PSERC Power Systems Engineering Research Center
*Empowering minds to engineer the future electric energy system*

# Technological Challenges in Designing the Future Grid

A Forum from the PSERC Future Grid Initiative
Funded by the Office of Electricity Delivery and Energy Reliability,
U.S. Department of Energy

June 27-28, 2012
L'Enfant Plaza Hotel
Washington, D.C.

## Agenda

### Wednesday, June 27

7:15-8:00 Registration. Coffee, Juice, Bagels, Fruit

8:00-8:30 **Introduction**
Vijay Vittal, Professor, Arizona State University, and Director, Power Systems Engineering Research Center

8:30-8:45 **Role of the Future Grid**
Patricia Hoffman, Assistant Secretary for Electricity Delivery and Energy Reliability, U.S. Department of Energy

8:45-10:15 **Technology Session 1: Power Delivery Infrastructure**

**Overview Presentation:** Jerry Heydt**,** Arizona State University

**Discussion Panel:**
Flora Flygt, Strategic Planning & Policy Advisor, American Transmission Co.;
Jim McCalley, Iowa State University
Robert Saint, Principal Engineer, National Rural Electric Cooperative Association
Peter Sauer, University of Illinois at Urbana/Champaign

**Discussion Facilitator:** Ward Jewell, Wichita State University

10:15-10:45 Break

10:45-12:15 **Technology Session 2: Operations and Planning**

**Opening Presentation:** Jim McCalley, Iowa State University

**Discussion Panel:**
George Angelidis, Principal, Power System Technology Development, California ISO
George Gross, University of Illinois at Urbana/Champaign
Tim Ponseti, Vice President of Transmission Reliability, Tennessee Valley Authority
David Whiteley, Executive Director, Eastern Interconnection Planning Collaborative

**Discussion Facilitator:** Ward Jewell, Wichita State University

12:15-1:15 Lunch

1:15-2:45 **Technology Session 3: Control and Protection**

**Opening Presentation:** Chris DeMarco, University of Wisconsin-Madison

**Discussion Panel:**
Bruce Fardanesh, Chief Technology Officer, New York Power Authority
Jay Giri, Director, Power System Technology, ALSTOM Grid
Mladen Kezunovic, Texas A&M University
Sakis Meliopoulos, Georgia Tech

**Discussion Facilitator:** Jim McCalley, Iowa State University

2:45-3:00 Break

3:00-4:30 **Technology Session 4: Communications and Information Infrastructure**

**Opening Presentation:** Lang Tong, Cornell University

**Discussion Panel:**
Jeff Gooding, IT General Manager of Smart Grid Engineering, Southern California Edison
Manimaran Govindarasu, Iowa State University
Tom Overbye, University of Illinois at Urbana/Champaign
Jeffrey Taft, Distinguished Engineer and Chief Architect, Cisco Connected Energy Networks Business Unit

**Discussion Facilitator:** Peter Sauer, University of Illinois at Urbana/Champaign

4:30-6:00 Poster session with light reception

## Thursday, June 28

| | |
|---|---|
| 7:15-8:00 | Registration. Coffee, Juice, Bagels, Fruit |
| 8:00-9:45 | **Technology Session 5: Variable Generation Integration**<br>**Opening Presentation:** Shmuel Oren**,** University of California at Berkeley<br>**Discussion Panel**:<br>Duncan Callaway**,** University of California at Berkeley<br>Hamid Elahi, General Manager, GE Energy<br>Charlie Smith, Executive Director, Utility Variable Generation Integration Group<br>Max Zhang, Cornell University<br>**Discussion Facilitator:** Chris DeMarco, University of Wisconsin-Madison |
| 9:45-10:00 | Break |
| 10:00-11:30 | **Technology Session 6: Computational Challenges**<br>**Opening Presentation**: Santiago Grijalva, Georgia Tech<br>**Discussion Panel:**<br>Alejandro Dominguez-Garcia, University of Illinois at Urbana/Champaign<br>Brian Gaucher, Smart Energy Program Manager, IBM<br>Kip Morison, Chief Technology Officer, BC Hydro<br>Sarah Ryan, Iowa State University<br>**Discussion Facilitator:** Chris DeMarco, University of Wisconsin-Madison |
| 11:30-12:30 | Lunch |
| 12:30-1:30 | **Workforce Session: Building the Future Grid Workforce**<br>**Presentations:** Wanda Reder, Vice President, Power Systems Services, S&C Electric, and Chanan Singh**,** Texas A&M University<br>**Discussion Facilitator:** Chanan Singh, Texas A&M University |
| 1:30-2:45 | **Perspectives on Overcoming the Technology Challenges**<br>**Speakers**:<br>Jay Giri, Director, Power System Technology, ALSTOM Grid<br>Robert J. Thomas**,** Cornell University<br>Stephen Whitley, President and CEO, New York Independent System Operator<br>**Discussion Facilitator:** Vijay Vittal |
| 2:45-3:00 | **Review of Forum Outcomes**<br>Vijay Vittal, Professor, Arizona State University, and Director, Power Systems Engineering Research Center |

# Future Grid Initiative Overview

"The Future Grid to Enable Sustainable Energy Systems: An Initiative of the Power Systems Engineering Research Center (PSERC)" is funded by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability. For more information, go to http://www.pserc.org/research/FutureGrid.aspx.

In this Initiative, PSERC will investigate requirements for a systematic transformation of today's electric grid to enable high penetrations of sustainable energy systems. A giant transformation in the electric grid is underway. The grid is evolving away from a network architecture with relatively few large, hierarchically-connected, tightly synchronized energy resources supplying large, medium, and very many small passive consumers. It is evolving toward a network driven by many highly variable distributed energy resources mixed with large central generation sources, energy storage, and responsive users equipped with embedded intelligence and automation to meet their unique energy needs while co-existing and interacting within a complex dynamic network system.

How the grid will evolve is an open question. In part, the future grid will be dependent on the resource technology decisions that can make a significant difference in the types of generation and demand resource technologies that are deployed. The working assumption of this proposal is that the future grid needs to support high penetrations of sustainable energy systems. The evolution will also be affected by decision-making objectives and flexibility across the grid. For example, tight synchronicity and balancing constraints may be relaxed through an architecture based on autonomous local energy clusters and microgrids that localize the quality standards. The future grid will also rely on an IT infrastructure with underlying communications networks that will enable the physical network, and will closely interact and support the performance objectives of sustainable energy systems. Finally, regional differences in energy resources will affect the requirements for the future grid.

The effective transformation of the grid will require identification and solution of major operating, planning, workforce, and economic challenges. To seamlessly integrate renewable resources in the grid, research and development must address challenges that high penetration levels of these energy resources will have in power system planning and operation, and in grid interconnection. Furthermore, new tools must be developed that explicitly account for the uncertainty and associated risks with such high levels of renewable resource penetration. The existing workforce and the students going into power and energy engineering careers need to be educated so that they can envision and develop the new approaches and technologies to maintain grid reliability and economy. There will need to be adaptation by the distributed resources and consumers, and by smart delivery technologies to avoid barriers detrimental to the energy system objectives. Many digital technologies are fairly mature and could be utilized to enable such adaptation. What is missing are basic problem formulations, modeling, analysis and decision support tools as enablers of such adaptation.

Engineering the envisioned sustainable energy systems is a problem of highly complex heterogeneous and dynamic network systems in an uncertain environment with diverse and distributed objectives. PSERC researchers will use their knowledge of today's operating and planning paradigms for electric power grids, as well as their knowledge of today's SCADA, EMS, DMS, and market systems, as the starting point for introducing new paradigms and transition strategies from today's legacy systems.

# Future Grid Research Areas and Tasks

- **Thrust Area 1: Electric Energy Challenges of the Future** (Leader: Gerald Heydt, Arizona State Univ.)
  - Integrating Transmission and Distribution Engineering Eventualities (Gerald Heydt, Arizona State Univ.)
  - Robust and Dynamic Reserve Requirements (Kory Hedman, Arizona State Univ.)
  - A National Transmission Overlay (Jim McCalley, Iowa State Univ.)
  - Wide Area Control Systems (Mani Venkatasubramanian, Washington State Univ.)

- **Thrust Area 2: Control and Protection Paradigms of the Future** (Leader: Chris DeMarco, Univ. of Wisconsin-Madison)
  - Requirements for Hierarchical Coordinated Control and Protection of the Smart Grid (Anjan Bose, Washington State Univ.)
  - Hierarchical Coordinated Control of Wind Energy Resources and Storage for Electromechanical Stability Enhancement of the Grid (Chris DeMarco, Univ. of Wisconsin-Madison)
  - Hierarchical Coordinated Protection of the Smart Grid with High Penetration of Renewable Resources (Mladen Kezunovic, Texas A&M Univ.)

- **Thrust Area 3: Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid** (Leader: Shmuel Oren, Univ. of California at Berkeley)
  - Mitigating Renewables Intermittency Through Non-Disruptive Distributed Load Control (Duncan Callaway, Univ. of California at Berkeley)
  - Probabilistic Simulation Methodology for Evaluating the Impact of Renewable Intermittency on Operations and Planning (George Gross, Univ. of Illinois at Urbana/Champaign)
  - Planning and Market Design for Using Dispatchable Loads to Meet Renewable Portfolio Standards and Emissions Reduction Targets (Tim Mount, Cornell Univ.)
  - Direct and Telemetric Coupling of Renewable Energy Supply with Deferrable Demand (Shmuel Oren, Univ. of California at Berkeley)

- **Thrust Area 4: Workforce Development** (Leader: Chanan Singh, Texas A&M Univ.)
  - PSERC Academy: A Virtual Library of Thousands of Short Videos (Raja Ayyanar, Arizona State Univ.)
  - A Course in Energy Economics (James Bushnell, Iowa State Univ.)
  - Comprehensive Educational Tools for Reliability Modeling and Evaluation of the Emerging Smart Grid (Chanan Singh, Texas A&M Univ.)
  - Synchrophasor Education for Students and Professionals (Mladen Kezunovic, Texas A&M Univ.)
  - Energy Processing for Smart Grid Technology (James Momoh, Howard Univ.)
  - Course Development - Critical Infrastructure Security: The Emerging Smart Grid (Anurag Srivastava, Washington State Univ.)

- **Thrust Area 5: Computational Challenges and Analysis Under Increasingly Dynamic and Uncertain Electric Power System Conditions** (Leader: Santiago Grijalva, Georgia Institute of Technology)
  - Real-Time PMU-Based Tools for Monitoring Operational Reliability (Alejandro D. Dominguez-Garcia, Univ. of Illinois at Urbana-Champaign)
  - Decision-Making Framework for the Future Grid (Santiago Grijalva, Georgia Institute of Technology)

  - Hierarchical Probabilistic Coordination and Optimization of DERs and Smart Appliances (Sakis Meliopoulos, Georgia Institute of Technology)
  - Computational Issues of Optimization for Planning (Sarah Ryan, Iowa State Univ.)

- **Thrust Area 6: Engineering Resilient Cyber-Physical Systems** (Leader: Tom Overbye, Univ. of Illinois at Urbana/Champaign)
  - Operational and Planning Considerations for Resiliency (Ian Dobson, Iowa State Univ.)
  - Resiliency with Respect to Low Frequency, High Consequence Events (Tom Overbye, Univ. of Illinois at Urbana/Champaign)
  - Improved Power Grid Resiliency through Interactive System Control (Vijay Vittal, Arizona State Univ.)

**Broad Analysis: A White Paper Collection**

- **The Information Hierarchy for the Future Grid (**Leader: Peter Sauer, Univ. of Illinois at Urbana-Champaign)
  - Cyber-Physical Systems Security for the Smart Grid (Manimaran Govindarasu, Iowa State Univ.)
  - Communication Needs and Integration Options for AMI in the Smart Grid (Vinod Namboodiri, Wichita State Univ.)
  - Information and Computation Structures for the Smart Grid (Lang Tong, Cornell Univ.)
  - Networked Information Gathering and Fusion of PMU Measurements (Junshan Zhang, Arizona State Univ.)

- **Grid Enablers of Sustainable Energy Systems** (Leader: Jim McCalley, Iowa State Univ.)
  - Primary and Secondary Control for High Penetration Renewables (Chris DeMarco, Univ. of Wisconsin-Madison)
  - Toward Standards for Dynamics in Electric Energy Systems (Marija Ilic, Carnegie Mellon Univ.)
  - Future Grid: The Environment (Ward Jewell, Wichita State Univ.)
  - High Capacity Interregional Transmission Design: Benefits, Risks and Possible Paths Forward (Jim McCalley, Iowa State Univ.)
  - Distributed and Centralized Generation – A Comparison Approach (James Momoh, Howard Univ.)

# Bibliography from the PSERC Future Grid Initiative

(as of 6/24/2012)

All of the materials listed below are available at the PSERC Future Grid Initiative website.

## Thrust Areas and Tasks (web link)

Research in the Future Grid Initiative, supported by the Office of Electricity Delivery and Energy Reliability, U.S. DOE, is divided into thrust areas. Each thrust area has tasks in which research is being conducted on a particular topic. The overall final report will be ready in the fall of 2013.

Available Thrust Area White Papers:

- Technology Challenges in Designing the Future Grid to Enable Sustainable Energy Systems. This is a synthesis of the technology challenges in the thrust areas.
- Electric Energy Challenges of the Future
- Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid
- Workforce Development - Meeting the Educational Challenge of the Smart Sustainable Grid
- Computational Challenges and Analysis under Increasingly Dynamic and Uncertain Electric Power System Conditions
- Engineering Resilient Cyber-Physical Systems

## Broad Analysis White Papers and Webinars (web link)

As a part of the Future Grid Initiative, PSERC is working to stimulate thought about solutions to what can be called “broad analysis” needs. A broad analysis need covers questions that are typically well beyond the scope of typical academic research projects in terms of size and definition. The questions are not strictly engineering, often involving issues of policy as well as stakeholder perspectives and impacts.

Available White Papers on the Topic **“**The Information Hierarchy for the Future Grid**”**

- Cyber-Physical Systems Security for the Smart Grid
- Communication Needs and Integration Options for AMI in the Smart Grid
- Networked Information Gathering and Fusion of PMU Data

Available White Papers on the Topic **“**Grid Enablers of Sustainable Energy Systems**”**

- Transmission Design at the National Level: Benefits, Risks and Possible Paths Forward
- Primary and Secondary Control for High Penetration Renewables
- Future Grid: The Environment
- Toward Standards for Dynamics in Electric Energy Systems
- Distributed and Centralized Generation - A Comparison Approach

# ABOUT PSERC

**http://www.pserc.org**

## Our core purpose:

Empowering minds to engineer
the future electric energy system

## What's important to us:

Pursuing, discovering and transferring knowledge

Producing highly qualified and trained engineers

Collaborating in all we do

## What we're working toward:

An efficient, secure, resilient, adaptable, and economic electric power infrastructure serving society

A new generation of educated technical professionals
in electric power

Knowledgeable decision-makers
on critical energy policy issues

Sustained, quality university programs
in electric power engineering

# PSERC's Industry Members in 2012

**ABB**
**ALSTOM Grid**
**American Electric Power**
**American Transmission Company**
**Arizona Public Service**
**BC Hydro**
**Bonneville Power Administration**
**California ISO**
**CenterPoint Energy**
**CISCO Systems**
**Duke Energy**
**Entergy**
**EPRI**
**Exelon**
**First Energy Corporation**
**GE Energy**
**Institut de Recherche d'Hydro-Quebec**
**ISO New England**
**Lawrence Livermore National Lab**
**Midwest ISO**
**National Renewal Energy Lab (NREL)**
**National Rural Electric Coop. Assn. (NRECA)**
**New York ISO**
**New York Power Authority**
**Pacific Gas & Electric Company**
**PJM Interconnection**
**PowerWorld Corporation**
**RTE-France**
**Salt River Project**
**San Diego Gas & Electric**
**Southern California Edison**
**Southern Company**
**Southwest Power Pool**
**Tennessee Valley Authority**
**Tri-State Generation and Transmission**
**U.S. Department of Energy**
**Western Area Power Administration**

# Collaborating Universities and Site Directors

**Arizona State**
(Jerry Heydt)

**Berkeley**
(Shmuel Oren)

**Carnegie Mellon**
(Marija Ilic)

**Colorado School of Mines**
(P.K. Sen)

**Cornell**
(Lang Tong)

**Georgia Tech**
(Sakis Meliopoulos)

**Howard Univ.**
(James Momoh)

**Illinois**
(Peter Sauer)

**Iowa State**
(Venkataramana Ajjarapu)

**Texas A&M**
(Mladen Kezunovic)

**Washington State**
(Anjan Bose)

**Wichita State**
(Ward Jewell)

**Wisconsin**
(Chris DeMarco)

# Director, Deputy Director, Founding Director

Vijay Vittal, PSERC Director, Arizona State University (Vijay.Vittal@asu.edu, 480-965-1879
Dennis Ray, Deputy Director (djray@engr.wisc.edu, 608-265-3808)
Robert J. Thomas, Cornell University, Founding Director

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# Forum Presentations and Panelist Comments

# Table of Contents for Presentation Materials

Note: Any additional presentation materials will be available on the PSERC website.

# Future Grid Initiative

## Technology Challenges in Designing the Future Grid to Enable Sustainable Energy Systems

**Vijay Vittal**

Director, Power Systems Engineering Research Center

Ira A. Fulton Chair Professor, Arizona State University

Future Grid Forum
June 27-28, 2012
Washington D.C.

## Forum Objectives

- Identify the technological challenges to meet the requirements of the future grid
- Describe and receive comments regarding the challenges being addressed in the PSERC Future Grid Initiative and any results that have already been achieved
- Identify challenges beyond the Future Grid Initiative and determine whether those challenges are being addressed
- Explore how solutions to these challenges could integrate seamlessly into a legacy system

## Your feedback is important

- Panelists will provide comments.
- Audience will be invited to participate in a facilitated discussion and provide written feedback.
- Ideas will be captured on flipcharts.

## National Energy Challenges

**Energy independence, affordability**

**Energy reliability, security, efficiency**

**Economic development and job security**

**Environmental concerns and impact of climate change**

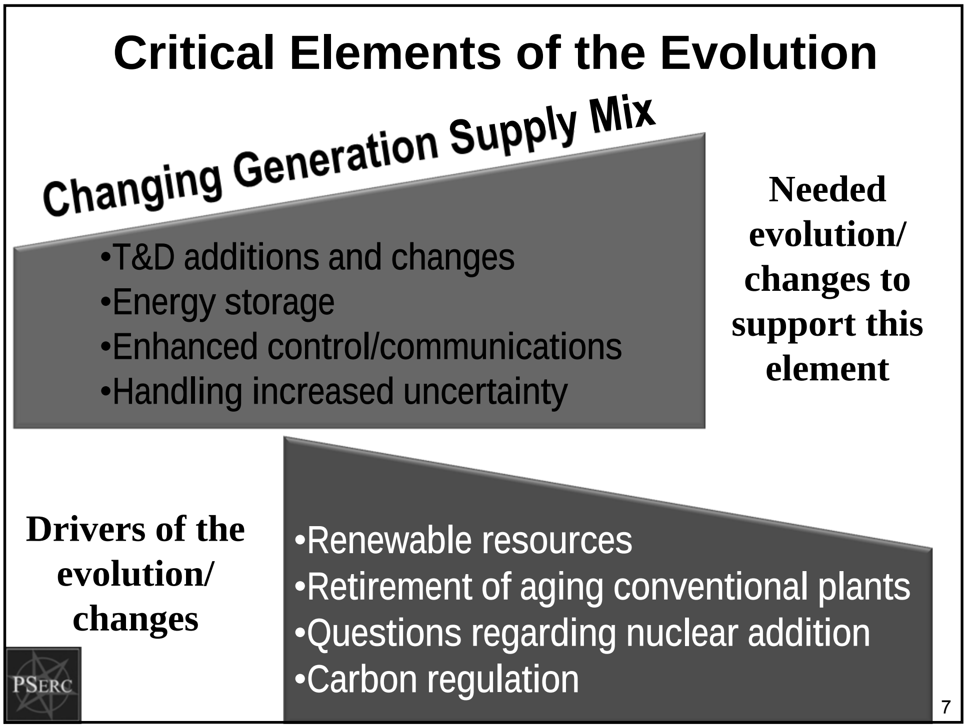
**Aging infrastructure, technology change, workforce needs**

# Range of Energy Solution Options

| Renewable resource technologies |
|---|
| Energy efficiency |
| Demand resources |
| Market solutions |
| Nuclear energy technologies |
| Develop domestic resources |
| Improved asset utilization |
| Electric transportation |
| Carbon capture and storage |
| Energy storage |

# Overarching Issues

- Given this set of national energy solutions, how does the electric grid infrastructure **evolve** to **accommodate** these solutions?
- What elements constitute the **building blocks** of this **evolution**?
- Given the **large capital investment** in the **legacy grid,** what steps are required to **seamlessly transition** from the legacy grid to accommodate the elements of the proposed building blocks?



