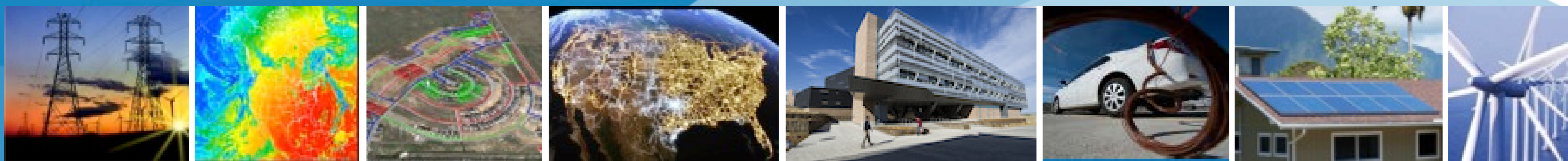
Power Systems
Engineering Center



Advanced Power Electronic Functionality for Renewable Energy Integration with the Power Grid

Ben Kroposki, PhD, PE, FIEEE
Director – Power Systems Engineering Center
National Renewable Energy Laboratory

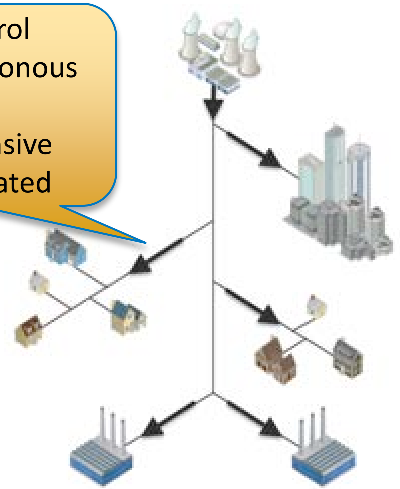
2016 8th International Power Electronics and Motion Control Conference - ECCE Asia (IPEMC 2016-ECCE Asia)
Hefei, China
May 22 - 25 2016

NREL/PR-5D00-66741

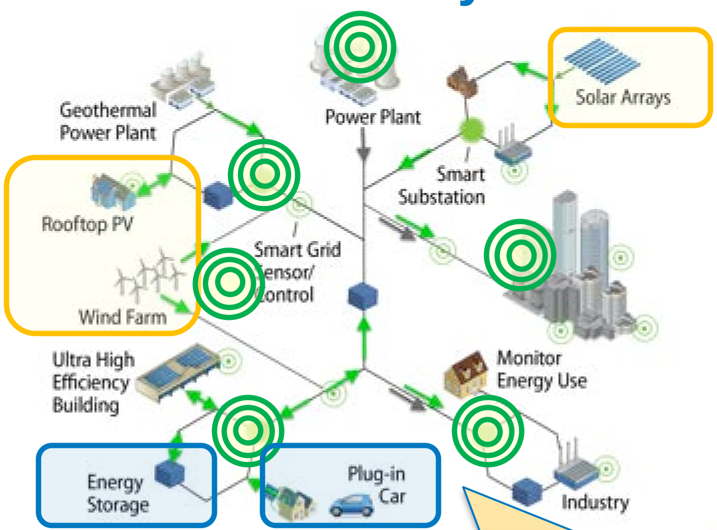
Evolution of the Power Grid

Current Power System

- Central Control
- Large Synchronous Generation
- Carbon Intensive
- Highly Regulated



