Power Electronics for Solar Grid Integration – A DOE Perspective

Guohui Yuan, Department of Energy

Solar Energy Technologies Office Overview

MISSION

We accelerate the **advancement** and **deployment of solar technology** in support of an **equitable** transition to a **decarbonized energy system by 2050**, starting with a decarbonized power sector by 2035

WHAT WE DO

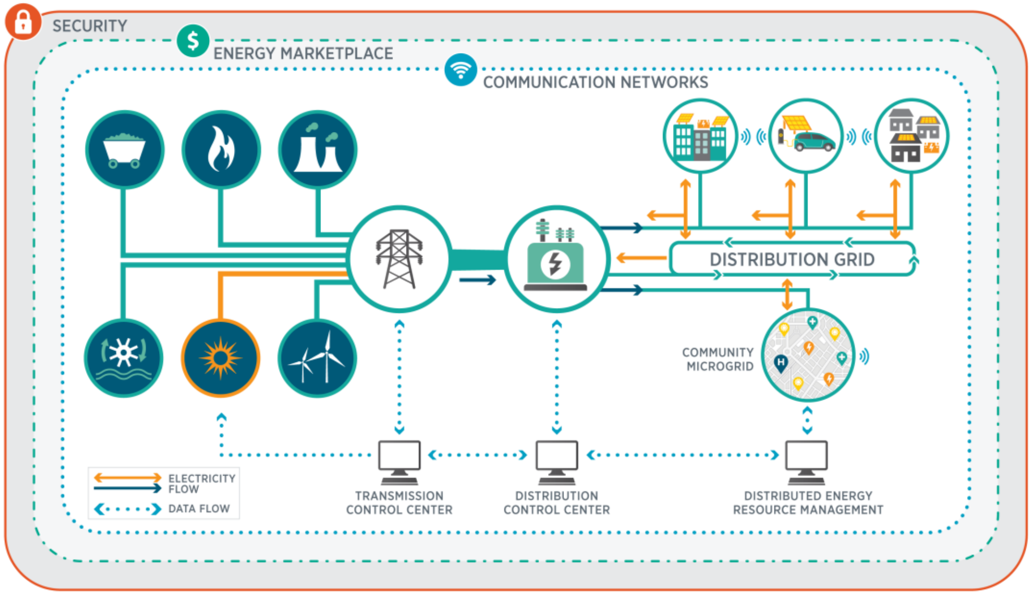
Drive innovation in technology and soft cost reduction to make solar **affordable** and **accessible** for all Americans

Enable solar to support the **reliability**, **resilience**, and **security** of the grid

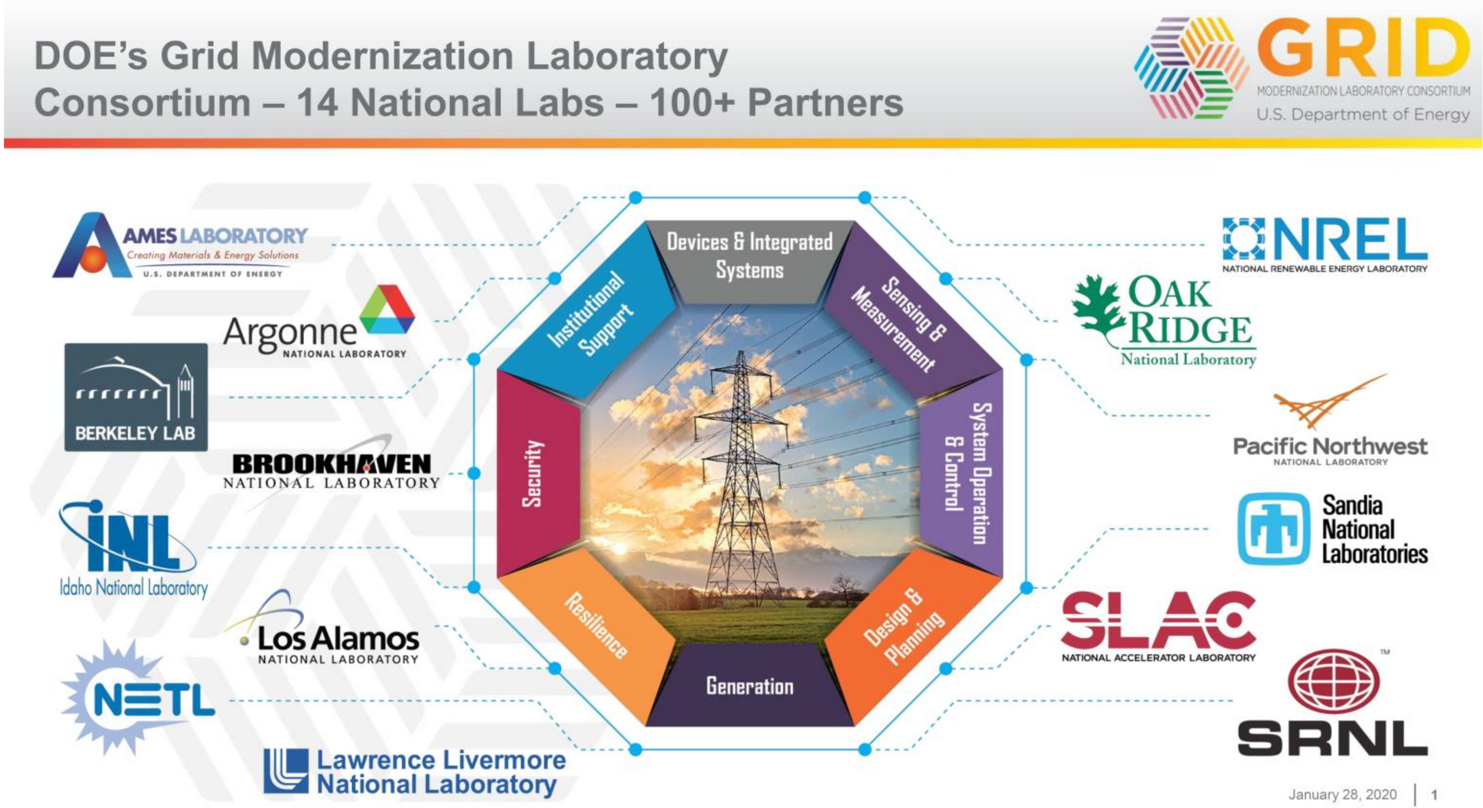
Support **job growth**, **manufacturing**, and the **circular economy** in a wide range of applications