## Critical Elements of the Evolution

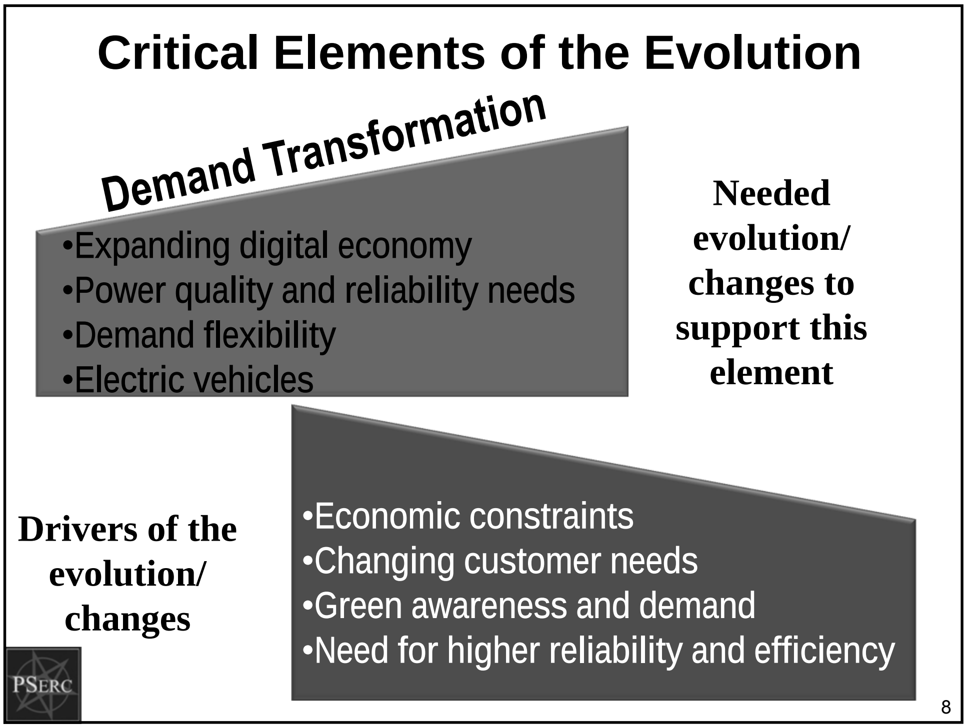
**Changing Generation Supply Mix**

- T&D additions and changes
- Energy storage
- Enhanced control/communications
- Handling increased uncertainty

**Needed evolution/ changes to support this element**

**Drivers of the evolution/ changes**

- Renewable resources
- Retirement of aging conventional plants
- Questions regarding nuclear addition
- Carbon regulation



## Critical Elements of the Evolution

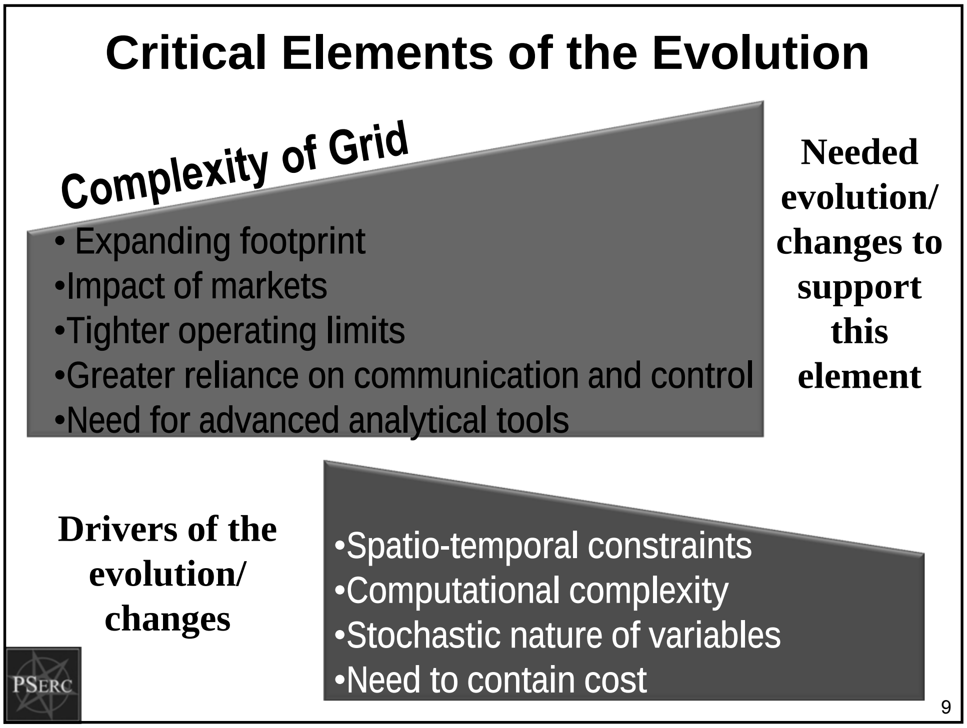
**Demand Transformation**

- Expanding digital economy
- Power quality and reliability needs
- Demand flexibility
- Electric vehicles

**Needed evolution/ changes to support this element**

**Drivers of the evolution/ changes**

- Economic constraints
- Changing customer needs
- Green awareness and demand
- Need for higher reliability and efficiency



## Critical Elements of the Evolution

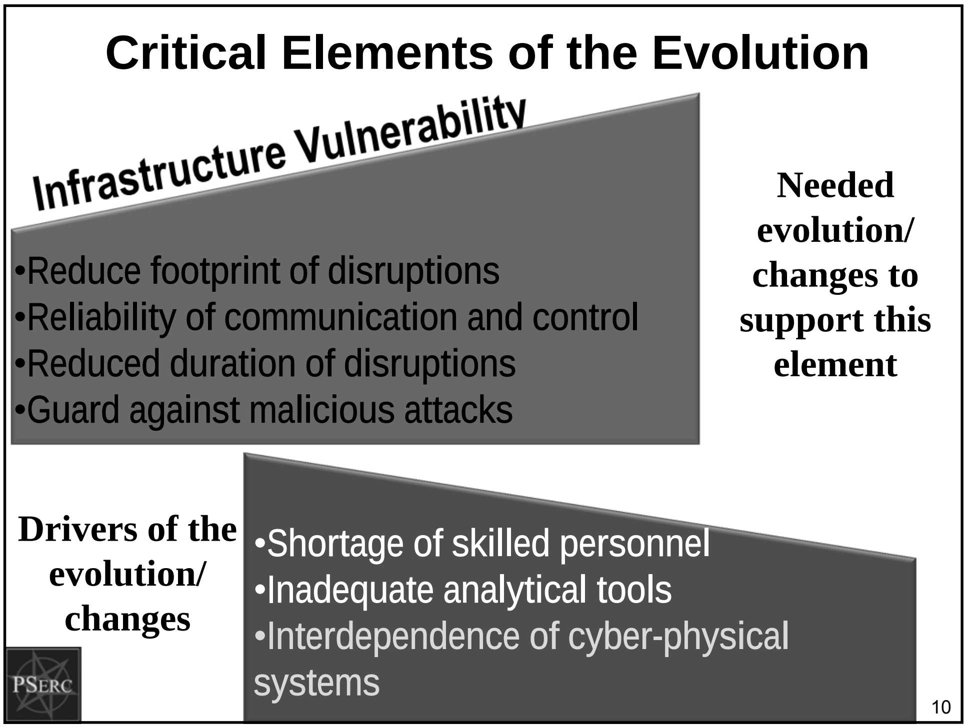
**Complexity of Grid**

- Expanding footprint
- Impact of markets
- Tighter operating limits
- Greater reliance on communication and control
- Need for advanced analytical tools

**Needed evolution/ changes to support this element**

**Drivers of the evolution/ changes**

- Spatio-temporal constraints
- Computational complexity
- Stochastic nature of variables
- Need to contain cost



## Critical Elements of the Evolution

**Infrastructure Vulnerability**

- Reduce footprint of disruptions
- Reliability of communication and control
- Reduced duration of disruptions
- Guard against malicious attacks

**Needed evolution/ changes to support this element**

**Drivers of the evolution/ changes**

- Shortage of skilled personnel
- Inadequate analytical tools
- Interdependence of cyber-physical systems

# Future Grid Initiative – Thrust Areas

## Thrust Area 1- Electric Energy Challenges of the Future

- Transmission system design
- Substantive changes in power distribution system design
- Dynamic balancing of load and generation
- Wide area controls, including integrative controls in transmission and distribution systems

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# Future Grid Initiative – Thrust Areas

## Thrust Area 2 - Control and Protection Paradigms of the Future

- Requirements for the communication and computation architecture for hierarchical coordinated control and protection
- Hierarchical coordinated control of transient stability
- Hierarchical coordinated protection

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## Future Grid Initiative – Thrust Areas

### Thrust Area 3 - Renewable Energy Integration and the Impact of Carbon Regulation on the Electric Grid

- The potential of harnessing the inherent flexibility of certain load types, such as heating and cooling and PHEV charging
- The deployment of distributed and system level storage devices to mitigate the variability
- Uncertainty of renewable resources

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## Future Grid Initiative – Thrust Areas

### Thrust Area 4 - Workforce Development

- Development of educational tools to meet the needs of the current and future engineers who will be managing these complex cyber-physical systems as well as innovating to bring further transformations

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# Future Grid Initiative – Thrust Areas

## Thrust Area 5 - Computational Challenges and Analysis Under Increasingly Dynamic and Uncertain Electric Power System Conditions

- Decision making framework for the future grid
- Computational issues of optimization for planning
- Hierarchical probabilistic coordination and optimization of DERs and smart appliances
- Real-time PMU-based tools for monitoring operational reliability

# Future Grid Initiative – Thrust Areas

## Thrust Area 6 - Engineering Resilient Cyber-Physical Systems

- Low frequency high consequence event
- Resiliency with respect to preventing cascading failures
- Monitoring and control to increase grid resiliency

# Broad Analysis Work

- Stimulating thought about solutions to “broad analysis” needs
- Broad analysis topics:
  - The information hierarchy of the future grid
  - Grid enablers of sustainable energy systems
- White papers and archived webinars available on the PSERC website

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# Technology Challenges

- Key technology challenges associated with the activities of each thrust area
- Important objective of seamless transition into the legacy grid

## Key Challenges in Thrust Area 1

- National transmission overlay?
  - Technology to use AC versus DC
  - If AC, consideration of ultra high voltage levels, six phase and related poly-phase transmission
  - If DC, consideration of multi-terminal DC and meshed DC transmission
  - Need for a DC circuit breaker
  - Implications of the use of high temperature, low sag conductors
  - Utilization of compact transmission designs to optimize hard to find right of way

## Thrust Area 1 – Contd.

- Robust and dynamic reserve requirements
  - Determination of an optimal reserve requirement
  - Examination of reliability criteria associated with reserve requirements
  - Probabilistic risk assessment of reserve requirements

- Wide area control
  - Designing robust, coordinated, and reliable wide area controls
  - Tailoring wide area controls to dedicated applications
  - Locating wide area controls
  - Coordination of wide area controls
  - Real time adaptation of wide area controls

# Key Challenges in Thrust Area 1 – contd.

- Critical need for high levels of energy storage at the bulk power level
  - Need for high energy density storage other than pumped hydro in the Gigawatt-days range
  - Economically viable energy storage
  - Determination of the level of renewable resource penetration and associated variability that would render the cost to benefit ratio of energy storage to favorable ranges

# Key Challenges in Thrust Area 2

- Communication and computational requirements for hierarchical coordinated control and protection
  - Requirements on communication latency and quality of service
  - Robust communication networks with associated software development
  - Design and development of databases to handle massive volumes of data
  - Communication requirements within control areas and associated constraints on latency, bandwidth, protocols and communications technology
  - Needed enhancements for simulation and design applications to support control and protection applications
  - Simulations tools to analyze interdependent cyber-physical systems to examine required performance aspects
  - Cyber security requirements

# Key Challenges in Thrust Area 2

- Hierarchical decomposition of protection systems
  - Predictive protection
  - Inherently adaptive protection
  - Corrective protection
  - New architectures for coordinated hierarchical protection systems

# Key Challenges in Thrust Area 3

- Exploiting demand side flexibility as a hedge against renewable resource supply uncertainty instead of using conventional generation resources
  - Is this paradigm shift viable?
  - Optimal strategies needed to operate the system reliably
  - Business models needed to aggregate load flexibility
  - Centralized versus decentralized approach comparison
- Utilizing non-disruptive distributed load control to mitigate renewable resource variability
  - Developing high fidelity models for thermostatically-controlled loads
  - Evaluating the ability of such loads to provide the desired benefit
  - How well would load control work in comparison to the same control achieved by generators?
  - What are infrastructure needs for implementing this approach?

# Key Challenges in Thrust Area 3 – contd.

- Market design to utilize dispatchable loads to meet renewable portfolio standards and emission reduction targets
  - Can variability of renewable resources be accurately characterized stochastically?
  - Can future needs for frequency regulation and generation/load following be accurately estimated under different renewable resource penetration levels and emission targets?
  - Can dispatchable loads be aggregated in order to examine engineering/economic feasibility?

# Key Challenges in Thrust Area 3 – contd.

- Need for stochastic optimization tools for planning and operation
  - Adequate representation of system complexity
  - Representation of production costing and reliability assessment
  - Consideration of correlated behavior of loads and supply resources
  - Validity of analysis over a time horizon
  - Guaranteeing computational tractability

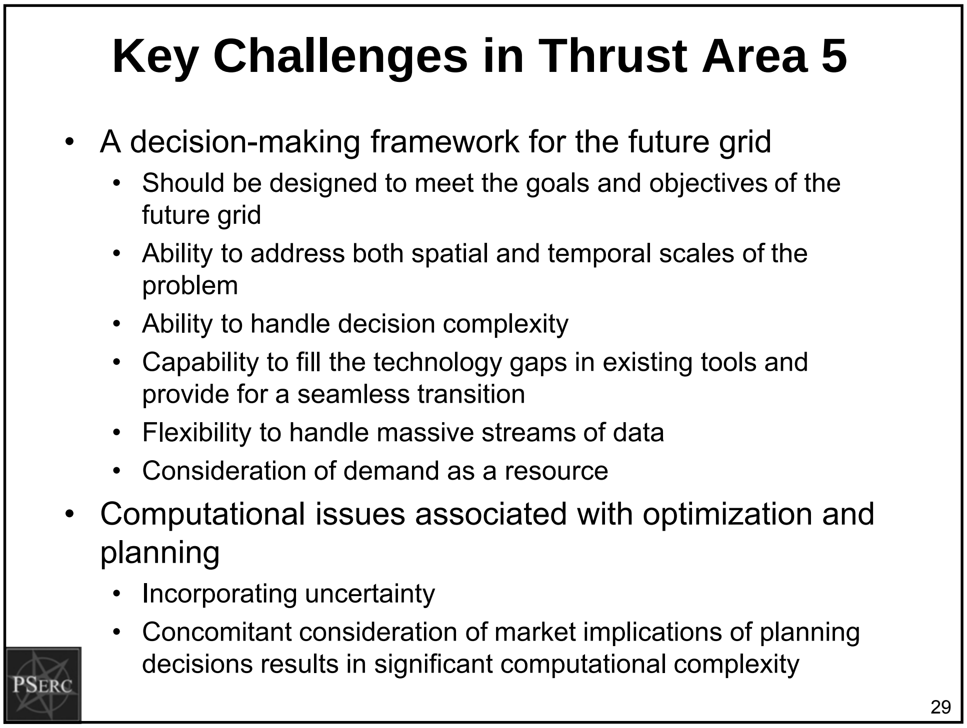
# Key Challenges in Thrust Area 4

- Steps to tackle the projected workforce shortage
  - Need to address workforce needs across the spectrum – skilled workers, engineers and managers
  - Play to our strengths of meeting needs at the BS, MS and PhD levels
  - U.S. power engineering academic workforce is also graying

- Curriculum redesign to meet the needs of the future grid
  - Need solid grounding in basic power engineering fundamentals
  - Evolve curriculum to address needs in complementary disciplinary areas which are essential in engineering the grid of the future

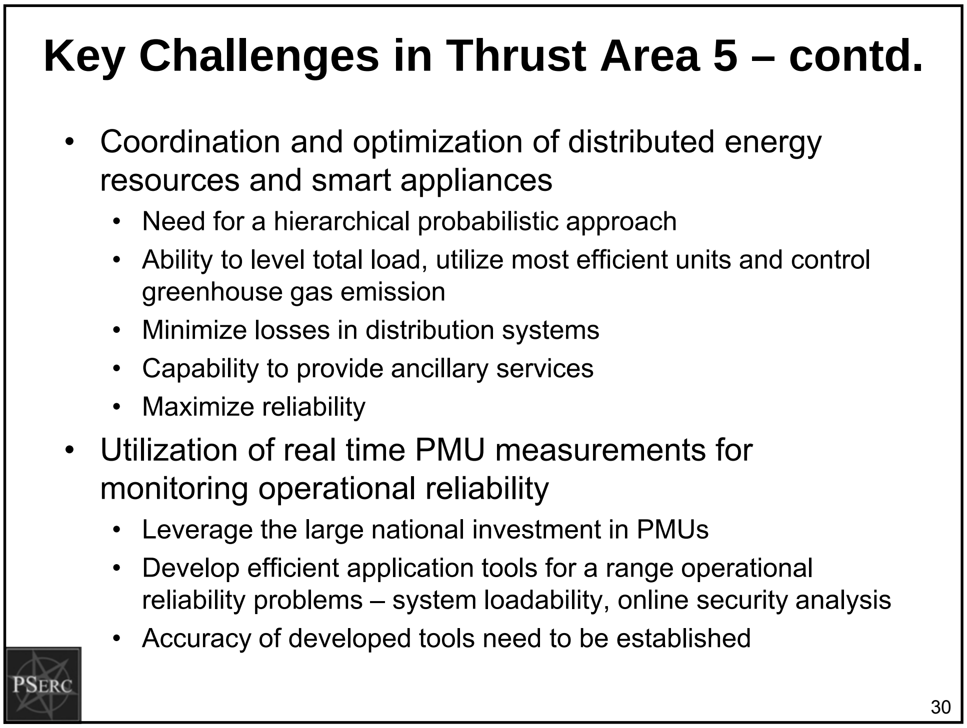
# Key Challenges in Thrust Area 4 – contd.

