Renewable Systems Integration And Networked Microgrids: Where's the Storage?

Dr. Rush D. Robinett III

Sandia National Laboratories

Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2011-6823C

Introduction: My Filters/Biases

- Aerospace engineer by training
  - Dynamics, Controls, and Optimization
  - TAMU and UT-Austin
- Looking for a driving/dominant input for a controller design (stability; single point failure)
- Applying it to self-organizing, complex adaptive systems
  - Networked Microgrids and Smart Grid

A Path From Today's Grid To The Future (Smart) Grid

Basic Problem: How do we create a stable, resilient, sustainable, optimized grid of the future with high penetration (up to 100%) of variable renewables?

- **This is a hunt for the replacement of lost energy storage**
  - *Fossil fuel*
  - *Large spinning machines (inertia)*
- **From 100% energy storage solution to ?%**
- **How do we trade information flow and energy storage for dispatchable fossil fuel?**

A Path From Today's Grid To The Future (Smart) Grid (cont.)

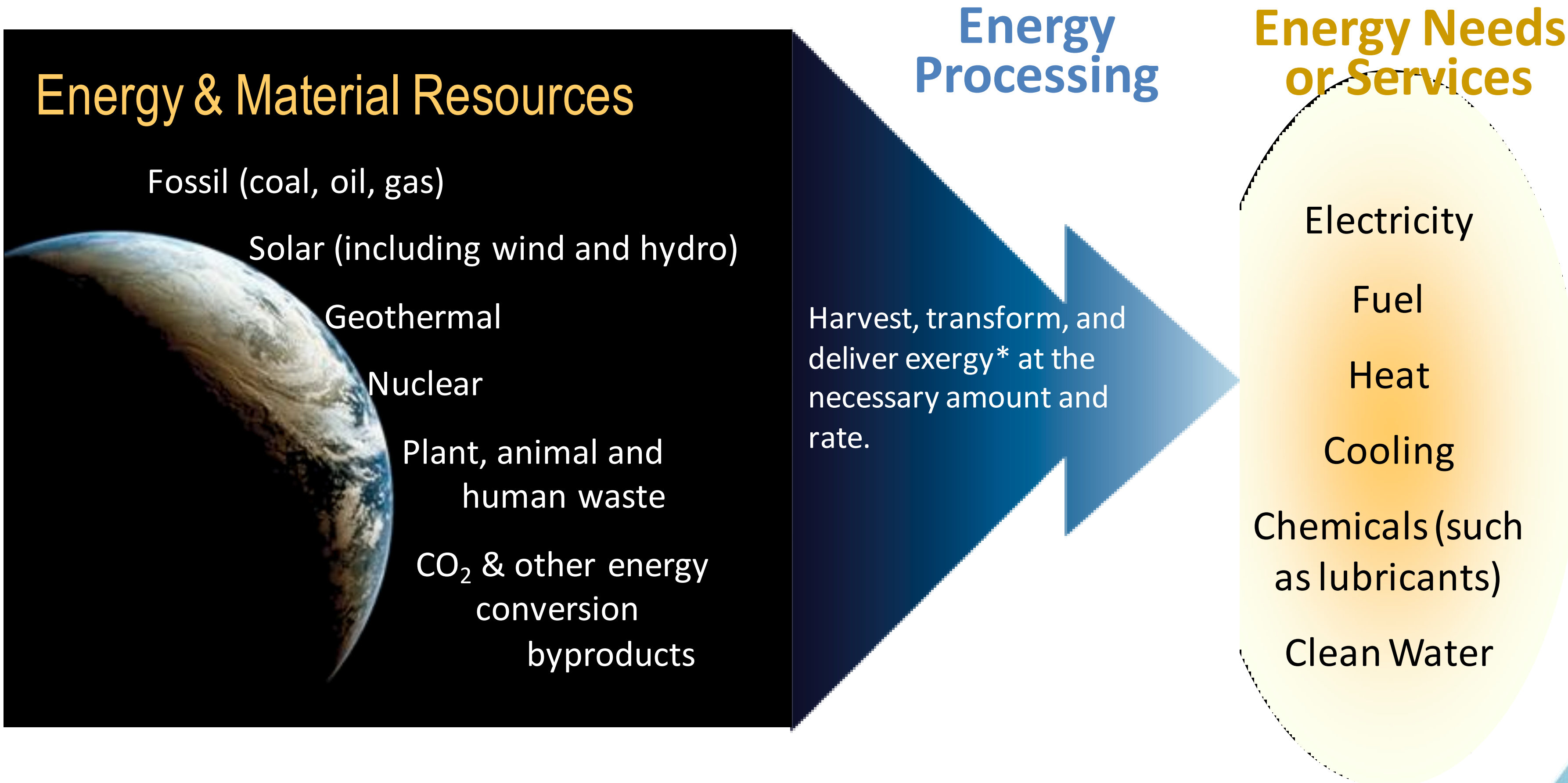
System Questions:

1. How do we compare energy supplies apples-to-apples?
2. How do we stabilize the grid of the future without fossil/dispatchable supply?
3. How do we compare energy storage technologies

   including dispatchable loads?
4. How do we minimize the required information flow and additional energy storage to replace fossil/dispatchable supply?

Sandia National Laboratories

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



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

Apples-to-Apples Metric

Exergy is the elixir of life.

Exergy ***that portion of energy available to do work***

(i.e.,ordered energy that is out of equilibrium with its environment; Hydro-power)

Elixir a substance held capable of prolonging life indefinitely

(i.e., sustainable; fountain of youth)

Sandia National Laboratories

Fundamentals of Thermodynamics

- Insights from the Laws of Thermodynamics:
  - The energy of the Universe is constant
  - The entropy of the Universe tends to a maximum

Fundamentals of Thermodynamics (Cont.)

Said another way:

I. "Energy" can be neither created nor destroyed, only changed from one form to another.

II. In using any form of Energy, it is not all "Available" to perform useful "Work". A portion of it is "Unavailable" and must be discarded, usually in the form of "Heat".

III. All processes and activities involve Energy changes and hence must obey Laws I and II. These changes always result in the degradation of some Available Energy into Unavailable Energy.

Sandia National Laboratories

Fundamentals of Thermodynamics (Cont.)

These insights have been likened to being in a one-sided poker game with Mother Nature, where the stakes are Exergy.

I. *You can't win.*
   (You cannot get more out than you put in.)

II. *You can never break even.*
   (The "House" always takes a percentage of the stakes.)

III. *You can't even get out of the game.*
   (All of existence involves Exergy.)

Confusing Energy and Exergy

Economics: Looking for a scarce resource

- Energy is conserved; not a scarce resource
- Exergy is consumed/degraded; is a scarce resource.

Confusing Energy and Exergy (Cont.)

Efficiency: 2^{nd} Law versus 1^{st} Law

- A second law efficiency is the ratio of the minimum amount of available work required to do a particular job to the amount of available work used to do the job.
- Contrast this with a first law efficiency which is the ratio of energy out to energy in.

First Law of Thermodynamics (1)

- A statement of the existence of a property called Energy
  - Energy is a state function that is path independent
  - A conservative function in the context of mechanics
  - Path independent work: adiabatic work where no heat is exchanged with the environment
  - Raising and lowering a mass in a friction-less way referred to as a weight process. In this process, no entropy is transferred or created in this reversible system.

$$E_2 - E_1 = -W_{12}$$

E_i – Energy at state i of system

W_{12} – Work done by system between states 1 and 2

Source: E.P. Gyftopoulos and G.P. Beretta, **Thermodynamics, Foundations and Applications**, MPC, NY, 1991.

Sandia National Laboratories

First Law of Thermodynamics (2)

- A corollary of the First Law that is often referred to as the First Law is

$$dE = \delta Q - \delta W$$

$dE -$ change of state; path independent

$\delta Q -$ flow of heat; path dependent

$\delta W -$ work done by the system; path dependent

- Energy balance equation for work and heat interactions and identified as the conservation of energy

Second Law of Thermodynamics (1)

A statement of the existence of stable equilibrium states and of special processes that connect these states together

- **Equilibrium State:** A state that does not change with time while the system is isolated from all other systems in the environment
- **Stable Equilibrium State:** A finite change of state cannot occur, regardless of interactions that leave no net effects in the environment
- **Restate Second Law:** Among all the allowed states of a system with given values of energy, number of particles, and constraints, one and only one is a stable equilibrium state

Source: E.P. Gyftopoulos and G.P. Beretta, Thermodynamics, Foundations and Applications, MPC, NY, 1991.

Sandia National Laboratories

Second Law of Thermodynamics (3)

- The entropy production during an irreversible process is:

$$dS \geq \frac{\delta Q}{T}$$

where

$$dS = d_e S + d_i S$$

$d_e S$ - Entropy change due to exchange of energy and matter (entropy flux)

$d_i S$ - Entropy change due to irreversible processes

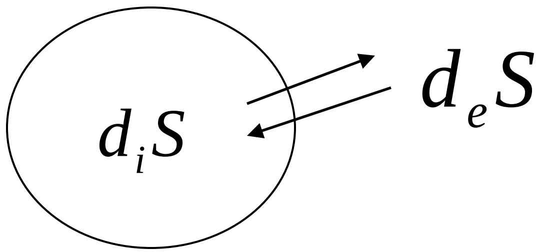
- Entropy balance equation

Source: D. Kondepudi and I. Prigogine, **Modern Thermodynamics: From Heat Engines to Dissipative Structures**, John Wiley & Sons, New York, N.Y., 1999.

Sandia National Laboratories

Second Law of Thermodynamics (4)

- The entropy fluxes and irreversible entropy production



- The irreversible entropy production

$$d_iS = \sum_k F_k dX_k \geq 0$$

where $F_k - k^{th}$ thermodynamics force

$X_k - k^{th}$ thermodynamics flow

which appears to be a scaled power flow or work rate with a scaling factor of

$$1/T_0$$

Sandia National Laboratories

Local Equilibrium – Exergy

- **Local Equilibrium:** Thermodynamic quantities are well-defined concepts locally (i.e., within each elemental volume)
  - Temperature is not uniform, but is well defined locally
  - Non-equilibrium systems: define thermodynamic quantities in terms of densities
  - Thermodynamic variables become functions of position and time

- Rate Equations
  - Energy:

$$\dot{E} = \sum_j \dot{Q}_j + \sum_k \dot{W}_k + \sum_l \dot{m}_l (h_l + ke_l + pe_l + \ldots)$$

  - Entropy:

$$\dot{S} = \dot{S}_e + \dot{S}_i = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_k \dot{m}_k s_k + \dot{S}_i$$

$$\dot{S}_i = \sum_l F_l \dot{X}_l \geq 0$$

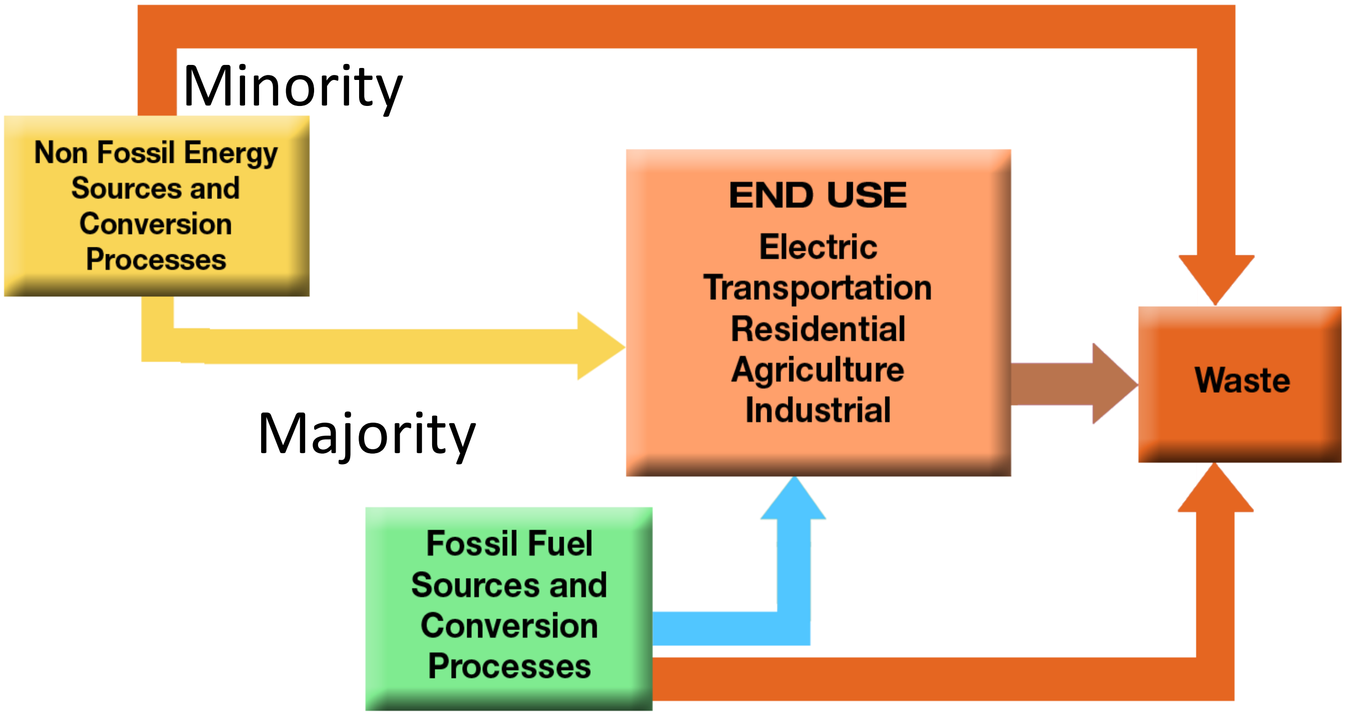
  - Exergy (Available work)

$$\dot{\Xi} = \dot{E} - T_O \dot{S} = \sum_j \left(1 - \frac{T_O}{T_j} \dot{Q}_j\right) + \sum_k (\dot{W}_k - p_O \dot{\bar{V}}) + \sum_l \dot{m}_l \zeta_l^{Flow} - T_O \dot{S}_i$$

Sandia National Laboratories

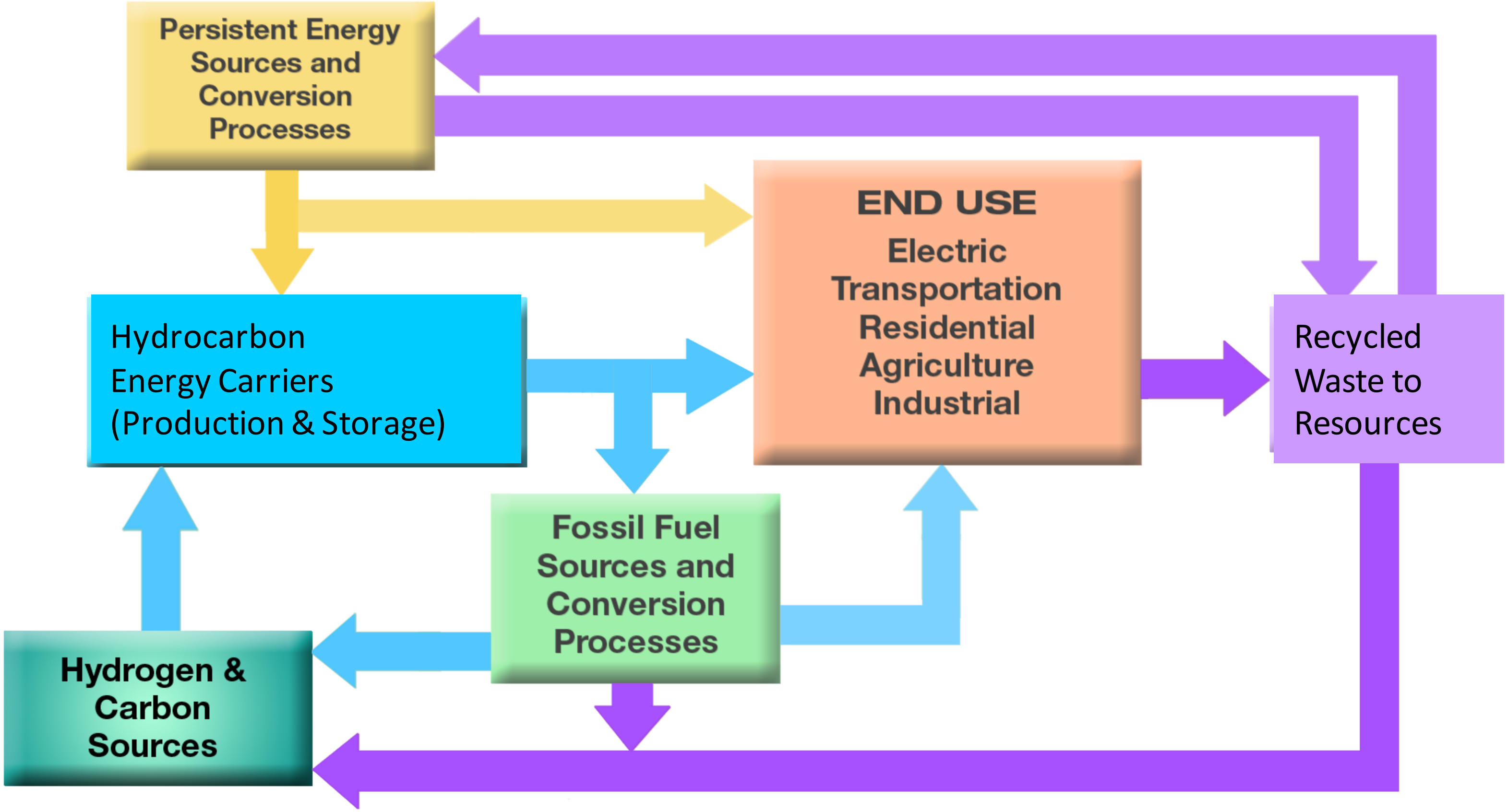
The Current Energy System is Full of Losses, an Open Cycle, and Highly Vulnerable

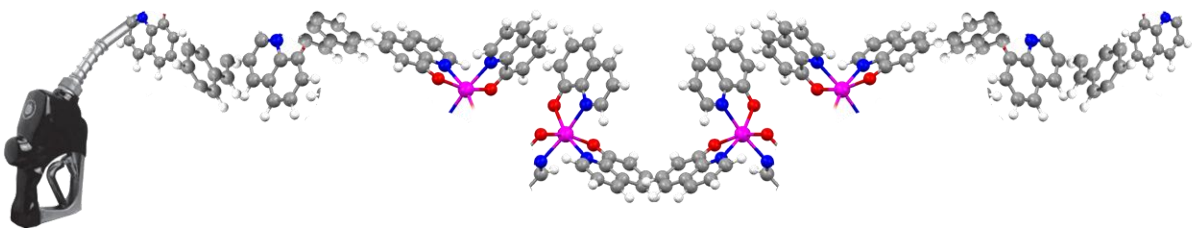
- **Fossil Fuel** dominated infrastructure.
- Over 50% of US energy **resources lost** in conversion and transport.
- **Diversity** of energy resources **difficult** to accommodate.
- Reliance on nature to **absorb waste** by-products.
- Infrastructure capacity, flexibility, and reliability is **limited**.
- **Resource competition** with India and China.
- **Unpredictable** and volatile energy prices.



Sandia National Laboratories

A Flexible, Adaptive Energy Infrastructure, with a Hydrocarbon "Core" Offers a Path Forward





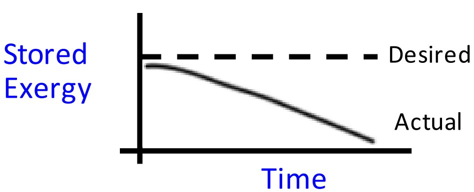
A Road To A Sustainable Future

Today: Open Cycle Systems	Near-Term: Closed Reversible Cycles	Mid-Term: Closed Sustainable Cycles	Far-Term: Fusion
2010	2015	2025	2050?

2010

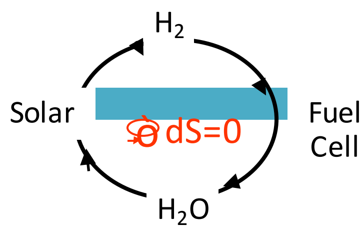
Example: Fossil Fuel Plant

- Heat Engine
- Combustion By-Products Exhausted to Atmosphere
- Biosphere Closes the Loop



2015

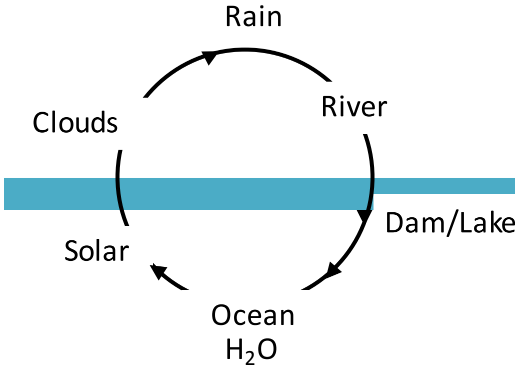
Examples: H_2 Production, Hybrid Vehicles



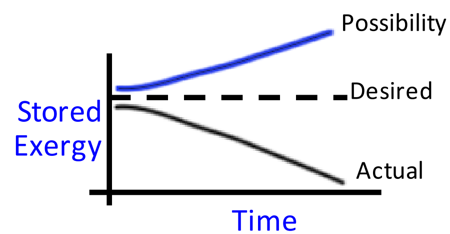
- Use closed cycles to improve efficient use of current available resources
- Equilibrium Thermodynamics

2025

Example: Hydropower



- Irreversible entropy productions (i.e., sediment) are compensated for by persistent availability
- Store excess availability for adaptability/self-organize
- Sustainable living energy infrastructure
- Non-equilibrium / irreversible thermodynamics



2050?

Vision: Bring Sun to the Earth (and Deep Space)

Sandia National Laboratories

Sustainability: Exergy/Entropy Limit Cycle

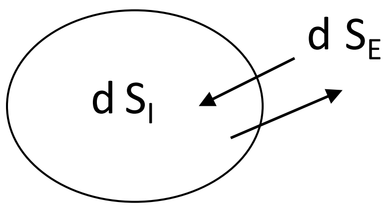
- **Bruntland Commission:** A form of sustainable development which meets the needs of the present without compromising the ability of future generations to meet their own needs.

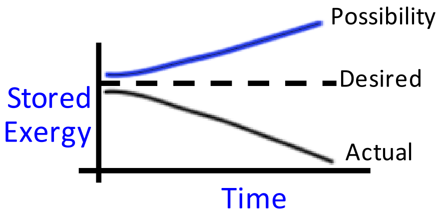
- **Technical Definition:** To provide continuous compensation of irreversible entropy production in an open system (to meet needs) with an impedance and capacity – matched persistent exergy source.

- **Survive**!; Exergy Parasite:

$$\text{Exergy Consumption Rate} = T_o * d(S_I)/dt$$

- **Ideal Situation**: $d\,S_I + d\,S_E \leq O$





- Example #1: Subsistence Farming

- Example #2: Hydroelectric Power

Sandia National Laboratories

Work, Energy, and Power (1)

- The work done by a force is $dW = \underline{F} \cdot d\underline{r}$

  $W -$ Work

  $\underline{F} -$ Force Vector

  $\underline{r} -$ Position Vector

- The power generated by a force is

$$P = \frac{d}{dt}W = \underline{F} \cdot \frac{d}{dt}\underline{r} = \underline{F} \cdot \dot{\underline{r}}$$

  $P -$ Power

  $\dot{\underline{r}} -$ Velocity Vector

- The kinetic energy can be derived from Newton's 2nd law $(\underline{F} = m\ddot{\underline{r}})$

$$dW = \underline{F} \cdot d\underline{r} = m\ddot{\underline{r}} \cdot d\underline{r} = m\dot{\underline{r}} \cdot d\dot{\underline{r}} = d\left(\frac{1}{2}m\dot{\underline{r}} \cdot \dot{\underline{r}}\right) = dT$$

$T = \frac{1}{2}m\dot{\underline{r}} \cdot \dot{\underline{r}} =$ Kinetic Energy

Work, Energy, and Power (2)

- The potential energy can be derived from a state function that is independent of time

$$\underline{F}(\underline{r}) \cdot d\underline{r} = -dV(r)$$

$$V(\underline{r}_1) - V(\underline{r}_2) = \int_{\underline{r}_1}^{\underline{r}_2} \underline{F}(\underline{r}) \cdot d\underline{r}$$

V — Potential Energy

with a conservative and path independent force field

$$\oint \underline{F} \cdot d\underline{r} = 0$$

$$\frac{dT}{dt} = \underline{F} \cdot \dot{\underline{r}} = -\frac{dV}{dt} \Rightarrow \frac{d}{dt}(T+V) = 0$$

$$\Rightarrow T + V = \overline{E} = \text{ Constant}$$

$\overline{E}$ – Total Energy (stored energy)

- $\overline{E}$ is often called the total energy in mechanics and is a state function that is path independent. We refer to it as the "stored energy" and will be identified as "stored exergy" since all of the energy can do work (available work).

Work, Energy, and Power (4)

- We will focus on “natural systems” (no explicit time-dependence)

$$\frac{d\overline{E}}{dt} = \frac{d}{dt}(T+V) = \underline{F}_{NC} \cdot \underline{\dot{r}}$$

- Non-conservative applied forces - perform work on and flow power into the system (generators) as well as dissipate energy within in the system by frictional forces (dissipators).
- Thermodynamics, the energy and entropy balances for an adiabatic irreversible work process where work is done on the system, no entropy is exchanged with environment, and irreversible entropy is produced through dissipation are

$$E_2 - E_1 = -W_{12}$$

$$S_2 - S_1 = S_{IRR}$$

$$\dot{\Xi} = \dot{W} - T_o S_i$$

Sandia National Laboratories

Hamiltonian Mechanics (3)

- **For most natural systems:**

$$\frac{\partial L}{\partial t} = 0$$

$$\dot{H}(\underline{q}, \underline{\dot{q}}) = \sum_{j=1}^{N} Q_j \dot{q}_j$$

Power (work/energy) flow equation

Sandia National Laboratories

Connect Thermodynamics To Hamiltonian Mechanics (3)

- **Hamiltonian is stored exergy since potential and kinetic energies are available work; Exergy rate relationship:**

$$\dot{H} = \sum_k Q_k \dot{q}_k = \underline{F}_{NC} \cdot \underline{\dot{q}}$$

$$\dot{\Xi} = \dot{W} - T_o \dot{S}_i = \sum_{j=1}^{N} Q_j \dot{q}_j - \sum_{l=N+1}^{M+N} Q_l \dot{q}_l = \underline{F}_{NC} \cdot \underline{\dot{q}}$$

a) $\dot{W}$ – Power flowing in (N generators)

b) $T_o \dot{S}_i$ - Power Dissipation (M Dissipators)

c) $\dot{S}_i = \sum_k F_k \dot{X}_k = \frac{1}{T_o} \sum_k Q_k \dot{q}_k \geq 0$ (Assuming Local Equilibrium)

Sandia National Laboratories

Line Integrals and Limit Cycles (1)

- Cyclic Equilibrium Thermodynamics:

$$\oint dU = \oint TdS - \oint pd\overline{V} = 0$$

$$\oint dE = \oint TdS - \oint dW = 0$$

$$\Rightarrow \oint pd\overline{V} = \oint TdS$$

$$\Rightarrow \oint dW = \oint TdS$$

- Cyclic Non-Equilibrium Thermodynamics with Local Equilibrium

$$\oint \dot{H}dt = \oint [\dot{W} - T_o\dot{S}_i]dt = 0$$

$$\Rightarrow \oint \dot{W}dt = \oint T_0\dot{S}_i dt$$

$$\Rightarrow \oint [\sum_{j=1}^{N} Q_j\dot{q}_j]dt = \oint [\sum_{k=N+1}^{M+N} Q_k\dot{q}_k]dt$$

A Path From Today's Grid To The Future (Smart) Grid (cont.)

Today's Grid | **Fossil** ▷ | **Fixed Infrastructure** ▷ | **Load** ▷

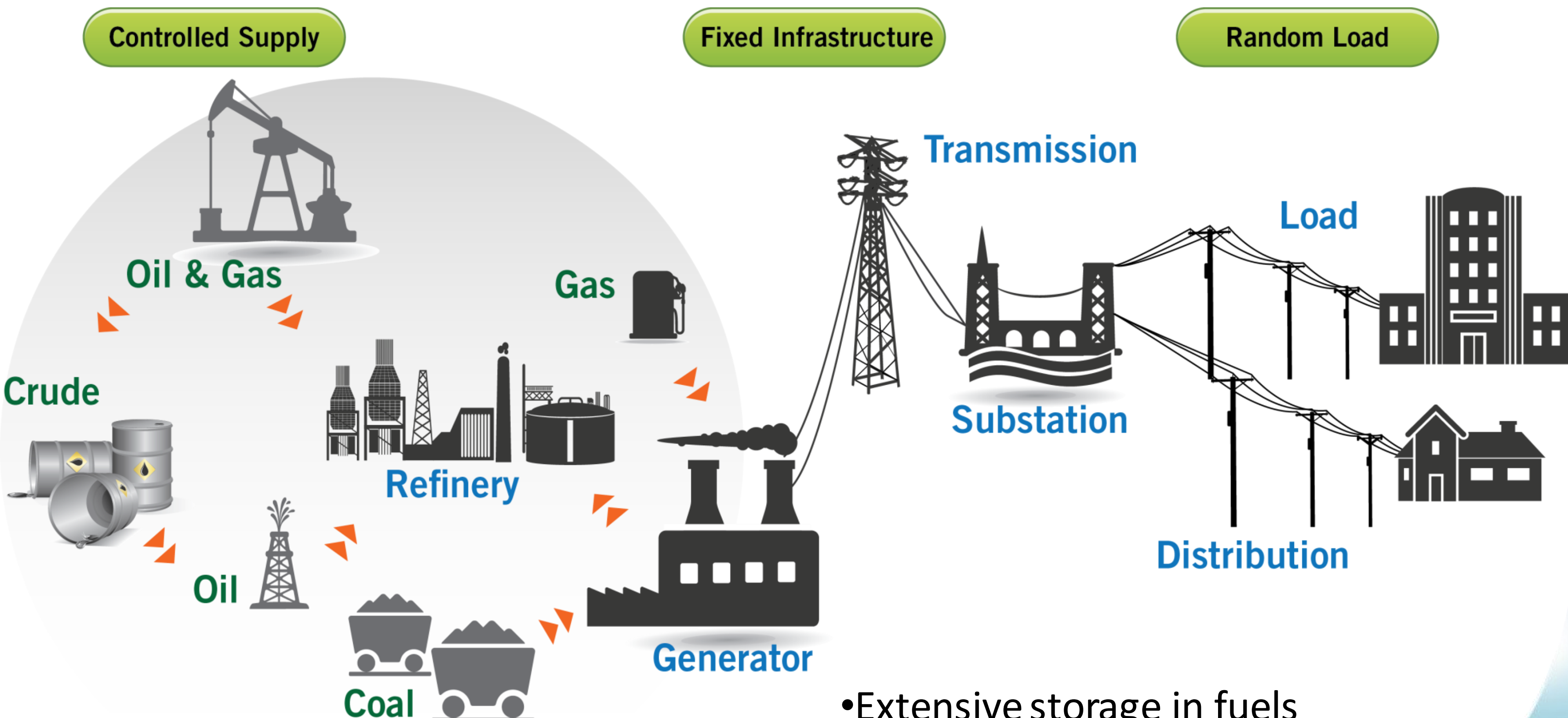
- **Large spinning machines → Large inertia (matrix); dispatchable supply with storage**
- **Constant operating conditions → well-ordered state**
- **Well-known load profiles → excellent forecasting**

$$[I]\dot{\underline{x}}=\underline{f}(\underline{x},\underline{u},t)\ ;\ [I]^{-1} \underline{\sim} [0] \ \rightarrow\ \dot{\underline{x}}=[I]^{-1}\,\underline{f}(\underline{x},\underline{u},t) \underline{\sim} \underline{0}\ ;\ \underline{x}(t)=\underline{x}_0$$

$$G-L\geq 0\ \forall t$$

Sandia National Laboratories

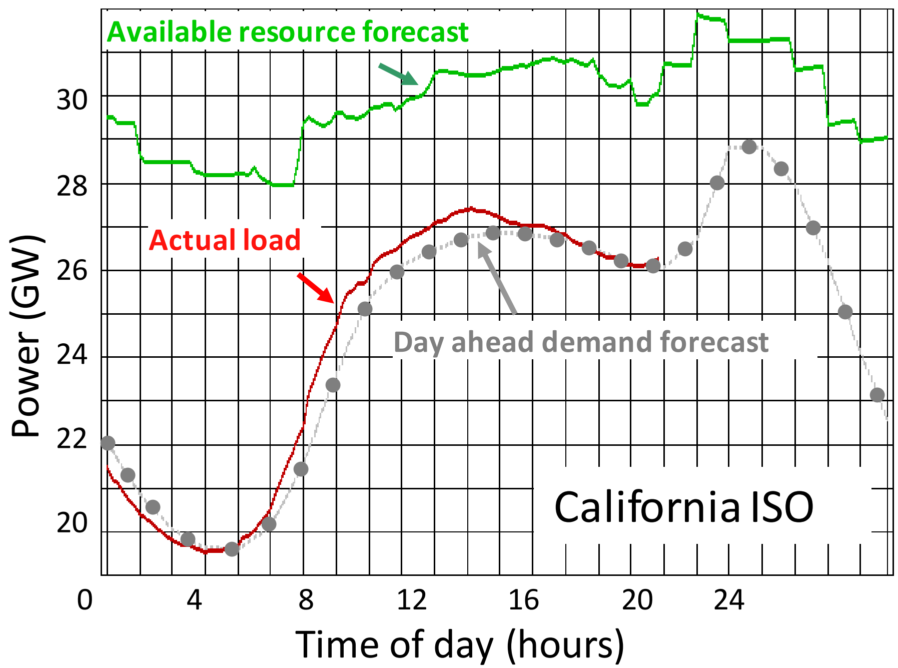
Today's Power Grid is Designed for Dispatchable Centralized Generation



