SAND2010-7644P

Sandia National Laboratories

Renewable Systems Integration And Microgrids

Operational Energy Security

…Exceptional service in the national interest

Sandia National Laboratories
Energy Security Program

Energy Security Roles

$250M DOE Energy Research Program

Support DoD on energy system, physical, and cyber security

System integrator for the DOE/NNSA

Energy Security Focus

Operational Energy Systems
- Electric Power Assurance
  - Microgrid, renewables, nuclear, storage, control systems, cyber
- Transportation Energy Assurance
  - Combustion research, renewable fuels

Climate Change Science
- Operational Impacts
- Assessments

DoD Installation Security Projects

Nuclear Design & Fuel Cycle

Combustion Research Facility

Distributed Energy Technology Laboratory

Sandia National Laboratories

Energy Challenge - Harvest, Transform, and Control Delivery of Available Energy

Energy & Material Resources

Fossil (coal, oil, gas)

Solar (including wind and hydro)

Geothermal

Nuclear

Plant, animal, and human waste

CO_2 & other energy conversion byproducts

Energy Processing

Harvest, transform, and deliver exergy* at the necessary amount and rate.

Energy Needs or Services

Electricity

Fuel

Heat

Cooling

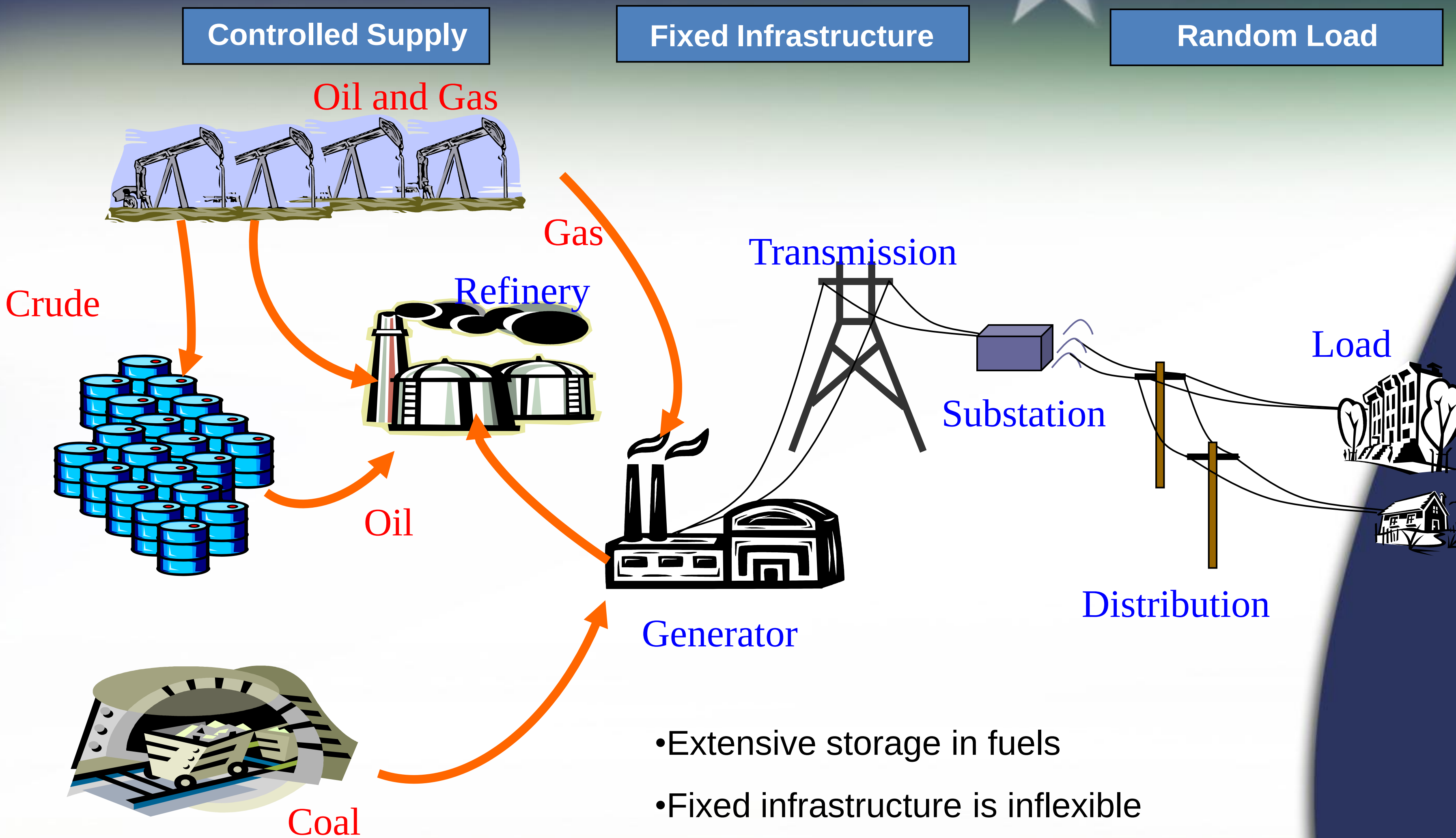
Chemicals (such as lubricants)

Clean Water

***EXERGY = AVAILABLE ENERGY = useful portion of energy that allows one to do work and perform energy services**

Sandia National Laboratories

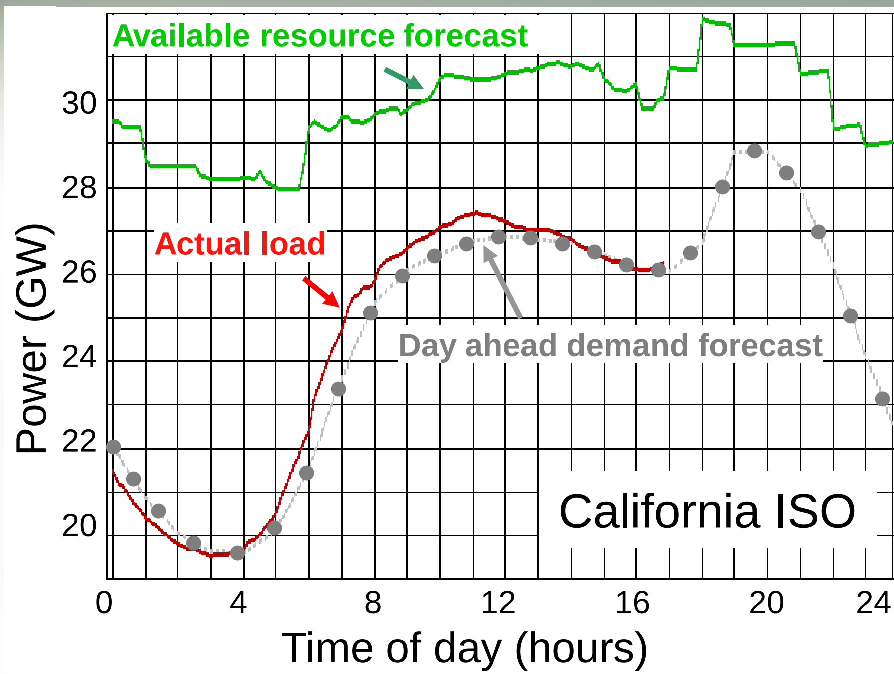
Today's Power Grid is Designed for Dispatchable Centralized Generation



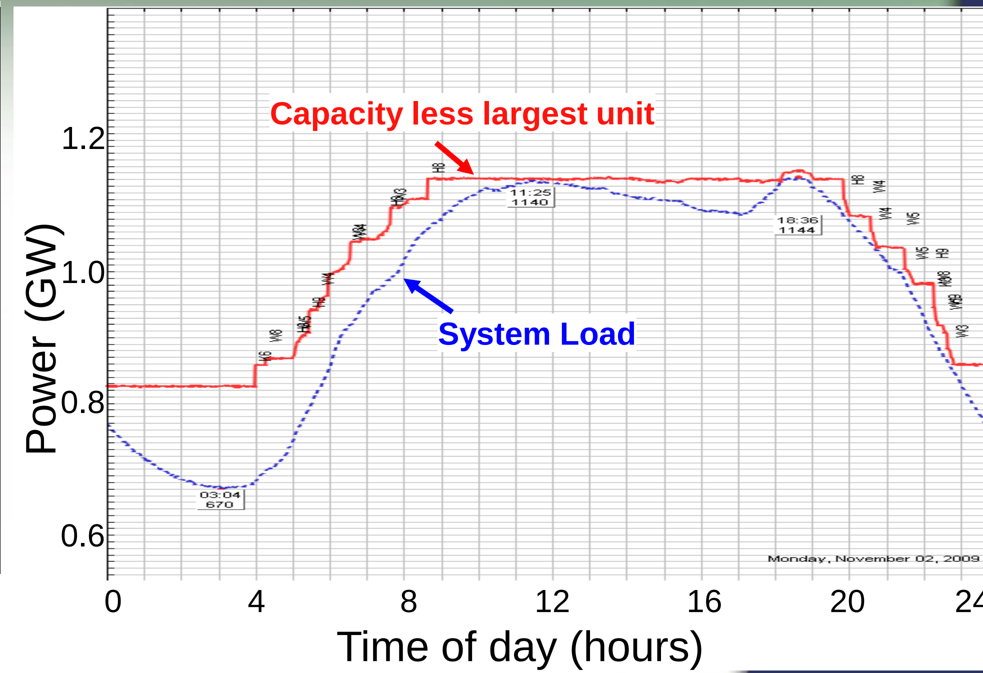
- Extensive storage in fuels
- Fixed infrastructure is inflexible
- Significant human interaction