- Leverage PSERC's broad spectrum of expertise to develop relevant and appropriate material to meet the interdisciplinary needs of education to engineer the future grid
  - E-learning techniques
  - Online course material
  - Textbooks
- In addition to updating university curriculum, critical need to provide life-long learning experiences to the practicing engineer
  - Self-paced online material
  - Short courses
- Textbooks



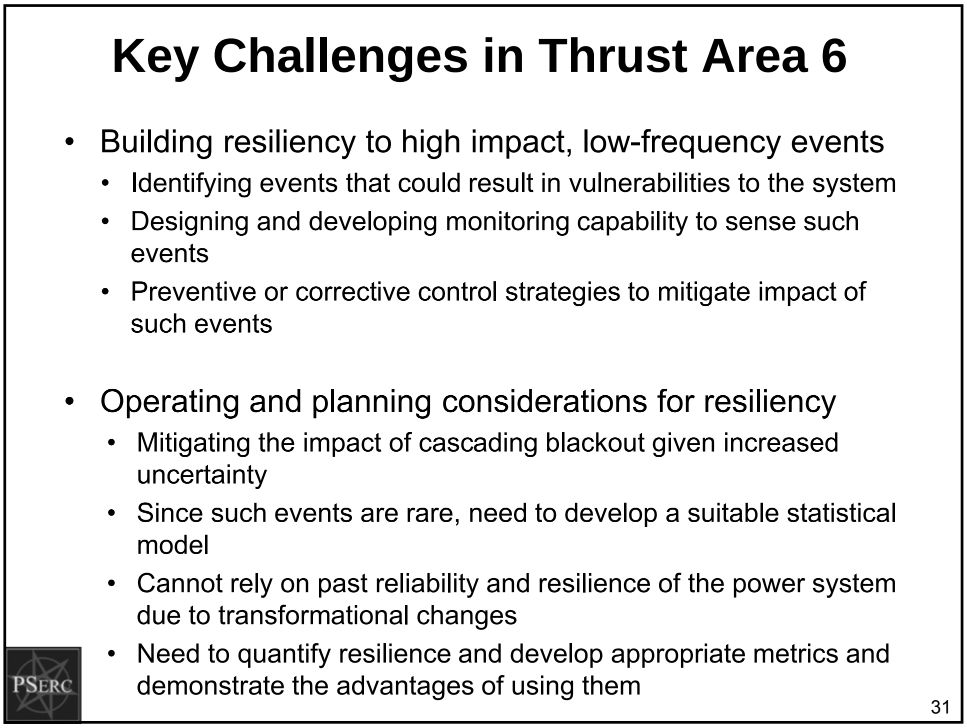
## Key Challenges in Thrust Area 5

- A decision-making framework for the future grid
  - Should be designed to meet the goals and objectives of the future grid
  - Ability to address both spatial and temporal scales of the problem
  - Ability to handle decision complexity
  - Capability to fill the technology gaps in existing tools and provide for a seamless transition
  - Flexibility to handle massive streams of data
  - Consideration of demand as a resource
- Computational issues associated with optimization and planning
  - Incorporating uncertainty
  - Concomitant consideration of market implications of planning decisions results in significant computational complexity



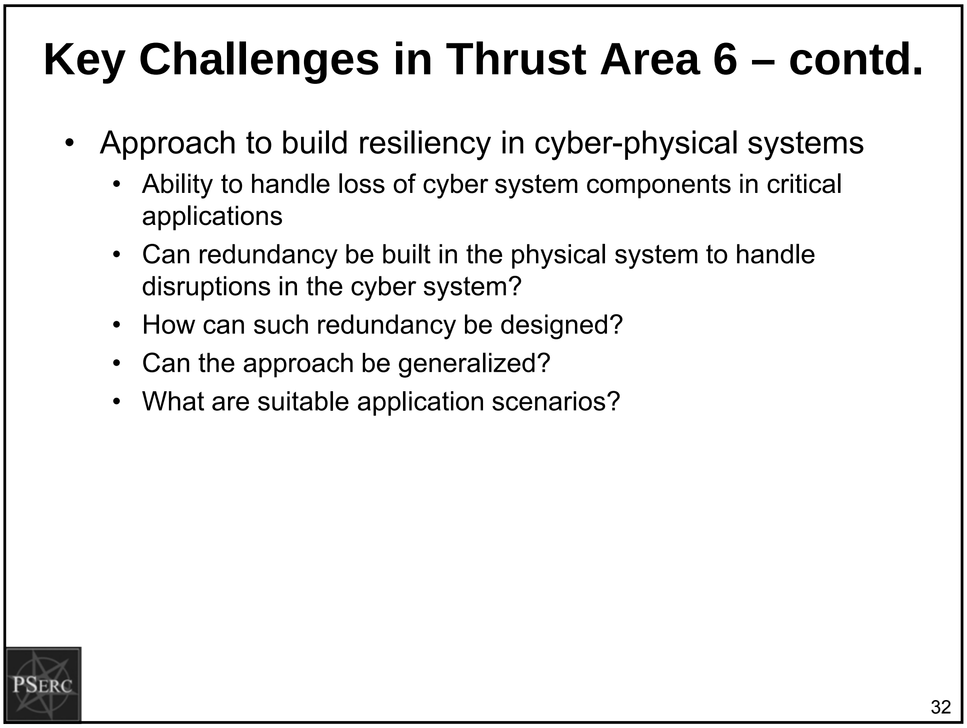
## Key Challenges in Thrust Area 5 – contd.

- Coordination and optimization of distributed energy resources and smart appliances
  - Need for a hierarchical probabilistic approach
  - Ability to level total load, utilize most efficient units and control greenhouse gas emission
  - Minimize losses in distribution systems
  - Capability to provide ancillary services
  - Maximize reliability
- Utilization of real time PMU measurements for monitoring operational reliability
  - Leverage the large national investment in PMUs
  - Develop efficient application tools for a range operational reliability problems – system loadability, online security analysis
  - Accuracy of developed tools need to be established



# Key Challenges in Thrust Area 6

- Building resiliency to high impact, low-frequency events
  - Identifying events that could result in vulnerabilities to the system
  - Designing and developing monitoring capability to sense such events
  - Preventive or corrective control strategies to mitigate impact of such events
- Operating and planning considerations for resiliency
  - Mitigating the impact of cascading blackout given increased uncertainty
  - Since such events are rare, need to develop a suitable statistical model
  - Cannot rely on past reliability and resilience of the power system due to transformational changes
  - Need to quantify resilience and develop appropriate metrics and demonstrate the advantages of using them



# Key Challenges in Thrust Area 6 – contd.

- Approach to build resiliency in cyber-physical systems
  - Ability to handle loss of cyber system components in critical applications
  - Can redundancy be built in the physical system to handle disruptions in the cyber system?
  - How can such redundancy be designed?
  - Can the approach be generalized?
  - What are suitable application scenarios?

## Conclusions

- Planning, operating, and maintaining the future grid will require fundamental changes in procedures, protocols, standards, analytical tools, criteria, services, and policies that have not been fully explored or developed
- Integration of power systems technologies with information, computing and communications technologies will require more of a multi-disciplinary focus than has ever existed in the power industry
- Adapting to uncertainty by adding resiliency to the system will become critically important in the future grid

PSERC

## PSERC Future Grid Website

http://www.pserc.org/research/FutureGrid.aspx

PSERC

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# Technology Session 1:
# Power Delivery Infrastructure

**Overview Presentation: Jerry Heydt,** Arizona State University

**Discussion Panel**: ; **Flora Flygt,** Strategic Planning and Policy Advisor, American Transmission Company; **Jim McCalley**, Iowa State University; **Robert Saint** Principal Engineer, National Rural Electric Cooperative Association; **Peter Sauer**, University of Illinois at Urbana/Champaign

**Discussion Facilitator: Ward Jewell**, Wichita State University

Future Grid Forum
June 27-28, 2012
Washington D.C.

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## Challenge areas for this session include:

- National transmission overlay
- Transmission alternatives (e.g., HVDC, AC, six-phase, alternative conductor technologies)
- Microgrids
- Distribution network infrastructure
- Large scale energy storage - interactions with power delivery infrastructure
- Distributed vs. centralized generation – interactions with power delivery infrastructure
- Demand response – interactions with power delivery infrastructure

| **Transmission** | **Distribution** |
|---|---|
| **Robustness through hardware enhancement** | **Robustness through smart design and operation** |

# Transmission alternatives

**Reasons for transmission expansion**

- Load growth
- Integration of wind and solar generation into the grid
- Alleviate transmission bottlenecks
- Connect asynchronous regions

**Load growth**

- Nearly flat in the last three years
- Central city growth
- Thermal limits could be alleviated, especially without extended outage of existing facilities

**Integration of renewables**

- Long distances encountered (e.g., Dakota – East)
- Modest concentration of generation
- Security limits, phase angle stability issues

# Transmission alternatives

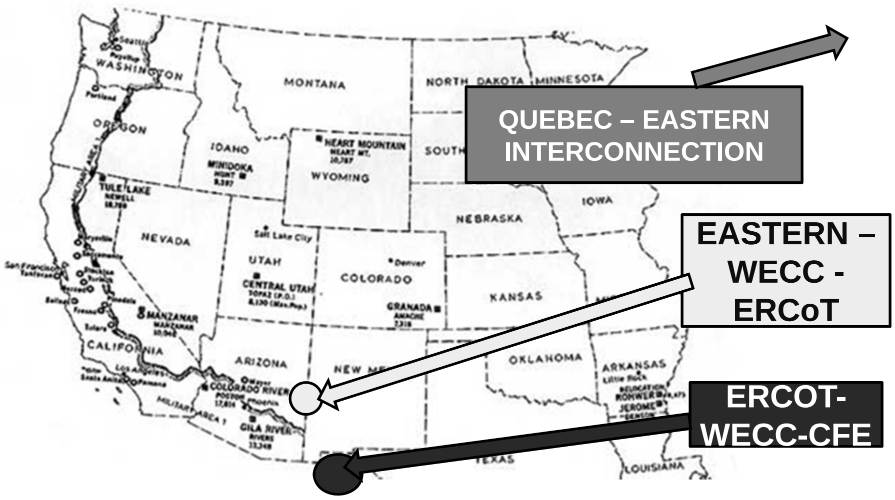
**Alleviate transmission bottlenecks**

- Alleviate overlapping RASs in critical paths
- Reduce exposure to *N-2* contingencies

**Connect asynchronous regions**

- The Tres Amigas project, merchant substation joining the Eastern, ERCOT, and WECC interconnection
- Other ‘sweet spots’ exist (e.g., near El Paso joining ERCOT-WECC-CFE)

# Transmission alternatives



QUEBEC – EASTERN INTERCONNECTION

EASTERN – WECC - ERCoT

ERCOT-WECC-CFE

**Asynchronous interconnection 'sweet spots'**

## What are the challenges in developing the fundamental building blocks of the future grid?

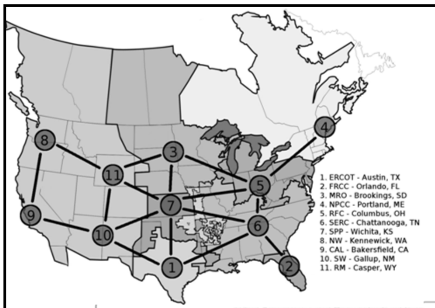
**Systems issues**

- Making the system theory robust enough to accommodate worst case scenarios, but cost effective enough to justify implementation
- Utilization of system theory that can accommodate *very different* scenarios and components – e.g., *uncertainty in infrastructure*
- Forecasting credible 'what if' scenarios

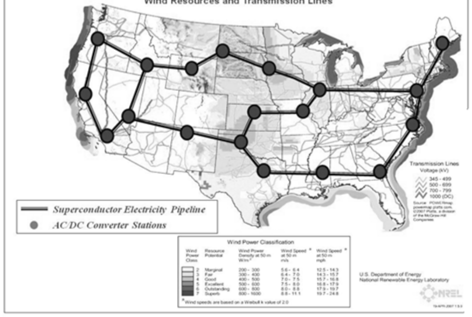
**Economic and socio-political issues**

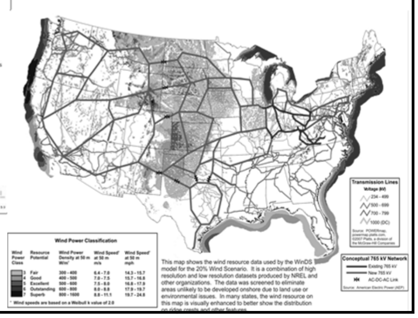
- Optimally investing in technologies for the future, e.g., road mapping transmission expansion
- Accommodating the present needs without sacrificing the effectiveness of future designs
- Managing the needs of each stakeholder / a multiobjective optimization – overcoming the cost / benefit specifics problem: who benefits, who pays?

**Example: coordinate growth of wind, solar, nuclear, geothermal, biomass, clean-coal, and natural gas generation to 2050**



The possibility of a transmission overlay that is consistent with other energy overlays: the subject of a sub-thrust in the PSERC Future Grid Initiative





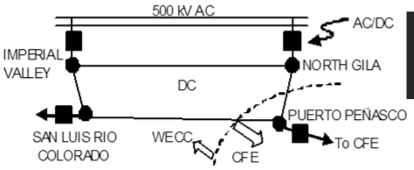
# A transmission overlay design

- Design U.S. national transmission overlays
- Develop associated design process to facilitate growth of wind, solar, nuclear, geothermal, biomass, clean-coal, and natural gas generation to 2050
- Assess value of each overlay design
- A project in the PSERC Future Grid Initiative spearheaded by Drs. McCalley and Aliprantis at Iowa State University

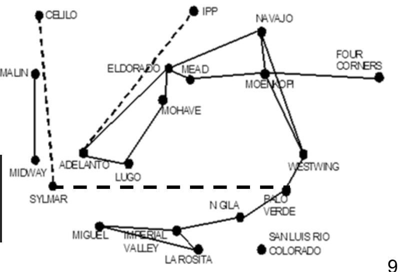
# Transmission alternatives

**Innovative concepts**

- **HVDC, particularly multi-terminal and networked**
- High temperature, low sag (HTLS) conductors
- Compact phase spacing
- Electronic connection, FACTS (again)
- Widespread placement of synchrophasor instrumentation (PMUs)



**A DC ‘network’ at the US-Mexico border**



**Conversion of the PDCI to a three terminal HVDC system**

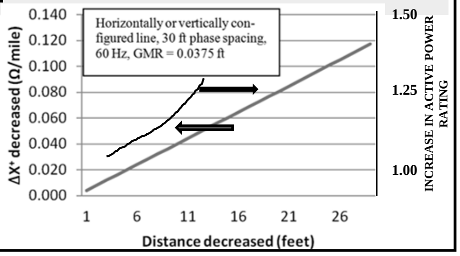
# Transmission alternatives

**Innovative concepts**

- HVDC, particularly multi-terminal and networked
- **High temperature, low sag (HTLS) conductors**
- **Compact phase spacing**
- Electronic connection, FACTS
- Widespread placement of synchrophasor instrumentation (PMUs)

**HTLS** has the salient advantage of approximately double ampacity. The positive sequence reactance of typical HTLS lines is slightly (~1 – 3%) lower than conventional conductors of the same size. There is little advantage from the point of view of improvement of phase angle stability. HTLS has the advantage of rapid construction (e.g., use of existing towers in reconductoring projects). The main disadvantage is cost.

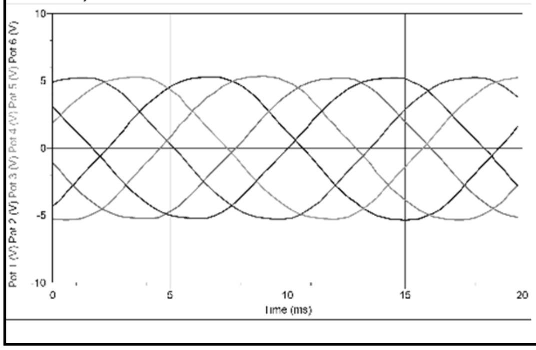
**Compact phase spacing** (e.g., reduction of ~30’ phase spacing to 15’ or even 9’) has an advantage of reduced positive sequence reactance ($x^+ = x_s - x_m$). This can give higher security limits for long lines. The disadvantages include failure to comply with some industry and accepted state standards, safety issues in live line maintenance. Compact spacing can be combined easily with HTLS.

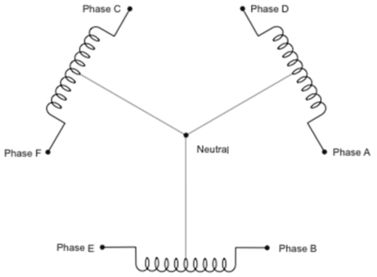


## Transmission alternatives

**Six phase transmission**

- Phase to phase voltage is equal to line to neutral voltage
- Narrower right of way
- Enhanced mutual coupling between phases
- The polyphase form of the symmetrical component transformation nonetheless has a ‘positive sequence’ that is





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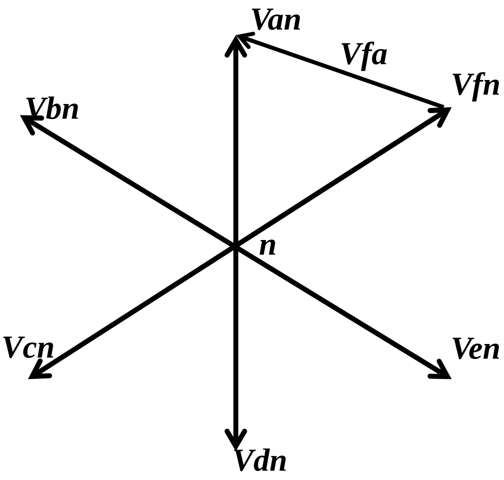
## Transmission alternatives



**Six phase line distinct advantages over a double circuit three-phase:**

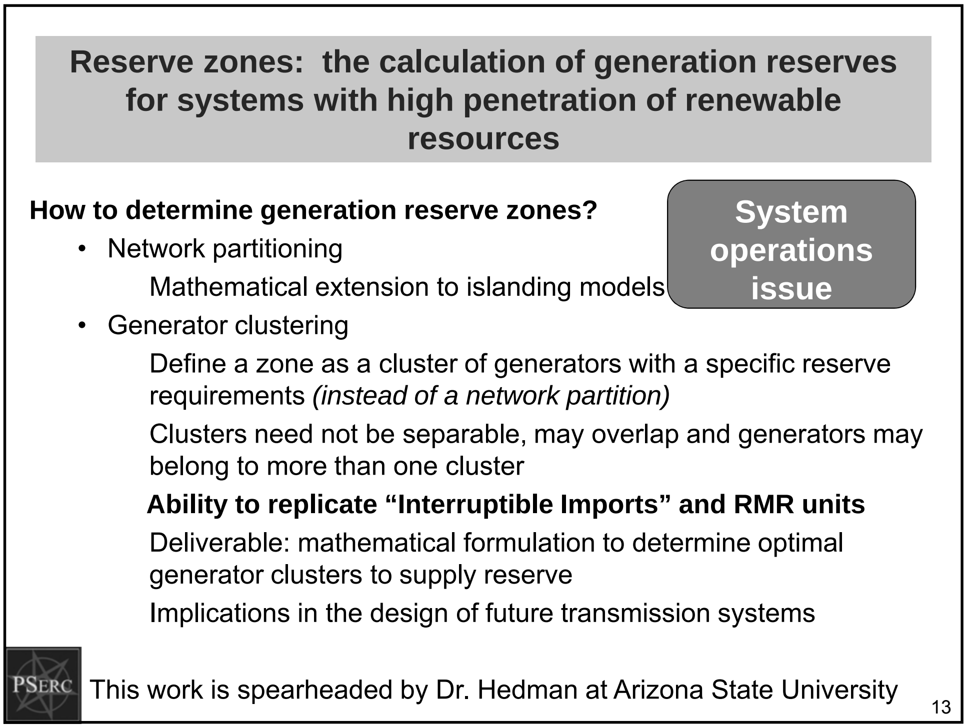
- Less right of way requirement
- Lower positive sequence reactance per mile
- Less insulation requirement
- Higher active power transmission capability
- Ease in interface with three phase systems
- Lower power quality impact for rectifier / inverter facilities