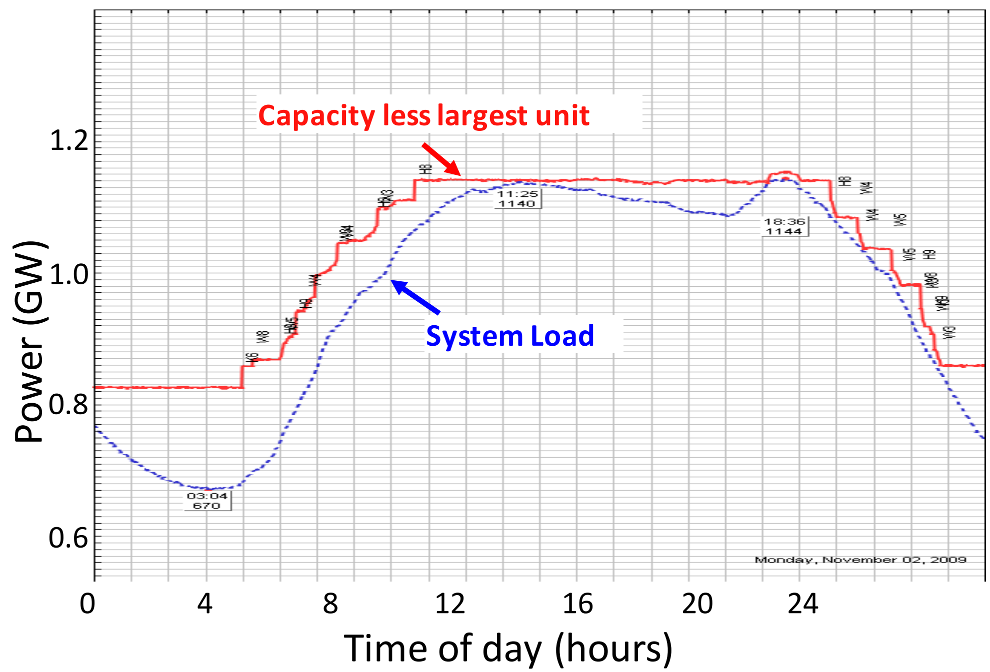
- Extensive storage in fuels
- Fixed infrastructure is inflexible
- Significant human interaction

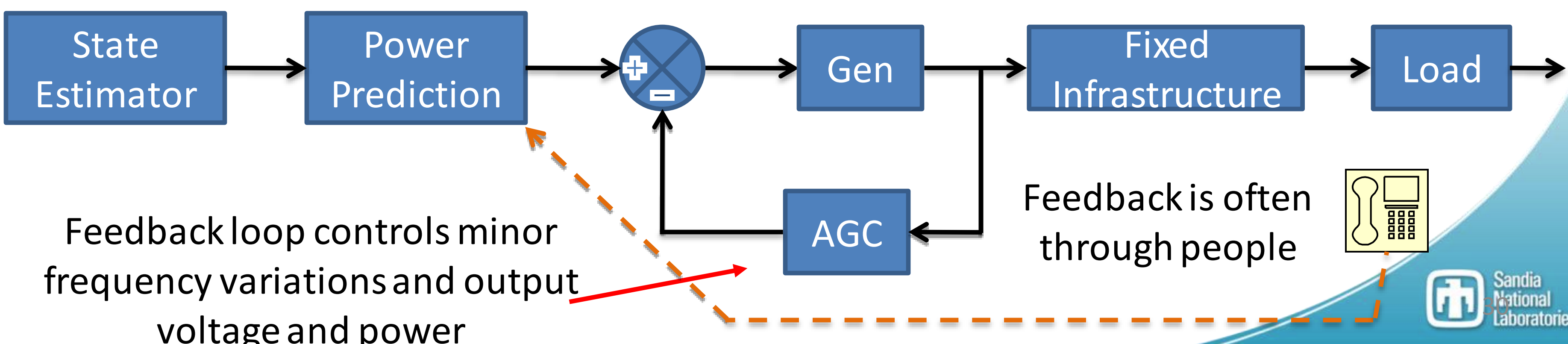
Loads are Predictable, Allowing Essentially Open-loop Grid Control

Forecasting is used to set generation



Hawaiian Electric Co. daily load vs capacity

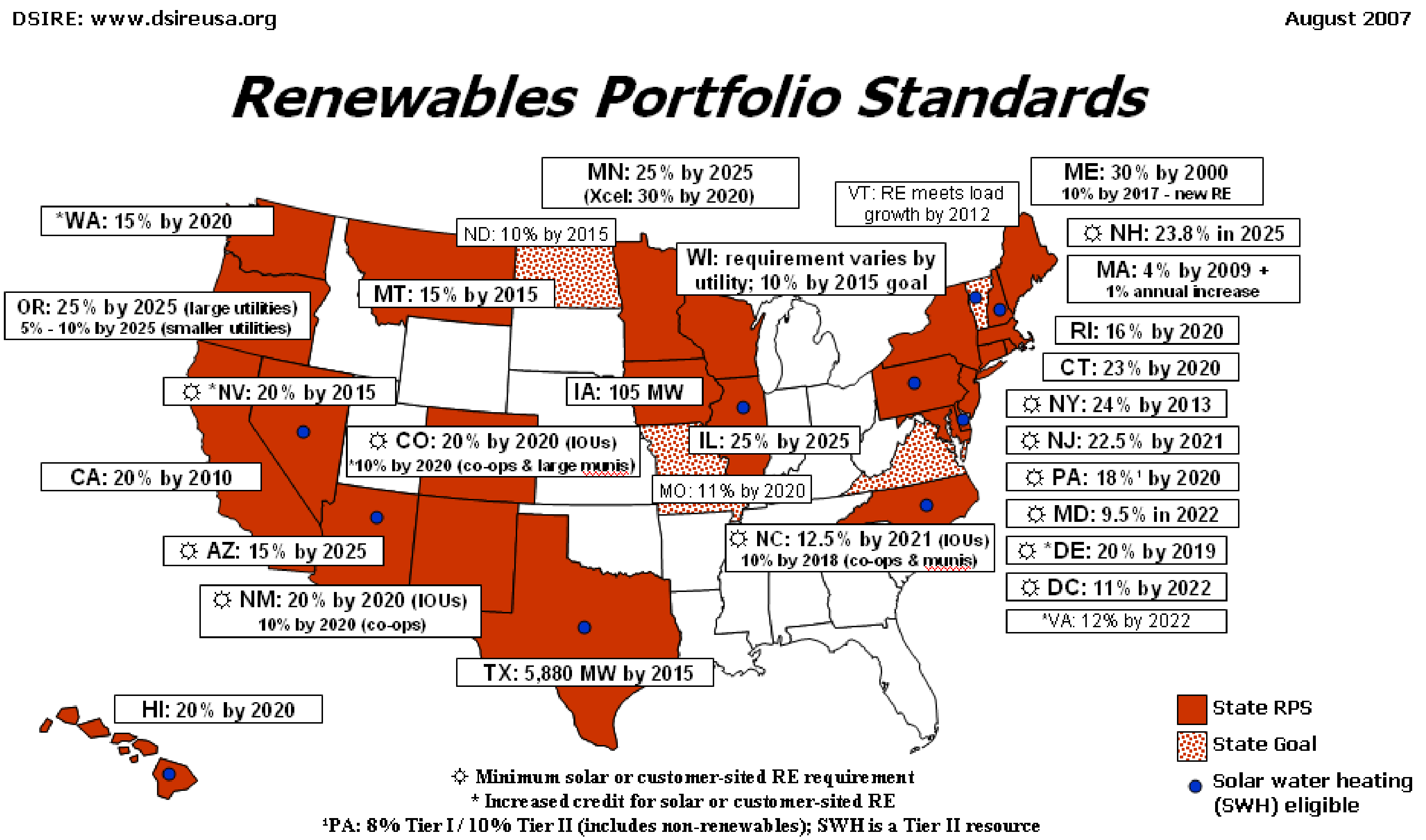




An Emerging Market:

Preparing for Large-Scale Renewable Energy Integration

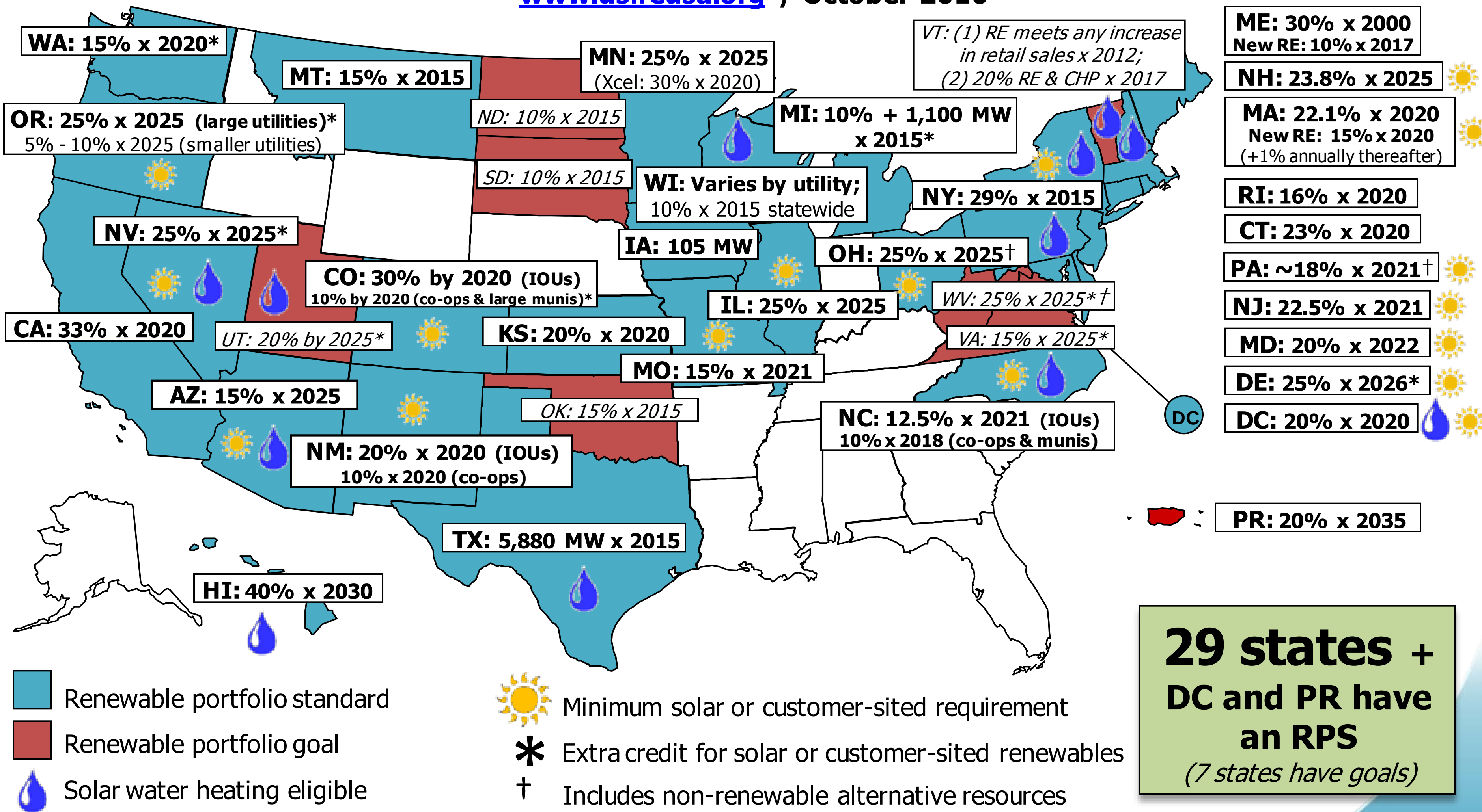
New Market Scenario: **Climate change concerns, renewable portfolio standards, incentives, and accelerated cost reduction driving steep growth in U.S. renewable energy system installations.**



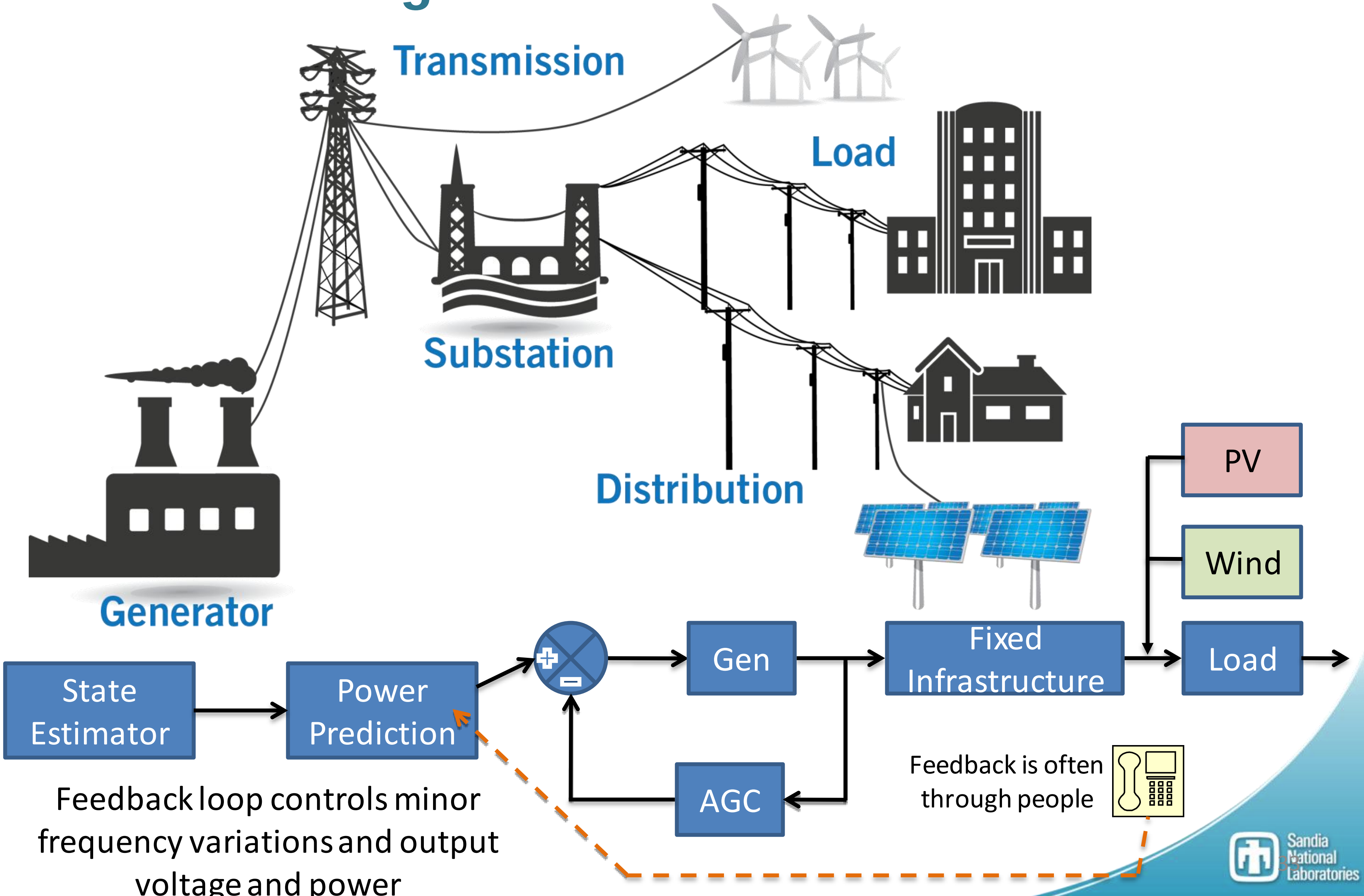
Sandia National Laboratories

Latest RPS Policies

www.dsireusa.org / October 2010

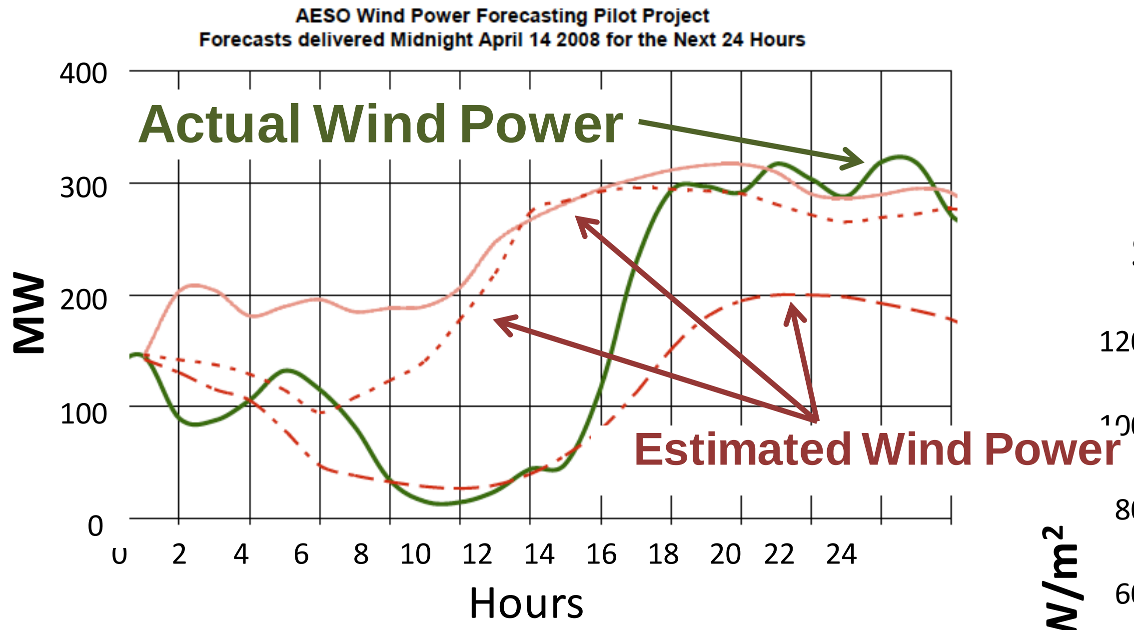


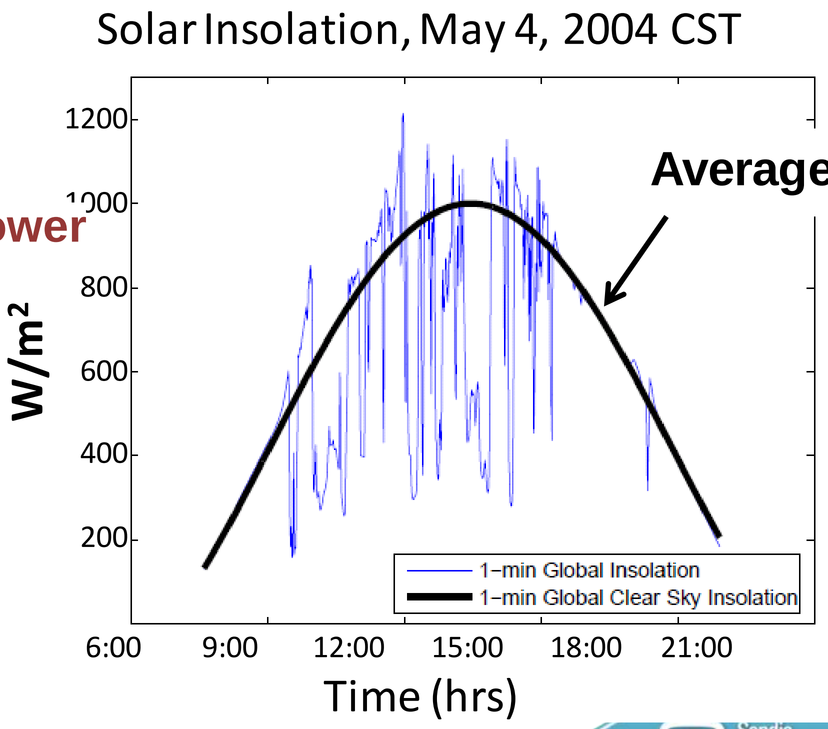
Today, Stochastic Renewable Sources are Treated as Negative Loads



Stochastic Sources (Negative Loads) Complicate Load Forecasting

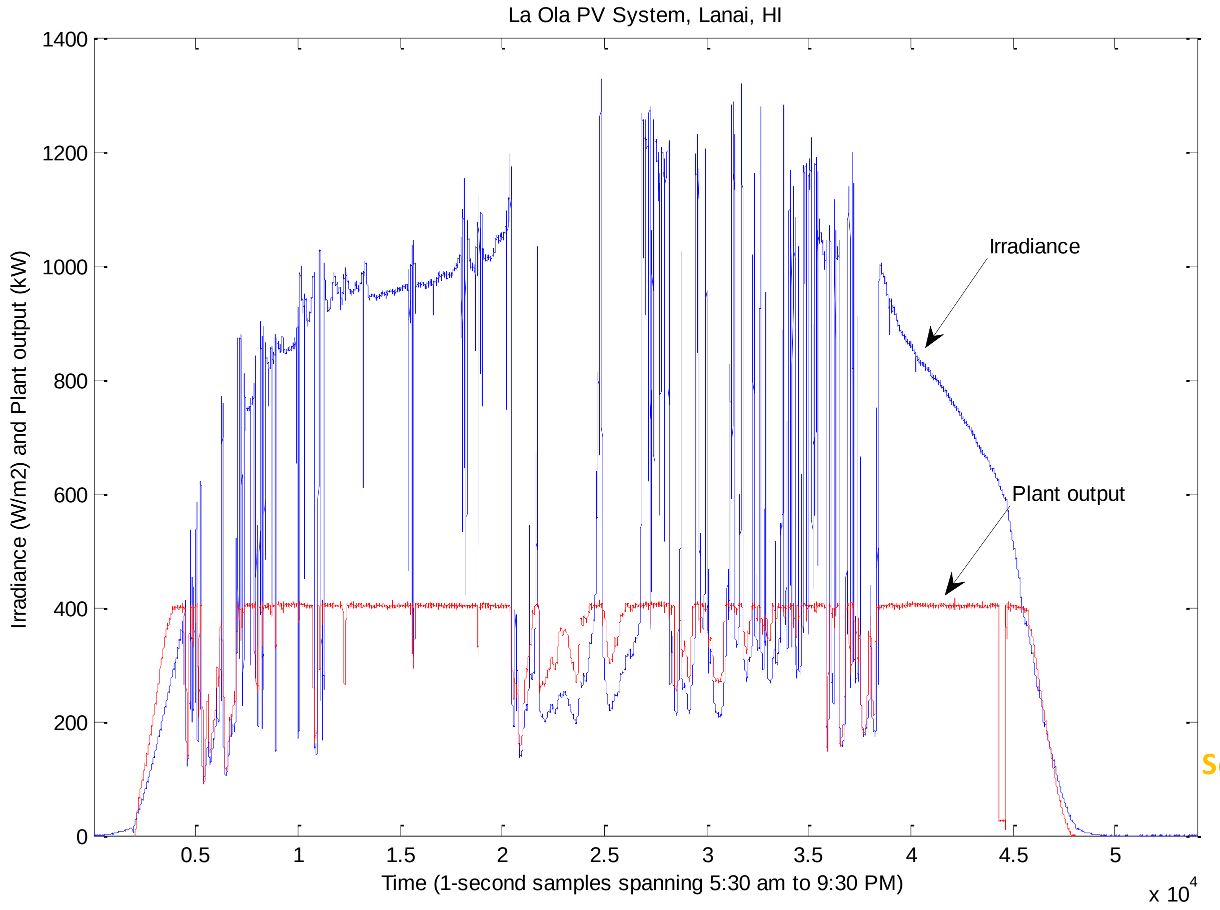
Wind power forecasting example





This is weather forecasting!

PV Output Can Vary Considerably on an Average Day



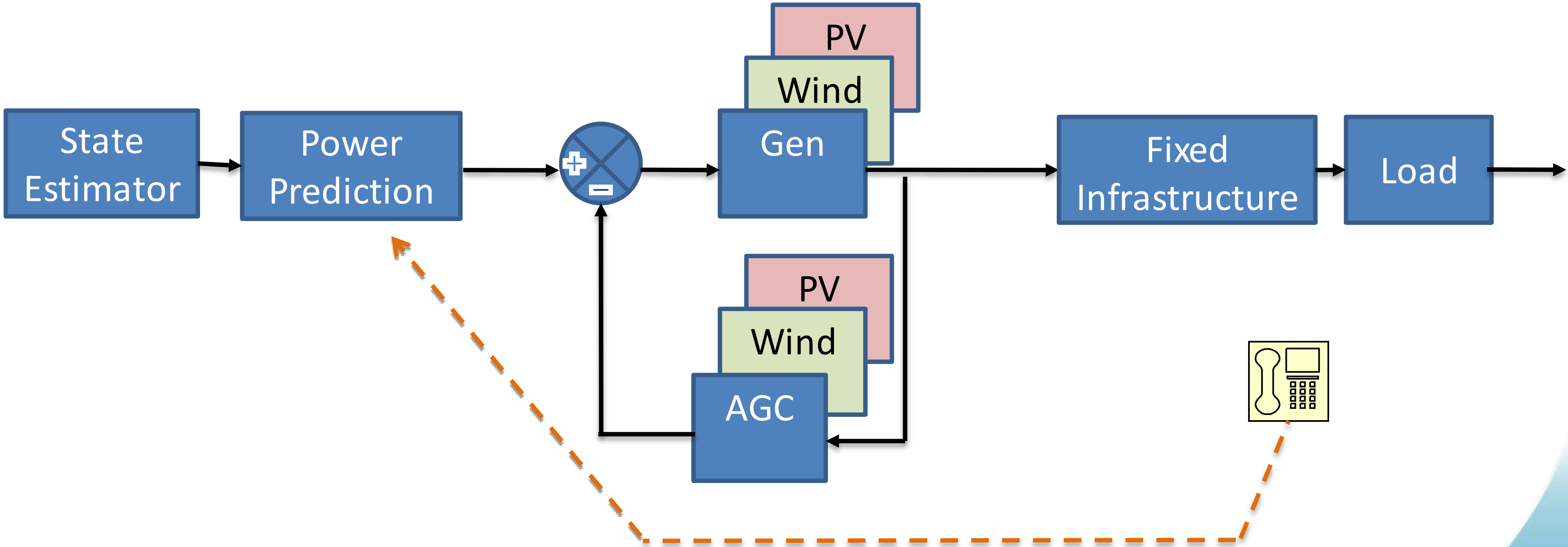
Source: SunPower

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)**

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!

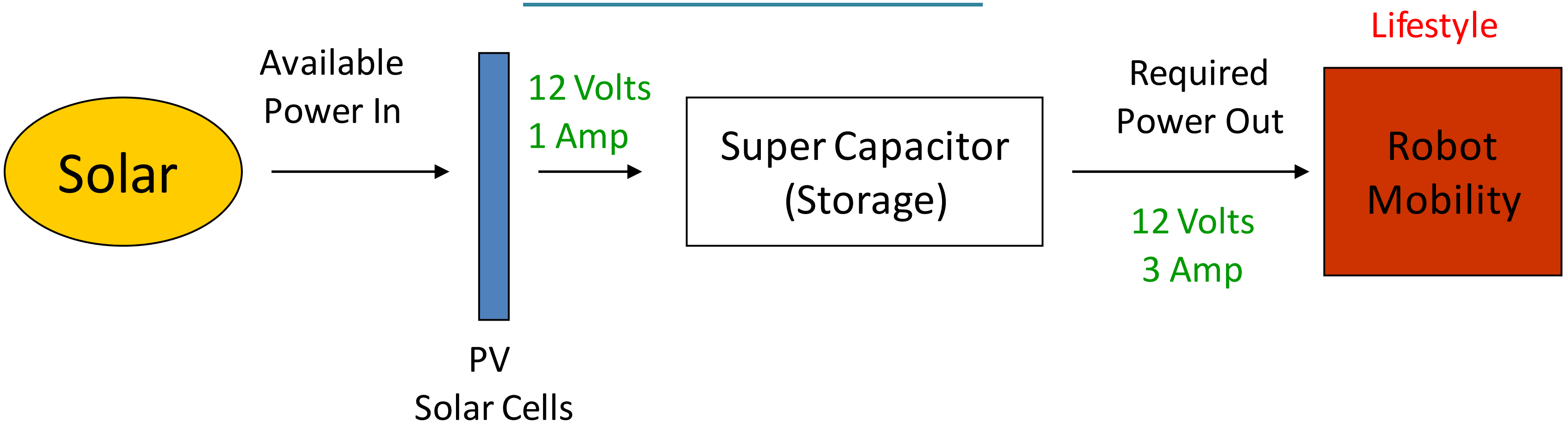
A Path From Today's Grid To The Future (Smart) Grid (Cont.)

<u>Retain Today's Grid:</u> Replace lost storage with serial or parallel additional energy storage

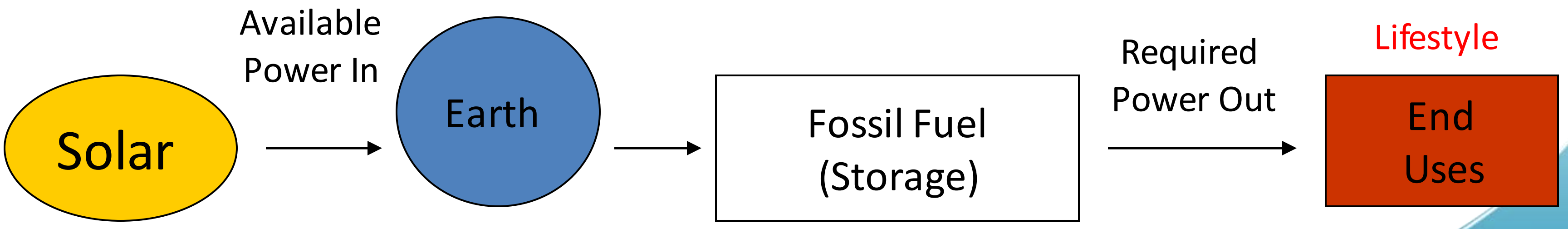
Storage: Impedance and Capacity Matching Solution

Specific applications justify electrical energy storage solutions

Autonomous Mars Rover

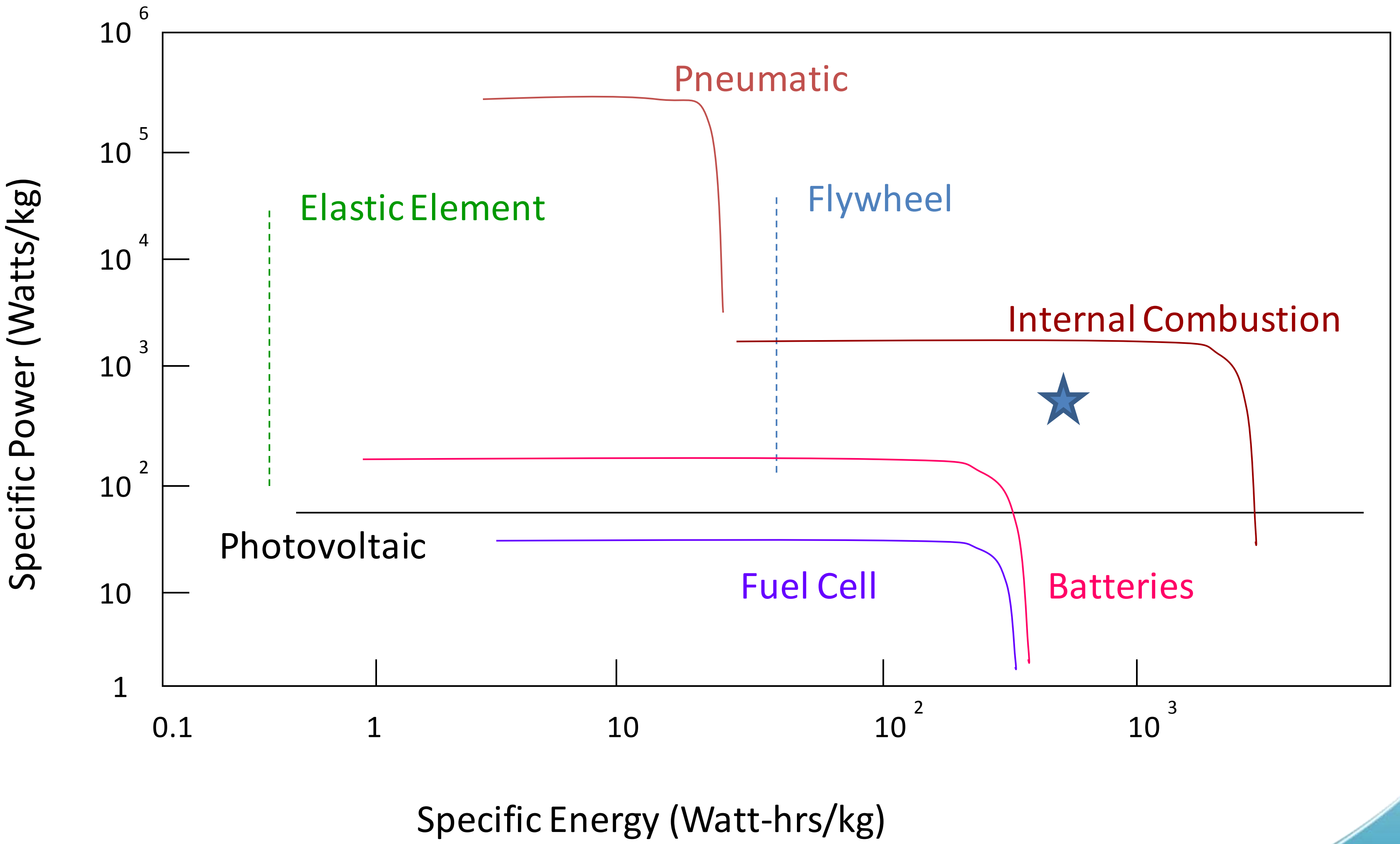


Autonomous Man on Earth



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

Impedance/Capacity Mismatch (Duty Cycle)



Sandia National Laboratories

A Path From Today's Grid To The Future (Smart) Grid (cont.)