Future Power Systems



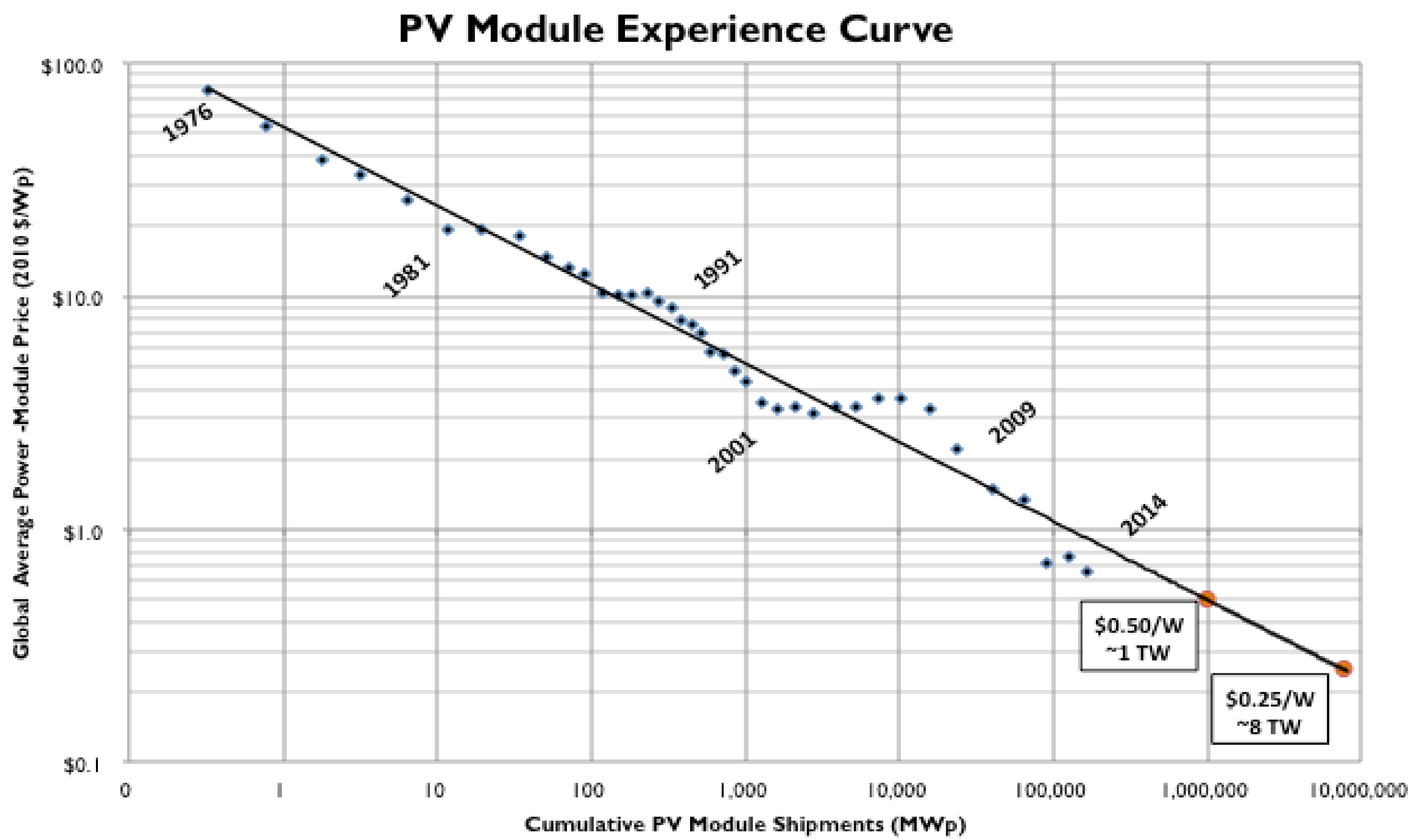
DRIVERS
- Increased variable gen
- More bi-directional flow at distribution level
- Increased number of smart/active devices
- Evolving institutional environment

New Challenges in a Modern Grid

- New energy technologies and services
- Increasing penetration of variable renewables in grid
- New communications and controls (e.g. Smart Grids)
- Electrification of transportation
- Integrating distributed energy storage and load controls
- More power electronics based generation, storage, and loads

Current Situation for Renewable Integration

PV Module Prices



Examples of Large PV and Wind Plants in USA

Photo Credit: NREL

Solar Star
Rosamond, CA
Photovoltaic
579 MW

Topaz Solar Farm
San Luis Obispo County, CA
Photovoltaic
550 MW

Ivanpah
Mojave Desert, CA
Solar Thermal
392 MW

Photo Credit: NREL

Alta Wind Energy Center
Tehachapi Pass, CA
600 Vetas Wind Turbines
1,547 MW
2,680.6 GWh/yr

Capricorn Ridge Wind Farm
Sterling and Coke County, TX
407 GE & Siemens Turbines
663 MW

Shepard's Flats
Arlington OR
338 GE Turbines
845 MW
2,000 GWh/yr

Addressing High Pen PV in Hawaii

Technology Addressed

Interconnection challenges when connecting distributed PV into the electrical distribution grid such as in Hawaii (HECO).

Impact

Hawaii is moving towards 100% renewable energy and this project will work to improve the safety, reliability and stability of the electric power systems that include high levels of distributed PV.

Photo Credit: SolarCity

- Research demonstrated the ability of advanced power inverters to mitigate the impacts of high penetration of solar PV on distribution grids.
- As a result, HECO has now indicated it will expedite the installations of solar PV systems on circuits up to 250% of daytime minimum load if the PV systems are installed with advanced inverters that meet stricter requirements.

