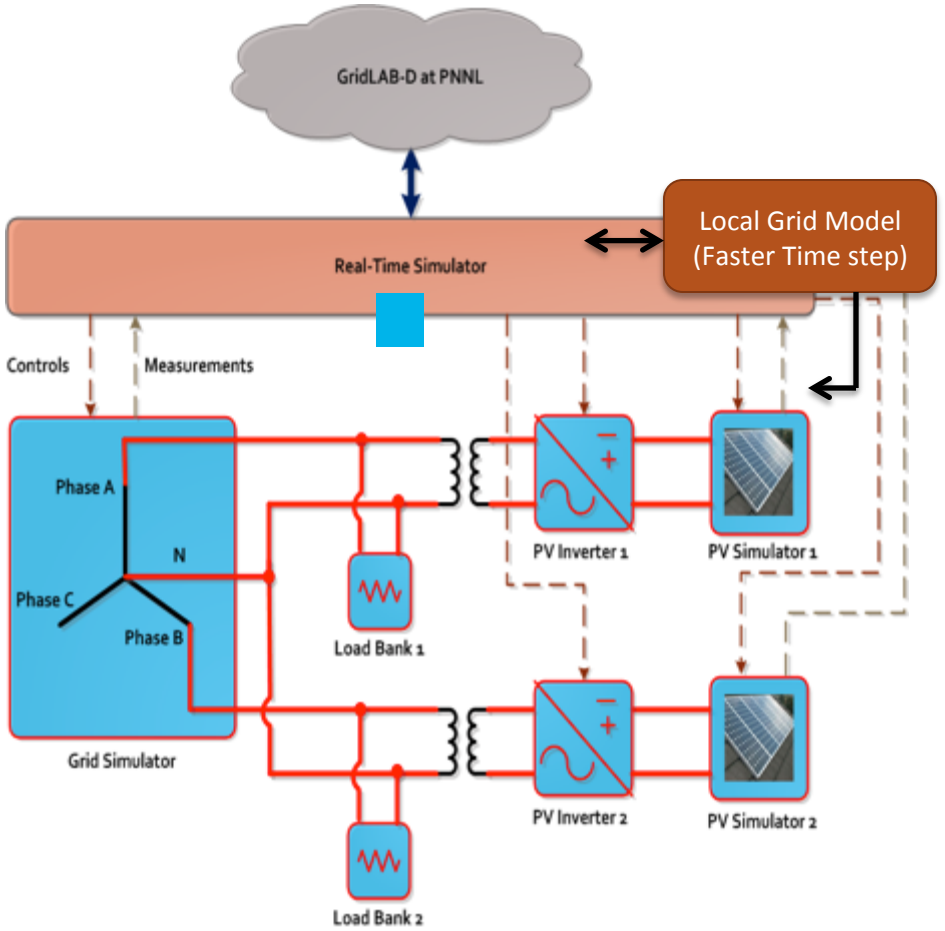
- **Full Power Testing**
- **Both Utility and Grid Simulator Connections**
- **Regenerative Capability of Grid Simulator demonstrated (pushing power back to the utility)**
- **Inverter Advanced Functionality demonstrated**



Remote PHIL Project
(connecting NREL and PNNL)

Energy Systems Integration

- Support PHIL tests of faster dynamic events such as
  - Voltage transients
  - Power quality
  - Protection coordination
  - Frequency regulation
- Added local co-simulation model will allow for simulation of fast events
- Utility control model would continue to simulate SCADA-class data acquisition and control signals



ESIF – Smart Power Lab

Energy Systems Integration

Research in the Smart Power Laboratory focuses on the development and integration of smart, connected technologies, including distributed and renewable energy resources and smart energy management. The 5,300-ft^2 laboratory is designed to be highly flexible and configurable to enable a range of smart power activities—from developing advanced inverters and power converters to testing residential- and commercial-scale meters and control technologies.

Lab Functions

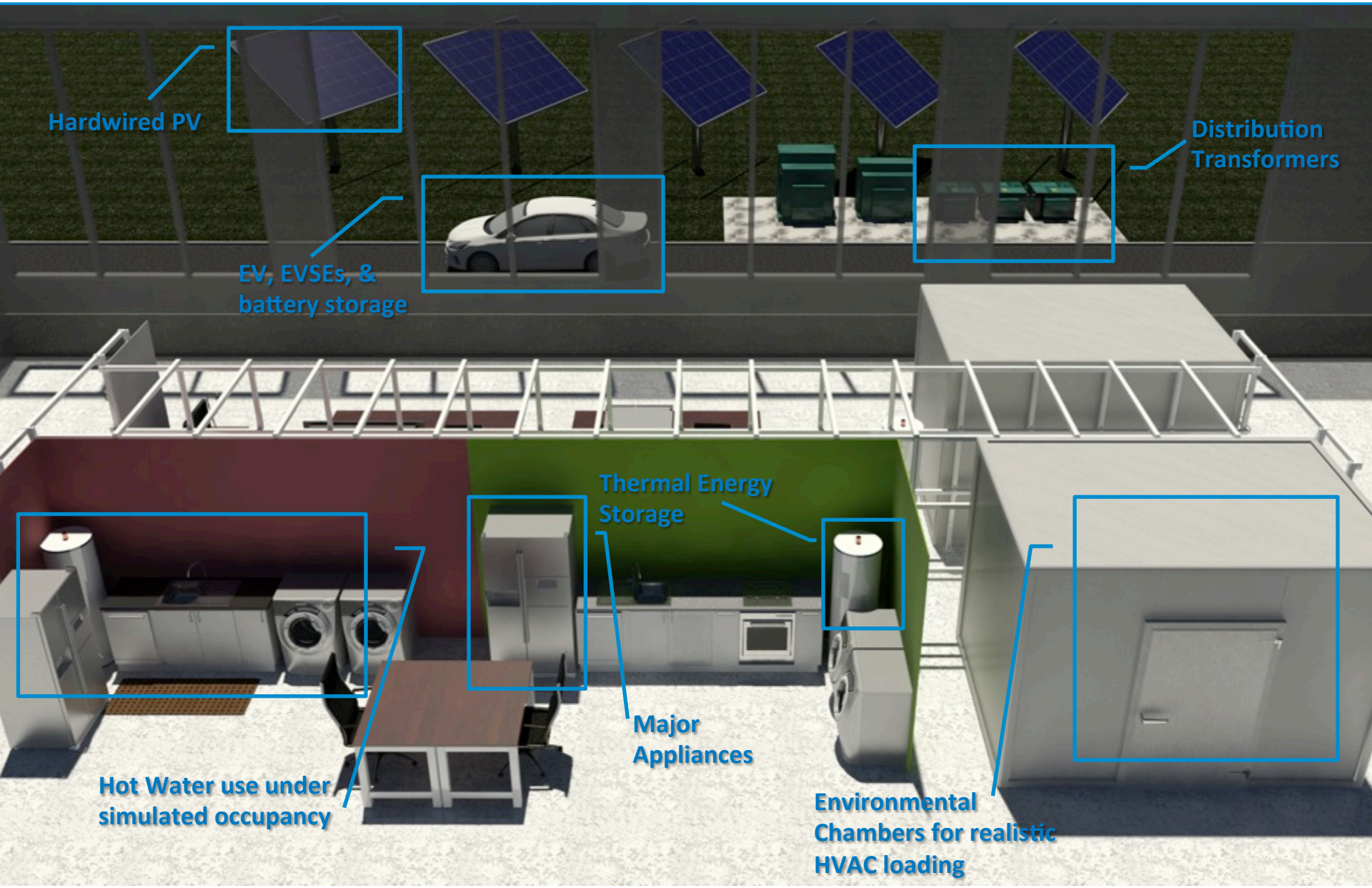
- Residential scale distributed resources, smart appliances, and HVAC evaluations
- Interoperability and communications testing
- Individual Test labs for development and testing of the power electronics components and circuits used in renewable energy integration
- Instrument development area for basic electronics work

Major Lab Equipment

- AC power supplies
- 45kW and 15kW grid simulators
- Opal RT and RTDS Hardware-in-the-Loop Systems
- Connections to REDB
- 3 Smart home appliances (refrigerators, water heaters, dish washers, etc.)
- 2 environmental chambers to test small HVAC systems

Smart Homes

Energy Systems Integration



ESIF – Energy Storage Lab

Energy Systems Integration

At the Energy Storage Laboratory, research focuses on the integration of energy storage systems (stationary and vehicle-mounted) and their interconnection with the utility grid. Includes batteries, ultra-capacitors, flywheels, compressed air, etc.

