Outline of This Presentation

SAND2011-3716P

- **Introduction to Sandia National Laboratories**
- **Overview of PV technologies, markets today**
- **Variability of High Penetration PV on the Grid:**
  - Step 1: Define the problem
  - Step 2: Develop the near-term technology solutions
  - Step 3: Conduct the longer-term R&D
  - Step 4: Implement and iterate

Sandia's Heritage

"Exceptional service in the national interest"

THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

Sandia National Laboratories

Sandia locations

Albuquerque, New Mexico

Livermore, California

Emeryville, California

Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex, Texas

Tonopah, Nevada

The Evolution of Our Mission

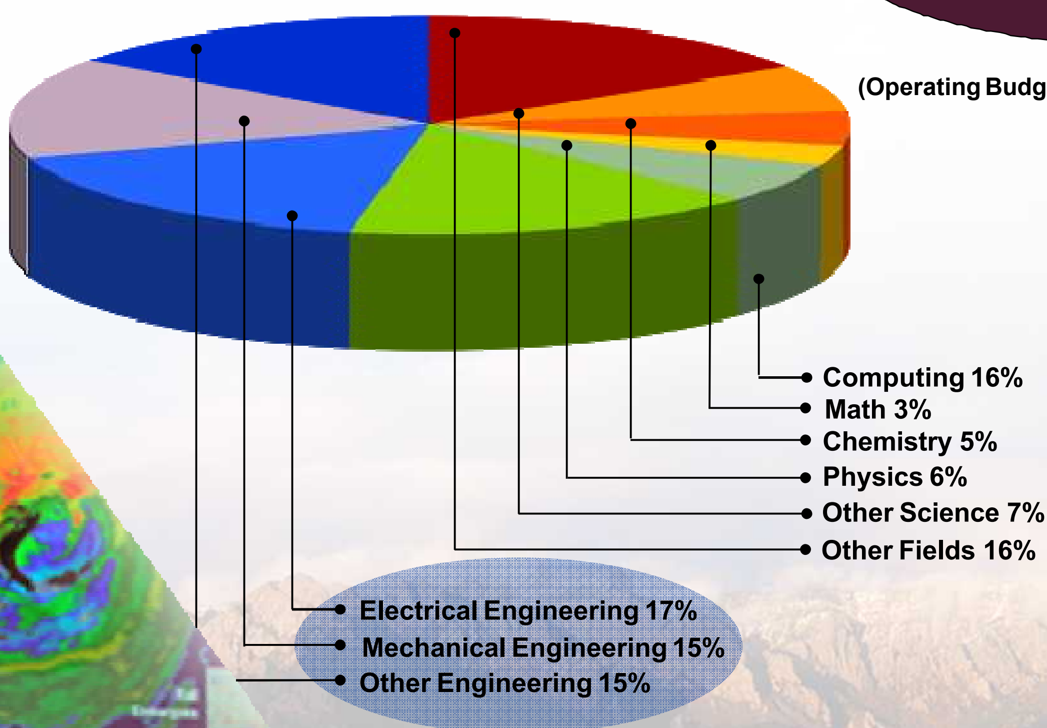
1950s	1960s	1970s	1980s	1990s	2000s
Production engineering and manufacturing engineering	Development engineering	Multiprogram laboratory	Research, development and production	Post-Cold War transition	Expanded national security role

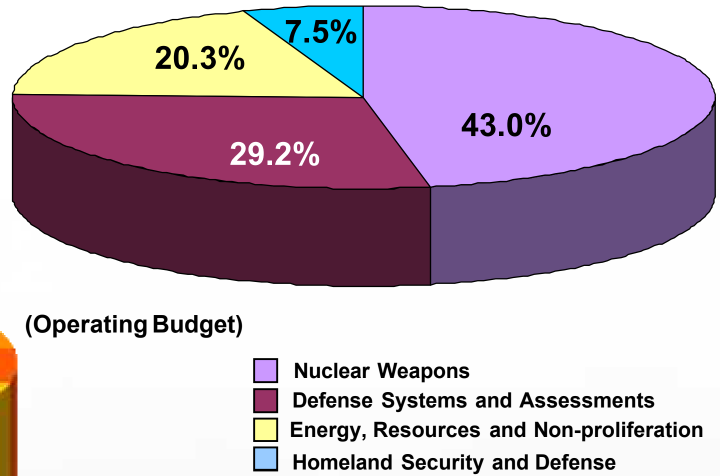
Sandia National Laboratories

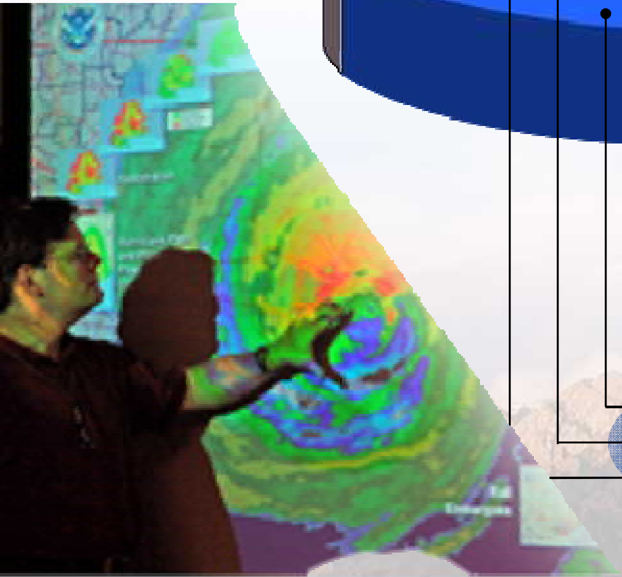
People and Budget

- **FY10 permanent workforce: 8,478**
- **FY10 budget: $2.4B**

Technical Staff (3,921) by Degree (Start of FY09)







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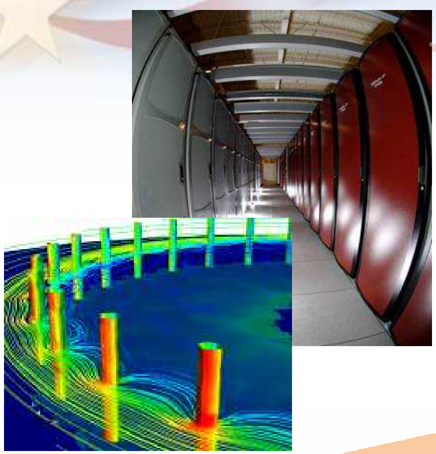
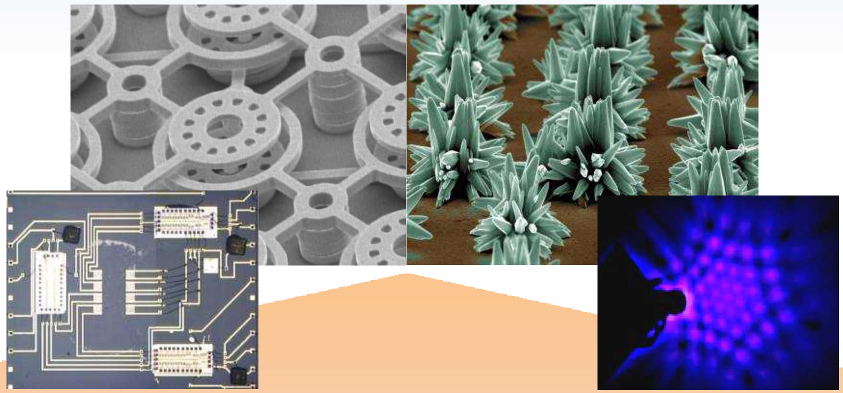
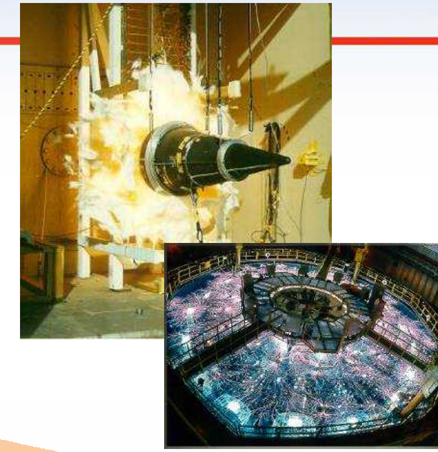
Sandia's Research Disciplines Drive Capabilities



High Performance Computing

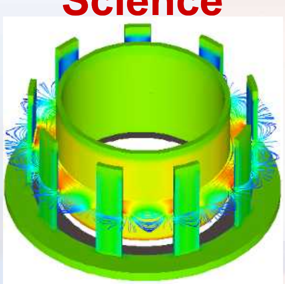


Nanotechnologies & Microsystems

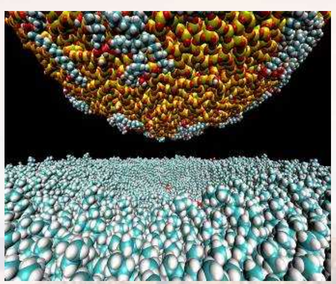


Extreme Environments

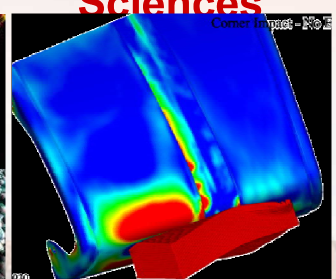
Computer Science



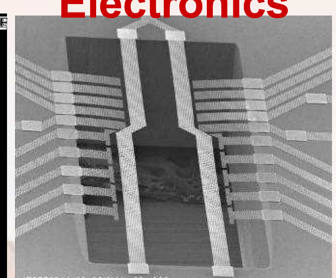
Materials



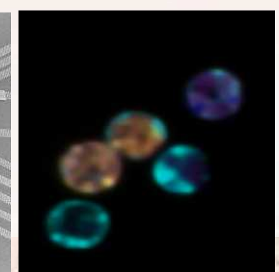
Engineering Sciences



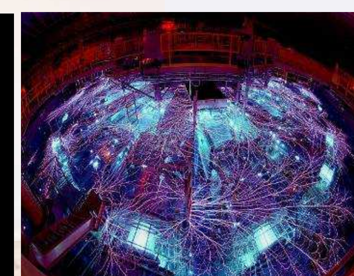
Micro Electronics



Bioscience



Pulsed Power



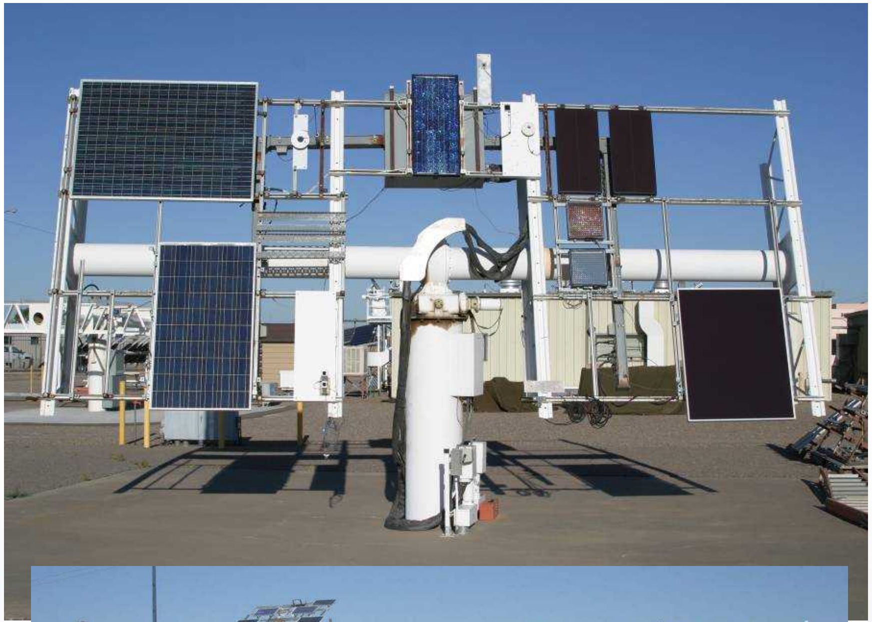
Research Disciplines

Photovoltaic Systems Evaluation Laboratory conducts performance and reliability assessments

- Dual-axis tracker and weather instrumentation for measuring performance of all module technologies

- Long-term performance of small systems allows for performance, model validation, early failure assessments

- Cell-level one-sun, spectral response, temperature response, and laser beam induced current for systems assessments



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Distributed Energy Technologies Laboratory conducts controlled-environment grid integrations

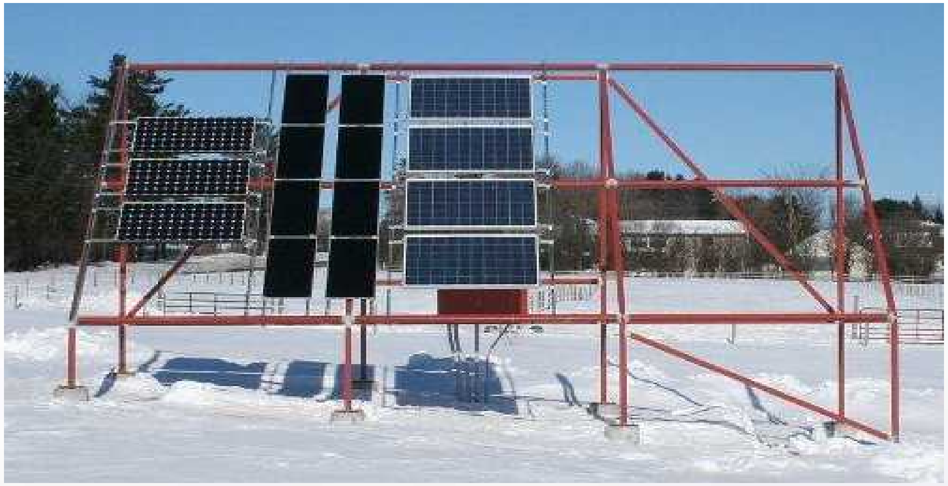
- **Configurable testbed where new hardware integrations can be tested and optimized**
- **Simulation of precise daily load profiles to represent several different microgrids:**
  - A single residence (with multiple loads)
  - Multiple residences
  - One or more commercial buildings
  - A mix of these situations (non-balanced loads)
- **Addition of generators and motor loads to the microgrid to simulate real life situations**

Distributed Energy Technologies Laboratory

Sandia Utilizes an Integrated "Systems" Approach to Improving PV Systems Cost, Performance, and Reliability

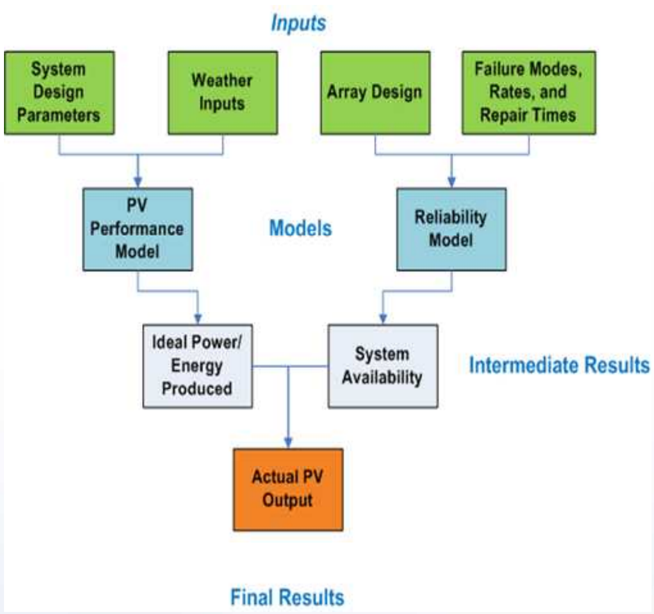
Example: System Long Term Exposure (SLTE) study in collaboration with University of Vermont

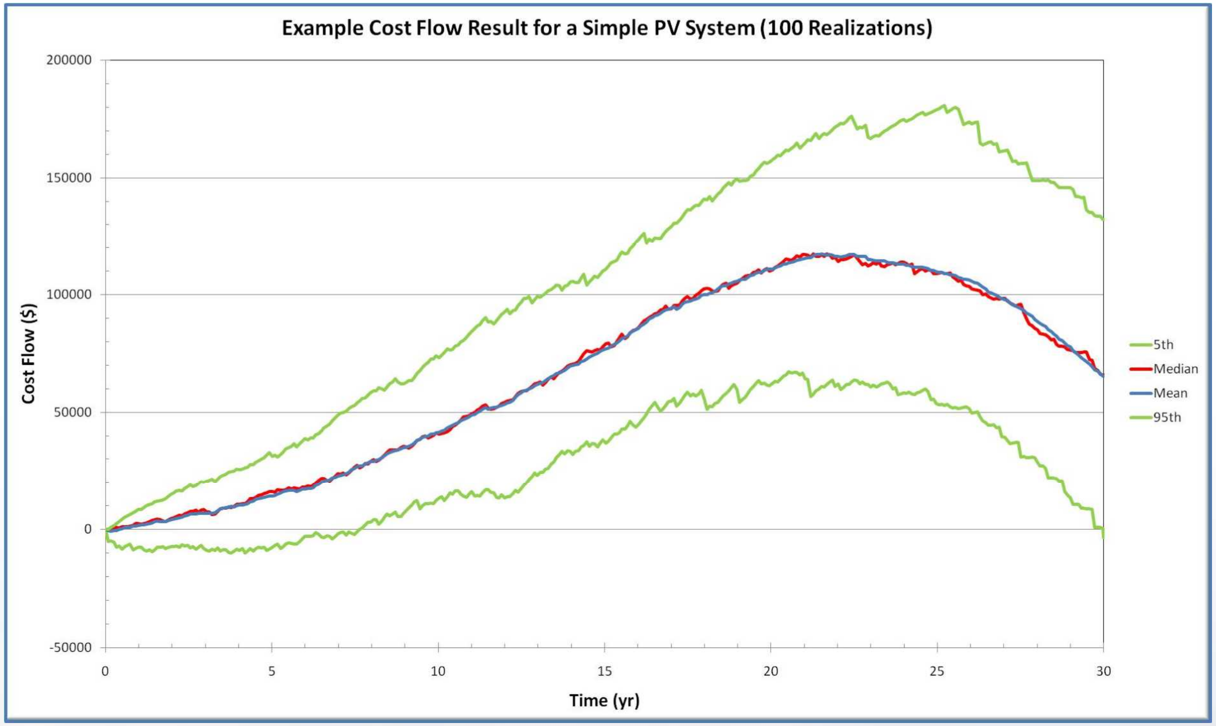
- **Identical, pre-characterized PV systems installed in**
  - New Mexico – hot and dry
  - Florida – hot and humid
  - Vermont - cold
- **Long-term study to determine degradation rates of PV technologies, failure modes**
- **Drives improvements to system-level performance, reliability models**
- **Provides datasets for performance model validation**