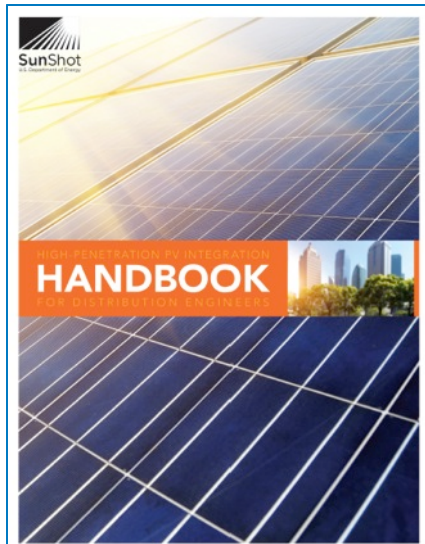
Photo Credit: Kroposki

http://www.nrel.gov/docs/fy15osti/64173.pdf

NREL/Southern Cal Edison Hi-Pen PV Integration Project

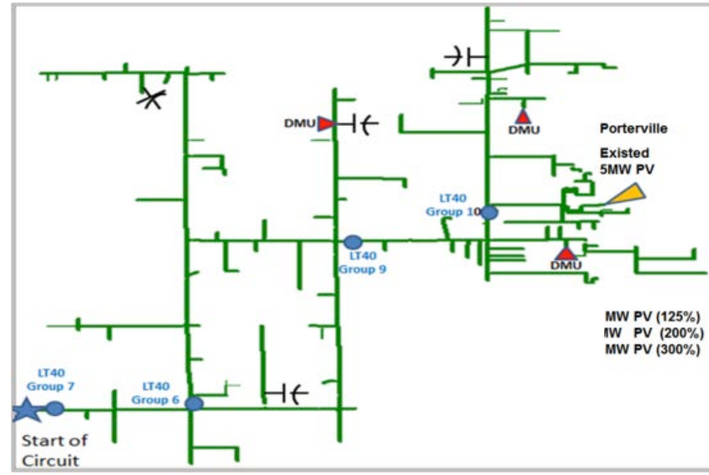
Technology Addressed

- Develop PV impact study methods
- Demonstrate advanced PV inverters ability to mitigate impacts
- Develop a high-pen PV integration handbook for distribution engineers

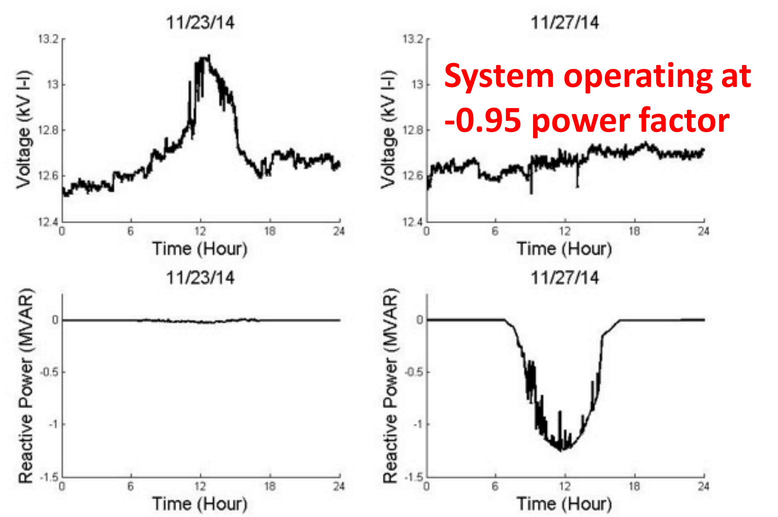


Impact

- Benchmarked the use of **quasi-static time-series simulations for PV impact studies against transient-level analysis**
- Completed the first PHIL evaluation of a utility scale PV inverter
- Completed three field demonstrations of the capabilities/impact of advanced PV inverters



Case Study Circuit (5 MW PV system near the end-of-circuit)



Point-of-interconnection voltage and reactive power exchange before (left) and during (right) the field demonstration

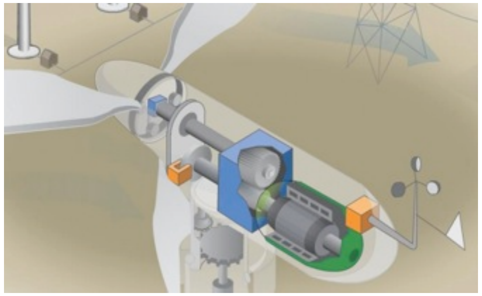
http://www.nrel.gov/docs/fy16osti/63114.pdf