**And some disadvantages:**

- More complex transformer connections and specially constructed transformers
- Greater exposure to line-ground faults
- More complex protection issues

PSERC

In the long term, even higher phase order may be realized with advantages of bulk power transmission



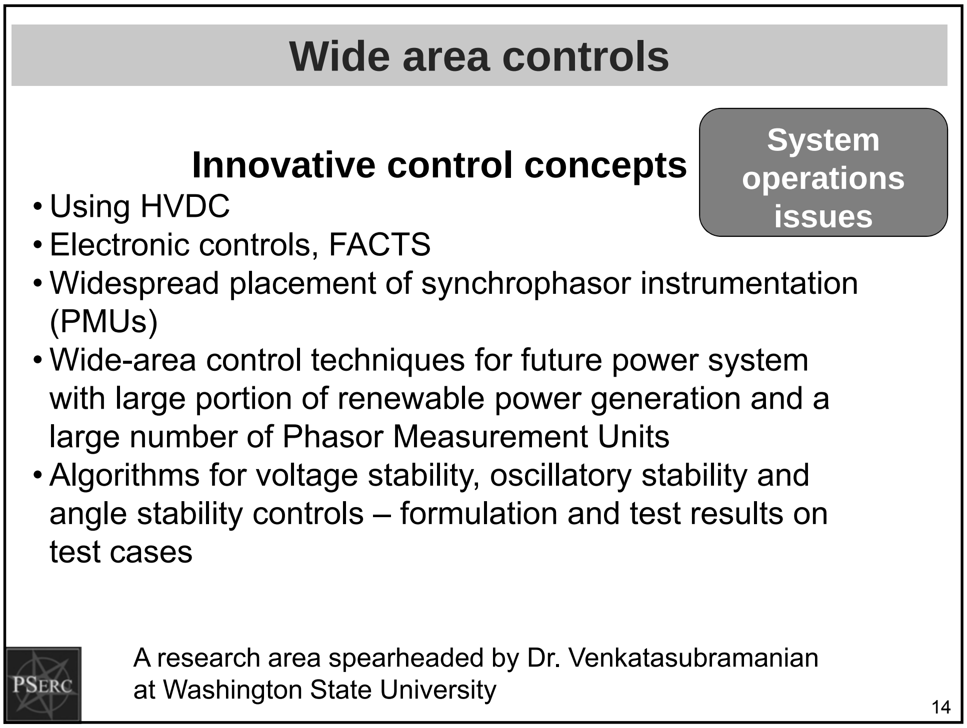
## Reserve zones: the calculation of generation reserves for systems with high penetration of renewable resources

**System operations issue**

**How to determine generation reserve zones?**

- Network partitioning
  - Mathematical extension to islanding models
- Generator clustering
  - Define a zone as a cluster of generators with a specific reserve requirements *(instead of a network partition)*
  - Clusters need not be separable, may overlap and generators may belong to more than one cluster
  - **Ability to replicate "Interruptible Imports" and RMR units**
  - Deliverable: mathematical formulation to determine optimal generator clusters to supply reserve
  - Implications in the design of future transmission systems

This work is spearheaded by Dr. Hedman at Arizona State University



## Wide area controls

**System operations issues**

### Innovative control concepts

- Using HVDC
- Electronic controls, FACTS
- Widespread placement of synchrophasor instrumentation (PMUs)
- Wide-area control techniques for future power system with large portion of renewable power generation and a large number of Phasor Measurement Units
- Algorithms for voltage stability, oscillatory stability and angle stability controls – formulation and test results on test cases

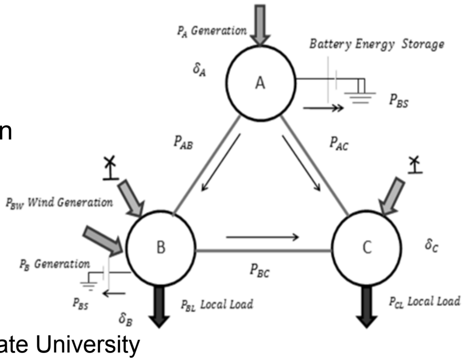
A research area spearheaded by Dr. Venkatasubramanian at Washington State University

# Large scale energy storage

- **Pumped hydro**
  - Deployed on a gigawatt scale in the U.S. (20 GW at 39 sites and installations range from 50 MW to 2100 MW).
  - Sites store 10 hours or more, making the technology useful for load leveling
- **Compressed air energy storage (CAES)**
  - Appropriate load leveling because it can be constructed in capacities for 100 to 300 MW.
  - Can be discharged in 4 to 24 hours
  - Usually combined with combustion turbines.
- **High energy batteries**
  - Two types
    - high temperature batteries (sodium sulfur battery)
    - liquid electrolyte flow batteries
  - Disadvantages: expensive, short lifetime

# Large scale energy storage

- Store energy in the off peak period, discharge during the peak
- Reduces load in critical circuits
- Better enables 100% utilization of wind resources
- In a 6 GW system, tests show reduction of operating costs by 2.5 to 10%
- High speed ramp rates – useful for reserve margin especially with wind energy systems
- Substantial DoE research effort



A research effort by G. Heydt at Arizona State University

- **•No large scale demonstration without substantial subsidy**
- **•Difficult to obtain a positive benefit / cost ratio for any *one* advantage obtained**
- **•Some storage requires specialized circumstances (e.g., pumped hydro geography)**
- **•No strong acceptance by industry**

## Distribution system characteristics

**Higher levels of electronically processed loads**

- Higher distribution primary voltages (e.g., 35 kV primaries)
- Fast acting electronic controls
- Rooftop residential photovoltaic impact
- Increased residential sector
- Innovative protection and fault detection

- Presently, studies show that distribution loads are about 30% electronically processed (e.g., ASDs, electronic lighting, rectifier loads)
- Expected to reach ~50% by 2020
- Main growth: industrial drives, electronic lighting, computer / IT loads (rectifiers)

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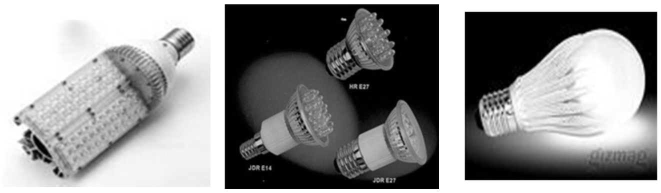
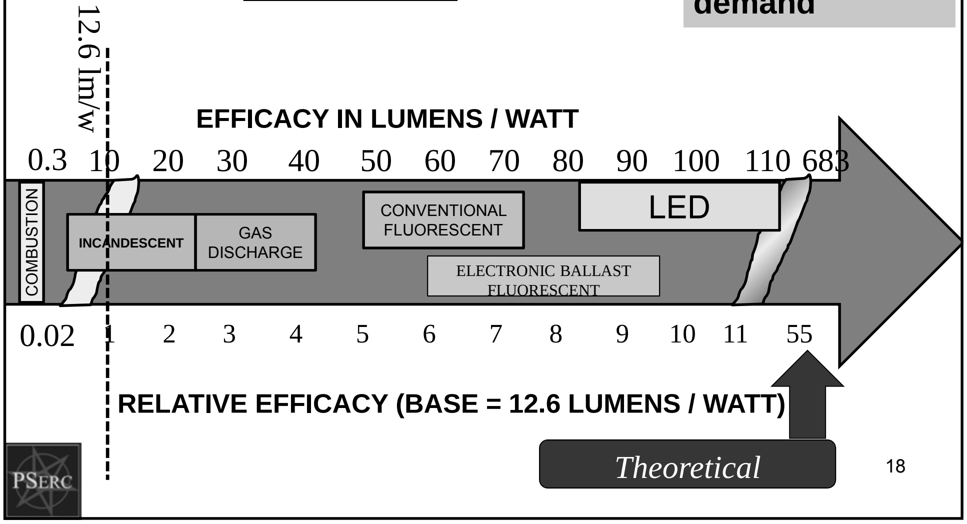


**Lighting is estimated to be 20 to 25% of the total electrical demand**



## Distribution system challenges

- Higher distribution primary voltages (e.g., 35 kV class, to reduce losses)
- Greater reliance on networked primaries – in inner cities as well as less load-dense areas
- Utilization of underground circuits , balancing mean time to failure and repair time (especially in storm prone areas)
- Revisiting tried-and-true standards to allow distributed generation (including reactive power resources), and distributed energy storage
- Judicious use of electronic controls (hybrid solid state transformer , fault interrupter)
- Consideration of higher distribution secondary voltages (e.g., such as 240 V outside of North America)
- Nonstandard frequencies in distribution secondaries for electronic lighting

## Challenge areas:  summary

- National transmission overlay coordinating all energy resources
- Utilization of transmission alternatives and hardware (e.g., HVDC, AC, six-phase, higher phase order, alternative conductor technologies)
- Microgrids
- Distribution network infrastructure and standardization
- Large scale energy storage - interactions with power delivery infrastructure
- Distributed vs. centralized generation – interactions with power delivery infrastructure
- Demand response – interactions with power delivery infrastructure

| **Transmission** | **Distribution** |
|---|---|
| **Robustness through hardware enhancement** | **Robustness through smart design and operation** |

# Panelist Comments
# Technology Session 1: Power Delivery Infrastructure

**Flora Flygt, Strategic Planning & Policy Advisor, American Transmission Co.**

1. Wind load shapes – I know that NREL has extensive information for 2006 but that is the only year. We need to replicate that effort for at least a couple more years and at different meter heights given the technological advances. We need to do this particularly because 2006 was a very odd wind year and studies using this information (because it is the only information available at the granular level that is needed) are depending on that and also because of the variability of the wind from year to year (e.g., MISO showed wind availability at the peak ranging from 0% to 67% depending on the year). After we collect a couple of full years, if the cost is prohibitive, a sampling methodology should be developed that could be used to expand and update the data set.
2. Wind forecasting – both short term (Day Ahead) and long term. For the short term we need better weather forecasting tools. For the long term we need a model/approach that enables people to cover a multiple set of possible outcomes efficiently.
3. How to model distributed resources in the future – the reality is outstripping the research on this. We need a study of what could happen in 2030 for instance with expanded smart grid applications and automated controls – what might the price and performance of DR look like under that scenario?
4. Power flow models or methodologies that can handle the much larger data sets that are needed to do interconnection wide planning. Right now the models run for days and we need to develop models that will substantially mimic the performance of the smaller models but run efficiently. This is especially true for long term planning studies where you need to be able to do a lot of scenarios and sensitivities to inform the discussion.
5. Value of transmission – we need to have research and discussion on what values from transmission can be monetized. This is a more in the market area rather than pure engineering but it requires the intersection of financial and market analysts, economists and engineers. This is more broad brush but we need to be able to talk about and agree on the value this is going to bring to everyone or we won't be able to use all the great technological fixes we are coming up with.
6. Development and use of scenarios and sensitivities for long term transmission planning and how to use results to make decisions. Again, this is more broad brush but my experience is that people don't understand different techniques and perhaps are not used to using this type of approach to do transmission planning (because it is already so complicated) and there are so many different types of analyses that should be done. Those include economic analysis for many different variables that could be monetized, and the many different types of reliability analysis, e.g., steady state, dynamics, etc. Again this would require the intersection of financial and market analysts, economists and engineers.

**Jim McCalley, Iowa State University**

1. What are the best ways to identify preferred generation portfolios, and how much should we utilize policy-driven incentive mechanisms to achieve them?
2. Should generation build-out lead transmission development, or should we design and build transmission to facilitate the generation portfolio we desire to obtain?
3. What are the engineering methods and procedures for developing attractive designs in terms of topologies, technologies, and right-of-way usage for high-capacity interregional transmission?
4. How would a high-capacity interregional transmission network change grid operations?
5. What is the best technology portfolio (ICE, PHEV, CNG, metro-rail, high-speed rail) and fuel portfolio (petroleum, electric, natural gas, and biofuels) for future passenger transportation systems?
    a. What impact does electric systems design have on the answer to this question?
    b. How much impact will the answer to this question have on electric systems design?
6. How can we, in future infrastructure designs, most effectively utilize the strengths of both distributed generation/microgrids and centralized generation/high capacity transmission?

**Robert Saint, Principal Engineer, National Rural Electric Cooperative Association**

Future Grid Challenges from the Distribution Operations Perspective

1. Interoperability
    - More data, more systems that need to interoperate (Distribution SCADA, Outage Management Systems (OMS), Real-Time Consumer Meter Data, Geographic Information Systems (GIS), Automated Vehicle Location (AVL), Work Force Management, Customer Information Systems (CIS), etc.)
    - Communication to Consumers/Consumer Owned Systems (outage notification, pre-pay notification, demand response/control communication)
2. Interconnected sources/loads
    - Distributed Generation (much of it variable output)
    - Distributed Energy Storage
    - Demand Response
        - o Variable Pricing
        - o Prices to devices
        - o Direct Control (both local control and control by the distribution utility)
    - Micro-grids (most with interconnection to grid as backup)
3. Power Quality/Reliability issues
    - Overcoming the perception that dispersed generation brings better reliability
    - Dealing with large fluctuations in source/load
    - Dealing with increased levels of harmonics

**Peter Sauer, University of Illinois at Urbana/Champaign**

1. What features should the power delivery infrastructure have?
2. Advanced communication networks need to be integrated with the power delivery network functionality.
3. What is the business case (business plan) for the delivery system?
4. What is better - distributed or centralized storage?
5. What voltages and frequencies should we use?
6. What other business opportunities could be coupled with electric power delivery?

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# Technology Session 2: Operations and Planning

**James McCalley**

Iowa State University

Future Grid Forum
June 27-28, 2012
Washington D.C.

## Outline

- Operational challenges
- Planning challenges:
  - Planning via rolling 100-year explorations
  - Multi-sector modeling to capture interdependencies
  - Multiobjective assessment
  - Resilience metric: op-cost increase to events
  - Flexibility metric: adaptation cost
  - Handling uncertainty
  - Public education and policy
- Concluding comment

## Operational challenges

- Frequency, regulation, load following, reserves:
  - What, besides UFLS settings, drives the need for bounding frequency deviation and duration?
  - How to properly evaluate cycling of fossil-fired units?
  - How to determine the right portfolio of ramping capabilities?
  - What technologies should be used: CTs, wind/solar, demand-side, storage, HVDC?
  - How should markets be designed to achieve the above?
  - What should be the size of the balancing area?
- Monitoring and controlling system stress:

  ➔Need “lever” to smoothly control system stress (controlling flows exceeding limits does not accomplish this)
- Capability to respond to high-consequence events

  ➔Need software to provide decision support for operators.

  ➔Need to account for “cost” of excessive technological complexity.

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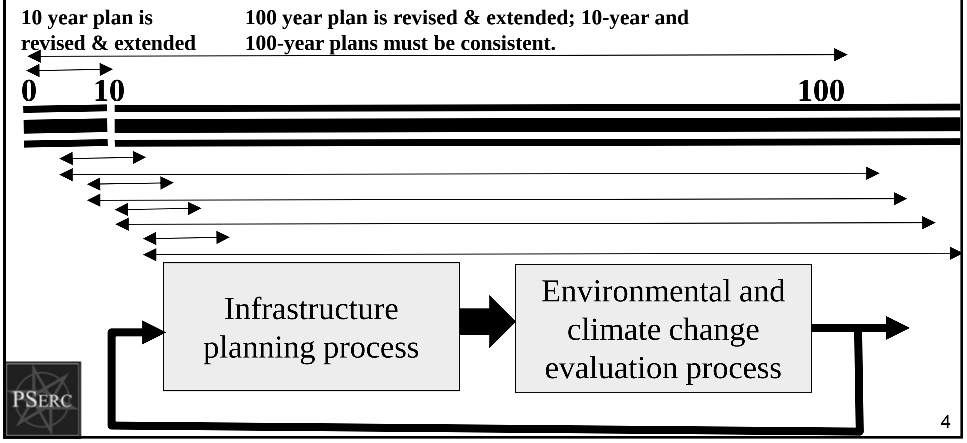
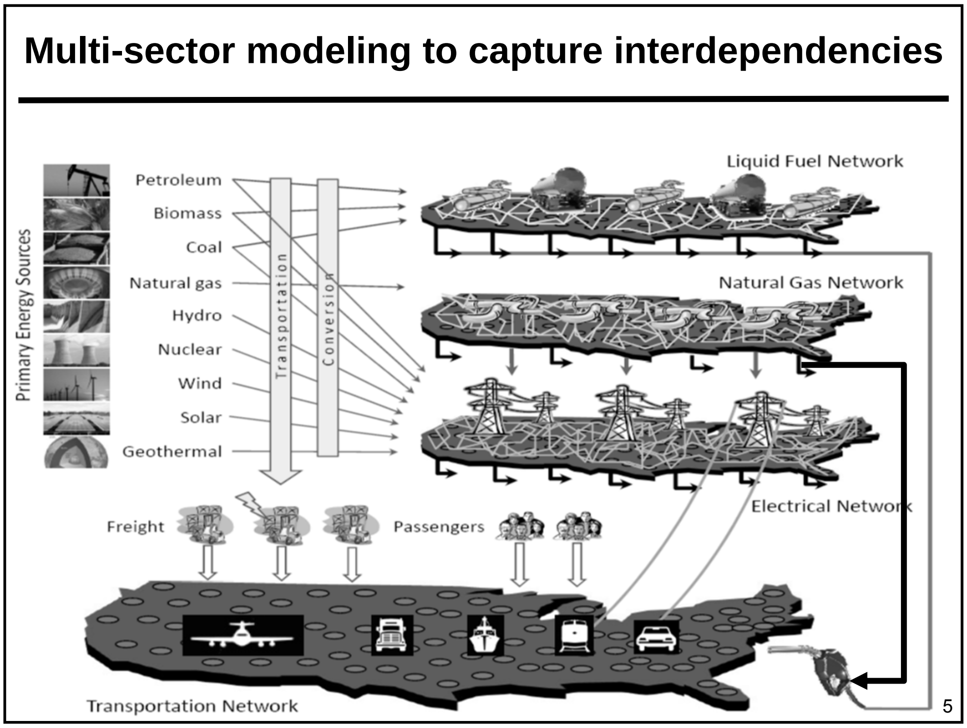
## Planning via rolling 100-year explorations

- Equipment lives 40-70 years
- Greenhouse gas effects on climate take decades
- Major infrastructure build requires 5-10 years