SETO Systems Integration (SI) Program

The Systems Integration (SI) subprogram supports early-stage research, development, and demonstration (RD&D) of technologies and solutions – focusing on technical pillars **data, analytics, control, and hardware -** that advance the **reliable, resilient, secure and affordable** integration of solar energy onto the U.S. electric grid.



GMI – DOE-Wide Collaboration



SETO System Integration Research Areas

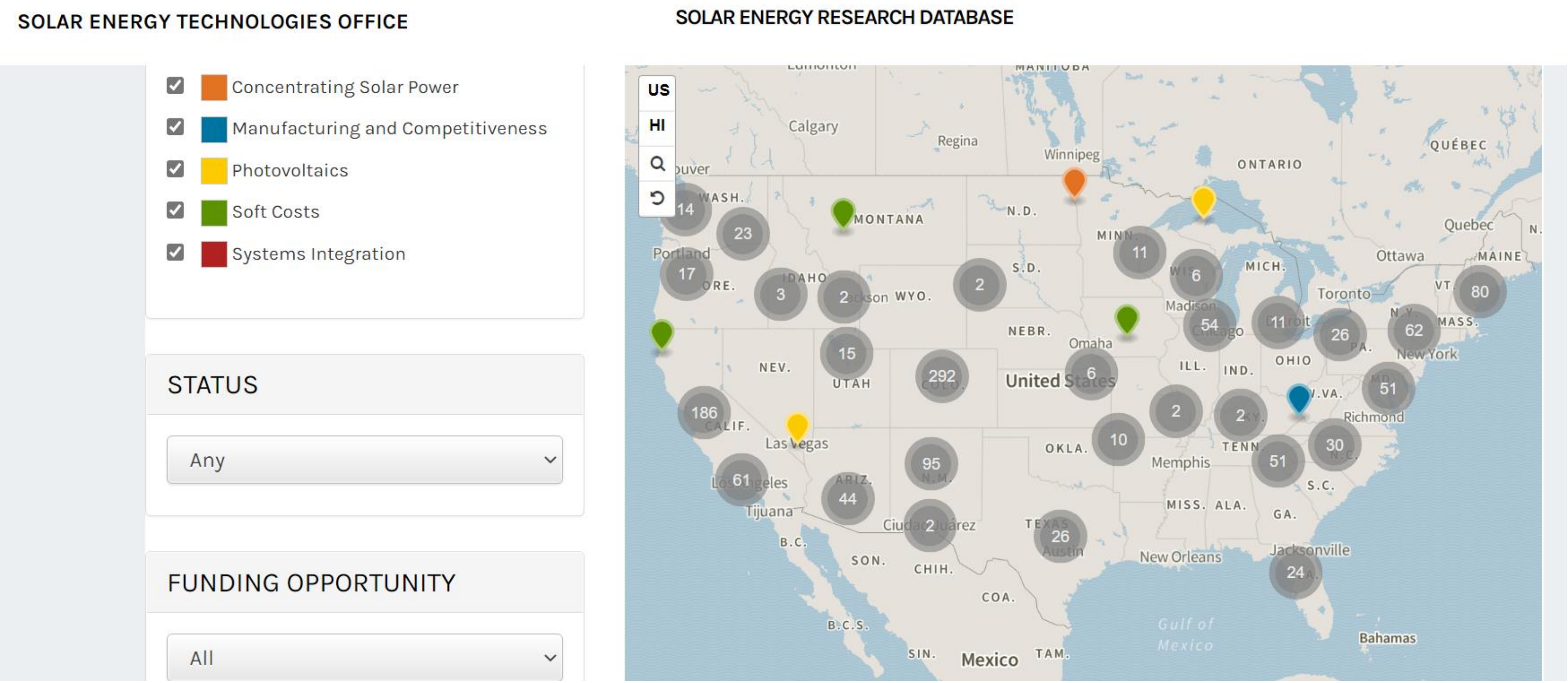
- **Grid Planning with High Solar**
  - Power system modeling
  - Solar forecasting
  - Codes and standards
  - Data and analytics
  - Integration studies