Future Grid:

1. High penetration of renewables: loss of storage
   - ➞ Loss of large spinning machines
   - ➞ Loss of dispatchable supplies
2. Variable operating conditions → variable state x(t)=?
3. Stochastic load profiles → renewables as negative loads

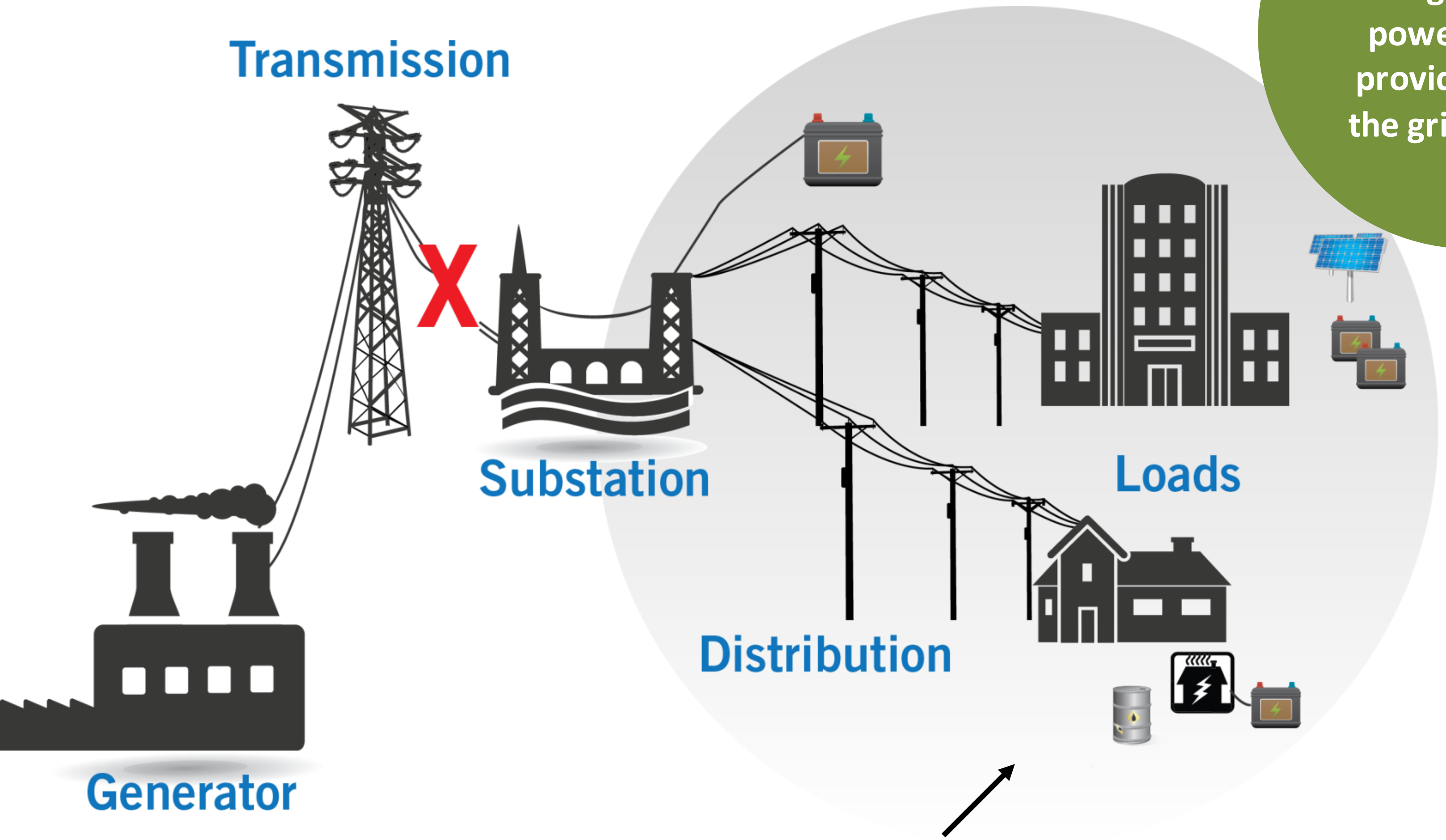
   $[I_F]\, \dot{\underline{x}} = \underline{f}_F(\underline{x},\underline{u},t) \rightarrow \dot{\underline{x}}_F(t) = [I_F]^{-1}\, \underline{f}_F(\underline{x},\underline{u},t)$

   $G-L \leq 0$ much of the time
4. Problem Restated: How do we regain
   a) Well-ordered state → $\underline{x}(t)$?
   b) Well-known load profiles?
   c) Dispatchable supply with energy storage?
   d) Stability and performance?
   e) An optimal grid?

Sandia National Laboratories

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

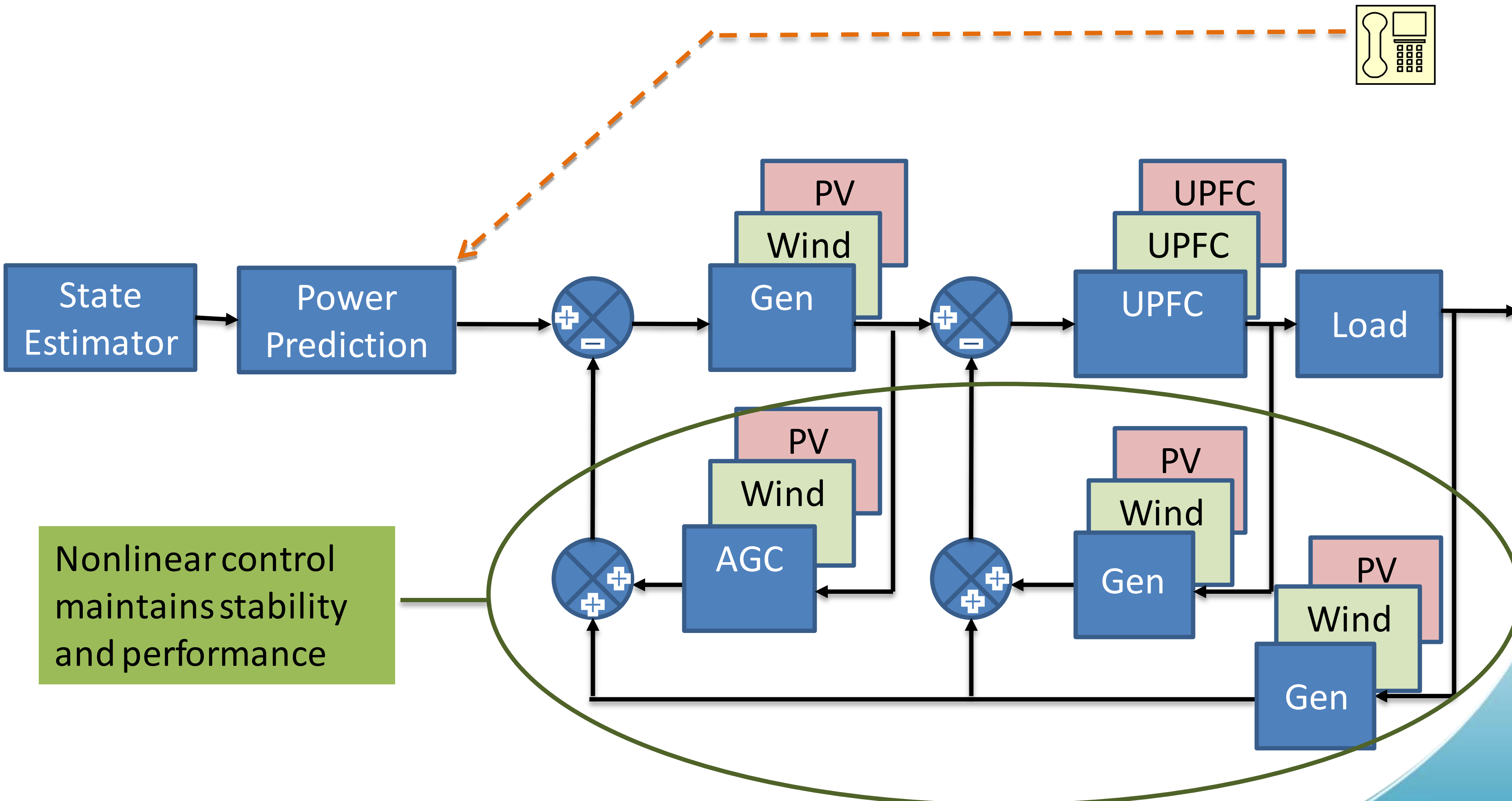
With distributed generation and storage, electric power can be provided when the grid is down



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

Sandia National Laboratories

Mid-Level Distributed Nonlinear Control Enables Stability and Transient Performance



UPFC - Unified power flow controllers

A Path From Today's Grid To The Future (Smart) Grid (cont.)

Our Solution Approach:

1. **A combination of feedback control and added energy storage**
   a) *Requires a trade-off between information flow (control) and added energy storage while simultaneously minimizing both*
   b) *Requires maximizing performance while ensuring stability*

2. **Develop a set of tools**

The Details:

1. **Need consistent models (equations of motion)**
   1. MATLAB / Simulink
2. **Need a consistent metric for all energy supplies, energy storage, and dispatchable loads**
   - Exergy: A measure of order

Sandia National Laboratories

Energy Storage and Dispatchable Loads (1)

A Path From Today's Grid To The Future (Smart) Grid (cont.)

3. **Need to stabilize the grid and define stability boundaries (nonlinear)**
   - *Hamiltonian Surface Shaping and Power Flow Control (HSSPFC)*
   - *Measure of order*

4. **Need to span the space of solutions for optimization process**

RE ▷ **Fixed Infrastructure** ▷ **Load** ▷

- 0% storage; under-actuated; limited state space ($G-L \le 0 \ \forall t$)

Fossil ▷ **Fixed Infrastructure** ▷ **Load** ▷

- 100% storage; over-actuated; full state reachability ($G-L \ge 0 \ \forall t$)

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

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

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

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.

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

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

Individual microgrid Hamiltonian

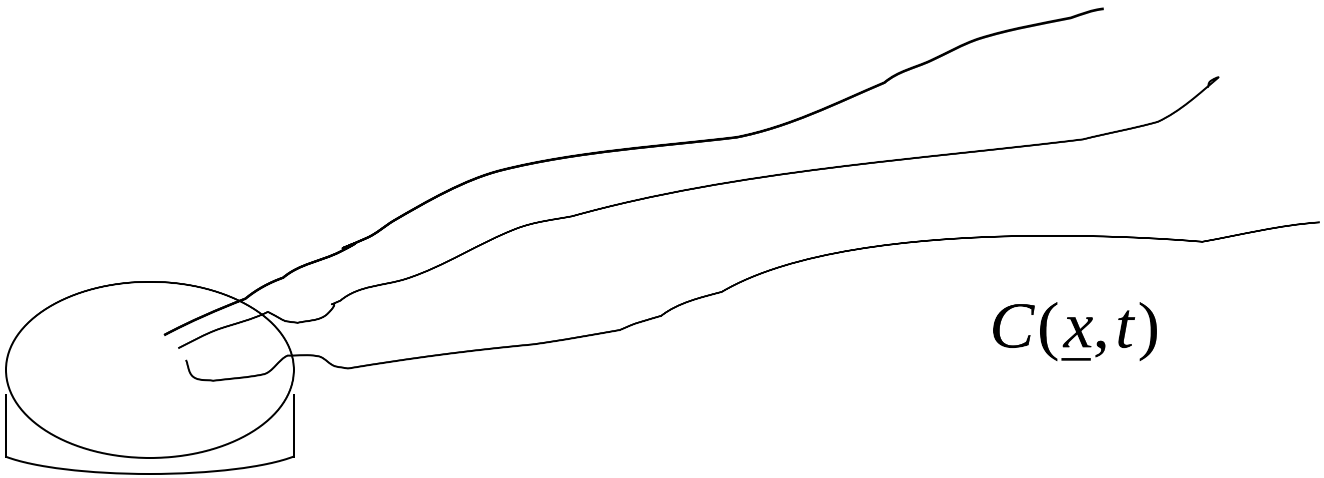
R.D. Robinett and D.G. Wilson, "Hamiltonian Surface Shaping with Information Theory and Exergy/Entropy Control for Collective Plume Tracing", ***Int. J. Systems, Control and Communications***, Vol. 2, Nos. 1/2/3, 2010

A Path From Today's Grid To The Future (Smart) Grid (cont.)

5. **Need to trade off/minimize information flow and energy storage while minimizing risk and uncertainty**

An Example of Minimizing Information Flow and the Physical System: Robotics

- **Problem**: Track a chemical plume to its source; find buried landmines



- **Characteristics**: 1- Nonlinear time/spatially varying plume field

  2-Complicated model-turbulence

  3-Difficult to correlate model to data in time/space

  4- Can't count on wind or water flow direction

  5- Sensor Latency

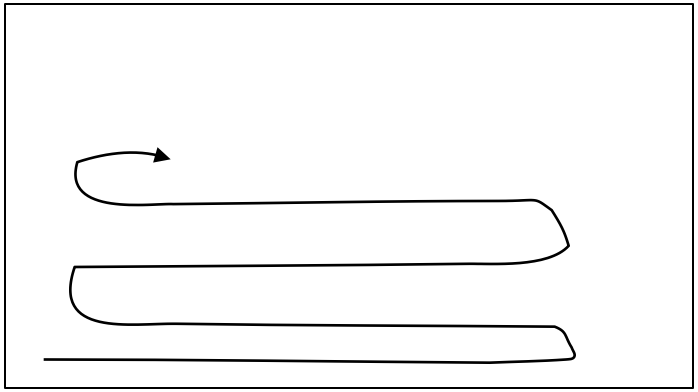
Solution ??

Sandia National Laboratories

Example #1: Robotic Collective Plume Tracing (2)

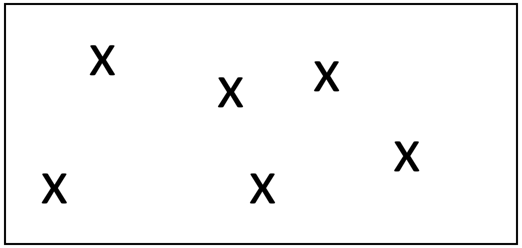
- **Possible solution:** Person with a chemical sensor and a GPS receiver

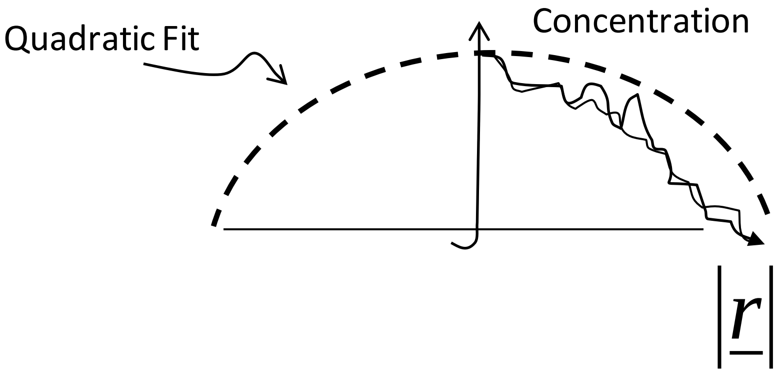
1. Time–spatial correlation issues
2. Sensor latency/dynamic range issues
3. No redundancy
4. Leads to exhaustive search



Example #1: Robotic Collective Plume Tracing (3)

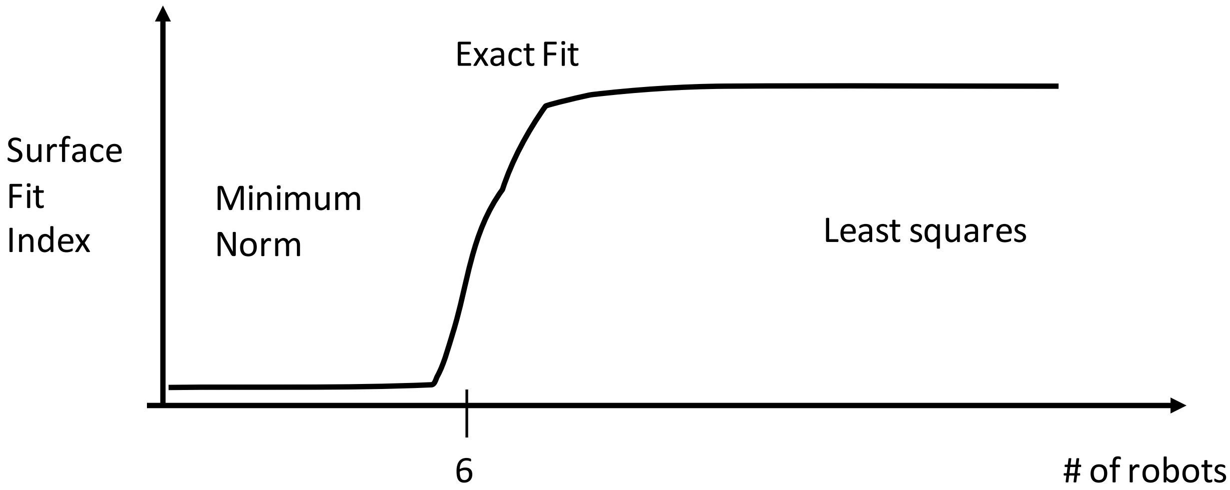
- **Collective Solution:** Team of simple robots performing a collective search
  - Distributed sensing
  - Decentralized control (optimization/Newton update)
  - Simple model of plume
  - Redundant
  - Independent of latency for stability (Performance?)
  - **Minimize processing, memory, and communications**
  - Beat down noise





Example #1: Robotic Collective Plume Tracing (4)

- **Emergent Behavior:** Quadratic fit w/o memory

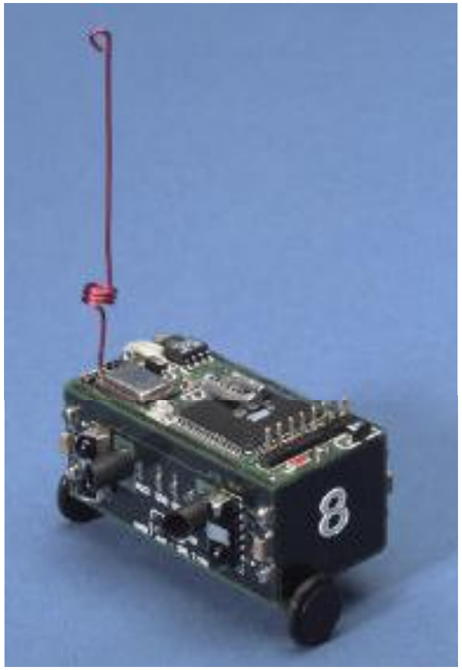


- **Evaluate Resource Utilization:** Trade-off between processing, memory, and communications
  - Baseline: Minimize all three simultaneously
    - 8 bit processor, no memory, broadcast 3 words

Sandia National Laboratories

Example #1: Robotic Collective Plume Tracing (5)

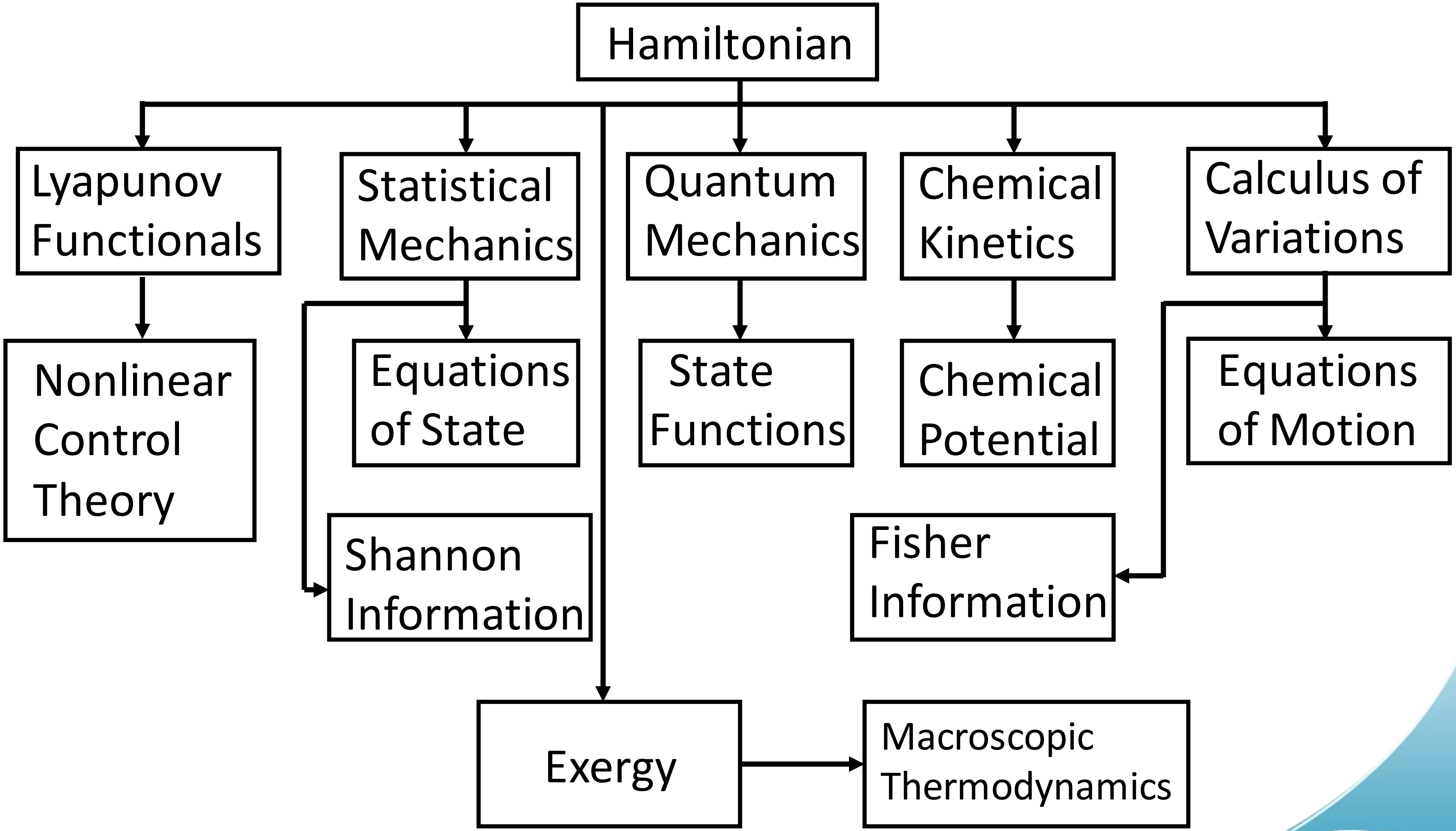
- Goal of DARPA Distributed Robotics [Ref. Byrne] Program: build smallest, dumbest robot that couldn't do anything other than random motion
- As a team of like robots - could solve complicated problem
- N land-based robots whose task to localize a source that emits a measurable scalar field F(x)
- Robots evaluate the field with a sensor and communicate locations and sensor measurements to neighboring robots
- Robots shared sensor information, but individually decided course of action based on their own estimate of plume field
- Robot samples its environment, broadcasts information to others



0.75x0.71x1.6 inches
Onboard temperature sensor
8-bit RISC processor
CSMA radio network
50 Kbits/sec data rate

Source: [Ref. Byrne] Byrne, et. al., *Miniature Mobile Robots for Plume Tracking and Source Localization Research*, J. MicroMech., Vol. 1, No. 3, 2002.

Example #1: Robotic Collective Plume Tracing (6)



Sandia National Laboratories

Example #1: Robotic Collective Plume Tracing (7)

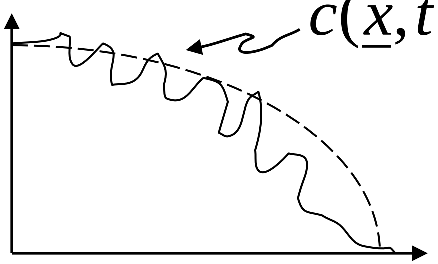
- **Kinematic Control** – No dynamics; assume tight autopilot loop; control velocity (speed)

1. Need to measure plume field: $c(\underline{x},t)$ – concentration at a point in time

2. Convert concentration measurements to range and bearing to target

   $\Rightarrow$ Fit a quadratic surface to distributed sensor measurements

   $\Rightarrow$ Perform decentralized Newton updates for feedback control



$$\hat{c}(\underline{x},t) = \hat{c}_o + \hat{c}_1^T \underline{x} + \frac{1}{2}\underline{x} + \hat{c}_2 \underline{x}$$

$$\frac{\partial \hat{c}}{\partial \underline{x}} = 0 \Rightarrow \underline{x}_{k+1} = -\alpha \hat{c}_2^{-1} \hat{c}_1 + x_k$$

3. Shape the "virtual potential" with a minimum (maximum) at $\underline{x}^* = -\hat{c}_2^{-1}\hat{c}_1$ for Hamiltonian to meet static stability requirements for the i^{th} robot:

$$H_i = V_{c_i}(\underline{x}_i) = \frac{1}{2}\hat{c}_1^T \hat{c}_2^{-1} \hat{c}_1 + \hat{c}_1^T \underline{x}_i + \frac{1}{2}\underline{x}_i^T \hat{c}_2 \underline{x}_i > 0 \quad \forall \underline{x}_i \neq \underline{x}^*$$

Example #1: Robotic Collective Plume Tracing (8)

And collective robots

$$H = \sum_{i=1}^{N} H_i = \sum_{i=1}^{N} V_{c_i} > 0 \quad \forall \underline{x}_i \neq \underline{x}^*$$

4. Design the power flow, time derivative of the Hamiltonian, to meet the dynamic stability requirements for the feedback controller

$$\dot{\underline{x}}_i = -\hat{c}_2^{-1}\left[\hat{c}_1 + \hat{c}_2 \underline{x}_i\right] = -\hat{c}_2^{-1}\hat{c}_1 - \underline{x}_i = \underline{x}^* - \underline{x}_i$$

Linear Tracker

$$\underline{x}_{cm} = \frac{1}{N}\sum_{i=1}^{N} \underline{x}_i \Rightarrow \dot{\underline{x}}_{cm} = \frac{1}{N}\sum_{i=1}^{N}\left[-\underline{x}_i + \underline{x}^*\right] = -\underline{x}_{cm} + \underline{x}^*$$

$$\dot{H}_i = \dot{\underline{x}}_i^T\left[\hat{c}_1 + \hat{c}_2 \underline{x}_i\right] = -\left[\hat{c}_1 + \hat{c}_2 \underline{x}_i\right]^T \hat{c}_2^{-1}\left[\hat{c}_1 + \hat{c}_2 \underline{x}_i\right] < 0$$

$$\dot{H} = \sum_{i=1}^{N} \dot{H}_i < 0$$

Sandia National Laboratories

Example #1: Robotic Collective Plume Tracing (10)

- **Information Theory** applied to:
  1. **Kinematic Control:** Shannon information /entropy

     a) Fundamental trade-off: processing, memory, and communications

     $\Rightarrow$ minimize all three simultaneously

     $\Rightarrow$ 8 bit processor, no memory, 3 words to communicate

     b) Stability: latency independent due to no dynamics; stop until next update/command

     c) Performance: limitation is the sensor update rate; 60 sec

     $\Rightarrow$ Channel/system capacity of an equiprobable source

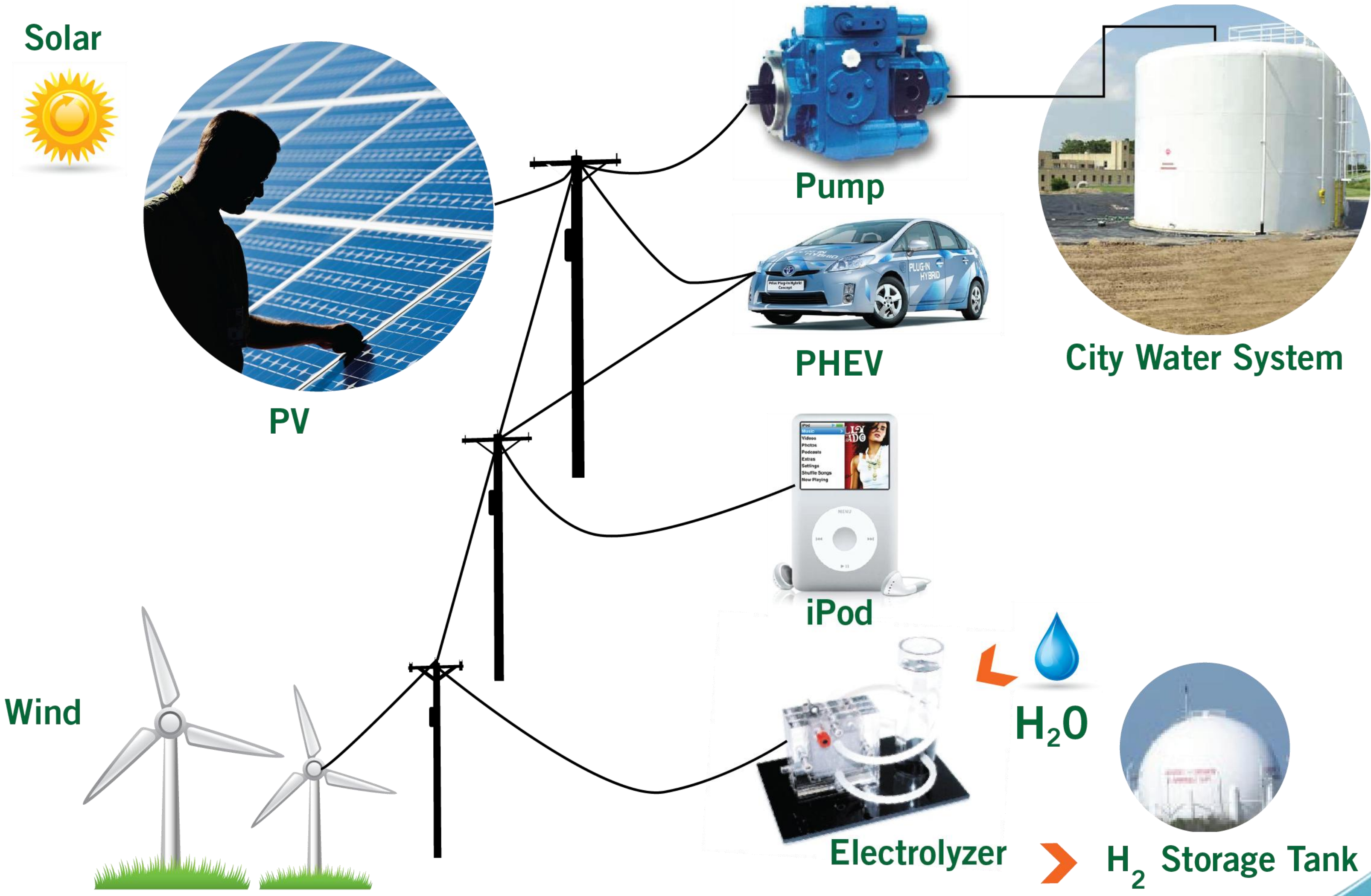
$$C_{ave} = \frac{\text{information}}{\text{time}} = \frac{1}{\tau}\log_2 n \frac{bits}{\sec} = \dot{H}_{ave}$$

$$n = (T_{HIGH} - T_{LOW})/\Delta T = 40/0.5 = 80 bits; T - temperature$$

$$\Rightarrow C_{ave} = \frac{1}{60}\log_2(80) < 0.1\frac{bit}{\sec}$$

COMM. Link =
50 Kbits/sec

Energy Storage and Dispatchable Loads (3)



Sandia National Laboratories

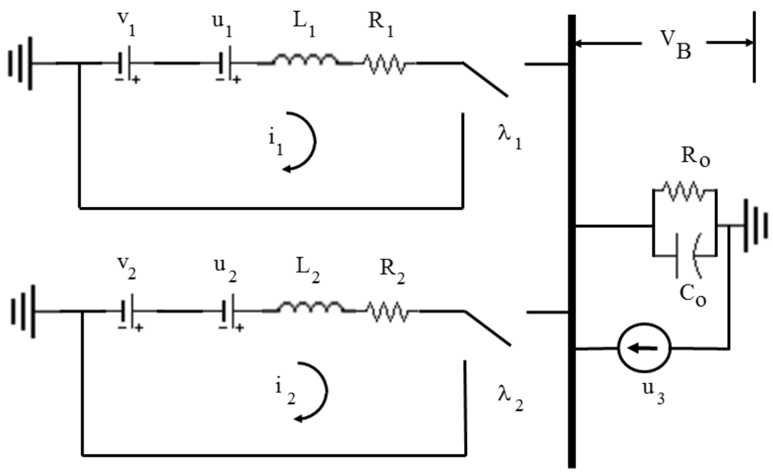
Example #3: DC Bus Microgrid Model 2 Boost Converter with Voltage Sources (1)

- Circuit equations for 2 boost converters and DC bus:

$$L_1 \frac{di_1}{dt} = -R_1 i_1 - \lambda_1 v_B + v_1 + u_1$$

$$L_2 \frac{di_2}{dt} = -R_2 i_2 - \lambda_2 v_B + v_2 + u_2$$

$$C_0 \frac{dv_B}{dt} = \lambda_1 i_1 + \lambda_2 i_2 - \frac{1}{R_0} v_B + u_3$$



- Re-written as state equations:

$$L_1 \dot{x}_1 = -R_1 x_1 - \lambda_1 x_3 + v_1 + u_1$$

$$L_2 \dot{x}_2 = -R_2 x_2 - \lambda_2 x_3 + v_2 + u_2$$

$$C_0 \dot{x}_3 = \lambda_1 x_1 + \lambda_2 x_2 - \frac{1}{R_0} x_3 + u_3$$

Emphasize: u1,u2, u3 are what generate specs (power, energy, frequency)

Sandia National Laboratories

Example #3: DC Bus Microgrid Model
2 Boost Converter with Voltage Sources (2)

- Represented in matrix form as:

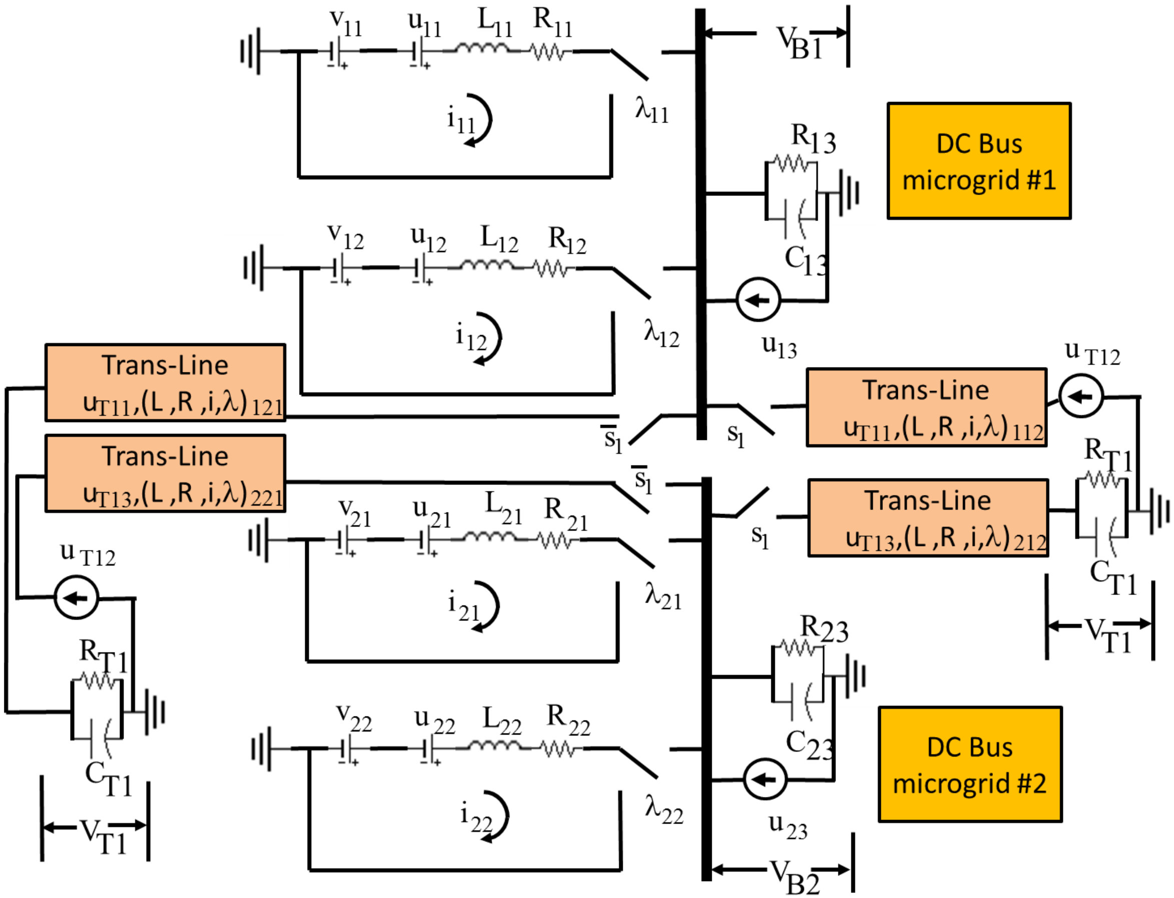
$$\begin{bmatrix} L_1 & 0 & 0 \\ 0 & L_2 & 0 \\ 0 & 0 & C_0 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{Bmatrix} = \begin{bmatrix} -R_1 & 0 & -\lambda_1 \\ 0 & -R_2 & -\lambda_2 \\ \lambda_1 & \lambda_2 & -\dfrac{1}{R_0} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix} + \begin{Bmatrix} v_1 \\ v_2 \\ 0 \end{Bmatrix} + \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix}$$

