NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Energy Systems Integration

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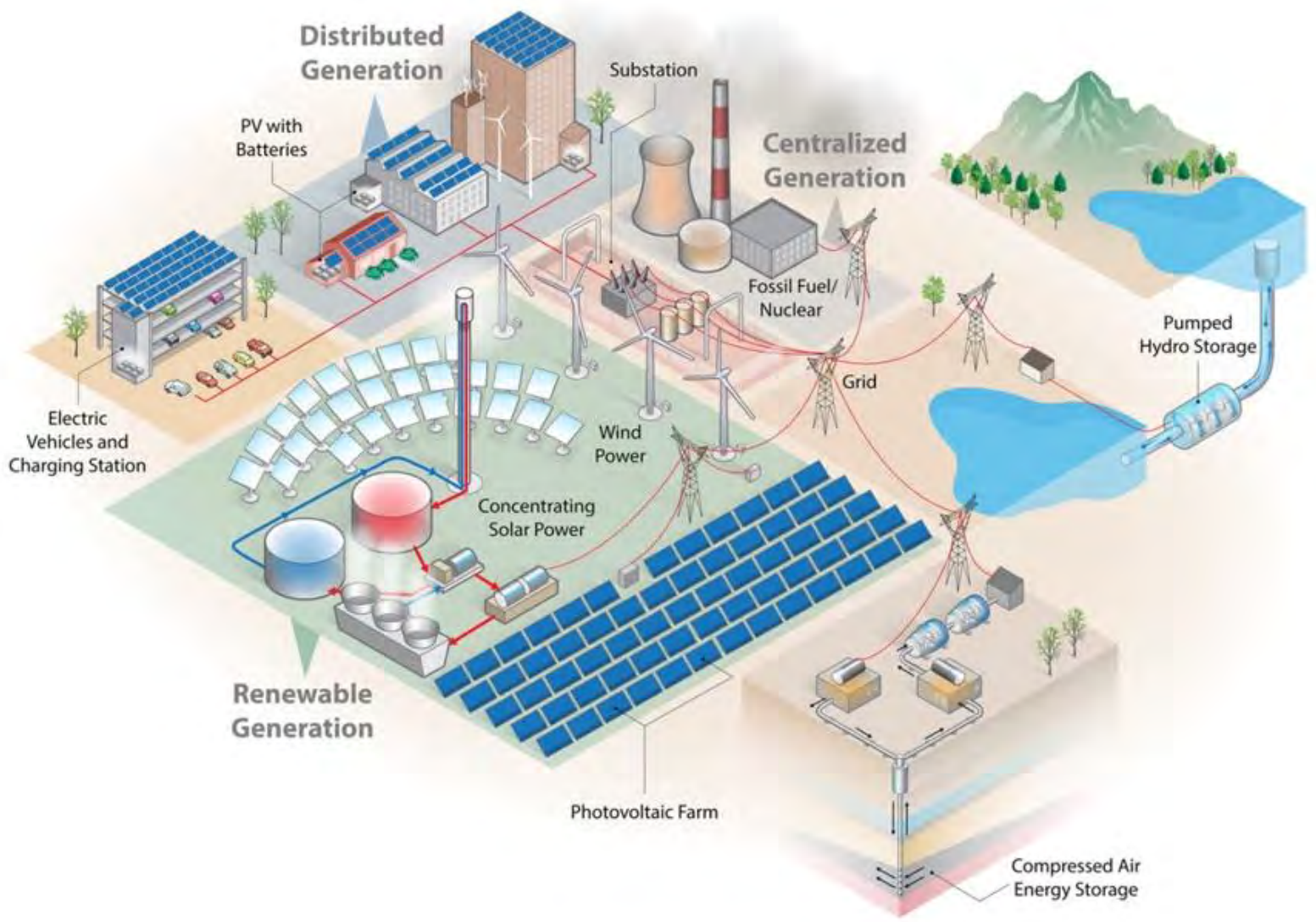
A Scenario of Future Energy System and the Grid



Energy integration of centralized grid, distributed generation, and transportation

Energy Systems Integration – The Facility

NREL | ENERGY SYSTEMS INTEGRATION FACILITY
U.S. DEPARTMENT OF ENERGY

Snapshot

- The nation's first integrated facility capable of conducting component and systems testing at megawatt-scale power.
- NREL's largest R&D facility (182,500 ft^2 /20,000 m^2)
- Houses ~200 staff and research partners
- Petascale HPC and state-of-the-art Data Center
- Integrated electrical, thermal, fuel, and data infrastructure
- More than 15 labs focusing on R&D of integrated energy systems
  - Electricity
  - Fuels
  - Transportation
  - Buildings & Campus

"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

Unique Advanced Capabilities

- 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 – Power Systems Integration Lab

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.

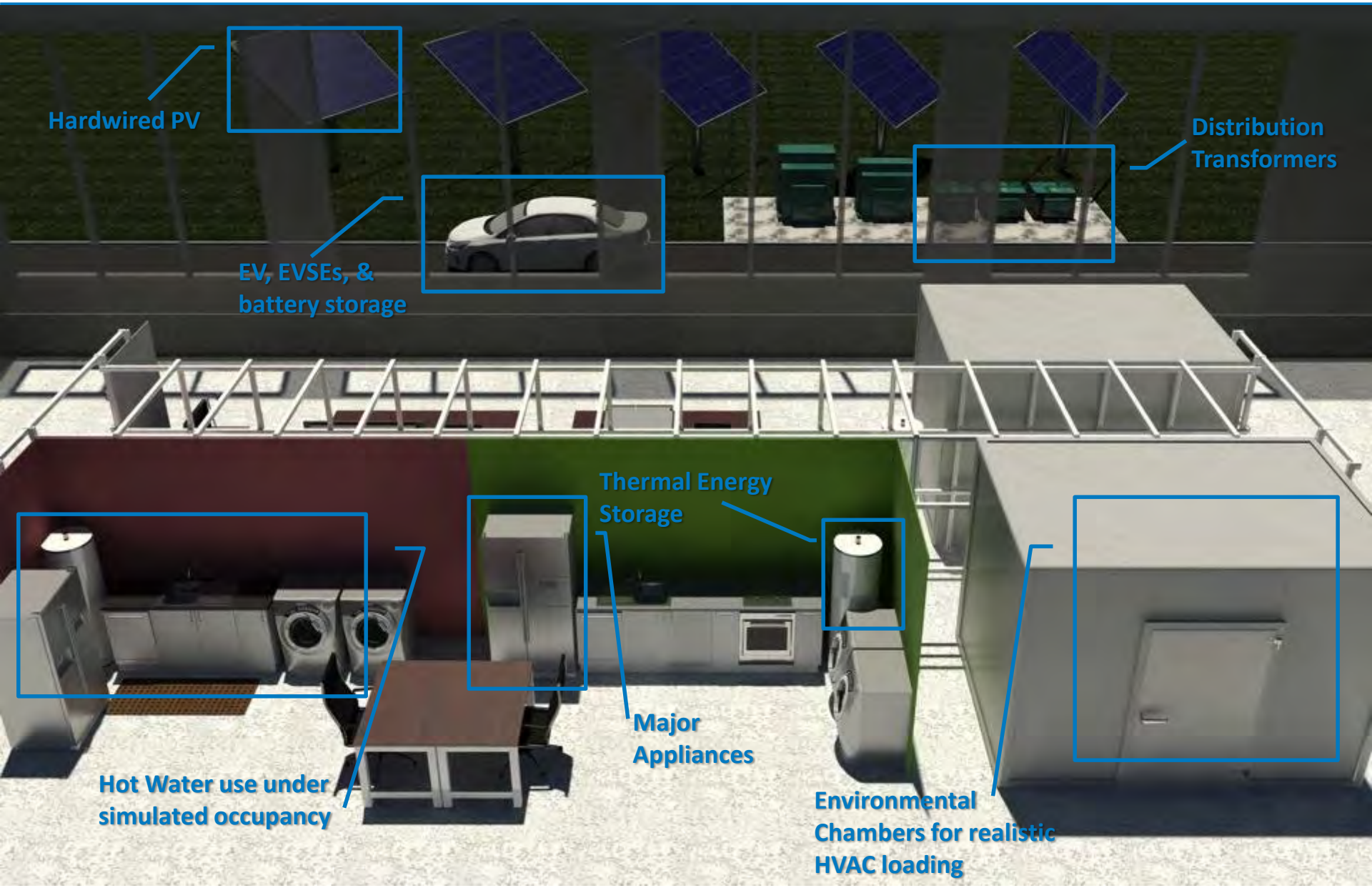
Lab Functions

- Main test lab for conducting 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
- Several 250kW DC power supplies
- 100 ton research chiller
- 750MBH research boiler
- Connections to REDB