- **Grid Operation with High Solar**
  - Situation awareness
  - Grid services
  - Control and protection
  - Sensing and communication

- **Resilience and Cybersecurity with Solar PV and DER**
  - Community microgrids
  - Design for cybersecurity
  - Validation, valuation, info sharing
  - Regional partnerships

- **Power Electronics**
  - Cost and reliability
  - Hardware testing
  - Control and grid interface
  - Grid-forming

Solar Energy Research Database



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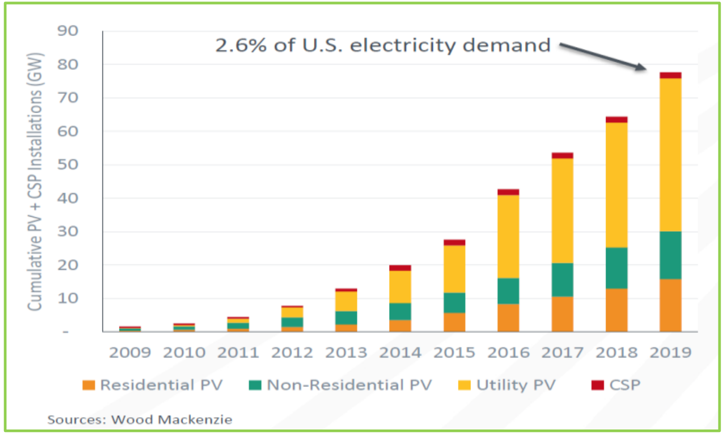
Many Challenges for Solar Grid Integration

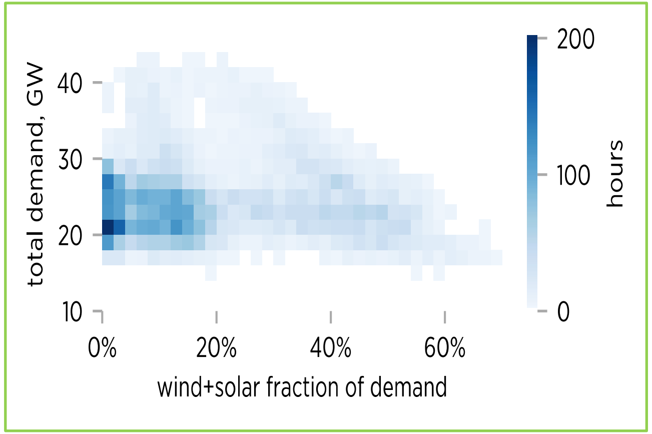
Rapid growth in installation

- *~60% utility-scale solar*
- *~40% distributed solar*

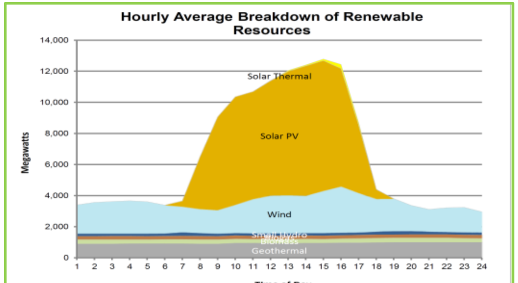


Uneven distribution solar resources in time and location

- *Some areas are already at high wind/solar levels (EIA, CAISO 2019)*



- *Daily renewable profile (CAISO)*



This graph shows the production of various types of renewable generation across the day.

- Weak grid and Low inertia
- Fast dynamics of IBR
- Variability and uncertainty
- Protection
- Situation awareness
- BTM DER control
- T&D interdependence
- Cybersecurity
- Resilience
- Cost/benefit
- Institutional challenges
- And others …

Emerging Challenges from Distributed Solar

- CAISO installed solar capacity:
  - Utility-scale: ~14,000MW
  - BTM Rooftop/small solar: ~5,000 MW (GTM)
- Contingency event:
  - Palo Verde: 2,750 MW (largest in WECC)
  - DOE/NERC reportable events
    - loss of 300MW firm load for 15 minutes
    - system-wide voltage reductions3 percent or more.
- Impact of DERs
  - DER cybersecurity standard underdevelopment
  - Customer owned devices
  - Vast numbers of devices
  - Complex interconnectivity
  - Knowledge gap between IT and OT

Source: NERC IRPTF Technical Report
BPS-Connected Inverter-Based Resource Modeling and Studies May 2020