- or compactly as:

$$M\dot{x} = Rx + v + u = \left[\bar{R} + \tilde{R}\right]x + v + u$$

Where the R matrix is written as a diagonal matrix, $\bar{R}$, and a skew-symmetric, $\tilde{R}$

Collective Control of Networked Microgrids with Variable Resources



- Feedback controllers are based on single DC bus microgrid which are self-similar to the networked DC bus microgrid problem
- Same analysis for single DC microgrid will be employed

$$M\dot{x} = Rx + v + u = \left[\bar{R} + \tilde{R}\right]x + v + u$$

Sandia National Laboratories

Collective DC Bus Microgrid Model Scales Linearly with Controls

- Example: 2 microgrids represented in matrix form as:

$$M\dot{x} = Rx + v + u = \left[\bar{R} + \tilde{R}\right]x + v + u$$

- where

$$x = \left[x_{11}, x_{12}, x_{13}, x_{121}, v_{T1}, x_{221}, x_{21}, x_{22}, x_{23}\right]^{T}$$

$$v = \left[v_{11}, v_{12}, 0, 0, 0, 0, v_{21}, v_{22}, 0\right]^{T}$$

$$u = \left[u_{11}, u_{12}, u_{13}, u_{T11}, u_{T12}, u_{T13}, u_{21}, u_{22}, u_{23}\right]^{T}$$

Similar terms in collective M (L,C components) and R matrices

Collective DC Microgrid
State-Space Model Matrix Definitions

$$M = \begin{bmatrix} L_{11} & & & & & & & & \\ & L_{12} & & & & & & \mathbf{0} & \\ & & C_{13} & & & & & & \\ & & & L_{121} & & & & & \\ & & & & C_{T1} & & & & \\ & & & & & L_{221} & & & \\ & \mathbf{0} & & & & & L_{21} & & \\ & & & & & & & L_{22} & \\ & & & & & & & & C_{23} \end{bmatrix}$$

$$R = \begin{bmatrix} -R_{11} & 0 & -\lambda_{11} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_{12} & -\lambda_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_{11} & \lambda_{12} & -g_{13} & \lambda_{121} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\lambda_{121} & -R_{121} & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & -g_{T1} & \lambda_{221} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\lambda_{221} & -R_{221} & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -R_{21} & 0 & -\lambda_{21} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -R_{22} & -\lambda_{21} \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_{21} & \lambda_{22} & -g_{23} \end{bmatrix}$$

Sandia National Laboratories

Example #3: DC Bus Microgrid Model
Duty Cycle Commands

- **Duty cycle commands are obtained from steady-state solution with u=0 as:**

$$0 = -R_1 x_1 - \lambda_1 x_3 + v_1$$

$$0 = -R_2 x_2 - \lambda_2 x_3 + v_2$$

$$0 = \lambda_1 x_1 + \lambda_2 x_2 - \frac{1}{R_0} x_3$$

- **Or in matrix form as:**

$$\left[\bar{R} + \tilde{R}\right] x + v = 0$$

- **Leads to quadratic equation in duty cycles:**

$$R_0 x_{3_0} \left(\frac{1}{R_1} \lambda_1^2 + \frac{1}{R_2} \lambda_2^2 \right) - R_0 \left(\frac{v_1}{R_1} \lambda_1 + \frac{v_2}{R_2} \lambda_2 \right) + x_{3_0} = 0$$

Example #3: DC Bus Microgrid Model HSSPFC Controller Design for Energy Storage (1)

- **Error state defined along with reference state vector:**

$$e = \tilde{x} = x_{ref} - x$$

$$M\dot{x}_{ref} = \left[\bar{R} + \tilde{R}\right] x_{ref} + v + u_{ref}$$

- **Assume reference state vector is constant and reference control becomes:**

$$u_{ref} = -\left[\bar{R} + \tilde{R}\right] x_{ref} - v \qquad (1)$$

- **Next step define the Hamiltonian as:**

$$H = \frac{1}{2}\tilde{x}^T M \tilde{x}$$

Static stability condition

- **And positive definite about** $\tilde{x} = 0$

Example #3: DC Bus Microgrid Model HSSPFC Controller Design for Energy Storage (2)

- **The Hamiltonian time derivative or power flow becomes:**

$$\dot{H} = \tilde{x}^T M \dot{\tilde{x}} = \tilde{x}^T \left[M\dot{x}_{ref} - M\dot{x} \right]$$

$$\dot{H} = \tilde{x}^T \overline{R} \tilde{x} + \tilde{x}^T \Delta u$$

- **where**

$$\tilde{x}^T \tilde{R} \tilde{x} = 0$$

- **and**

$$\Delta u = u_{ref} - u$$

Example #3: DC Bus Microgrid Model HSSPFC Controller Design for Energy Storage (3)

- **Next step, select a PI controller as:**

$$\Delta u = -K_P \tilde{x} - K_I \int \tilde{x} dt$$

$$u = u_{ref} - \Delta u \qquad (2)$$

- **Substitute and simplify leads to:**

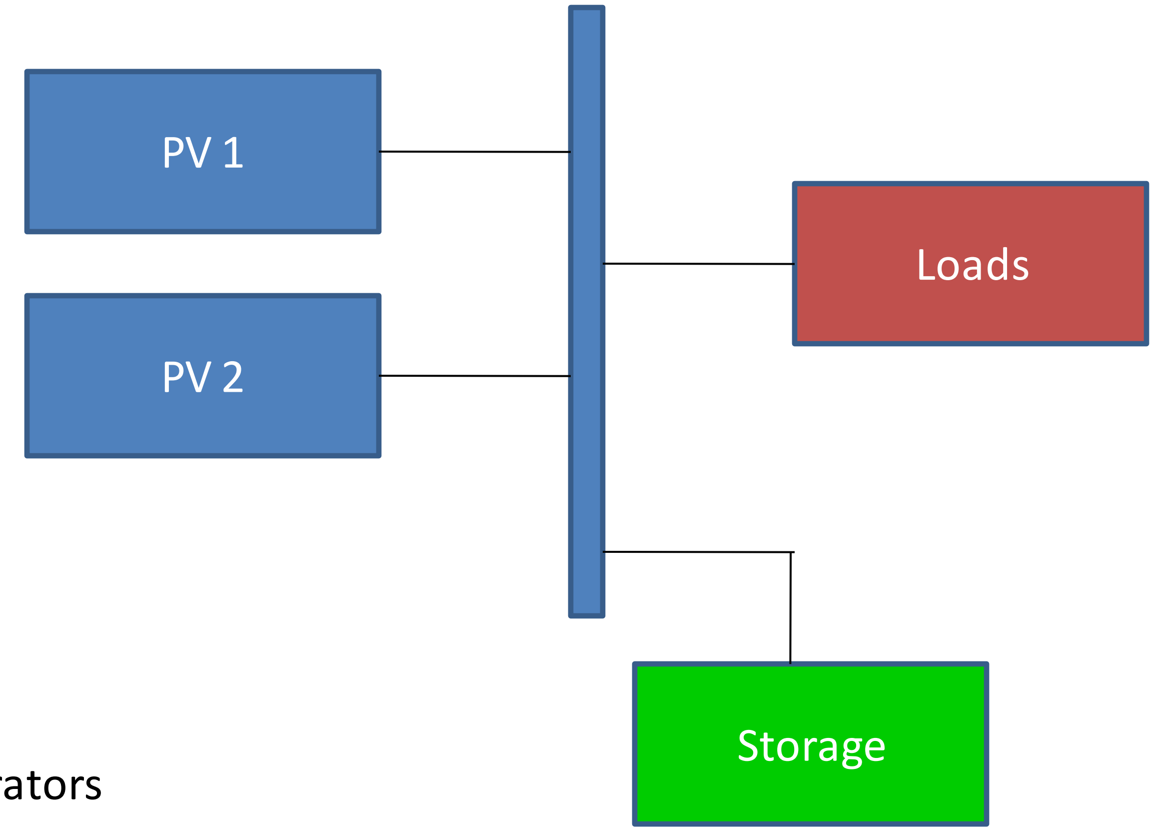
$$\dot{H} = \tilde{x}^T \left[\overline{R} - K_P \right] \tilde{x} - \tilde{x}^T K_I \int \tilde{x} dt < 0,$$

$$\tilde{x}^T \left[K_P - \overline{R} \right] \tilde{x} > -\tilde{x}^T K_I \int \tilde{x} dt$$

Dynamic stability condition

HSSPFC Implementation Scenario Collective Microgrid Components

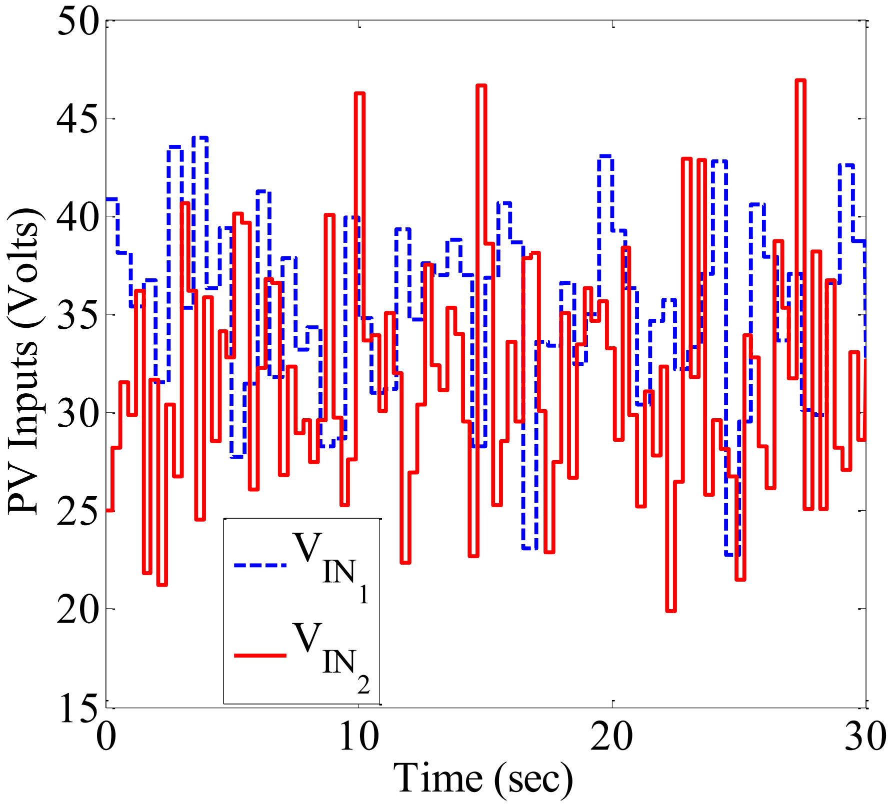
Scenario 1



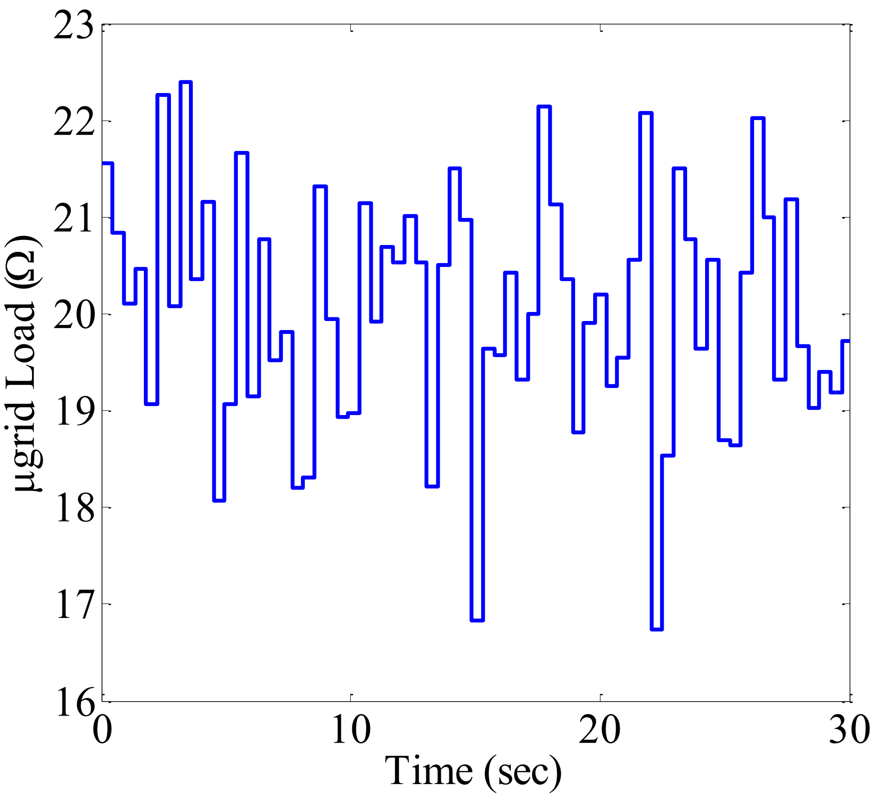
- 2 PV Generators
- Storage
- Variable Loads

Sandia National Laboratories

Numerical Results Idealized Random PV Source Inputs and Loads



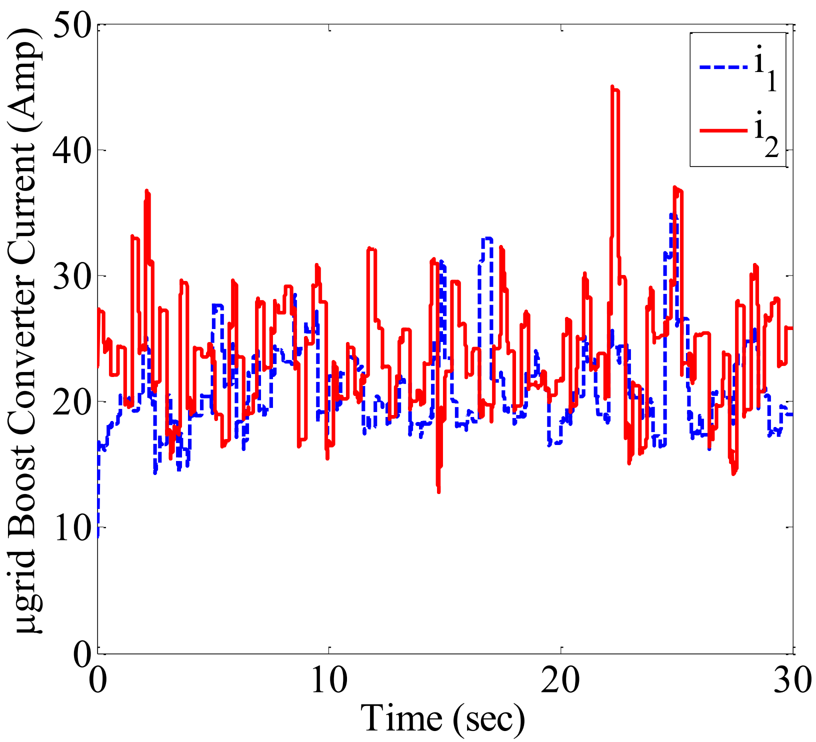
PV source Inputs



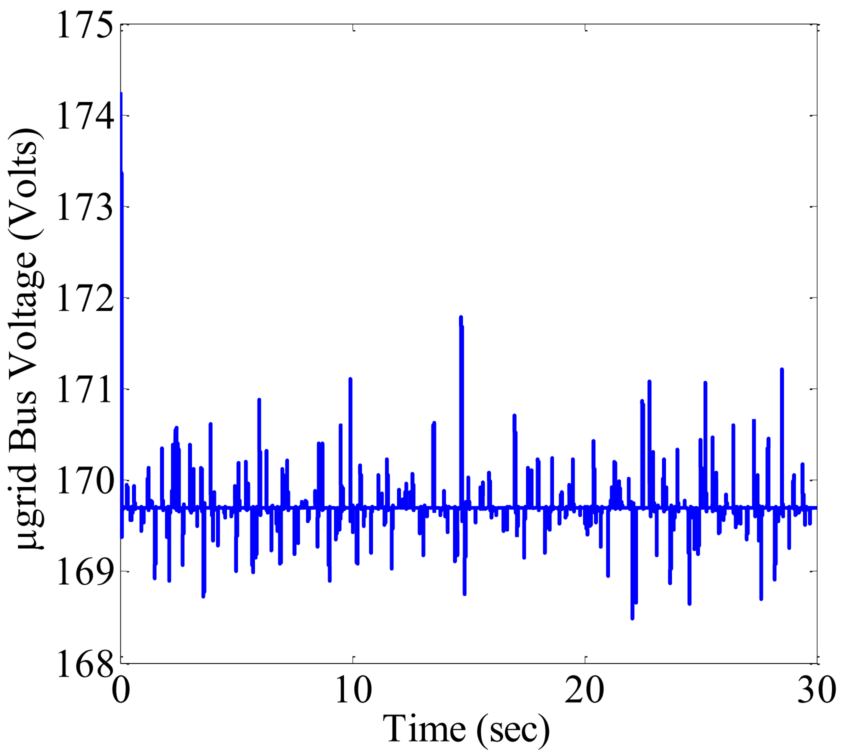
Random Loads

Sandia National Laboratories

Numerical Simulation Results Boost Converter Currents and Bus Voltage

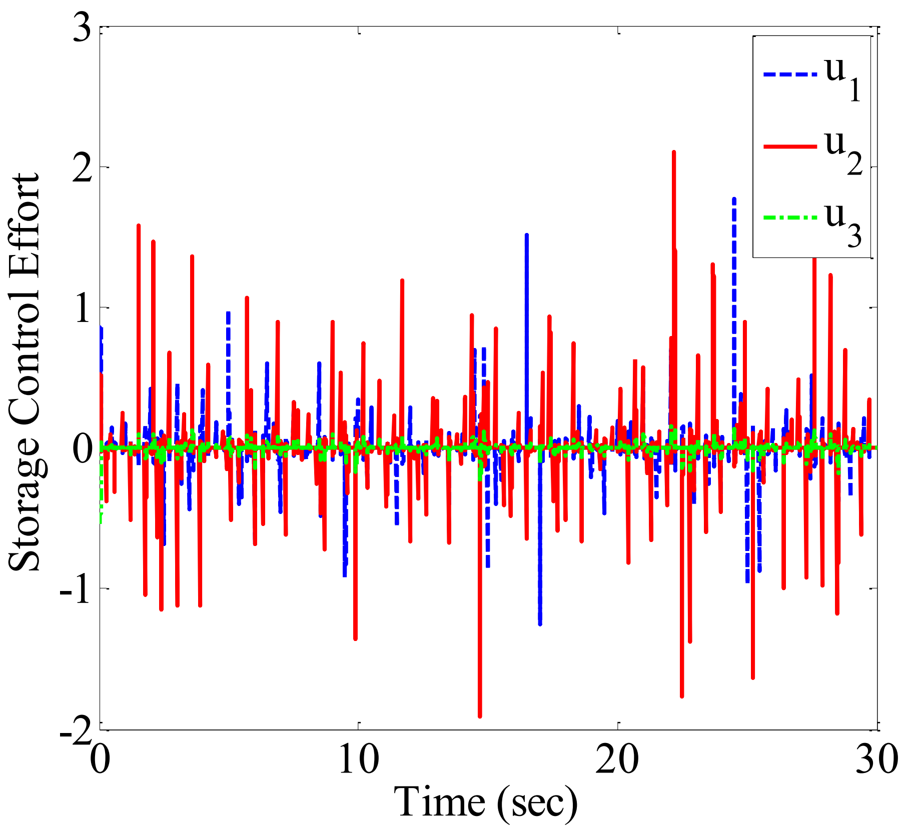


Boost Converter Currents

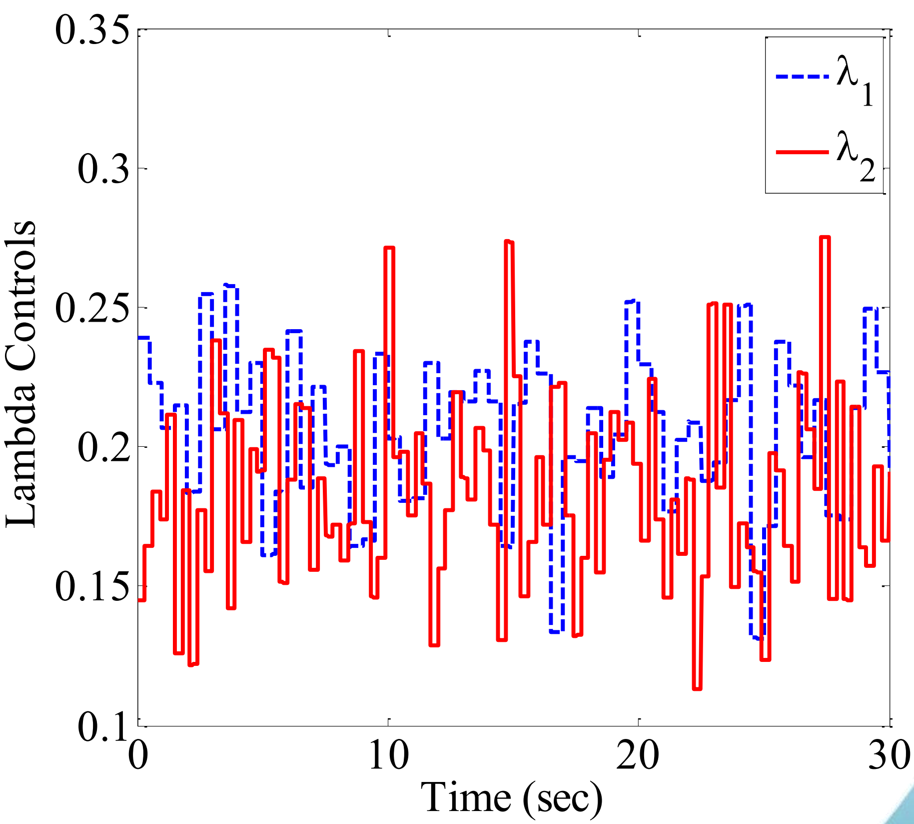


Bus Voltage

Numerical Simulation Results Storage Control Effort and Ideal Lambda Controls



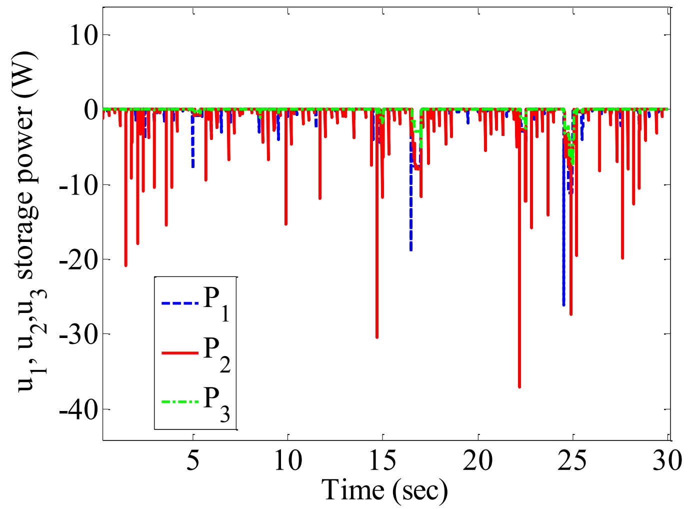
Storage Control Effort

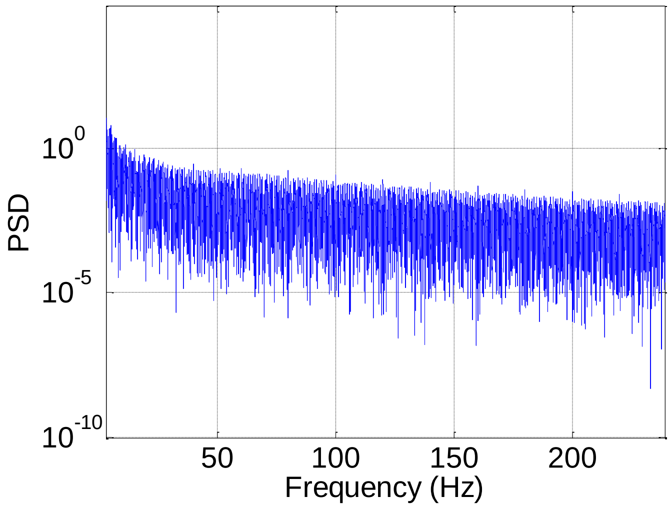


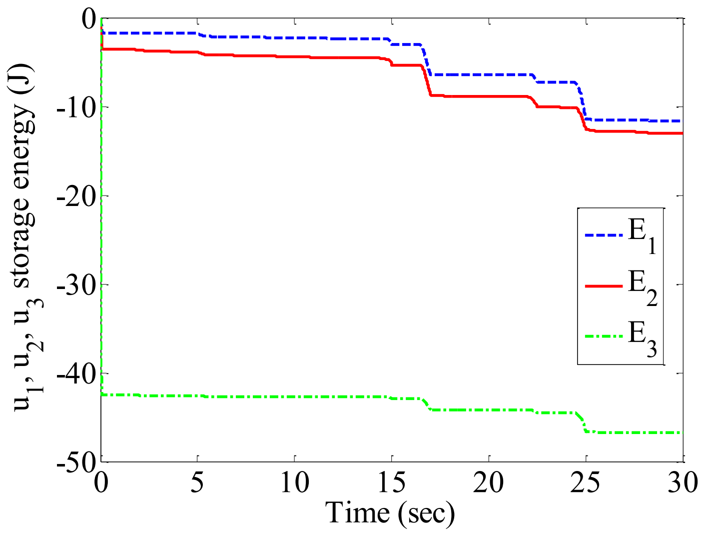
Lambda Controls

Energy Storage Requirements Scenario 1

- **Power Requirements**
- **Energy Requirements**
- **Frequency Response (PSD) Requirements**







Specifications for the microgrid and/or UPFC based on (Power, Energy, Frequency PSDs)

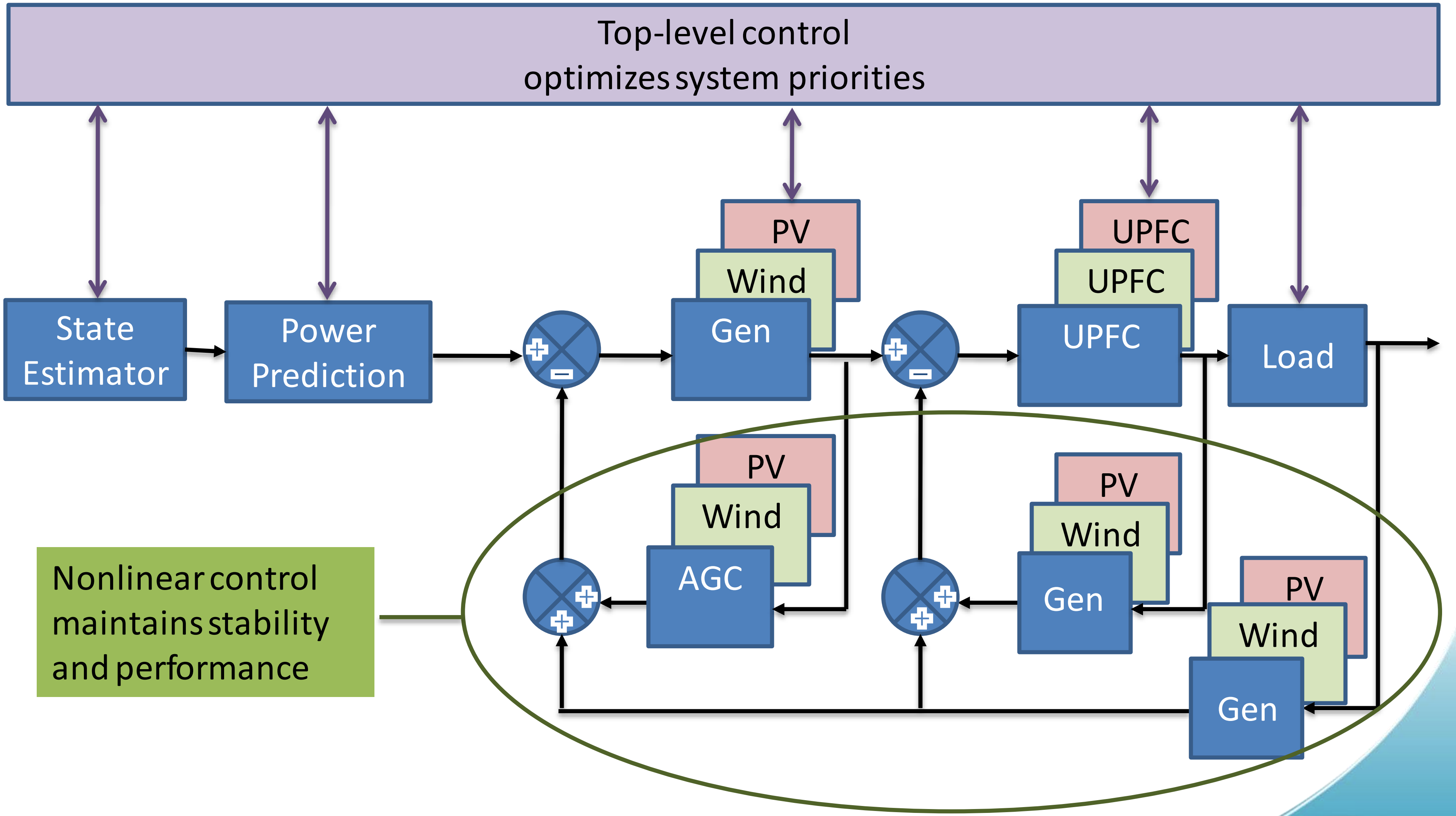
A Path From Today's Grid To The Future (Smart) Grid (cont.)

6. **Need to optimize over many metrics: Cost, Security, Risk of Lost Load (specify energy storage), etc.**

    - *Agent-based informatics*

Sandia National Laboratories

Top-Level Control Enables Prioritization and System Adaptability



UPFC - Unified power flow controllers

Sandia National Laboratories

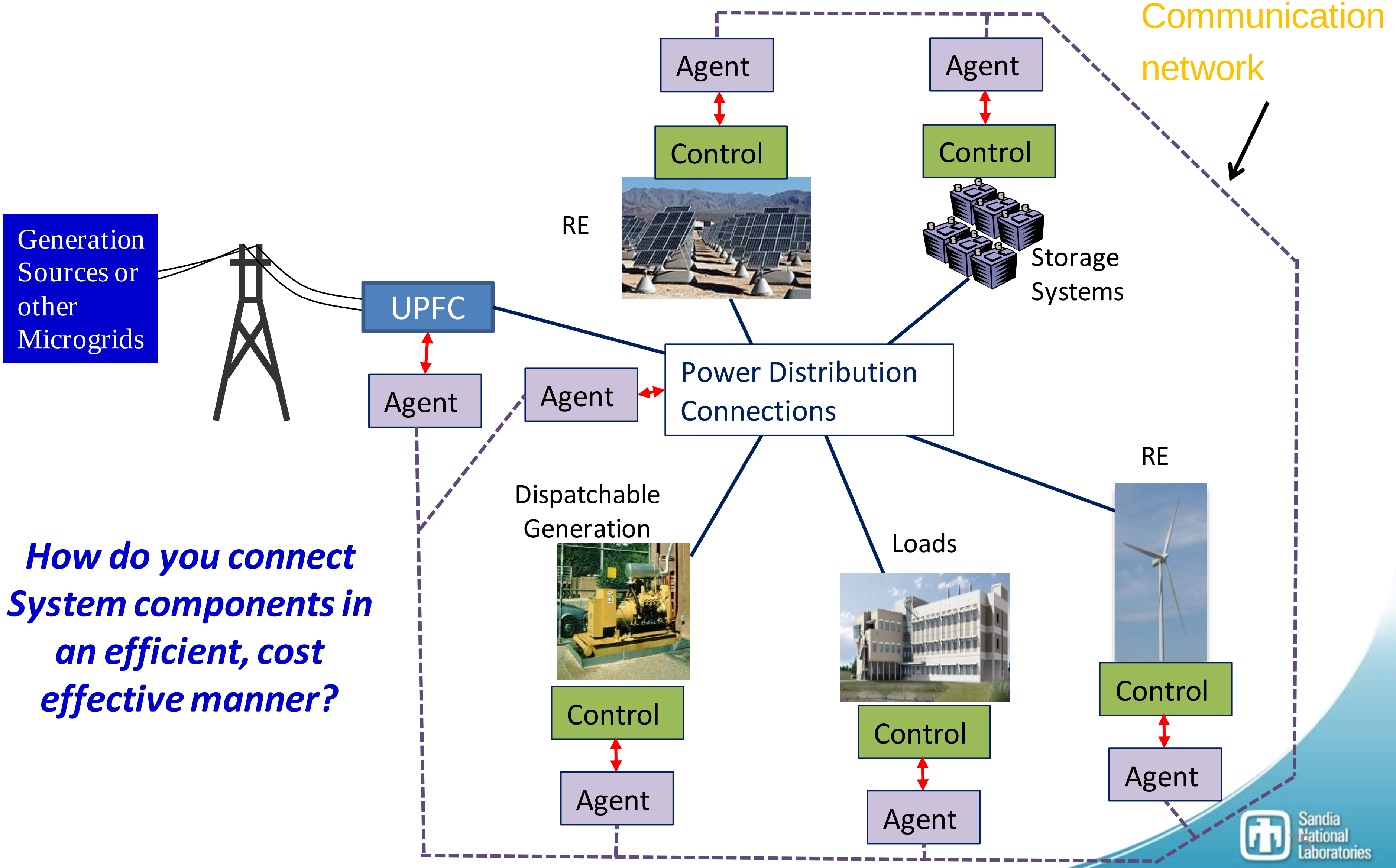
A Path From Today's Grid To The Future (Smart) Grid (cont.)