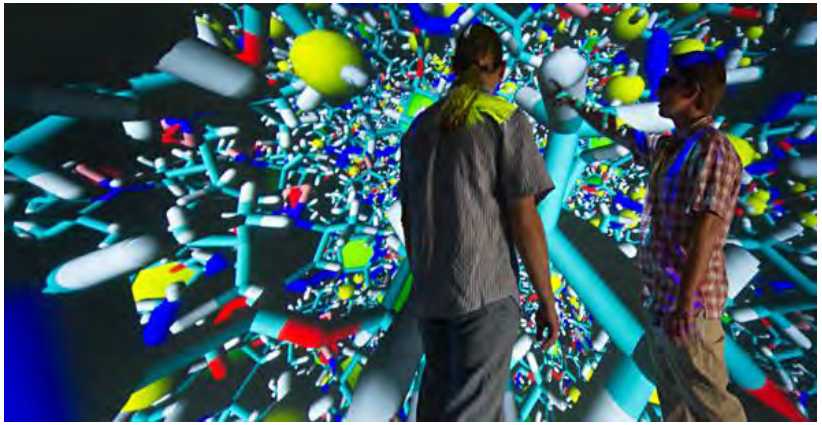
The Future - Smart Homes



Where the Future Energy System Starts

ESIF Provides

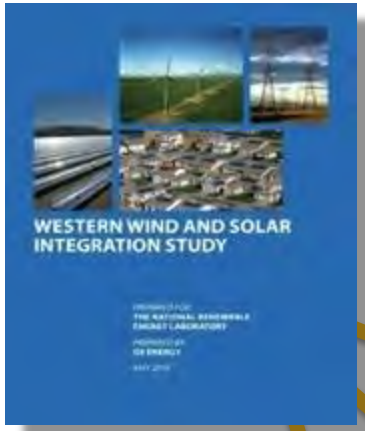
- End-to-end System Experimentation
- Integration of electrical, thermal, fuel, communications systems
- Evaluation of MW scale systems
- High performance computing and advanced analytics
- Integration of hardware and simulation environments



Energy System Operations

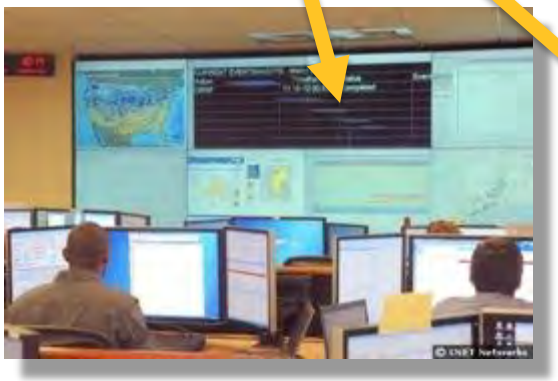
A Flight Simulator for Energy System Operators

"connecting integration studies to operations"

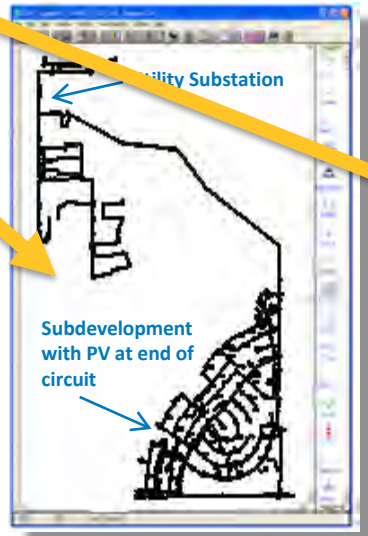


Operations techniques development for:

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



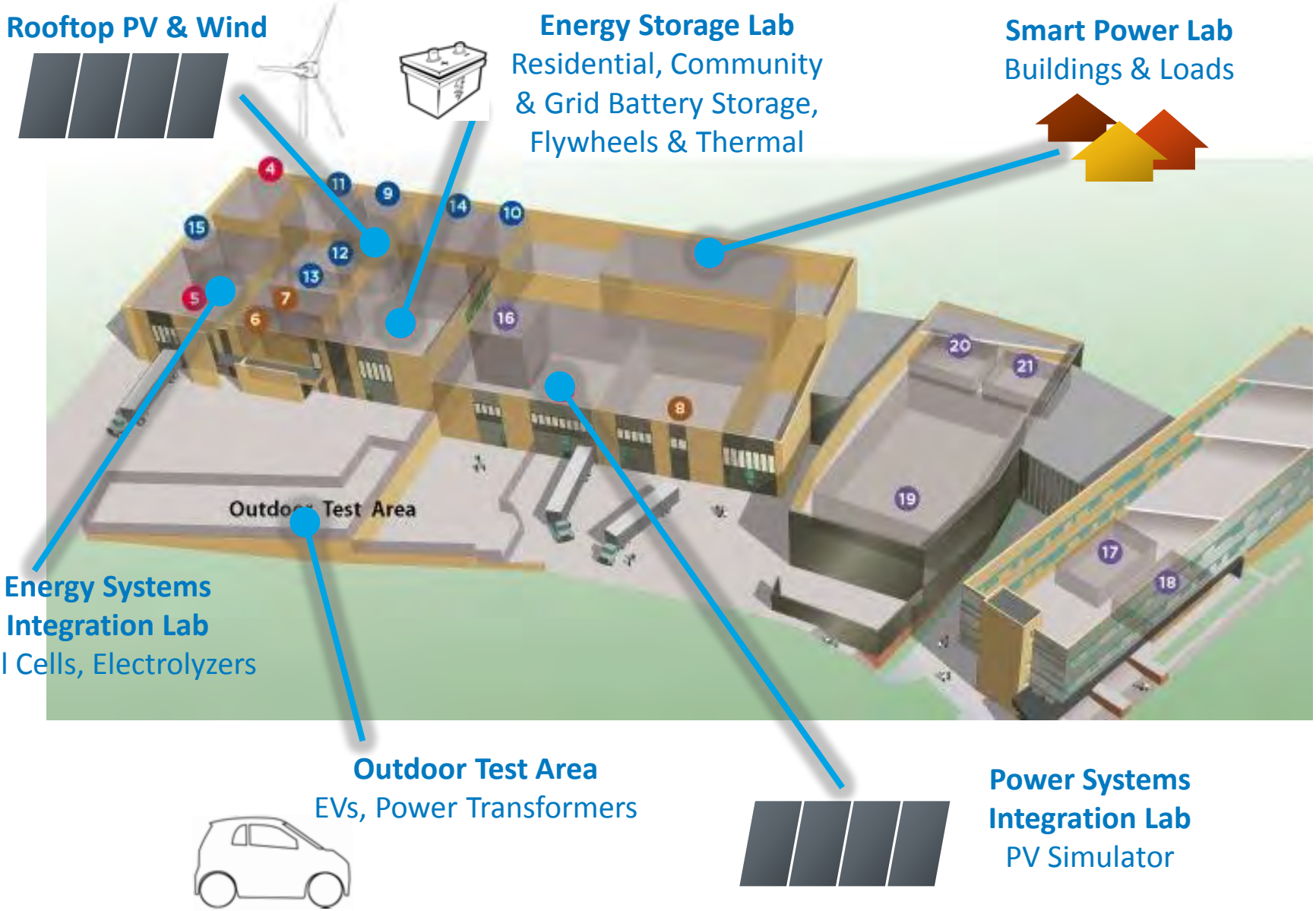
Transmission



Distribution

Campus Energy Dashboard

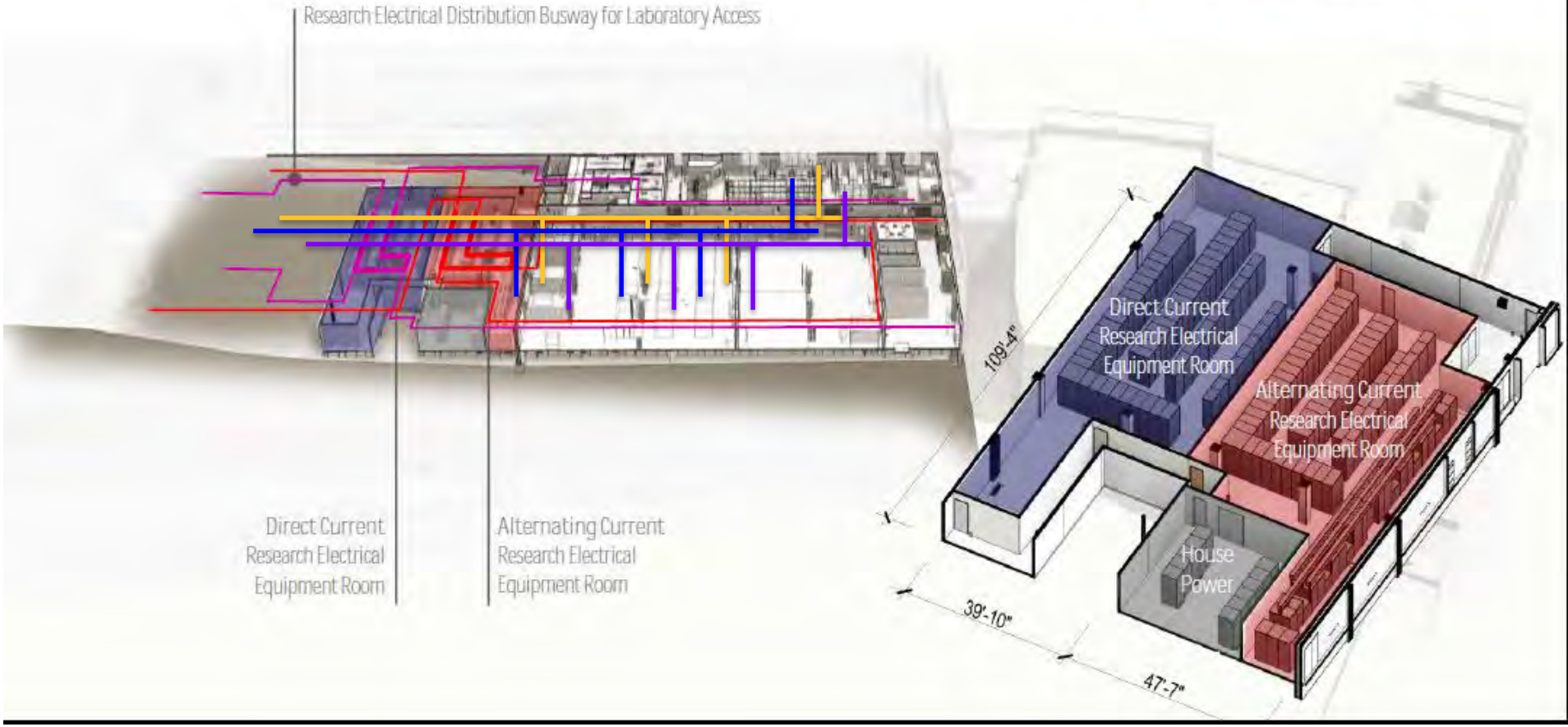
Integrated System Experimentation



ESIF Research Infrastructure

- 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)

- Utility Scale Research
- 1.5 MW – Single Source REDB
- 1 M – Micro Grid Simulation

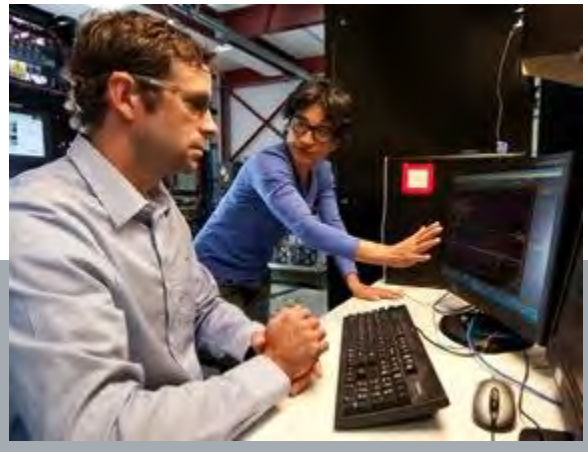


Control Room and Visualization Labs

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

Large-Scale Grid, PV and Load Simulators

Additional Equipment

- PV Simulators
  - 100 kW Ametek TerraSAS
- DC Supplies
  - 250 kW AeroVironment AV-900
- Load Banks
  - 100 kW R-L (portable)
  - 100 kW R (portable)
- Small grid simulators
  - 45 kW Ametek MX45
  - 15 kW Elgar
- Diesel generators
  - 125kVA and 80 kVA Onan/Cummins
  - 300kVA Caterpillar
- Hydrogen Systems
  - Electrolyzers: 50kW, 10kW
  - Storage tanks
  - Fuel cells
- Real-Time Digital Simulators
  - Opal-RT (3 racks)
  - RTDS (1 rack)







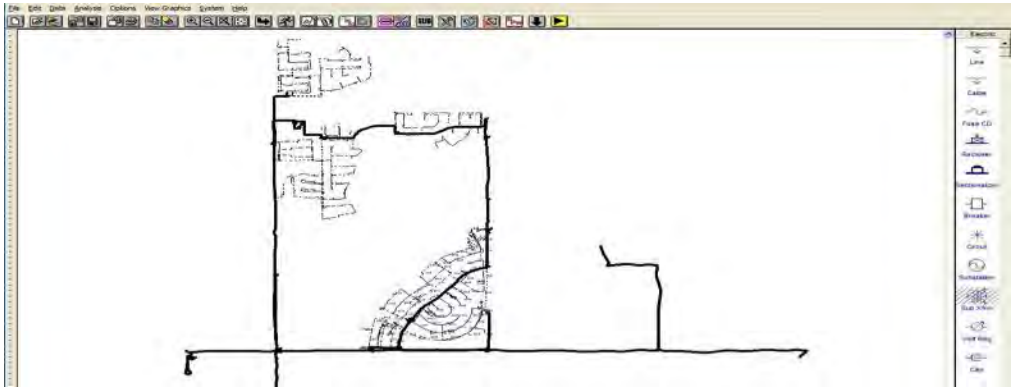
High Performance Computing

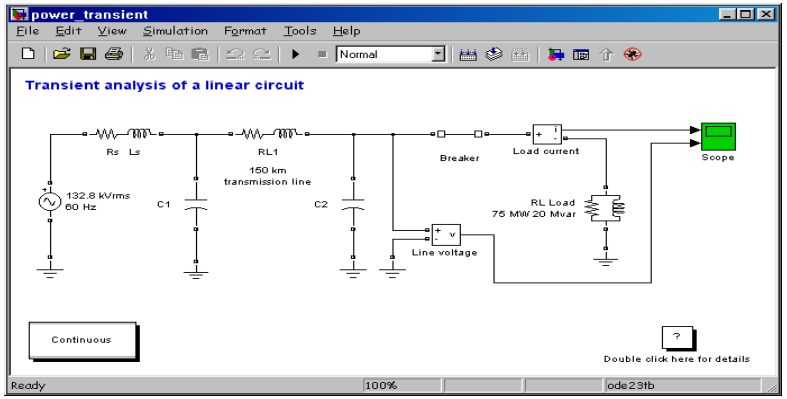
One of NREL's most powerful energy research tools —the High Performance Computer at the ESIF Data Center— leads to increased efficiency and lower costs for important renewable energy research and technologies that include:

- Solar photovoltaics
- Wind energy
- Energy storage
- Electric vehicles
- Large-scale integration of renewables with the smart grid.

Distribution System Simulation Tools

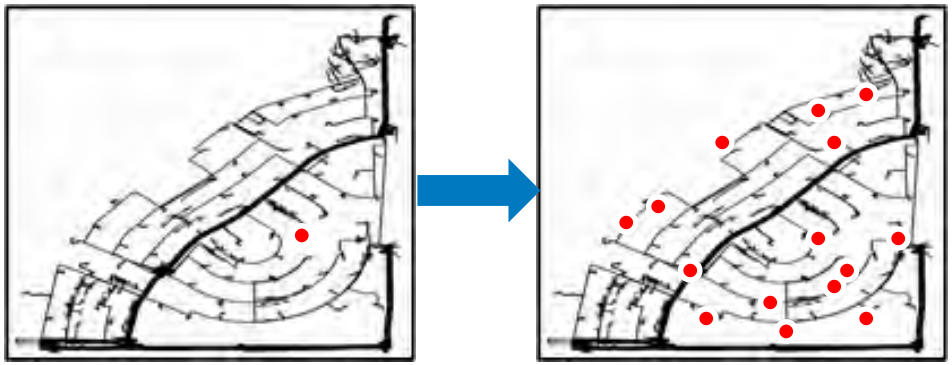
- Modeling of electrical distribution systems to determine power flow, voltage drop, power quality, short-circuit characteristics, protection coordination, and stability
- Modeling Package Competencies:
  - Steady-state analysis (single point or time-series): CYMEDIST, SynerGEE, DEW, OpenDSS, GridLAB-D
  - Dynamic analysis: PSSE, PSLF
  - Transient : SimPowerSystems, PSCad