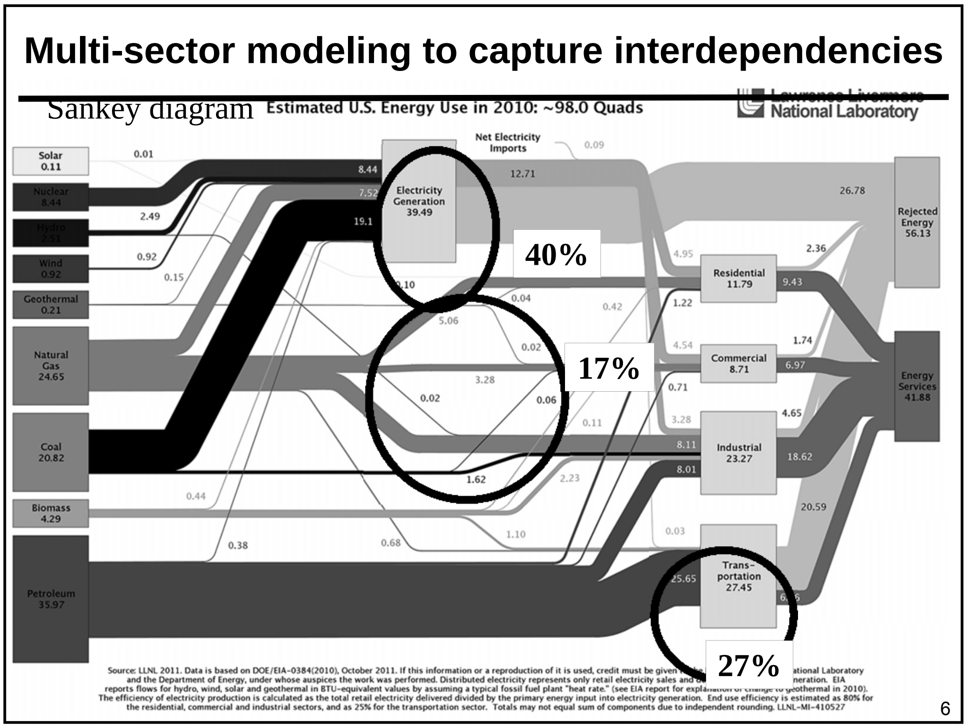


**10 year plan is revised & extended**

**100 year plan is revised & extended; 10-year and 100-year plans must be consistent.**



### Multi-sector modeling to capture interdependencies



### Multi-sector modeling to capture interdependencies

Sankey diagram

Estimated U.S. Energy Use in 2010: ~98.0 Quads

40%

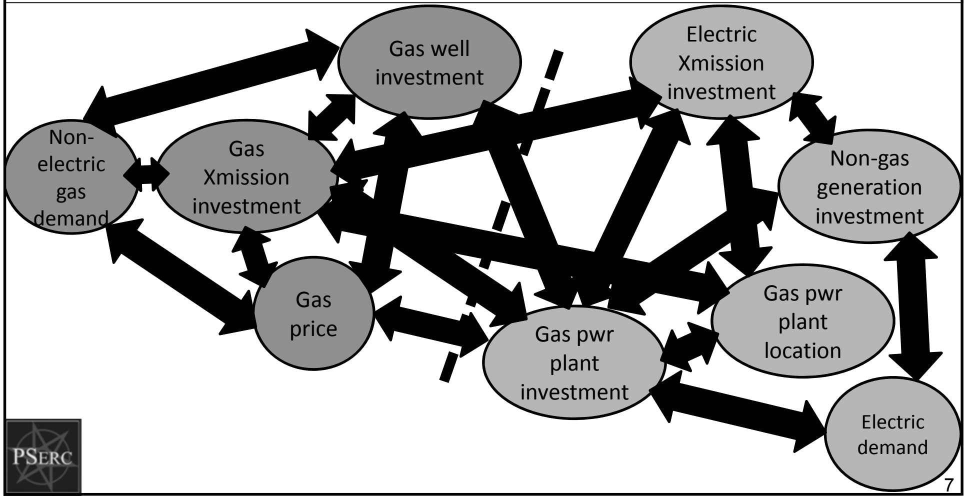
17%

27%

Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. If this information or a reproduction of it is used, credit must be given ational Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and neration. EIA reports flows for hydro, wind, solar and geothermal in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." (see EIA report for expla to geothermal in 2010). The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

## Multi-sector modeling to capture interdependencies

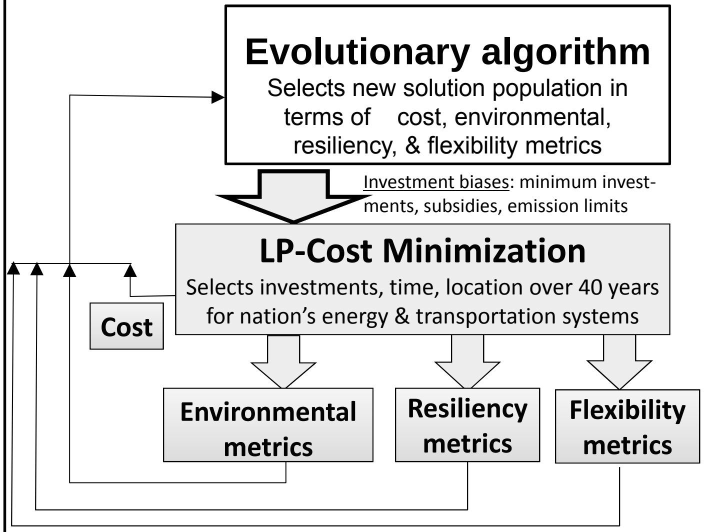
**Cooptimized analysis informs investment decisions on bulk electric & natural gas systems, accounting for interdependencies between them.**



## Multi-sector modeling to capture interdependencies

- Food, water, biofuels and steam power plants:
  - Water withdrawal=41/39% agrcltre/power; consumption=85/3%. How to utilize our limited land / water resources to achieve good balance between energy production & human consumption?
- Passenger transportation and energy:
  - What is the best technology portfolio (ICE, PHEV, CNG, metro-rail, high-speed rail) & fuel portfolio (petroleum, electric, natural gas, and biofuels) for future passenger transportation systems?
- Freight transportation and energy:
  - How should location of electric resources and transmission be balanced with the cost and impact of transporting fuels?
  - Are there attractive combinations of geographic relocation for energy-intensive industries AND growth in technology / location of electric infrastructure? Could reduction in coal usage free freight transport to move products of relocated industries?

# Multiobjective assessment



**Evolutionary algorithm**

Selects new solution population in terms of cost, environmental, resiliency, & flexibility metrics

Investment biases: minimum investments, subsidies, emission limits

**LP-Cost Minimization**

Selects investments, time, location over 40 years for nation’s energy & transportation systems

**Cost**

**Environmental metrics**

**Resiliency metrics**

**Flexibility metrics**

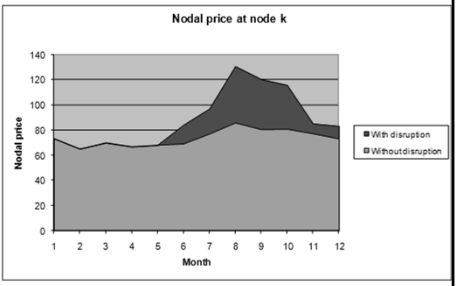
**➔FINDS SOLUTIONS WITH GOOD TRADEOFFS BETWEEN DIFFERENT METRICS.**

# Resilience metric: op-cost increase to events

**Resilience: Ability to minimize & recover from event consequences.**

**Concept: Consider events and consequences exhibiting measureable changes with design variation.**

**Perspective: 40yr, national multisector model.**

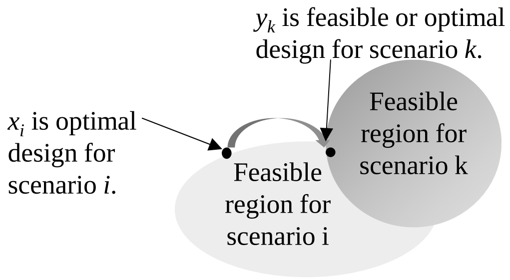


**Extreme Events:**

**Six month loss of rail access to Powder River Basin coal;**
**One year interruption of 90% of Middle East oil;**
**Permanent loss of U.S. nuclear supply;**
**Six month interruption of Canadian gas supply;**
**One year loss of U.S. hydro resources due to extreme drought;**
**Sustained flooding in the Midwest that destroys crops, reducing the availability of biofuels, and interrupts key corridors of east-west railroad system.**

**Consequences: Increase in 1-year operational costs.**

# Flexibility metric: adaptation cost



$y_k$ is feasible or optimal design for scenario *k*.

$x_i$ is optimal design for scenario *i*.

Feasible region for scenario k

Feasible region for scenario i

**The <u>adaptation cost</u> of $x_i$ if scenario *k* happens is the minimum cost to move $x_i$ to a feasible or optimal design $y_k$ in scenario *k*. It measures the cost of a wrong decision: we planned for scenario i but scenario k happened.**

The most flexible plan is the $x_i$ that minimizes the sum of all adaptation costs over all scenarios, i.e.,

$$\text{Find } x_i \text{ such that } \sum_{\text{Scenarios } k \neq i} AdaptationCost(x_i \text{ to } y_k) \text{ is minimum.}$$

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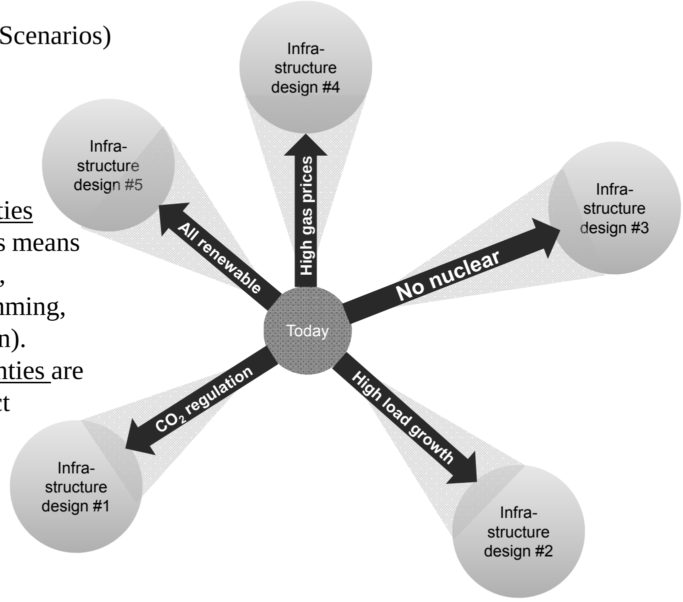
# Handling Uncertainty

Global uncertainty (Scenarios)

Local uncertainty



1. <u>Local uncertainties</u> handled by various means (e.g., Monte Carlo, stochastic programming, robust optimization).
2. <u>Global uncertainties</u> are explored as distinct scenarios.

# Public Education and Policy

*2006 survey:

What is the impact of nuclear power plants on $CO_2$ emissions?

**80% got it wrong**

**2008 survey:

Which costs more today: electricity from wind turbines or electricity from coal-fired plants?

**82% got it wrong**

#2009 survey (women):

67% identify coal power plants as a big cause or somewhat of a cause of global warming, 54% think the same about nuclear energy;
43% don’t know that coal is the largest source of US electricity.

##2003, 2007 survey:

For both survey years, “People see alternative fuels (hydro, solar, wind) as cheap and conventional fuels as expensive.”

*T. Curry, et al., “A survey of public attitudes towards climate change and climate change mitigation technologies in the United States: Analyses of 2006 Results,” Publication LFEE 2007-01-WP, MIT Laboratory for Energy and the Environment.
#M. D;Estries, “Survey: Women fail on energy knowledge,” July 3, 2009, report on a survey commissioned by Women Impacting Public Policy  and Women’s Council on Energy and the Environment.
**H. Klick and E. Smith, “Public understanding of and support for wind power in the United States,”Renewable Energy, Vol. 35, July 2010, pp. 1585-1591.
## S. Ansolabehere, “Public attitudes toward America’s energy options,” MIT-NES-TR-008, June 2007.

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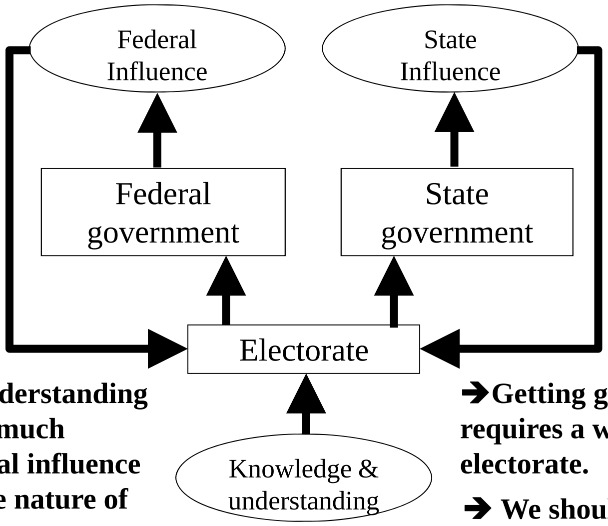
# Public Education and Policy



Federal Influence

State Influence

Federal government

State government

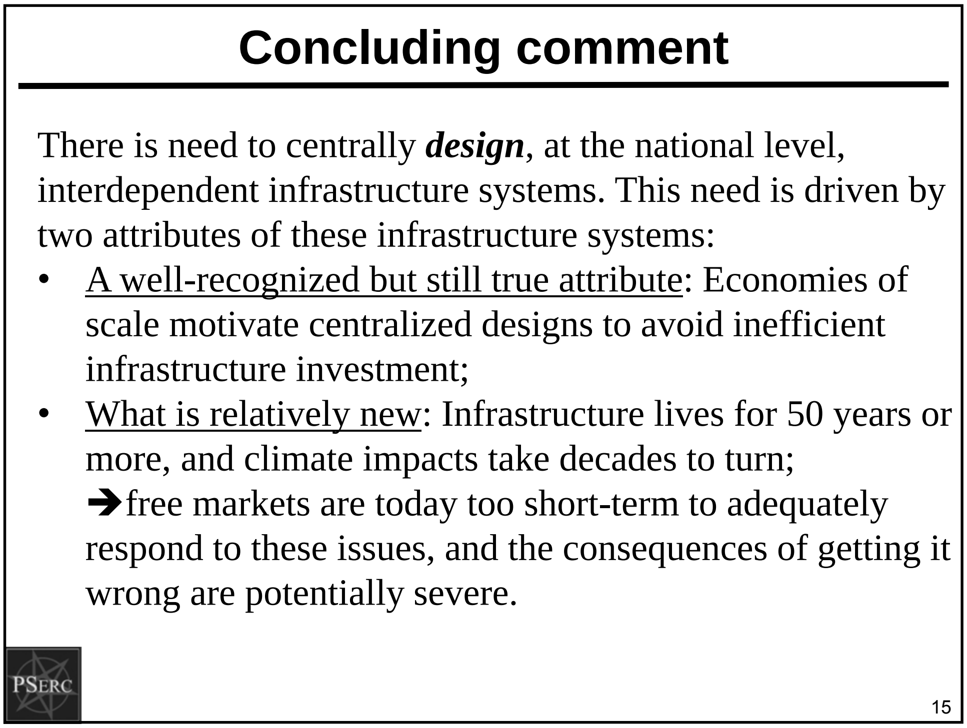
Electorate

Knowledge & understanding

**➔Public understanding affects how much governmental influence occurs & the nature of that influence.**

**➔Getting good policy requires a well-informed electorate.**

**➔ We should help electorate see the impact on their lives of each infrastructure design.**



## Concluding comment

There is need to centrally ***design***, at the national level, interdependent infrastructure systems. This need is driven by two attributes of these infrastructure systems:

- <u>A well-recognized but still true attribute</u>: Economies of scale motivate centralized designs to avoid inefficient infrastructure investment;
- <u>What is relatively new</u>: Infrastructure lives for 50 years or more, and climate impacts take decades to turn;
  ➔free markets are today too short-term to adequately respond to these issues, and the consequences of getting it wrong are potentially severe.

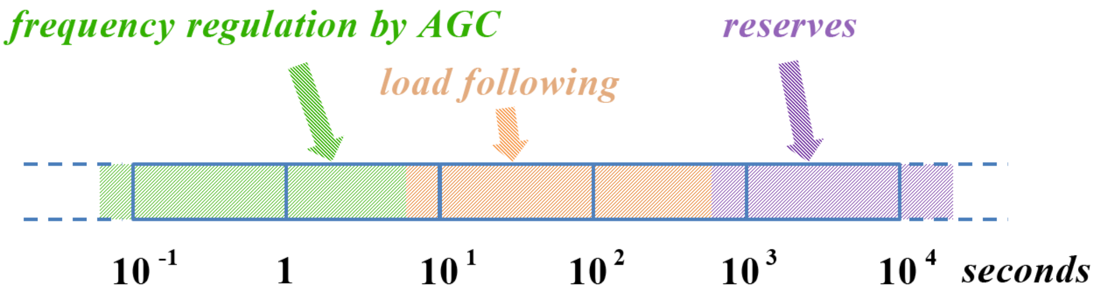
# Panelist Comments
# Technology Session 2: Operations and Planning

### George Angelidis, Principal, Power System Technology Development, California ISO

1. The future is almost here!
   - 33% Renewable Policy Standard in CA by 2020
   - Once-through cooling regulation
   - Greenhouse gas emission regulation
   - Carbon tax
   - Radical change in generation fleet characteristics
   - Higher requirements for regulation and operating reserves
   - Emerging need for new ancillary services: load following and flexible capacity
2. Planning Challenges
   - Reduced voltage support capability
     - Most wind turbines and solar plants cannot generate reactive power
     - No market for reactive power = no incentives
   - Reduced frequency response
     - No market for primary reserve = no incentives
   - Reduced system inertia
     - Stability limits must be reevaluated
   - Reduced fault current
   - Protection schemes must be redesigned
3. Operations Challenges
   - Renewable energy production forecast
   - Maintain generation fleet flexibility for load following
   - Reevaluate operating reserve requirements
     - What constitutes largest contingency?
   - Visibility, dispatch, and metering of distributed generation and demand response
4. Market Design Challenges
   - New models for new technology
     - Limited Energy Storage Resource model
     - Dispatchable Demand model
   - New market commodities and ancillary services
     - Regulation mileage
     - Dynamic transfers for renewable energy imports
     - Flexible ramp capacity
     - Primary reserve
     - Reactive power
     - Load following

**George Gross, University of Illinois at Urbana-Champaign**

1. The deepening penetration of variable/intermittent resources introduces wide and sudden changes during their operations creating the **need for flexibility** with adequate ramping capability over a wide range of time scales for essential services:



2. System planners and operators need **appropriate tools** to gain better understanding of, and ability to deal with, the intermittency and variability resource impacts in key areas
   - improved **forecasting tools** over shorter and longer-term periods to explicitly take into account the meteorological sources of uncertainty
   - models appropriate for the representation of the **dynamic behavior of renewable resources** and their interactions with conventional units and control elements and their incorporation into existing dynamic simulation tools
   - stochastic and robust methods for unit commitment/economic dispatch scheduling of large-scale systems with the ability to adaptively set reserves and adequate ramping capability requirements for the controllable resources, including storage and DRRs, to securely and economically meet the load at the various time scales
   - computationally efficient **probabilistic simulation tools** to quantify the economic, reliability and environmental impacts of the integration of renewable resources over longer-term periods for planning, investment, operations and analysis applications

3. Implementation of new power system components to provide:
   - additional flexibility in controllable resources with higher ramping capabilities, shorter start-up times and reduced down time requirements
   - judicious deployment of short-term and longer-term arbitrage-based energy storage devices
   - pervasive deployment of demand response resources
   - extensive deployment of smart-meters to automatically control loads
   - effective integration of battery vehicle aggregations.

4. Stand-alone operation of a microgrid over longer-term periods using community storage

**Tim Ponseti, Vice President of Transmission Reliability, Tennessee Valley Authority**

1. New Tools that Should be Developed
    - Tools that help give early warnings and help defend against Cyber Attacks, EMP events, and Physical attacks.
    - Tools that can simultaneously optimize resources and transmission constraints (both in the planning horizon and the operating, real-time horizon).
    - Tools that calculate and rank real-time operating risk based on amount of variable generation deployed, non-firm schedules in play, generation linked to single gas pipeline, loss of all lines in a common transmission corridor (e.g., plane crash, sabotage). Point being to consider multiple contingencies in real-time....making operators more aware of multi-contingency risks they face.