Lab Functions

- Testing energy storage components when integrated with renewable energy electrical systems:
  - Performance
  - Efficiency
  - Safety
  - Model validation
  - Long duration reliably

Major Lab Equipment

- DC Power Testing station 250 kW, up to 900 Vdc
- Grid Simulator connections
- REDB Connections
- Research Chiller & Boiler
- 600kW PV Simulator
- EV Chargers

V2G and Smart EVs

Energy Systems Integration

- NREL is developing testing procedures for V2G applications
- Validates safe interconnection during:
  - Abnormal Voltage/Frequency
  - Synchronization
  - Unintentional Islanding
  - Open-phase
- Measures performance
  - Efficiency
  - Distortion

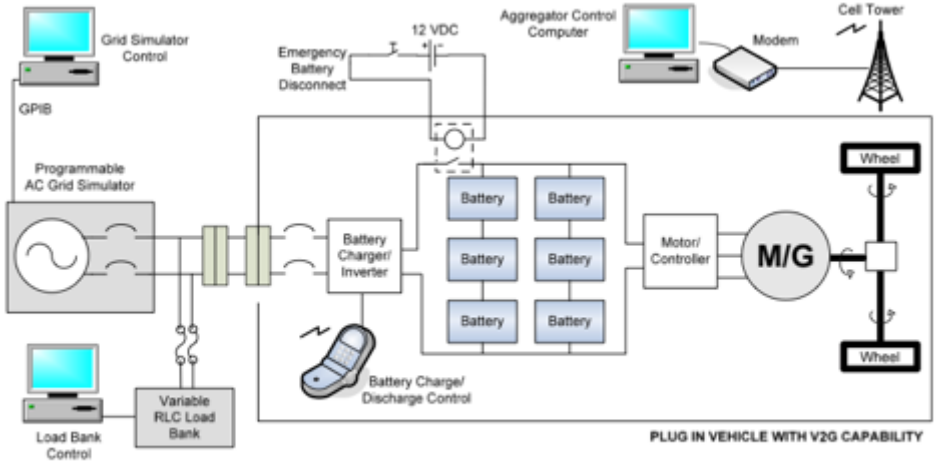
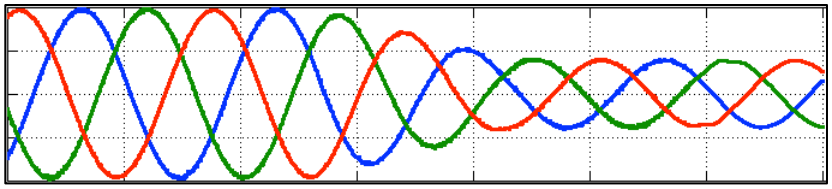


Figure 2. Example of V2G test setup



ESIF – Energy Systems Integration Lab

Energy Systems Integration

The Energy Systems Integration Laboratory provides a flexible, renewable-ready platform for research, development, and testing of state-of-the-art hydrogen based and other energy storage systems.

Lab Functions

- Assessment of the technical readiness, performance characterization, and research to help industry move these systems towards optimal renewable-based production and efficient utilization of hydrogen
- Testing of electrolyzers, fuel cells, compression equipment, delivery systems

Major Lab Equipment

- Gas Chromatograph
- Ion Chromatograph
- PEM electrolyzer
- Alkaline electrolyzer
- Fuel cell
- H2 high pressure compressor
- Two high pressure testing bays fully rated for testing systems to 15,000 psig

ESIF –Outdoor Test Areas

Energy Systems Integration

The outdoor test areas at the ESIF allow for testing either at 480 Volts or 13.2 kiloVolts

MV Major Lab Equipment

- 1MVA 13.2kV to 480 Y-Y transformers
- Connections to REDB, Utility
- Distribution transformers
- EV Chargers

LV Major Lab Equipment

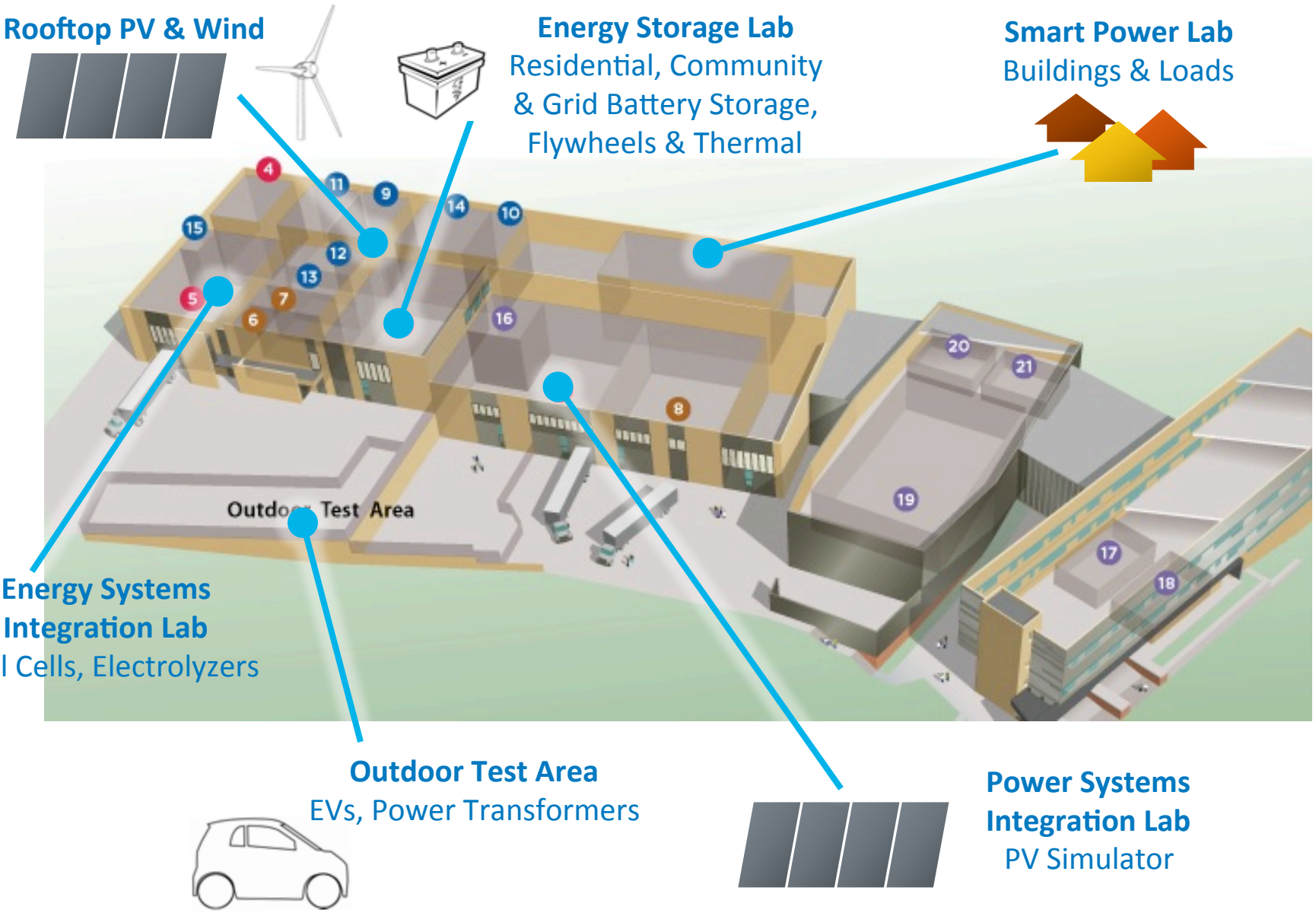
- 80kW and 125kW Gensets
- 100kW, 250kW load banks
- Capstone Microturbine
- Connections to REDB