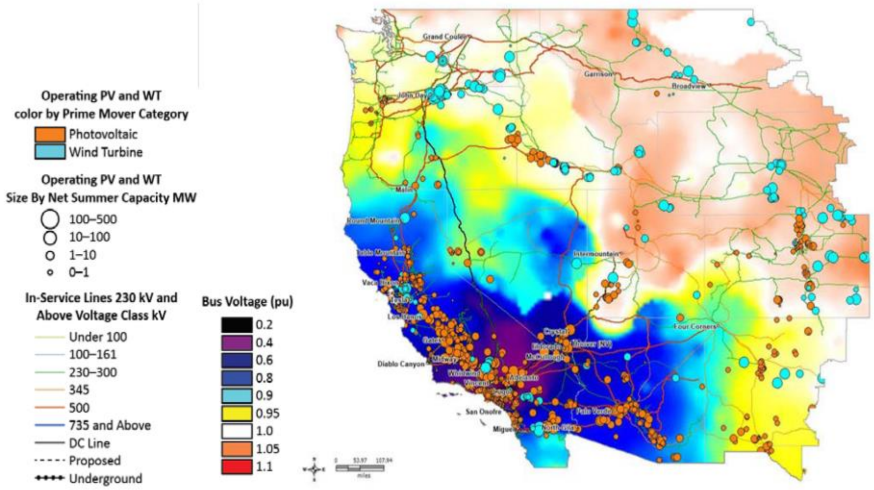


Figure 2.1: BPS Bus Voltages during On-Fault Conditions for Fault in Southern California

Renewable Integration and Grid Stability

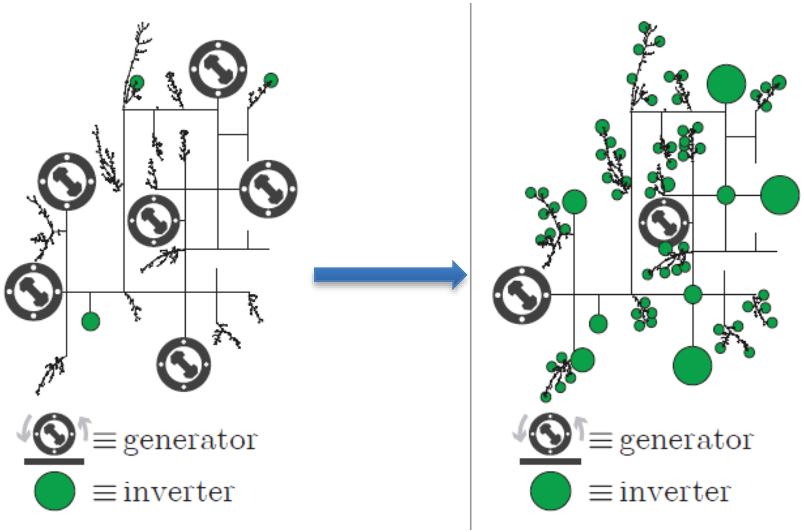
- Major Events
  - February 2021, TX winter storm power outage
  - August 2020, CA rolling blackout
  - 8/09/2019, UK blackout
    - lightening strike
    - 150MW of small embedded generation disconnected; further 350MW of embedded generation disconnected
    - 737MW offshore windfarm output reduction
    - 45 minute outage for 1.1 million customers
  - 10/09/2017, Southern CA Canyon 2 Fire
    - transmission fault;
    - 900 MW of solar PV resources lost; PV inverters trip off due to momentary cessation in response to voltage transients
  - 9/28/2016, South Australian blackout
    - Extreme weather (high wind, high temperature)
    - 456 MW wind generation reduction
    - 850,000 customers lost power for hours
  - 8/16/2016, Southern CA Blue Cut fire
    - transmission fault
    - 1200 MW of solar PV resources lost; PV inverters trip off due to frequency during transients

- NERC/DOE/Industry Response

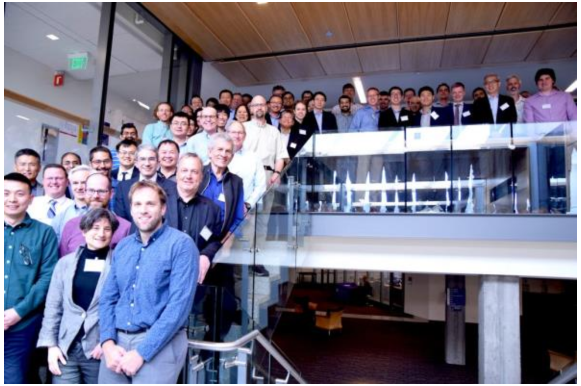
A Paradigm Shift – Power Electronics-based Electric Grid

Grid-Forming Inverters and Controls
In addition to grid-following, wind and solar need to have cooperative, grid-forming capabilities

DOE-funded NREL Grid-Forming Inverter project (2015-)
https://www.energy.gov/eere/solar/



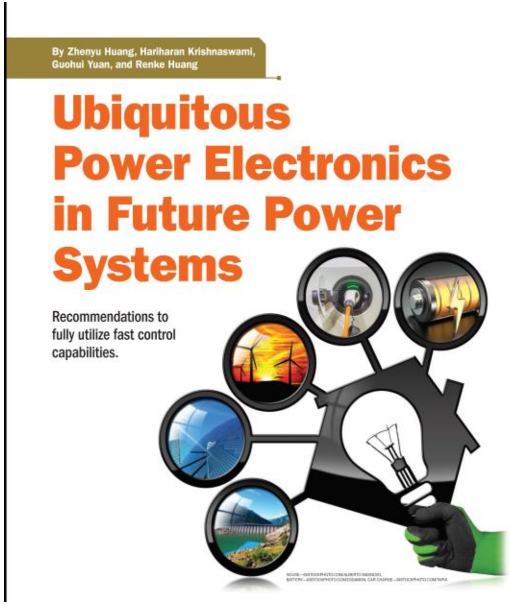
University of Washington Grid-forming Inverters Workshop (April 2019)