2. Wish List of Technologies, System Characteristics and Operations Capabilities
    - Pumped Storage
    - More Dispatchable Load
    - More Flexibility in controlling resources – especially those whose output varies widely
    - Need market for Reactive Power and other Ancillary Services
    - Built-in Protection schemes for single phase induction motors (residential HVAC units) – FIDVR solution. Note: FIDVR is Fault-Induced Delayed Voltage Response (key root cause of brownouts/blackouts and near blackouts of cities with large blocks of residential HVAC units).
    - Day ahead Predictability and Real time visibility for Bulk Electric System operators regarding fuel supply for gas, wind, solar generation

3. Characteristics that any successful operations/electric power systems technologies and tools must have:
    - accurate, flexible, and capable
    - durable and maintainable (with a ready supply of spare parts for when it breaks),
    - operator friendly - have good visualization - and good man-machine interface
    - recognizable value
    - should make it easier to comply with NERC reliability standards - not tougher

**David Whiteley, Executive Director, Eastern Interconnection Planning Collaborative**

*Based on experience gained from DOE sponsored interconnection studies work*

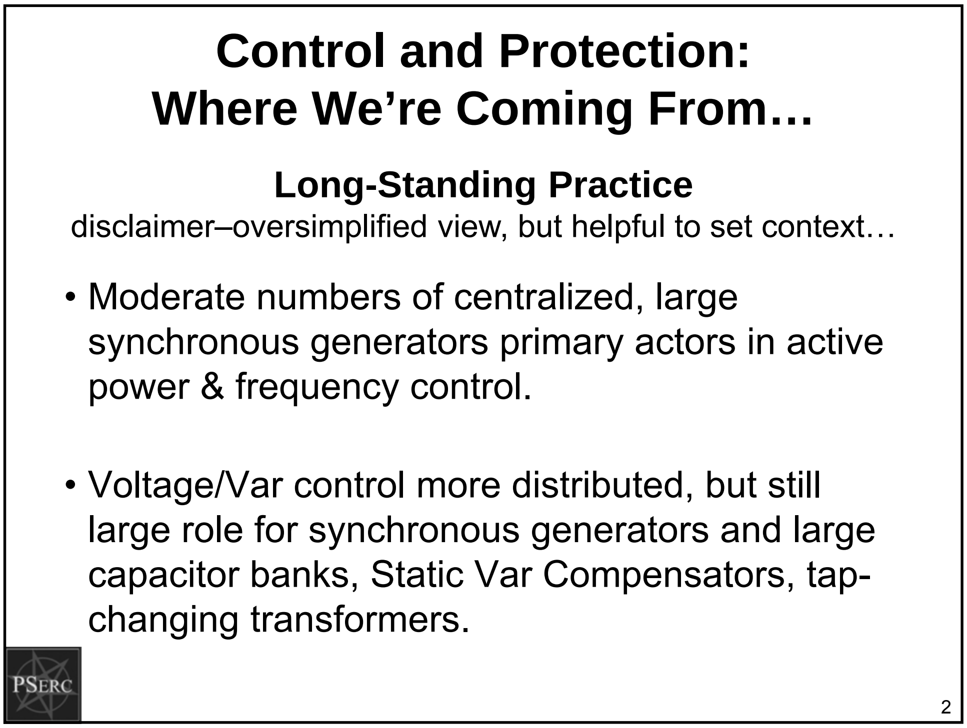
1. Study design (different potential futures vs. refining a singular future) dictates the type of modeling and tools that are required.
2. The history of system development matters.
3. Economics must continue to be considered as a (if not the) key driver.
4. Studies are needed of the best ways to interact with stakeholders in assessing potential changes in energy policies
5. The interaction of postulated additions to the system is difficult to analyze in unison particularly if they represent new or advanced technology.
6. New models and tools are needed to control and integrate significant HVDC transmission into the predominantly AC system.

# Technology Session 3: Control and Protection

**Chris DeMarco**

University of Wisconsin-Madison

Future Grid Forum
June 27-28, 2012
Washington D.C.



## Control and Protection: Where We're Coming From…

### Long-Standing Practice

disclaimer–oversimplified view, but helpful to set context…

- Moderate numbers of centralized, large synchronous generators primary actors in active power & frequency control.
- Voltage/Var control more distributed, but still large role for synchronous generators and large capacitor banks, Static Var Compensators, tap-changing transformers.

# Control and Protection: Where We're Coming From…

- Measurement & control hierarchy, based on time-scale and geographic "reach."
- On time scales of electromechanical dynamics (secs), fast measurement and control action almost exclusively local.
- On quasi-static time scale (10's of secs-to-hours), slower measurements, wider coordination primarily via periodic setpoint updates.

# Control and Protection: Where We're Coming From…

- Most protection and relaying focused on local equipment, not system level (possible exception–under frequency load shed).
- Given local focus, little ability to anticipate conditions that might require relay action – purely reactive.
- Little consideration of impact of relaying as action to steer system state.

## Control and Protection: Where We're Coming From…

- Little co-design between protection & control. Protection set boundaries of acceptable operation, within which control is to function
- Relaying uses its own dedicated measurement & data, largely unshared with outside world.

## Control and Protection: Characteristics of Challenges Today

MANY challenges with growing penetration of renewable and distributed generation.

- Large component of stochastically varying power injections, with volatile characteristics very different from historic load variation.
- Even when such sources participate in control, much larger number of distributed control actors, with narrow range of control.

## Control and Protection: Characteristics of Challenges Today

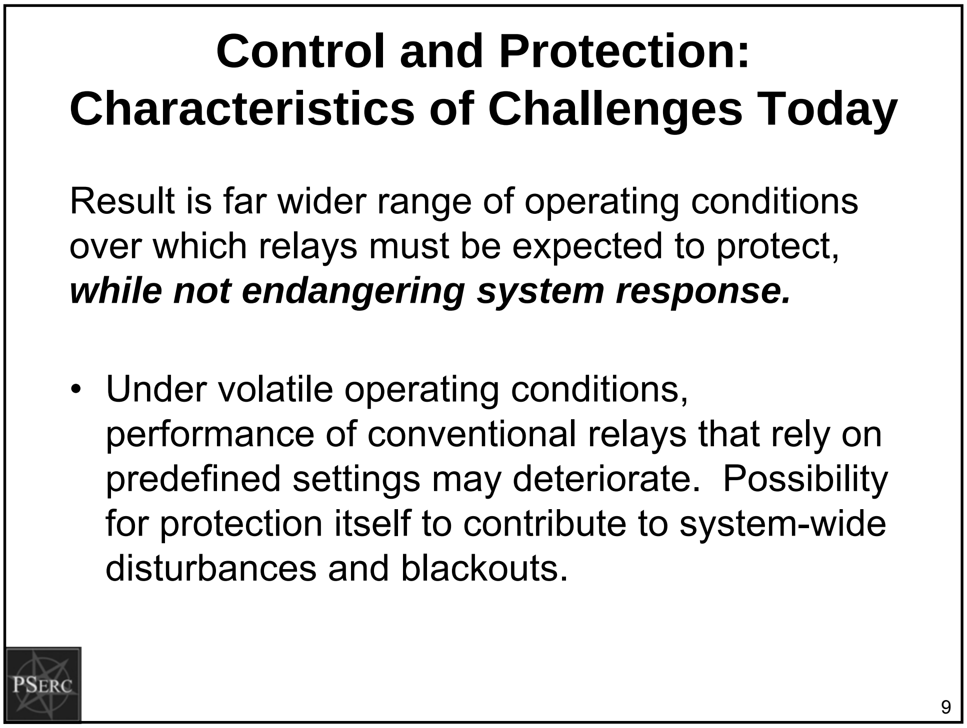
Emerging trends for new avenues of control carry some common challenges…

…larger number of distributed elements contributing to grid control, while simultaneously serving multiple objectives (e.g., consider responsive load and vehicle-to-grid storage technologies as contributors to grid regulation).

## Control and Protection: Characteristics of Challenges Today

Similar trends yield challenges in protection:

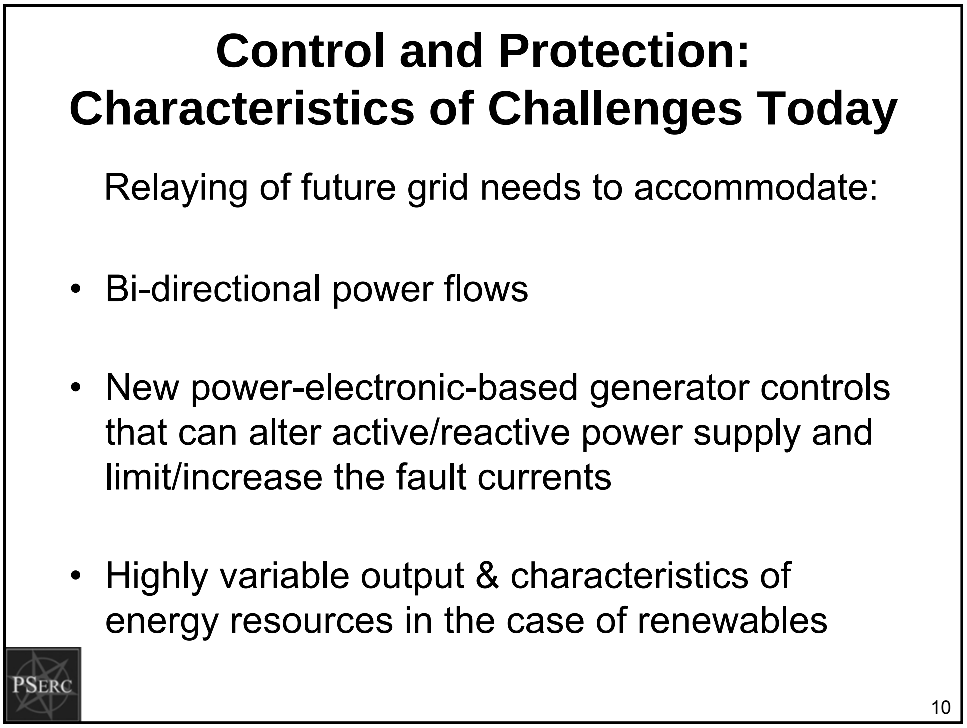
- Abrupt changes in generation patterns
- Extensive switching of power system configuration
- High penetration of distributed generation (DG)



# Control and Protection: Characteristics of Challenges Today

Result is far wider range of operating conditions over which relays must be expected to protect, ***while not endangering system response.***

- Under volatile operating conditions, performance of conventional relays that rely on predefined settings may deteriorate. Possibility for protection itself to contribute to system-wide disturbances and blackouts.



# Control and Protection: Characteristics of Challenges Today

Relaying of future grid needs to accommodate:

- Bi-directional power flows
- New power-electronic-based generator controls that can alter active/reactive power supply and limit/increase the fault currents
- Highly variable output & characteristics of energy resources in the case of renewables

# Control and Protection: Frameworks for Future

Key enabling technologies: improvement in measurement and communication*.*

- Synchrophasors and other high bandwidth measurements key. We now have “eyes and ears” into system dynamics measurements.
- From analytic control perspective, previously hard to observe dynamic modes become much more observable.

# Control and Protection: Frameworks for Future

Premise 1: Local controller can have much more intelligence, allowing it to “look out” to and control dynamics of neighboring states.

- In terms of control methods, allows ***dynamic*** state observation to be much more widely utilized. Opens door to powerful array of modern, state-feedback based control design, previously impractical in power grid.

# Control and Protection: Frameworks for Future

Premise 2: Greater high-speed "reach down" from more centralized intelligence.

- Low latency, secure communication will allow use more cost-effective use of wide area information in control. "Hierarchically-coordinated" architecture coordinate more rapidly from regional control to local actuators.

# Control and Protection: Frameworks for Future

Premise 3: "Predictive Protection"

- Vulnerability analysis deployed at the control center level, with alert to substations when threats show need monitor relays at vulnerable components ("beyond relay blocking").
- Prediction of potential for protection mis-operation, as early warning of routes to failure evolving contingencies.

# Control and Protection: Frameworks for Future

Premise 4: "Inherently Adaptive Protection"

- Relay operation based on feature recognition in full range waveform measurements.
- Seek to move beyond simple threshold or fixed settings – use advanced tools of statistical signal processing in decision to operate.

# Control and Protection: Frameworks for Future

Premise 5: "Corrective Protection"

- Intelligence of protection should not "quit" after relay operates.
- For example, upon transmission line tripping, fault location algorithm seeks to validate correctness – in case of unconfirmed fault condition, system component (transmission line) can be quickly restored.

# Control and Protection: Frameworks for Future

Summary Premise of Hierarchically-Coordinated Communication/Control/Protection:

**Control Informs Protection and Protection Informs Control**

- Predictive protection key example of control informing protection.
- Protection informs control through high speed communication of critical topology status updates, “sharing” of relay measurements.

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# Panelist Comments
# Technology Session 3: Control and Protection

**Bruce Fardanesh, Chief Technology Officer, New York Power Authority**

The NEED: More coordinated and closer to real-time power system control and operation

Requirements:

1. High quality sensory and measurement feedback; robust and redundant communications
2. Local and System-Wide State Estimation
3. Non-iterative State Estimation, advanced computational methods and High Performance Computing
4. Advanced Control algorithms for System-Wide Coordinated (most likely multi-level hierarchical) Control

**Jay Giri, Director, Power System Technology, ALSTOM Grid**

1. Intelligent use of synchrophasor data to enhance grid operations
2. Develop synergies between existing control center functions and emerging synchrophasor analytics
3. Advanced tools for automated grid control - decentralized and wide area control schemes
4. Enhancing Operator Situational Awareness with data from diverse grid measurement sources
5. Mining historical data archives of grid measurements - to develop best practices and signatures for real-time alerts
6. Develop solutions to mitigate impact on grid operations caused by growth of renewables, distributed generation, demand response

**Mladen Kezunovic, Texas A&M University**

1. Integrate substation data and automatically extract knowledge for use by multiple utility groups
2. Invent relaying approaches that are predictive, corrective and adaptive
3. Effectively protect wind power generators and plants under low level short-current and low voltage ride-through
4. Develop risk-based analysis of assets based on condition data
5. Define new generation of EMS systems
6. Devise unified multi-scale modeling approach that allows for detailed interpretation of spatiotemporal data

**Sakis Meliopoulos, Georgia Tech**

1. Protection schemes and coordination have become very complex due to the multifunctional capability of numerical relays. We need new ways of dealing with complexity and greater automation in coordinating complex protection schemes.
2. Renewables with power electronic interfaces add to the complexity as their fault currents are comparable to load currents. Protection schemes are typically based on wide separation between fault and load currents. We need new protection paradigms to deal with these new technologies.
3. Renewables may be typically connected to distribution systems. The present approach to distribution system protection is optimized for radial systems. Renewables create bidirectional flow of load and fault currents. The protection approach for distribution systems must be re-engineered.
4. New technologies such as GPS synchronized measurements, more accurate relay instrumentation can facilitate new approaches to protection. EPRI's setting-less protection initiative could enable robust protection schemes for renewables without the need for complex coordination procedures.

# Technology Session 4: Communication and Information Hierarchy

**Lang Tong**

Cornell University

Future Grid Forum
June 27-28, 2012
Washington D.C.

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## Emerging operating regimes

- ☐ Greater integration of renewable (stochastically varying) sources
- ☐ Distributed generation and demand response
- ☐ Prolific use of information technology for home/personal energy management
- ☐ Large penetration of electric vehicles and the need of large scale charging

## Technology drivers

- PMUs: high resolution measurements for enhanced observability in time (and space?).
- Smart meters and wireless networks: enhanced observability in the distribution network
- Smart phones and HEM devices: empower user choices.
- Cloud computing: unprecedented computation power and storage capability
- Cyber-physical system: cyber security, cross-network effects….

## What makes future different….

### Big Data:

- interesting, timely, multi-scale, multi-type, locational, bad, and malicious.
- impractical to communicate, no place to store, overwhelming in size and complexity, difficult to learn, and maybe dangerous to use.

## Broader analysis of issues:

- Are existing computation, communication, and networking paradigms adequate?
- What are the new considerations in the design of the information network for the future grid?

## Outline

- Distributed processing: a fundamental limit
- Information hierarchy in time
- Information hierarchy in space
- Architectural considerations

## Consistency, time-criticality, and scalability

The information network for the future grid should be

- always available and responsive
- fault tolerant, resilience to attacks
- Consistent in making decisions

More precisely, it means **CAP**

- **C**onsistency: atomic, linearizable data (all nodes should see the same data at the same time)
- **A**vailability: every request receives a response
- **P**artition tolerance: system continues to operate despite arbitrary message loss.

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## Brewer’s conjecture

*At most two of the CAP properties (consistency, availability, and partition tolerance) can be achieved at the same time.*

- Fundamental limits on real-time distributed systems
- Proved for certain computation structures

Engineering compromises have to be made, and understanding information and computation hierarchy is essential

# Information hierarchy in time

- Time sensitive decisions are essential for the integration of stochastic generations and demand side participation.

- Information hierarchy in time addresses the problem of what kind of information is required and by what time decisions have to be made.

- The value of information diminishes if it is delivered in time. Can TCP/IP guarantees it?

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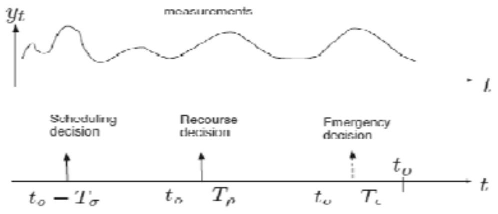
# Information hierarchy in time: risk limited dispatch

- Generation is stochastic and long term prediction is inaccurate.
- But prediction improves as the decision horizon shortens.



- Multi-stage stochastic decision

## Information hierarchy in time: large scale EV charging

- Information structure: real-time electricity price, whether condition, the state of the grid, and when the charging has to be completed.
- Large scale EV charging can be modeled as a deadline scheduling problem with power constraints
- Significant reduction in peak power consumption can be achieved by intelligently managed charging.

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## Information hierarchy implications

- Conditioning: different information hierarchies give different conditioning mechanisms.
- Network architecture: (decentralized vs. data fusion)
- Quality of Service: various delay measures (average is not good enough)
- Networking imperfections
  - Synchronization, missing packets, inconsistent information, bad data…..
- Complexity and costs

## Information hierarchy in space

- ☐ Information hierarchy in space addresses the problem of collecting and disseminating information to a large geographical area: where to collect, what are the networking requirements, data resolution, and latency.
- ☐ Information generated at different spatial locations may be inconsistent, erroneous, out of date, even malicious.
- ☐ Recall Brewer's conjecture and the CAP Theorem.
- ☐ How does the quality of data affect the quality of grid operation (state estimation, real-time market operations, etc.)

PSERC

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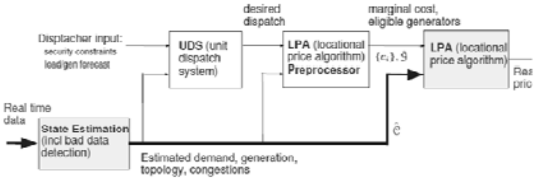
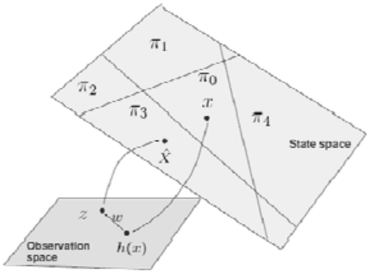
## How data affect real-time operation





- ☐ Small data perturbation can introduce large price changes.
- ☐ Bad and malicious data can affect network operations

PSERC

## Two hierarchical structures

- Two hierarchical structures under uncertainties and in changing environment:

- Networking imperfections: delays and errors in representation (rate-distortion tradeoff).
- One structure can have significant advantage over the other in decision quality.