SunShot U.S. Department of Energy

Active Power Control from Variable Generation

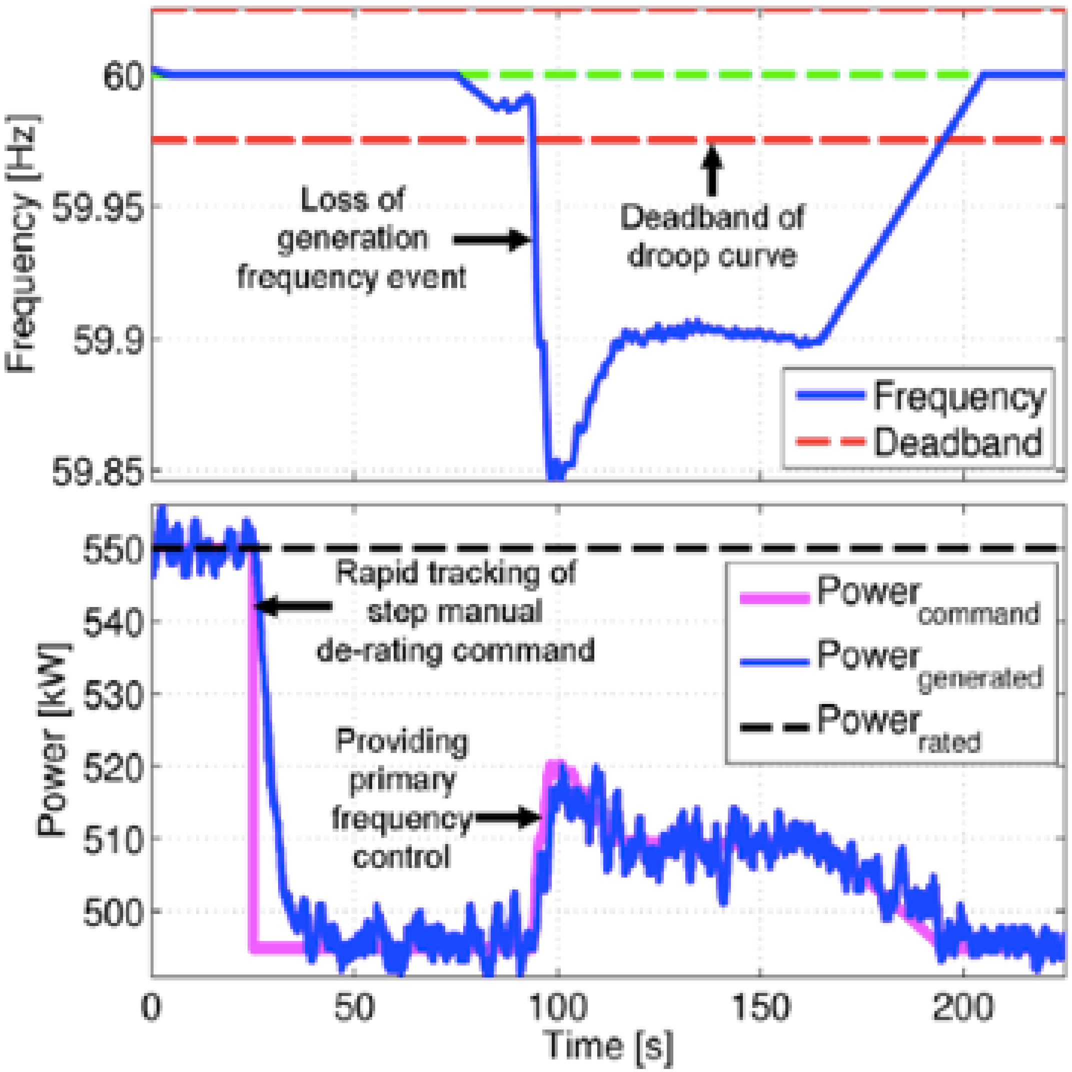
Technology Addressed

- Understanding how Variable Generation (Wind and Solar) can provide primary and secondary reserves.



Impact

- Inertial control, Primary Frequency Control (PFC), and Automatic Generation Control (AGC) from Wind and Solar is feasible with negligible impacts on loading



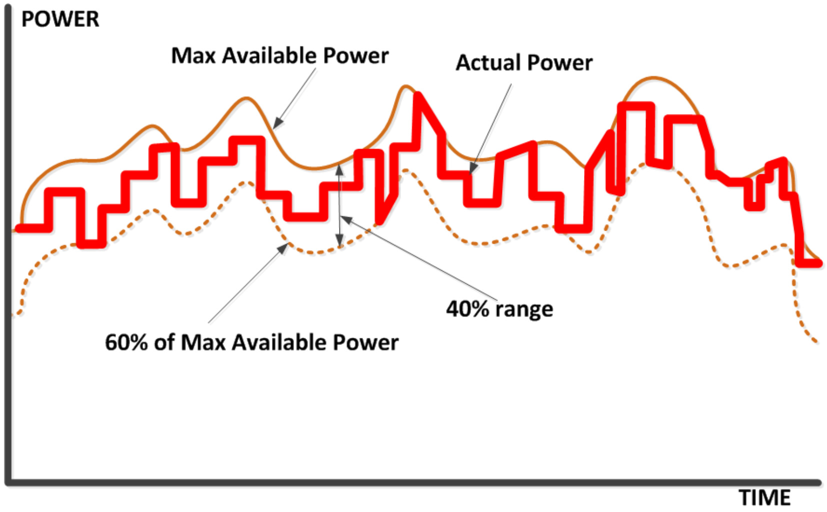
http://www.nrel.gov/docs/fy14osti/60574.pdf

PV provides grid services for Puerto Rico

Technology Addressed

- **PV participated in Automatic Generation Control (AGC)**
  - Follow AGC signal within 40% of available power
- **PV provided frequency droop response**
  - Both up and down-regulation
  - 5% and 3% symmetric droop
- **Fast Frequency Response (FFR) tests**
  - Test plant's ability to deploy all reserve within 500 ms
  - Three new controls were implemented and validated

Photo Credit: AES



Impact

First of a kind real-world experiment using PV systems to maintain large grid stability

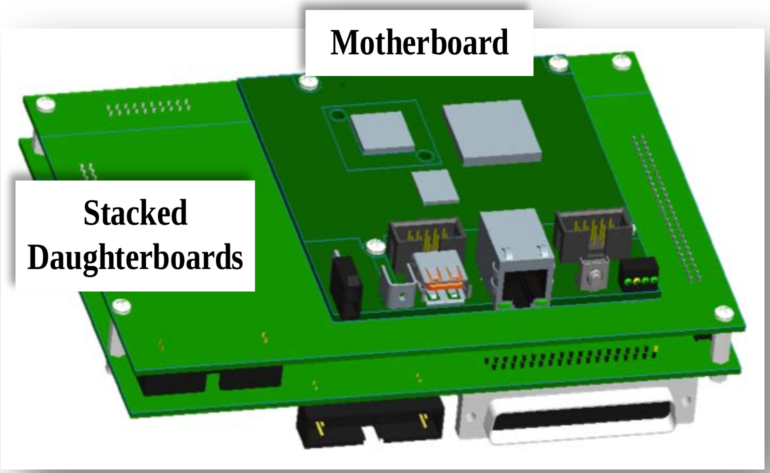
http://www.nrel.gov/docs/fy16osti/65368.pdf

SunShot U.S. Department of Energy

Additively Manufactured PV Inverter (AMPVI)

Technology Addressed

Develop a unique PV inverter that combines high-voltage Silicon Carbide with additive manufacturing to achieve better performance and reliability at lower cost.