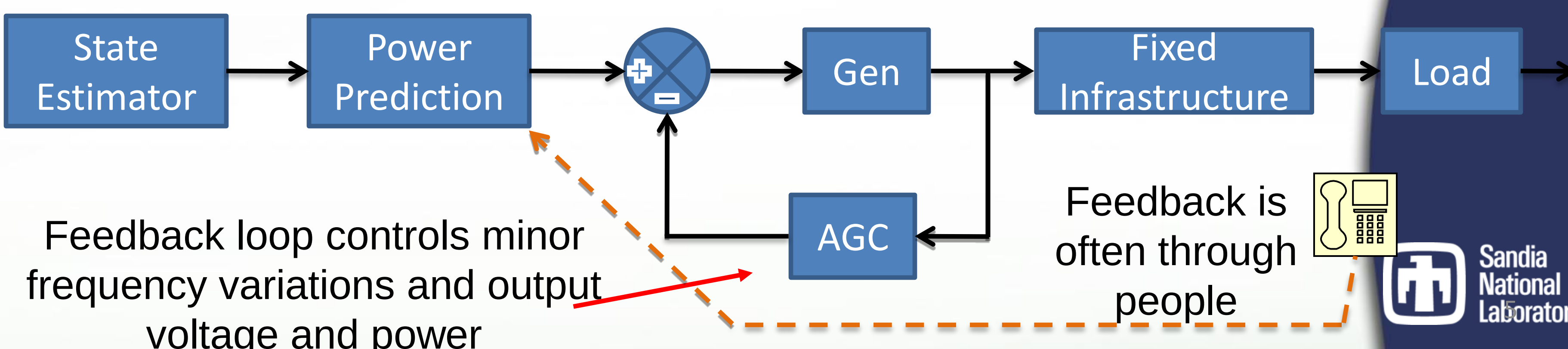
Loads are Predictable, Allowing Essentially Open-loop Grid Control

Forecasting is used to set generation



Hawaiian Electric Co. daily load vs capacity

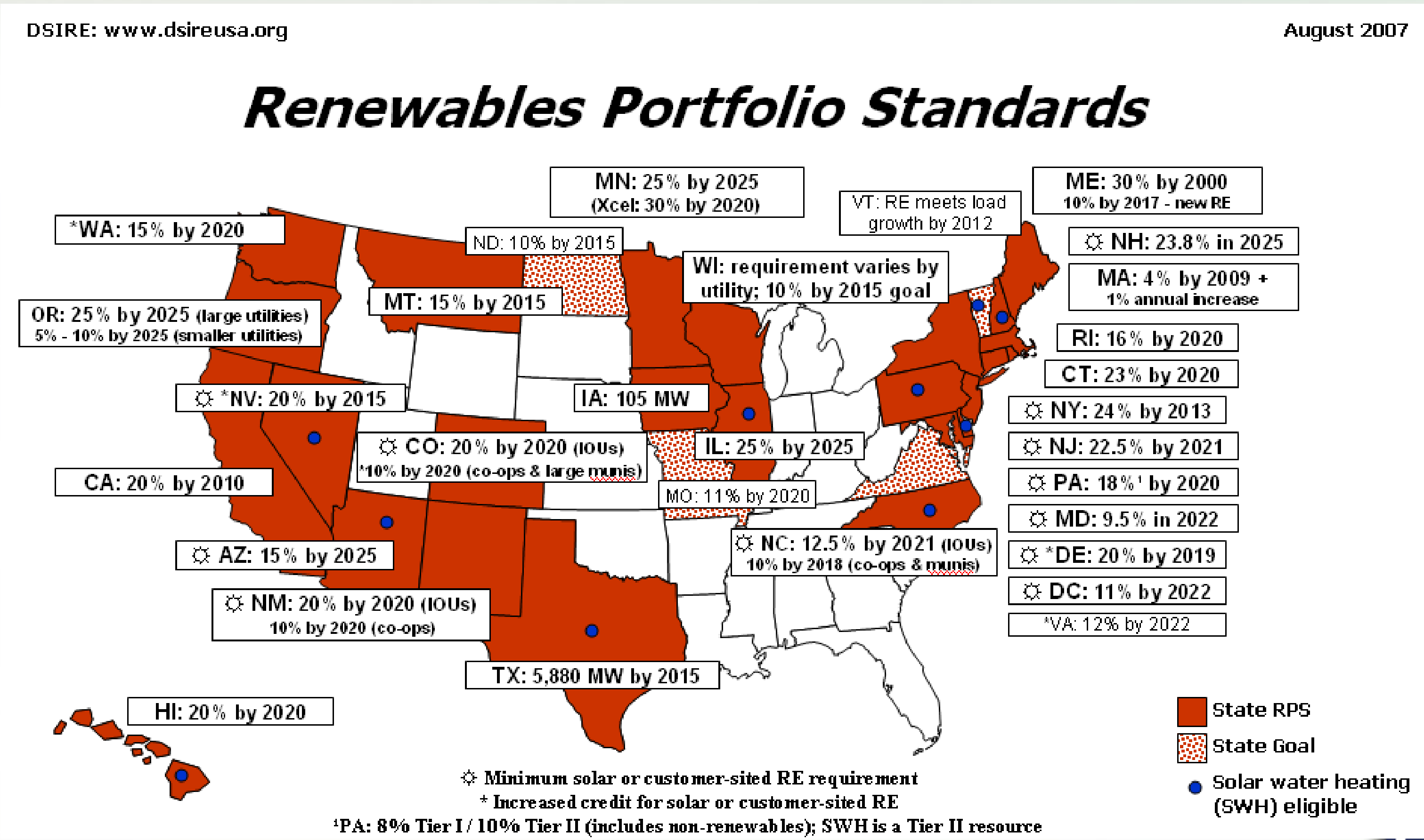




Sandia National Laboratories

An Emerging Market:
Preparing for Large-Scale Renewable Energy Integration

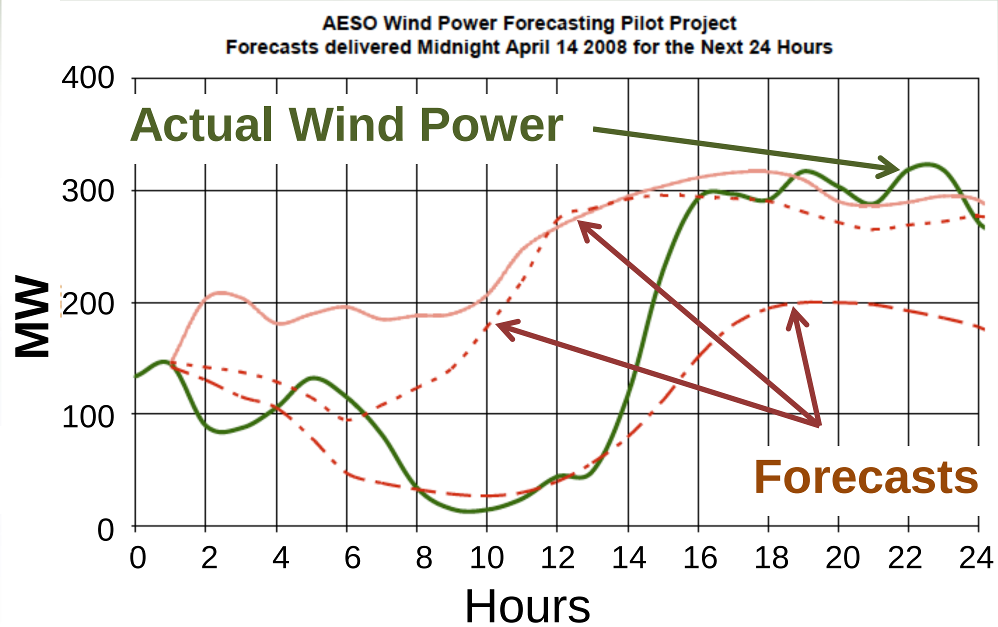
New Market Scenario: Climate change concerns, renewable portfolio standards, incentives, and accelerated cost reduction driving steep growth in U.S. renewable energy system installations.