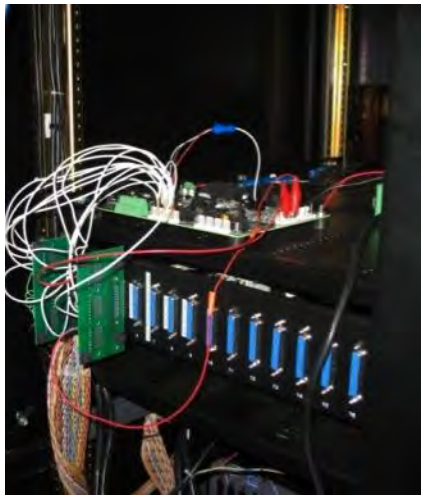




Simulation Analysis & Applications

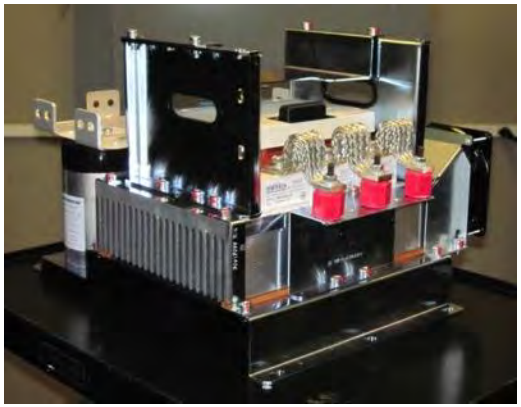
- Distribution system planning
  - Placement of generation
  - Optimal dispatch and control of assets
  - Studies of high-penetration renewables scenarios
- Validation of individual power system components in a distribution system
  - Rapid prototyping of new power system components
  - Smart grid interoperability testing

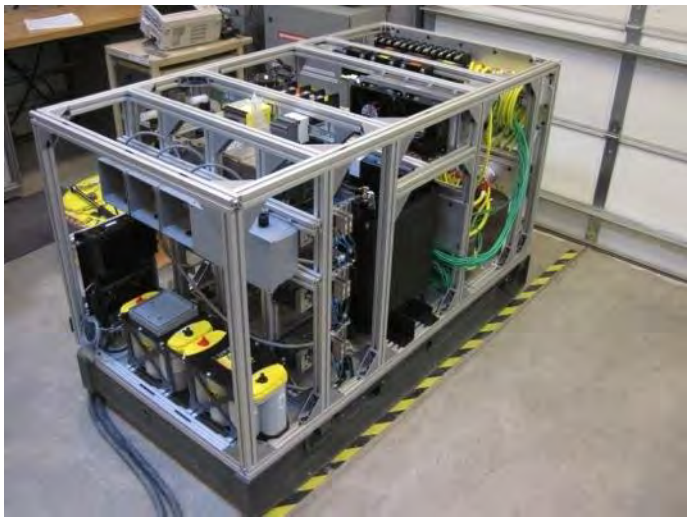




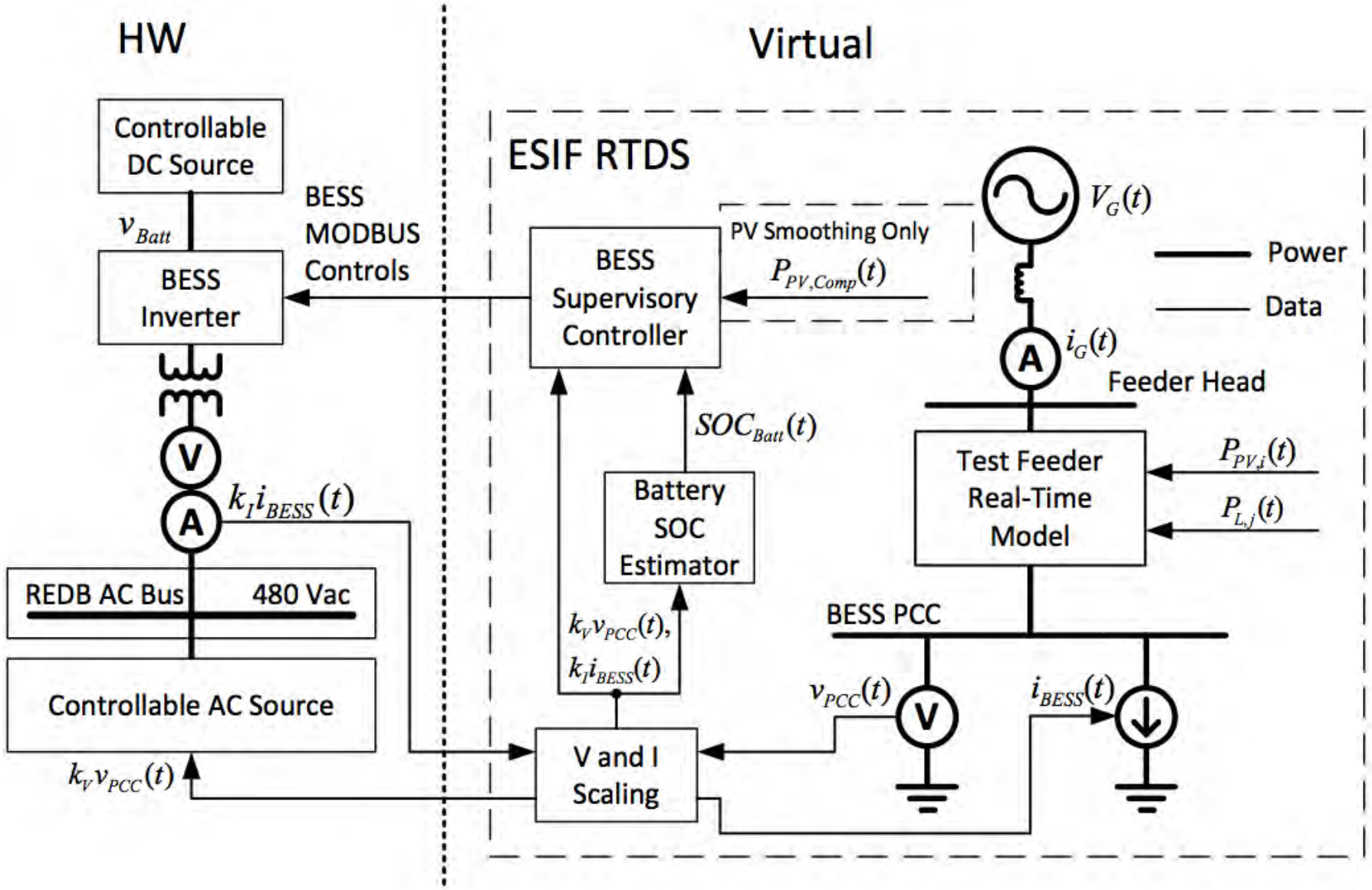
Power Electronics

- Design and construction of various PE converters from scratch such as PV inverter, battery charger, new converter topologies for DER
- Development of low-cost, reliable modular power electronics building blocks and advanced controller hardware
- Component selection, design and development of complete PE solutions such as microgrid, stand-alone hybrid power systems, grid-tied DER systems