NREL/TP-5D00-73476, November 2020

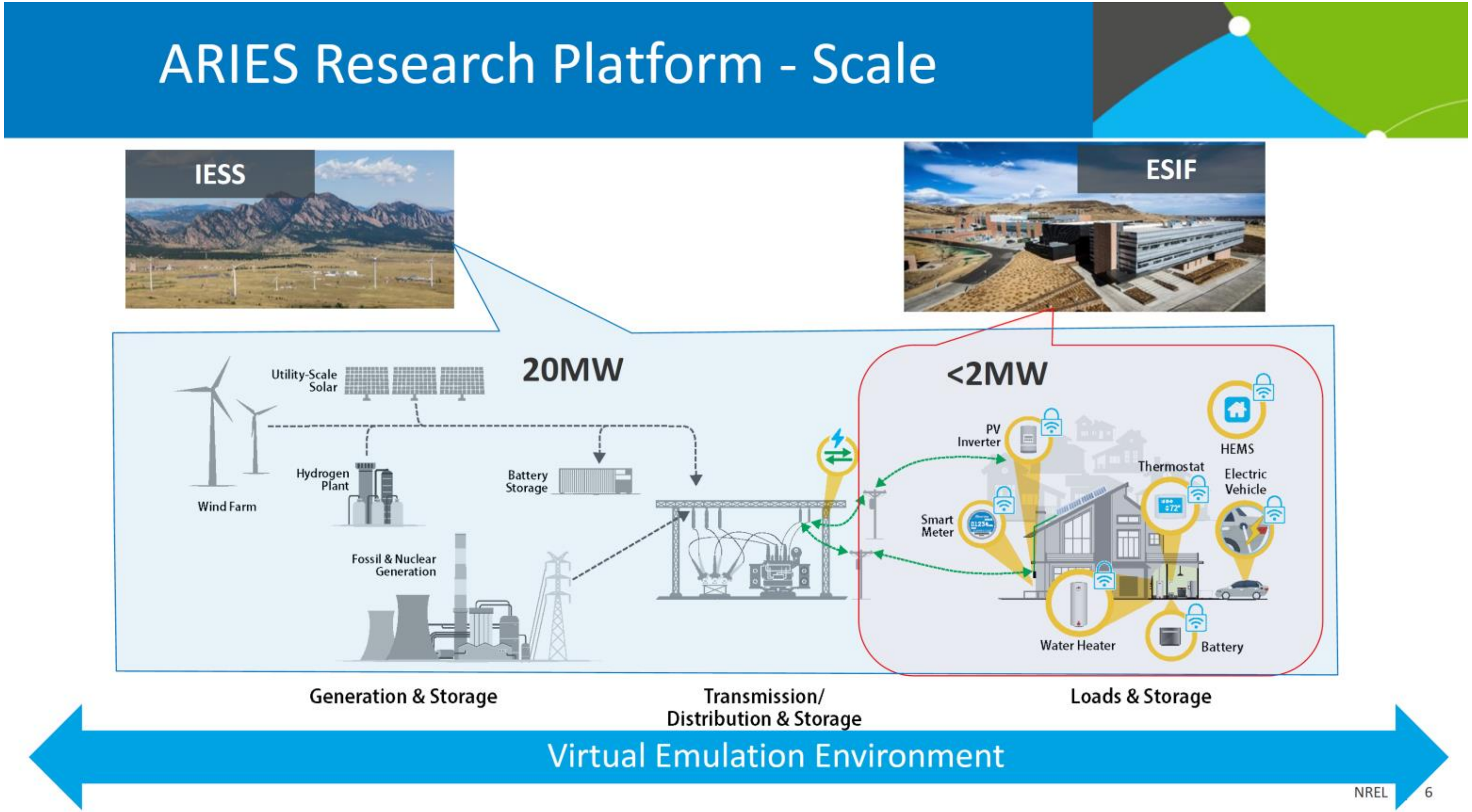
SETO Power Electronic Research

- DOE funding initiative
  - In 2020, SETO and WETO announced to invest $25M in a consortium for grid forming technology research
  - In 2019 and 2020, SETO selected several projects in power electronics and hybrid system controls
- PEGI Research platform
  - Solar grid integration at very high penetration levels
  - Integration of multiple technologies (wind, ES) at scale
  - Interdependency of bulk power and DERs
  - Real world testing environment
- Industry partnerships
  - Joint technology development
  - Testing and validation of vendor product functionalities
  - Collaboration with utilities to address practical issues
  - Engagement with broader stakeholders