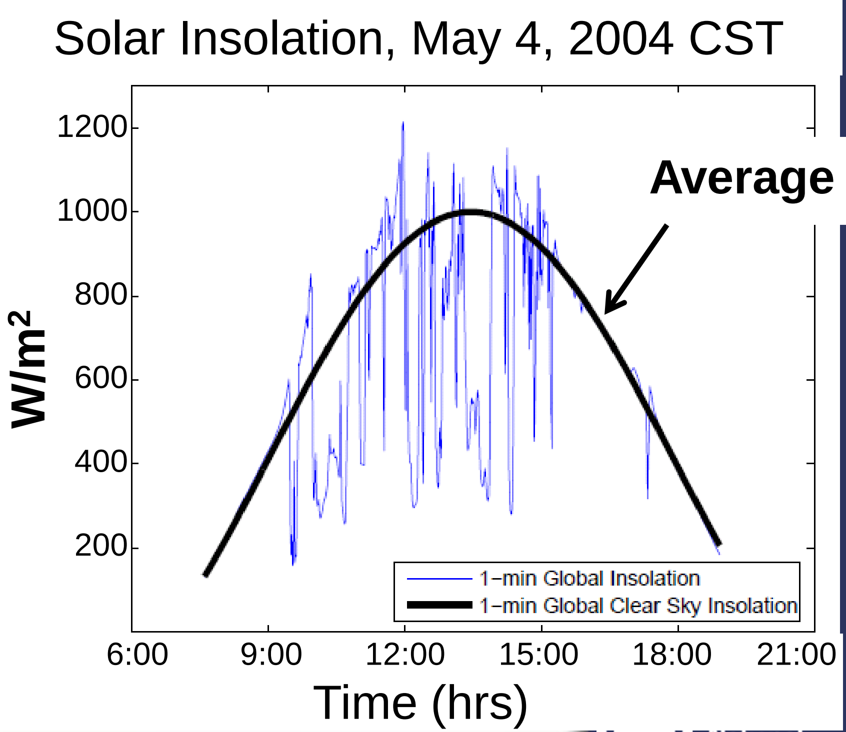


Sandia National Laboratories

Stochastic Sources (Negative Loads) Complicate Load Forecasting

Wind power forecasting examples

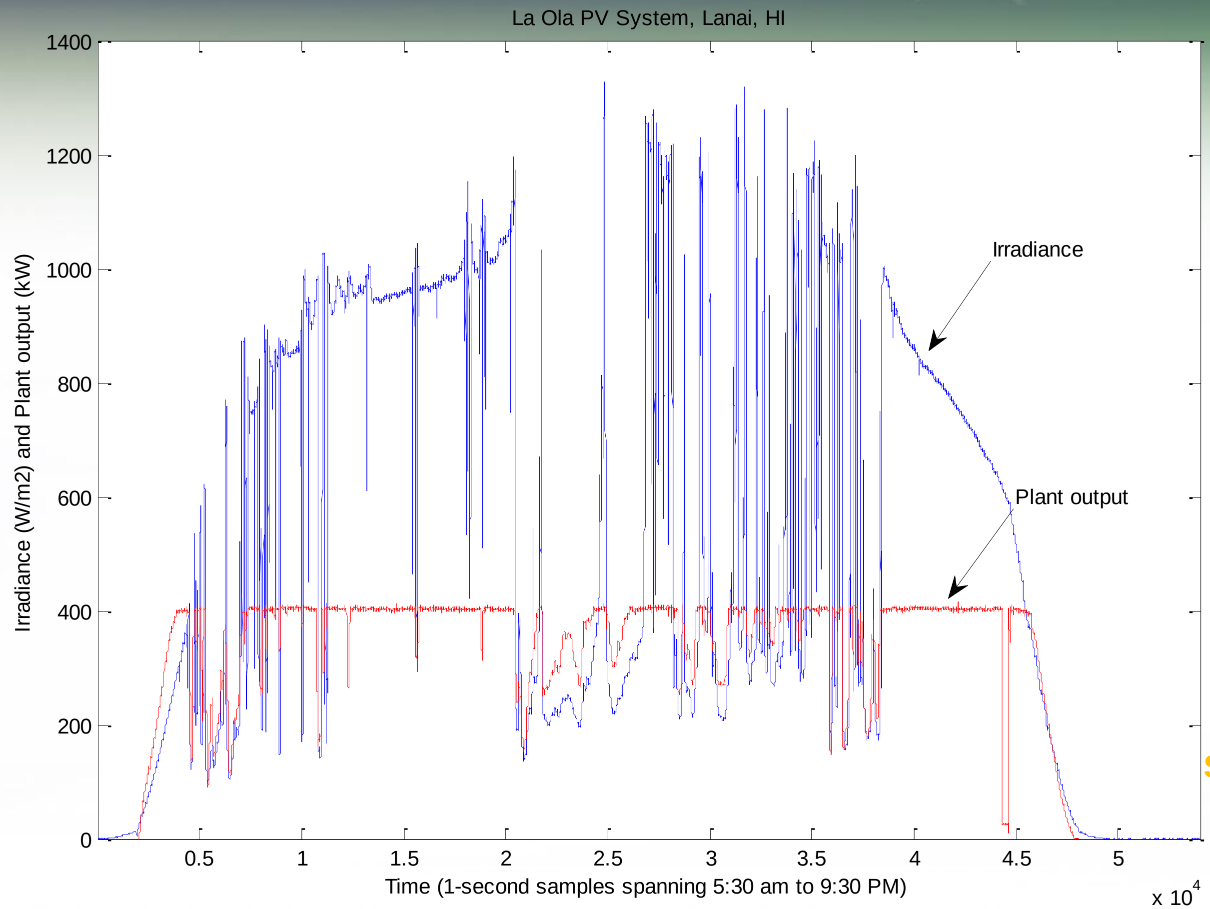




This is weather forecasting!

National Laboratories

PV Output Can Vary Considerably on an Average Day

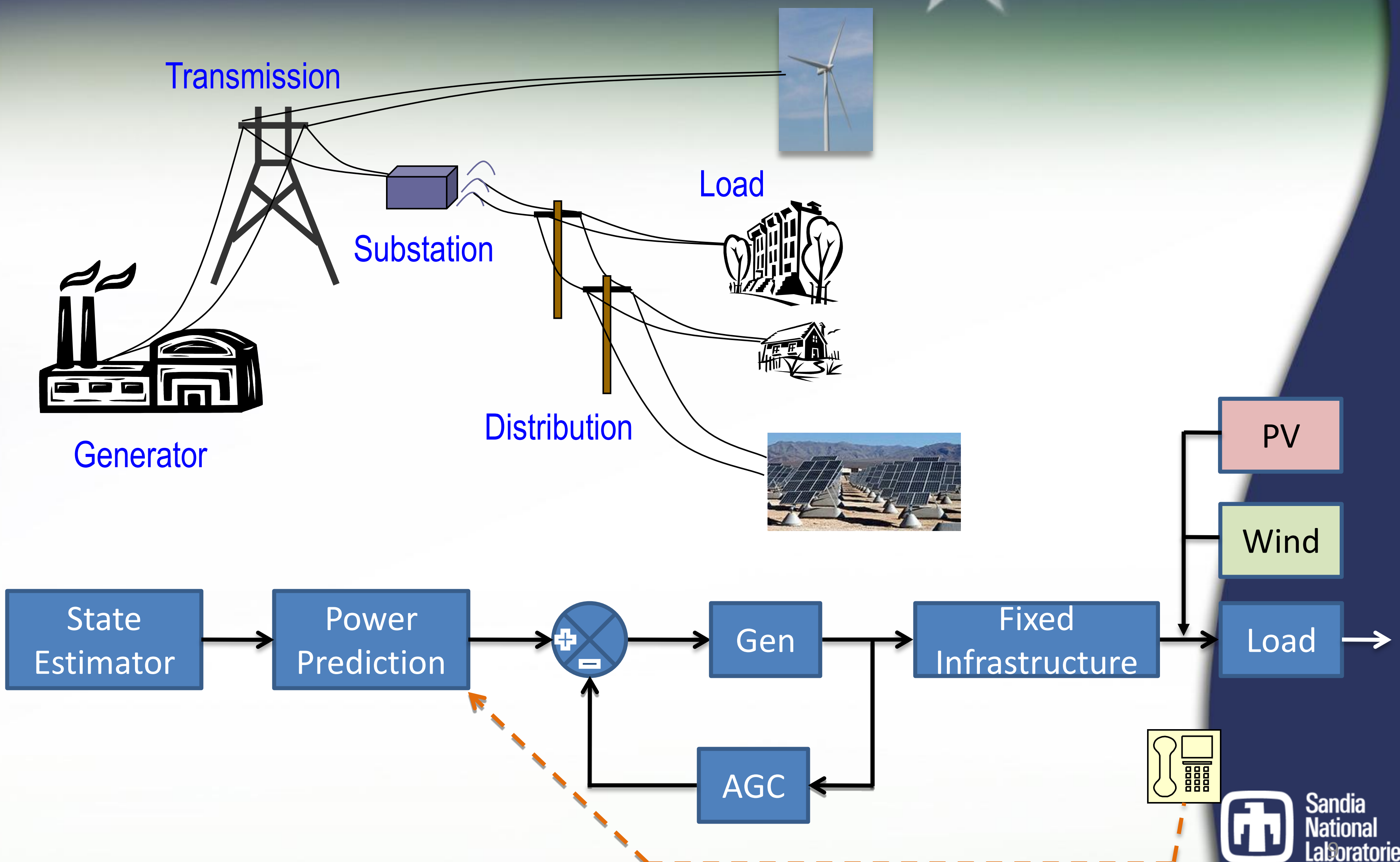


Source: SunPower
Castle & Cooke

- Irradiance and PV system ac output for a typical partly cloudy day in July
- PV system rating: 1,200 kW ac, presently limited to 400 kW ac (intentionally)

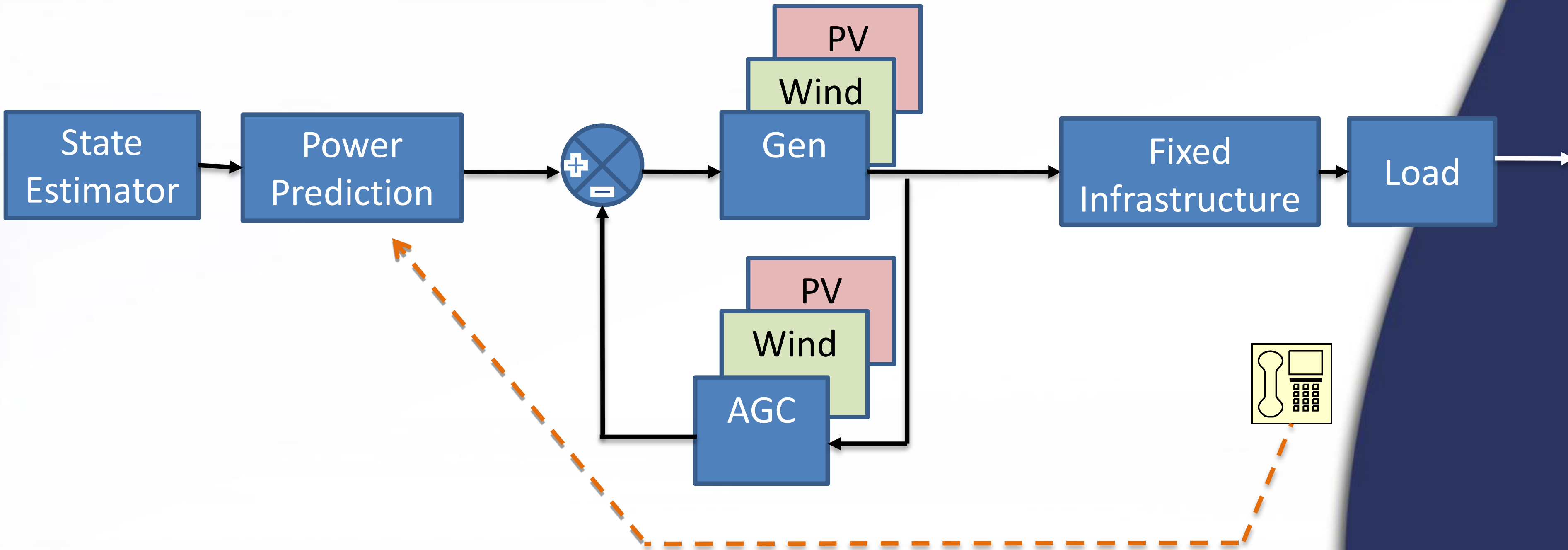
Sandia National Laboratories

Today, Stochastic Renewable Sources are Treated as Negative Loads



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

System efficiency can increase with reduction in excess generation capacity.