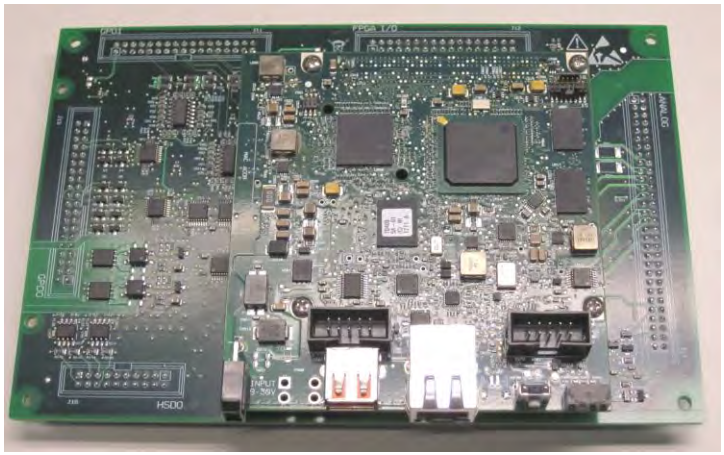


Grid Evaluation using Power Hardware in the Loop

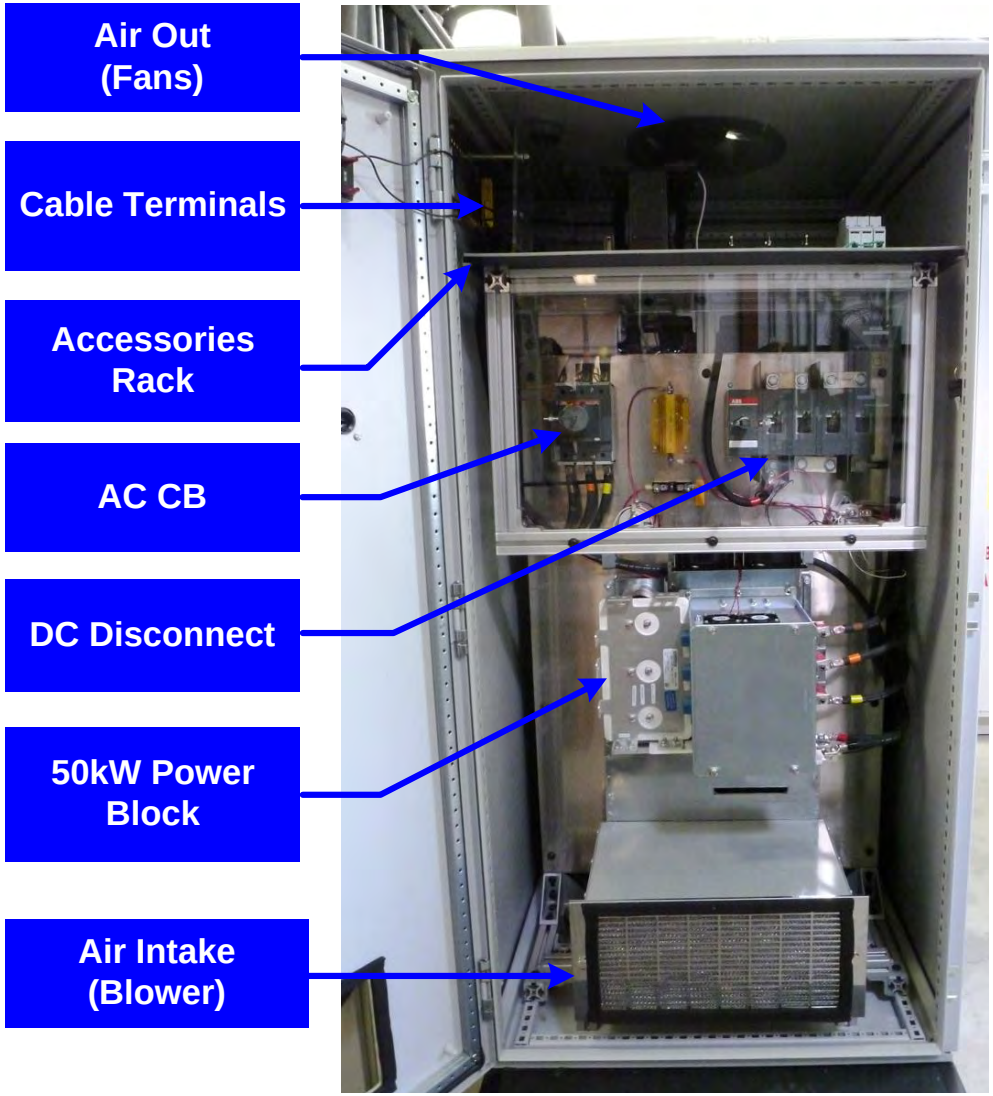


Modular Power Electronics

- Inverter Prototype Development
- Commercial and Residential Applications
- Modular Power Electronics
- Low Cost
- High Reliability



CEC Pre-production Inverter



Controls and Optimization

- Development of PE controller in various firmware platforms such as microcontrollers, DSP and FPGA and various programming languages such as C/C++, assembly, HDL, Simulink and LabView
- Development and implementation of advanced control functionalities such as VAR control, voltage regulation, stand-alone/grid connected operation, IEEE 1547 capability, MPPT, battery control, smart grid functions, microgrid operation
- Development of system-level control algorithms for hybrid power systems dispatch, load management and resource optimization
- System identification and auto-tuning of PE controllers
- Neural network and fuzzy logic based system optimization

Consolidated Utility Base Energy (CUBE)

- Simulate and design a hybrid power system which incorporates **solar** and **battery energy** to reduce fuel consumption by **diesel generator**s in the field.
- Build a prototype unit which implements the hybrid power system electronics and controls in a lightweight, mobile package.
- Validate fuel savings performance in Laboratory with simulated load profiles and standard army generator sets.

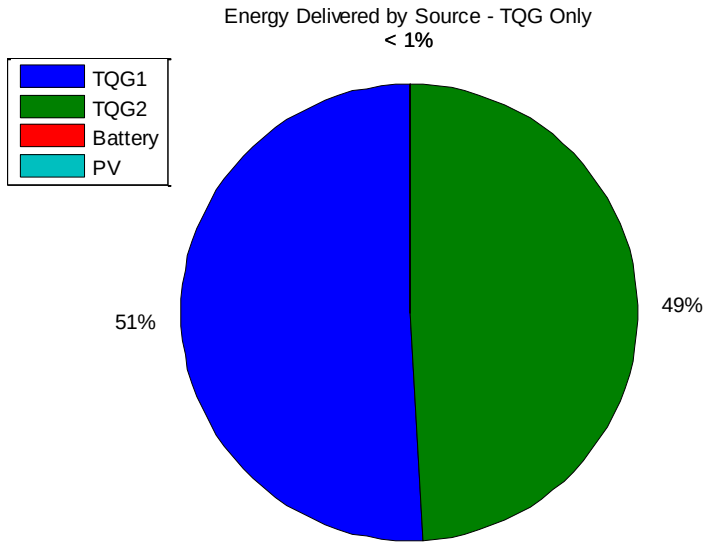
CUBE 24 Overview & 24 Hour Test Results

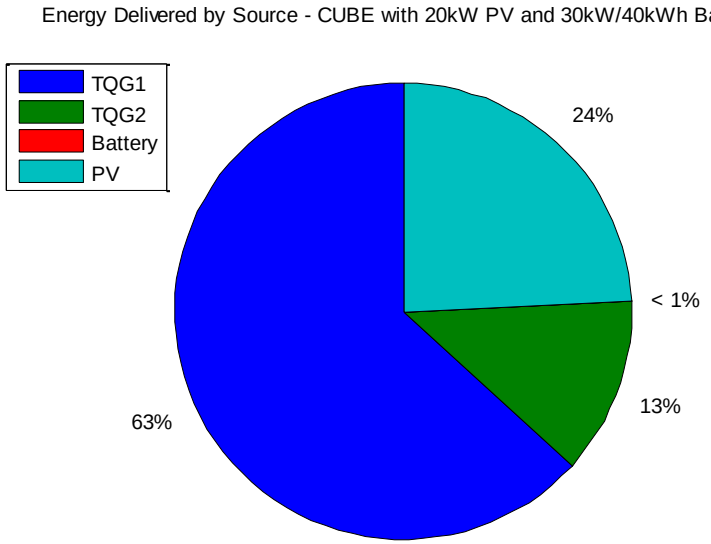
OVERVIEW

- **Integrated power electronic platform for 60 kW PV-Battery-Diesel mobile hybrid power system**
- **Connections**
  - 60 kW Load
  - Two 30 kW TQGs
  - Four 5 kW PV Arrays
  - One 30 kW Battery Bank
- **Partners**
  - Wyle Laboratories
  - U.S. Army Rapid Equipping Force (REF)
  - U.S. Army Expeditionary Energy and Sustainment Systems (E2S2)

24-HOUR TEST

- **Configuration**
  - Load Profile: Measured 1-minute load data to simulated FOB
  - Solar Profile: Measured 1-minute insolation data
  - Dispatch Strategy: Peak-Shaving (Battery acts as Regulating Reserve)
- **Results**
  - Fuel Savings: 31% (21 gallons)
  - Total Load Energy: 650 kWh
  - Battery Throughput: Less than 10 kWh
  - Battery Beginning / Ending SOC = 84.5% / 87.5%