Three PV Systems under study at UVM: two crystalline silicon and one thin film. Data collection to commence in April, 2011

Integrating Cost, Performance, and Reliability: Predictions Based on Experimental Results

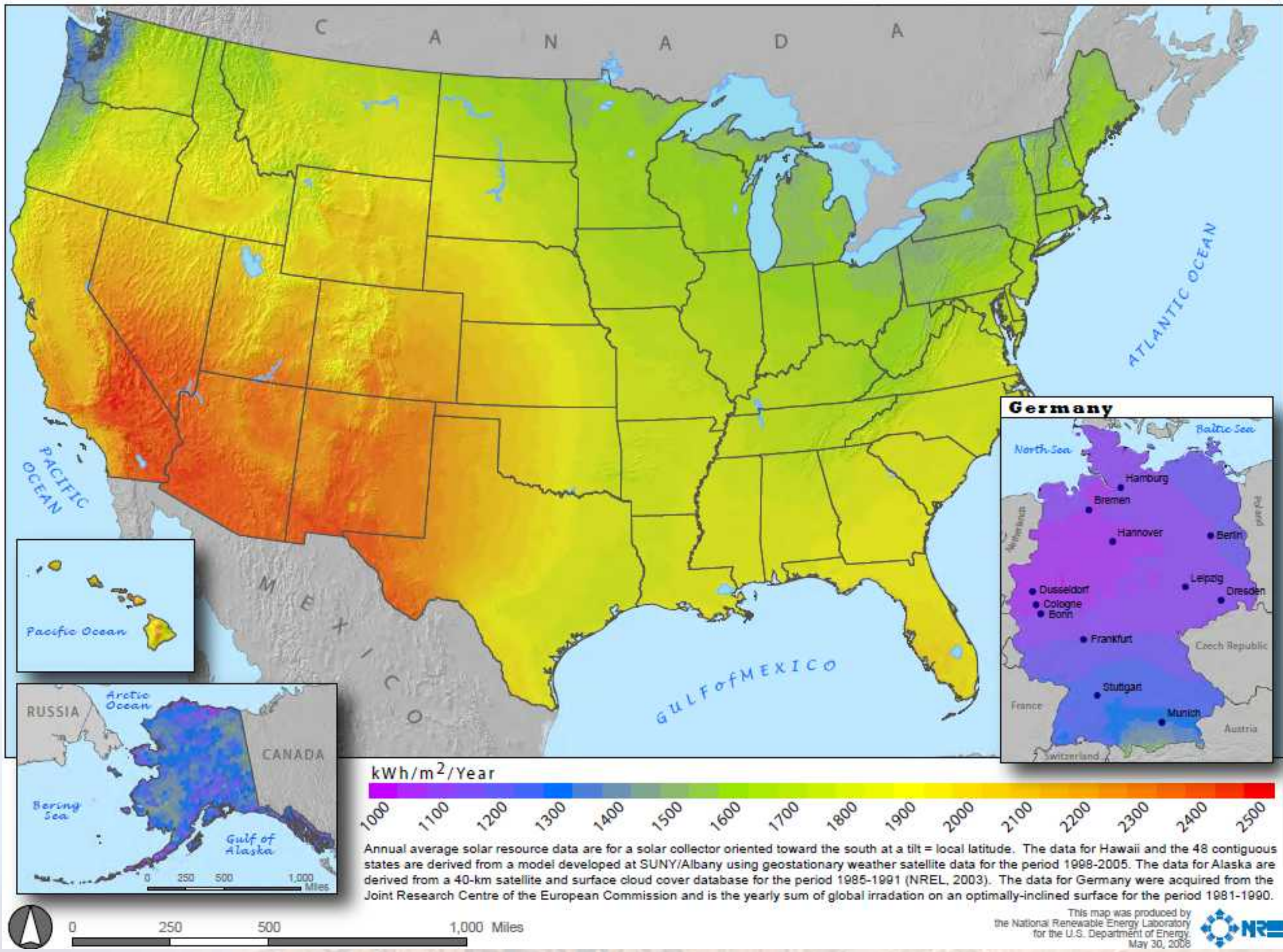




Tool for use in assessing system design tradeoffs and even R&D decisions

Also helps to reduce risk of financiers and developers of larger systems

U.S. Has Great Opportunities for Increased Solar Energy Applications

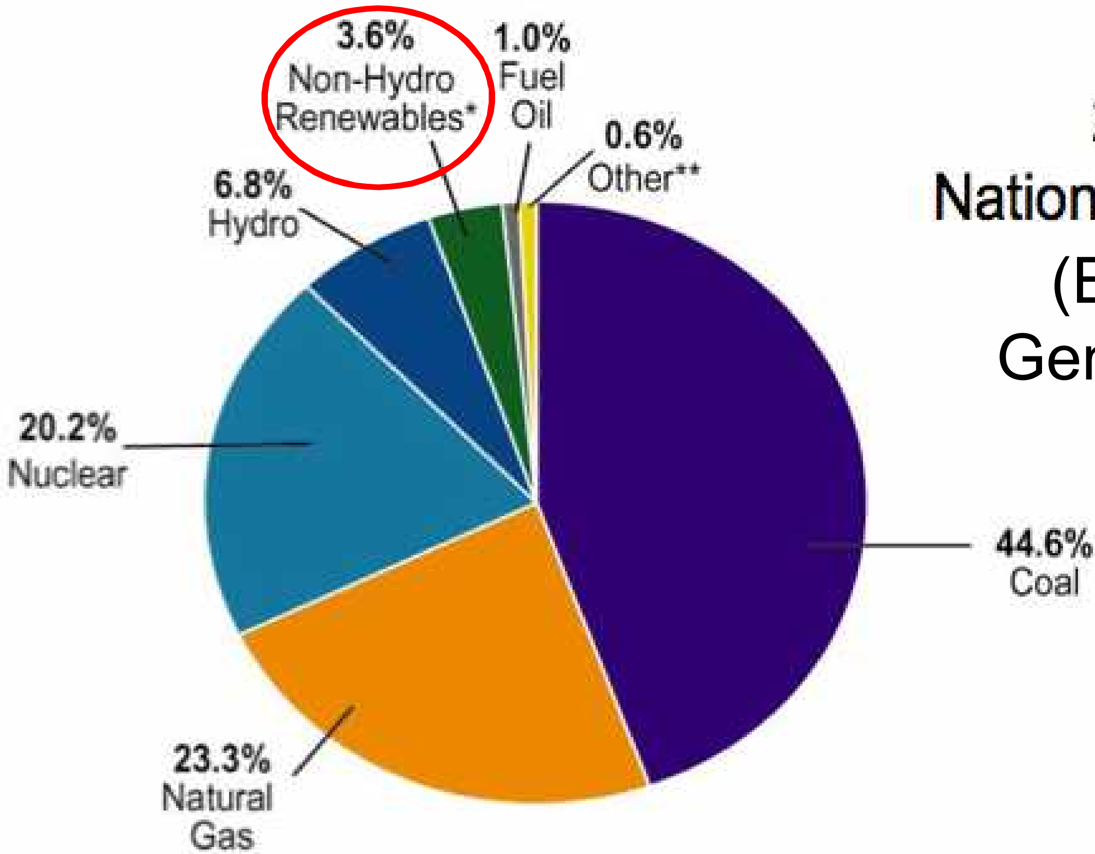


All of the electricity in the U.S. could be provided using:

- **Less than 2% of the land dedicated to cropland and grazing.**
- **Less than the current amount of land used for corn ethanol production.**

2009 PV Installs
Germany: 3.87GW
US: 485MW

However, Solar Utilization is Still Not on the Map



2009
National Fuel Mix
(Electric
Generation)

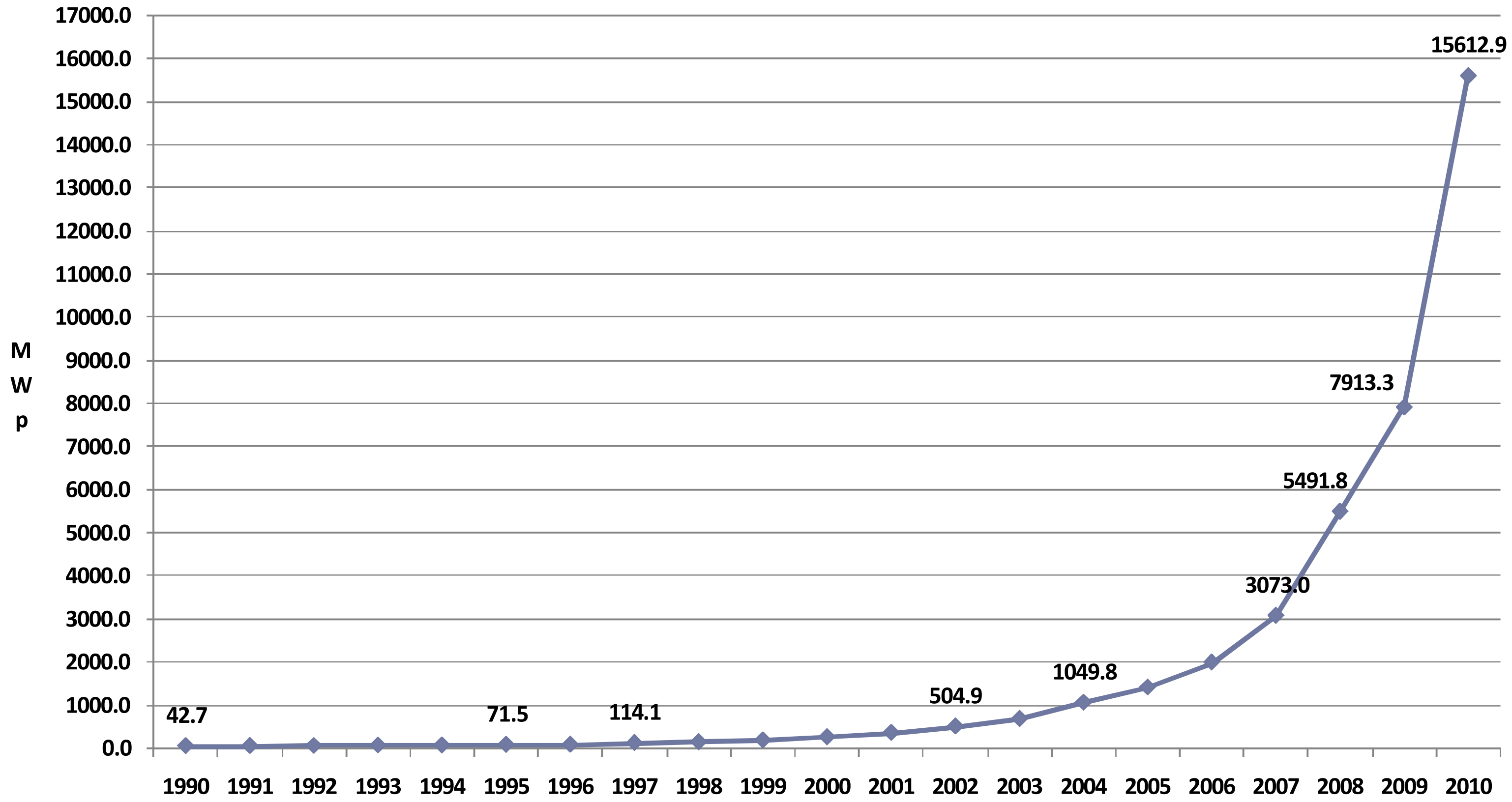
*Includes generation by agricultural waste, landfill gas recovery, municipal solid waste, wood, geothermal, non-wood waste, wind, and solar.

** Includes generation by tires, batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, and miscellaneous technologies.

Sum of components do not add to 100% due to independent rounding.

Source: U.S. Department of Energy, Energy Information Administration, Power Plant Operations Report (EIA-923); 2009 preliminary data.

PV Industry Growth: 1979 to 2009



20 year compound annual growth: 34%, five year CAGR to 2010 estimated at 62%

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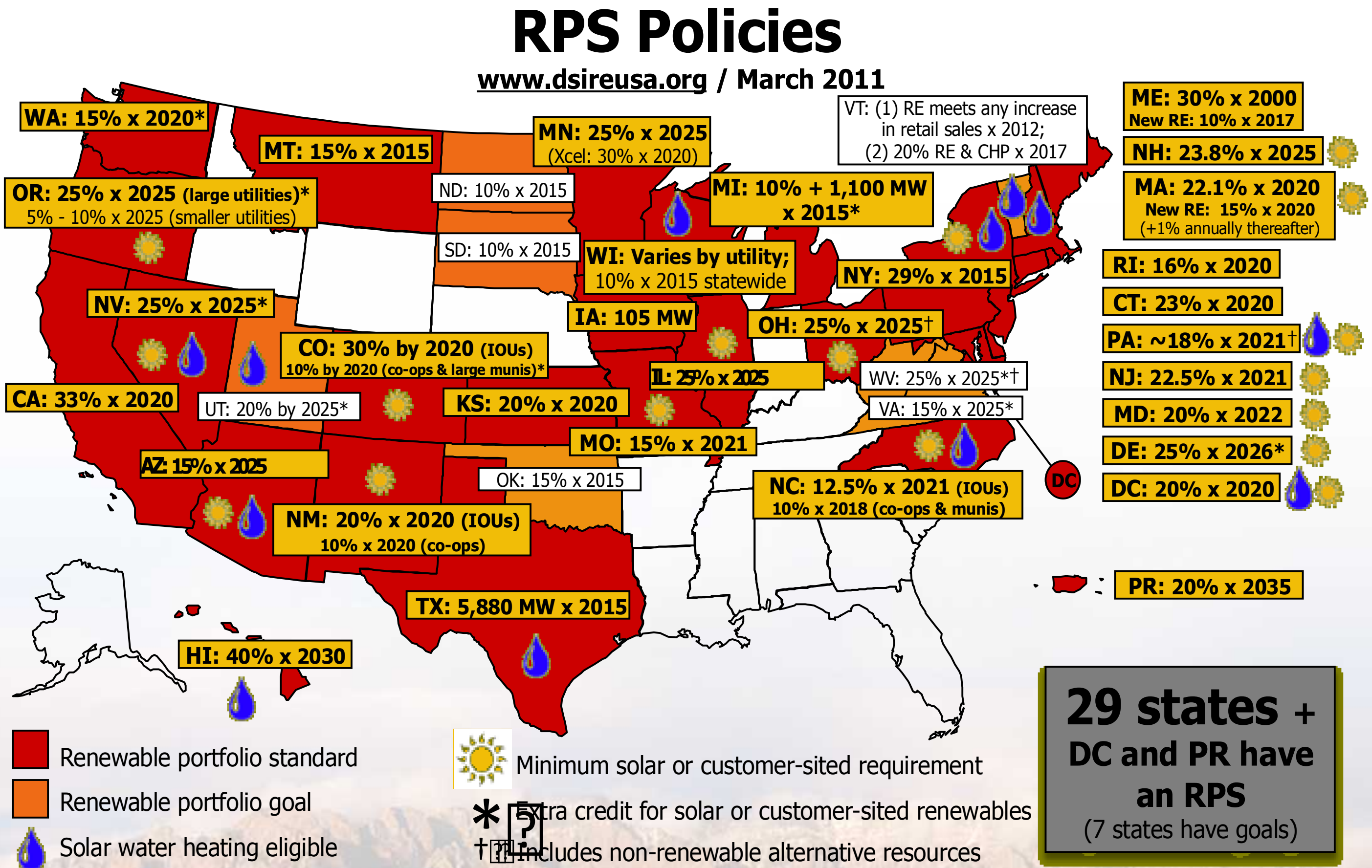
Renewable Portfolio Standards Are Gaining Ground Across the US

New Market Scenario: **Climate change concerns, renewable portfolio standards, incentives, and accelerated cost reduction driving steep growth in U.S. renewable energy system installations.**



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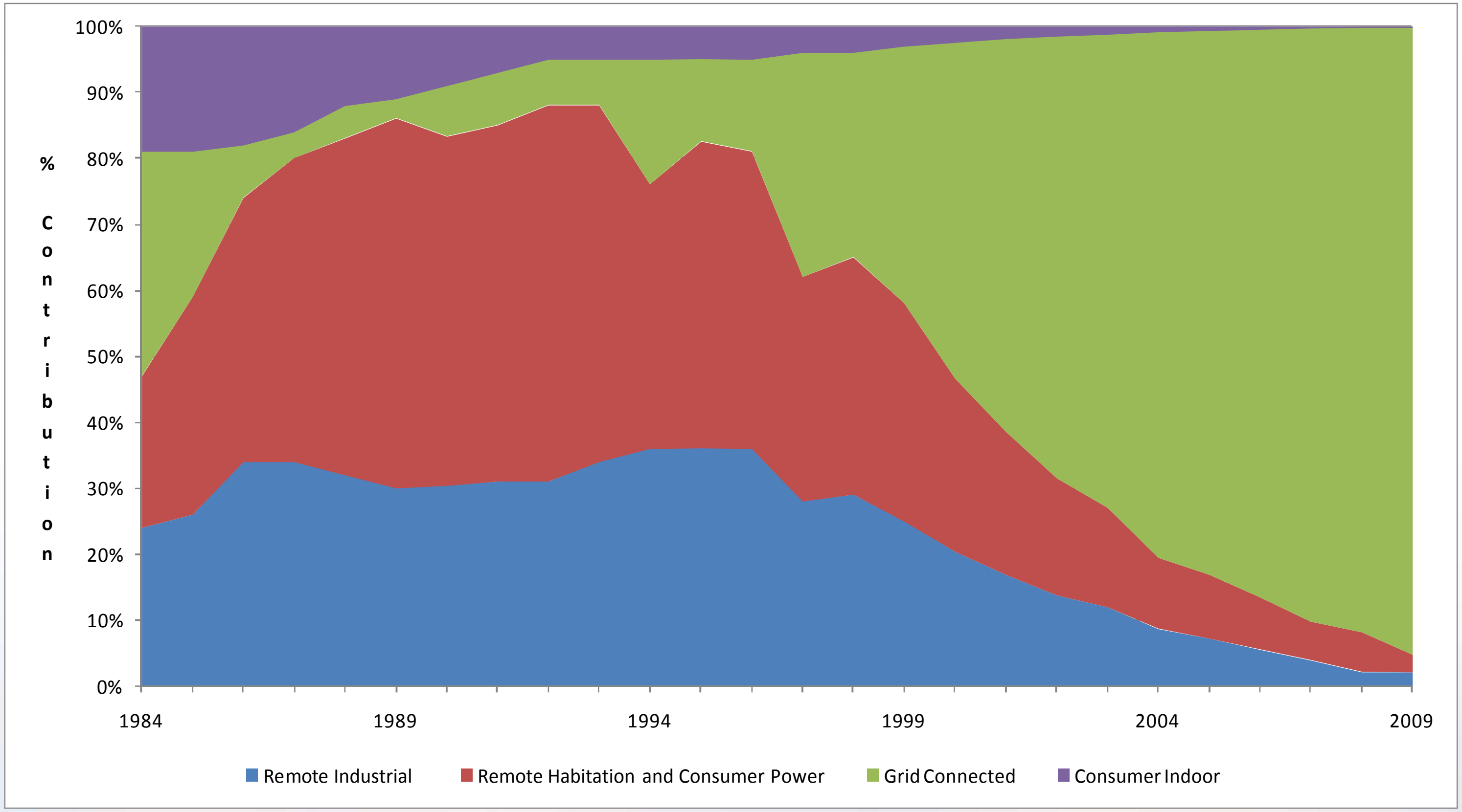
Application Contribution, 1983 to 2009



The field of utility-scale PV applications is VERY new!