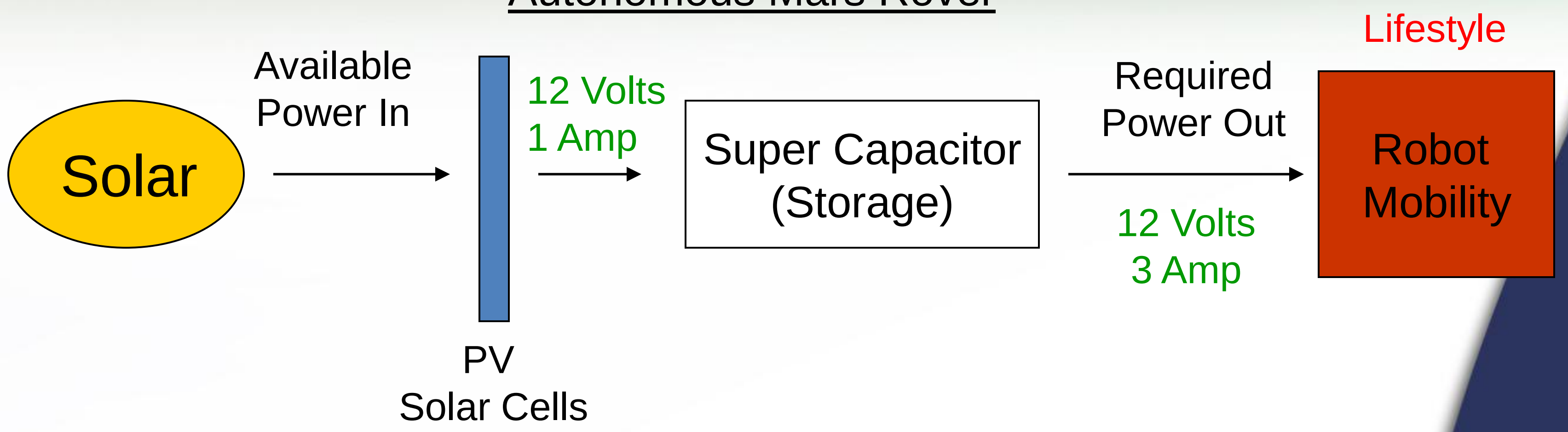
Both our generation and our loads are now random!

Sandia National Laboratories

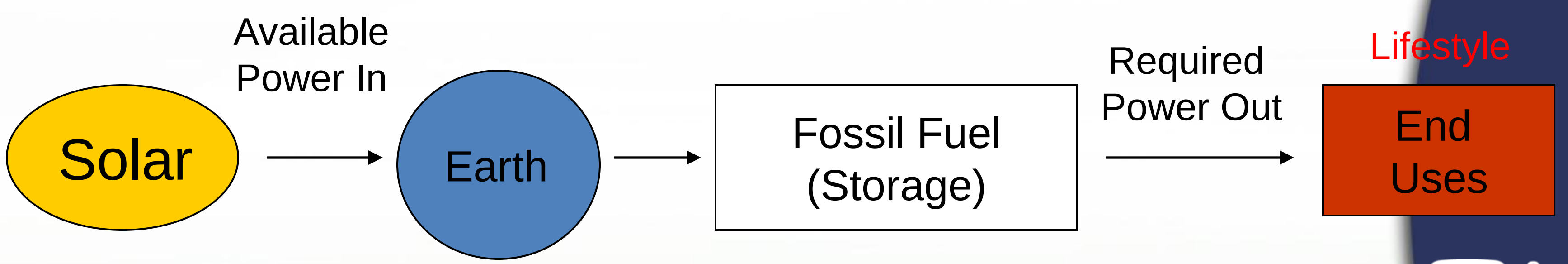
Storage: Impedance and Capacity Matching Solution