7. **Need a flexible, overkill testbed**

    - *Can "dumb it down" to find optimal designs to calibrate mod/sim*

Sandia National Laboratories

A Highly Interconnected Microgrid Will Result from these Advancements

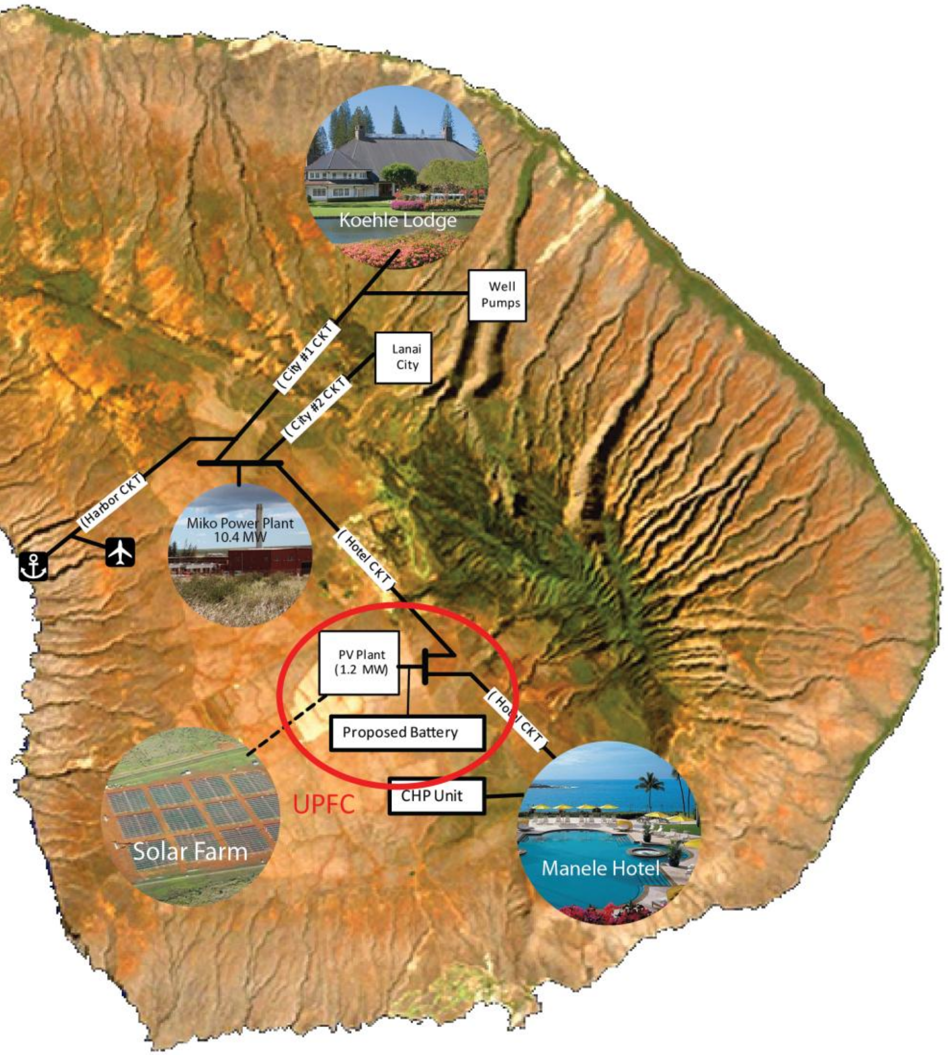


How do you connect System components in an efficient, cost effective manner?

Sandia National Laboratories

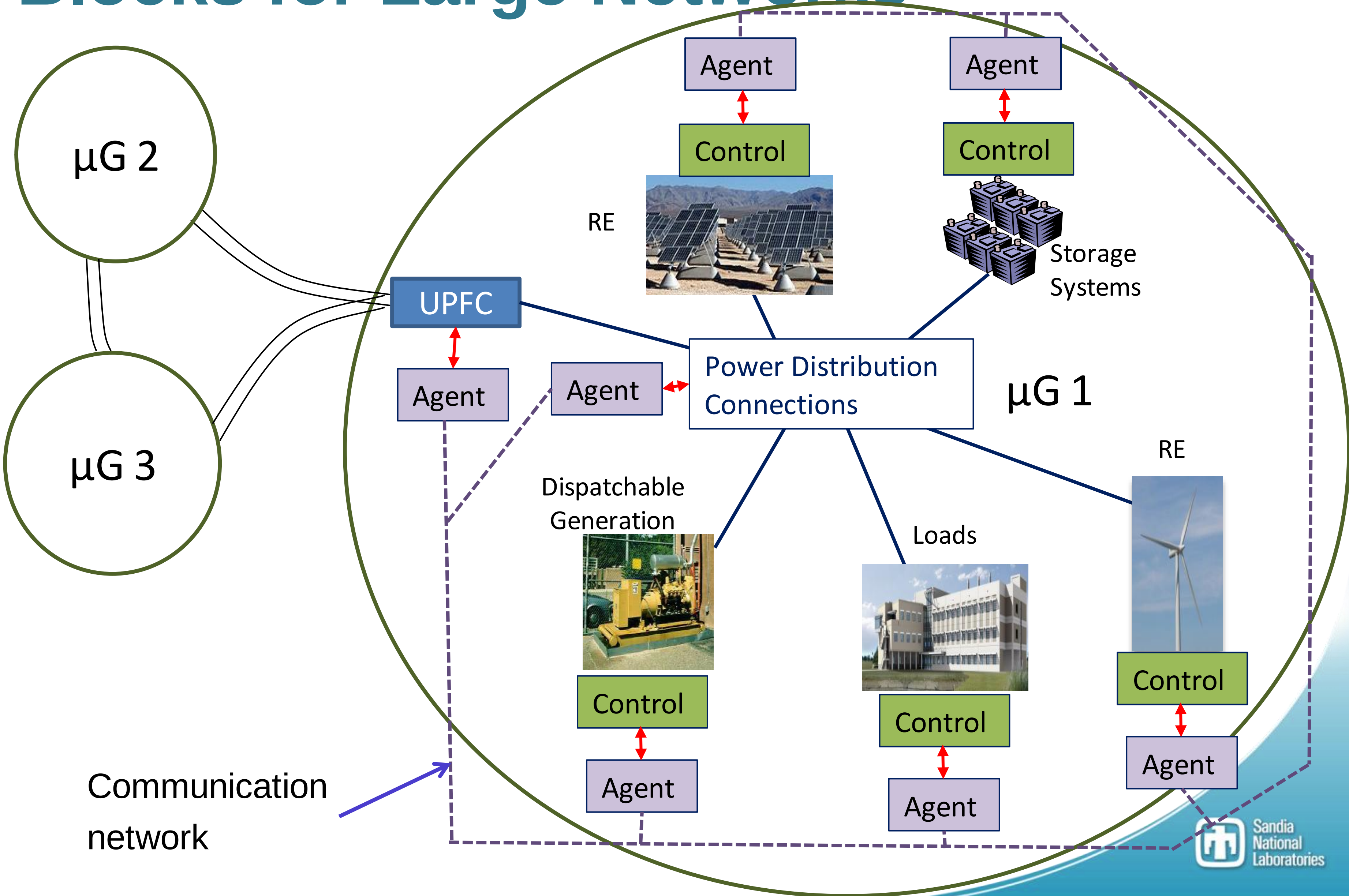
The Test Bed For Lana'i-like Grids

- 5.5 MW peak load (~3.5MW base)
- 10.4 MW diesel generation
- Solar Array – 1.2MW
- Renewables Penetration – 22% during peak (34% base)
- Energy Storage (June 2011)
  - Xtreme Power battery
  - 1.12MW; 500 kWh

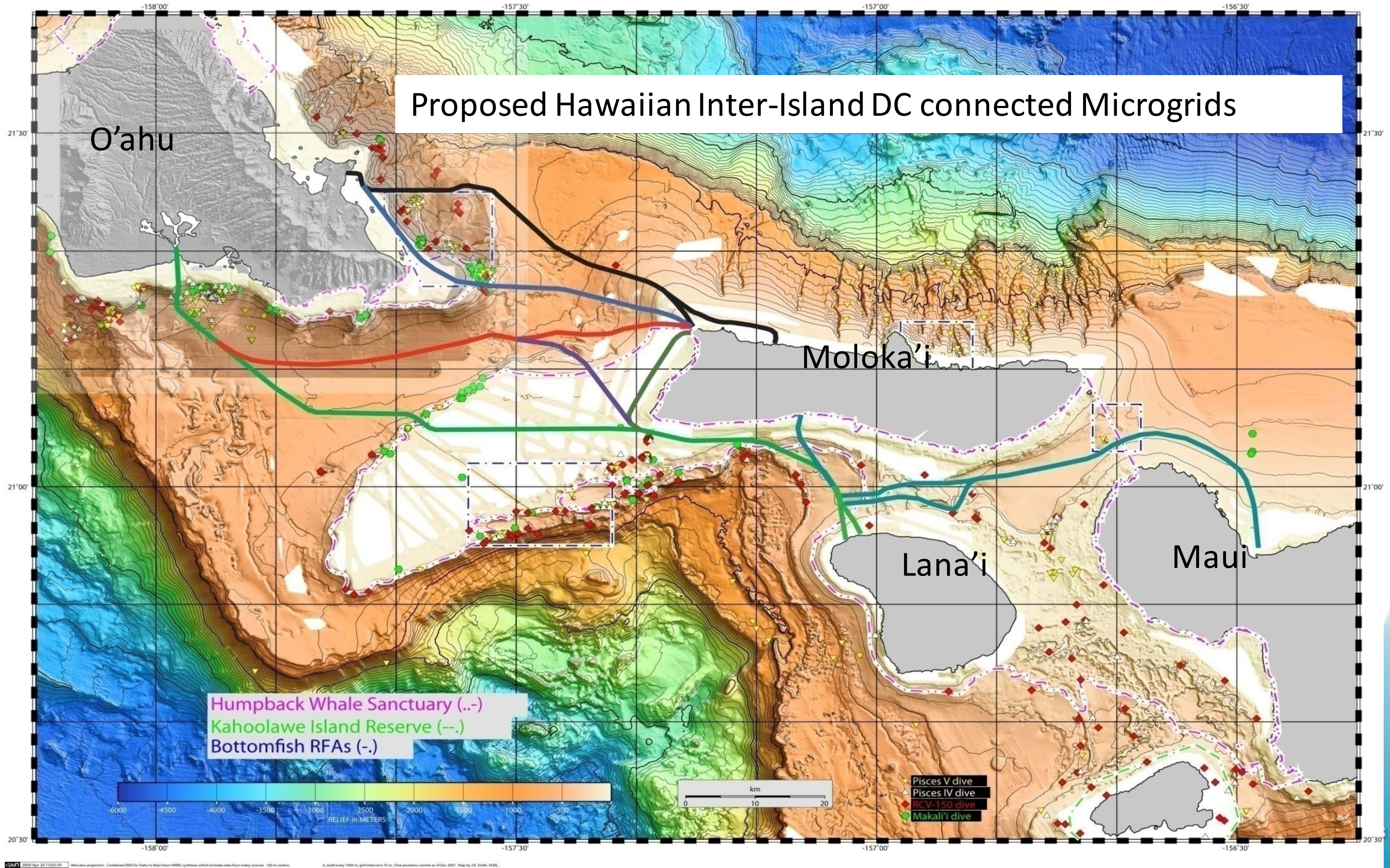


Sandia National Laboratories

These Microgrids will be Building Blocks for Large Networks



Hawaiian Inter-Island Transmission Cables will Integrate "Microgrids"

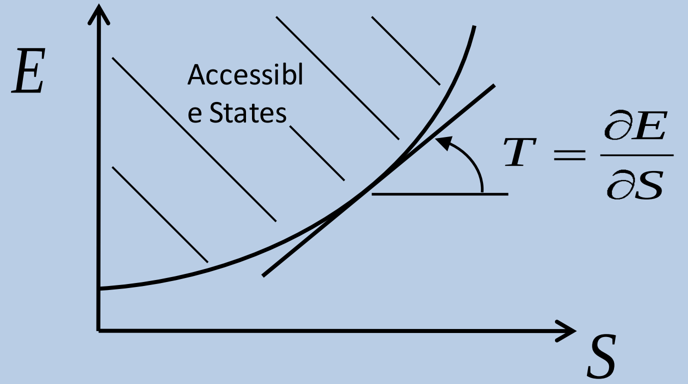


Thank You for Your Time and Engagement

Backup Slides

Second Law of Thermodynamics (2)

- Corollary to the Second Law: At a stable equilibrium state, the entropy will be at its maximum value
  - The energy will be at a minimum value, the temperature is positive and increasing, and the energy versus entropy curve for stable equilibrium states is convex.



  - A reversible process can be defined as interacting systems quasi-statically pass only through stable equilibrium states. The heat flowing between these interacting systems during a reversible process is

$$dQ = (\delta Q)_{REV} = TdS; \qquad T - temperature$$

  - The entropy production during a reversible process is

$$dS = \frac{dQ}{T}; \qquad S = 0 = \oint \frac{dQ}{T}$$

Work, Energy, and Power (3)

- If the force is a function of time, then the time dependent potential field results

$$\underline{F}(\underline{r},t)\cdot d\underline{r} = -dV(\underline{r},t)$$

and the stored energy is modified as

$$\frac{d}{dt}(T+V) = \frac{\partial V}{\partial t}$$

- Non-conservative forces can be included by adding the power flow due to non-conservative force as

$$\underline{F} = \underline{F}_c + \underline{F}_{NC}$$

$\underline{F}_c$ – Conservative Force (Potential Field)

$\underline{F}_{NC}$ – Non-Conservative Force

Sandia National Laboratories

Work, Energy, and Power (4)

$$\frac{d\overline{E}}{dt} = \frac{d}{dt}(T+V) = \frac{\partial V}{\partial t} + \underline{F}_{NC} \cdot \dot{\underline{r}}$$

- We will focus on "natural systems" (no explicit time-dependence)

$$\frac{d\overline{E}}{dt} = \frac{d}{dt}(T+V) = \underline{F}_{NC} \cdot \dot{\underline{r}}$$

- Non-conservative applied forces - perform work on and flow power into the system (generators) as well as dissipate energy within in the system by frictional forces (dissipators).
- Thermodynamics, the energy and entropy balances for an adiabatic irreversible work process where work is done on the system, no entropy is exchanged with environment, and irreversible entropy is produced through dissipation are

$$E_2 - E_1 = -W_{12}$$

$$S_2 - S_1 = S_{IRR}$$

$$\dot{\Xi} = \dot{W} - T_o S_i$$

Sandia National Laboratories

Hamiltonian Mechanics (1)

- **Lagrangian**: $L = T(\underline{q}, \underline{\dot{q}}, t) - V(\underline{q}, t)$

  $t -$ *Time Explicitly*

  $\underline{q} -$ *N Dimensional Generalized Coordinate Vector*

  $\underline{\dot{q}} -$ *N Dimensional Generalized Velocity Vector*

- **Equations of Motion:** $\frac{d}{dt}\left(\frac{\partial L}{\partial \underline{\dot{q}}}\right) - \frac{\partial L}{\partial \underline{q}} = \underline{Q}$

  $\underline{Q} -$ Generalized Force Vector

- **Hamiltonian**: $H \equiv \sum_{j=1}^{N} \frac{\partial L}{\partial \dot{q}_i} \dot{q}_i - L(\underline{q}, \underline{\dot{q}}, t) = H(\underline{q}, \underline{\dot{q}}, t)$

Sandia National Laboratories

Hamiltonian Mechanics (2)

- **Canonical Momentum:**

$$p_i = \frac{\partial L}{\partial \dot{q}_i}$$

$$H(\underline{q}, \underline{p}, t) = \sum_{i=1}^{N} p_i \dot{q}_i - L(\underline{q}, \underline{\dot{q}}, t)$$

- **Hamilton's Canonical Equations of Motion:**

$$\dot{q}_j = \frac{\partial H}{\partial p_j}$$

$$\dot{p}_j = -\frac{\partial H}{\partial q_j} + Q_j$$

- **Time Derivative of the Hamiltonian:**

$$\dot{H} = \sum_{j=1}^{N} (\dot{p}_j \dot{q}_j + p_j \ddot{q}_j - \frac{\partial L}{\partial t} - \frac{\partial L}{\partial q_j} \dot{q}_j - \frac{\partial L}{\partial \dot{q}_j} \ddot{q}_j)$$

$$= \sum_{j=1}^{N} Q_j \dot{q}_j - \frac{\partial L}{\partial t}$$

Connect Thermodynamics To Hamiltonian Mechanics (1)

- **Conservative Mechanical Systems:**

a) $\dot{H} = 0$ and $H =$ Constant

b) Conservative Force (storage device)

$$\oint \underline{F} \cdot d\underline{r} = \oint \underline{F} \cdot \dot{\underline{r}} dt = \oint \underline{Q} \cdot \dot{\underline{q}} dt = 0$$

For any closed path

Sandia National Laboratories

Connect Thermodynamics To Hamiltonian Mechanics (2)

- **Reversible Thermodynamic Systems:**

$$dS = \frac{dQ}{T}$$

$$\oint dS = \oint \frac{dQ}{T} = 0$$

$$\oint dS = \oint [d_e S + d_i S] = \oint [\dot{S}_e + \dot{S}_i] dt = 0$$

$$\Rightarrow \dot{S}_e = \frac{\dot{Q}}{T}$$ and $\dot{S}_i = 0$ (Second Law)

- **Irreversible Thermodynamic Systems:**

for $\oint dS = \oint [\dot{S}_e + \dot{S}_i] dt = 0$

then $\dot{S}_e \leq 0$ and $\dot{S}_i \geq 0$

Sandia National Laboratories

Connect Thermodynamics To Hamiltonian Mechanics (4)

d) Assumptions applied to exergy rate equation (Irreversible Adiabatic Work Process):

$$\dot{Q}_i \cong 0$$

$$1 - \frac{T_o}{T_j} \cong 0$$

$$p_o \dot{\bar{V}} = 0$$

$$\sum_k \dot{m}_k \zeta_k^{FLOW} = 0$$

e) A conservative system is equivalent to a reversible system when

$$\dot{H} = 0 \quad \text{and} \quad \dot{S}_e = 0$$

then $\dot{S}_i = 0$ and $\dot{W} = 0$

Sandia National Laboratories

Line Integrals and Limit Cycles (2)

- Sorting Power Terms:

a) Conservative Terms

$$\oint \underline{F}_c \cdot \underline{\dot{q}} dt = 0 \Rightarrow \text{Potential functions}$$

b) Generator Terms

$$\int_c \underline{F}_{NC} \cdot \underline{\dot{q}} dt > 0 \Rightarrow \int_c [\sum_{j=1}^{N} Q_j \dot{q}_j] dt > 0$$

c) Dissipator Terms

$$\int_c \underline{F}_{NC} \cdot \underline{\dot{q}} dt < 0 \Rightarrow \int_c [\sum_{k=N+1}^{N+M} Q_k \dot{q}_k] dt < 0$$

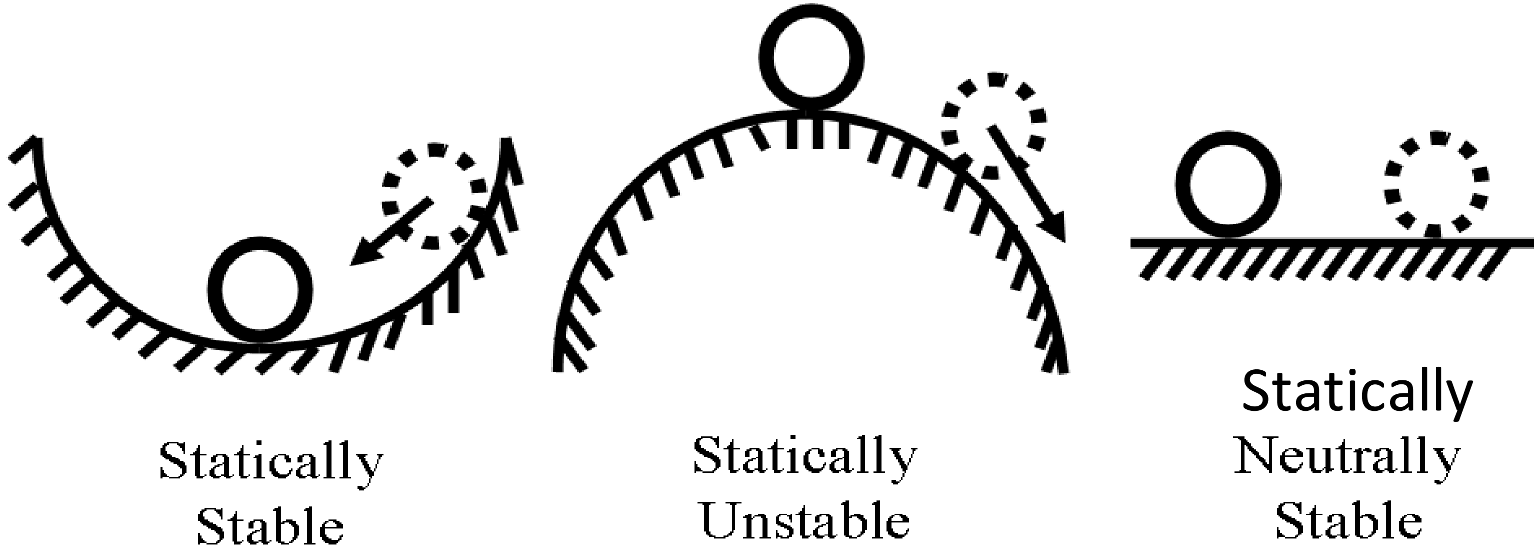
Sandia National Laboratories

Static and Dynamic Stability (1)

Static Stability: (Necessary Condition for Stability)

– If the forces and moments on a body caused by a disturbance tend initially to return (move) the body towards (away from) its equilibrium state, the body is statically stable (unstable)

- An equilibrium state is an unaccelerated motion wherein the sums of the forces and moments on the body are zero.
- Static neutral stability occurs when the body is disturbed and the sums of the forces and moments on the body remain zero which occurs when the system has a rigid body mode, zero stiffness in the system.



Source: J.D. Anderson, Jr., **Introduction to Flight**, McGraw-Hill, 1978.
R.D. Robinett III, *A Unified Approach to Vehicle Design, Control, and Flight Path Optimization*, PhD Dissertation, Texas A&M University, 1987.

Sandia National Laboratories

Static and Dynamic Stability (2)

Static stability of a re-entry vehicle flight stability

- For an axisymmetric re-entry vehicle, the static margin determines the static stability.
- The static margin (SM) is the difference in length between the center-of-mass and the center-of-pressure relative to the nose of the re-entry vehicle.

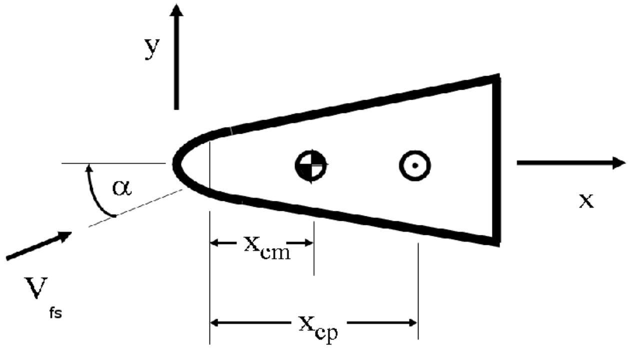
$$SM = xcp - xcm$$

xcp = center-of-pressure location
xcm = center-of-mass location

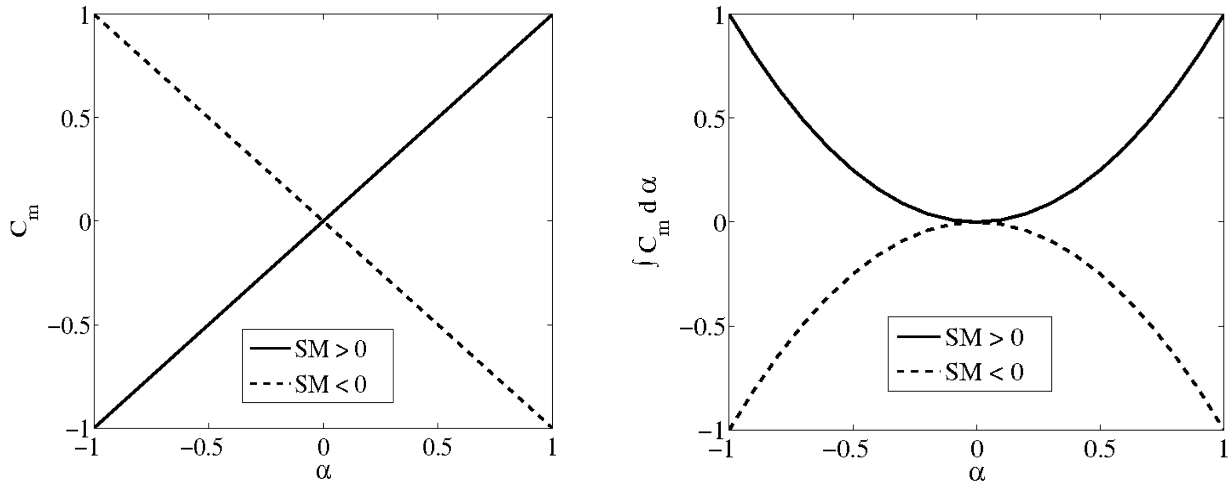
- If SM < 0, the re-entry vehicle is statically unstable. If SM > 0, the re-entry vehicle is statically stable.

Sandia National Laboratories

Static and Dynamic Stability (3)



Static margin



Aerodynamic moment (left) and integral of aerodynamic moment with respect to angle of attack (right)

Static and Dynamic Stability (4)

- **Static Stability:** Energy storage surface, Hamiltonian, is a constant.

$$H = T + V = E$$

- Equations of motion in second order form (no non-conservative forces)

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \underline{\dot{q}}}\right) - \frac{\partial L}{\partial \underline{q}} = \underline{0}$$

- Statically stable if

$$H(\dot{x}, x) > 0 \qquad V(x) > 0 \qquad \forall x \neq x_e, \dot{x} \neq \dot{x}_e$$
$$H(\dot{x}_e, x_e) = 0$$

- Statically unstable if

$$V(x) < 0 \qquad \forall x \neq x_e$$
$$V(x_e) = 0$$

- Statically neutral stable if

$$V(x) = 0 \qquad \forall x$$

Sandia National Laboratories

Static and Dynamic Stability (5)

- **Dynamic Stability:** Defined in terms of the time history of the motion of a body after encountering a disturbance,
  - *A body is dynamically stable (unstable) if, out of its own accord, it eventually returns to (deviates from) and remains at (away from) its equilibrium state over a period of time.*

- A dynamically neutral stable body occurs when a limit cycle exists.
- A dynamically stable body must always be statically stable, but static stability is <u>not</u> sufficient to ensure dynamic stability. Therefore, static stability is a <u>necessary</u> condition for stability and dynamic stability is a <u>sufficient</u> condition for stability.
- Natural Hamiltonian system with externally applied non-conservative forces and/or moments that is statically stable.
- Equations of motion are given in second order form as

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \underline{\dot{q}}}\right)-\frac{\partial L}{\partial \underline{q}}=\underline{Q}$$

J.D. Anderson, Jr., **Introduction to Flight**, McGraw-Hill, 1978.

R.D. Robinett III, *A Unified Approach to Vehicle Design, Control, and Flight Path Optimization*, PhD Dissertation, Texas A&M University, 1987.

R.D. Robinett III, *What is a Limit Cycle?*, Int'l Journal of Control, Vol. 81, No. 12, Dec. 2008, pp. 1886-1900.

R.D. Robinett III and D.G. Wilson, *Collective Systems: Physical and Information Exergies*, Sandia National Laboratories, SAND2007-2327 Report, March 2007H.N. Abramson, **Introduction to the Dynamics of Airplanes**, Ronald Press, 1958.

Static and Dynamic Stability (6)

- The system path/trajectory traverses a positive definite energy surface (statically stable). The time derivative of the energy/Hamiltonian surface defines the power flow into, dissipated within, and stored in the system. Average power flow calculations for limit cycles.
- Dynamically stable if the power flow on the average drives the perturbed system to a lower energy state which eventually converges to the statically stable equilibrium state,

$$\dot{H}_{AVE} = \frac{1}{\tau_c}\int_0^{\tau_c} \dot{H}dt < 0$$

- Dynamically unstable if the power flow on the average drives the perturbed system to a higher energy state

$$\dot{H}_{AVE} = \frac{1}{\tau_c}\int_0^{\tau_c} \dot{H}dt > 0$$

- Dynamically neutral stable if the power flow on the average produces a limit cycle

$$\dot{H}_{AVE} = \frac{1}{\tau_c}\oint_{\tau_c} \dot{H}dt = 0$$

Sandia National Laboratories

Energy Storage Surface and Power Flow: Hamiltonian Surface Shaping and Power Flow Control (1)

- **Hamiltonian Surface Shaping and Power Flow Control (HSSPFC):** Two-Step Process
  - First step shapes the energy (Hamiltonian) storage surface with proportional feedback and/or acceleration feedback
  - Energy storage surface determines the static stability
  - Second step shapes the paths/trajectories of the system constrained to this surface (storage mechanisms) with derivative and/or integral feedback
  - Power flow determines dynamic stability
- **First Step Example:** Hamiltonian Surface Shaping of a conservative linear and cubic nonlinear spring system.

$V(x) = -\frac{1}{2}kx^2 + \frac{1}{2}k_{NC}x^4$ for $k, k_{NL} > 0$ and the proportional controller is $u_P = -K_p x,$

that leads to the Hamiltonian $H = \frac{1}{2}m\dot{x}^2 + \frac{1}{2}[K_p - k]x^2 + \frac{1}{4}k_{NC}x^4 > 0 \quad \forall x \neq 0, \dot{x} \neq 0$

which is statically stable if $K_p - k > 0$

The equation of motion becomes

$$m\ddot{x} - kx + k_{NL}x^3 = u = -K_p x$$

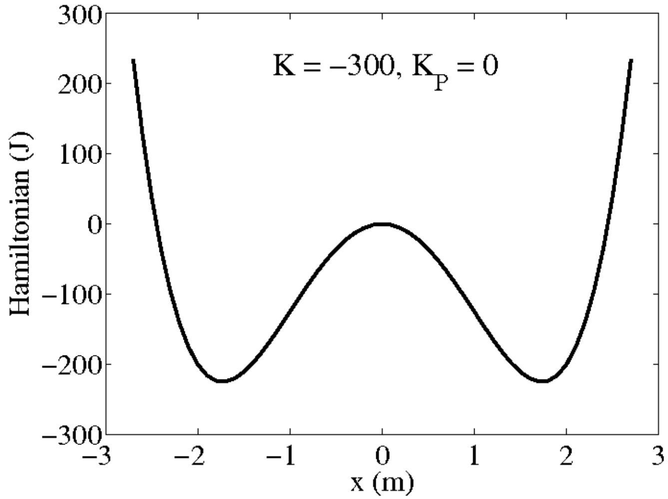
$$m\ddot{x} + [K_p - k]x + k_{NL}x^3 = 0$$

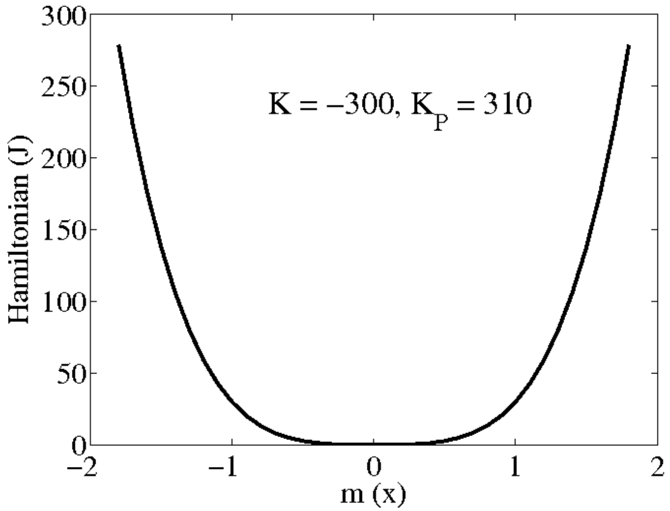
Trajectories that result from the following equation of motion

$$m\ddot{x} + [K_p - k]x + k_{NL}x^3 = -K_D x - K_I \int x dt$$

Sandia National Laboratories

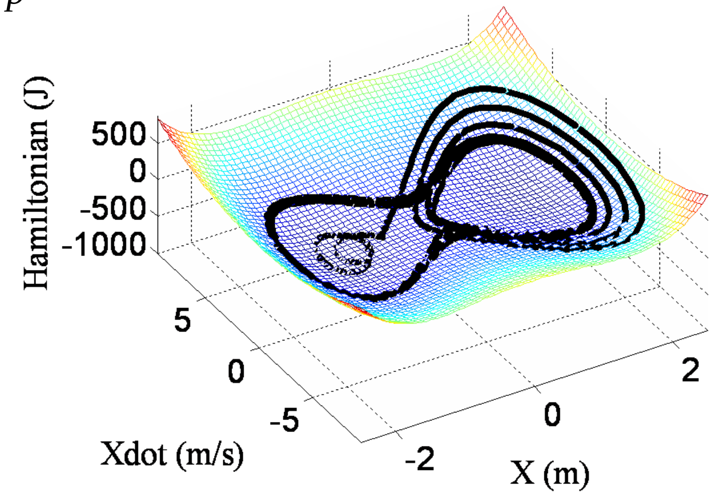
Energy Storage Surface and Power Flow: HSSPFC (2)



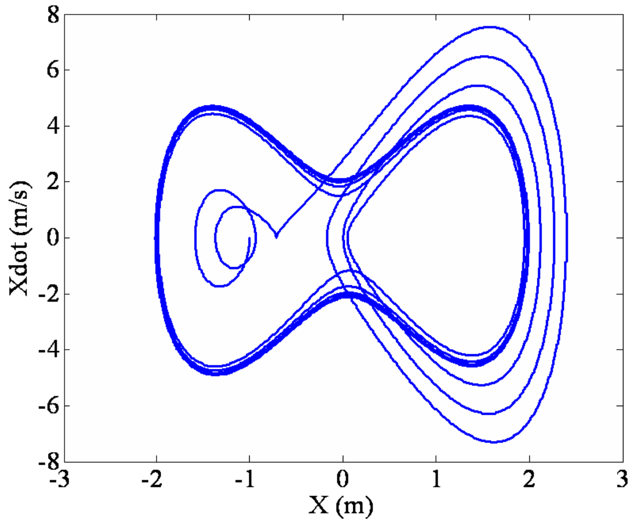


$k > K_p$

H = 0.5*(K_P+k)*x^2 + 0.5*m*xdot^2+0.25*k_NL*x^4



CASE 10 PID Control Nonlinear System Phase Plane



Energy Storage Surface and Power Flow: HSSPFC (3)