ESIL Major Lab Equipment

- H_2 storage vessels
- H_2 IC engine testing
- H_2 Vehicle fueling station

Integrated System Experimentation

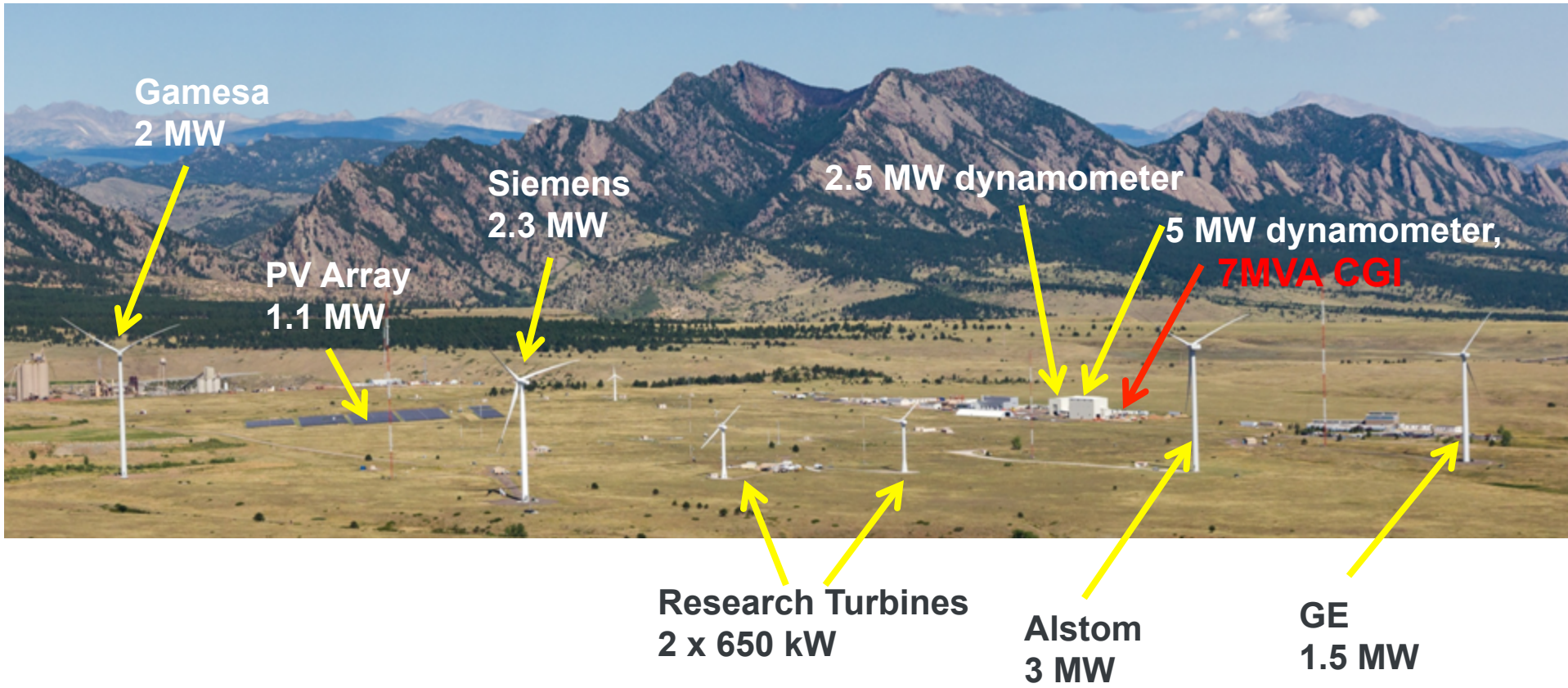
Energy Systems Integration



NWTC Test Site

Energy Systems Integration

- Total of 11 MW variable renewable generation currently at NWTC test site
- There are many small wind turbines (under 100 kW) installed as well
- 2.5MW and 5 MW dynamometers
- 7 MVA Controllable Grid Interface (CGI) for grid compliance testing
- Multi-MW energy storage testing capability under development