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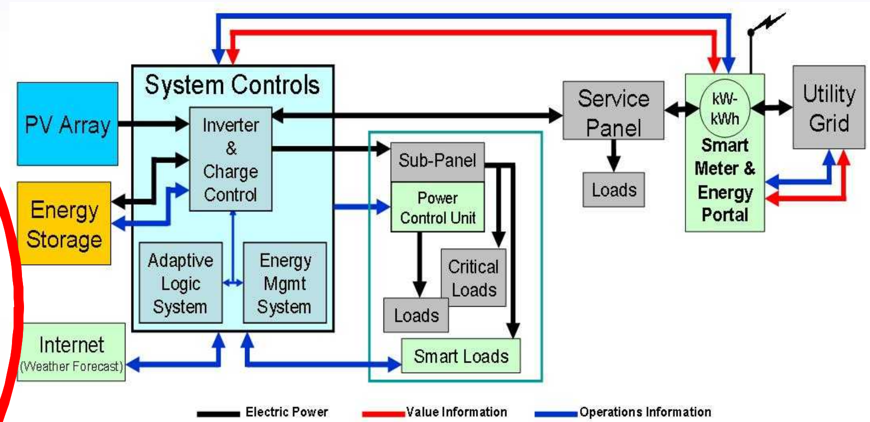
PV Plants are Getting BIG!

Olmedilla Park Solar Power Plant (60 MW)

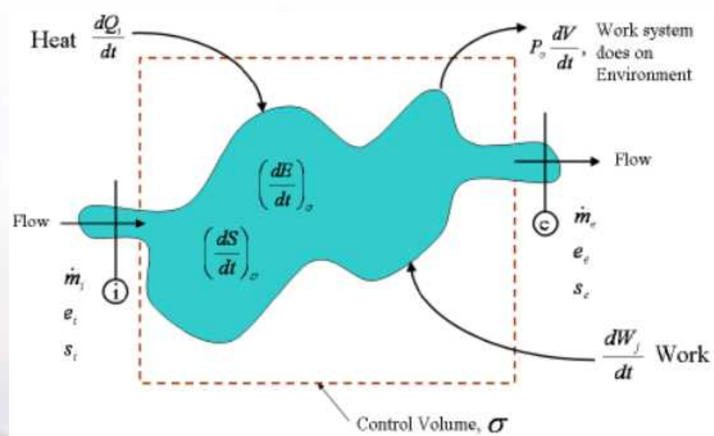
Waldpolenz Solar Park (40 MW)

Variability of High Penetration on the Electric Grid

Step 1: Define the problem - Collect data and build predictive models



Step 2: Develop near-term solutions - SEGIS



Step 3: Longer-term R&D – unifying, scalable, nonlinear control theory; advanced communications engineering

Step 4: Close the loop – implement new technologies in the lab and field

Renewable System Interconnection (RSI) Study
(focus on distributed PV technology)

- DOE completed 14 reports in 2008 available at:
  - http://www1.eere.energy.gov/solar/solar_america/rsi.html

- **RSI Reports**
  - **Advanced Grid Planning and Operations**
  - **Utility Models, Analysis and Simulation Tools**
  - **Advanced PV System Designs and Technology Requirements**
  - **Development of Analysis Methodology for Evaluating the Impact of High Penetration PV**
  - **Distribution System Performance Analysis for High Penetration PV**
  - **Enhanced Reliability of PV Systems with Energy Storage and Controls**
  - **Transmission System Performance Analysis for High Penetration PV**
  - **Renewable System Interconnection Security Analysis**
  - **Solar Resource Assessment: Characterization and Forecasting to Support High PV Penetration**
  - **Test and Demonstration Program Definition to Support High PV Penetration**
  - **Value Analysis**
  - **PV Business Models**
  - **Production Cost Modeling for High Levels of PV Penetration**
  - **PV Market Penetration Scenarios**

Studying System Impacts of Variability

- **Increases in variable generation can affect operations over all time frames**
  - Regulation
  - Unit Commitment and Economic Dispatch
  - Resource Adequacy
  - Add to costs of grid operations
- **Need for validated predictions of PV system output**
  - Across various sizes
  - Across geographies
  - Using little ground-sensor data
- **Inputs for impact studies to determine least cost, least impact options**

"Easy" Week

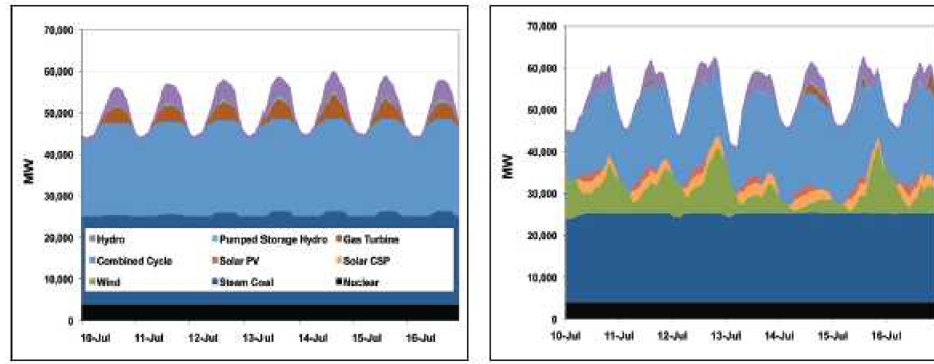


Figure 3 – 35% renewables have a minor impact on other generators during an easy week in July, 2006. WestConnect dispatch - no renewables (left) and 30% case (right)

"Hard" Week

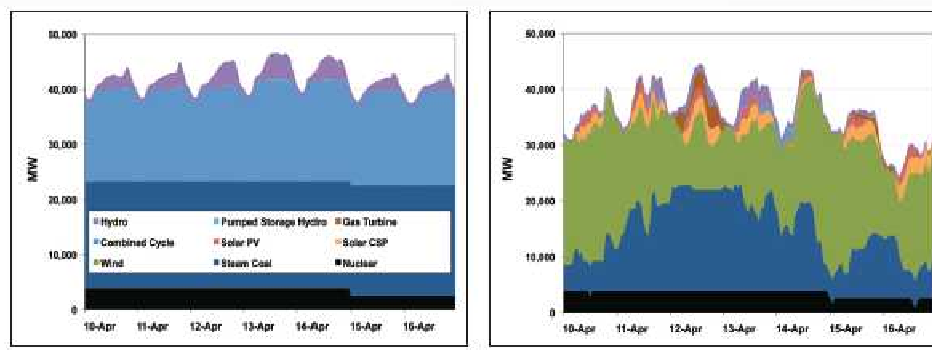
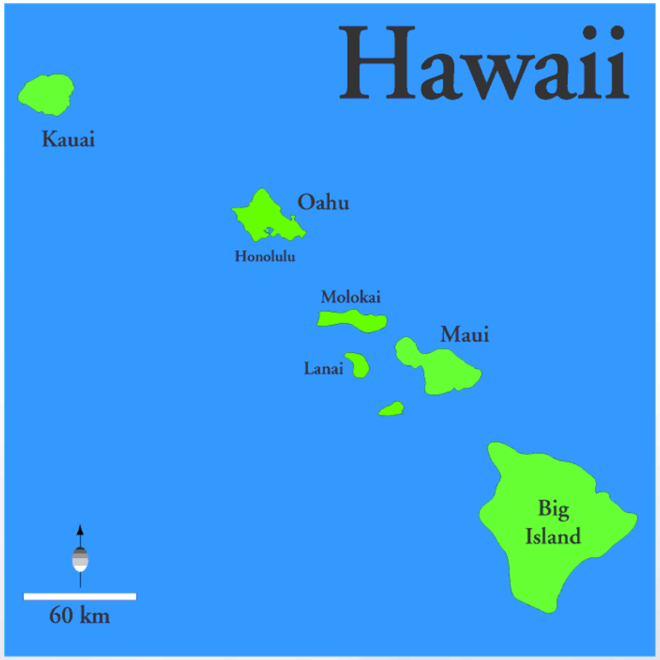


Figure 4 – 35% renewables have a significant impact on other generation during the hardest week of the three years (mid-April 2006). WestConnect dispatch - no renewables (left) and 30% case (right)

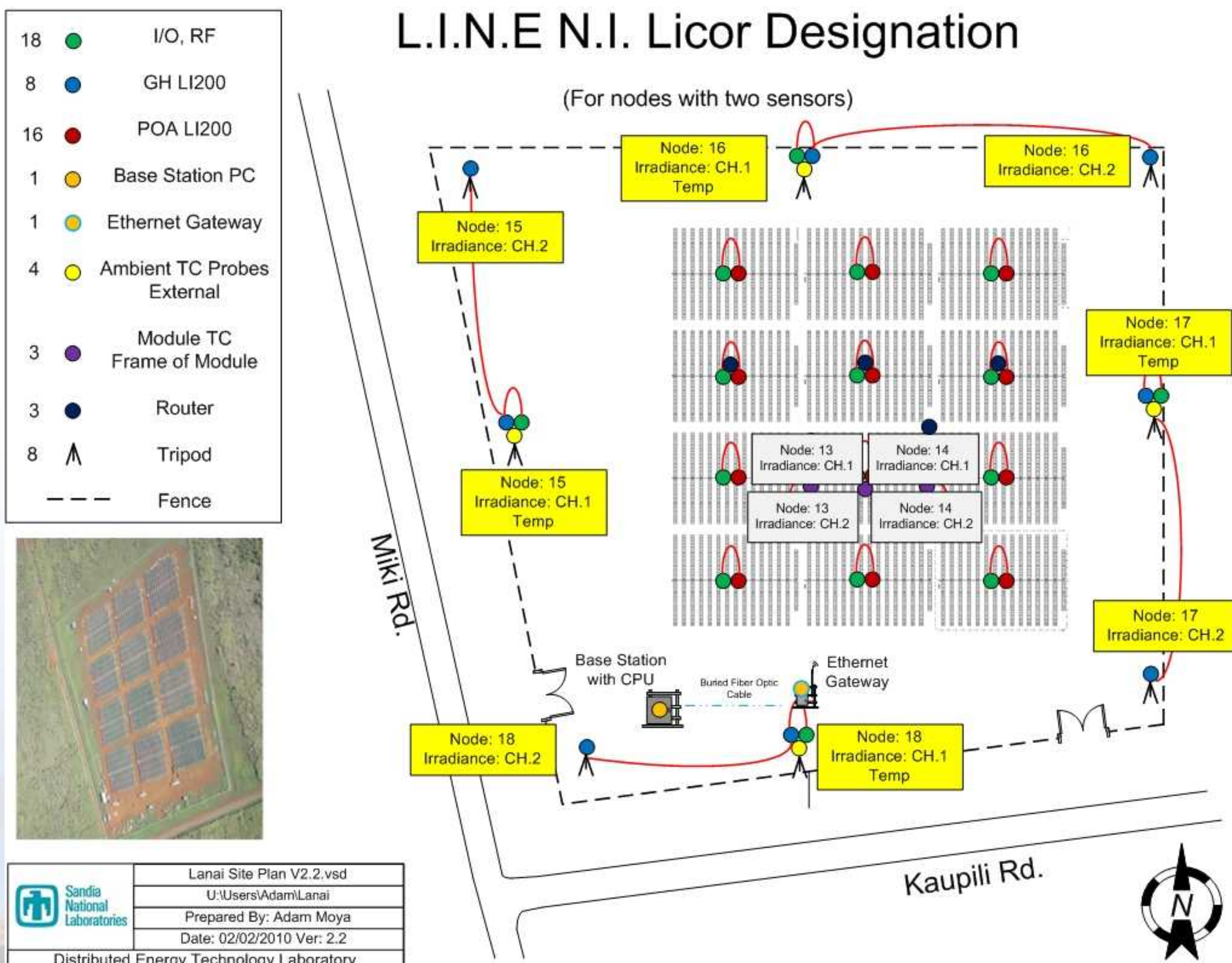
Figures from Western Wind and Solar Integration Study, 2010

Getting a Handle on Variability: The Lanai, Hawaii, Experiment

- **The Lanai electric grid has one of the highest penetration rates of PV generation in the world.**
  - Lanai peak load = 4.7 MW_{AC}
  - La Ola Solar Farm generation capacity = 1.2 MW_{AC}
- **Interconnection requirements currently limit PV output to 600 kW in order to prevent high ramp rates from cloud transients.**
- **Many clouds – good place to look at impacts of variability**



Lanai Sensor Site Layout

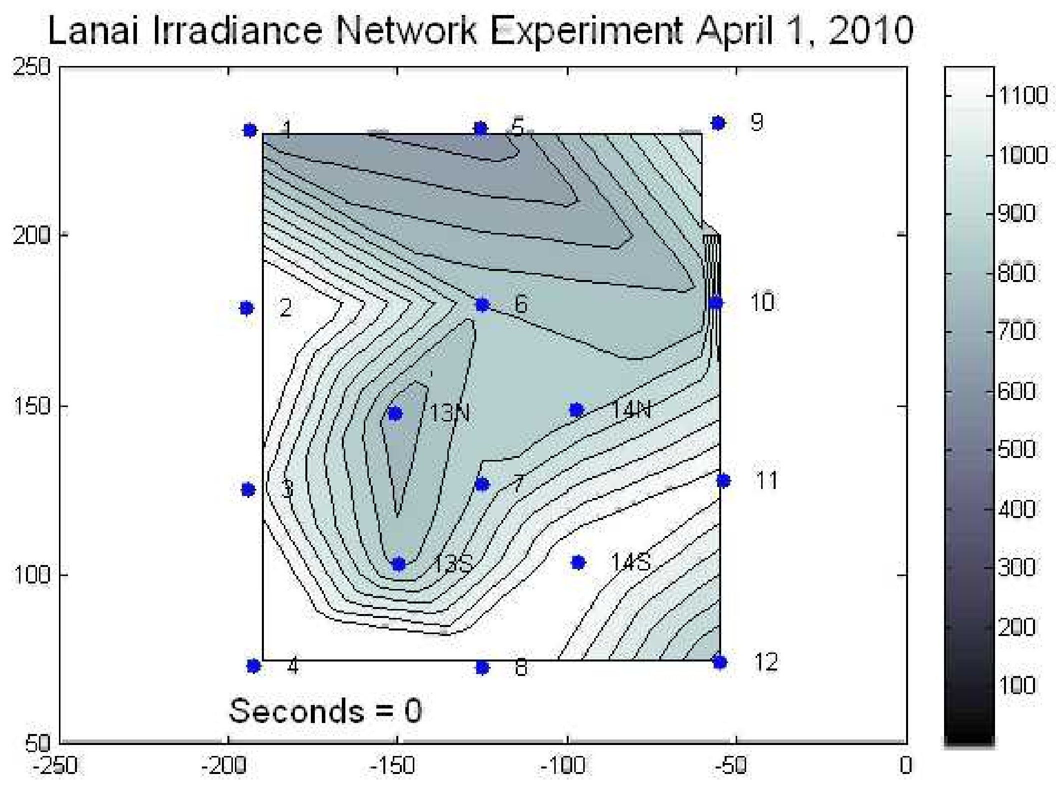


System Includes:

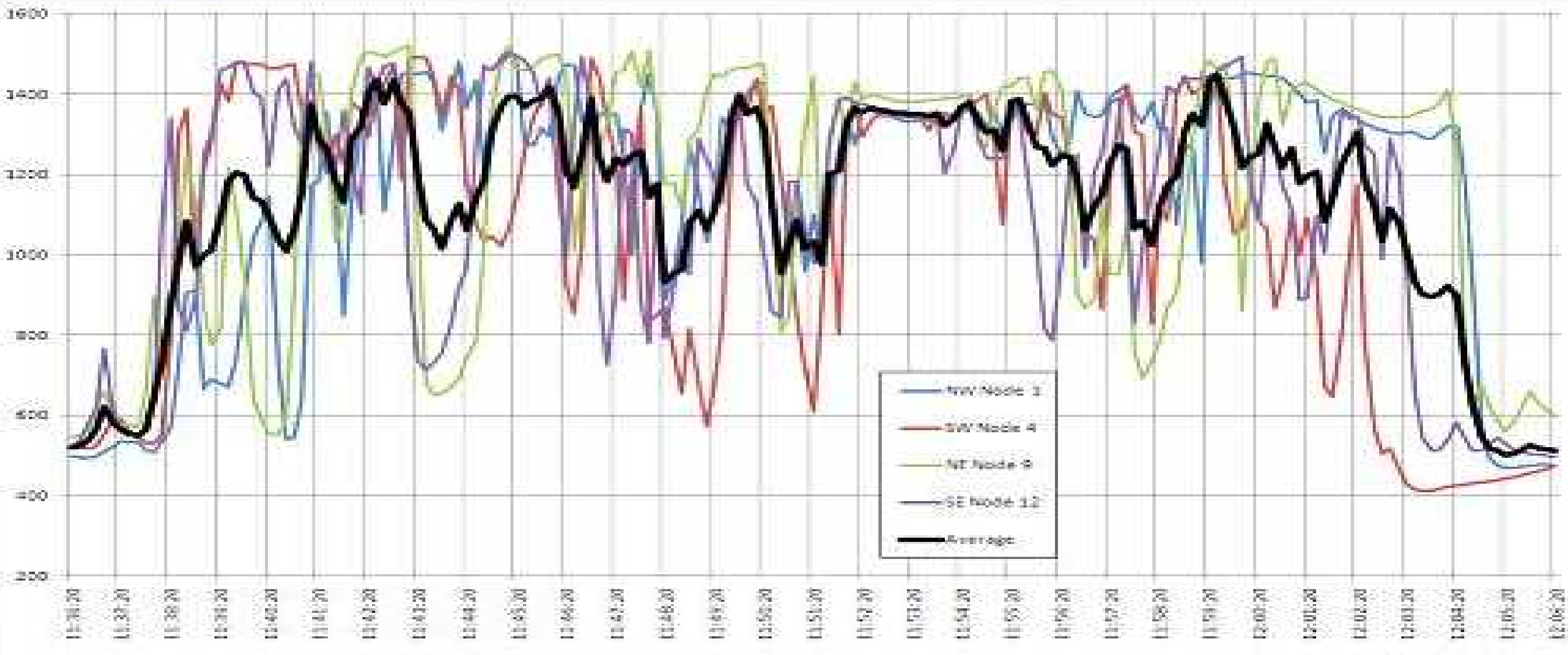
- 16 POA Irradiance
- 8 GH Irradiance
- 3 Module Temp.
- 5 Ambient Temp.