- **Second Step:** Power Flow Control shapes the path/trajectory across the energy storage surface by designing the balance of power flowing into versus the power being dissipated within the system as a function of the power being stored in the system. Power Flow Control is implemented with derivative feedback and/or integral feedback portion of the control law.
- Time derivative of the Hamiltonian is partitioned into generators, $\dot{W}$, dissipators, $T_o \dot{S}_i$, and storage terms, $\dot{H}$, in order to design the power flow balance defined by

$$\dot{H} = \dot{W} - T_o \dot{S}_i$$

- Derivative feedback is a dissipator that creates irreversible entropy,

$$u = -K_D \dot{x} \quad \Rightarrow T_o \dot{S}_i = K_D \dot{x}^2$$

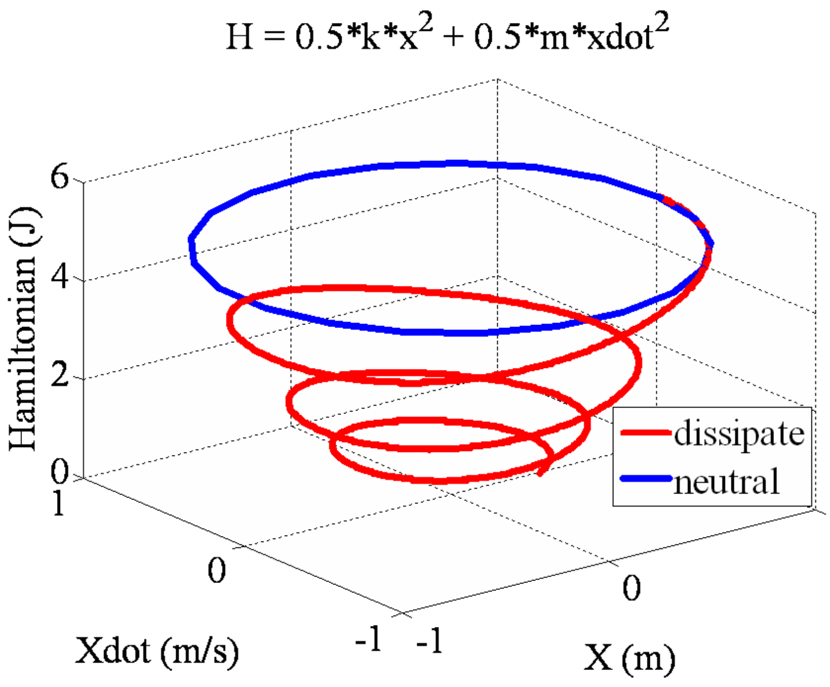
- Integral feedback is a generator that flows power into the system,

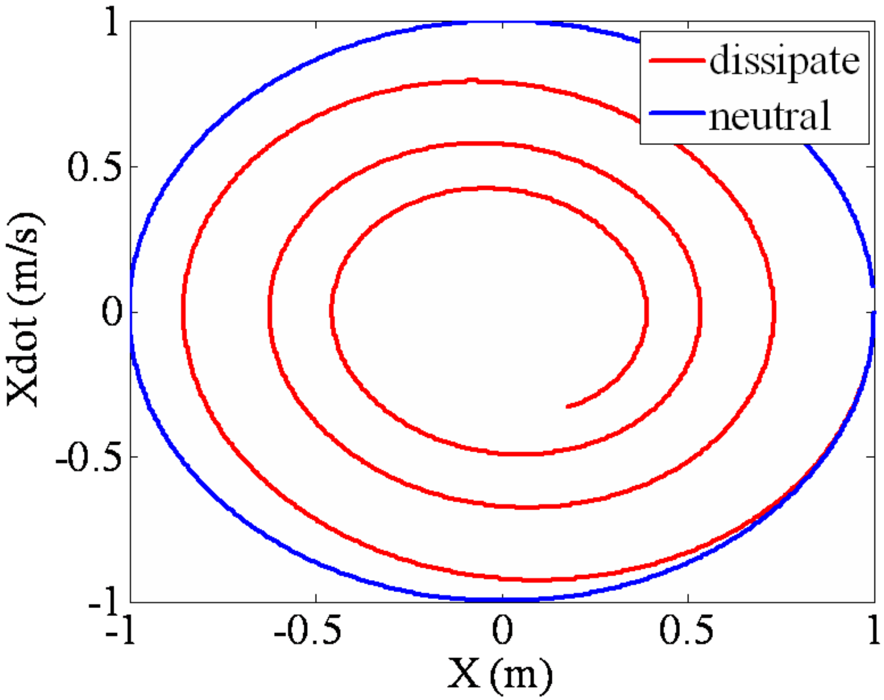
$$u = -K_I \int x dt \Rightarrow \dot{W} = -K_I \int x dt \dot{x}$$

- **Second Step Example:** Power flow control of the linearized mass, spring, damper system

Energy Storage Surface and Power Flow: HSSPFC (4)

$$m\ddot{x} + kx = -c\dot{x}$$





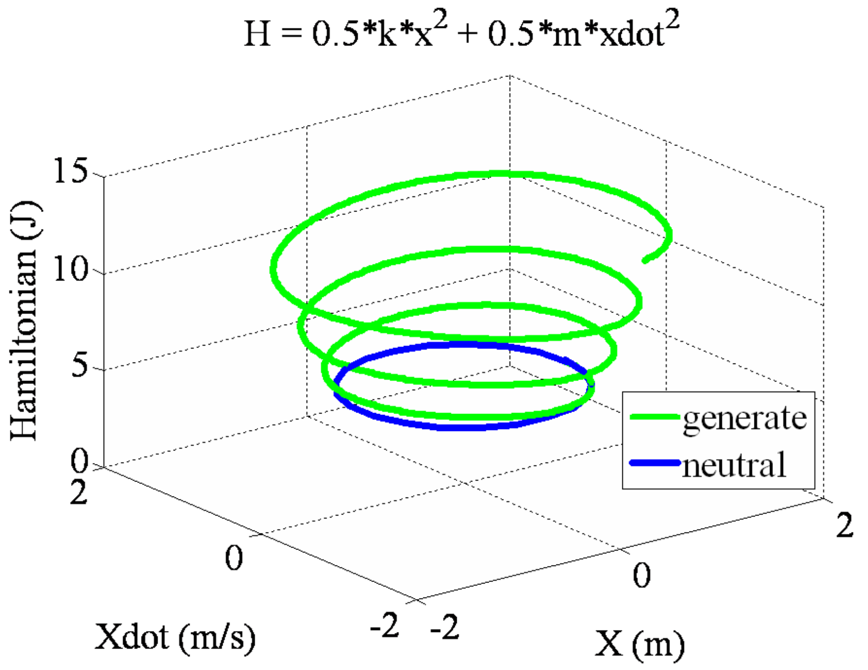
$$c > 0, \quad \int_o^{\tau_c} \dot{W} dt < \int_o^{\tau_c} T_o \dot{S}_i dt$$

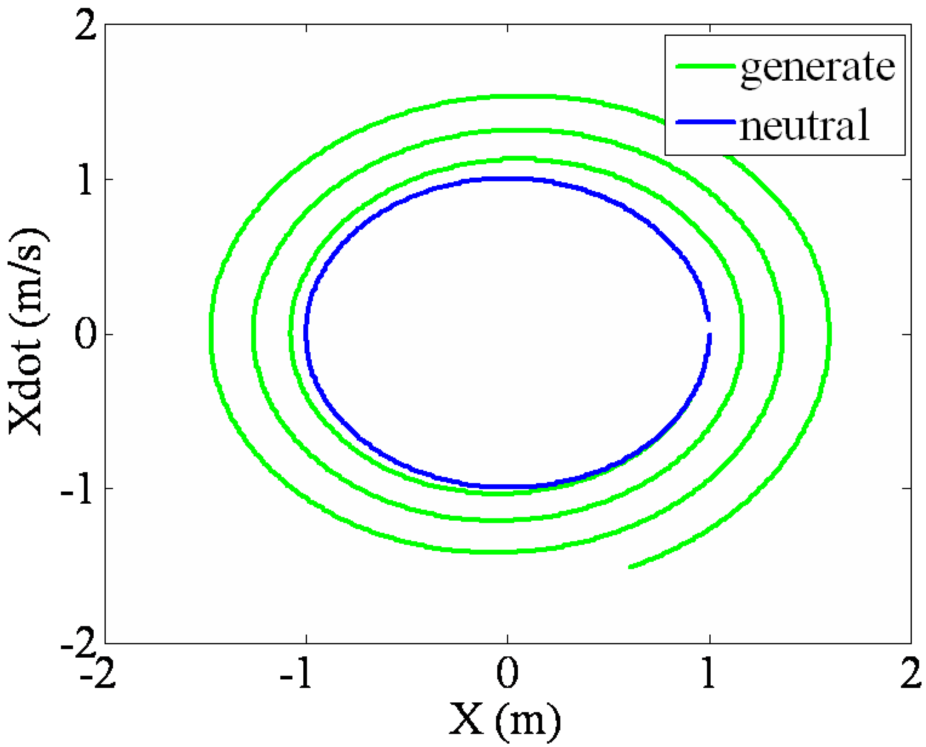
Dynamically Stable

Sandia National Laboratories

Energy Storage Surface and Power Flow: HSSPFC (5)

$$m\ddot{x}+kx=c\dot{x}$$



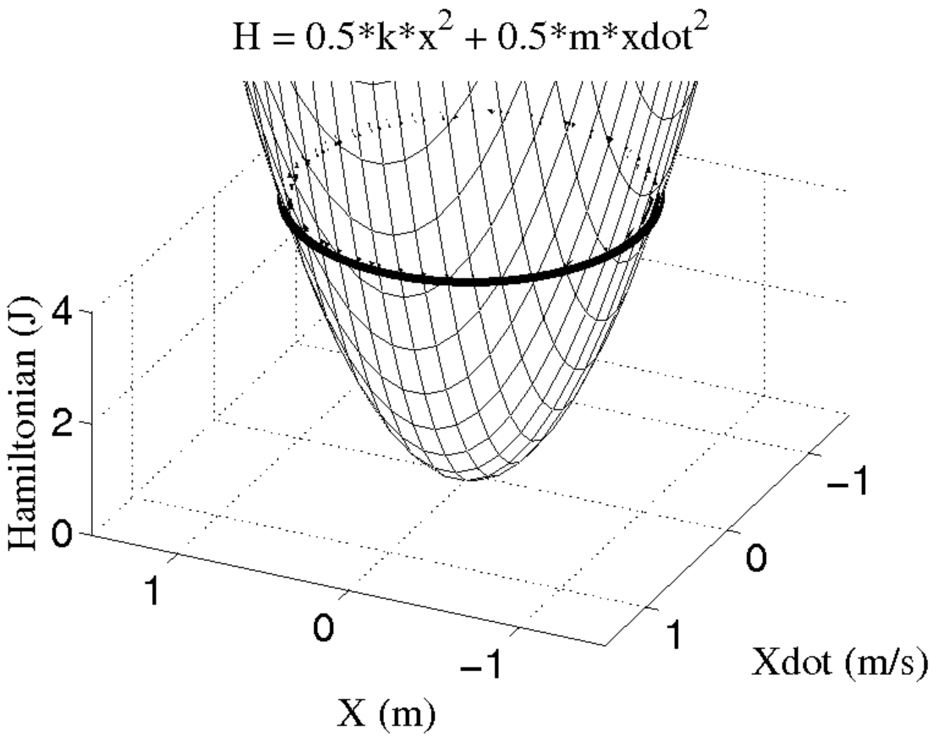


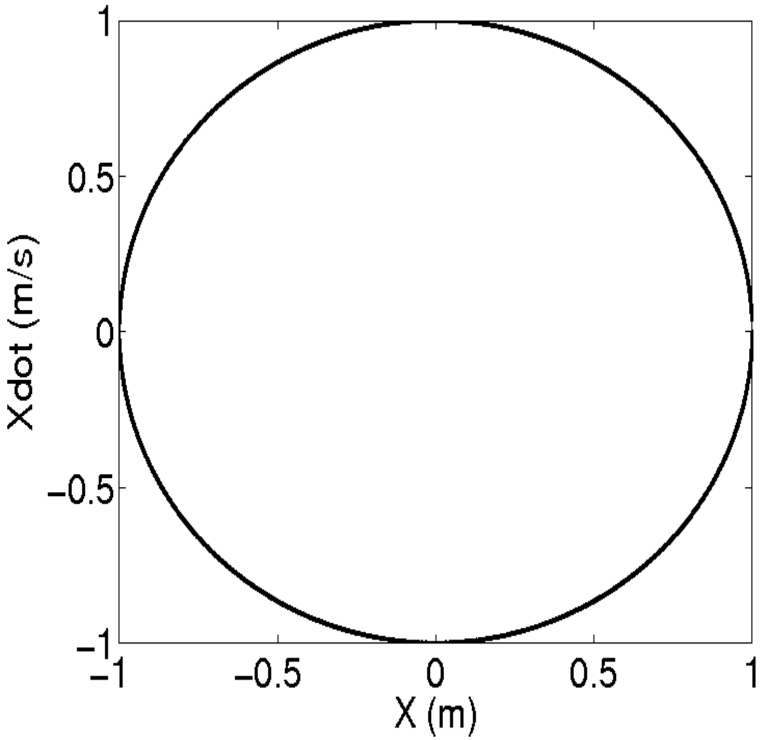
$$c>0,\quad \int_o^{\tau_c}\dot{W}dt>\int_o^{\tau_c}T_o\dot{S}_i dt$$

Dynamically Unstable

Energy Storage Surface and Power Flow: HSSPFC (6)

$$m\ddot{x} + kx = 0$$



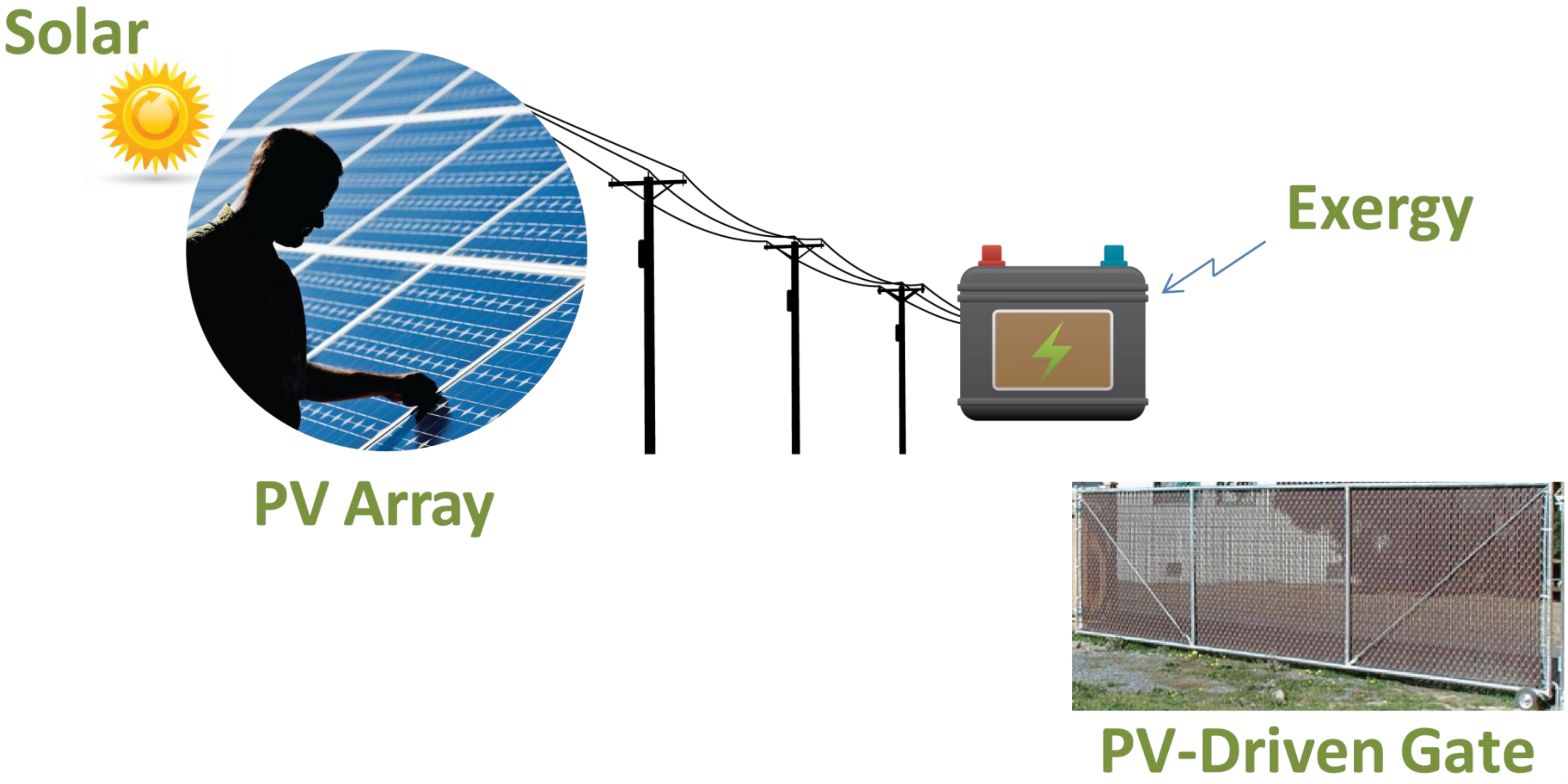


$$c = 0,\ \int_o^{\tau_c} \dot{W} dt = \int_o^{\tau_c} T_o \dot{S}_i dt$$

Dynamically Neutral Stable

Sandia National Laboratories

Energy Storage and Dispatchable Loads (2)



Sandia National Laboratories

Example #1: Robotic Collective Plume Tracing (9)

- **Kinetic Control** – dynamics included: $m_i \ddot{\underline{x}}_i = \underline{u}_i$

1. Shape the Hamiltonian surface to meet the static stability requirements for the i^{th} robot

$$H_i = T_i + V_{c_i} = \frac{1}{2} \dot{\underline{x}}_i^T M_i \dot{\underline{x}}_i + V_{c_i} > 0 \quad \forall \dot{\underline{x}}_i, \underline{x}_i \neq \dot{\underline{x}}^*, \underline{x}^*$$

and the collective of robots

$$H = \sum_{i=1}^{N} H_i = \sum_{i=1}^{N} \left[T_i + V_{c_i} \right] > 0$$

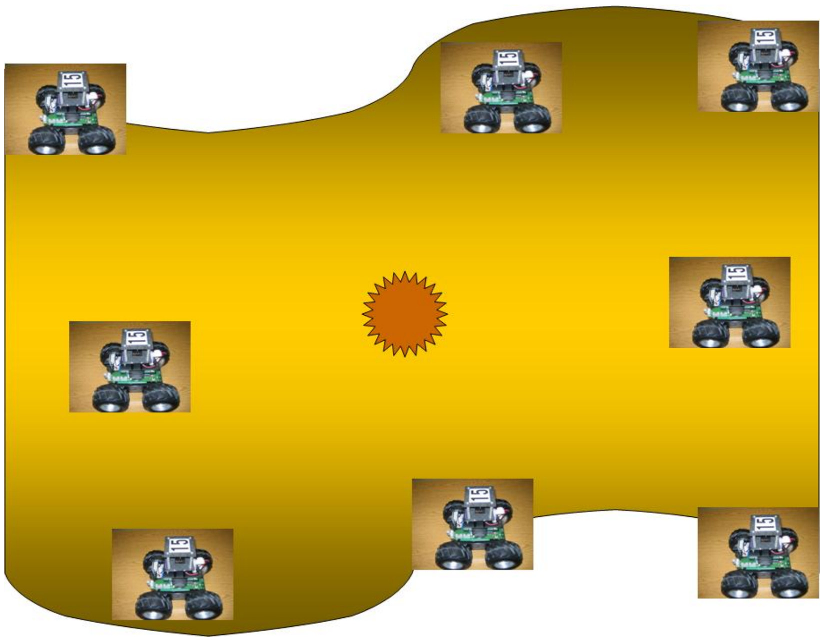
2. Design the power flow, time derivative of the Hamiltonian, to meet the dynamic stability requirements for the feedback controller

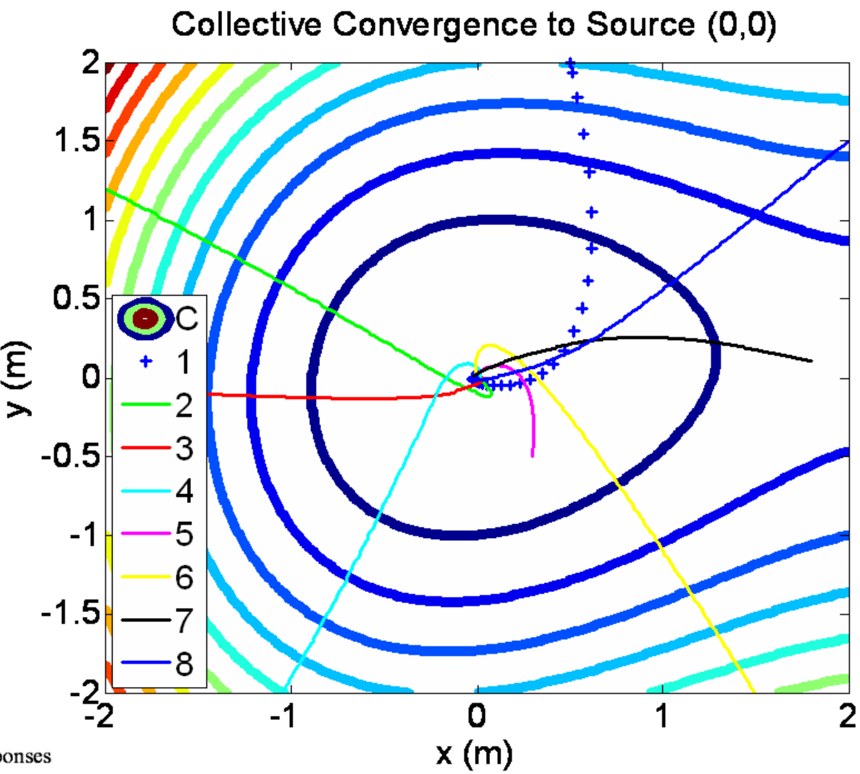
$$\underline{u}_i = -\frac{\partial V_{c_i}}{\partial \underline{x}} - K_I \int \underline{x}_i dt - K_D \dot{\underline{x}}_i$$

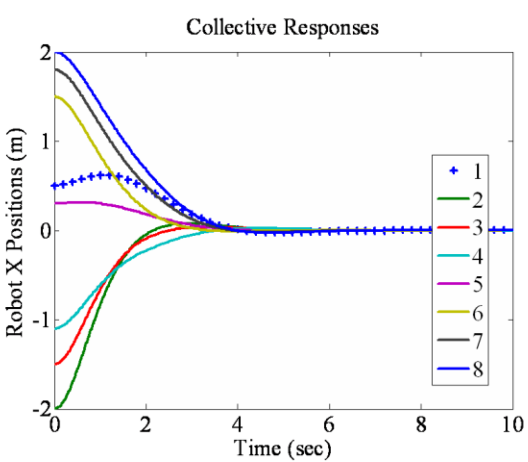
$$\dot{H}_i = \dot{\underline{x}}_i^T \left[M_i \ddot{\underline{x}}_i + \frac{\partial V_{c_i}}{\partial \underline{x}} \right] = \dot{\underline{x}}_i^T \left[K_I \int \underline{x}_i dt - K_D \dot{\underline{x}}_i \right] < 0$$

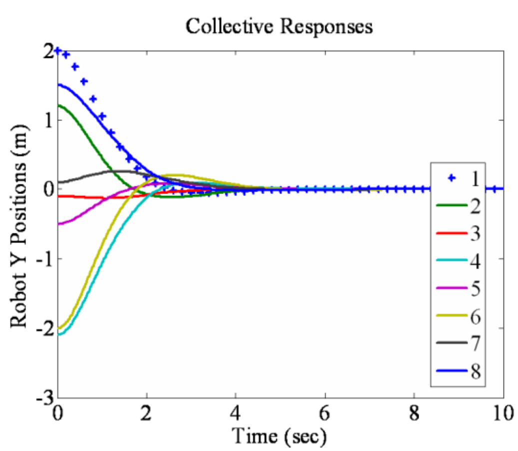
$$\dot{H}_i = \sum_{i=1}^{N} \dot{H}_i < 0$$

Example #1: Collective Robots Numerical Results





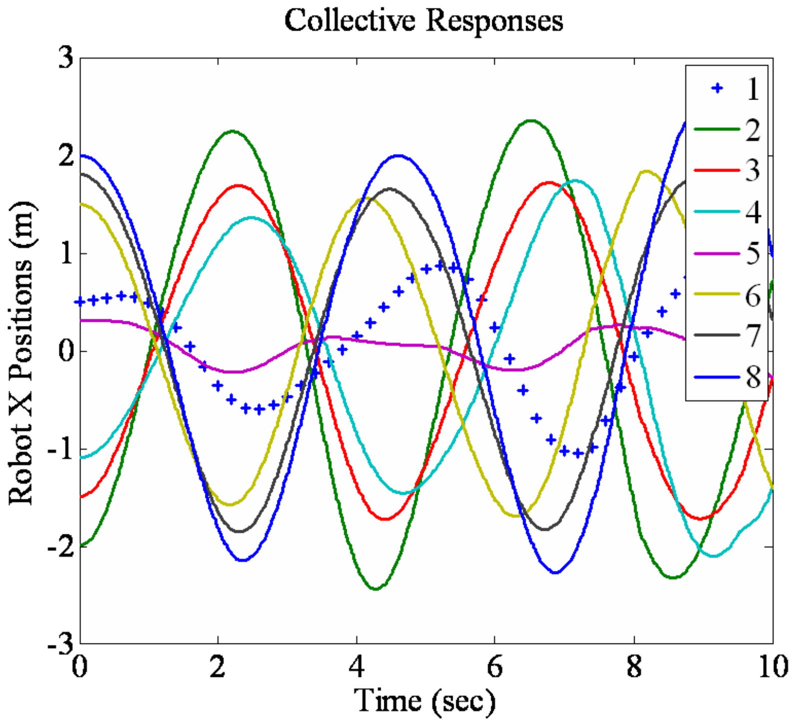


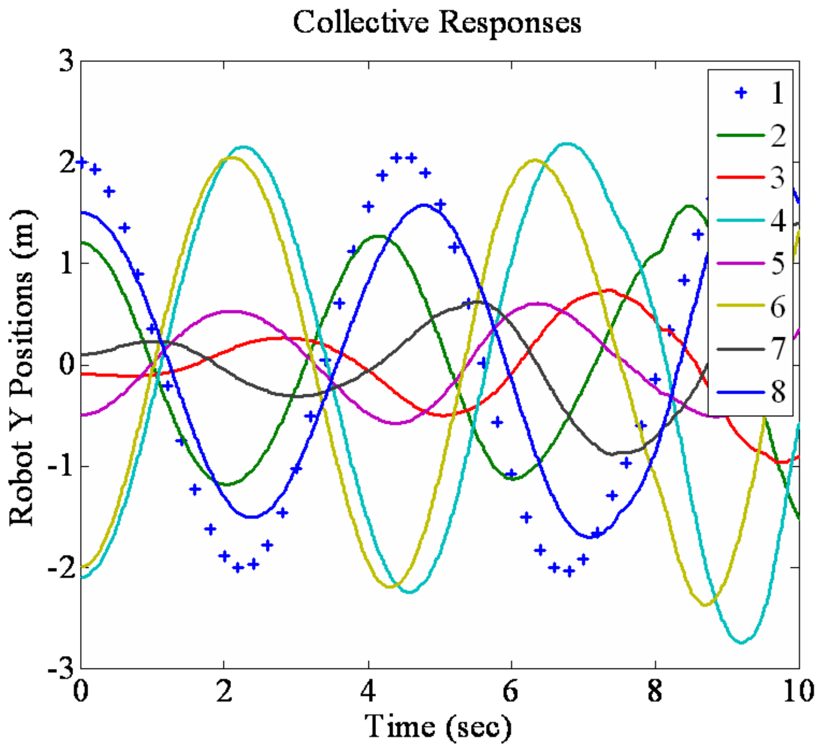


Convergence:
Dissipative > Generative
for the collective

Example #1: Collective Robots Stability Boundary

- Collective robot oscillations at the limit cycle





Example #1: Robotic Collective Plume Tracing (11)

2. Kinetic Control: Fisher Information

a) Fisher Information – Measure of how well the receiver can estimate the message from the sender.

Shannon Entropy – Measure of the sender's transmission efficiency over a communications channel

b) Hamiltonian is exergy; portion of energy that can do work; physical and information exergies

c) Fisher Information:

$$I = \int \left(\frac{\partial \ln p(x)}{\partial x} \right)^2 p(x)dx = \int \frac{1}{p(x)} \left(\frac{\partial p(x)}{\partial x} \right)^2 dx = 4 \int \left(\frac{\partial q(x)}{\partial x} \right)^2 dx$$

$q^2(x) = p(x)$ – "Real Amplitude" function of the probability density function

Example #1: Robotic Collective Plume Tracing (12)

d) 'Mean Kinetic Energy" interpretation of Fisher Information

$$I = 4\int \dot{q}^2 dt = 4\int \frac{2}{m} T dt$$

From Quantum Mechanics in the "Classical Limit" of the expectation of the momentum squared

$$\langle p^2 \rangle = \frac{\hbar^2}{2m} \int \left| \frac{\partial \Psi(x,t)}{\partial x} \right|^2 dx$$

Sandia National Laboratories

Example #1: Robotic Collective Plume Tracing (13)

$\hbar$ - Dirac's constant

$\Psi(x,t)$ - wave function

$\langle \; \rangle$ - expectation operator

The classical limit is reached when

$$\frac{d}{dt}\langle p\rangle_t = m\frac{d^2}{dt^2}\langle x\rangle_t = -\left\langle \frac{dV(x)}{dx}\right\rangle_t = \langle F(x)\rangle_t$$

Is equivalent to

$$m\frac{d^2}{dt^2}x_{classical} = -\frac{dV(x_{classical})}{dx_{classical}} = F(x_{classical})$$

Example #1: Robotic Collective Plume Tracing (14)

Which occurs when

$$x_{classical} = \langle x \rangle$$

and

$$\left(\Delta x\right)^2 = \left\langle \left(x - \langle x \rangle\right)^2 \right\rangle \text{ is small}$$

This occurs when

$$F(x) = F\left(\langle x \rangle\right) + \left(x - \langle x \rangle\right) F'\left(\langle x \rangle\right) + \frac{1}{2!}\left(x - \langle x \rangle\right)^2 F''\left(\langle x \rangle\right) + \ldots$$

which leads to

$$\langle F(x) \rangle \approx F\left(\langle x \rangle\right) + \langle x - \langle x \rangle \rangle F'\left(\langle x \rangle\right)$$

$$\approx F\left(\langle x \rangle\right)$$

Example #1: Robotic Collective Plume Tracing (15)

e) Fisher Information Equivalency and Exergy

$$\tilde{H} = \tilde{T} + \tilde{V} + \tilde{V}_c + \tilde{V}_I = \sum_{i=1}^{N} \frac{1}{m_i} H_i$$

where $\tilde{T} = \sum_{i=1}^{N} \frac{1}{m_i} T_i$

$$\tilde{V} = \sum_{j=1}^{N} \frac{1}{m_j} V_j = \text{ potential}$$

$$\tilde{V}_c = \sum_{k=1}^{N} \frac{1}{m_k} V_{c_k} = \text{ control potential}$$

$$\tilde{V}_I = \sum_{l=1}^{N} \frac{1}{m_l} V_{I_l} = \text{ information potential}$$

Example #1: Robotic Collective Plume Tracing (16)

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

$$\dot{I} + \dot{J} = \tilde{H} > 0 \quad \forall\, \underline{\dot{x}}, \underline{x} \neq \underline{\dot{x}}^*, \underline{x}^*$$ (Static stability)

$$\ddot{I} + \ddot{J} = \dot{\tilde{H}} < 0$$ (Dynamic stability)

Where $J = 8\int \left(\tilde{V} + \tilde{V}_c + \tilde{V}_I\right) dt =$ Bound Fisher Information

Source:[Ref. Frieden] B.R. Frieden, **Physics from Fisher Information: A Unification**, Cambridge University Press, 1999.