Wind-Battery Hybrid Project

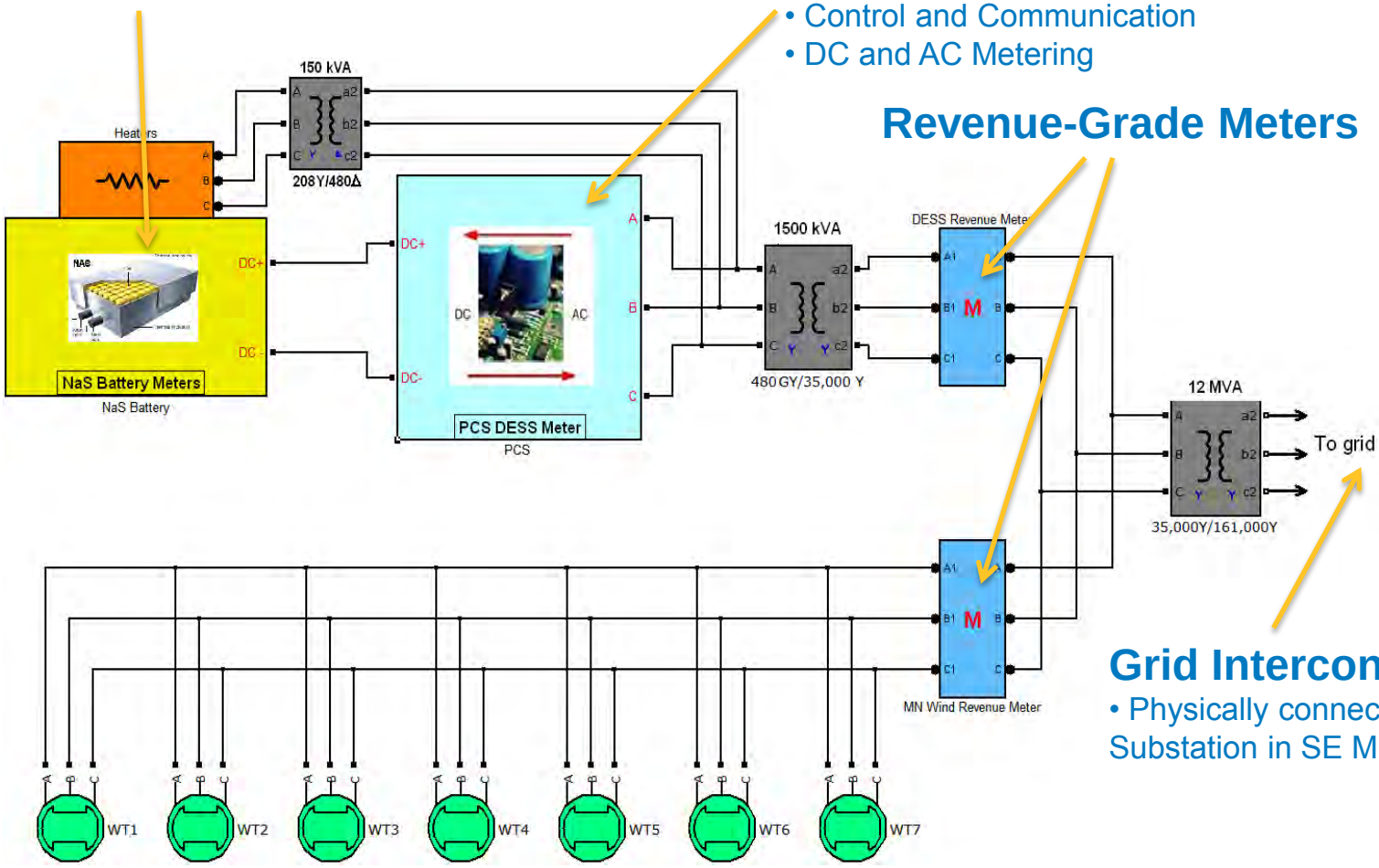
1 MW Sodium-Sulfur Battery

- Provides 1 MW for 7 hours

Power Conversion System

- DC/AC Conversion
- Control and Communication
- DC and AC Metering

Revenue-Grade Meters



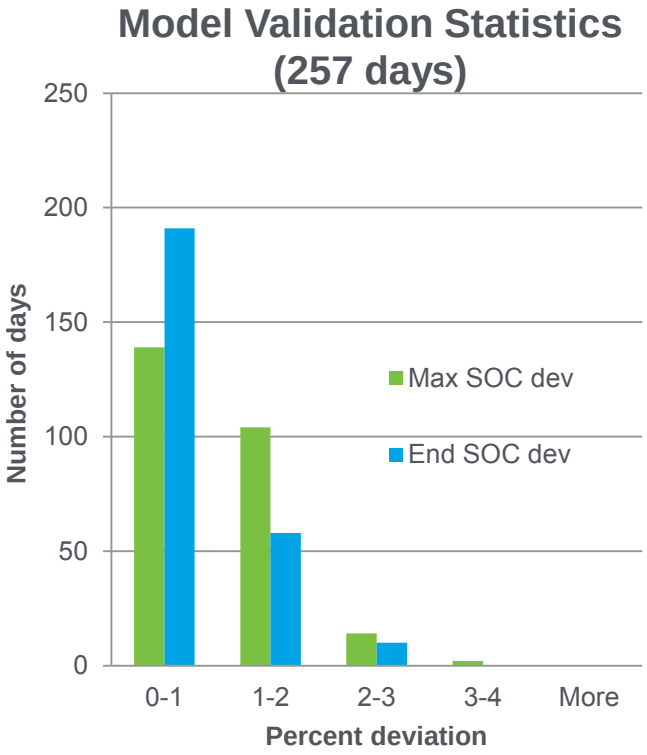
Grid Interconnection

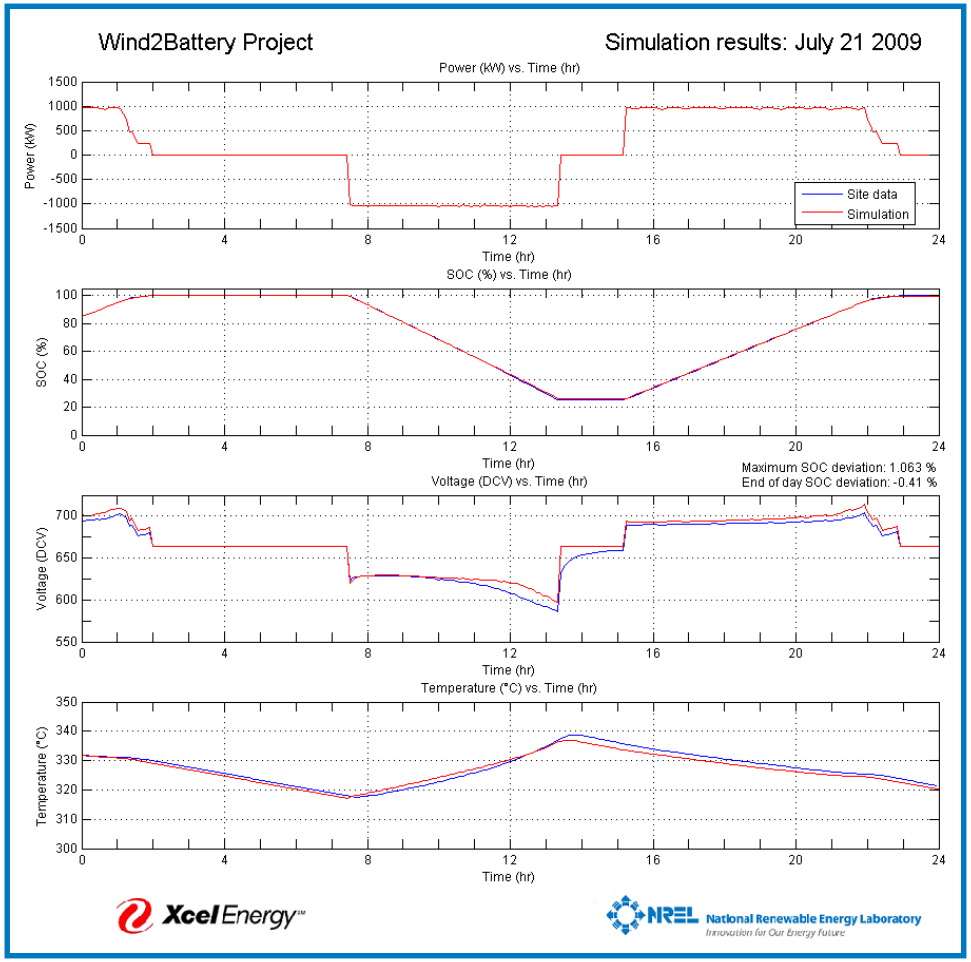
- Physically connected at a Substation in SE Minnesota

7x Vestas 1.65 MW Wind Turbines

Energy Storage Models for Day Ahead

- Model was validated against 257 days of testing on the battery
- Model predicted SOC within 3% of the actual on nearly all 257 days