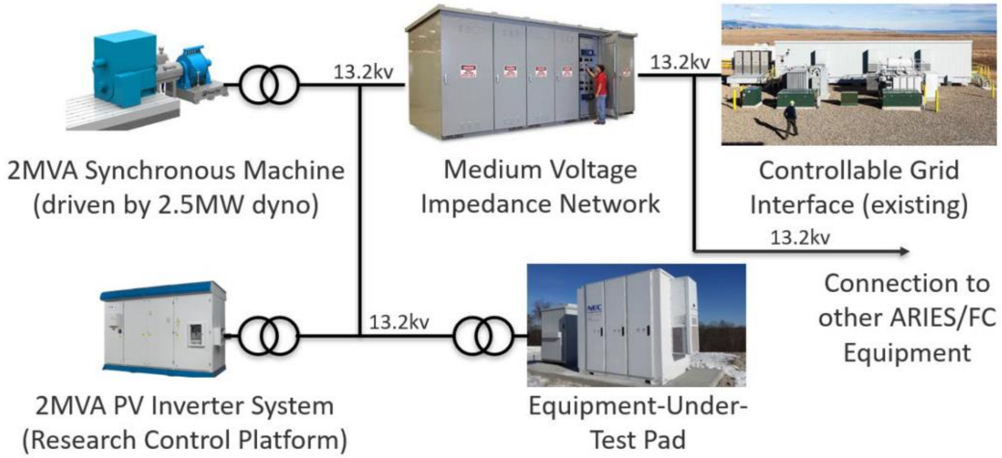
IEEE Electrification Magazine (September 2020)

Building World Class Test Facility



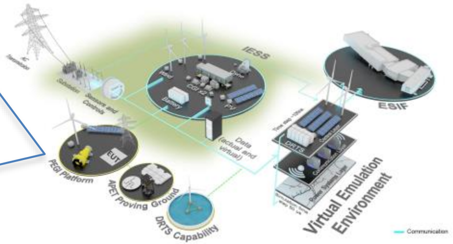
(Barry Mather, NREL)

Power Electronics Grid Interface (PEGI)



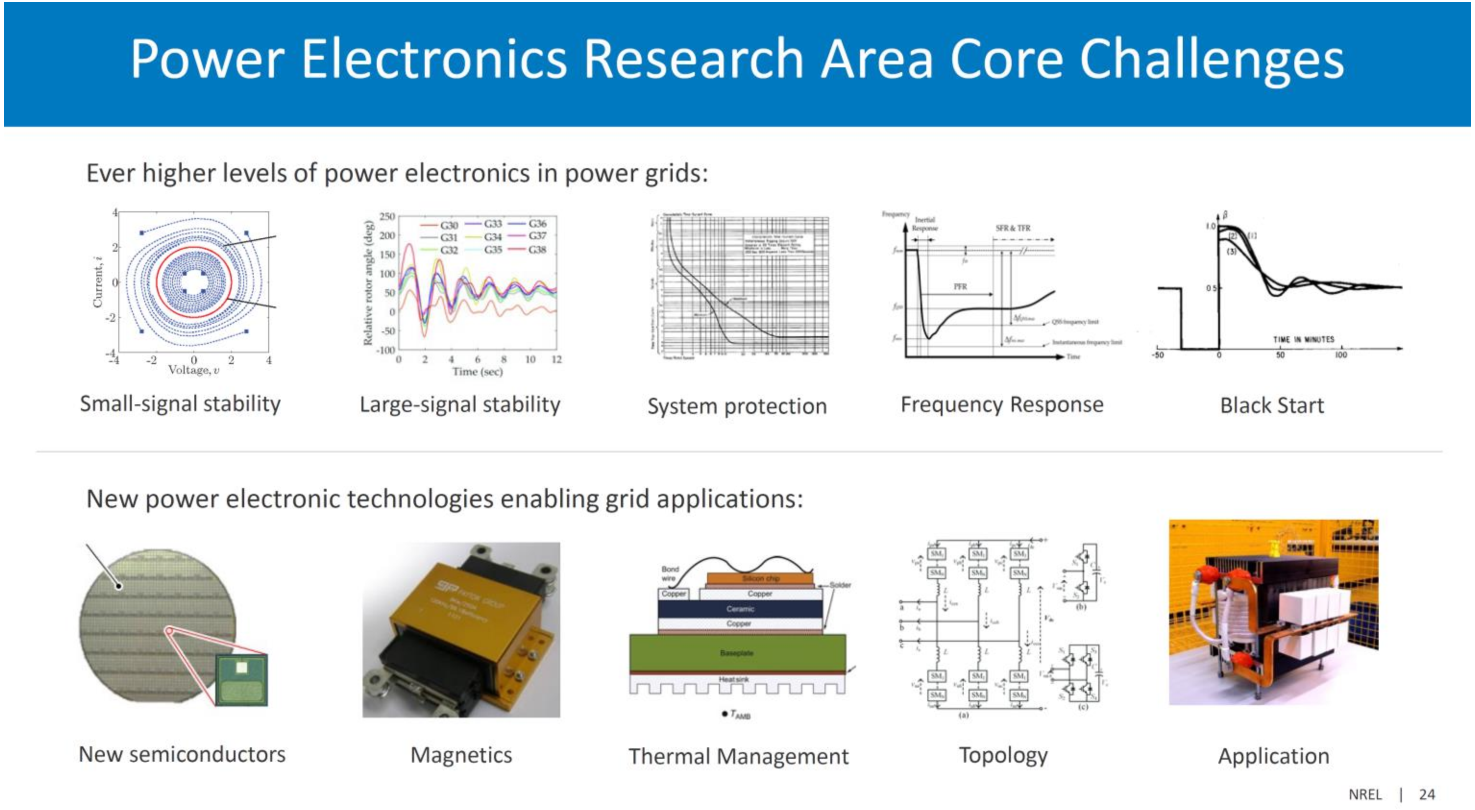
Power Electronic Grid Interface (PEGI) Platform