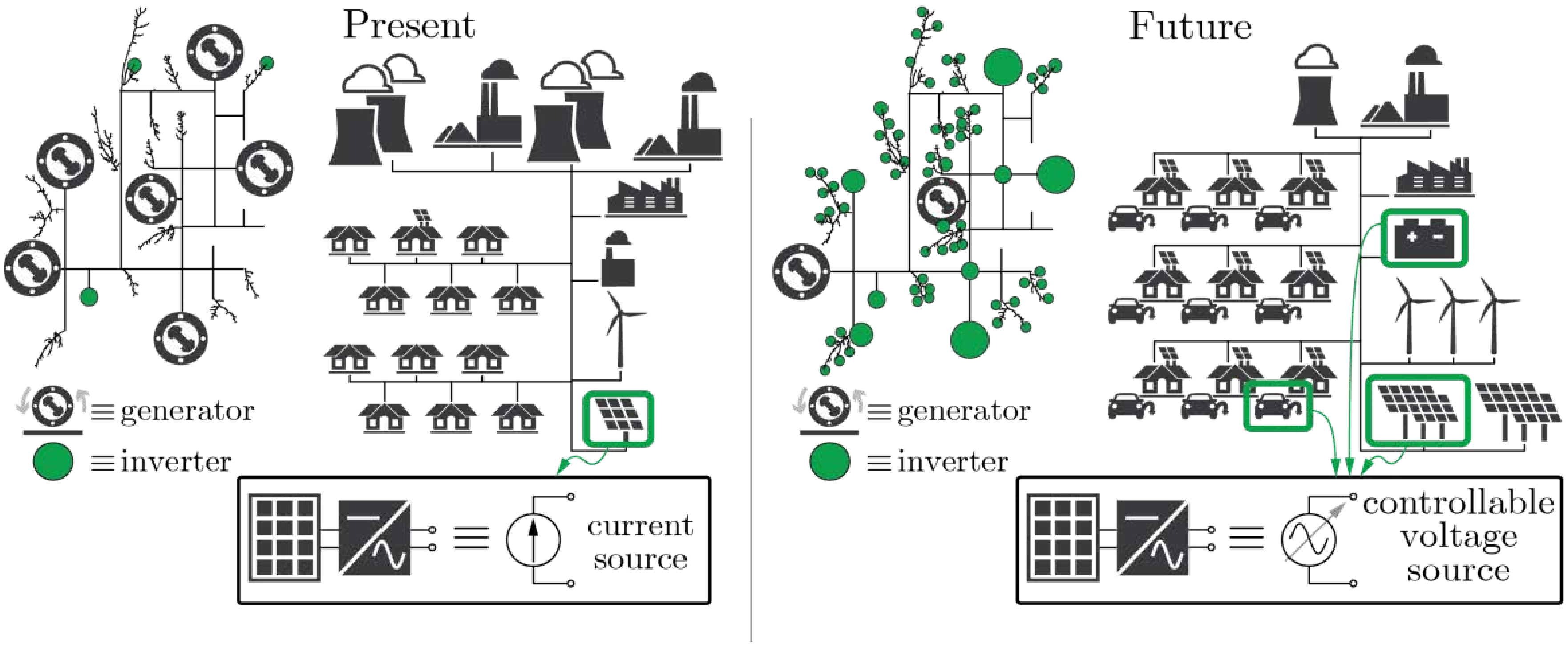


Impact

- Superior technical capabilities in term of energy conversion, but also mitigates market barriers for SiC-based PV inverters.
- A cost-optimized yet flexible controller board based on a motherboard-daughterboard approach.
- Superior grid support capabilities from the PV inverter due to the use of SiC with a wider safe operating area and better control bandwidth.

Future Grids with High Levels of Power Electronics Based Sources

Stabilizing the Grid in the Future



Synchronous generator based power system with inverters using grid-following controls