Array power output data is added to the data stream

Sensor Network Shows Wide Variation in Irradiance Across Lanai Array



Lanai: Average Irradiance Exhibits Less Variability Than Individual Sensors



- **Plot represents 30 minutes of variability**
- **Note 1500 W/m2 amplitudes**

Does this average irradiance approximate system output?

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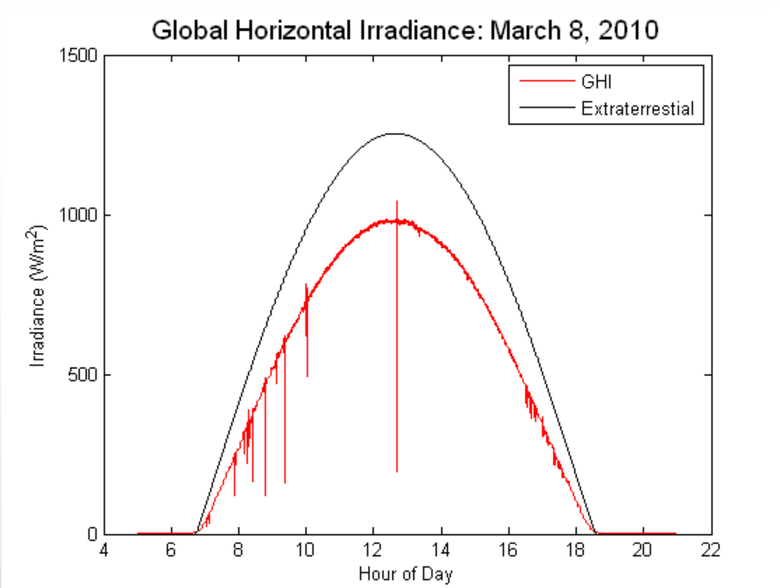
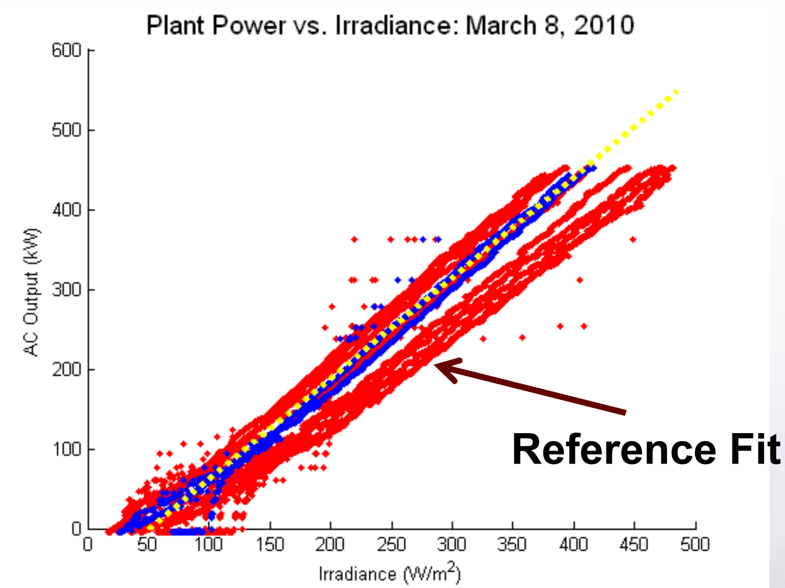
Plant Power vs. Irradiance: Clear Day

- **Uncurtailed power is nearly linear with spatially averaged irradiance on clear day.**
- **Examine data from uncurtailed periods**
  - Each of the 12 inverters are curtailed separately at 50 kW.



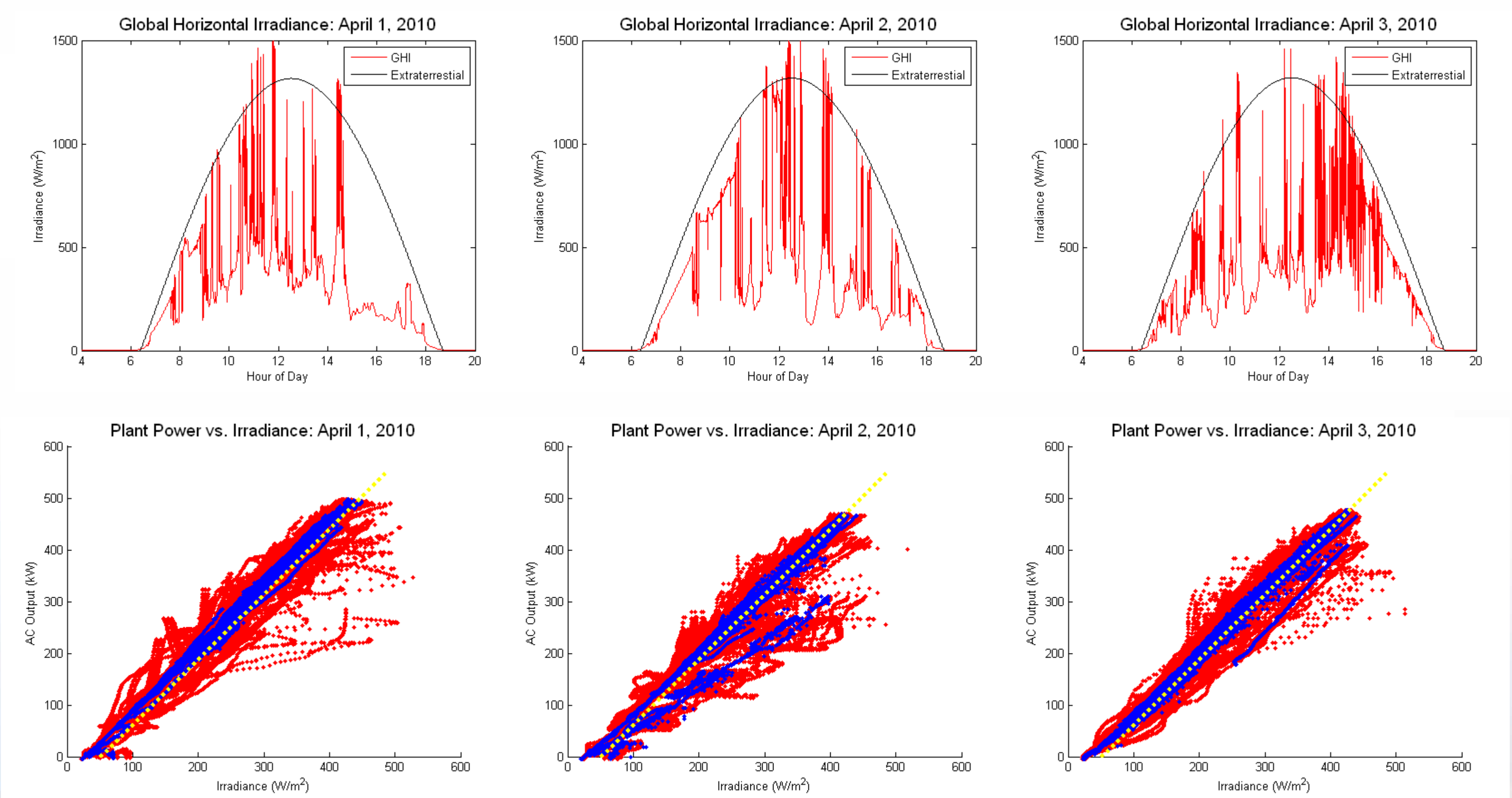


Kuszmaul, S., A. Ellis, et al. (2010). Lanai High-Density Irradiance Sensor Network for Characterizing Solar Resource Variability of MW-Scale PV System. 35th IEEE PVSC, Honolulu, HI.

Red = Single Irradiance Sensors (5)

Blue = Network Average Irradiance

Plant Power vs. Irradiance: Variable Day

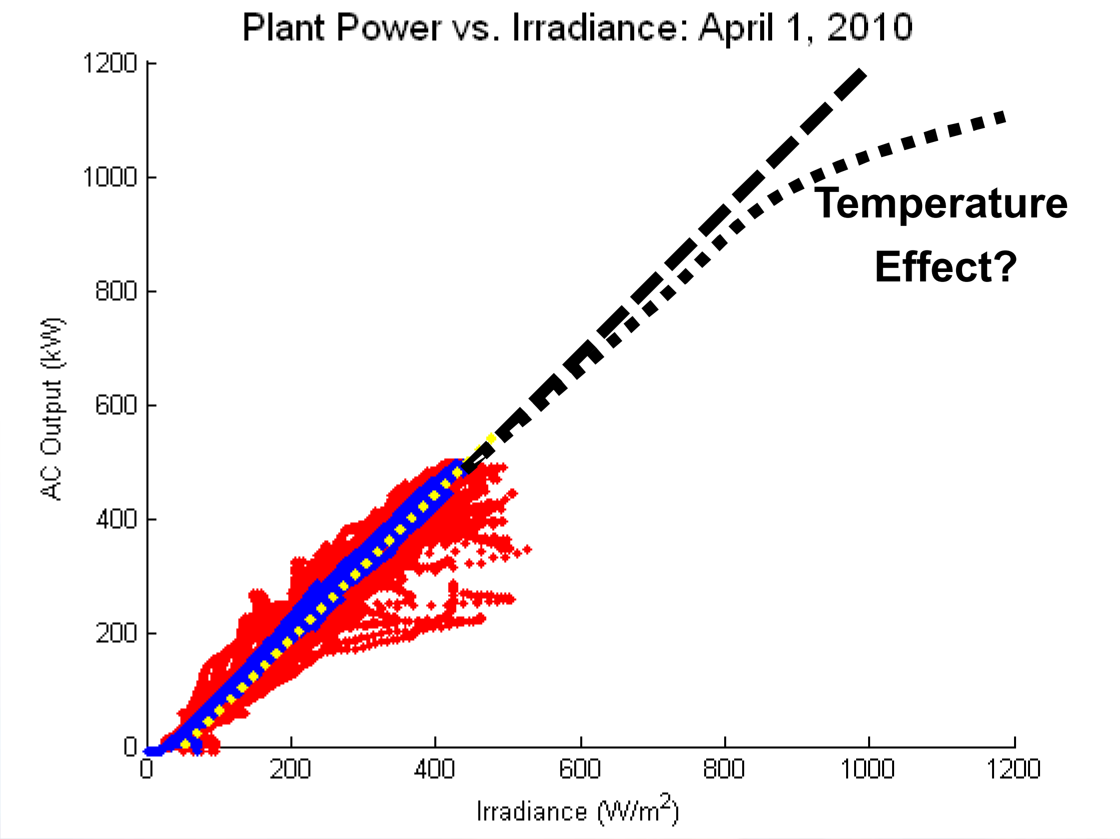


Red = Single Irradiance Sensor

Blue = Network Average Irradiance

Hansen et al, 2010

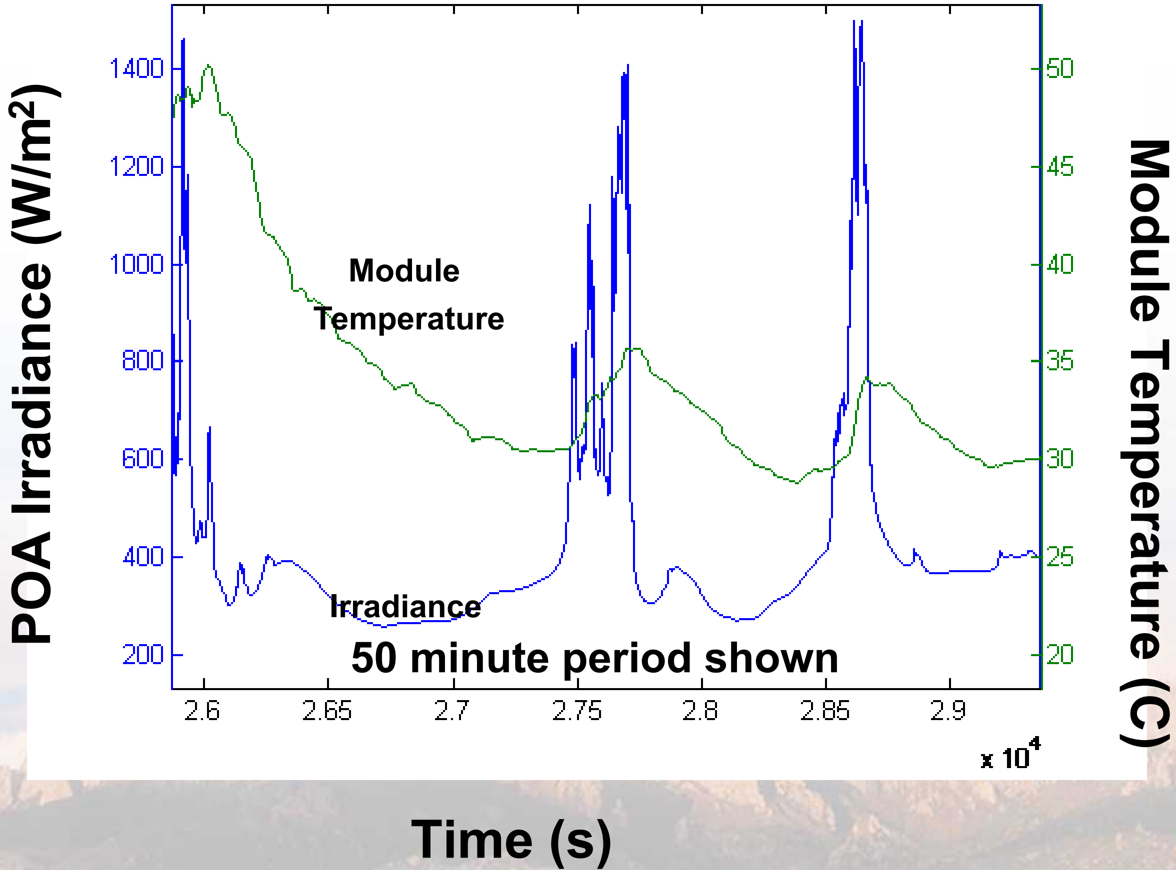
Plant Power vs. Irradiance: Prediction



- **Spatial average irradiance is a good predictor of plant power output.**
- **At higher irradiance the apparent linear trend may deviate due to rising cell temperatures**

Module Thermal Response

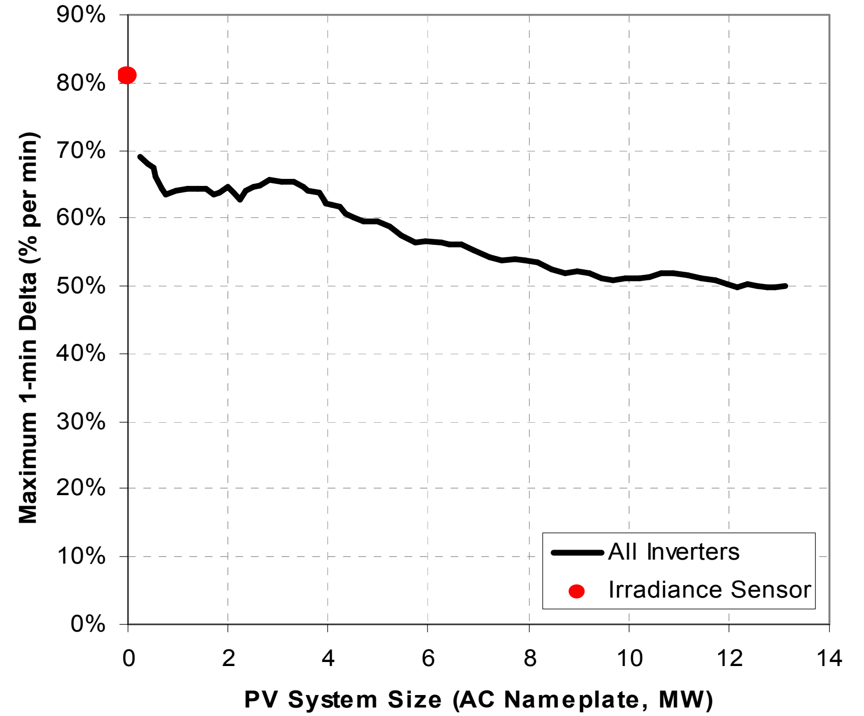
- Irradiance changes much faster than module temperature.
  - Steady-state model (e.g. King et al., 2004) will not work.
  - Transient thermal modeling approaches will be applied.