Software Tool Development

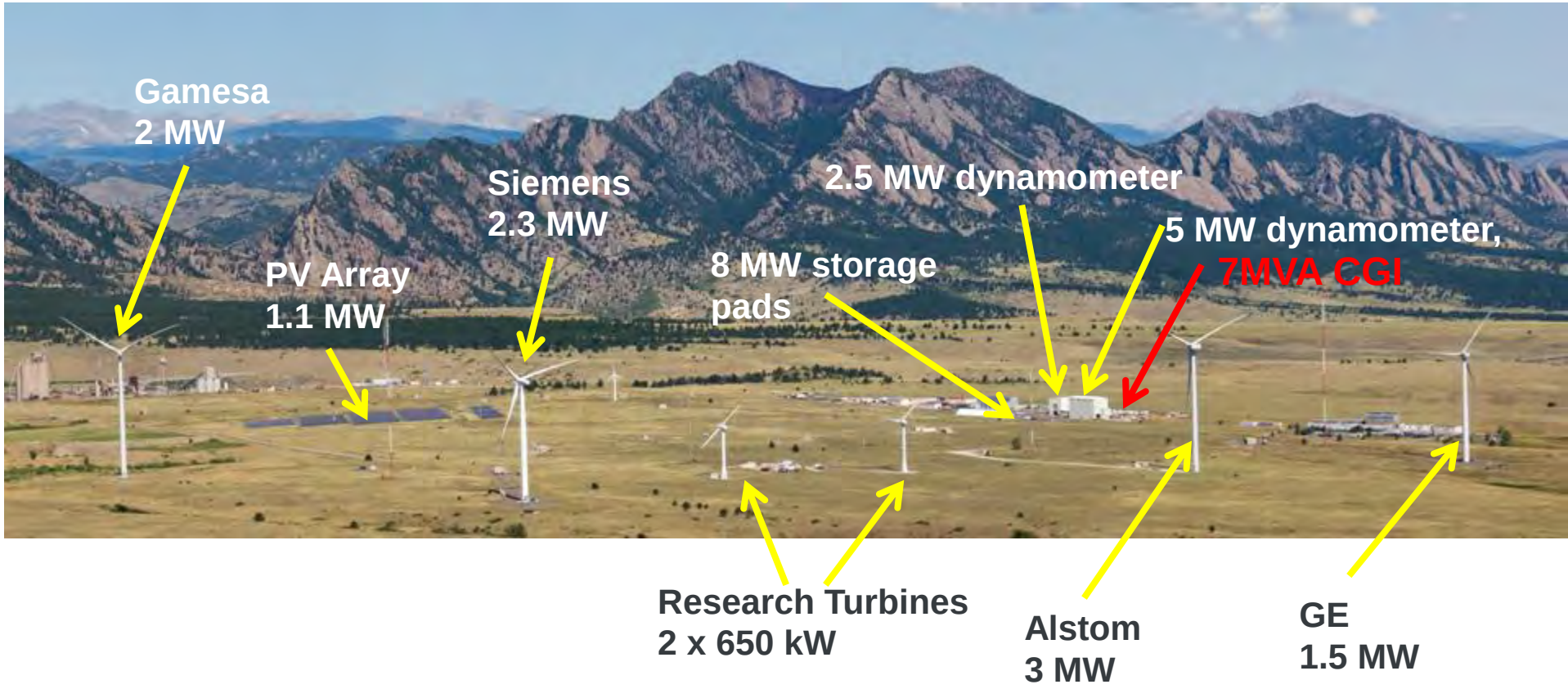
- REopt PV+storage web tool development
- SAM
- High Fidelity Fast Running Multi-scale Multi-physics Battery Pack Software
- Battery Life Predictive Models for Grid Applications

Simulation and Analysis Partners

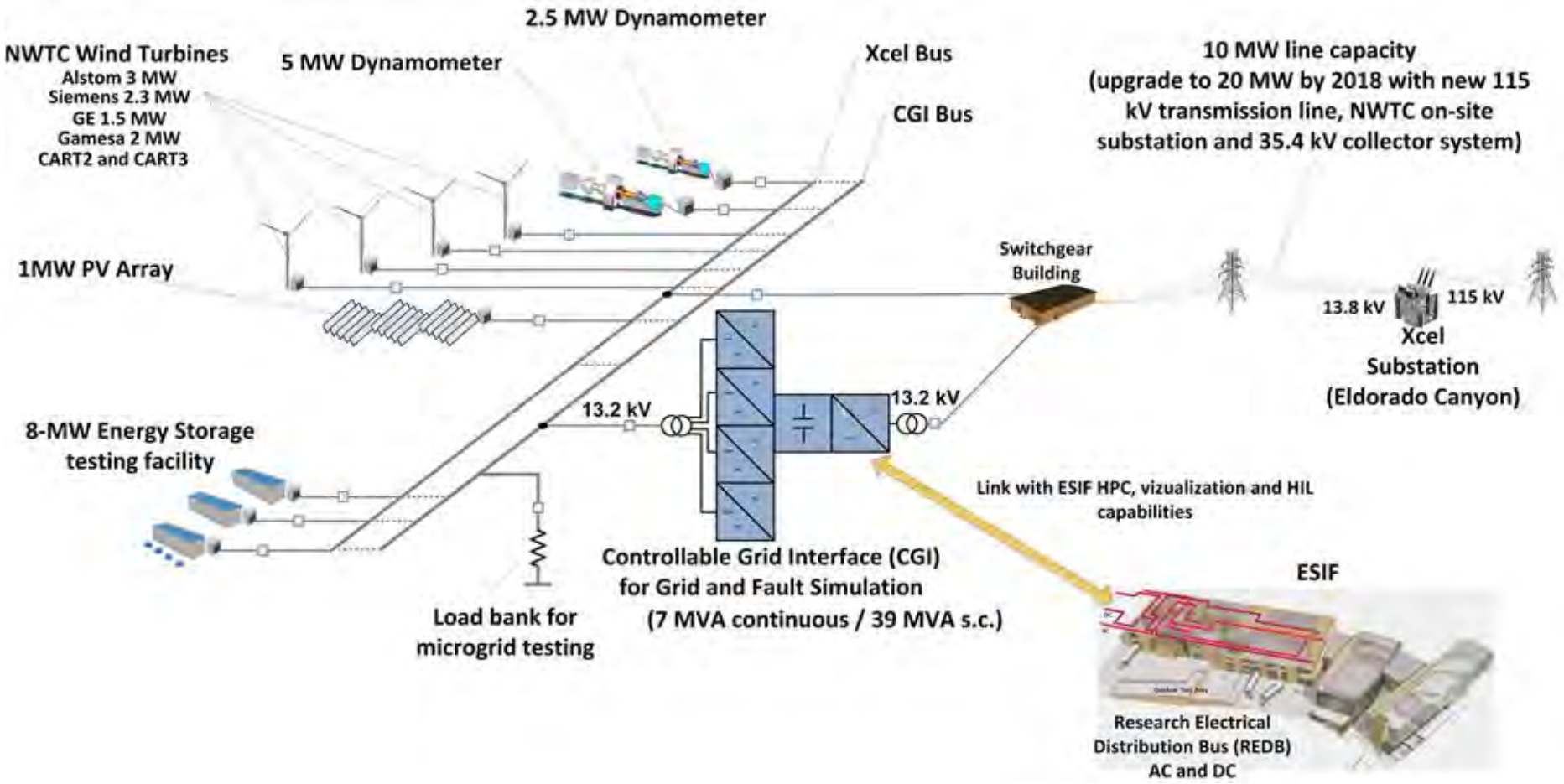
- Aircraft Industry
- Commercial Buildings
- General Services Administration
- Residential Buildings
- Universities
- City of New York
- Time Warner
- Honeywell
- NELHA
- Alcatraz
- Alaskan Villages
- Clean Energy Collective
- Bureau of Reclamation
- NASA
- Wells Fargo
- Miami University of Ohio
- Main Islands
- Air Force
- Army-Fort Carson
- Department of Defense
- Power Africa

National Wind Technology Center

- 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 test pads (pre-wired for 8MW capacity)



Energy Management Storage Testing at NWTC



National Wind Technology Center (NWTC)

NWTC (7MVA) Controllable Grid Interface

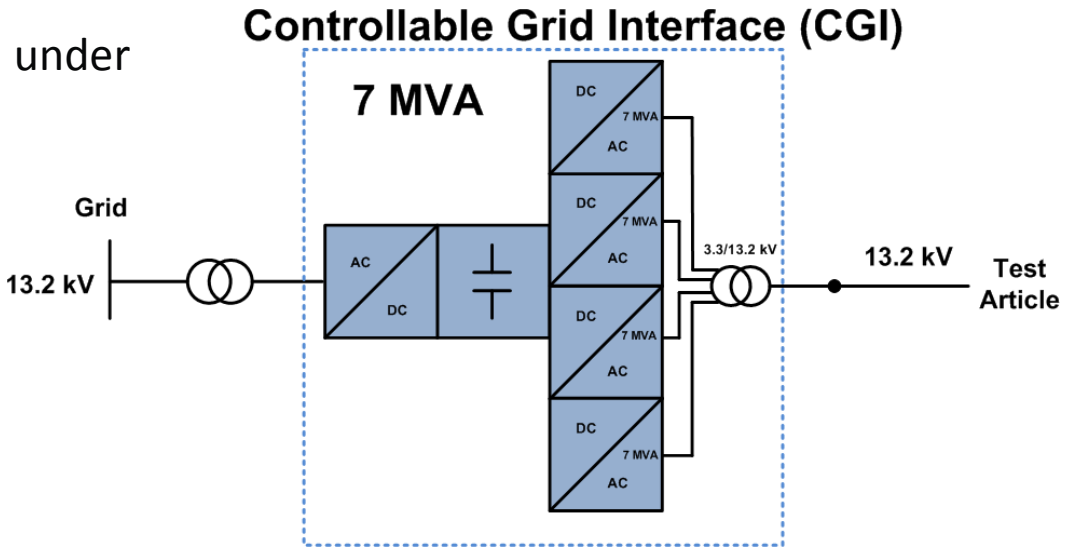
CGI Main Technical Characteristics

Capabilities

- Balanced and unbalanced over and under voltage 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
- 50 Hz tests

Power rating

- 7 MVA continuous
- 39 MVA short circuit capacity (for 2 sec)
- 4-wire, 13.2 kV



What can be tested using CGI?