## Some research challenges

- Co-existence of different networks: private, public, local, wide area, data fusion, control center networks, etc.
- Layered architecture for real-time and delay sensitive operations:
  - Network topology and traffic elasticity
  - Cooperation among intermediate nodes
  - Security considerations
- Wireless infrastructure for intelligent peripherals
  - Bandwidth and interference constraints
- Cloud computing
  - Distributed computation under CAP constraints
  - Security and privacy.

## Summary remarks

- ☐ The information network is not a data network; it serves challenging operating objectives of a large complex and highly dynamic system.
- ☐ Uncertainties are fundamental. Over provision may not be the right approach; imperfections and uncertainties must be part of the design.
- ☐ Time is critical. Deadline matters. Best effort may not be good enough.
- ☐ Big data represent a fundamental challenge for the future grid.

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# Panelist Comments
# Technology Session 4:
# Communications and Information Infrastructure Session

**Jeff Gooding, IT General Manager of Smart Grid Engineering, Southern California Edison**

The evolving electric utility: from bulk generation delivery to distributed energy coordination

1. Transitioning from grid stability based on physics to stability through “fly by wire” aka Smart Grid technologies
2. Applied systems thinking in Smart Grid System of Systems architecture evolutions (from silos to secure private cloud)
3. Evolving utility services for a distributed energy future
4. Common cyber security services as a model for intelligent, standards based infrastructure deployment
5. Smart grid skill gaps in the utility industry

**Manimaran Govindarasu, Iowa State**

Cyber-Physical Systems Security for Smart Grid

1. Legacy nature of infrastructure – threats/attacks evolve/move faster than defense
2. High Impact Low Frequency (HILF) events – Coordinated, intelligent cyber attacks
3. Real-time situational awareness & Information sharing
4. Cyber Infrastructure Security vs. Application-level Security
5. Paradigm shift: “From fault-resilient design To attack-resilient design”
6. Risk modeling, tools, data sets, and validations

**Tom Overbye, University of Illinois at Urbana/Champaign**

1. Information Overload: Turning Data into Decisions
    - Need for improved information analysis techniques, leveraging domain expertise
2. Communications and the Grid: The Challenges in Closing the Loop
    - Need for tight coordination between power grid opportunities and cyber infrastructure constraints
3. Low Frequency, High Impact Events: The Elephant in the Room
    - Need for infrastructure design that provides the necessary resiliency with Geomagnetic Disturbances (GMDs) as one example
4. Cyber-Physical Dependencies: Bridging the Gap
    - Need for development of engineers with good knowledge in both domains

**Jeffrey Taft, Distinguished Engineer and Chief Architect, Cisco Connected Energy Networks Business Unit**

1. Power grid is gradually being destabilized through a variety changes including VER/DER, rotational inertia reduction, and responsive loads
2. At low penetrations the impacts on grid control are minimal but at scale they are severe, due in part to hidden coupling effects
3. Grid control architecture has been experiencing evolving structural chaos in attempts to handle new functions and requirements
4. Grid control problem complexity is growing beyond the ability of traditional methods to handle
5. Solutions can be found in three areas:
    - regularization of grid control macro architecture
    - distribution of intelligence
    - use of layered optimization methods

# Session 5

# Renewable Energy Integration: Technological and Market Design Challenges

**Shmuel Oren**

University of California at Berkeley

Future Grid Forum
June 27-28, 2012
Washington D.C.

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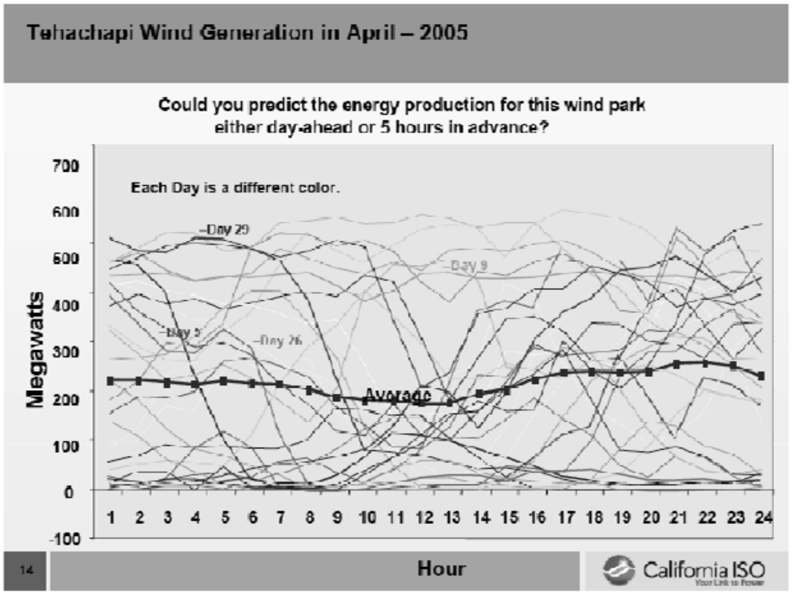
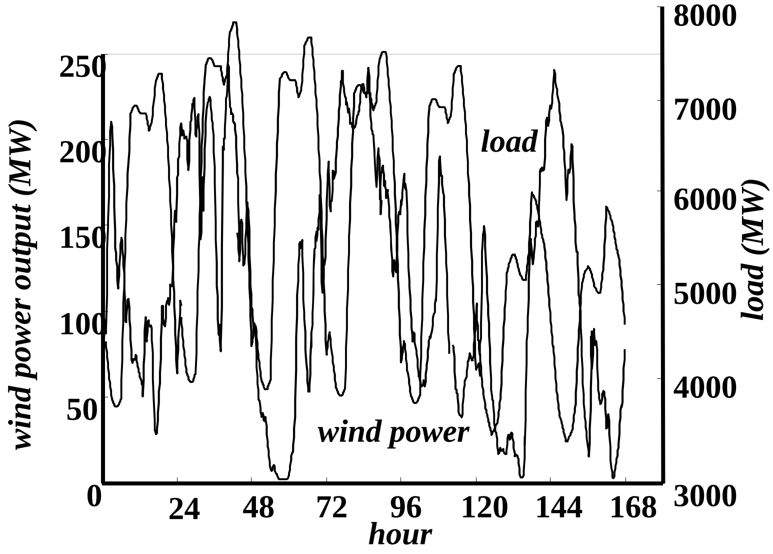
## Uncertainty

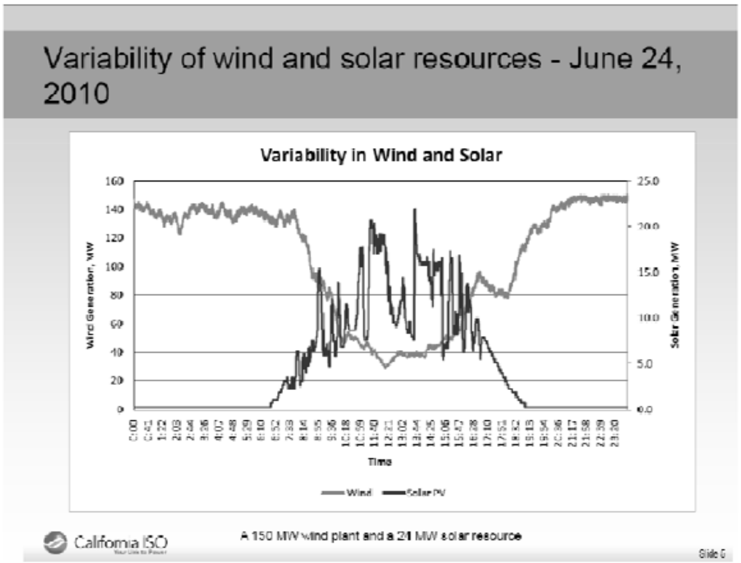

Tehachapi Wind Generation in April – 2005

Could you predict the energy production for this wind park either day-ahead or 5 hours in advance?

# Negative Correlation with Load



# Variability

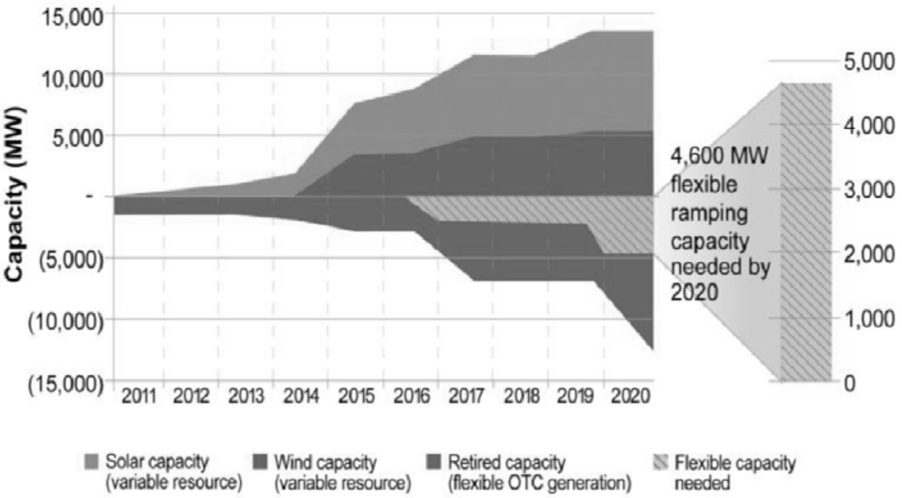


Variability of wind and solar resources - June 24, 2010

A 150 MW wind plant and a 24 MW solar resource

Slide 6

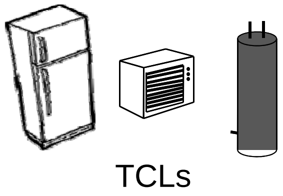
# Conventional Solution



Source: CAISO

# The DR Alternative to Expanding Flexible Thermal Generation

- Mobilizing demand response (DR) and a paradigm shift to “load following available supply” provides an economically viable and sustainable path to a renewable low carbon future.
    - Price responsive load
    - Energy efficiency
    - Deferrable loads:
        - EV/PHEV
        - HVAC
        - Water heaters
        - Electric space heaters
        - Refrigeration
        - Agricultural pumping

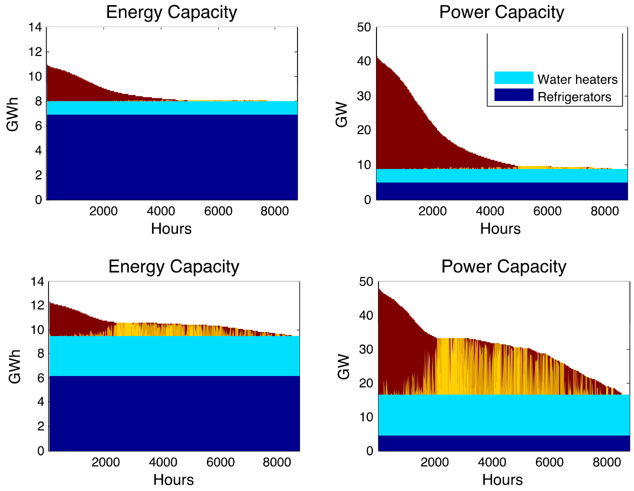


# How BIG is the Resource Potential?

Estimates for most of California (5 largest utilities) based on RECs and CEC data.

2012 Resource Duration Curve

2020 Resource Duration Curve, assuming increased efficiency and 30% of water/space heaters converted to electric



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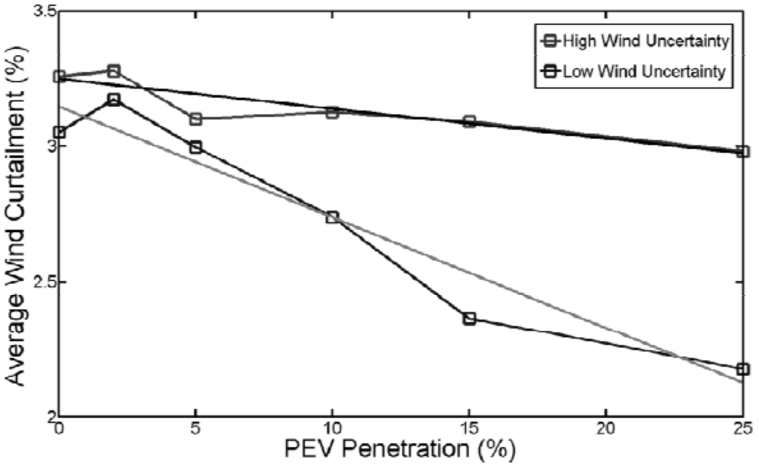
# Potential for Wind + PEV Coupling

## (Based on NYISO case study)



# Challenges

- Develop distributed control paradigms and business models for mobilizing demand response to mitigate the uncertainty and variability introduced by massive integration of renewable energy resources
- Develop market mechanisms that will incentivize load response and flexibility and correctly price uncertainty (or uncertainty reduction) on the demand and supply side.
- Develop dispatch and planning tools that can explicitly account for uncertainty, variability and flexibility (e.g. storage) in resource optimization and reserves procurement.
- Develop simulation tools that can account for increased uncertainty in verifying system and market performance

PSERC

# Task 3.1

## Direct and Telemetric Coupling of Renewable Energy Resources with Flexible Loads

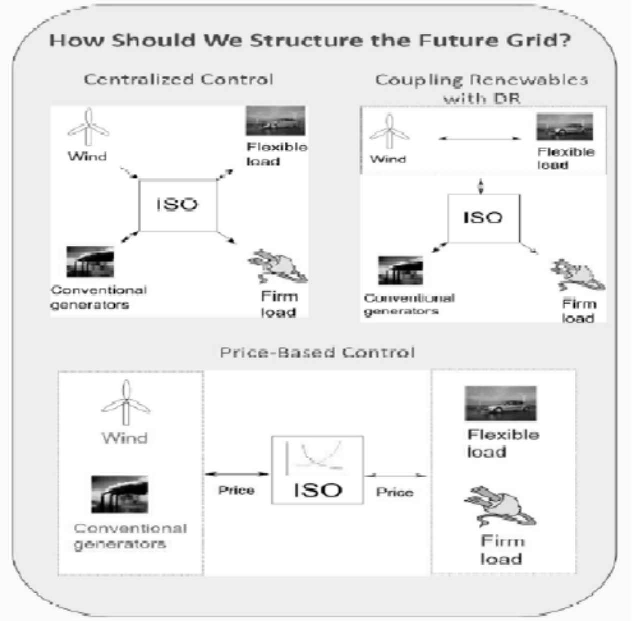
Shmuel Oren

Anthony Papavasiliou

UC Berkeley

PSERC

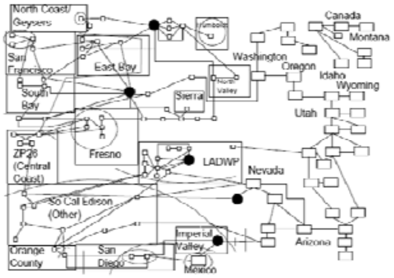
# Alternative DR Paradigms



# Evaluation Methodology

- Comparison requires explicit accounting for uncertainty for consistent determination of locational reserves.
- Stochastic unit commitment optimization accounts for uncertainty by considering a limited number of probabilistic wind and contingency scenarios, committing slow reserves early with fast reserves and demand response adjusted after uncertainties are revealed.
- Economic and reliability outcomes are calculated using Monte Carlo simulation with large number of probabilistic scenarios and contingencies

# California Case Study



- 225 buses
- 375 transmission lines
- 124 units (82 fast, 42 slow)
- 53665 MW power plant capacity
- 42 scenarios
- Four studies
  - With transmission constraints, contingencies:
    - No wind
    - Moderate (7.1% energy integration, 2012)
    - Deep (14% energy integration, 2020)
  - Deep (14% energy integration) without transmission constraints, contingencies

- Stochastic Optimization captures nearly 50% of gains under perfect forecasting of load and wind outcomes
- Direct coupling marginally more expensive than a centralized market but reduces load shedding due to better representation of load flexibility
- Transmission constraints can play a significant role in determining cost and resource adequacy

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# Task 3.3

## Planning and Market Design for Using Dispatchable Loads to Meet Renewable Portfolio Standards and Emissions Reduction Targets

Timothy Mount
Robert Thomas
Max Zhang
Cornell University

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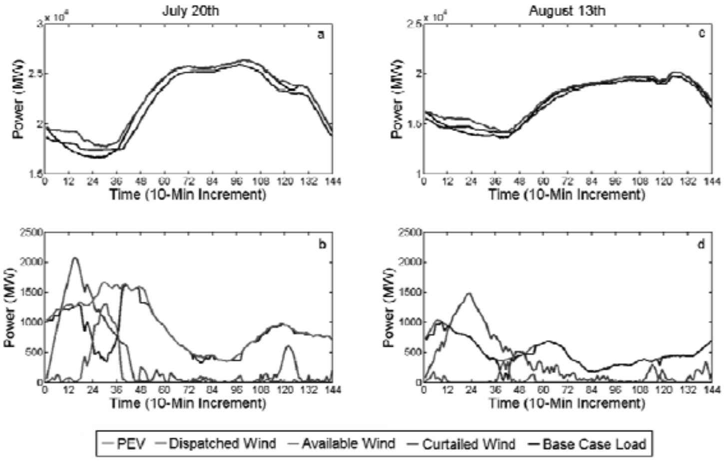
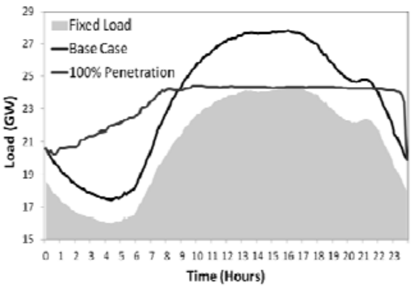
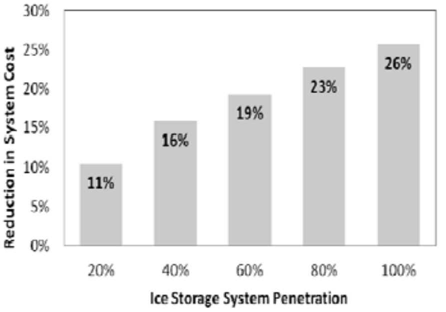
# Wind and PEV Dispatch Patterns



In scenarios with significant wind curtailment, curtailment largely occurs in the valley-load hours. Similar pattern is observed for PEV dispatch. Valley-load smoothing is performed to reduce generator start ups and shut downs, and ramping operations which increase production and maintenance cost.

# Price Responsive Ice Storage Systems





- Case study aimed to evaluate the benefits of aggregating Ice Storage Systems in large commercial and industrial buildings in New York State to reduce NYSO system costs.
- Heuristic methods were used to reduce system costs for a two-settlement market operation, where both steady-state and ramping costs are taken into consideration.
- Optimal allocation manages to reduce peak load and total system cost, and flatten out the load profile.