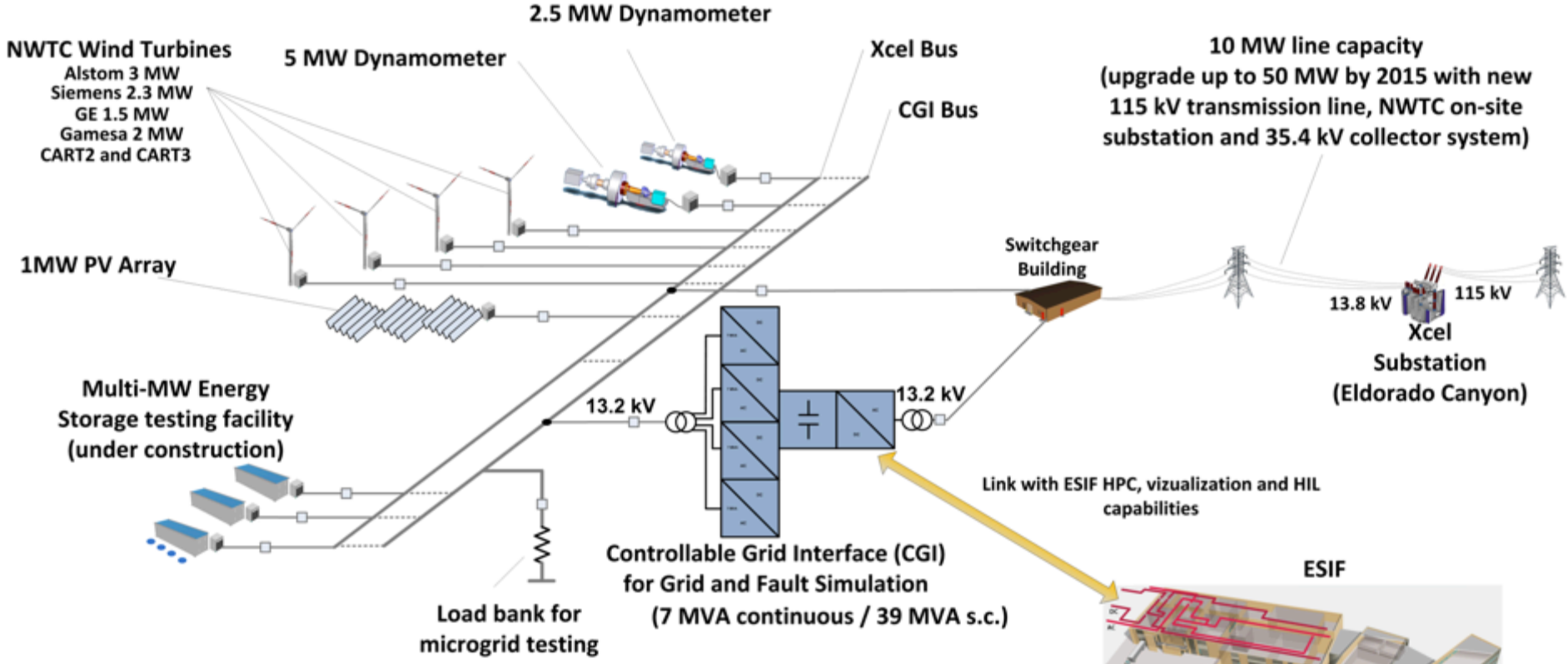
NWTC 7-MVA Controllable Grid Interface

Energy Systems Integration

- Installed at NWTC test site in Nov 2012
- Commissioning and characterization testing – end of 2013
- Row 4 / turbine bus connection – FY14
- Energy storage site connection – end of 2014

NWTC Dual-Bus Test Site Concept

- Highly flexible and configurable system level multi-MW testing/demonstration platform
- Most components in place and operational
- Switchgear upgrade to connect field turbines is under way (FY14 task)
- Energy storage testing facility to become on-line by the end of 2014



- Possible to test grid connected generation
- Micro grids / EMS
- Combination of technologies / Advanced controls

ESIF – Where the Future Energy System Starts

Energy Systems Integration

ESIF Provides

- End-to-end System Experimentation
- Across electrical, thermal, fuel, communications systems
- Evaluation of MW scale systems
- High performance computing and advanced analytics
- Integration of hardware and simulation environments

For Partnering Opportunities contact:

Bryan Hannegan – Assocoate Lab Director ESI - byran.hannegan@nrel.gov
Ben Kroposki – ESI Director – benjamin.kroposki@nrel.gov
Martha Symko-Davies – ESI Business Development - Martha.Symko.Davies@nrel.gov

Additional Labs in ESIF

ESIF – Electrical Characterization Lab

Energy Systems Integration

The Electrical Characterization Laboratory supports detailed electrical characterization of components and systems. This laboratory allows researchers to test the ability of equipment to withstand high voltage surges and high current faults, including equipment using standard and advanced fuels such as hydrogen.

Lab Function

- Provides a safe environment for conducting high voltage surge testing and high current short circuit tests on equipment

Major Lab Equipment

- Surge generator system for simulating lightning strikes and other high voltage, high current events
- Separate ventilation system
- Video links to main test area
- Class 1; Division 2 approved

ESIF – Fuel Cell Dev and Test Lab

Energy Systems Integration

The Fuel Cell Development and Test Laboratory supports fuel cell research and development projects through in-situ fuel cell testing. Testing capabilities include single-cell fuel cells and fuel cell stacks.

Lab functions

- Bench top testing of Fuel Cells and Fuel Cell Stacks.
- Thermochemical, electrochemical, and thermomechanical analysis of fuel cell MEA materials.

Major Lab Equipment

- Single cell and segmented cell fuel cell test stations
- Microelectrode workstation
- Environmental chamber for membrane mechanical testing
- Calibration equipment
- Spatial testing capabilities using 121-channel 50cm2 segmented cell system or multi-channel potentiostat
- Comprehensive host of state-of-the-art fuel cell diagnostics

ESIF – Energy Systems Fabrication Lab

Energy Systems Integration

The Energy Systems Fabrication Laboratory supports NREL's fuel cell and electrochemical cell research. The lab is used for the manufacture of components for fuel cells and electrochemical cells using a variety of techniques. Fabricated components include catalysts, thin-film and gas diffusion electrodes, and membrane electrode assemblies.

Lab functions

- Supports fuel cell and electrochemical cell related research
- Fuel Cell MEA fabrication and characterization
- Wet chemical synthesis and fabrication of materials and device components

Major Lab Equipment

- Hot press
- Vacuum table
- Vapor Sorption Workstation
- Workstation EGA (evolved gas analysis)

ESIF – Manufacturing Lab

Energy Systems Integration

The Manufacturing Laboratory features a web line suitable for use in developing and validating quality control techniques for manufacturers of low temperature and high temperature fuel cells. Capabilities support initial proof-of-concept studies through prototype system development and in-line validation.

Lab functions

- Continuous web processing (roll-to-roll) equipment and various diagnostic measurement platforms.
- Develops rapid and non-destructive quality-control techniques to help manufacturer's scale-up production while maintaining quality.
- Evaluates and develops diagnostic systems for in-line quality control of fuel cell membrane electrode assembly components.

Major Lab Equipment

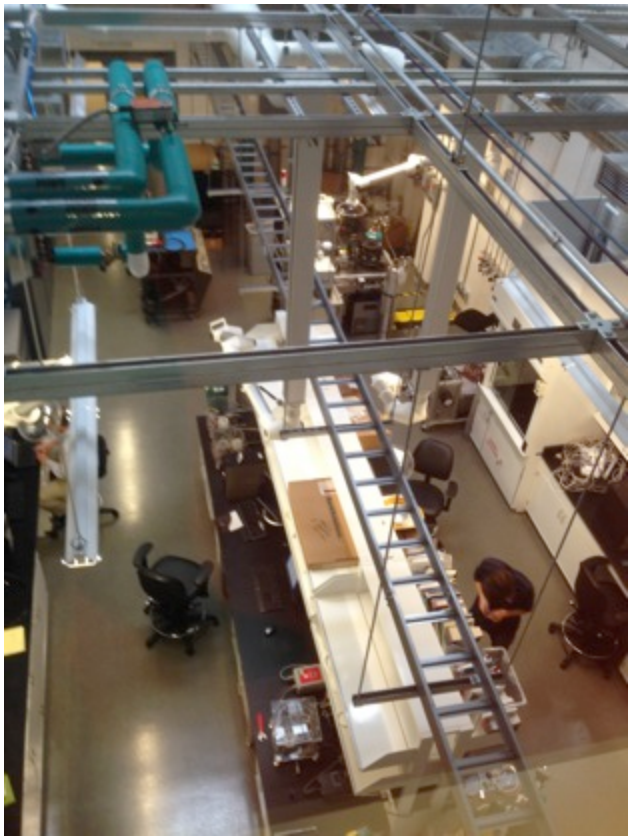
- Continuing Processing Line
- Unwind/Wind Modules
- Optical Diagnostic Test Platform
- Process/Instrumentation Modules

ESIF – Materials & Electrochemical Characterization Labs

Energy Systems Integration

The Materials & Electrochemical Characterization laboratories use advanced diagnostic tools for material characterization on fuel cell materials.

The **Materials Characterization Laboratory** covers multiple analytical operations, with the overall goal of troubleshooting synthetic materials or process streams to improve performance.



The **Electrochemical Characterization Laboratory** concentrates on the development and characterization of new materials for PEMFCs such as electrocatalysts, catalyst supports in terms of electrochemical activity, electrochemical surface area and corrosion/ durability.

Currently the labs are focused on fuel cells, however many of the fabrication and characterization capabilities apply to other energy storage devices, such as batteries.

ESIF – Energy Systems Sensor Lab

Energy Systems Integration

The Energy Systems Sensor Laboratory tests hydrogen and its use for the development of codes and standards in order to take the current technology to the level it needs to be in the future.