Example #1: Summary and Conclusions

- Analyze and design "emergent" behaviors to enable a team of simple robots to perform plume tracing with assistance of information theory
- Demonstrated fundamental nature of Hamiltonian function in design of collective systems
- Equivalences between physical and information-based exergies shown for Shannon information, Fisher Information, and virtual fields
- Fisher Information Equivalency developed that can serve as an ideal optimization functional to measure performance and stability of collective system with respect to required information resources

Sandia National Laboratories

Fisher Information: Storage and Information Flow (1)

- **Measure of order: Cramer Rao Bound**

$$e^2 I \geq 1$$

$e^2 =$ **mean-square error (of a parameter)**

$I =$ **Fisher information**

$$I = \int \left(\frac{\partial p(x)}{\partial x} \right)^2 \frac{1}{p(x)} dx$$

  - **For p(x) Gaussian implies** $e^2 = \sigma^2 =$ **variance**
  - **Implies:** $I = \frac{1}{\sigma^2}$
- **Opposite of Shannon Entropy: Measure of disorder**

Sandia National Laboratories

Fisher Information Storage and Information Flow (2)

- **Specific Forms:**

a)

$$I = 8\int T dt = 8\int \frac{1}{2}\dot{x}^T M \dot{x} dt$$

- *Infinite bus of grid:* $M^{-1} \cong 0 \Rightarrow x(t) \approx x_0$

b) **Equivalence between Exergy, Hamiltonian, and Fisher information**

- *Compare values of energy storage and information flow (adaptive, estimation, communication links, central vs. decentralized, etc.)*

c) **Minimize I:**

$$I + J = 8\int H dt = 8\int (T + V) dt = 8\int (T + T_C + V + V_C + V_I) dt$$

- Where T_C, V_C - control feedback and V_I - adaptive control

➢ *Constraints:* $\ddot{I} + \ddot{J} = 8\left[\dot{H}\right] = 8\left[G - L\right] = 0$

➢ *Additional cost functionals:* $\hat{J}_1 = \int \left[G\right]^2 dt, \hat{J}_2 = \int \left[L\right]^2 dt$

Fisher Information Storage and Information Flow (3)

d) Maximize Efficiency: Power factor =1

- *Balance T+V for 60 Hz (eigenvalues)*

e) I is the inverse of the covariance matrix

- **Stochastic optimal control: parameter/state estimation**
- **Nonlinear: Fokker-Plank equation**

f) Minimize Risk of Lost Load

- **Risk (probability) minimized with required energy storage**
- **Agent-informatics layer**

Example #2: Today's Grid Common Model 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

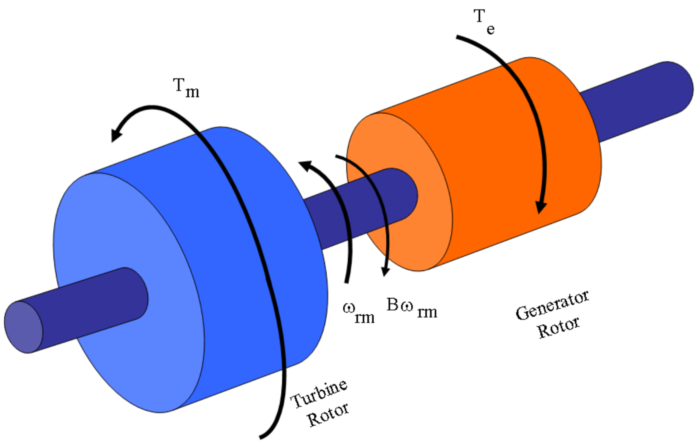
$$M_k \dot{\omega}_k = P_{mk} - E_k'^2 G_{kk} - D_k \omega_k - \sum_{\substack{l=1 \\ l \neq k}}^{n} \left(C_{kl} \sin(\delta_{kl}) + F_{kl} \cos(\delta_{kl}) \right)$$

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

- **Various network components assumed to be <u>insensitive to changes in frequency</u>**
- **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 <u>constant (P_{mk})</u>**
- **Saliency is neglected**
- **Stator resistance is neglected**

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

Example #2: 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 r

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

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:

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

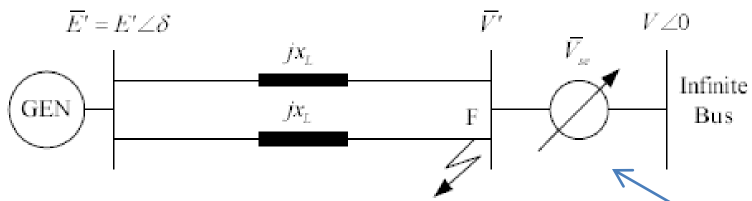
$$H = \frac{1}{2}J\dot{\delta}^2 + P_{max}(-\cos\delta)$$

$$\dot{H} = \left[J\ddot{\delta} + P_{max}\sin\delta - P_m\right]\dot{\delta} = -B\dot{\delta}$$

llow)

Sandia National Laboratories

Example #2: Design of the OMIB with UPFC Using HSSPFC



UPFC

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

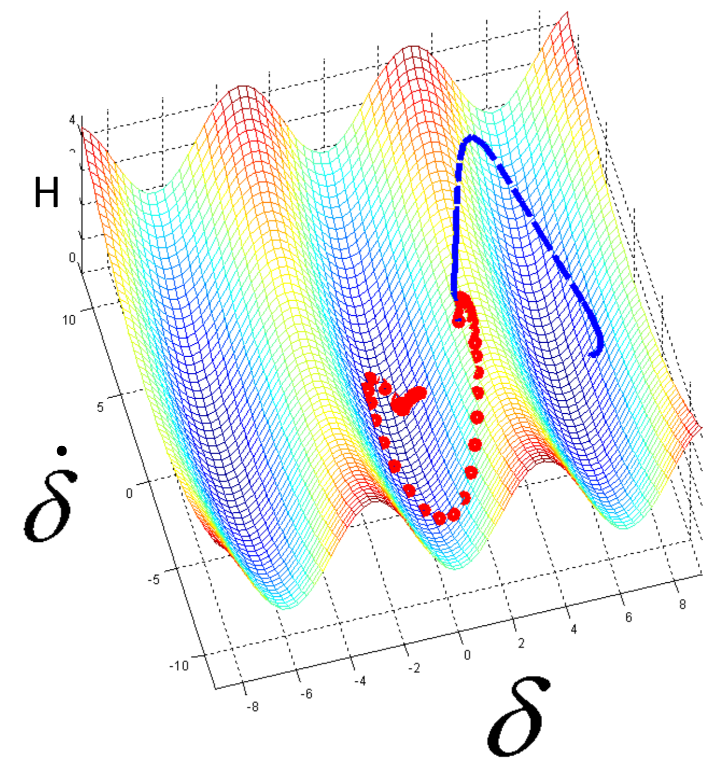
$$\delta_s = \sin^{-1}\left(\frac{P_m}{P_{\max}}\right)$$

-Dynamic stability condition (power flow):

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

- Integrator: faster system

Hamiltonian Surface



Example #3: DC Bus Microgrid

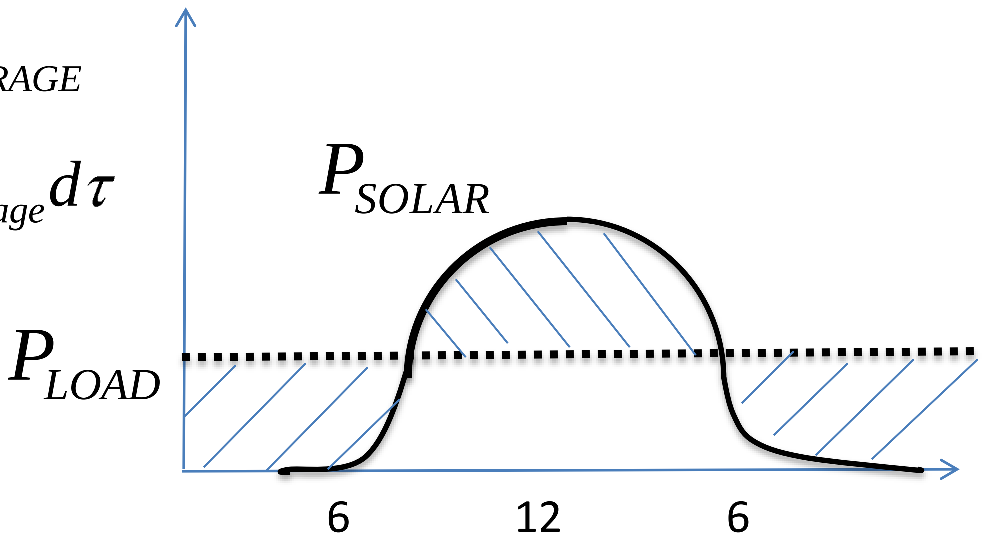
- Feedback controller design for integration of renewable energy into DC bus microgrid
- Feedback controller decomposed into two parts:
  - Feedback guidance command for boost converter duty cycle
  - HSSPFC implements energy storage systems
- Duty cycle servo control fully coupled
- HSSPFC completely decoupled due to skew-symmetric form analogous to Spacecraft and Robotic systems
- Configuration: DC bus with 2 boost converters for investigation of 0%-100% energy storage evaluation, specifications, and requirements

Example Optimization Cost Functional

$$P_{IN_{1_{max}}} + P_{IN_{2_{max}}} \geq P_{LOAD_{max}} + P_{STORAGE}$$

$$\oint P_{IN_{total}} d\tau = \oint P_{Load} d\tau + \oint P_{Storage} d\tau$$

$$E_{IN_{total}} = E_{Load} + E_{Storage}$$



- **Simple solar example:**
- Over the cycle match the generation with the load
- Two areas below the line need to match single area above line
- Defines storage charge/discharge requirements over the cycle
- Tool can be used to help design storage systems given actual microgrid scenario (generation, loads, storage)

Sandia National Laboratories

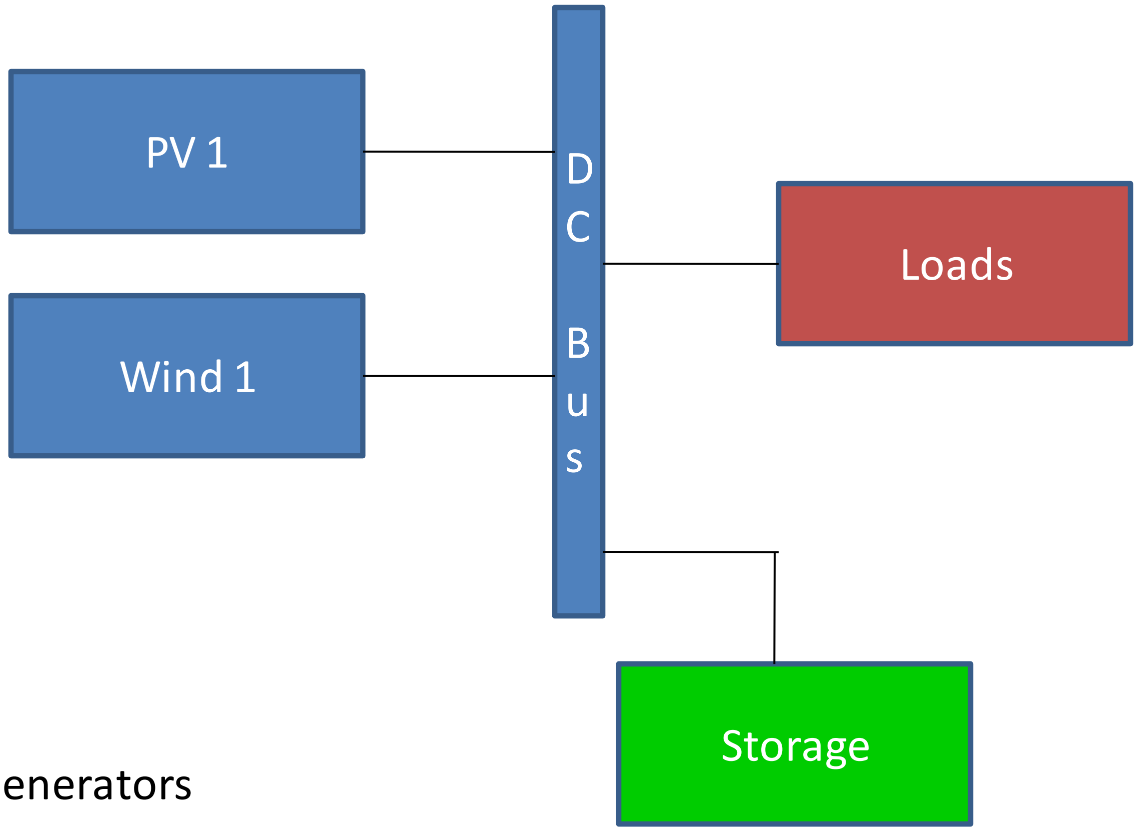
Example #3: DC Bus Microgrid Model HSSPFC for Energy Storage Design Observation

- **It is useful to discuss several observations about equations (1) and (2):**
  a) Equation (1) is an equivalent guidance command that is fully coupled in the states and dependent upon the duty cycle commands. The duty cycle commands will be determined from an optimization routine (SQP, DP, etc.) when desired cost functions and constraints are included.
  b) For renewable energy sources, v will be time varying and possibly stochastic which leads to an under-actuated system, for 0% energy storage, u=0.
  c) For fossil energy sources, v will be dispatchable with excess capacity which leads to an over-actuated systems with 100% energy storage even with u=0.
  d) For u not equal to zero, microgrid with 100% transient renewable energy sources(PV and wind) will lead to requirements for energy storage systems (power, energy, frequency specs., etc.).
  e) Controller, u, is decoupled which simplifies design procedure.

Sandia National Laboratories

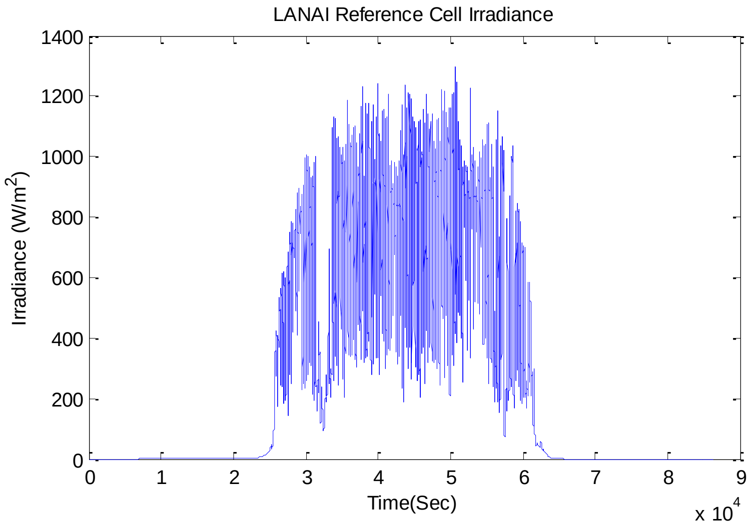
HSSPFC Implementation Scenario Collective Microgrid Components

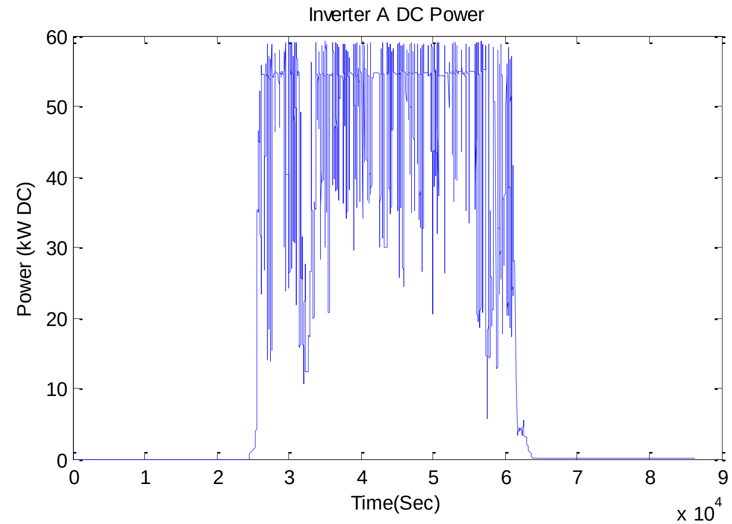
Scenario 2

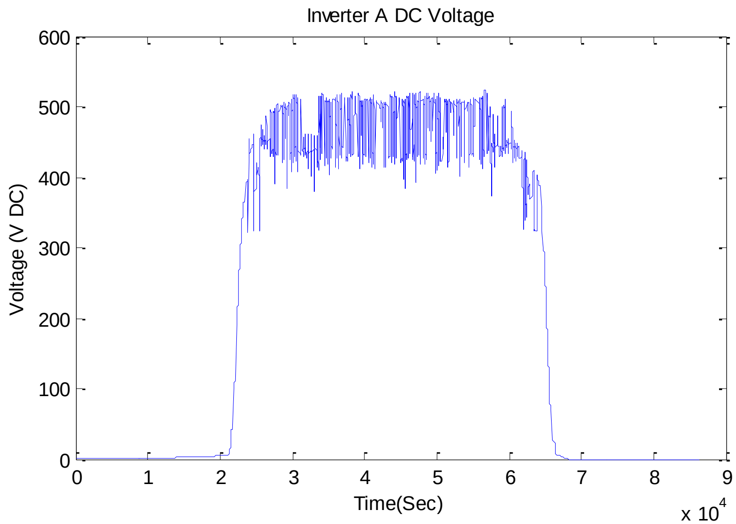


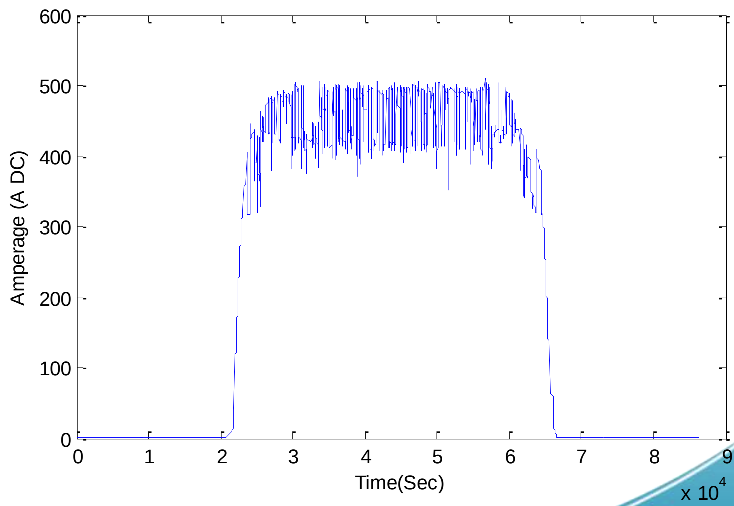
- 2 Variable Generators
- Storage
- Variable Loads

PV Data Lanai Microgrid System





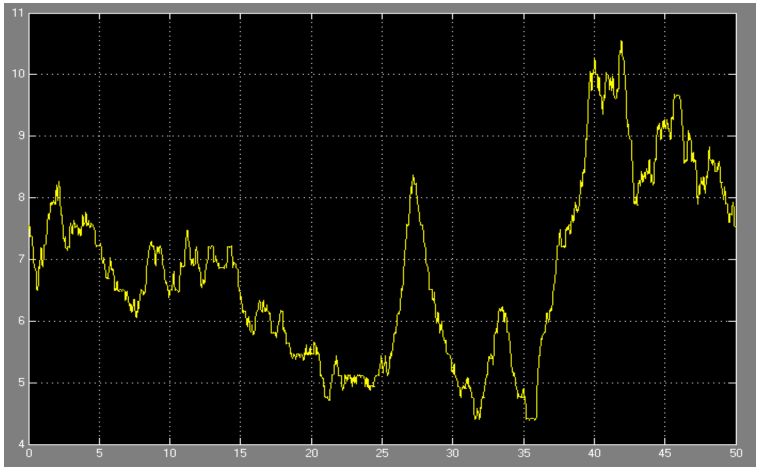




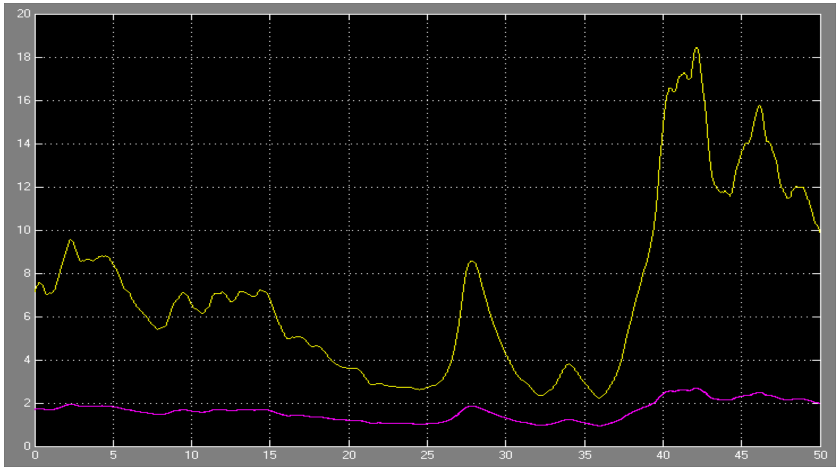
Sandia National Laboratories

Variable Speed Wind Turbine Utilizing Bushland Test Site Data

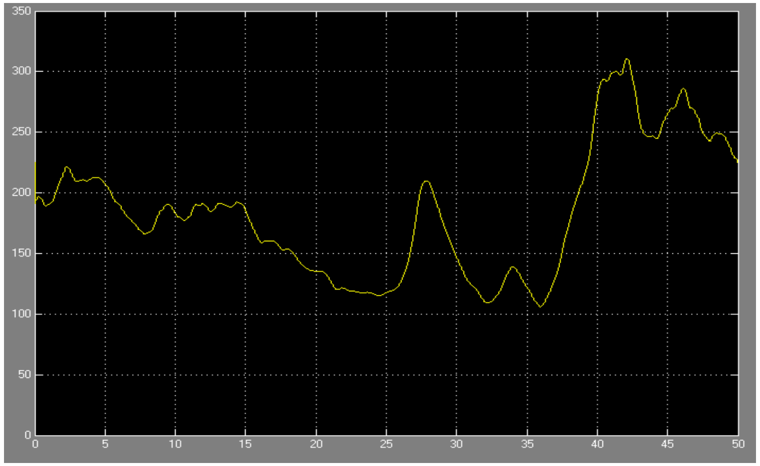
Wind Speed (m/s) *data from Bushland test site*



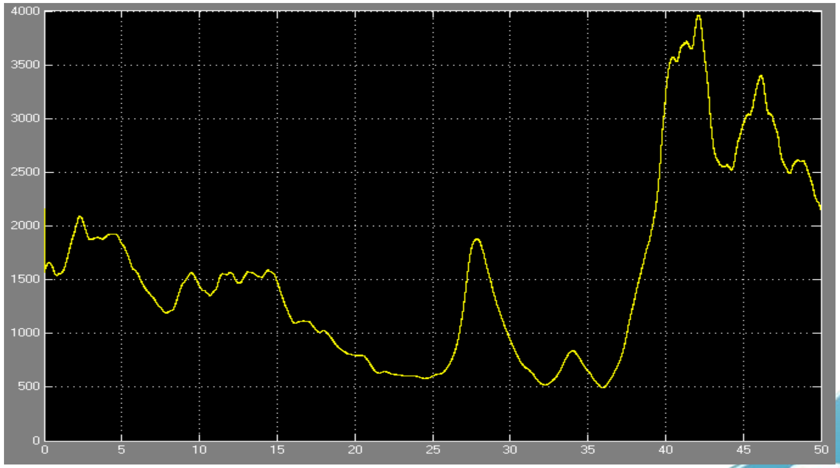
d and q axis currents (Amps)



Rotor speed (RPM)

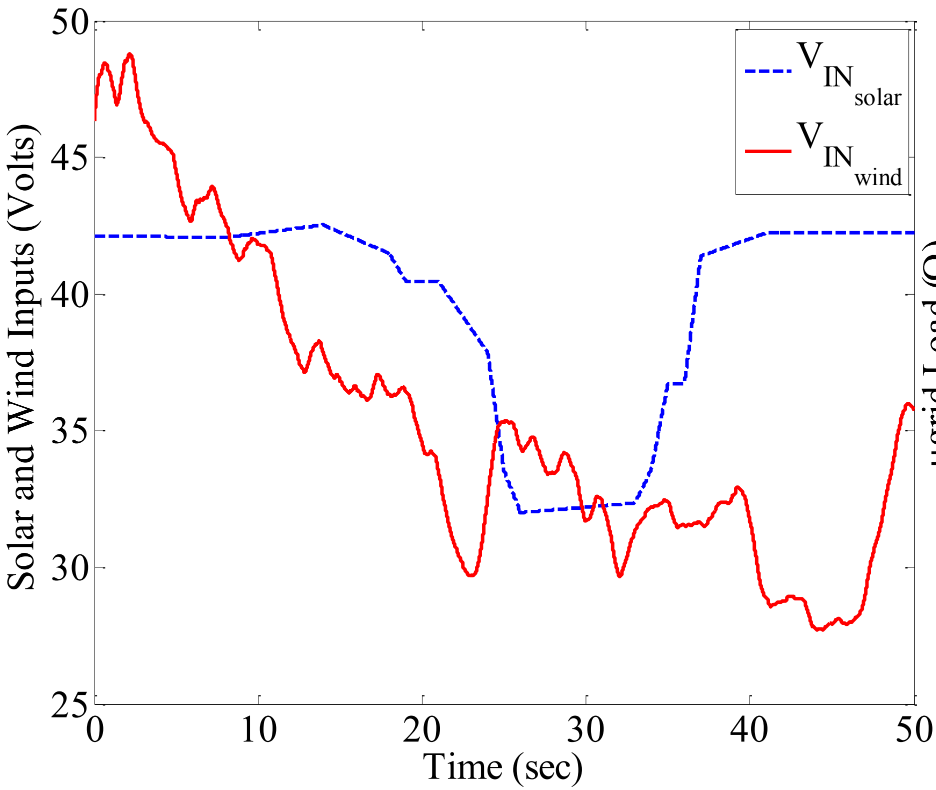


Real Power Out (W)

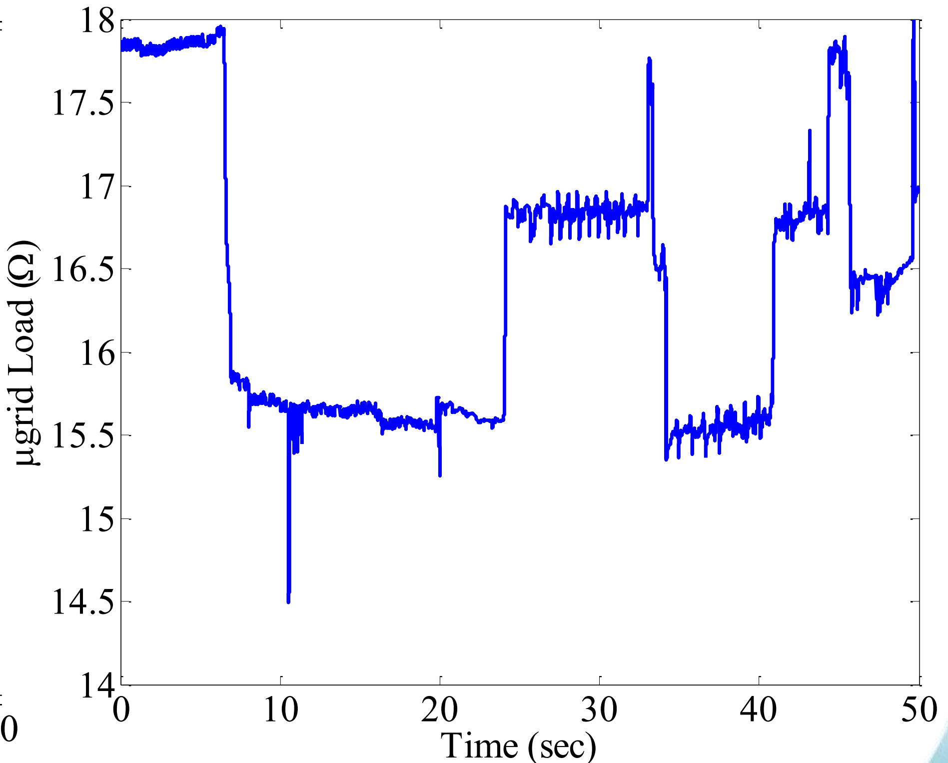


Sandia National Laboratories

Numerical Results Solar, Wind and Loads Test Data



Solar and Wind Inputs from Test Data

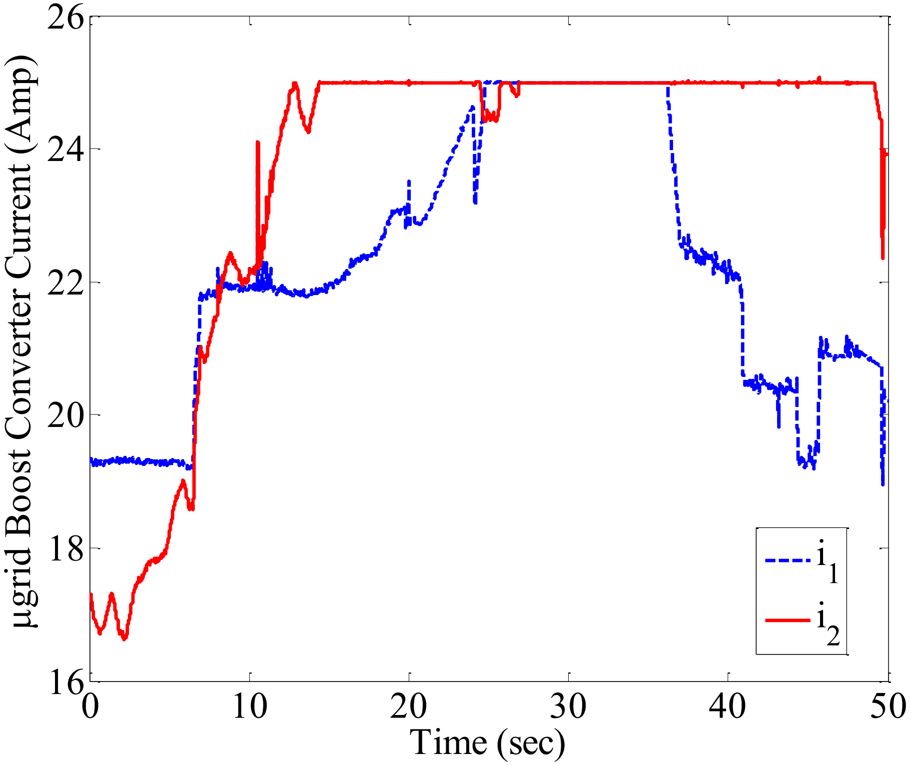


Actual Load Profile

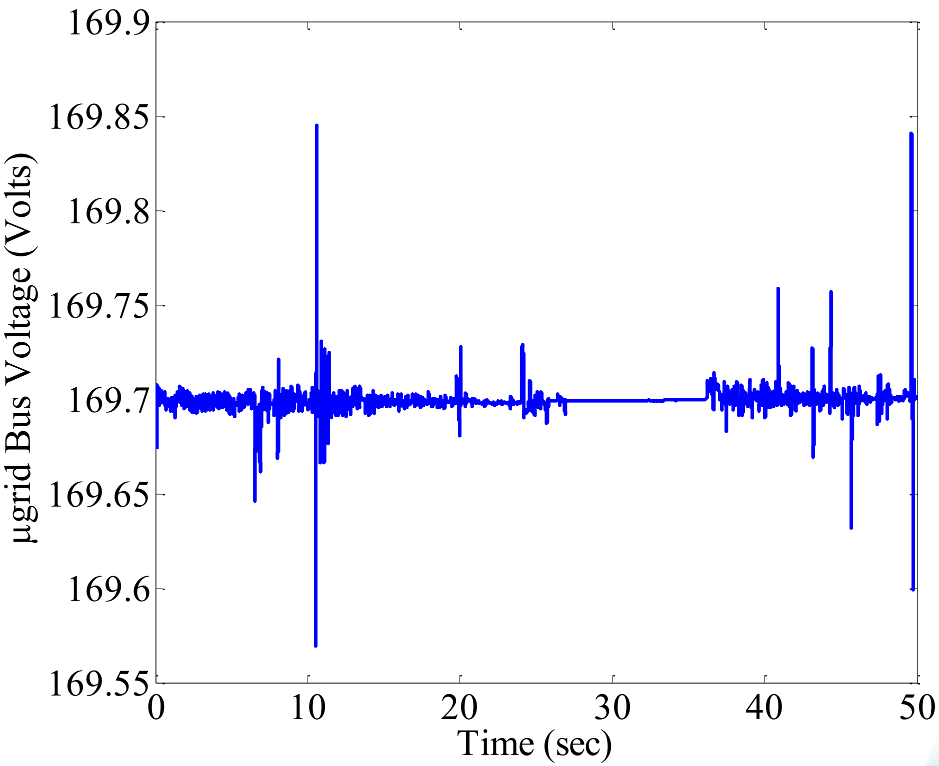
Scenario 2

Sandia National Laboratories

Numerical Simulation Results Boost Converter Currents and Bus Voltage



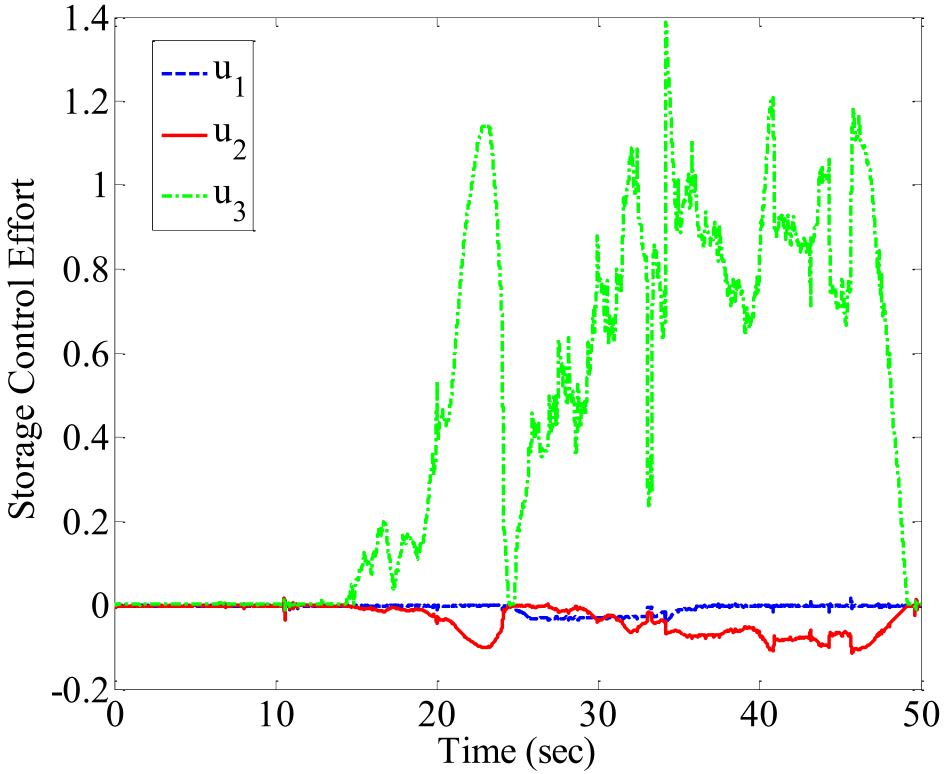
Boost Converter Currents
(Current saturation at 25 Amps)



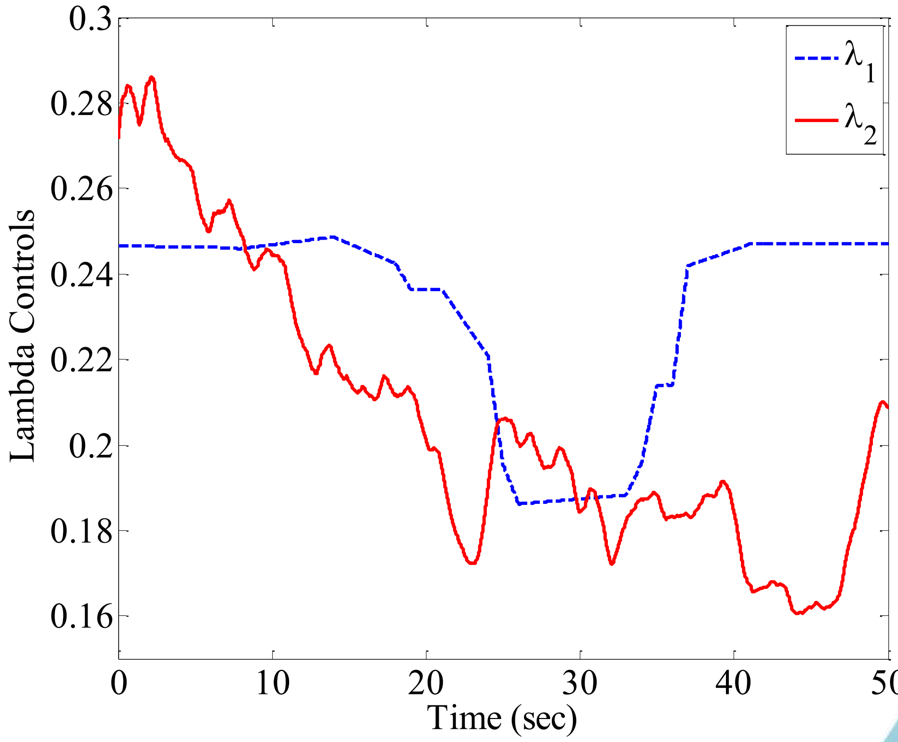
Bus Voltage
(Bus regulation 120*sqrt(2) +/- 5%)