Variable Generation: Larger Plants Mean Less Output Variation

- **The effect of geographical diversity is noticeable even within the footprint of large PV and wind plants**

14MW PV Plant at Nellis Air Force Base, Nevada



Figures from Mills et al., 2009

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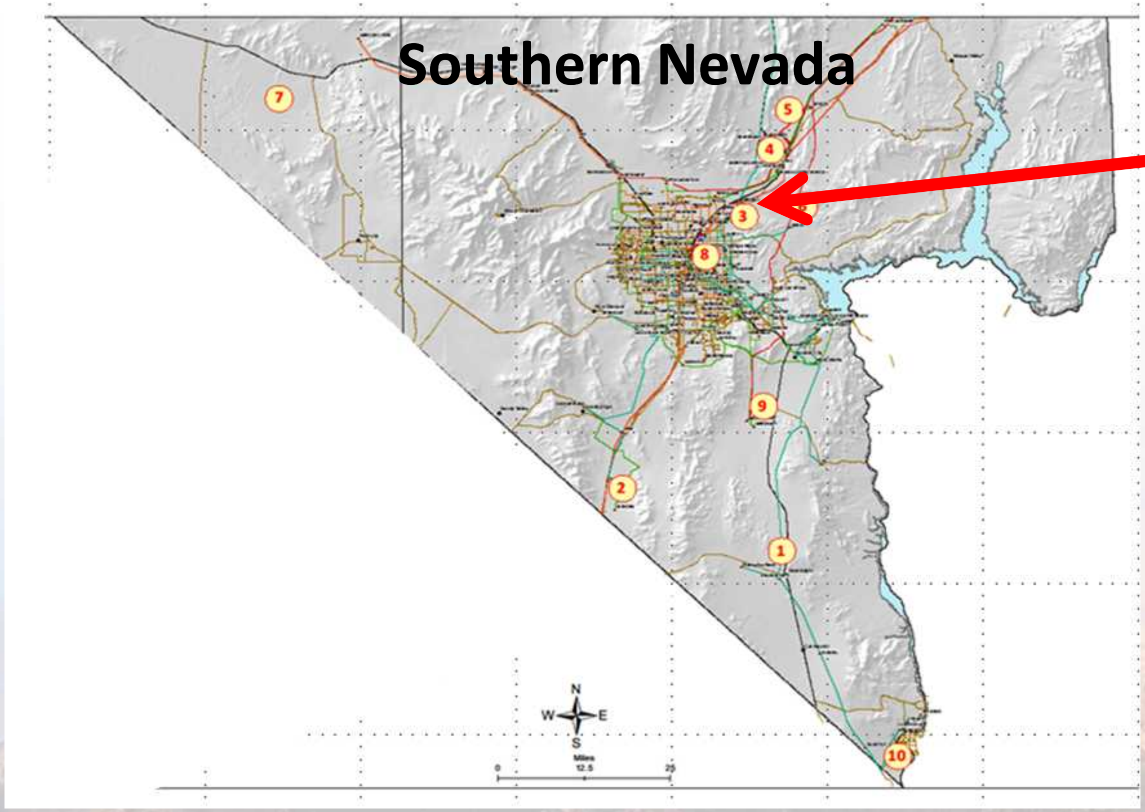
NV Energy Solar Integration Study

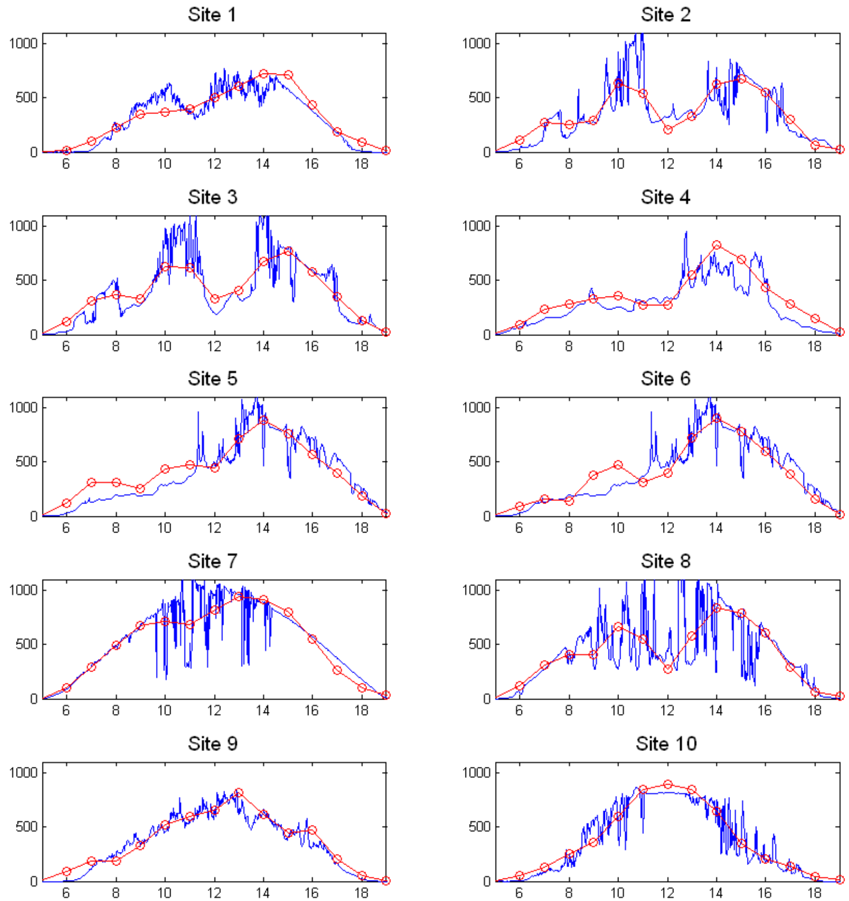
- Sandia has created 1-min PV output profiles for 2007 for 10 sites in southern Nevada for a Solar Grid Integration Study.
- Using integration of ground sensor and satellite data
- Used as inputs to an impact study to determine large-scale effects on transmission grid with Multi-100's of MW installed in territory.



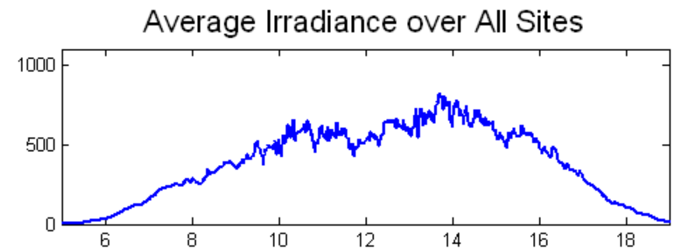
6 ground irradiance sensors in Las Vegas Valley with data from 2006 onward.

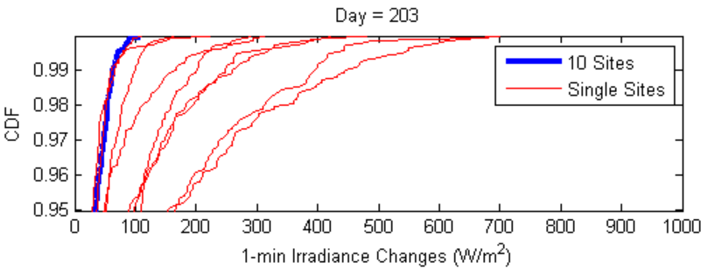
NV Energy Solar Integration Study:
Daily 1-Minute Data for 10 Selected Locations

Day of Year = 203



Model shows potential for ramp rate reduction with geographic diversity across 10 sites.





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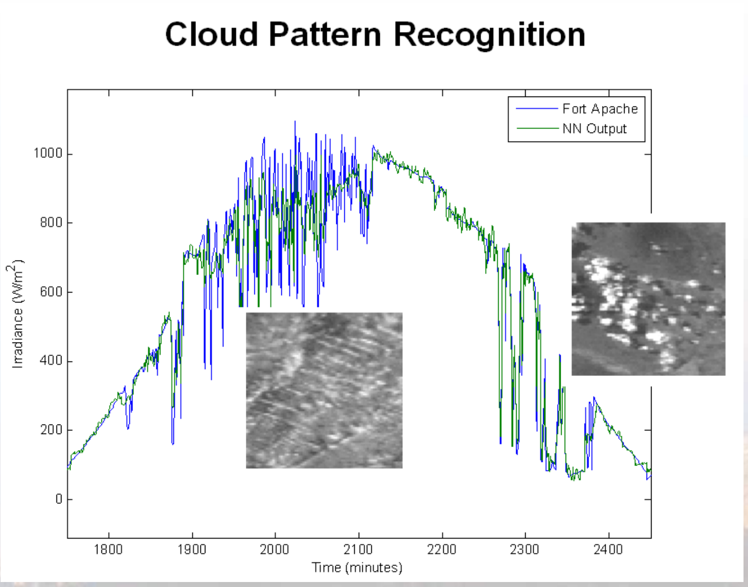
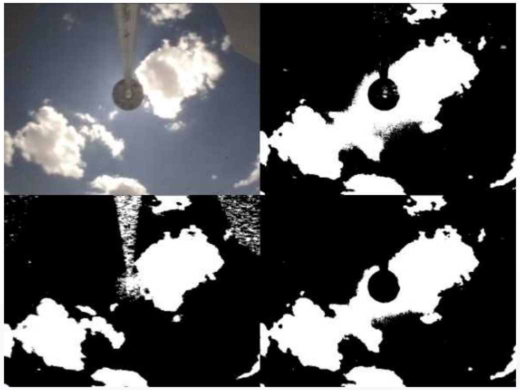
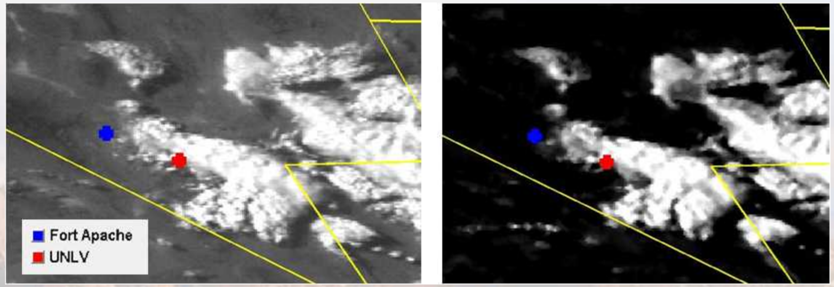
Sandia is Making Novel Use of Satellite Data to Predict System Variability

- **Sandia is developing methods to use sky and satellite imagery to predict and forecast PV output.**
- **Clouds are identified using background subtraction**
- **Variability estimated from images using artificial neural network**
- **Identify applications for forecasts**
  - Energy storage controls
  - System operations and planning





Ground Camera

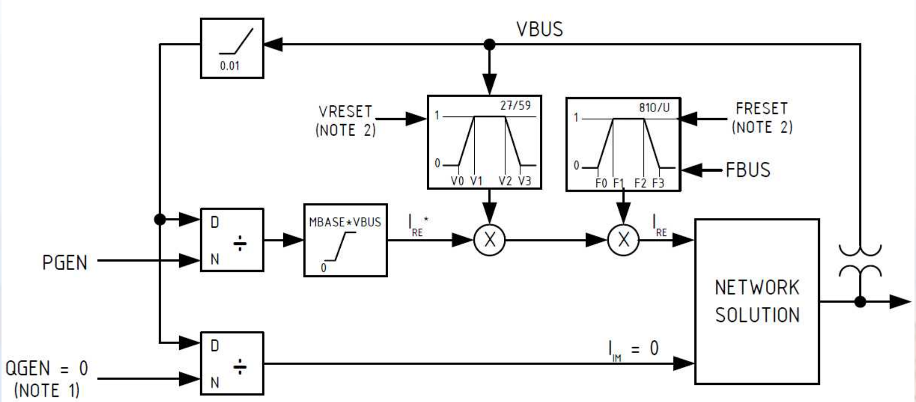


Satellite Imagery

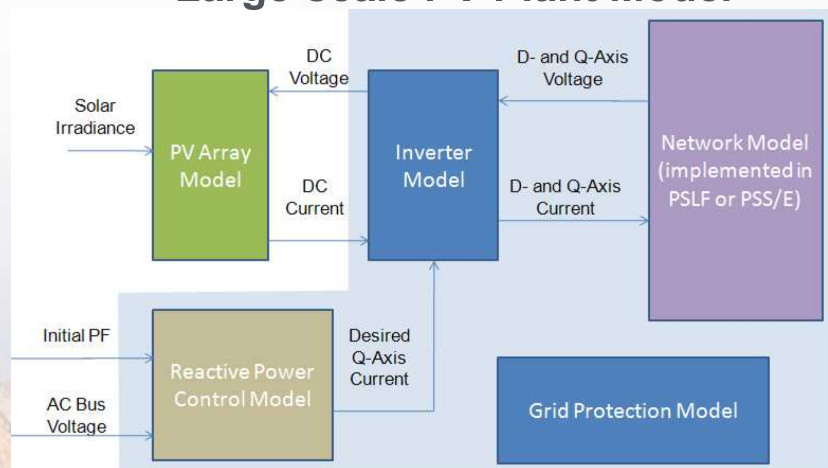
Generator Modeling: Helping Utilities Go Beyond Characterizing PV as “Negative Loads”

- **Sandia chairs WECC Renewable Energy Modeling Task Force, in coordination with NERC, IEEE, international orgs.**
- **Developing power flow and dynamic models and simulation guidelines for planning and interconnection studies**
  - Central-station and distribution-connected plants
  - Focus on PV, CPV and stirling (models exist for conventional CSP)
- **Active/reactive power control, dynamic current limits, inverter protection**
- **Validate and implement models in standard simulation software**

Large-scale PV Plant Model

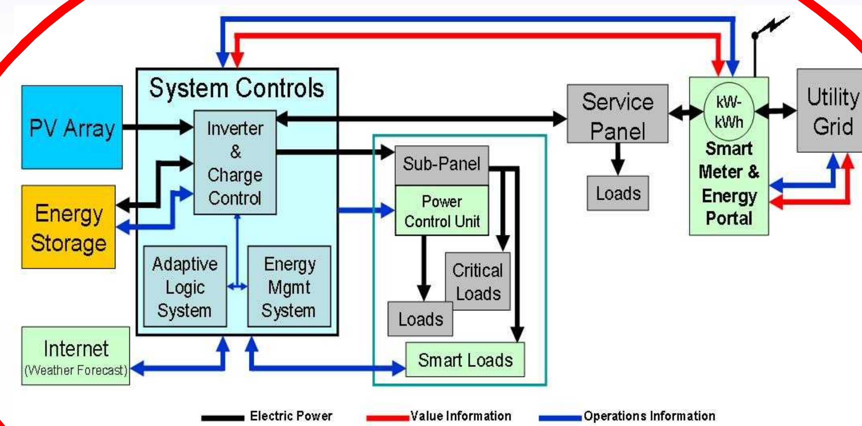


Large-scale PV Plant Model

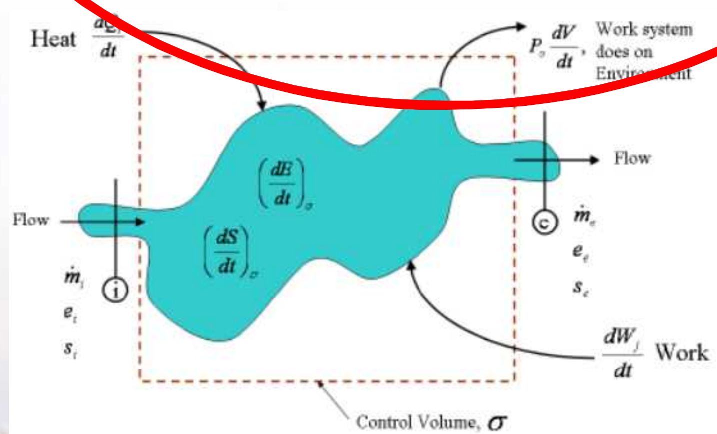


Variability of High Penetration on the Electric Grid

Step 1: Define the problem - Collect data and build predictive models



Step 2: Develop near-term solutions - SEGIS

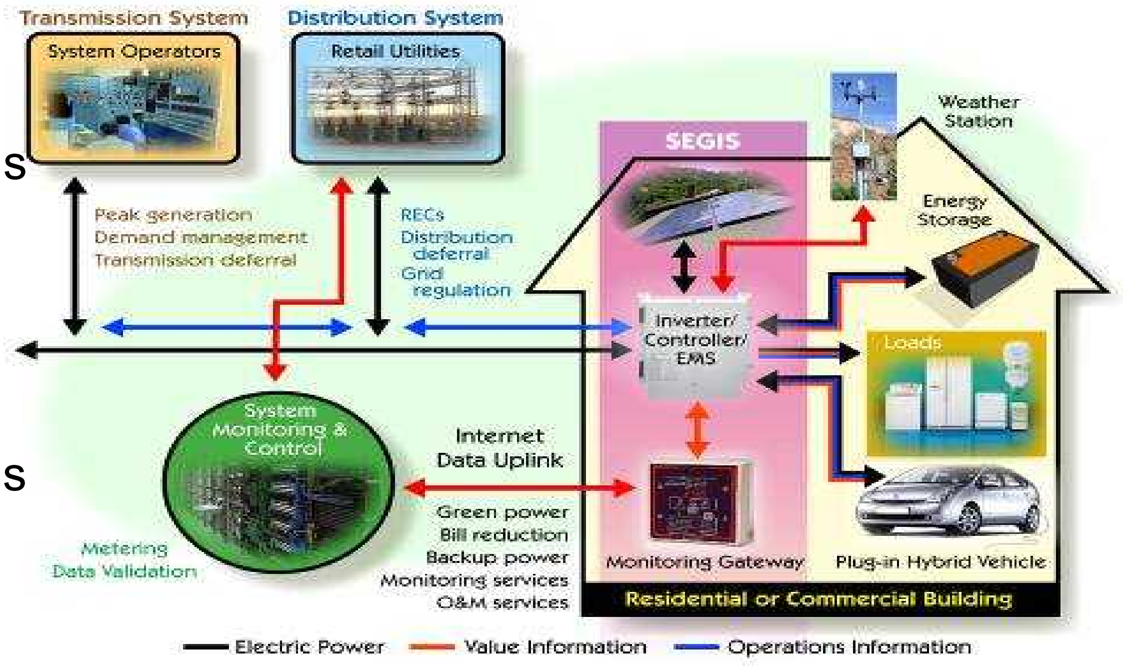


Step 3: Longer-term R&D – unifying, scalable, nonlinear control theory; advanced communications engineering