To inverter dominated power system using next-generation grid-forming controls

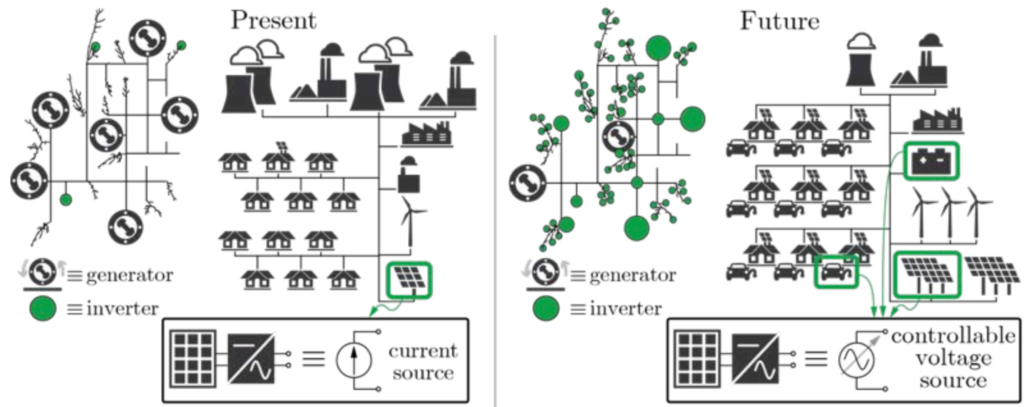
Stabilizing the Grid in 2035 and Beyond Project

Technology Addressed

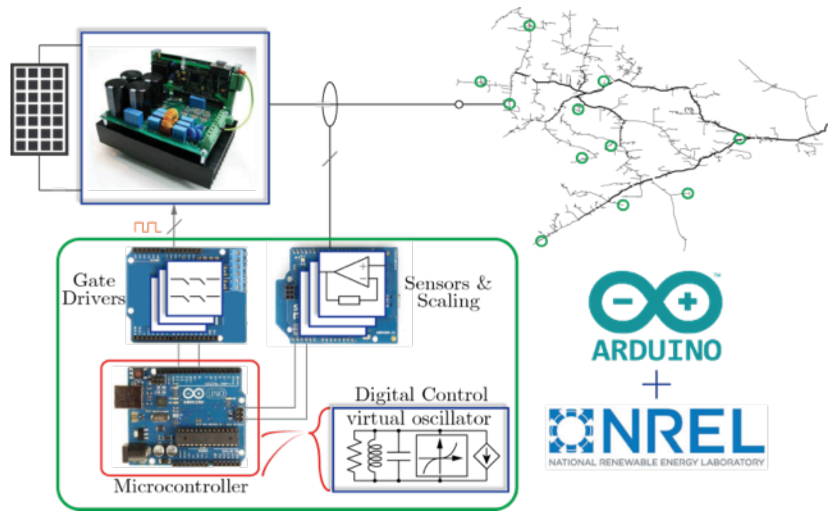
Develop distributed inverter controllers which provide a low- resistance path from the current inertia-dominated grid paradigm to a future grid paradigm dominated by low-inertia power systems with 100's of GWs of PV integration.

Impacts

- Develop modeling, analysis, and design framework for grid-stabilizing PV inverter controllers.
- Design, build, and prototype digital microcontrollers to implement proposed PV inverter controllers.
- Extensive evaluation of control strategy via analytical modeling, simulation, and experimentation.
- Engage with PV inverter manufacturers and utilities during project



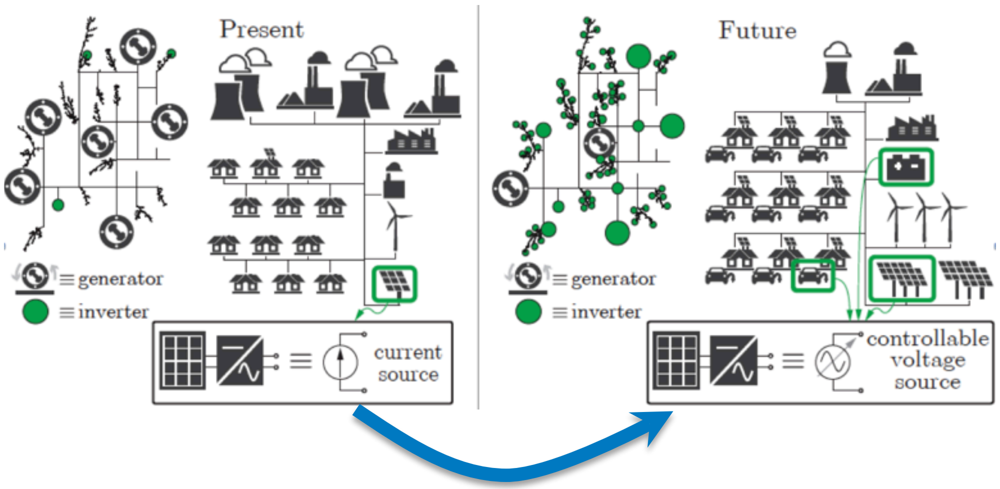
From grid-following controls → To next-generation grid-forming controls



SunShot U.S. Department of Energy

Distributed Controls and Optimization

As we migrate from a centrally controlled, synchronous generator based grid to a highly distributed, inverter based system…