Scenario 2

Numerical Simulation Results Storage Control Effort and Ideal Lambda Controls



Storage Control Effort



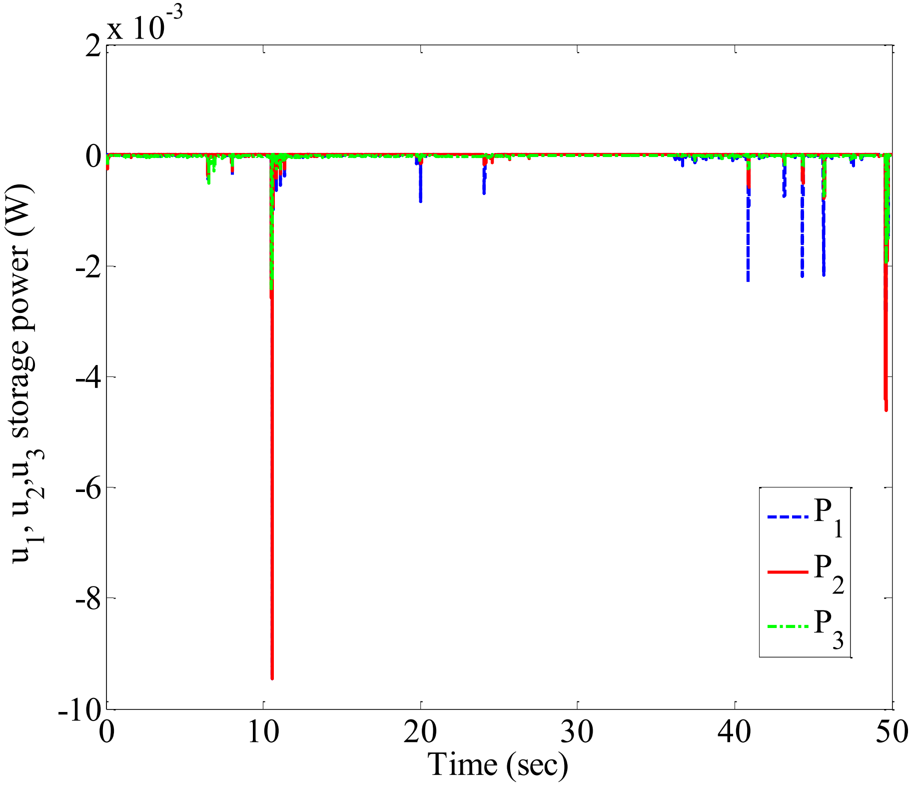
Lambda Controls

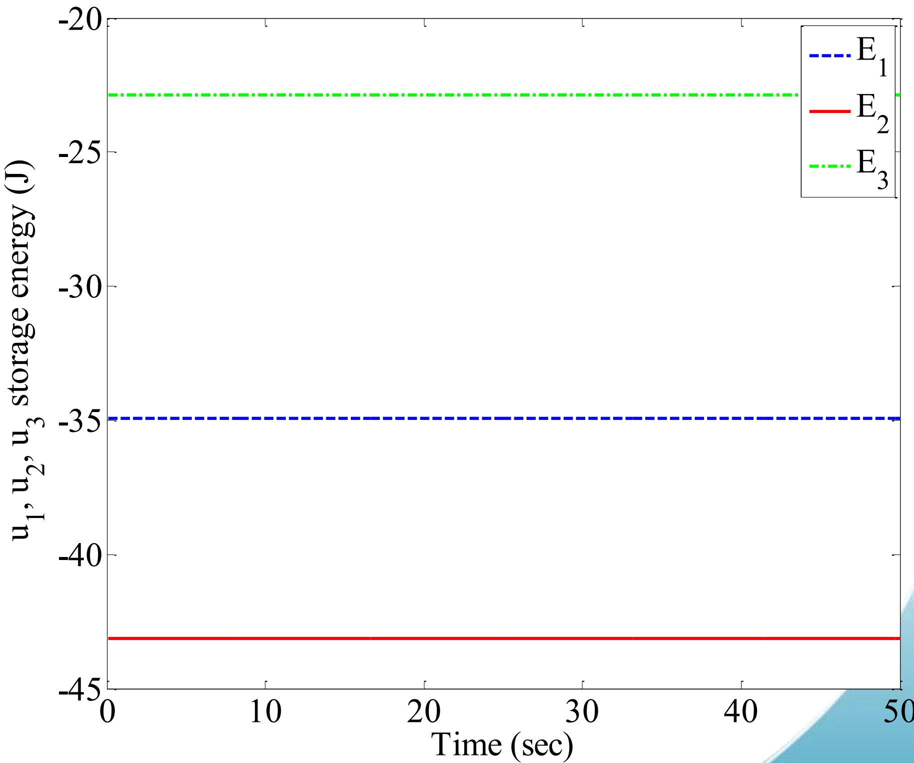
Scenario 2

Sandia National Laboratories

Energy Storage Requirements Scenario 2

- **Power Requirements**
- **Energy Requirements**
- **Frequency Response Requirements (see next chart for individual channels)**

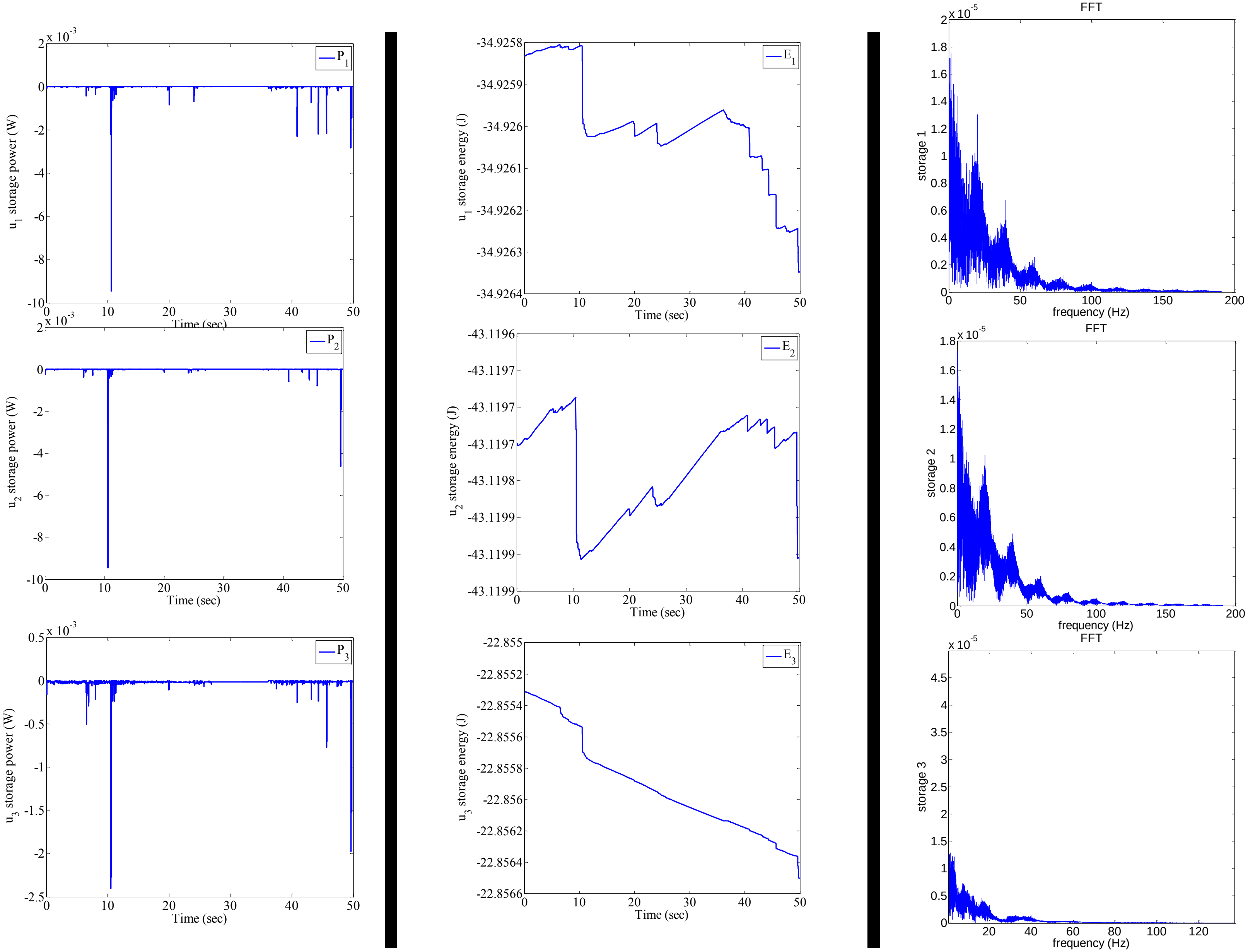




Specifications for the microgrid and/or UPFC based on:
(Power, Energy, Frequency PSDs)

Sandia National Laboratories

Energy Storage Requirements Scenario 2



DC Boost 1

DC Boost 2

DC Bus

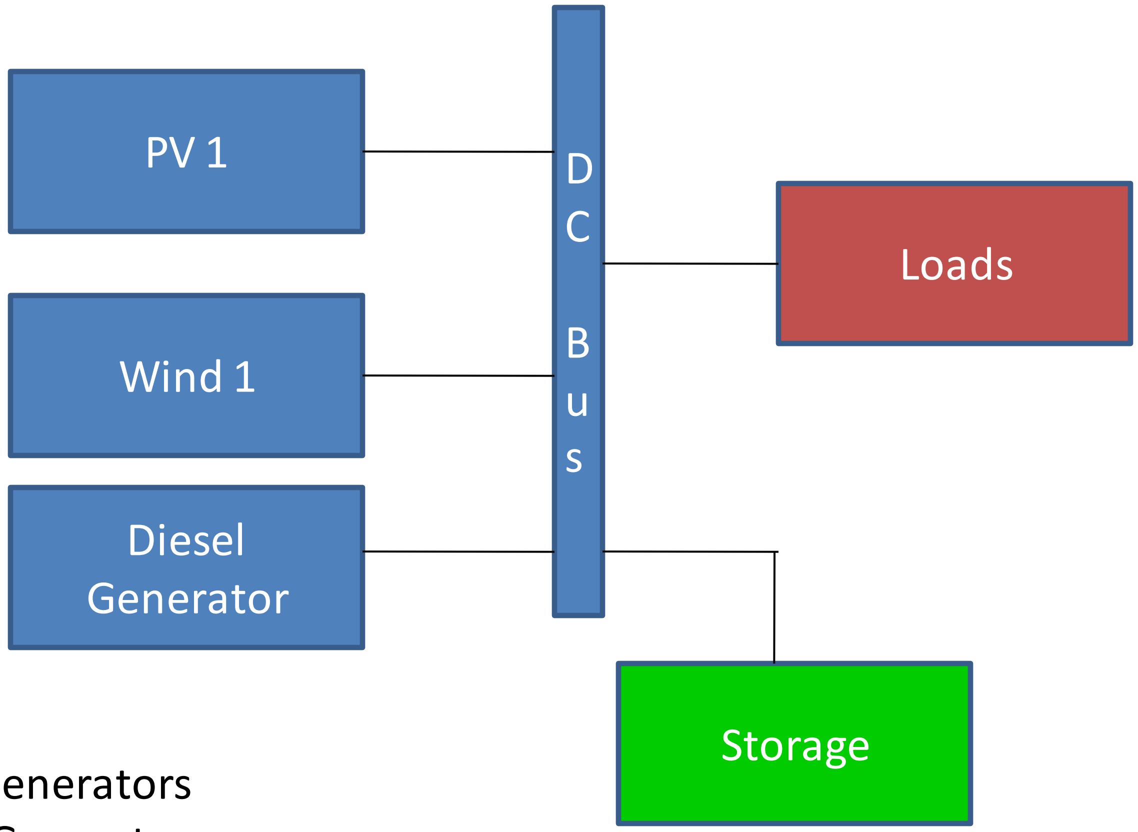
Power Requirements | Energy Requirements | Frequency Response

(requirements displayed for each channel - along the row)

Sandia National Laboratories

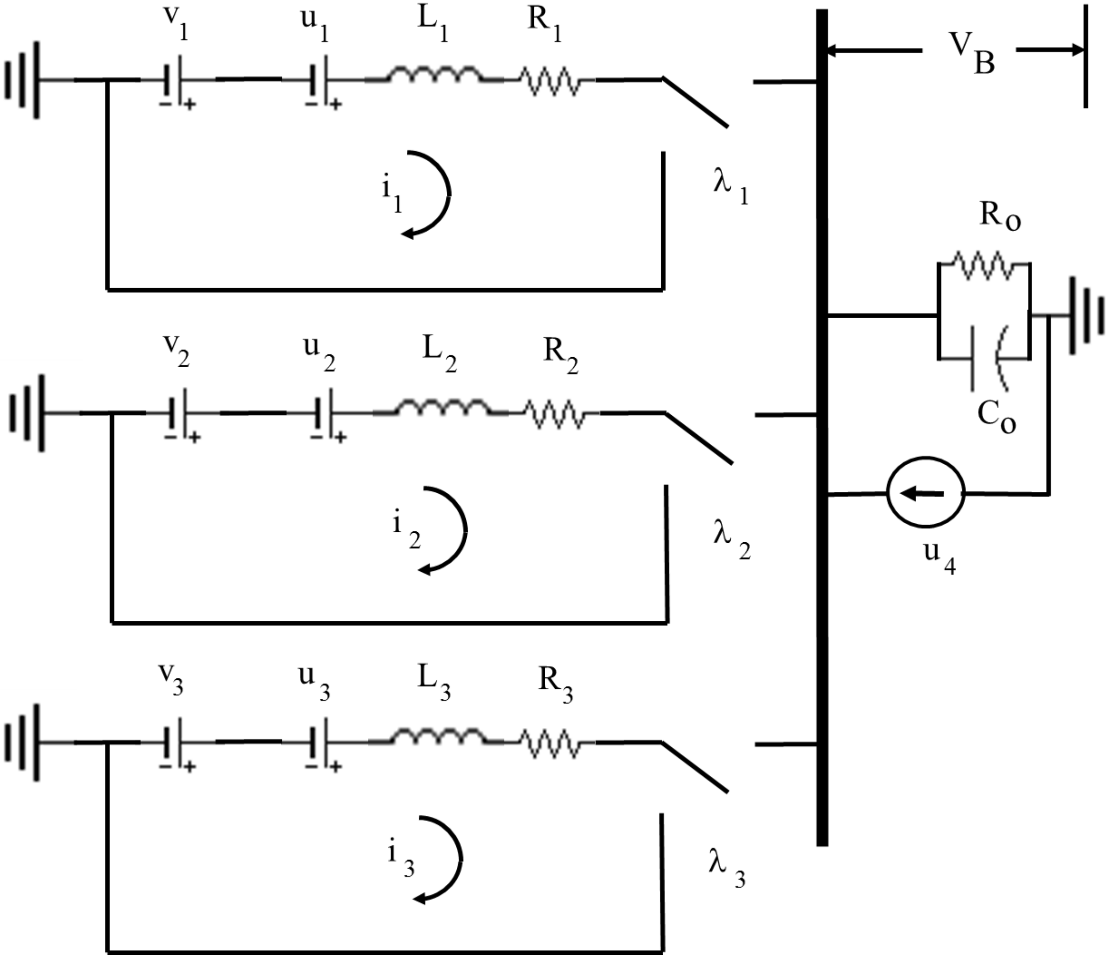
HSSPFC Implementation Scenario Collective Microgrid Components

Scenario 3



- 2 Variable Generators
- 1 Constant Generator
- Storage
- Variable Loads

Scenario 3 Microgrid Model

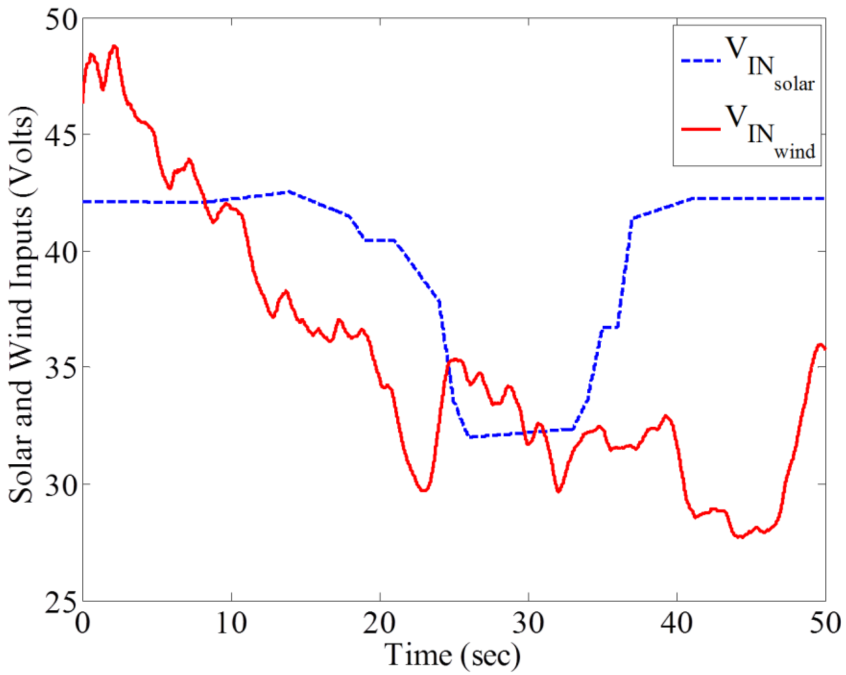


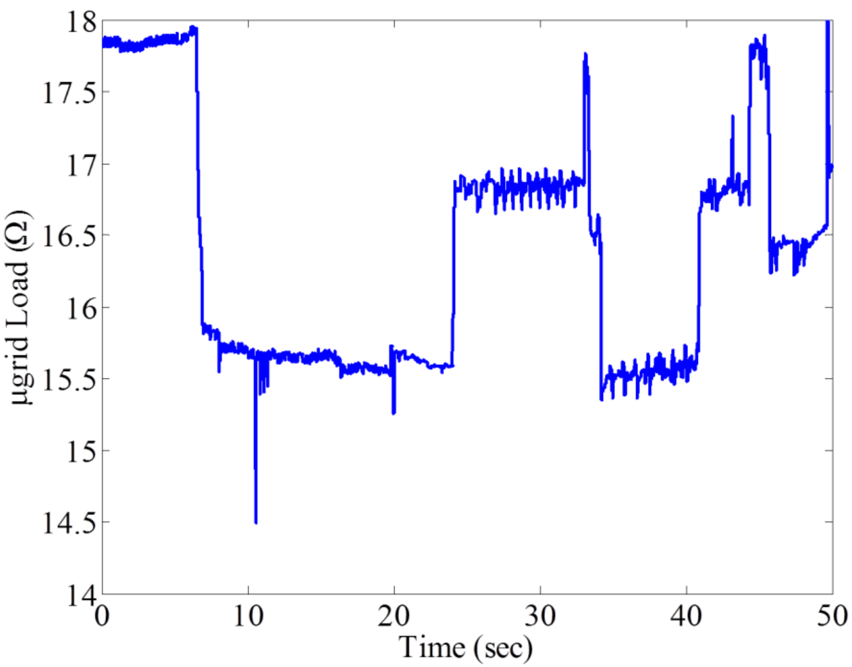
- Feedback controllers for integration of renewable energy to DC bus microgrid system

- Model used to produce energy storage requirements

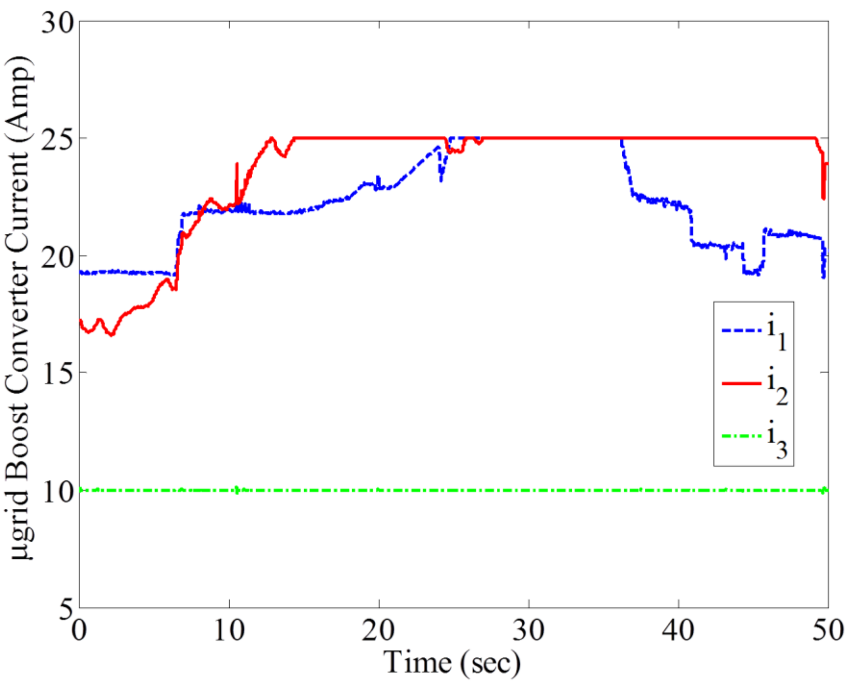
Sandia National Laboratories

Lanai PV and Bushland Wind Inputs and Realistic Variable Load Profile

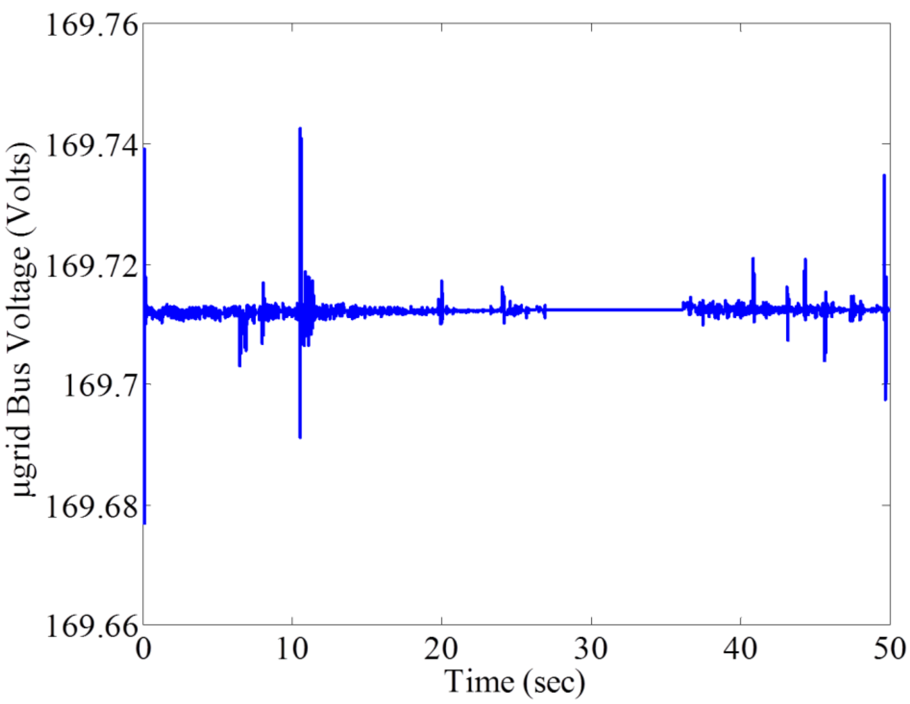




Numerical Simulation Results Boost Converter Currents and Bus Voltage



Boost Converter Currents
(Current saturation at 25 Amps)

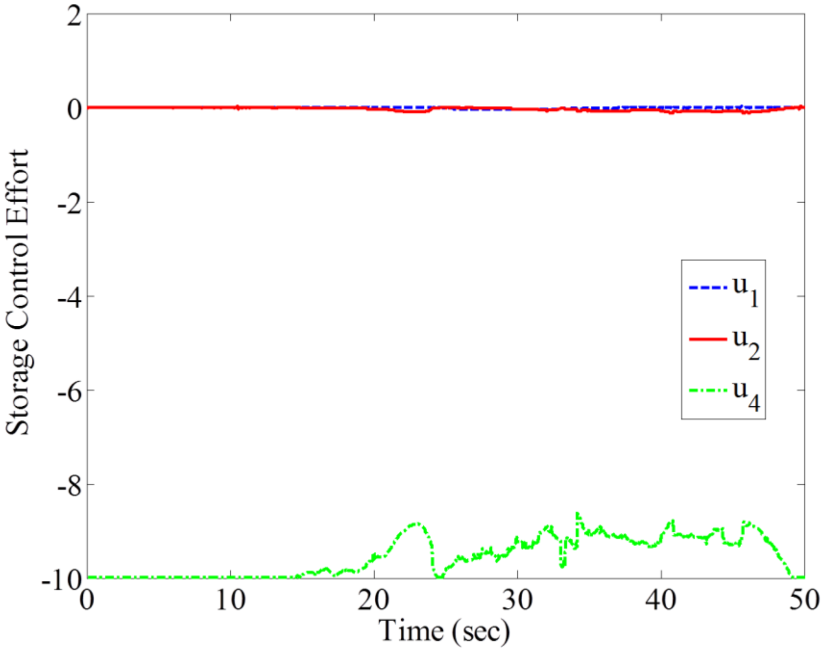


Bus Voltage
(Bus regulation 120* sqrt(2) +/- 5%)

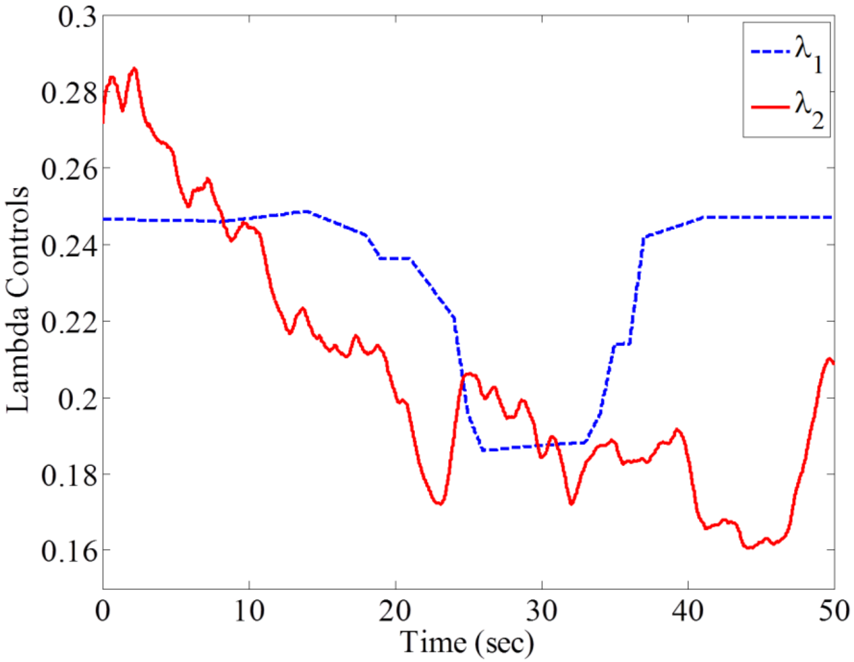
Scenario 3

Sandia National Laboratories

Numerical Simulation Results Storage Control Effort and Ideal Lambda Controls



Storage Control Effort

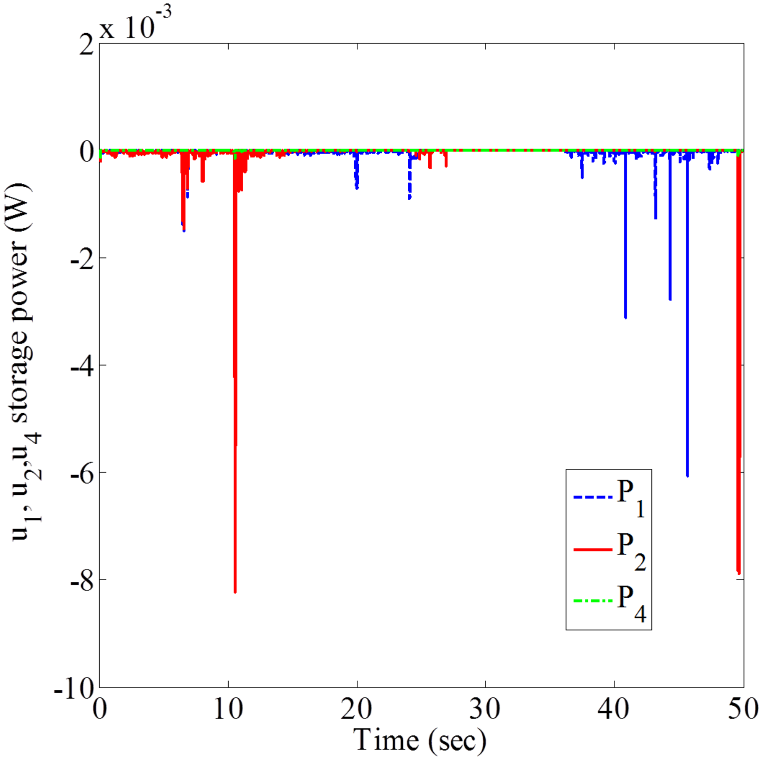


Lambda Controls

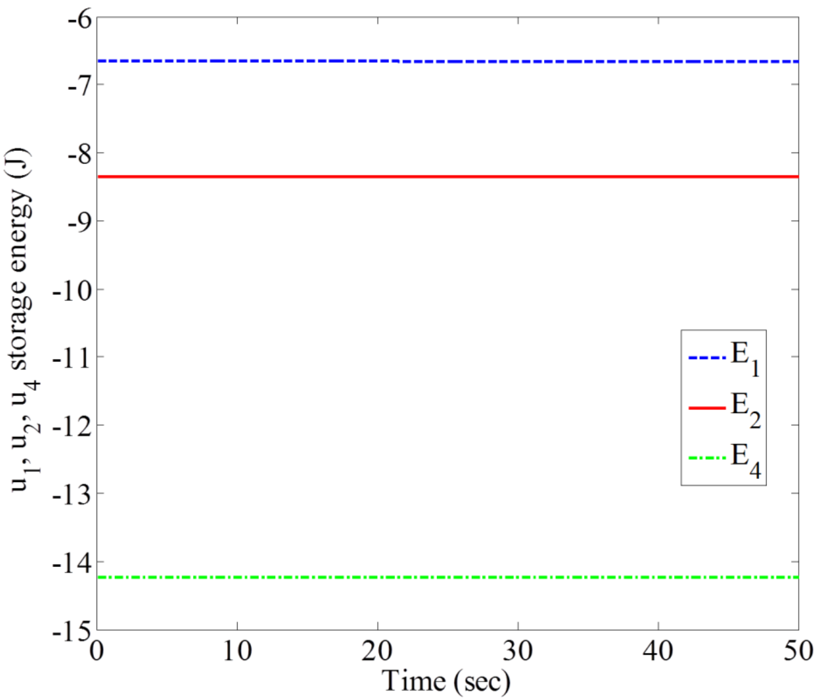
Scenario 3

Sandia National Laboratories

Energy Storage Requirements Scenario 3

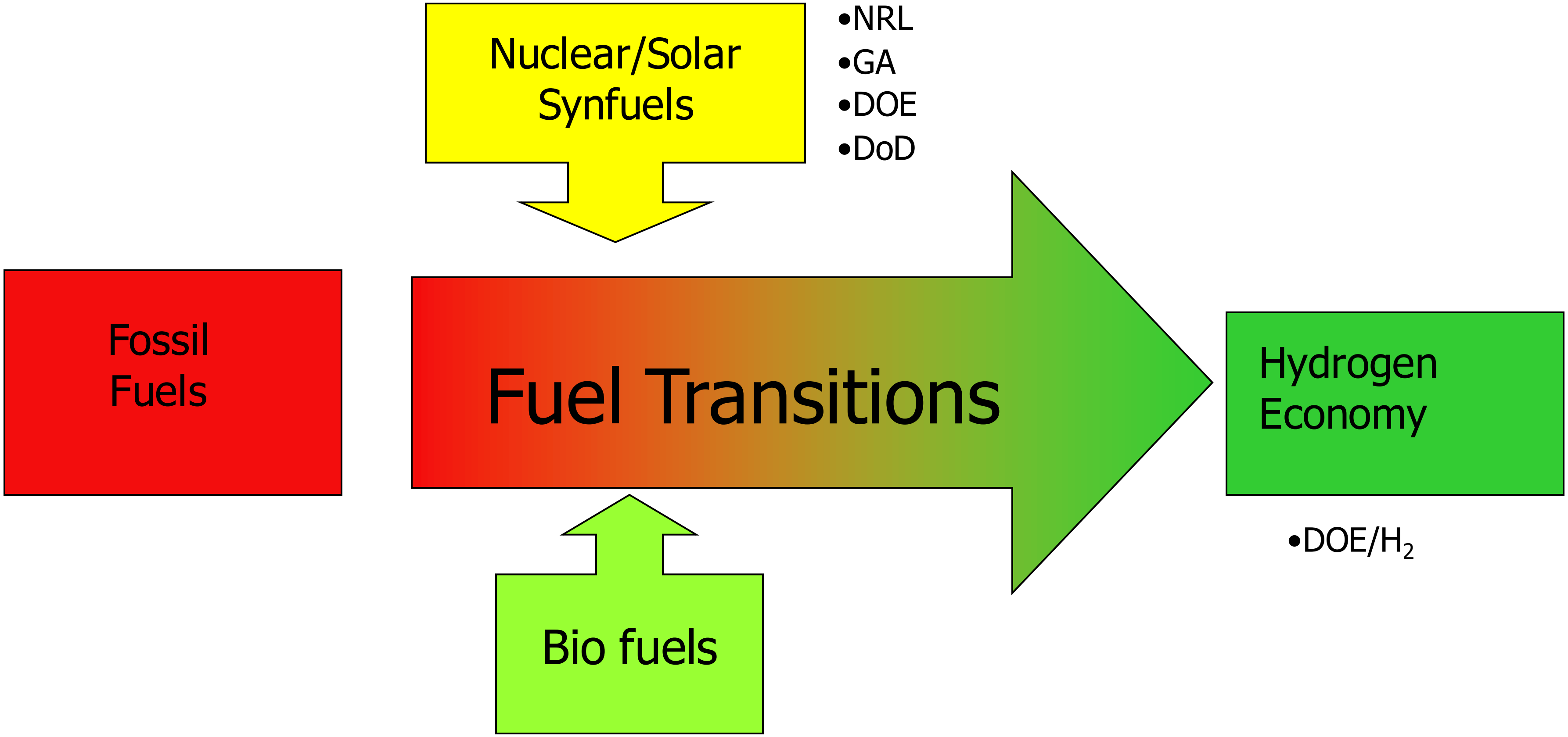


Power



Energy

Hydrocarbon Core Pathway



Transition Efficiencies:

Syn Fuels 10%

Ethanol/Bio .12-0.02%

CO_2 TAX