- Specific applications justify electrical energy storage solutions

Autonomous Mars Rover



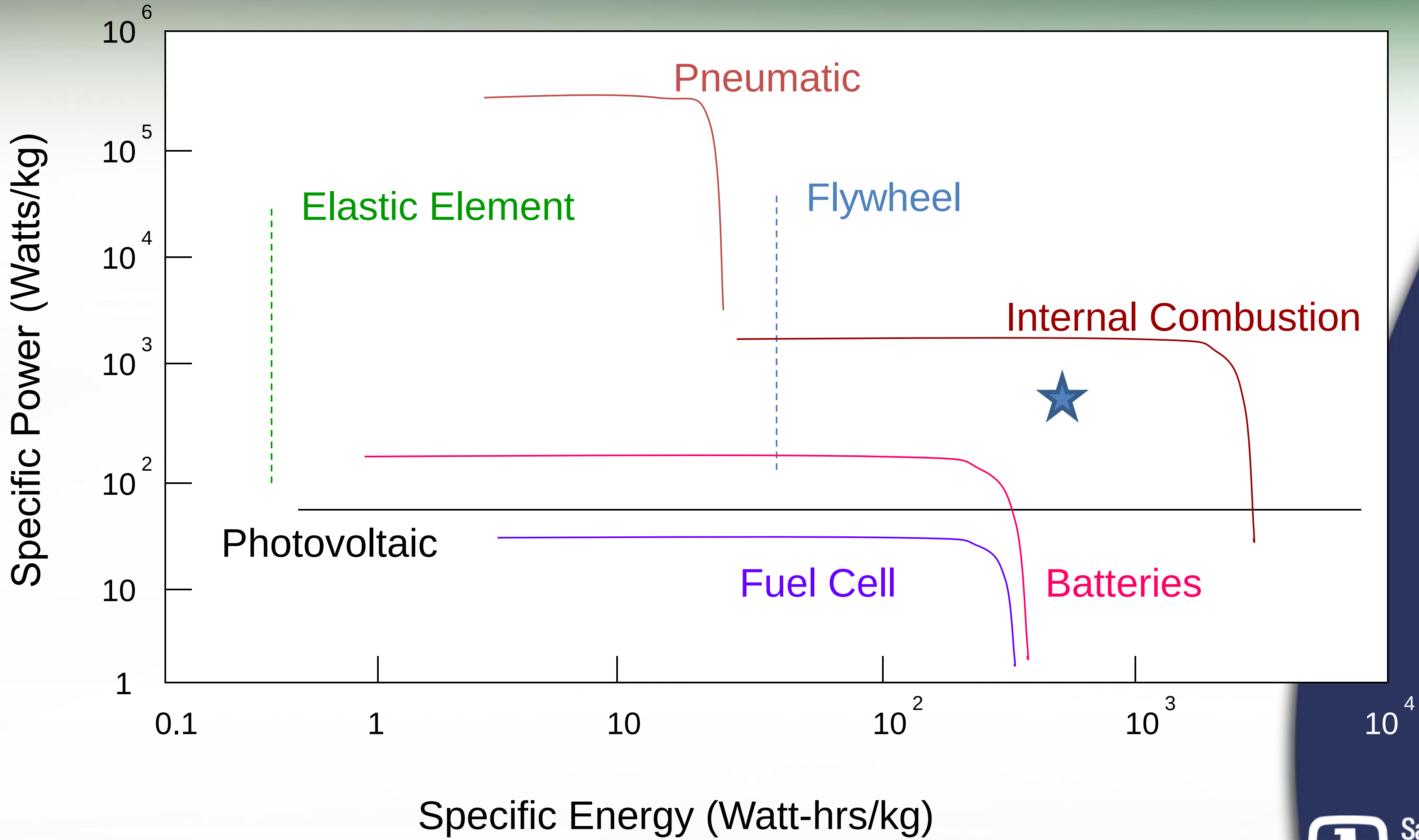
Autonomous Man on Earth



*NOTE: Required Power Out > Available Power In; Impedance/Capacity Mismatch

Sandia National Laboratories

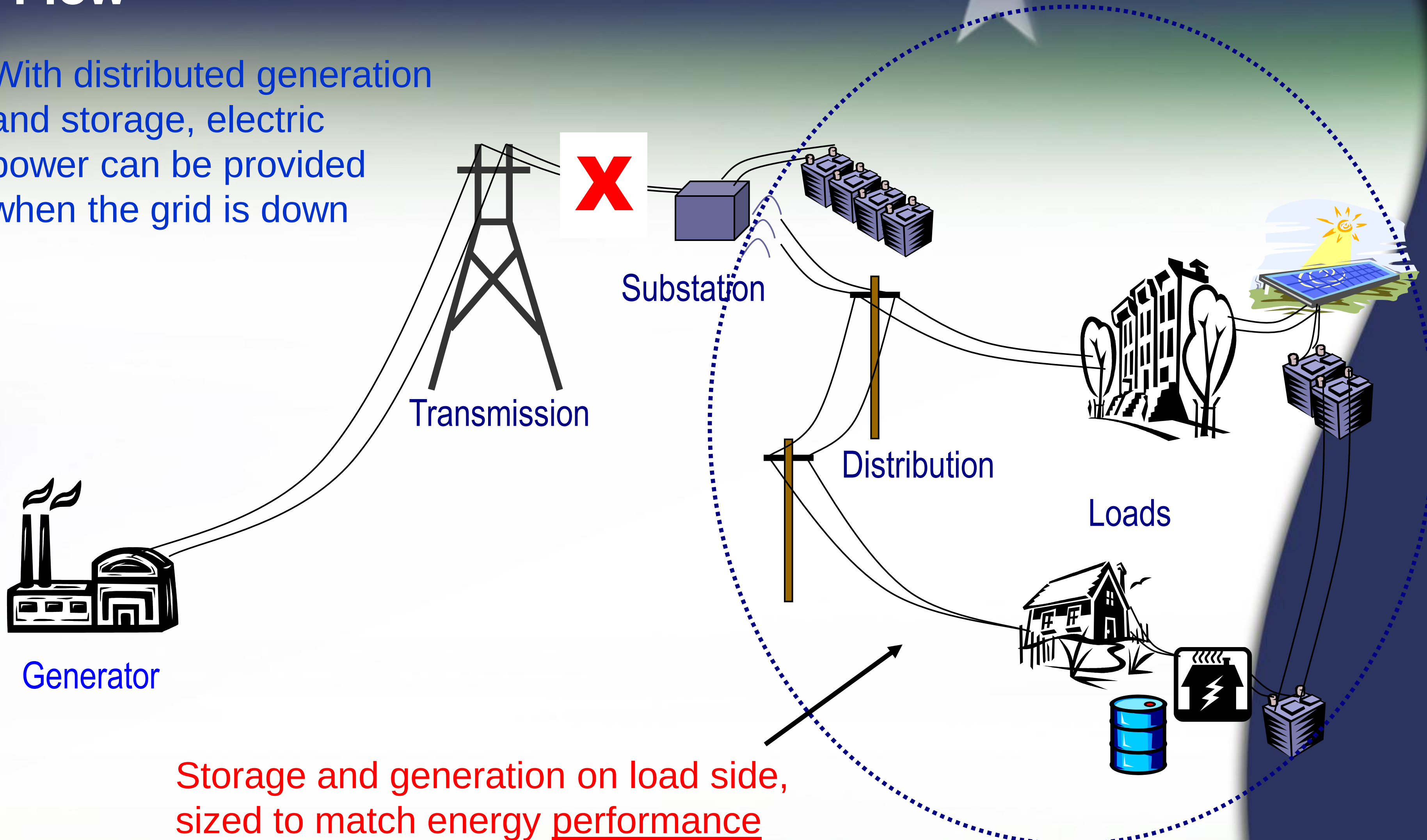
Impedance/Capacity Mismatch (Duty Cycle)



Sandia National Laboratories

Microgrids Can Provide a Pathway for More Effective Use of Renewable Energy: Optimized Storage and Info Flow

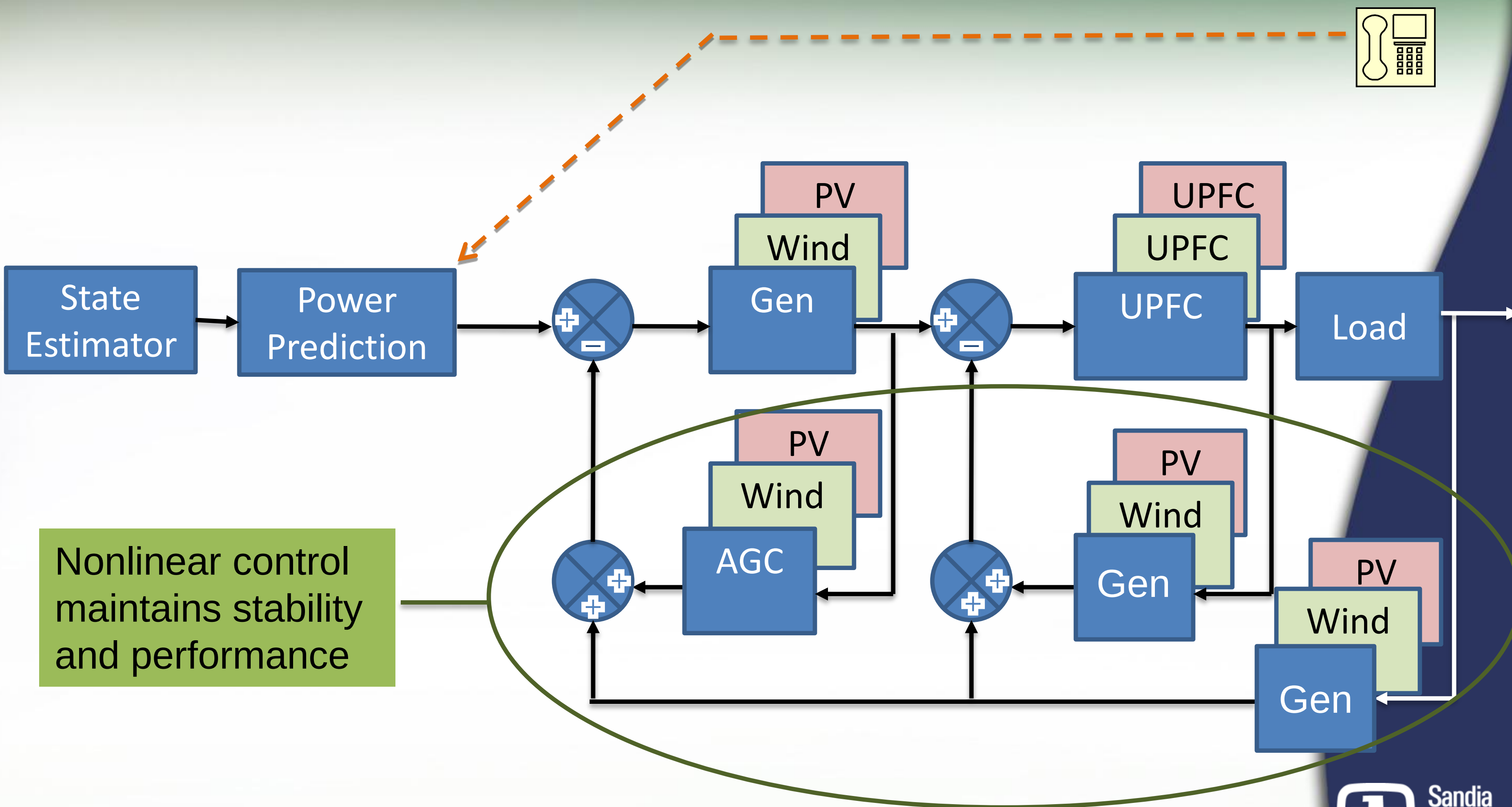
With distributed generation and storage, electric power can be provided when the grid is down



Storage and generation on load side, sized to match energy <u>performance</u> needs

Sandia National Laboratories

Low-Level Distributed Nonlinear Control Enables Stability and Transient Performance



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

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

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

Asymptotic stability
is achieved by satisfying the following constraints

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

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

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

Assumptions Limit Most Common Models Reduced Network Model (RNM)

- Each Synchronous Machine represented as voltage phase with constant magnitude E' behind transient reactance

$$\dot{\delta}_k = \omega_k$$

Instantaneous power balance

Modify to include variable definition

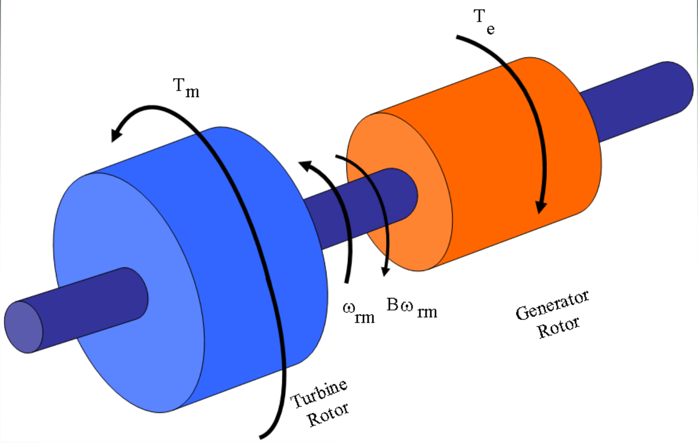
$$M_k \dot{\omega}_k = P_{mk} - E_k'^2 G_{kk} - D_k \omega_k - \sum_{\substack{l=1 \\ l \neq k}}^{n} \left(C_{kl} \sin(\delta_{kl}) + F_{kl} \cos(\delta_{kl}) \right)$$

$$where \quad D_k > 0 \quad M_k > 0$$

- Various network components assumed to be insensitive to changes in frequency
- Mechanical angle of Synch-Mach. rotor assumed to coincide w/ electrical phase angle of voltage phase behind transient reactance
- Loads represented as constant impedances thereby eliminating DAEs
- Mechanical power input to generators assumed constant (P_{mk})
- Saliency is neglected
- Stator resistance is neglected

*M Ghandhari, “Control Lyapunov Functions: A Control Strategy for Damping of Power Oscillations in Large Power Systems,” KTH, 2000

Simplest Network Model: One-Machine Infinite Bus (OMIB)