Lab functions

- Testing and analyzing sensors are over a range of controlled and monitored environmental conditions.
- Testing the impact of interferants and poisons.
- Evaluating the life span of sensors with separate dedicated life test fixtures.
- Testing of hydrogen sensors for process applications, including responses under high hydrogen concentrations.

Major Lab Equipment

- SSTL Sensor Test Apparatus
- Walk-in Fume Hood
- National Instruments Data Acquisition System
- Circulating Cooler
- Precision Digital Mass Flow Controllers

ESIF – Optical Characterization Lab

Energy Systems Integration

The Optical Characterization Laboratory provides state-of-the-art characterization and testing capabilities for assessing the optical surface quality and optical performance for various CSP technologies including parabolic troughs, linear Fresnel, dishes, and heliostats.

Lab Functions

- Optical testing of panels and systems
- Weathering of panels
- Structural analysis of CSP concentrator systems

Major Lab Equipment

- VSHOT (Video Scanning Hartman Optical Tester)
- Large Thermal Cycling Chamber (future)
- Weather Chamber
- SOFAST (Sandia Optical Fringe Analysis Slope Tool)

ESIF – Thermal Storage Materials Lab

Energy Systems Integration

In the Thermal Storage Materials lab, fluids and other materials are characterized and properties are measured—including their capacity to hold heat, resist corrosion, or operate within a required temperature range.

Lab functions

- Runs high-temperature instruments for the analysis of thermophysical properties.
- Small samples of candidate materials are prepared and characterized using differential scanning calorimetry, thermogravimetric analysis, and other specialized analytical methods.

Major Lab Equipment

- Scanning Calorimeter
- Thermal Gravimetric Analyzer
- Vulcon Furnace

ESIF – Thermal Storage Process & Components

Energy Systems Integration

The Thermal Storage Process and Components lab focuses on environmental performance—in a process environment—of fluids and materials for heat transfer and storage.

Lab Functions

- Performs pilot-scale thermal energy storage system testing through multiple charge and discharge cycles to evaluate heat exchanger performance and storage efficiency.
- Laboratory equipment can also be utilized to test instrument and sensor compatibility with hot heat transfer fluids.

Major Lab Equipment

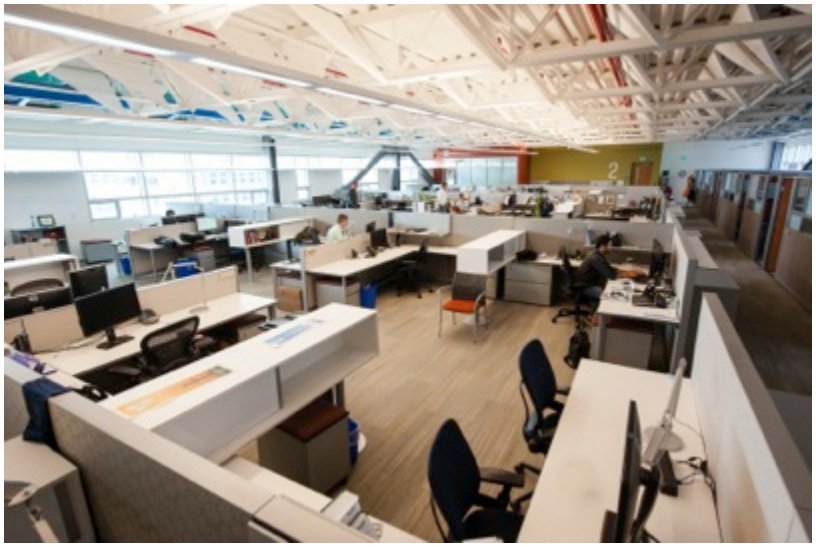
- Four 10 ft. X 10 ft. test bays for evaluation of 30kW thermal systems
- Custom test system to provide hot salt or molten metal heat transfer fluid to the test device
- Thermal energy storage process test loops
- Outdoor air feed and exhaust for system cooling
- HEPA-rated enclosure for testing systems containing nanomaterials

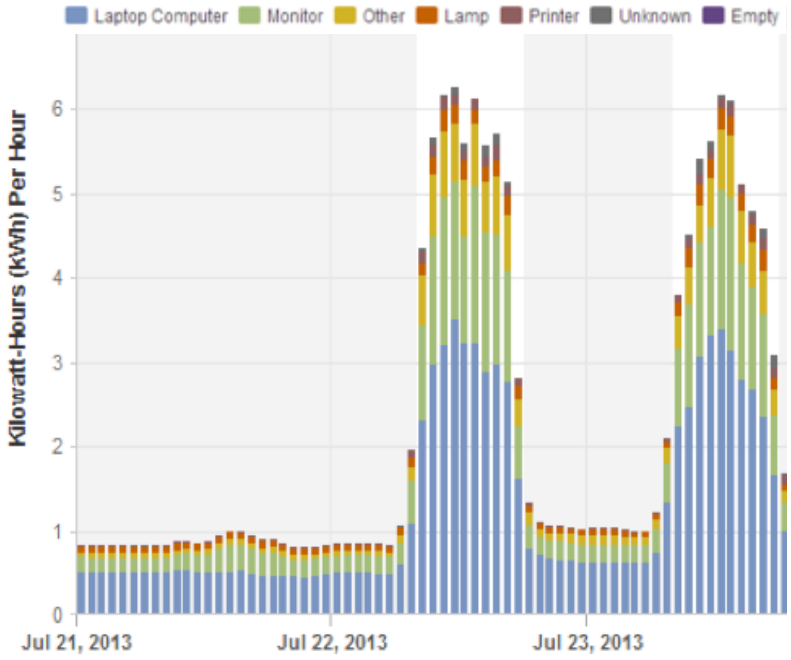
Smart Office Areas

Energy Systems Integration

- Integrated Energy Efficiency into Design and Operations
- High use of daylight
- Natural use of ventilation through operable windows
- Uses about 25% national average for energy in office space
- Installed Enmetric plug load control system
- Collecting circuit level load information in office area

Enmetric Plug Load Controller

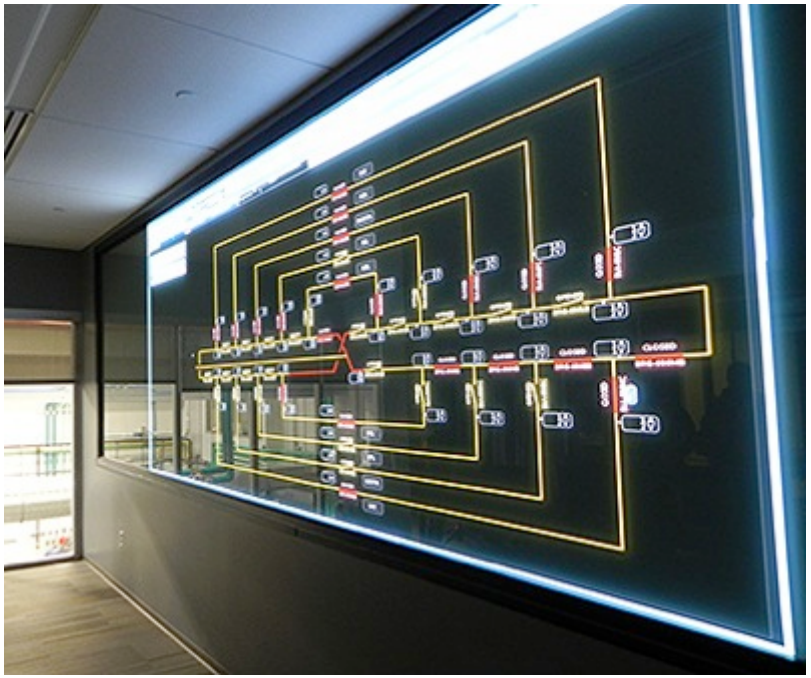




ESIF – Control Room and Viz Labs

Energy Systems Integration

In the ESIF Control Room, researchers can see the electrical bus, close switches, and checkout grid simulators. The Supervisory Control and Data Acquisition (SCADA) system in the ESIF monitors and controls research facility-based processes and gathers and disseminates real-time data for collaboration and visualization.