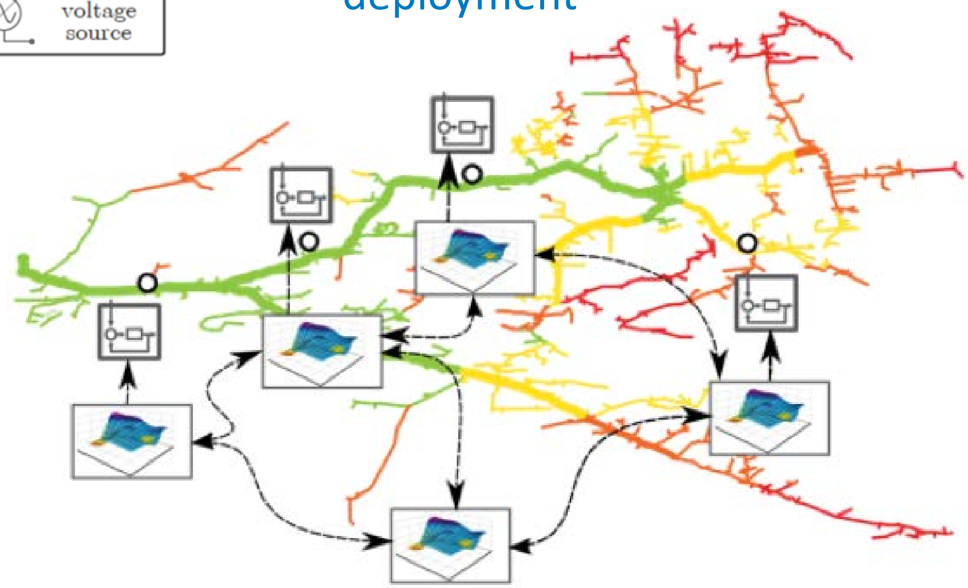


We need smart inverters with advanced functionality to maintain grid stability and…

Improved optimization for millions of controllable devices in the grid

Research Needs

- Control theory
- Advanced control and optimization algorithms
- Imbedded controllers in devices
- Linkage to Advanced Distribution Management Systems (ADMS)
- Validation of concepts and deployment



http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6920041

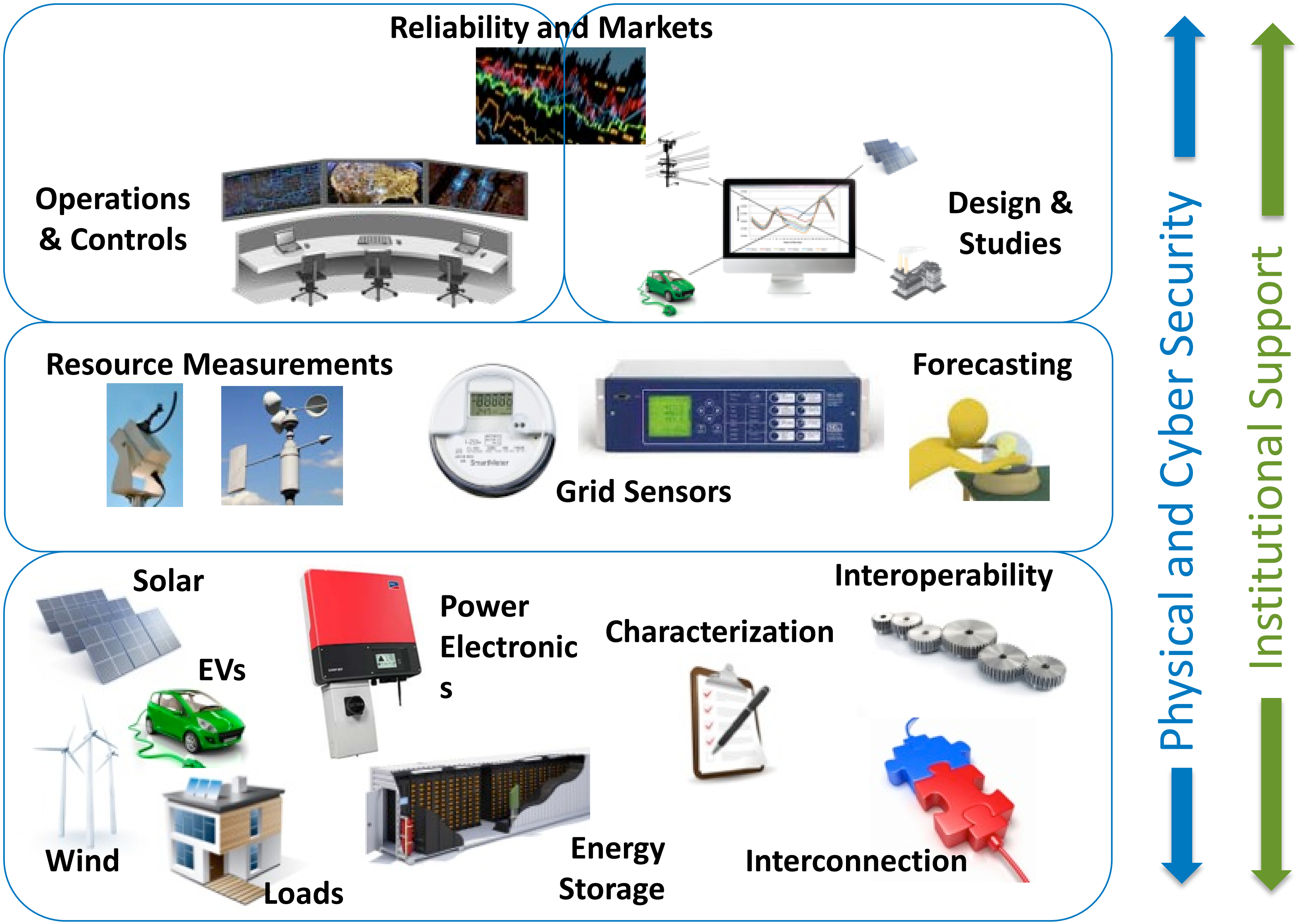
NREL – Power Systems Research

Design & Studies

Operations & Controls

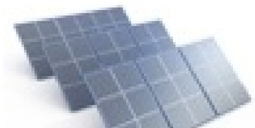
Sensing, Measurements, and Forecasting

Integrated Devices and Systems



NREL's Energy Systems Integration Facility (ESIF)