Turbine-Generator Rotor System

$T_m =$ Mechanical turbine torque N-m
$T_e =$ Electromagnetic counter torque N-m
$P_m =$ Mechanical turbine power W (constant)
$P_e =$ Electromagnetic counter torque W
$J =$ Mass polar moment of inertia
$B =$ Damping torque coefficient
$\omega_{RM} =$ Rotor shaft velocity in mechanical r/s
$\omega =$ Angular velocity in electrical r/s
$\delta =$ Power angle measured in electrical rad

$$T_m - T_e = J\dot{\omega}_{RM} + B\omega_{RM}$$

RNM:

$$\dot{\delta} = \omega$$

$$\dot{\omega} = \frac{1}{J}[P_m - P_e - B\omega]$$

$$\dot{\omega} = \frac{1}{J}\left[P_m - P_{\max}\sin(\delta) - B\omega\right]$$

$$\boxed{J\ddot{\delta} + P_{\max}\sin(\delta) = P_m - B\dot{\delta}}$$

Define Hamiltonian and Hamiltonian rate:

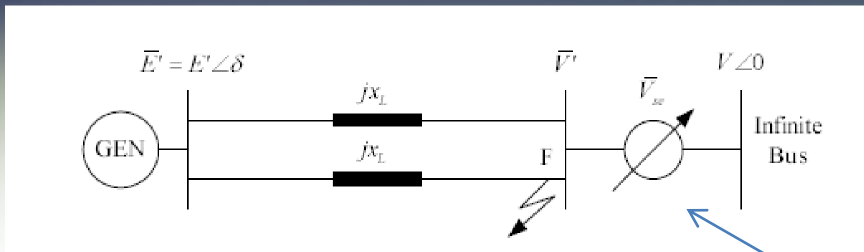
$$H = T + V \qquad \text{(Energy)}$$

$$H = \frac{1}{2}J\dot{\delta}^2 + P_{\max}(1 - \cos\delta)$$

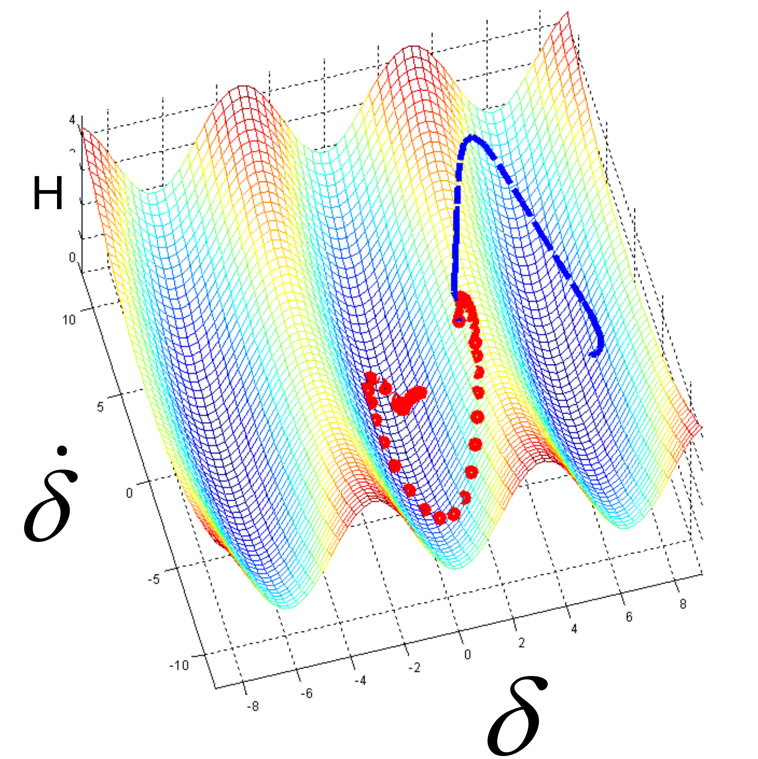
$$\dot{H} = \left[J\ddot{\delta} + P_{\max}\sin\delta - P_m\right]\dot{\delta} = -B\dot{\delta} \qquad \text{(Power flow)}$$

Sandia National Laboratories

Design of the OMIB with UPFC Using Hamiltonian Surface Shaping and Power Flow Control (HSSPFC)



Hamiltonian Surface



UPFC general controller form:

$$P_e = P_{\max}\left[(1+u_{e1})\sin(\delta) - u_{e2}\cos(\delta)\right]$$

Select nonlinear PID control laws:

$$u_{e1} = K_{P_e}\cos\delta_s + K_{D_e}\sin\delta\dot{\delta} + K_{I_e}\sin\delta\int_0^t(\delta-\delta_s)d\tau$$

$$u_{e2} = K_{P_e}\cos\delta_s - K_{D_e}\cos\delta\dot{\delta} - K_{I_e}\cos\delta\int_0^t(\delta-\delta_s)d\tau$$

Perform HSSPFC steps results in:

-Static stability condition:

$$H = \frac{1}{2}J\dot{\delta}^2 + P_{\max}(1+K_{P_e})(1-\cos(\delta-\delta_s))$$

- Region of stability increased

$$\delta_s = \sin^{-1}\left(\frac{P_m}{P_{\max}}\right)$$

-Dynamic stability condition (power flow):

$$\oint_\tau \left[B + P_{\max}K_{D_e}\right]\dot{\delta}^2 dt > -\oint_\tau \left[P_{\max}K_{I_e}\int_0^t(\delta-\delta_s)d\tau_1\right]\dot{\delta}dt$$

- Integrator: faster system response

Sandia National Laboratories

Variable Generation and UPFC Connected to Infinite Bus

Model:

$$J_T\dot{\omega}_r = -K_T\omega_r + T_a - T_g$$

$$\omega_r = \dot{\theta}_r$$

$$\delta = \theta_r - \theta_{ref}$$

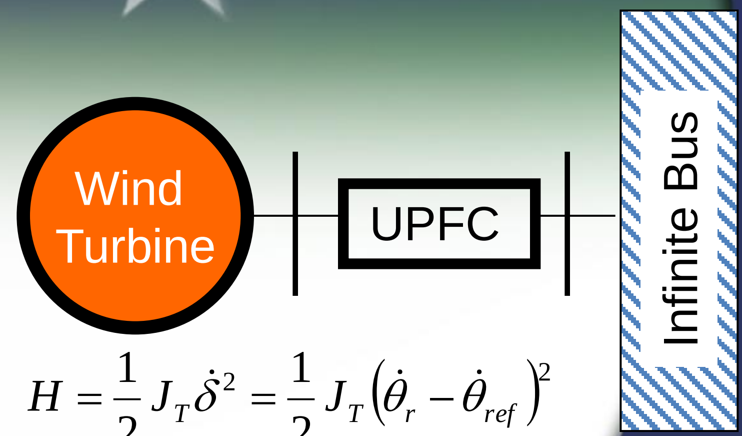
$$T_a = M\dot{\theta}_r^2$$

$$T_g = u_m + T_e$$

$$u_m = u_{m_{ref}} + \Delta u_m$$

$$u_{m_{ref}} = -J_T\ddot{\theta}_{ref} - K_T\dot{\theta}_{ref} + M\dot{\theta}_r^2$$

Variable (no longer constant)



Hamiltonian and Power Flow:

$$H = \frac{1}{2}J_T\dot{\delta}^2 = \frac{1}{2}J_T\left(\dot{\theta}_r - \dot{\theta}_{ref}\right)^2$$

$$\dot{H} = \left[-K_T\dot{\theta}_r + T_a - T_g - J_T\ddot{\theta}_{ref}\right]\dot{\delta}$$

$$\dot{H} = \left[-K_T\dot{\delta} - \Delta u_m - T_e\right]\dot{\delta}$$

Select wind generation and UPFC nonlinear PID controllers from HSSPFC:

$$\Delta u_m = fn(PID)$$

$$T_e = T_{e_{\max}}\left[\sin\delta + u_{e_1}\sin\delta - u_{e_2}\cos\delta\right]$$

$$u_{e_1} = fn(PID)$$

$$u_{e_2} = fn(PID)$$

Static stability condition and dynamic stability condition: similar to previous example

Sandia National Laboratories

Microgrid with UPFCs and Wind Turbine Connected to Grid (Infinite Bus)

Gen 2:

$$M_2\ddot{\delta}_2 = P_{m_2} - D_2\dot{\delta}_2 - C_{12}\sin\delta_{21} - C_{23}[(1+u_{21})\sin\delta_2 - u_{22}\cos\delta_2]$$

Wind Turbine:

$$J_T\ddot{\theta}_r = -K_T\dot{\theta}_r + T_a - T_g;$$

$$T_a = M\dot{\theta}_r^2, T_g = u_m + T_e,$$

$$u_m = u_{m_{ref}} + \Delta u_m; \delta_1 = \theta_r - \theta_{ref}$$

$$u_{m_{ref}} = -J_T\ddot{\theta}_{ref} - K_T\dot{\theta}_{ref} + M\dot{\theta}_r^2$$

$$\Delta u_m = K_{P_m}\delta_1 + K_{I_m}\int_0^t \delta_1 d\tau + K_{D_m}\dot{\delta}_1$$