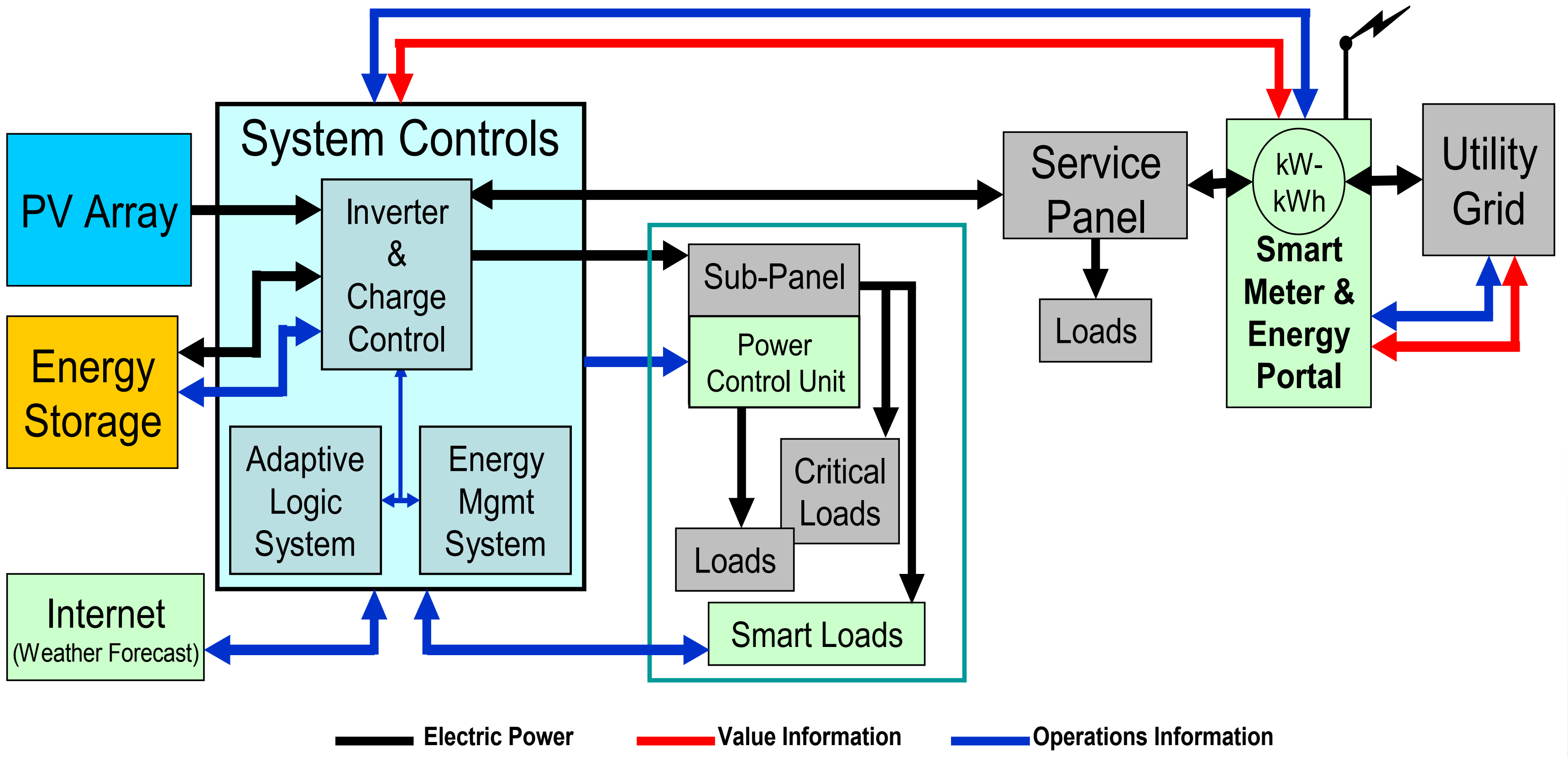
Step 4: Close the loop – implement new technologies in the lab and field

Solar Energy Grid Integration Systems (SEGIS): Linking High-Penetration PV and the Smart Grid

- Advanced inverter, controller, and balance-of-plant development
- System energy management, storage control, communications
- Power quality and reliability through VAr support, time-of-use control, etc
- Four US manufacturers with new product demonstrations this year
- Products range from module-scale to MW-scale applications



Intelligent Utility Interconnects Are Beginning



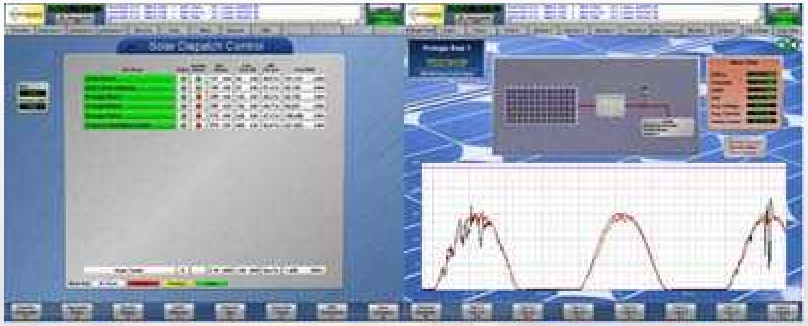
Important SEGIS Advances

- Systems Integrations
- Smart String Combiners
- VAR Support
- Maximum Power Point Tracking
- Low Voltage Ride-thru Functions
- Performance Predictions
- Intermittency Mitigation
- Component Utilization
  - Nano-crystal magnetics, Film Capacitors, Integrated Circuits,
- Communications Integration
  - Synchrophasors, Mesh Network, PLC, Wireless,

Impacts and Public Aspects of SEGIS

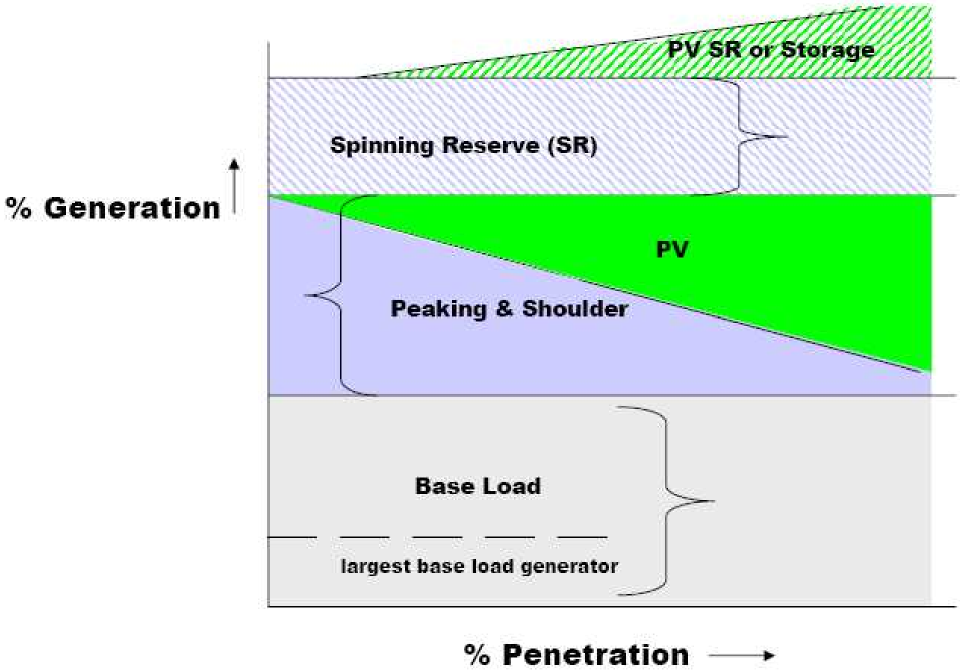
- New System Architectures Increase Types/Numbers of PV Applications
- Utility Dispatch Makes PV Look Like a Generator, NOT a Negative Load
- Utility Needs are Being Addressed
- Communications Add Value for Owner Economics and Utility Grid Stability
- Developments are Validating the Sanity of New Interconnect Standards
- System Integrations Improve Reliability and Functionality

Smart String Combiners



Dispatch and Monitoring

Storage for PV:
The Technology Solution to Intermittency



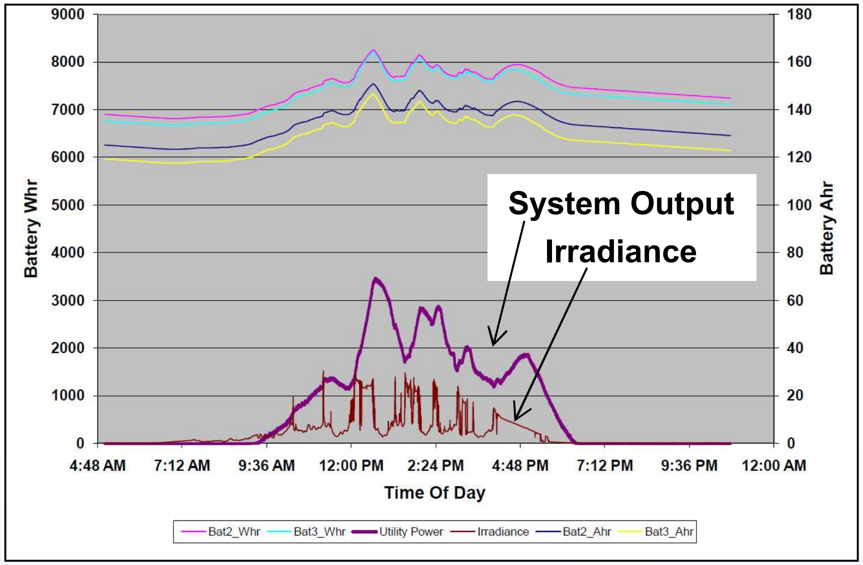
The need for additional spinning reserve or storage to back up intermittent PV generation at increasing levels of penetration.

Hanley et al, May 2008

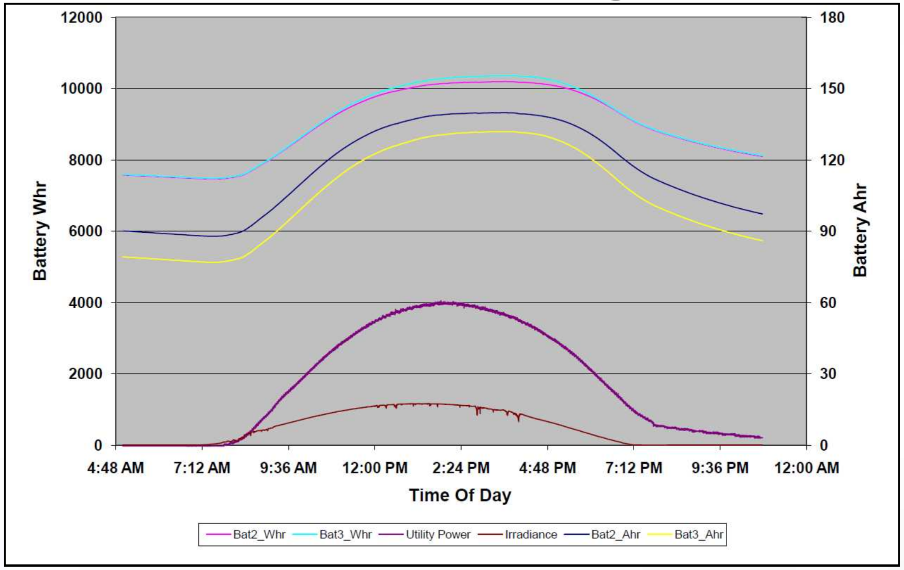
- Range of Technologies
  - Batteries
  - Capacitors
  - Flywheels
  - Compressed air
- Batteries most prevalent and near-term promising
- Increases complexity of system:
  - Initial cost
  - Operation and maintenance
- Current limitations:
  - Added cost
  - Physical capacity and cycle life

Storage Algorithms Under Development to Enhance Value of Interconnected PV Systems

Power Smoothing



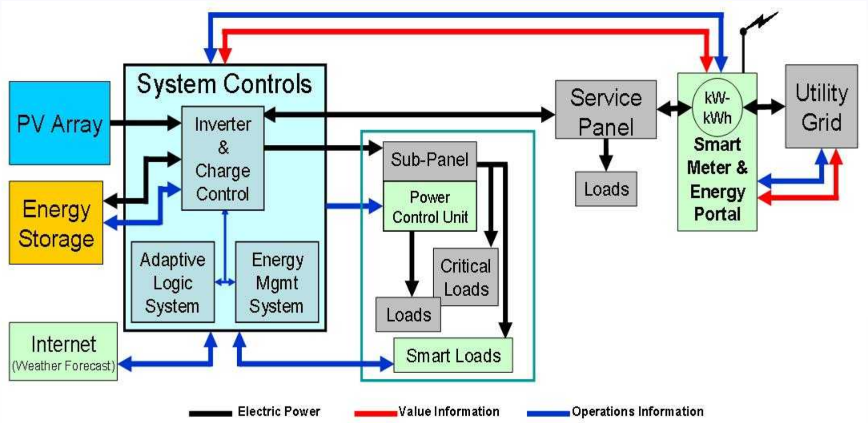
Peak Shifting



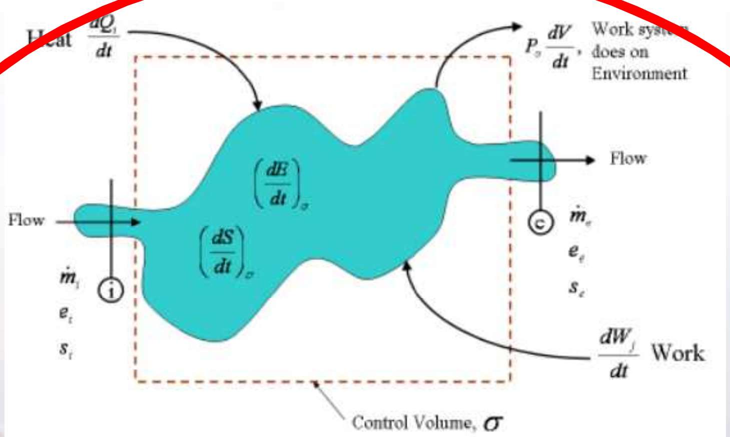
- Magnitude of effect depends on physical parameters of system, such as PV and storage capacities
- Applications will be driven by economic decisions: trade-off between cost of system and value of power/energy

Variability of High Penetration on the Electric Grid

Step 1: Define the problem - Collect data and build predictive models



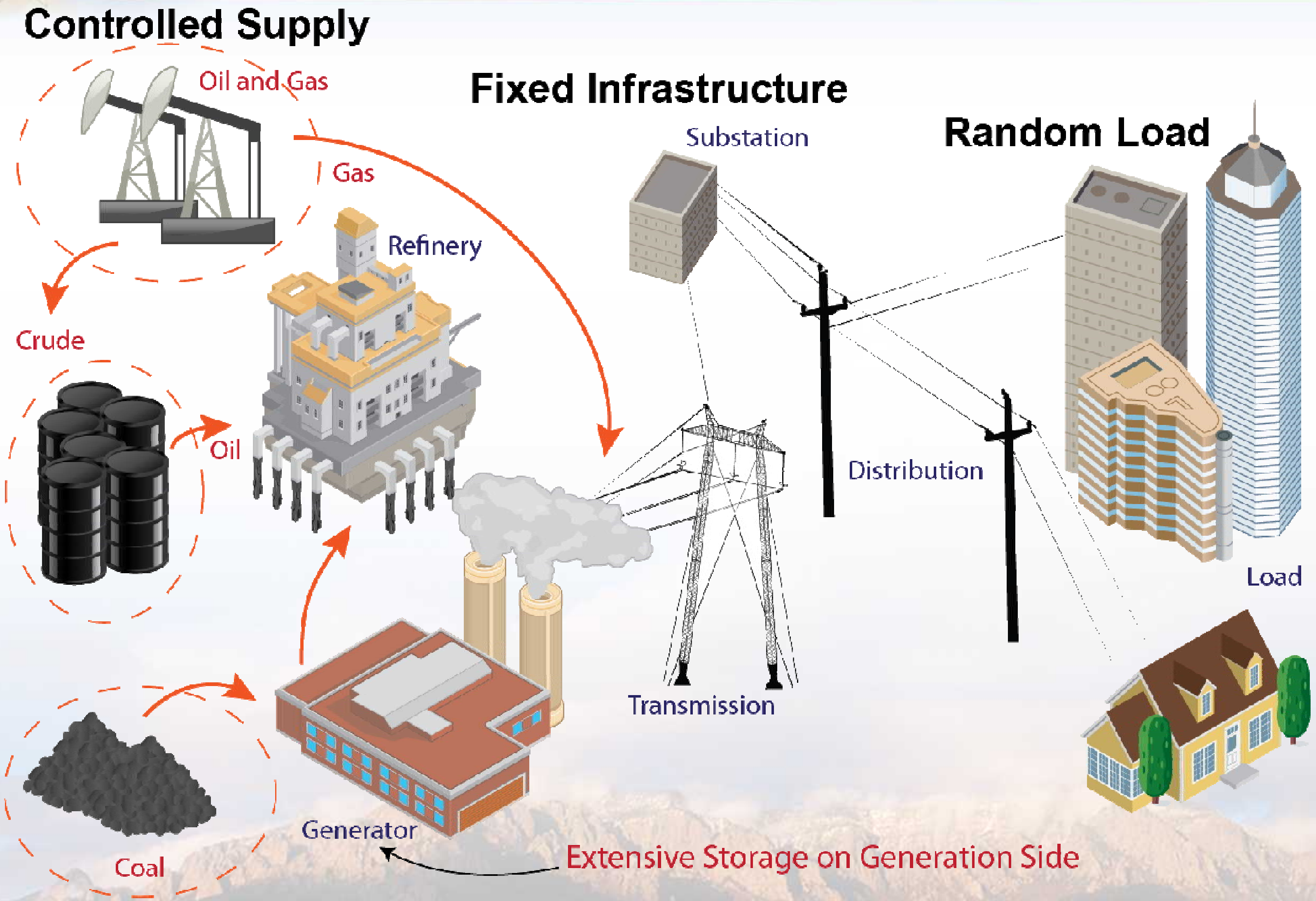
Step 2: Develop near-term solutions - SEGIS