ARIES Campus



Power Electronics R&D Focused Capabilities

Potential Research Areas



(Barry Mather, NREL)

Interconnection Standards for Inverter-Based Resources

Authority	Resource	Performance	Test & Verification & Model Validation
FERC / NERC?	BES[1] / BPS[3] — Transmission	• FERC Orders • NERC Reliability Standards & Guidelines	• NERC compliance monitoring & enforcement
NARUC / State PUCs?	BPS[3] — Sub-Transmission	• Not available **IEEE P2800**	• Not available **IEEE P2800.1**
NARUC / State PUCs?	DER[2]	• IEEE Std 1547-2018 ✓	• IEEE 1547.1-2020 • Ul 1741 (SB) • IEEE ICAP ✓

[1] NERC definition of Bulk Electric System: ≥100 kV with gross individual / aggregate nameplate rating greater than 20 MVA / 75 MVA

[2] DER connected at typical (radial) primary and secondary voltage levels

[3] transmission and meshed sub-transmission

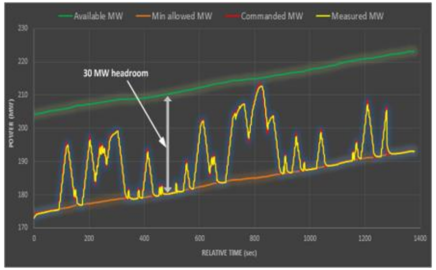
IEEE standards are voluntary industry standards and must be adopted by the appropriate authority to become mandatory (e.g., Transmission Owners, NERC, FERC).

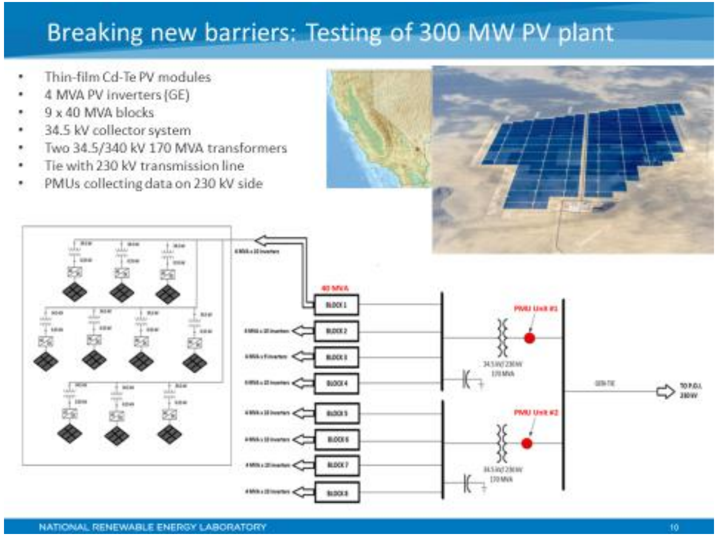
(Source: IEEE P2800 WG, Jens C. Boemer, et al)

Demonstration of Essential Reliability Services from Solar PV

- NREL/CAISO/First Solar partnering in the 300-MW PV System Commissioning Test
- Winner of NARUC Innovation Award in 2017

- 4-sec AGC signal provided to PPC
- 30 MW headroom
- Tests were conducted for 30 minutes at:
  - Sunrise
  - Middle of the day
  - Sunset
- 1-sec data collected by plant PPC





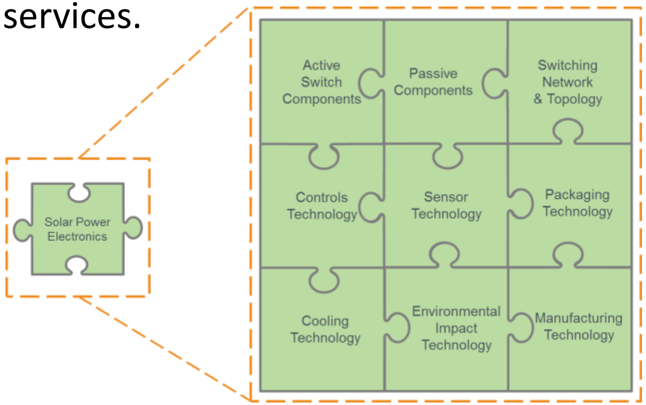
Courtesy: NREL, Vahan Gevorgian
http://www.nrel.gov/docs/fy17osti/67799.pdf

"These data showed how the development of advanced power controls can enable PV to become a provider of a wide range of grid services, including spinning reserves, load following, voltage support, ramping, frequency response, variability smoothing, and frequency regulation to power quality."