Lab Functions

- The data from experiments throughout the facility is streamed to secure servers in the control room
- The SCADA supports a large visualization screen in the ESIF control room allowing researchers and partners to watch the experiment in real-time

Major Lab Equipment

- SCADA
- State-of-the-Art Visualization Screen

Transmission Grid Integration

NREL has a number of activities focused on bulk-power and transmission-level planning and operations, with a focus on grid integration of renewable energy and energy efficiency technologies and how it affects the bulk transmission grid.

Energy Planning, Modeling, and Analysis in Support of Grid Integration:

- Energy Imbalance Market Study
- Oahu Wind Integration and Transmission Study
- Hawaii Solar Integration Study
- Eastern Wind Integration and Transmission Study

State-of-the-art models and analysis techniques:

- System Advisor Model
- FESTIV
- Regional Energy Deployment System
- REFlex
- Wind/Solar/Hydrogen Deployment System

Transmission Grid Integration

Energy Systems Integration

Wholesale Electricity Market Design

Stakeholder Engagement

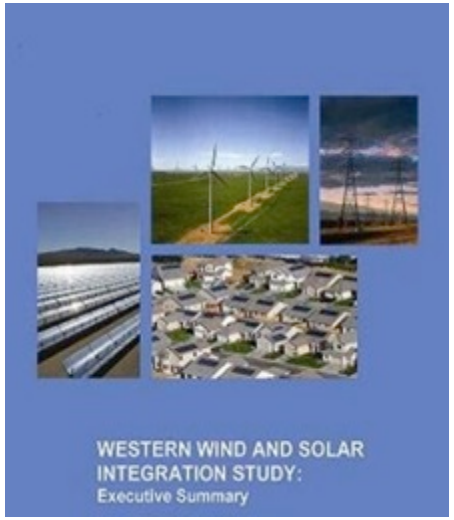
Power System Operations

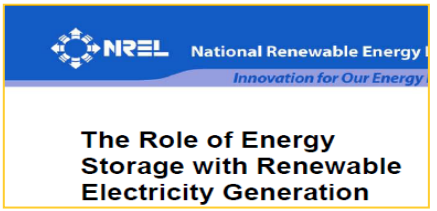
Power System Planning

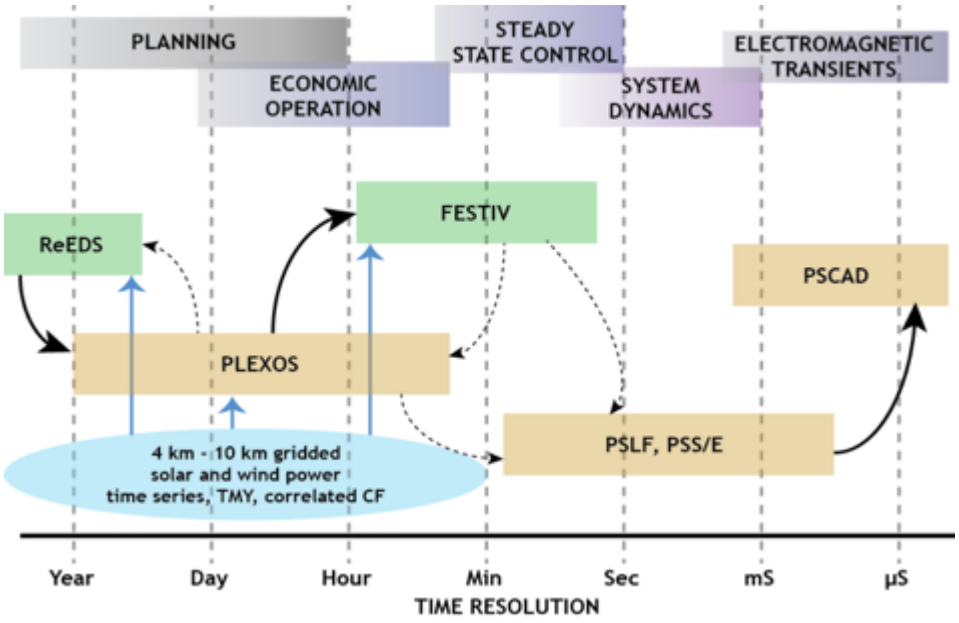
Operational Forecasting

Generator Modeling

Testing



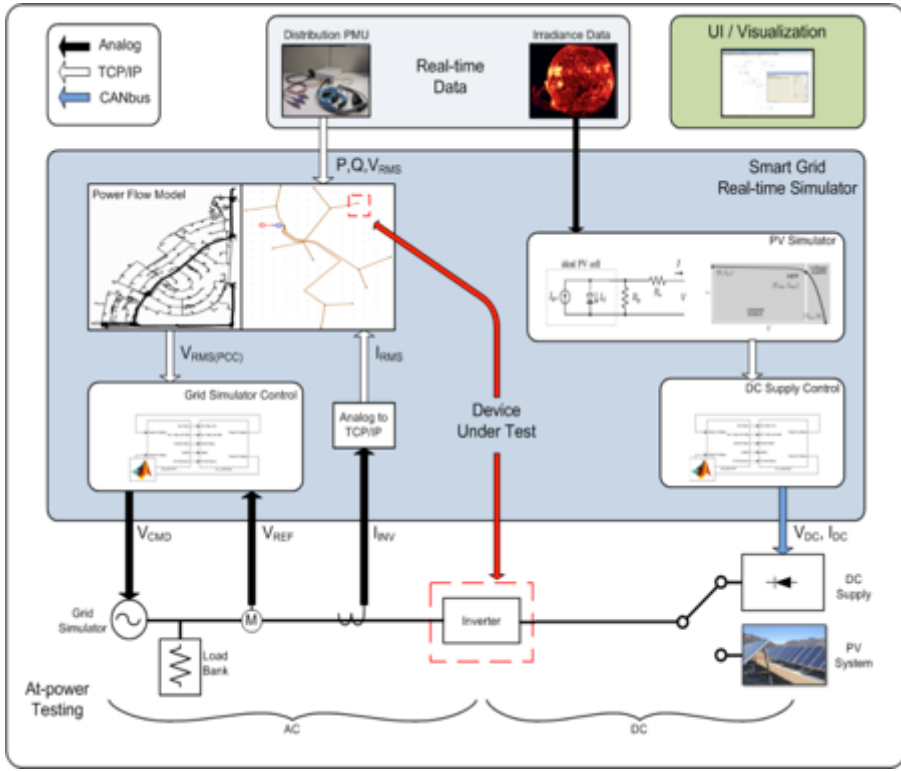




Distributed Energy System Integration

Energy Systems Integration

- Distribution RE impact studies
- Visualization and analysis
- Power system modeling and simulation.
- Microgrids/Campus Integration
- Power electronics and controls
- Power HW-in-the-loop (PHIL)
- Board and HW development