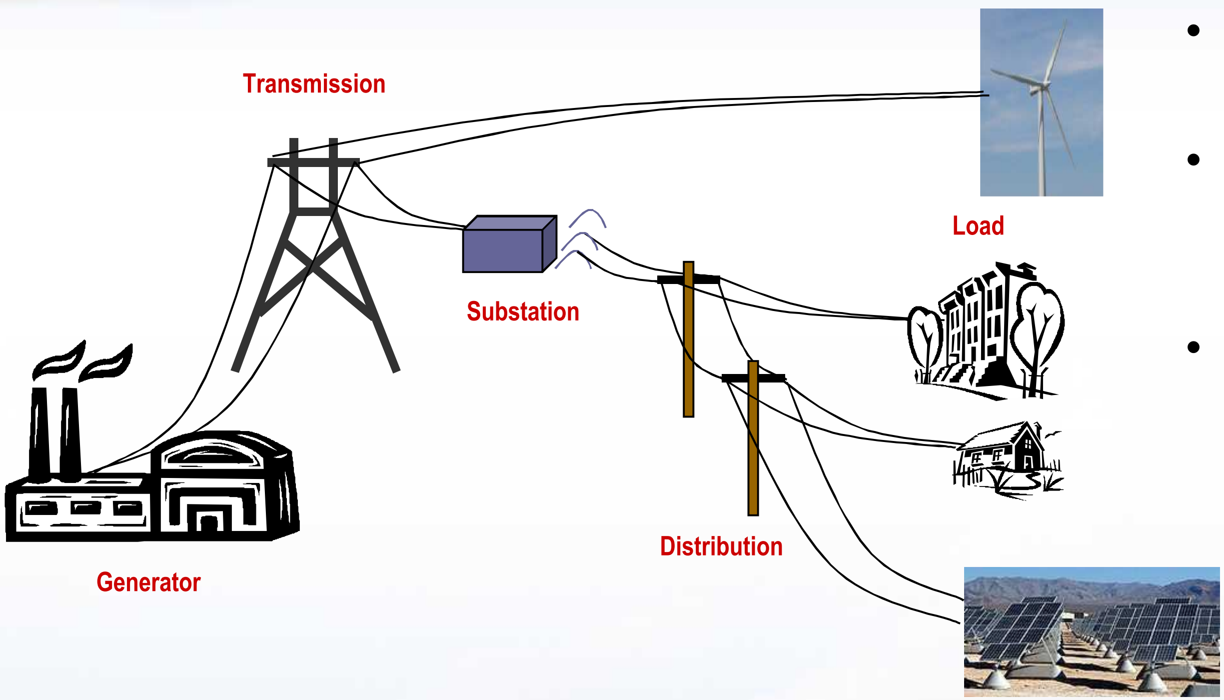
Step 3: Longer-term R&D – unifying, scalable, nonlinear control theory; advanced communications engineering

Step 4: Close the loop – implement new technologies in the lab and field

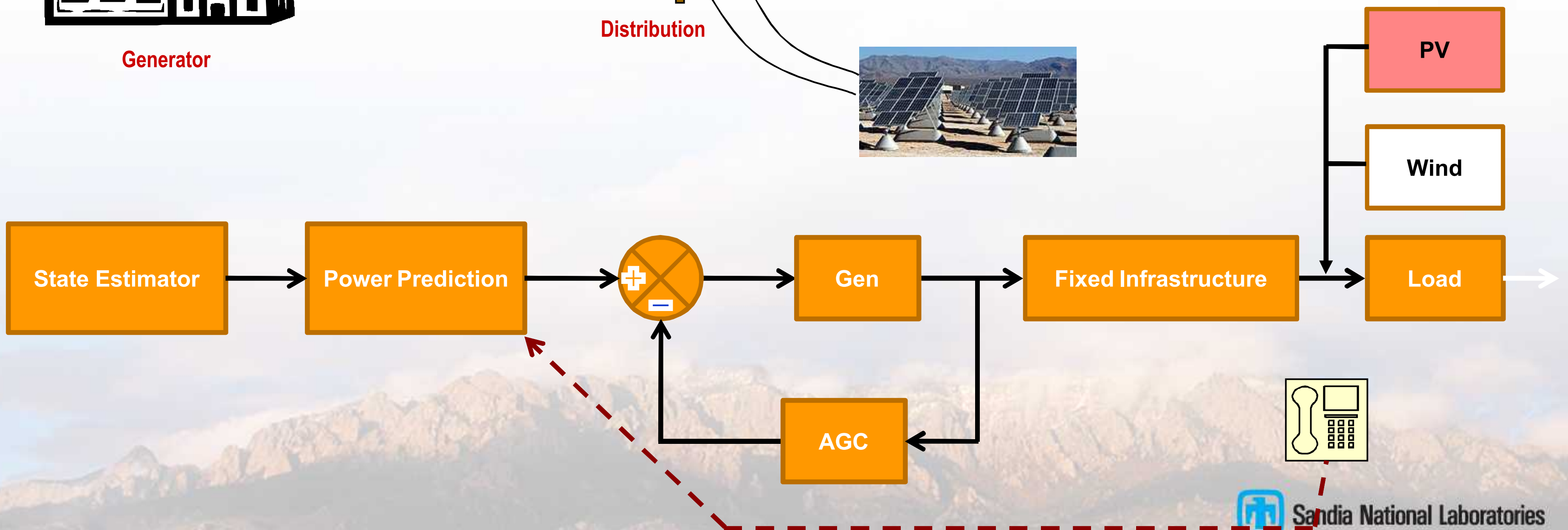
Today's Typical Topology for Fixed Installations



Today, Stochastic Renewable Sources are Treated as Negative Loads

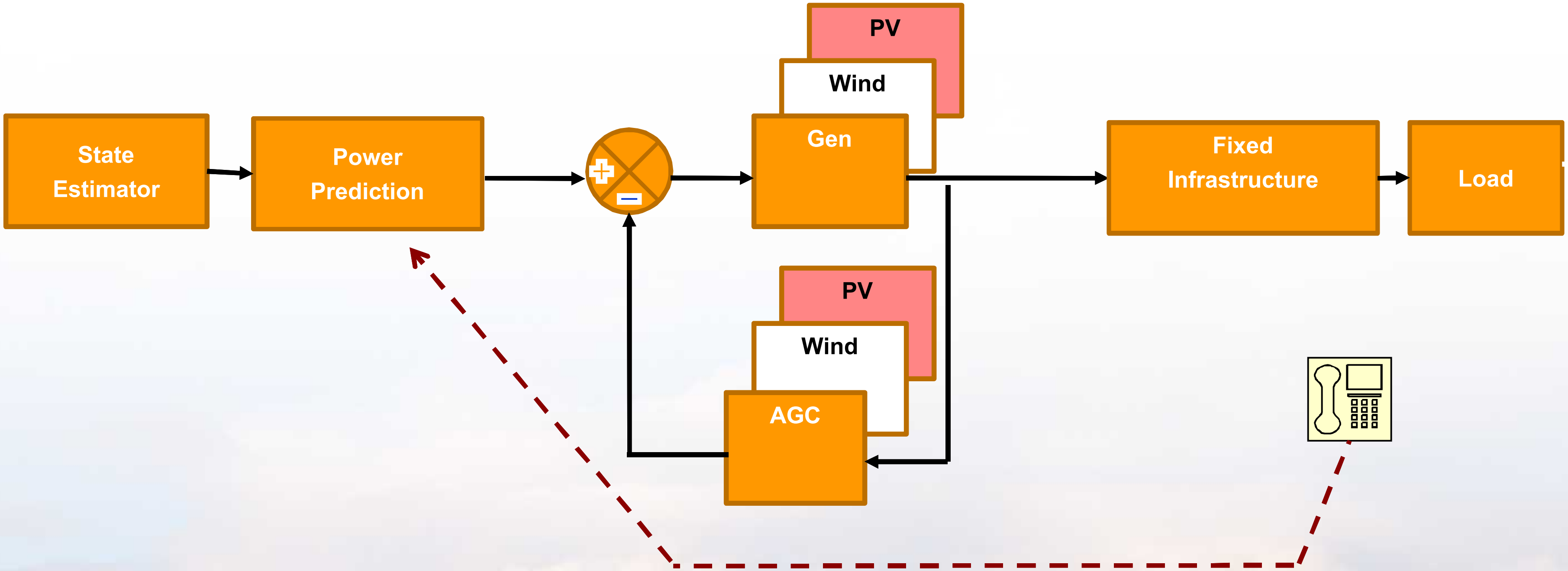


- Decreases predictability of loads
- Doesn't account for complexities of two-way power flow
- Still have the same "spinning reserve" issues



To Achieve Maximum Benefit
Renewable Energy Needs to be Treated as a Source

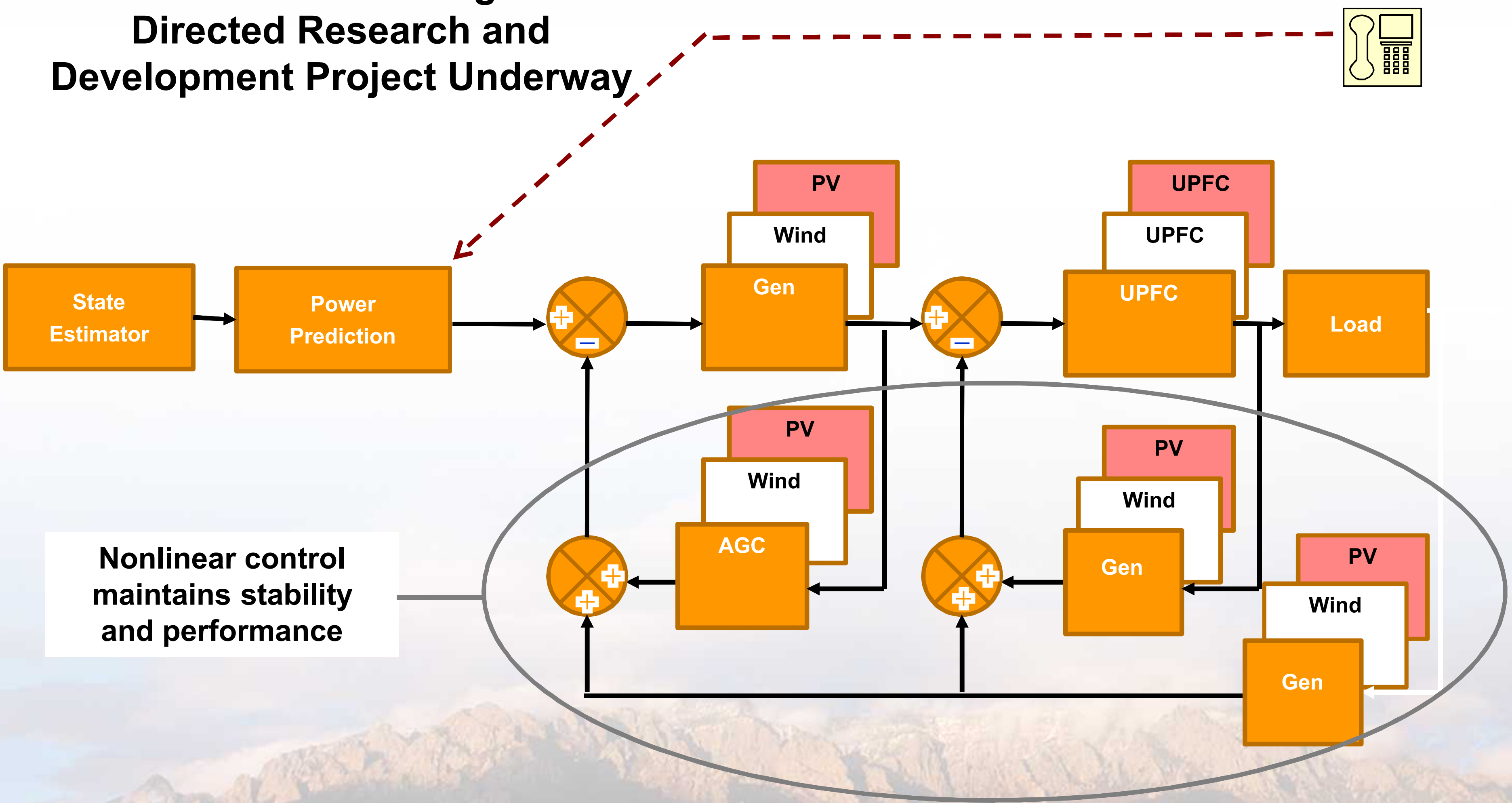
System efficiency can increase with reduction in excess generation capacity.



Both our generation and our loads are now random!

Low-Level Distributed Nonlinear Control Enables Stability and Transient Performance

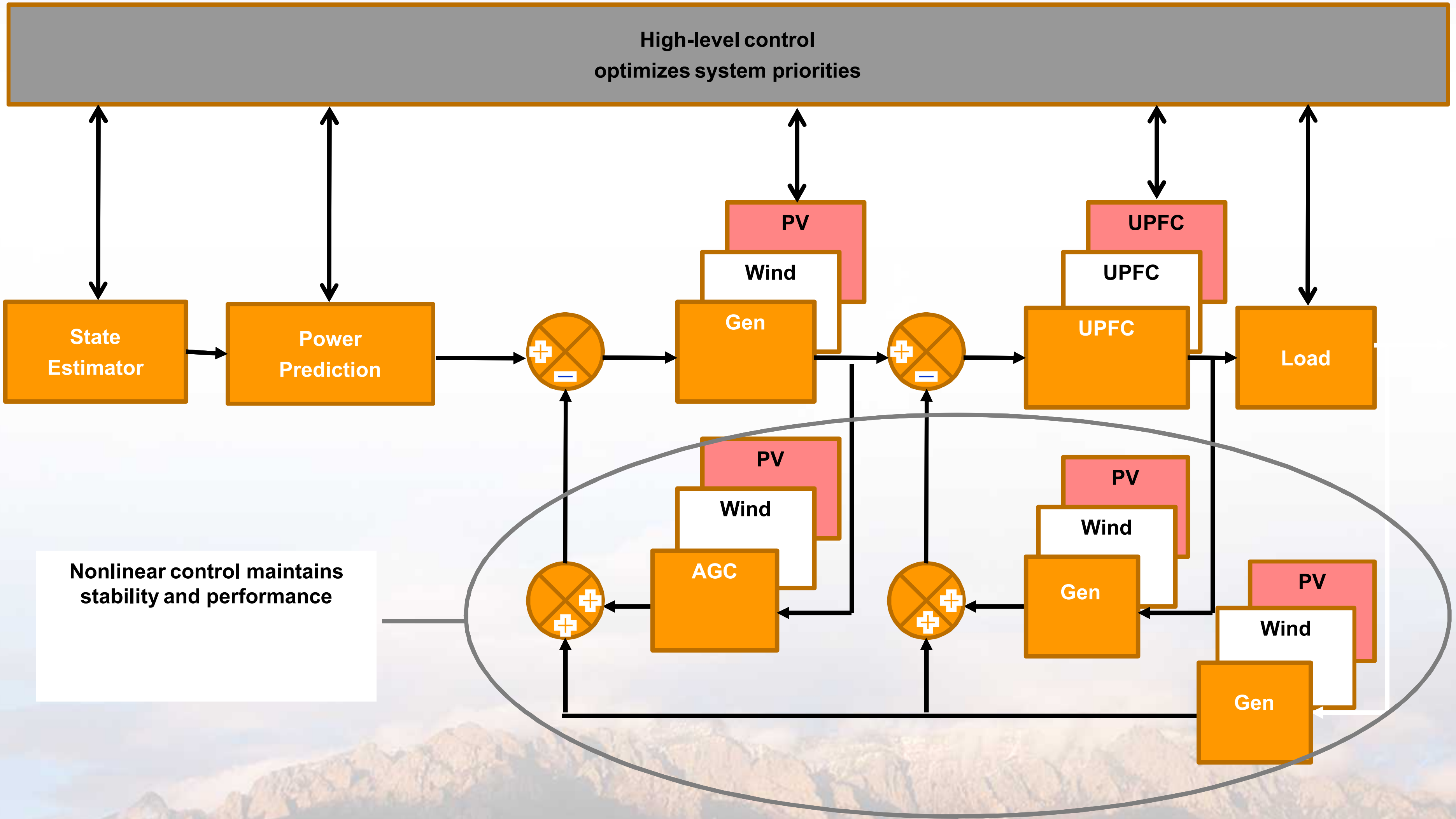
Sandia "Grand Challenge" Lab-Directed Research and Development Project Underway



Nonlinear control maintains stability and performance

UPFC - Unified power flow controllers

High-Level Control Enables Prioritization and System Adaptability



UPFC - Unified power flow controllers

SNL's Hamiltonian-Based Nonlinear Control Theory Addresses Stability and Performance

Equations from a microgrid can be used to construct a Hamiltonian.

Kinetic Energy | Potential Energy

$$H = [T(\dot{x}) + T_c(\dot{x})] + [V(x) + V_c(x)]$$

$$\dot{H} = [\dot{T}(\dot{x}) + \dot{T}_c(\dot{x})] + [\dot{V}(x) + \dot{V}_c(x)]$$

Asymptotic stability is achieved by satisfying the following

$$H > 0, \quad \forall x \neq x^* \quad \text{where} \quad V(x^*) + V_c(x^*) = 0$$

$$\int_0^{\tau_c} \dot{H} dt = \int_0^{\tau_c} [G - L] dt < 0$$

Addition of cost functions allow for optimization to a particular solution.

$$c = \int H dt$$

Chosen to minimize storage, conventional generation, etc.