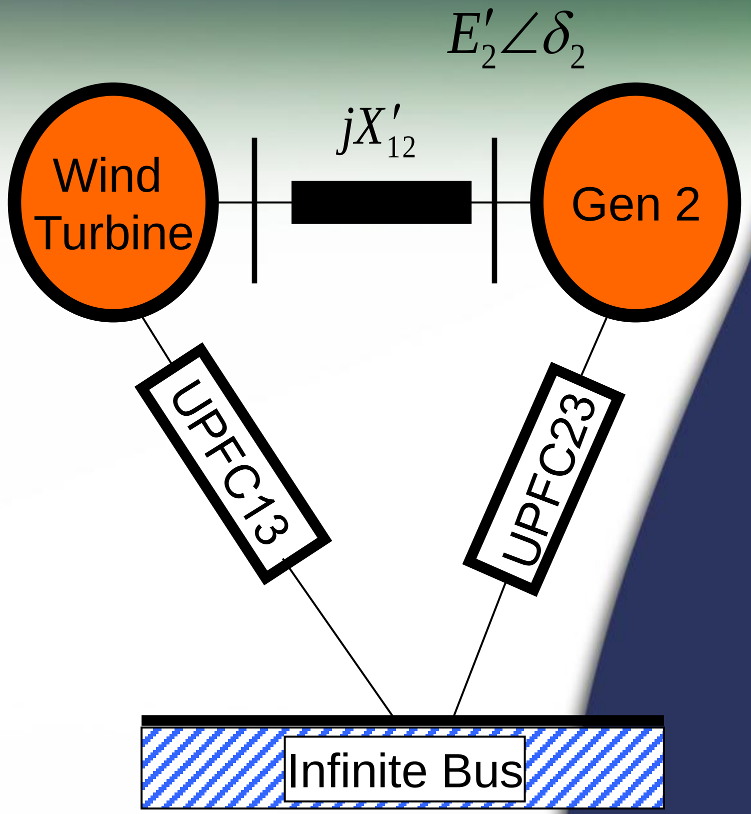
$$T_e = C_{13}[(1+u_{11})\sin\delta_1 - u_{12}\cos\delta_1] + C_{12}\sin\delta_{12}$$

$$H_T = \frac{1}{2}J_T\dot{\delta}_1^2 + \frac{1}{2}K_{P_m}\delta_1^2 + C_{12}[1-\cos\delta_{12}] + C_{13}[1-\cos\delta_1]$$

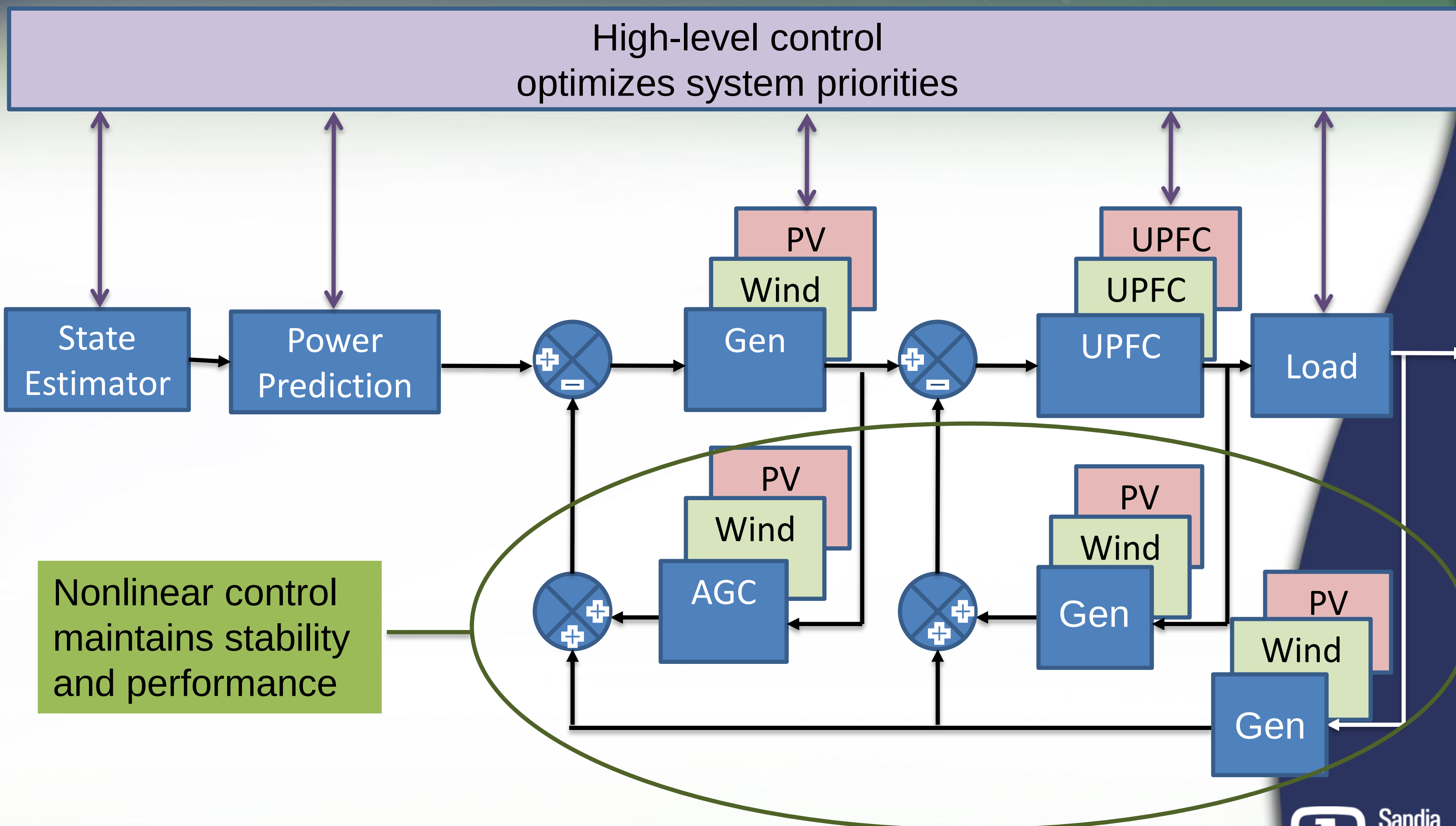
$$\dot{H}_T = [J_T\ddot{\delta}_1 + K_{P_m}\delta_1 + C_{13}\sin\delta_1 + C_{12}\sin\delta_{12}]\dot{\delta}_1 =$$

$$\left[-(K_T + K_{D_m})\dot{\delta}_1 - K_{I_m}\int_0^t \delta_1 d\tau - C_{13}(u_{11}\sin\delta_1 - u_{12}\cos\delta_1)\right]\dot{\delta}_1$$

$$\begin{bmatrix} J_T & 0 \\ 0 & M_2 \end{bmatrix}\begin{Bmatrix} \ddot{\delta}_1 \\ \ddot{\delta}_2 \end{Bmatrix} + \begin{Bmatrix} K_{P_m}\delta_1 + C_{13}\sin\delta_1 + C_{12}\sin\delta_{12} \\ C_{12}\sin\delta_{21} + C_{23}\sin\delta_2 \end{Bmatrix} = \begin{Bmatrix} -(K_T + K_{D_m})\dot{\delta}_1 - K_{I_m}\int_0^t \delta_1 d\tau - C_{13}(u_{11}\sin\delta_1 - u_{12}\cos\delta_1) \\ P_{m_2} - D_2\dot{\delta}_2 - C_{23}(u_{21}\sin\delta_2 - u_{22}\cos\delta_2) \end{Bmatrix}$$