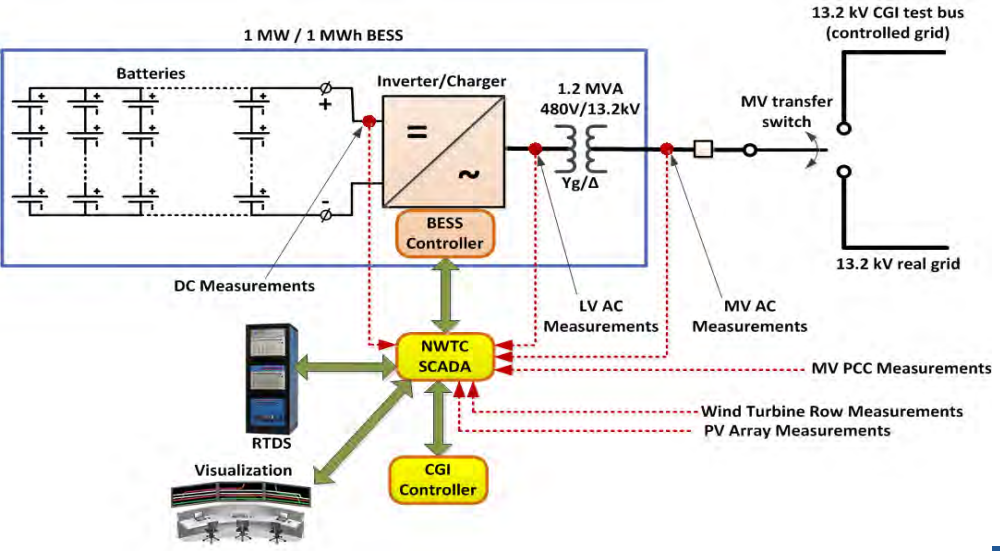
All controls that response directly to grid conditions on plant terminals*

- “Nasty” and ”Clean Room” grid conditions
- Inertial Response (synthetic synchronous inertia)
- Fast Frequency Response (FFR)
- Primary frequency response controls (governor droop-like control)
- Direct frequency control (for islands or microgrids)
- Black-start capability
- Voltage fault ride-through (LVRT, ZVRT, HVRT – 1, 2, 3 – phase) in accordance to any existing or future grid codes or standard
- Harmonic injections
- Reactive power controls (full reactive power range tests without impacting NTWC grid)
  - Weak and strong grid conditions
- Other advanced controls testing:
  - Inter-area oscillation damping controls
  - Sub-synchronous resonance (SSR) damping controls
  - Other plant-level controls using RTDS/HIL for larger plant simulation
  - Microgrid controls testing

Two NWTC Grid Battery Projects

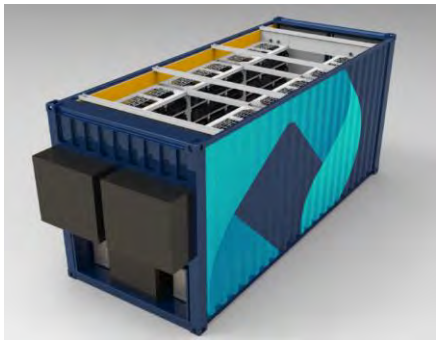
BESS Project 1

- NREL GPI funded BESS procurement
- Targeted capacity - 1MW/1MWh
- Expected delivery – end of 2016
- Long-term research objectives

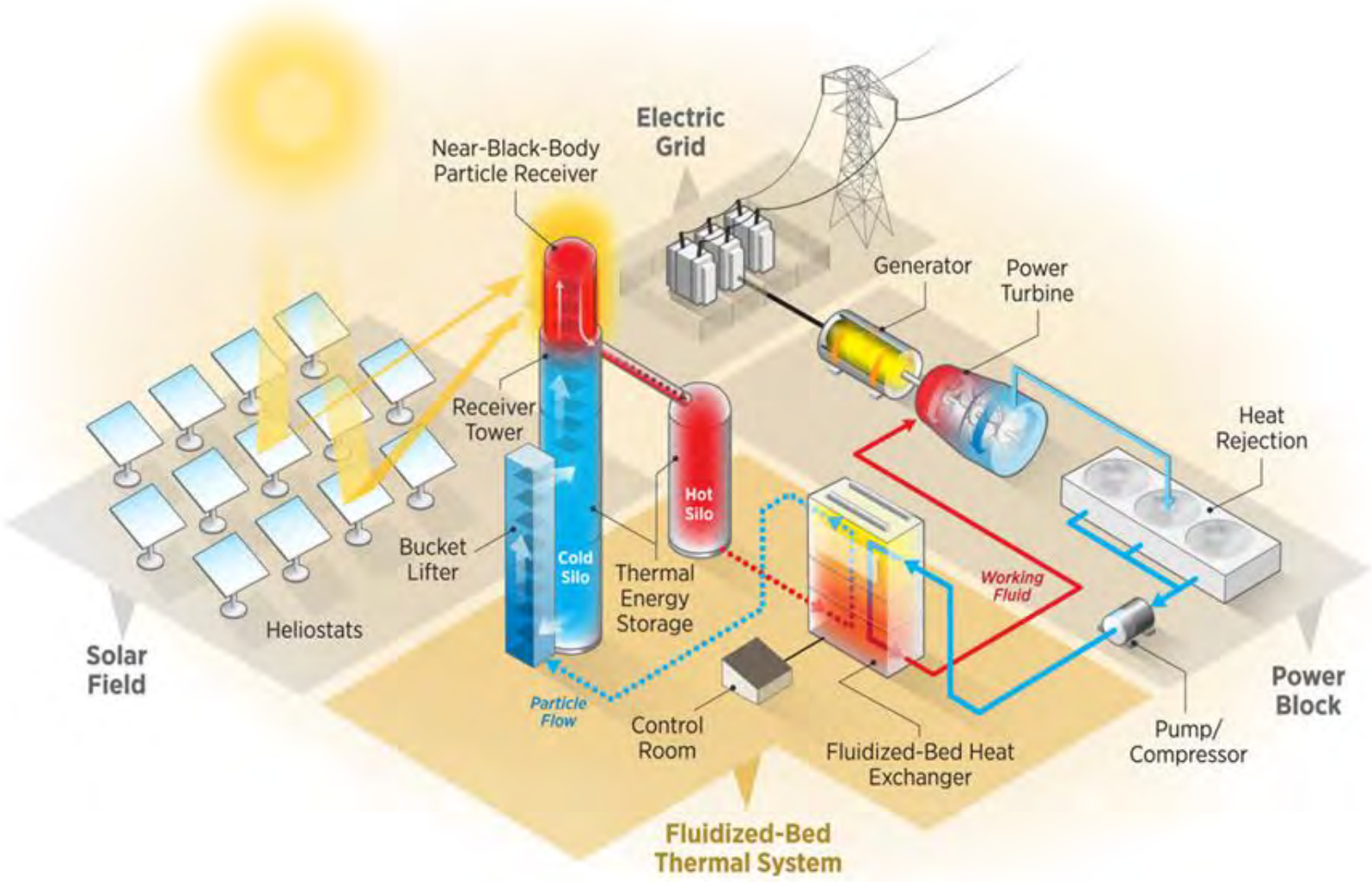


BESS Project 2

- Under BPA award ($600K) in collaboration with Powin Energy – 2 year project
- Targeted capacity - 1MW/1MWh
- Battery system provided by Powin as cost share ($1M)
- Expected delivery – January 2017
- Test T&D and renewable integration applications



CSP System with Thermal Energy Storage



- Concrete silo with insulation liner for particle-TES containment.
- Fluidized-bed heat exchanger for power generation.

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http://www.nrel.gov/esif/index.html