Fisher Information Equivalency provides link to and minimization of information flow and energy storage.

$$I + J = 8\int \left[\left(\overline{T} + \overline{T}_c\right) + \left(\overline{V} + \overline{V}_c\right) \right] dt = 8\int \overline{H} dt$$

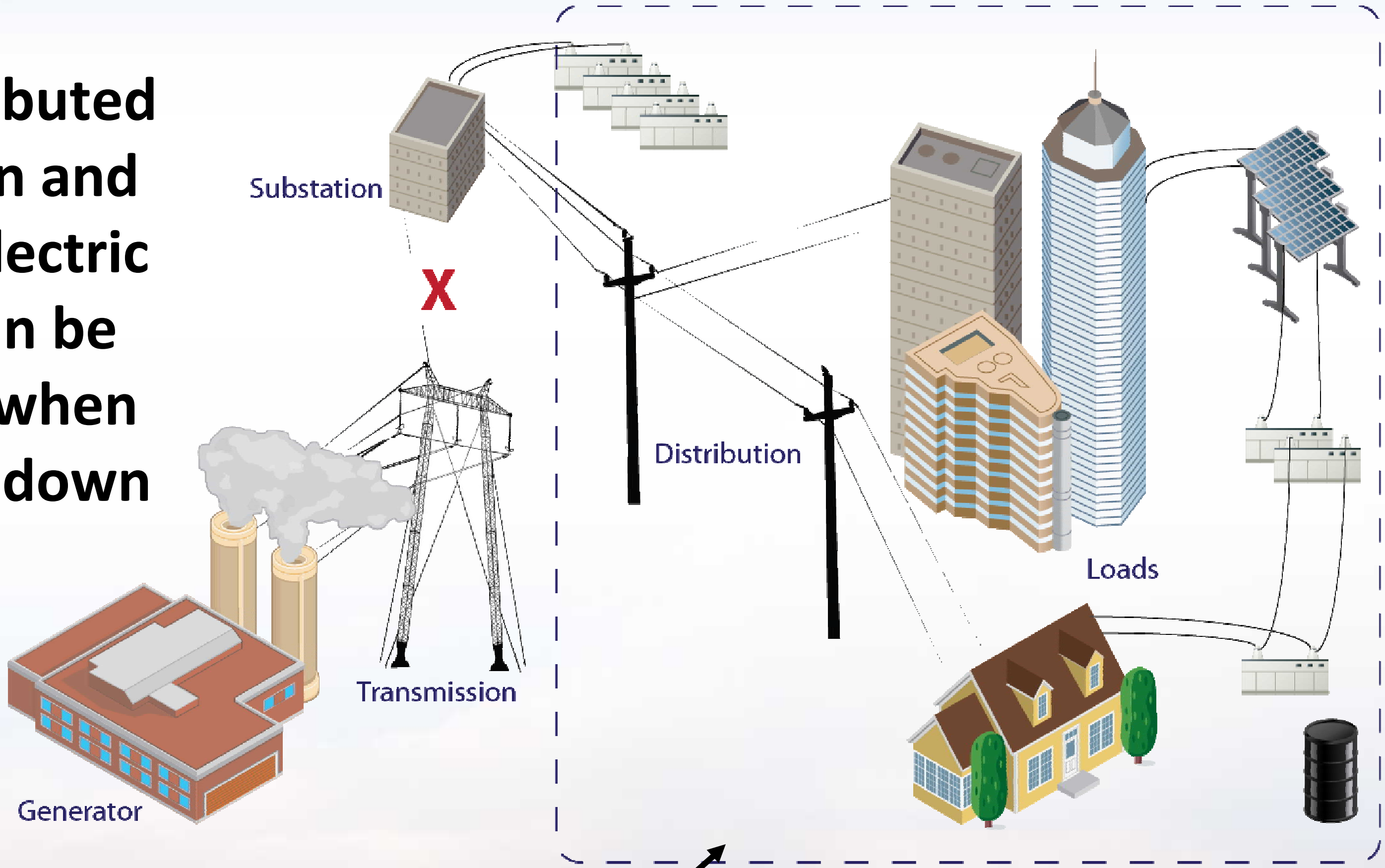
$$\frac{1}{\tau_c} \int_0^{\tau_c} [\ddot{I} + \ddot{J}] dt = \frac{8}{\tau_c} \int_0^{\tau_c} [\dot{\overline{H}}] dt < 0, \quad \text{where} \quad \overline{H} = \sum_{i=1}^{N} \frac{1}{m_i} H_i$$

Individual microgrid Hamiltonian

R.D. Robinett and D.G. Wilson, "Hamiltonian Surface Shaping with Information Theory and Exergy/Entropy Control for Collective Plume Tracing", *Int. J. Systems, Control and Communications,* Vol. 2, Nos. 1/2/3, 2010

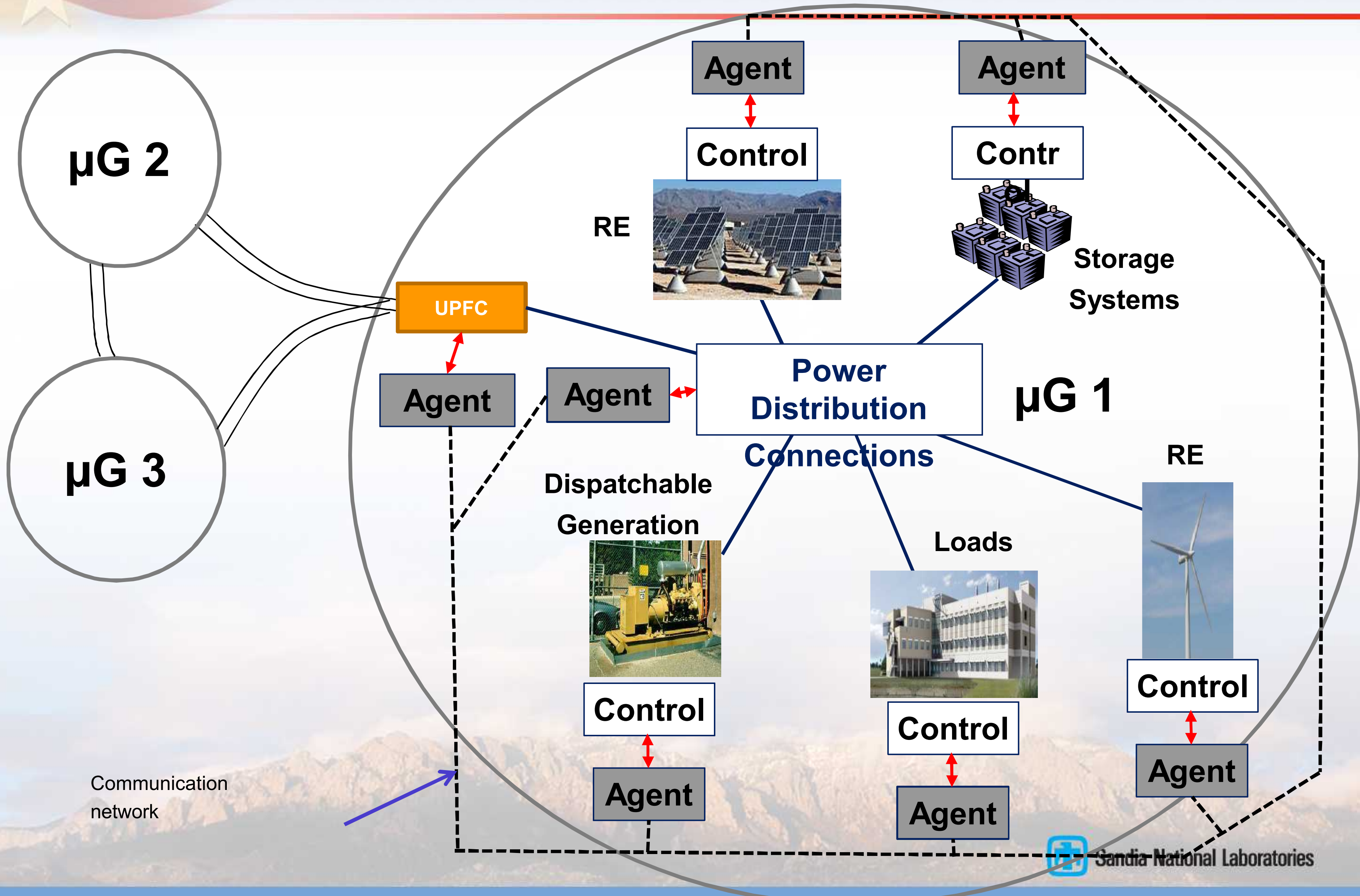
Microgrids can increase energy assurance

With distributed generation and storage, electric power can be provided when the grid is down



Storage and generation on load side, sized to match energy performance needs

These Advancements Will Lead to a Network of Highly Interconnected Microgrids



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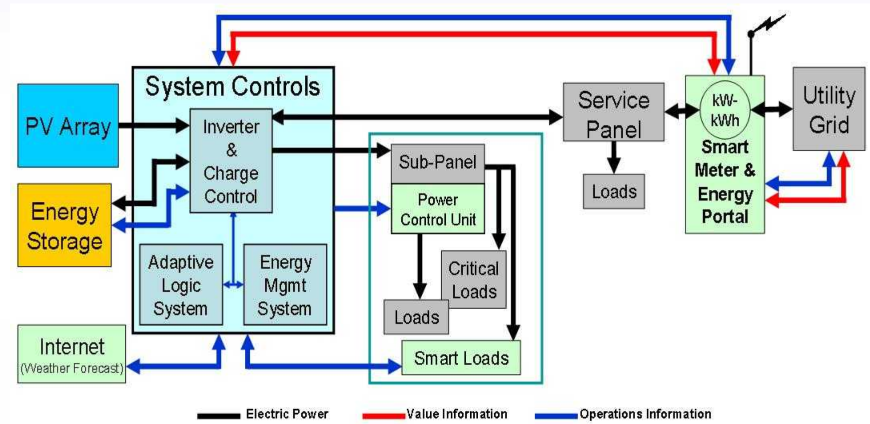
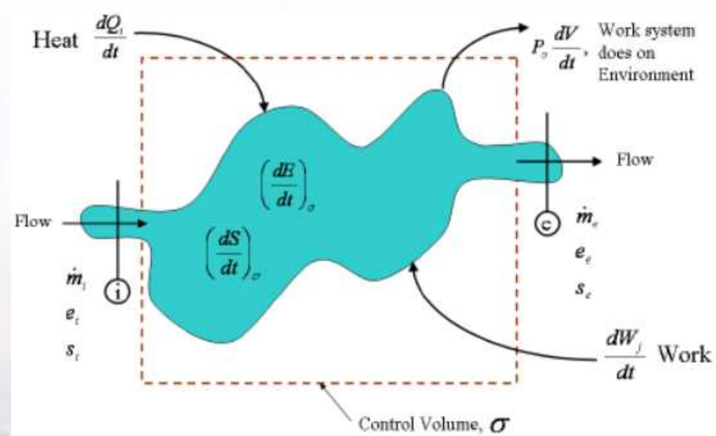
Variability of High Penetration on the Electric Grid

Step 1: Define the problem - Collect data and build predictive models



Step 2: Develop near-term solutions - SEGIS

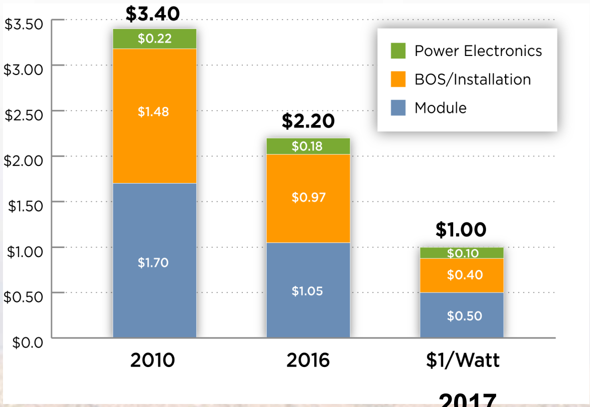


Step 3: Longer-term R&D – unifying, scalable, nonlinear control theory; advanced communications engineering

Step 4: Close the loop – implement new technologies in the lab and field

Example Lab and Field Demonstrations Underway

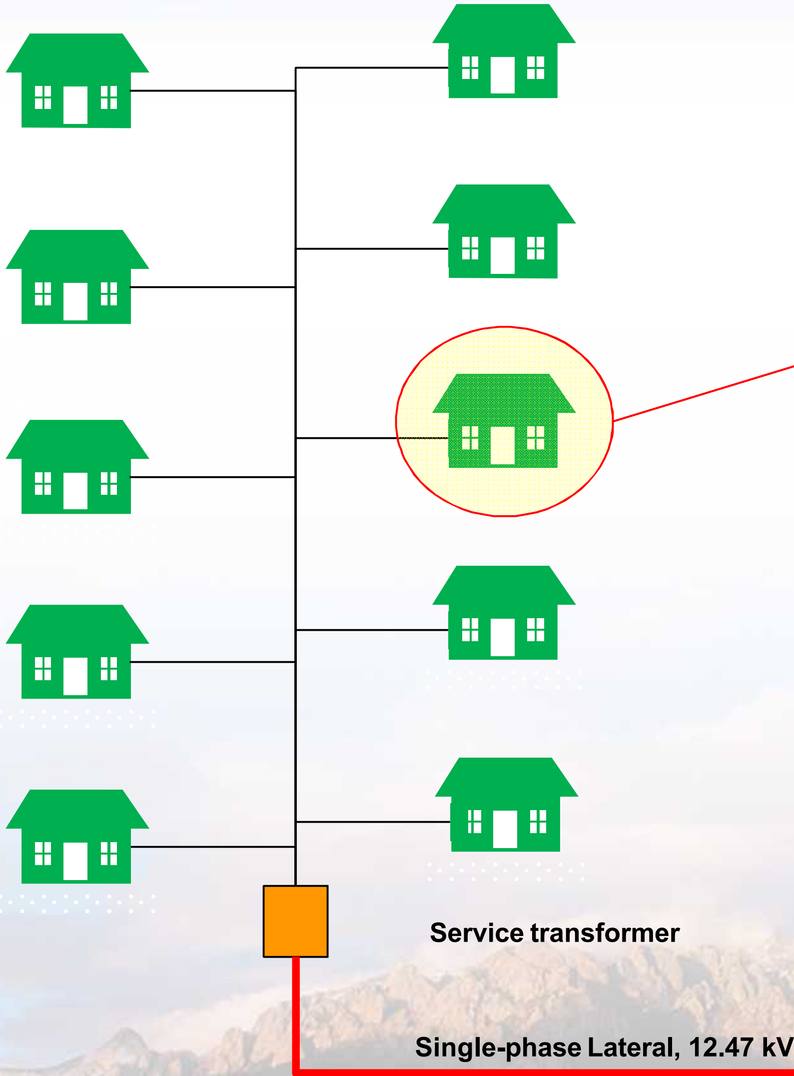
- **Expansion of Lanai "lessons learned" to 20MW field in Colorado**
  - Data collection just beginning now
- **Linking PV system measurements to grid impacts**
  - Installing Phasor Measurement Units at interconnects with large PV systems
- **SEGIS – Full-scale field demonstrations this summer**
- **Partnership with Electric Power Research Institute (EPRI): New communications protocols for advanced inverters**
- **Several DOE "SunShot" Funding Opportunity Announcements:**
  - SEGIS-AC (Advanced Concepts)
  - High-Penetration PV
  - PV-BOS
  - PV Manufacturing

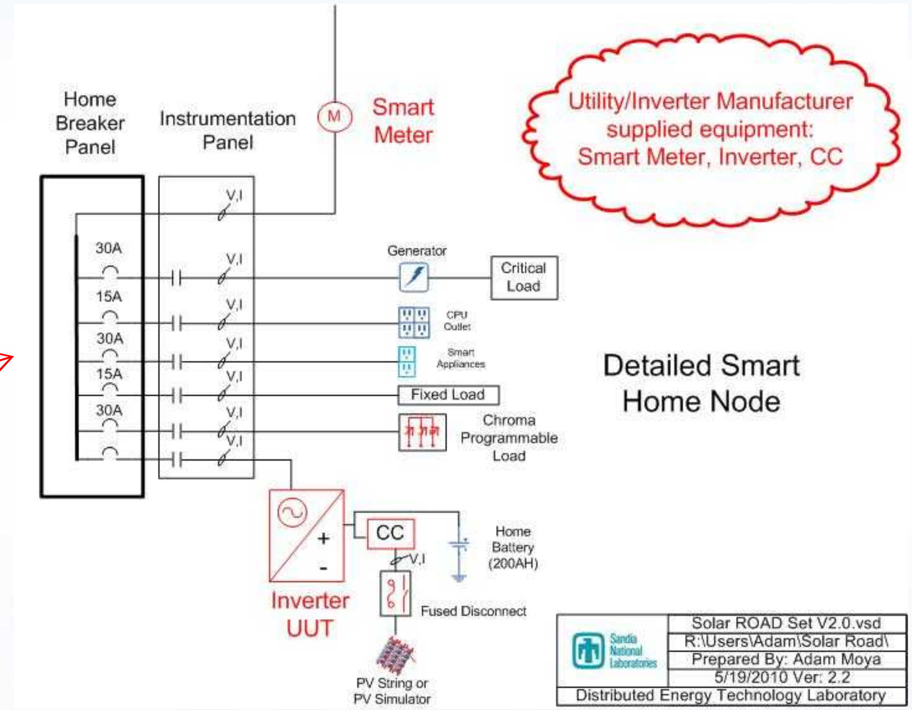


2017

Estimated | Current Goal | (DOE-Sunshot Goal)

Expansion of Distributed Energy Technologies Lab (DETL): Solar ROAD (Reconfigurable Open Architecture Design)





- **Replicate high PV penetration at residential scale**
  - **Multi-inverter interactions**
  - **Advanced controls integration**
  - **Microgrid and grid-connected simulations**
- **Tie to existing 3-phase microgrid to simulate utility feeder**

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Solar Power: The Path Forward

- **Technology**
  - PV: Factory-developed "systems" – low cost, easy install, high reliability
  - New approaches to high-penetration scenarios: distributed microgrids, "smart" energy management systems
  - STORAGE IS KEY!
- **Some things to watch for:**
  - Increasing focus on water-related issues and constraints on development
  - Nuclear concerns?
  - New building and community-scale energy management systems
  - Continued growth in utility-scale systems as prices drop and financing becomes available
  - New types of utilities based on distributed, "virtual" power plants
- **Career Opportunities Abound!**
  - Power Electronics, Power Systems – engineering tools for a new grid architecture and interconnectivity
  - Economics/Analysis/Finance - business models for suppliers and system operators
  - Sciences – physics, chemistry, etc: solutions for a clean energy infrastructure, including storage improvements
  - PowerPoint Specialists – please send me your resume!

Questions and Discussion

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