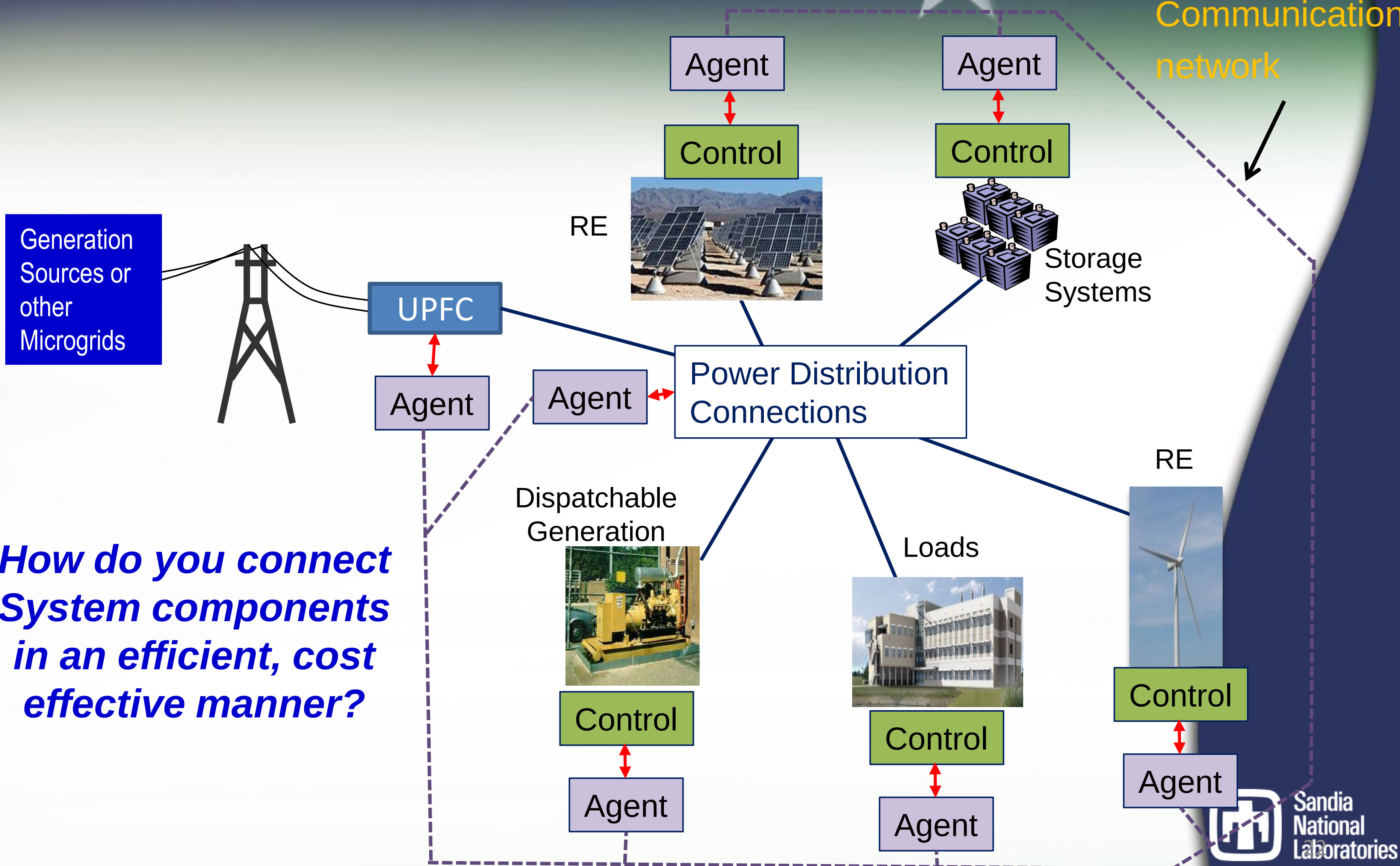


High-Level Control Enables Prioritization and System Adaptability



UPFC - Unified power flow controllers

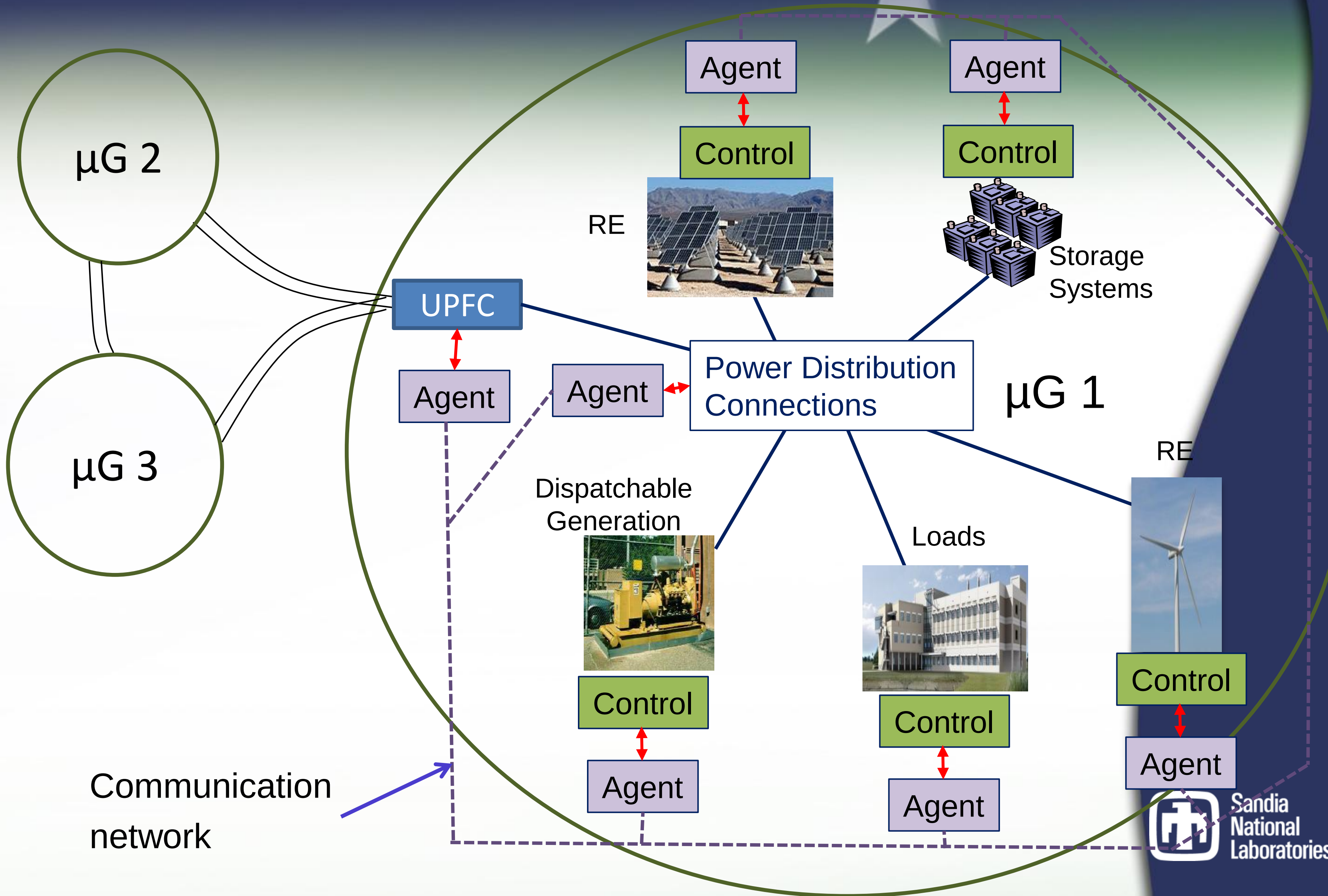
A Highly Interconnected Microgrid Will Result from these Advancements



How do you connect System components in an efficient, cost effective manner?

Sandia National Laboratories

These Microgrids will be Building Blocks for Large Networks



Sandia National Laboratories

DOE Has Identified Challenges That Must Be Addressed to Increase PV Penetration

- **14 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

http://www1.eere.energy.gov/solar/solar_america/rsi.html

Sandia National Laboratories

DOE is Addressing Wind Systems Integration Challenges

Challenges:

- Transmission Interconnection & Congestion
- Lack of knowledge of operational impacts and integration costs of wind energy
- Shortage of power system professionals with knowledge of wind energy
- Policy treatment of wind energy as an electricity resource

DOE Action:

- Assess wind's potential to serve our Nation's electricity needs
- Develop tools to assist the electric utility industry analyze wind energy
- Perform operational and interconnection studies with industry stakeholders nationwide
- Provide education curriculum for the next generation of wind energy professionals
- Reach out to federal, state, and local stakeholders on the challenges and solutions to wind energy integration

Results:

- Set the path for wind industry to accelerate its penetration
- Increase body of knowledge on wind/grid interconnection
- Help grow the delivery of emission-free energy from roughly 1 percent to the AEI's vision of 20 percent of our Nation's electricity usage

Sandia National Laboratories

Wind Radar Program

- **Project Goals:**
  - Streamline existing federal requirements
  - Establish coordinating mechanism
  - Identify technical solutions (wind turbine & radar side)
- **Long-Term Goal:**
  - Clear, timely, predictable Federal agency decision-making on wind siting processes
- **Past Accomplishments**
  - Supported interagency working group
  - Conducted radar baseline tests
  - Created wind radar interaction fact sheet
  - Performed case studies
  - Performed industry outreach
  - Supported IEA EU and NATO wind radar processes
  - Participated in joint DOE-INL-FAA-DOD assessments
- **Partners:** SNL, INL, DOD, DOE, DOT, DHS, FAA, USDA, Interior, Commerce, others TBD

Sandia National Laboratories

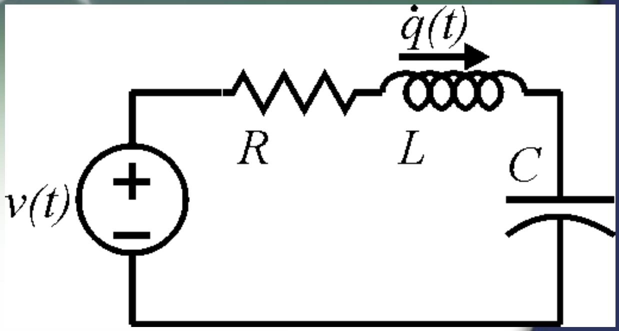
Next Steps, Summary, and Conclusions

- **Next Steps**
  - Continue to refine models/controls
  - Further numerical simulations
  - Baseline microgrid system analysis
- **Summary**
  - Renewables bring technical and operational challenges
  - We cannot continue to treat stochastic renewables as negative loads
  - Energy storage is not a silver bullet
- **Conclusions**
  - Microgrids can effectively align renewable energy resources with mission needs
  - Applied HSSPFC two-step process to analyze feedback controllers
  - Optimize UPFC with variable generation requirements

Backup Charts

Control Theory Needs to be Expanded from Simple to Complex Examples

Example system with control input v(t).



$$L\ddot{q} + \frac{1}{C}q = v(t) - R\dot{q}$$

PID controller: $v(t) = -k_p q - k_i \int q\,dt - k_d \dot{q}$

Hamiltonian:

$$H = \frac{1}{2}L\dot{q}^2 + \left(\frac{1}{2C}q^2 + \frac{1}{2}k_p q^2\right) = T(\dot{q}) + \left(V(q) + V_c(q)\right)$$

Control gains

Derivative of the Hamiltonian:

$$\dot{H} = \left[L\ddot{q} + \left(\frac{1}{C} + k_p\right)q\right]\dot{q} = \left[-k_i \int q\,dt - (R + k_d)\dot{q}\right]\dot{q}$$

Storage Generation, G Load, L

Controller gains are chosen for specific performance within the solution space defined by:

$$H = T(\dot{q}) + \left[V(q) + V_c(q)\right] > 0, \quad q \neq 0 \quad \text{where} \quad V(0) + V_c(0) = 0$$

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

R.D. Robinett and D.G. Wilson, **“**Nonlinear Power Flow Control Applied to Power Engineering”, Int’l Symposium on Power Electronics, Electrical Drives, Automation, and Motion, **SPEEDAM 2008,** June 11-13, Ischia, Italy, pp. 1420-7.

Sandia National Laboratories

Flexible AC Transmission System (FACTS) Power Electronic Controllers

- **Devices have two modes of operation**
  - Operating in shunt with power line: injected currents are controlled
    - Static Var Compensator (SVC)
  - Operating in series with the power line: inserted voltages are controlled
    - Unified Power Flow Controller (UPFC)
    - Controllable Series Capacitor (CSC)
    - Quadrature Boosting Transformer (QBT)
  - AKA Controllable Series Devices

- **Offer greater control of power flow**
- **Secure loading**
- **Damping of power system oscillations**

Injection Models of CSDs

•Valid for load flow and angle stability analysis
•Helpful to understand impact on power systems
•Model useful for purpose of developing control laws

Sandia National Laboratories