CGI Main Technical Characteristics

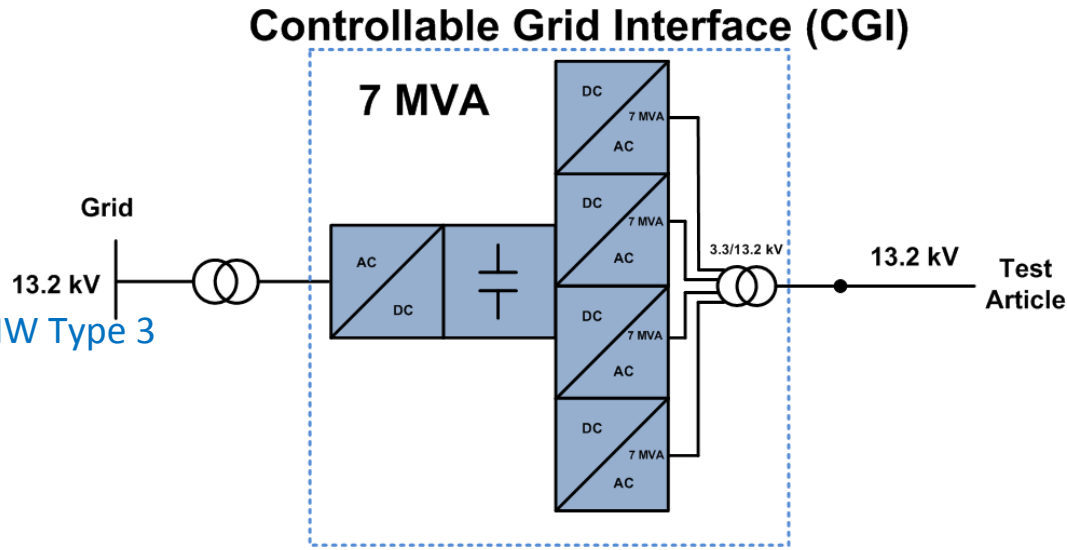
Energy Systems Integration

Power rating
- 7 MVA continuous
- 39 MVA short circuit capacity (for 2 sec)

Possible test articles
- Types 1, 2, 3 and 4 wind turbines
- Capable of fault testing of world's largest 6.15 MW Type 3 wind turbine
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies

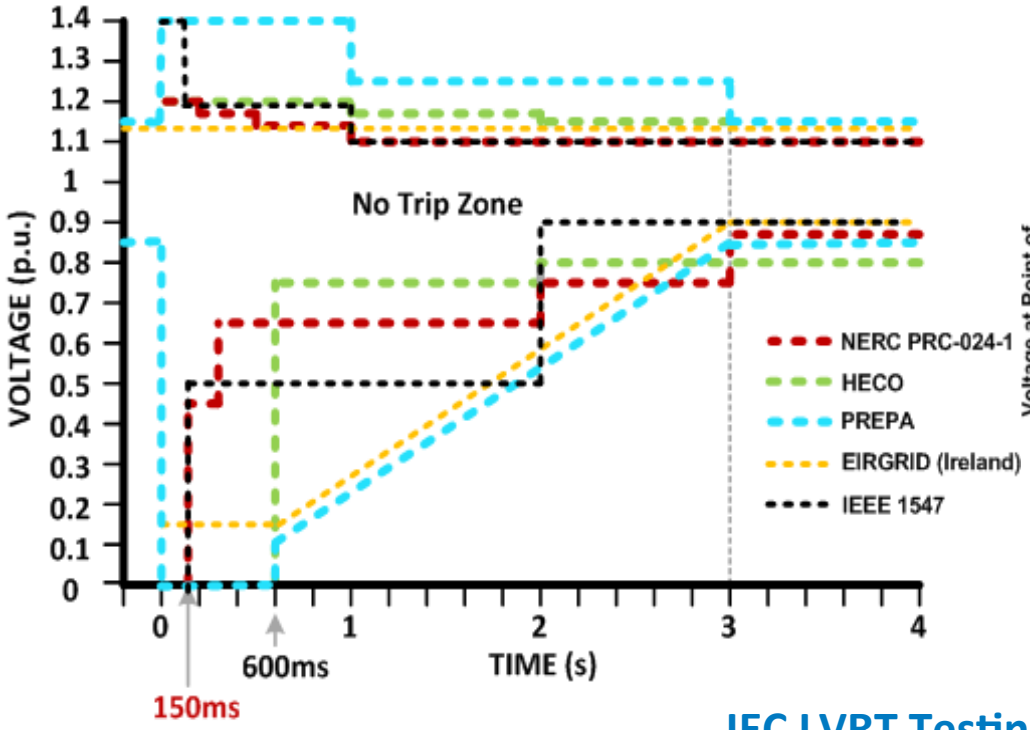
Voltage control (no load THD <5%)
- Balanced and un-balanced voltage fault conditions (ZVRT and 130% HVRT) – independent voltage control in each phase
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0-10 Hz) - SSR
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)

Frequency control
- Fast output frequency control (+/- 3 Hz)
- 50/60 Hz operation
- Simulate frequency response of various power systems
- RTDS / HIL capable

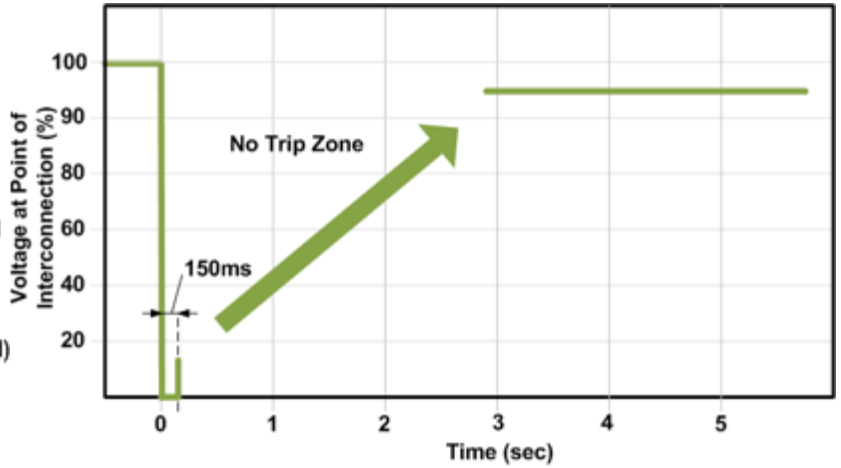


Capabilities
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing (over and under voltage and frequency limits)
- Islanding operation
- Sub-synchronous resonance conditions
- 50 Hz tests

Testing to All Interconnection Requirements and Grid Codes



FERC LVRT requirements (order 661-A)