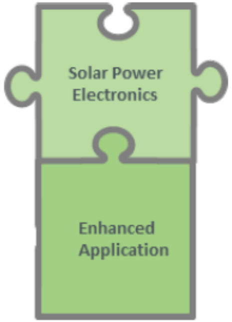
SETO Power Electronics Funding Program

- Selection announced in April 2018 (https://www.energy.gov/eere/solar/advanced-power-electronics-design-solar-applications-power-electronics)
- Objectives: a) significant reductions in the lifetime costs of power electronics (PE) for solar photovoltaic (PV) energy, and b) enable versatile control functionalities to support grid integration of solar PV for enhanced grid services.
- Projects ($20M)

Georgia Institute of Technology
North Carolina State University
University of Arkansas
University of Maryland at College Park
University of Washington
Virginia Tech
Flex Power Control
Oak Ridge National Laboratory
University of Texas at Austin



Topic Area 1: Optimization of constituent technologies for reduced lifetime costs



Topic Area 2: Conceptual modular PE for enhanced grid services

Inverter Lab Testing

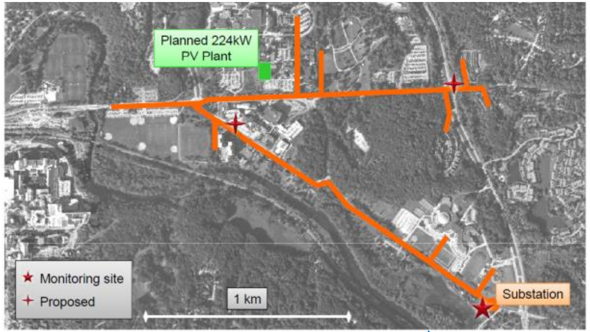
- Manufacturer lab testing
- Power HIL Modeling real feeder topology
- Using real event data

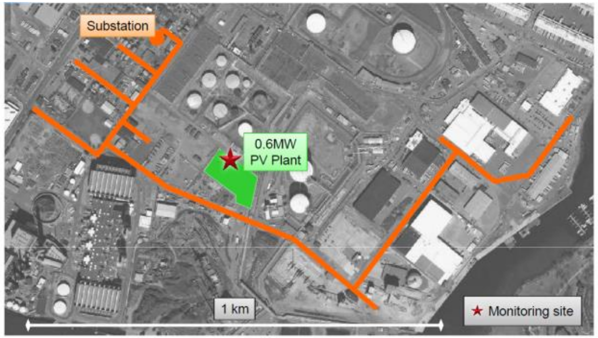
NREL ESIF

- Grid simulator
- PV simulator
- Communication
- Remote control

EPRI Knoxville Lab

Field Demonstration with Utility Partners

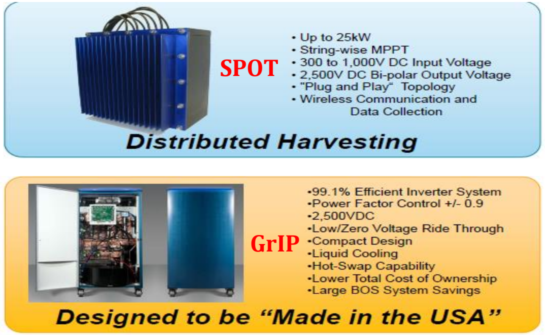




- Instrumentation
- Inverter upgrade
- PMC
- Communication
- DERMS software
- Remote control

Power Electronics Design Improvements – Cost Reduction and Lifetime Reliability

2500V/2.5MW Inverter System (**Alencon**)



ACPV module with microinverter (**SunPower/SolarBridge**)

Multi-Level Cascade Inverter (**Delphi**)

Smart-Grid Ready Inverter (**Yaskawa/Solectria**)

In Conclusion: The Grid is Rapidly Evolving

- **Low Inertia:** Power electronics-connected generation and consumption reduce the mechanical inertia in the system.
- **More Uncertain:** Uncertainties increase due to variable generation, smart loads, electric vehicles, generation and network contingencies, weather and cyber events, and hidden failures.
- **More Distributed:** The grid trends to having many small active resources such as rooftop PVs, smart appliances, and electric vehicles.

- **Responsive:** The high-speed control capabilities of power electronics present new opportunities for achieving a more ***responsive*** power grid.
- **Adaptive:** The solutions can and should make the grid more ***adaptive*** – ramping requirements, network reconfiguration, AC/DC hybrid operation and islanding at various granularities.
- **Scalable:** Small resources are more ***scalable*** through various combinations as needed, e.g. against cyber or physical disturbances and during outage recovery.

Solar Grid Integration Research Priorities

Solar generation has grown from less than 0.1 percent of the U.S. electricity supply 2010 to 3 percent per year in 2020 and rapidly expanding. In five states, solar electricity already represents more than 10 percent of total generation.

2010-2020 (low)

Solar maximize energy output to the grid

→

2020-2030 (medium)

Solar and storage contribute to essential reliability services

→

2030 – (high)

Solar, wind, storage, and power electronics technologies fully support the reliable operation of 100% clean electricity grid

For Questions:

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