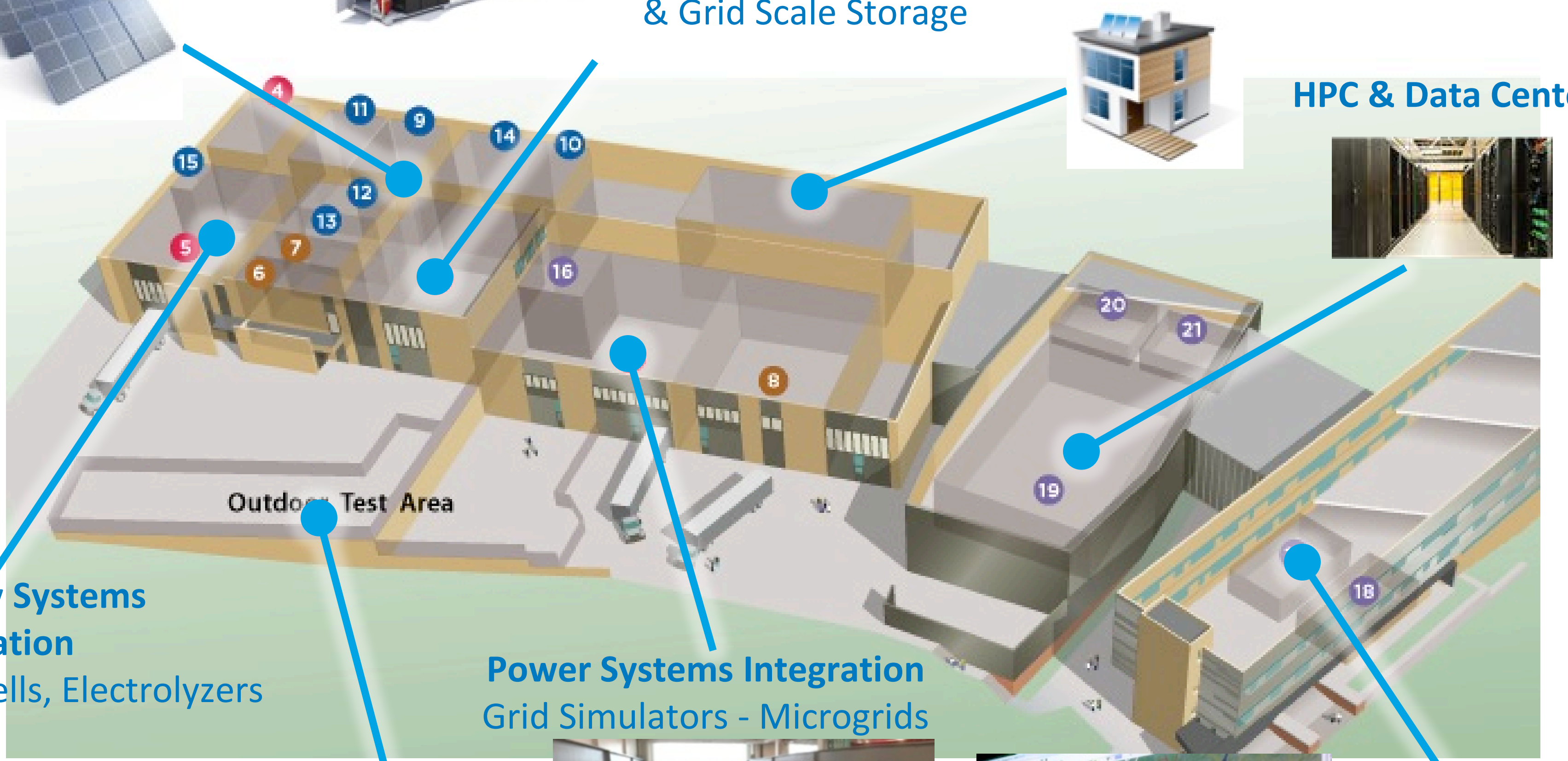
Rooftop PV



Energy Storage -
Residential, Community
& Grid Scale Storage

**Smart buildings &
controllable loads**

HPC & Data Center



Energy Systems Integration
Fuel Cells, Electrolyzers

Power Systems Integration
Grid Simulators - Microgrids

Outdoor Test Areas
EVs, Transformers,
Capacitor Banks,
Voltage Regulators

Advanced Distribution Management Systems

Thank You!

www.nrel.gov

NREL
NATIONAL RENEWABLE ENERGY LABORATORY