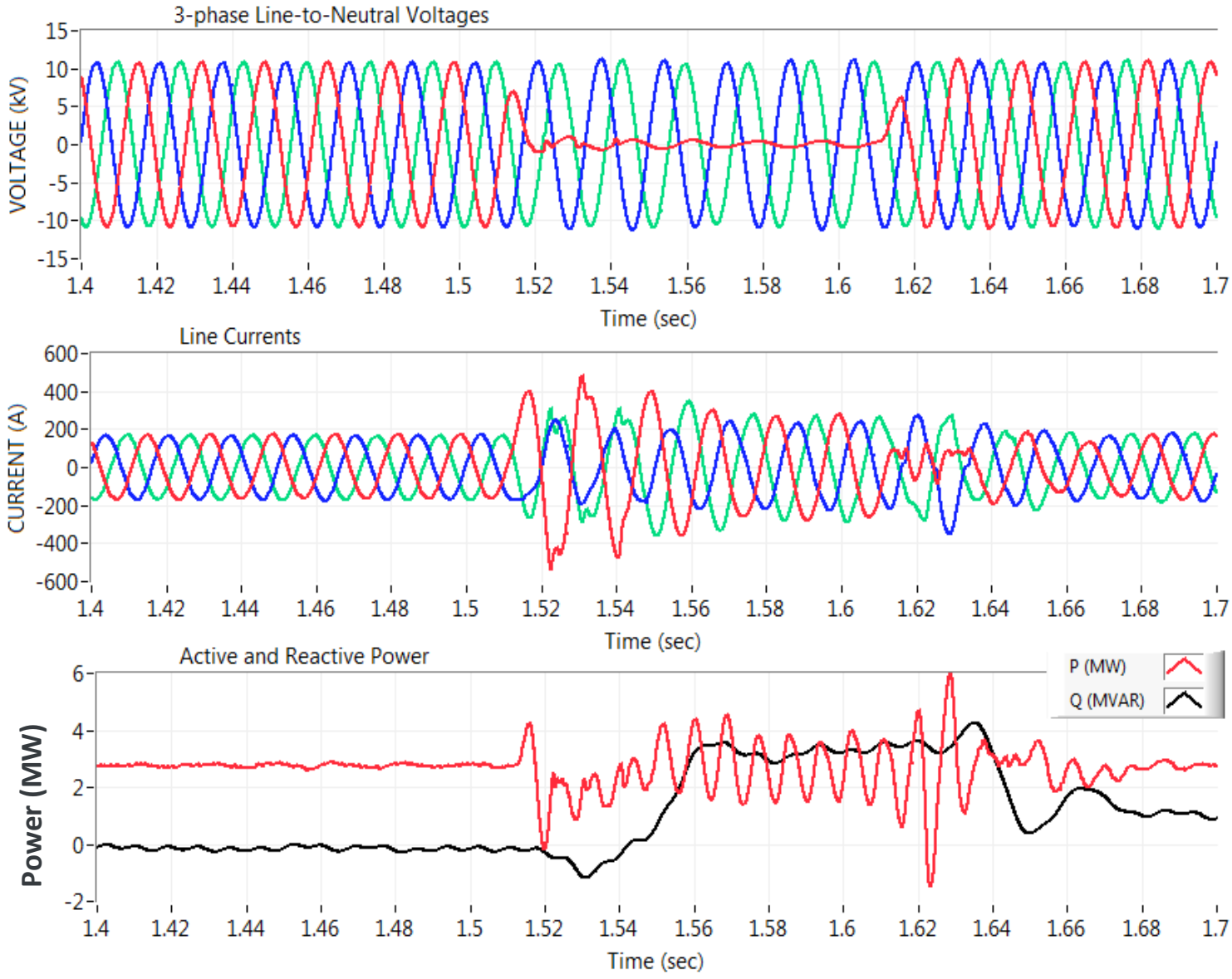


IEC LVRT Testing

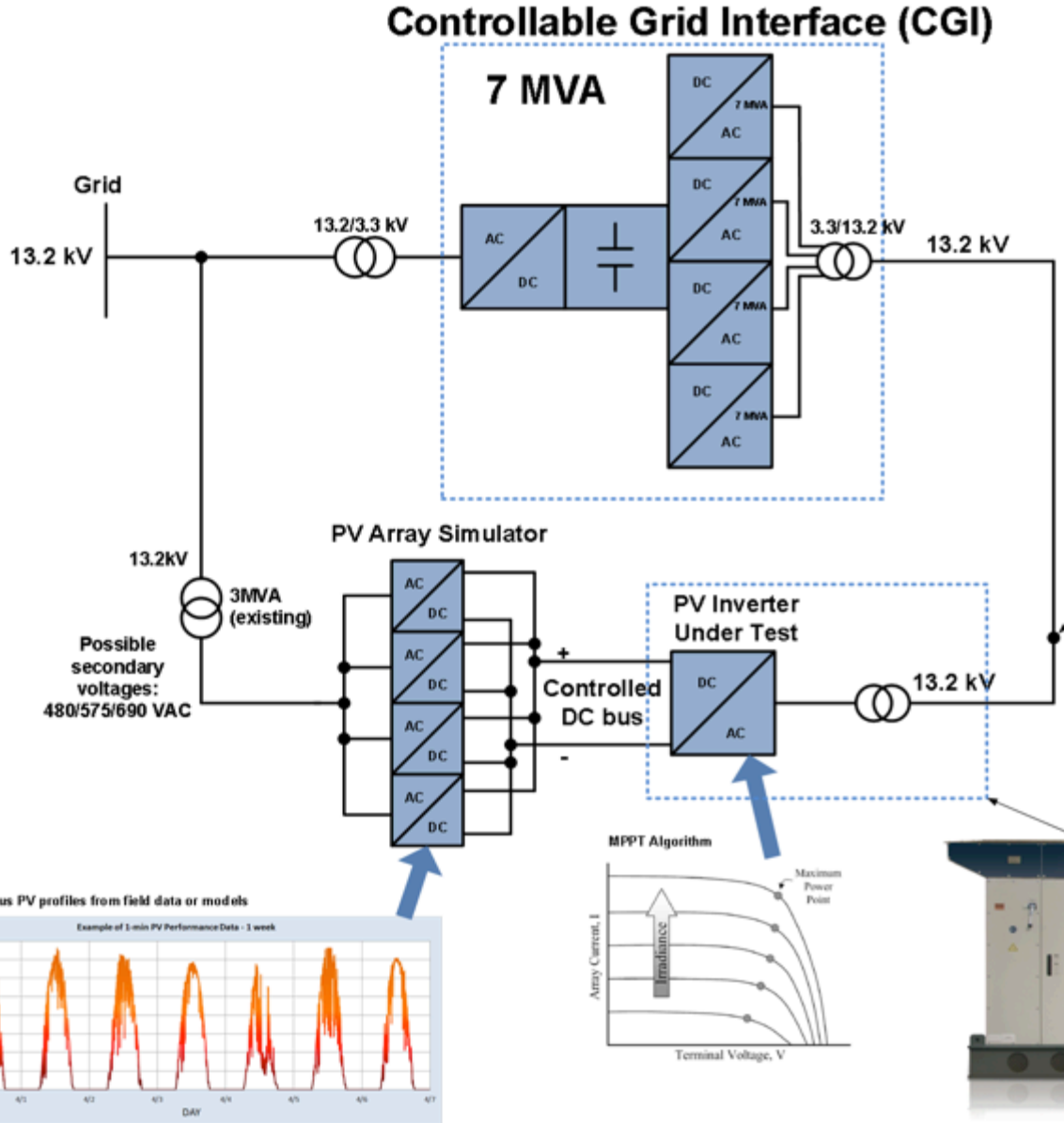
Fault Type	Voltage drop (fraction of nominal L-to-L voltage)	Fault Duration (ms)
Three-phase, balanced	0.9	500
Three-phase, balanced	0.5	500
Three-phase, balanced	0.2	200
Two Line-to-Line (L-L), unbalanced	0.9	500
Two Line-to-Line, unbalanced	0.5	500
Two Line-to-Line, unbalanced	0.2	200

Voltage Fault Emulation - Any Fault Scenario is Possible

Measured results for single-phase voltage fault test (CGI operating with 2.75MW wind turbine)



PV Inverter Testing Concept using NWTC CGI



Possible tests

- MMPT algorithms
- 50/60 Hz operation
- Voltage fault tests
- Advanced testing
  - Operation with reserves
  - Frequency response
  - Voltage control
  - Testing with energy storage