# Task 3.2

## Mitigating Renewables Intermittency through Nondisruptive Distributed Load Control

Duncan Callaway

Johanna Mathieu

UC Berkeley

PSERC

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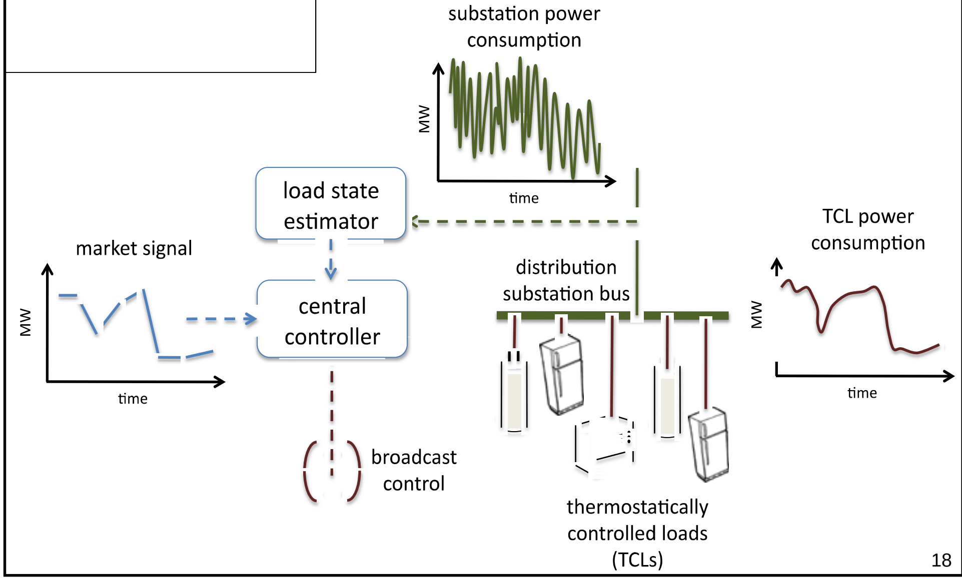
# Control Paradigm


substation power consumption

load state estimator

market signal

central controller

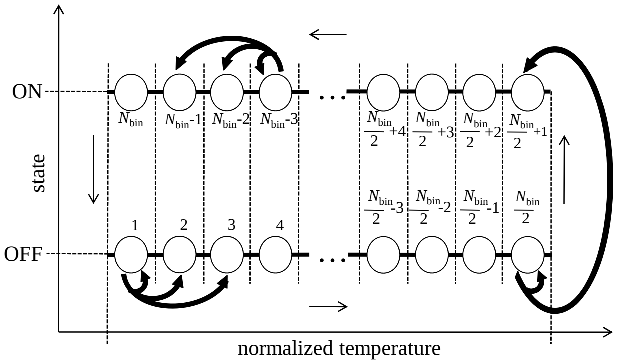
distribution substation bus

TCL power consumption

broadcast control

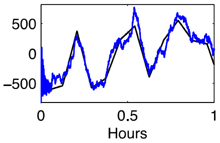
thermostatically controlled loads (TCLs)

# Modeling Aggregated TCLs: 'State Bin Transition Model'



A Markov Transition Matrix describes the movement of TCLs around the dead-band.

# Controlling TCLs to Track a 5-Minute Market Signal



# Task 3.4

## Probabilistic Simulation of Power Systems With Integrated Renewable, Demand Response and Storage Resources

Alejandro Dominguez-Garcia
George Gross
University of Illinois at Urbana/Champaign

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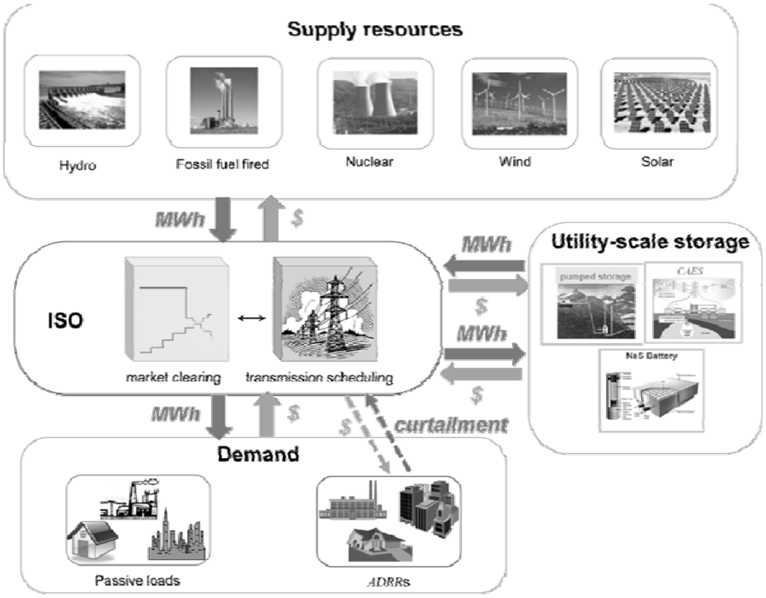
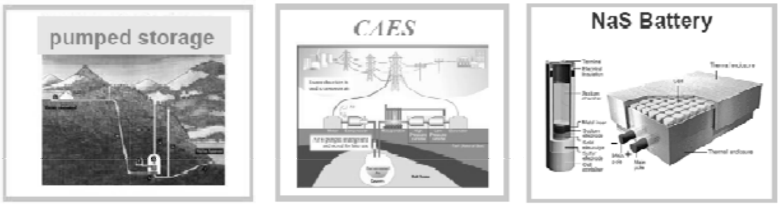
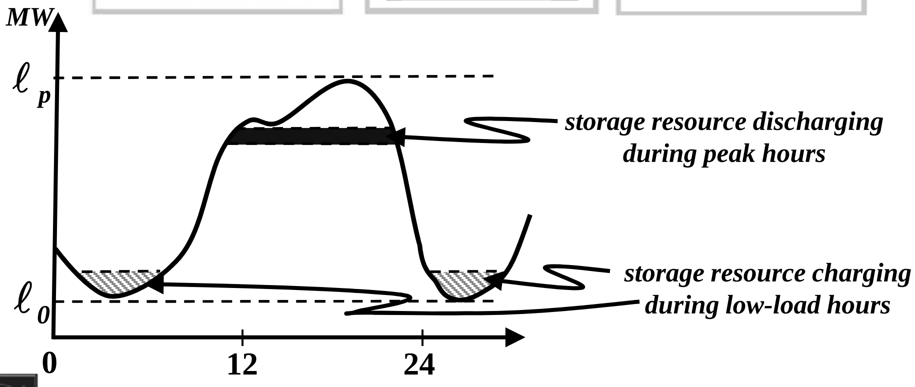
# Resource Mix Planning



# Utility-Scale Storage Application

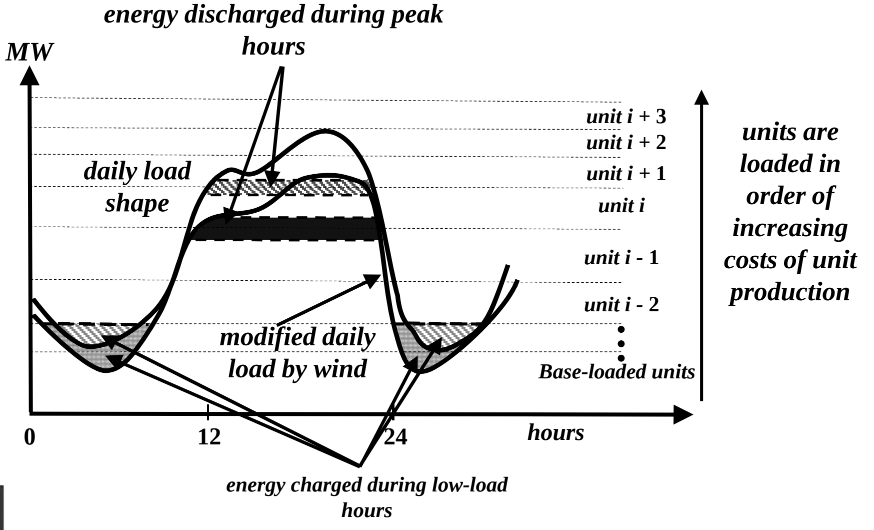




*storage resource discharging during peak hours*

*storage resource charging during low-load hours*

# Wind/Storage Interactions



*energy discharged during peak hours*

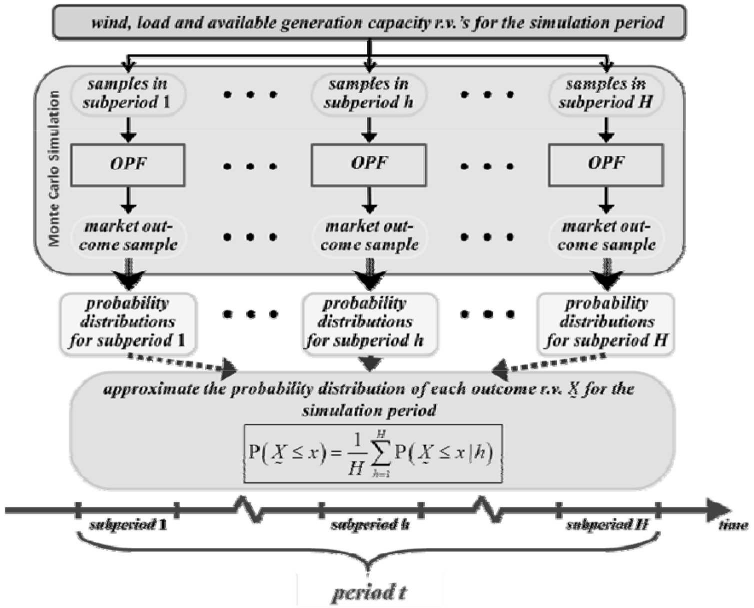
*daily load shape*

*modified daily load by wind*

*units are loaded in order of increasing costs of unit production*

*energy charged during low-load hours*

# Simulation Approach



$$P(\underset{\sim}{X} \leq x) = \frac{1}{H}\sum_{h=1}^{H} P(\underset{\sim}{X} \leq x \mid h)$$

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# Panelist Comments
# Technology Session 5: Variable Generation Integration

**Duncan Callaway, University of California at Berkeley**

1. We need to develop tools to integrate new resources (such as energy storage, responsive demand, and small DG) into grid planning and control room decisions
2. We need tools that facilitate aggregation of thousands of loads into monolithic (from the perspective of the system operator) controllable or dispatchable resources.
3. If residential and light commercial loads are to become significant resources in power system operations, we need ways to input their performance into the grid's SCADA/EMS system, at very low cost per load.
4. We need methods to understand and forecast spatial and temporal variability of distributed resources that are embedded in distribution systems and too small to meter / forecast individually
5. There is a need for analysis tools that evaluate the costs and benefits of energy storage systems to grid expansion and operations.

**Hamid Elahi, General Manager, GE Energy**

1. Supply: Thermal fleet flexibility…."plant like" features for renewable energy
2. Demand: Customer choice…..active participation
3. Delivery: More capacity (new corridors) and density (existing paths)
4. Fuel: Changing mix, price volatility, gas and electric market synergy
5. Markets: Harmonize a-d…continuous evolution
6. Standards: Fix old, develop new

**Charlie Smith, Executive Director, Utility Variable Generation Integration Group**

1. Direct coupling of renewable supply with deferrable demand, or demand management to satisfy global objectives?
2. Market design with a high penetration of renewable energy
3. Flexibility definition, probabilistic planning methods and metrics
4. Use of probabilistic wind plant output forecasts in unit commitment and production costing tools
5. Securing ancillary services from high penetration VG systems
6. Investigation of system stability in asynchronous systems

**Max Zhang, Cornell University**

1. Power systems responsive building thermal storage systems are needed to tap the potential in building demand response.
2. District energy systems can be designed to integrate variable generation, but incentives are needed.
3. A ramping market can be potentially effective in incentivizing integrating variable generation.
4. Technology development should aim to address the synergy among multiple energy/environmental targets and avoid unintended consequences.

# Technology Session 6: Computational Challenges

**Santiago Grijalva**

Georgia Institute of Technology

Future Grid Forum
June 27-28, 2012
Washington D.C.

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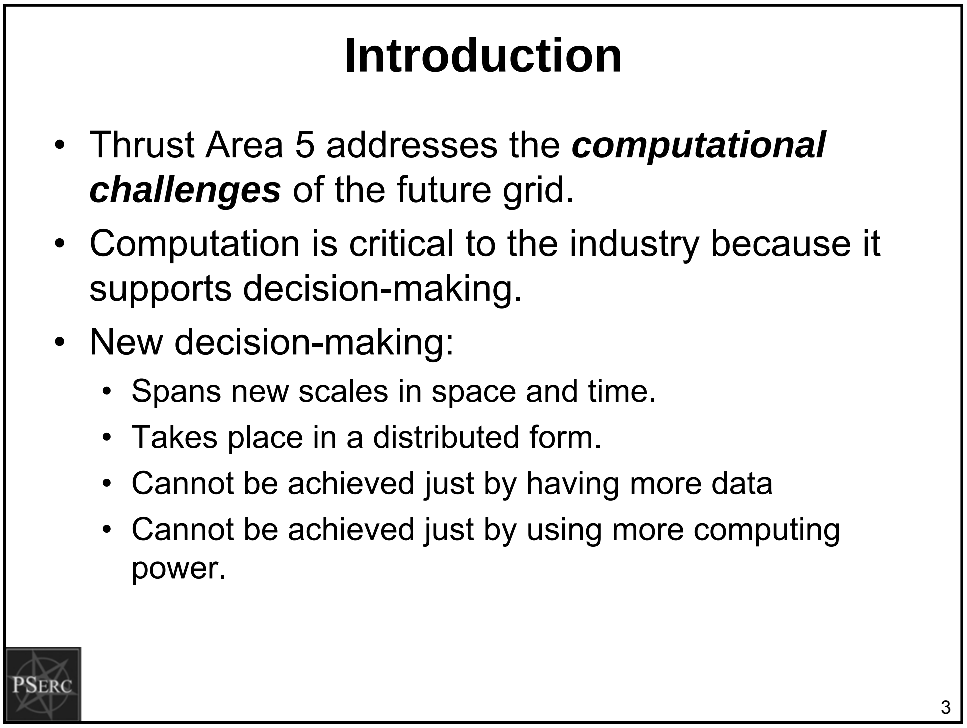
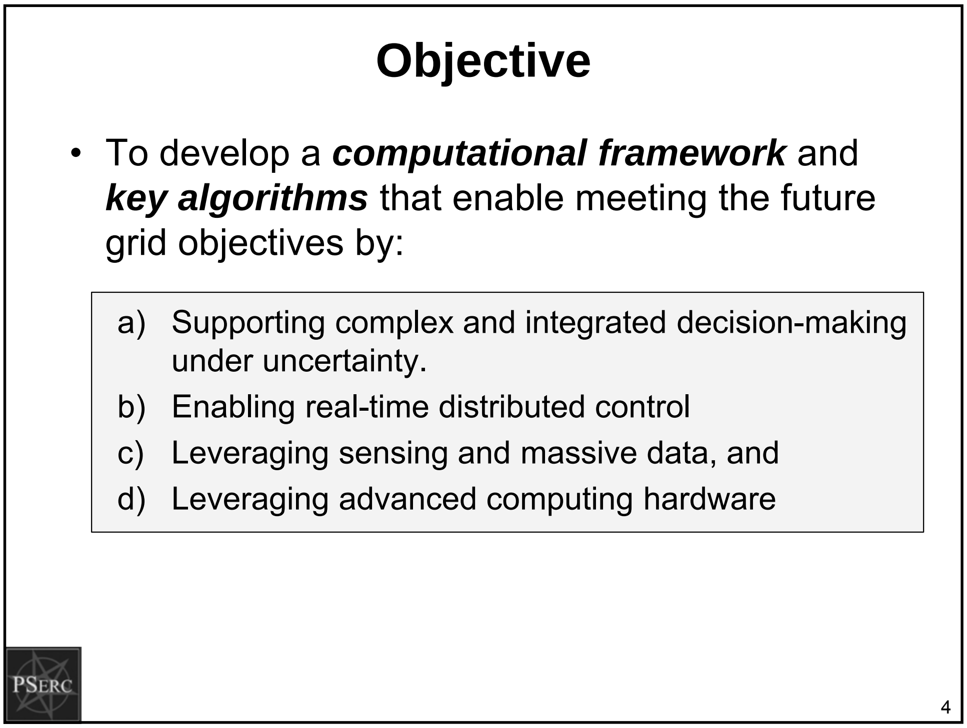
## Introduction

- The future grid must reach higher levels of Economy and Reliability (traditional objectives).
- At the same time the future grid has new objectives: Sustainability and Energy Security
- Meeting these objectives results in difficult and new computational problems:
  - Existing tools exhibit fundamental limitations.
  - PMU, AMI, and IED data provide great opportunities for improved industry processes:
    - Must organize and secure the data.



# Introduction

- Thrust Area 5 addresses the ***computational challenges*** of the future grid.
- Computation is critical to the industry because it supports decision-making.
- New decision-making:
  - Spans new scales in space and time.
  - Takes place in a distributed form.
  - Cannot be achieved just by having more data
  - Cannot be achieved just by using more computing power.

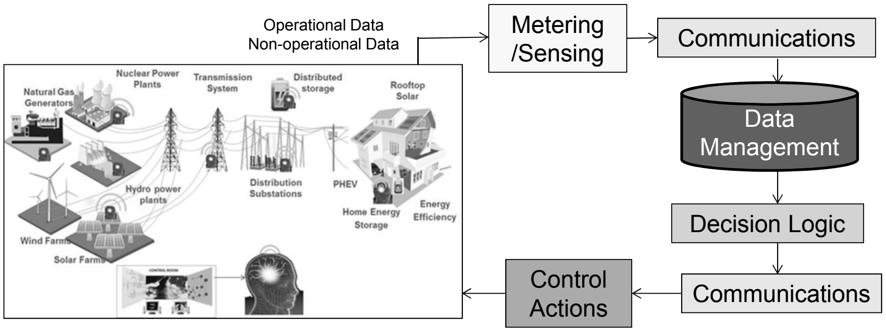


# Objective

- To develop a ***computational framework*** and ***key algorithms*** that enable meeting the future grid objectives by:

a) Supporting complex and integrated decision-making under uncertainty.
b) Enabling real-time distributed control
c) Leveraging sensing and massive data, and
d) Leveraging advanced computing hardware

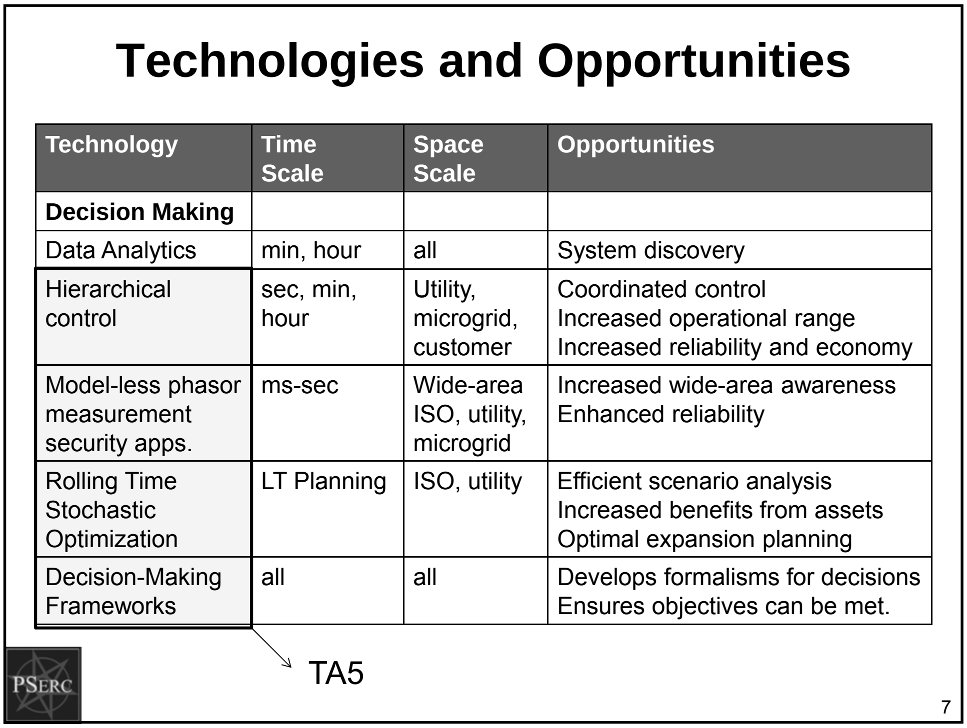
# Opportunities



- Major benefits can be achieved if emerging and legacy data is integrated in a seamless framework.
- Decision-making must capture emerging complex phenomena present at new temporal and spatial scales.

# Technologies and Opportunities

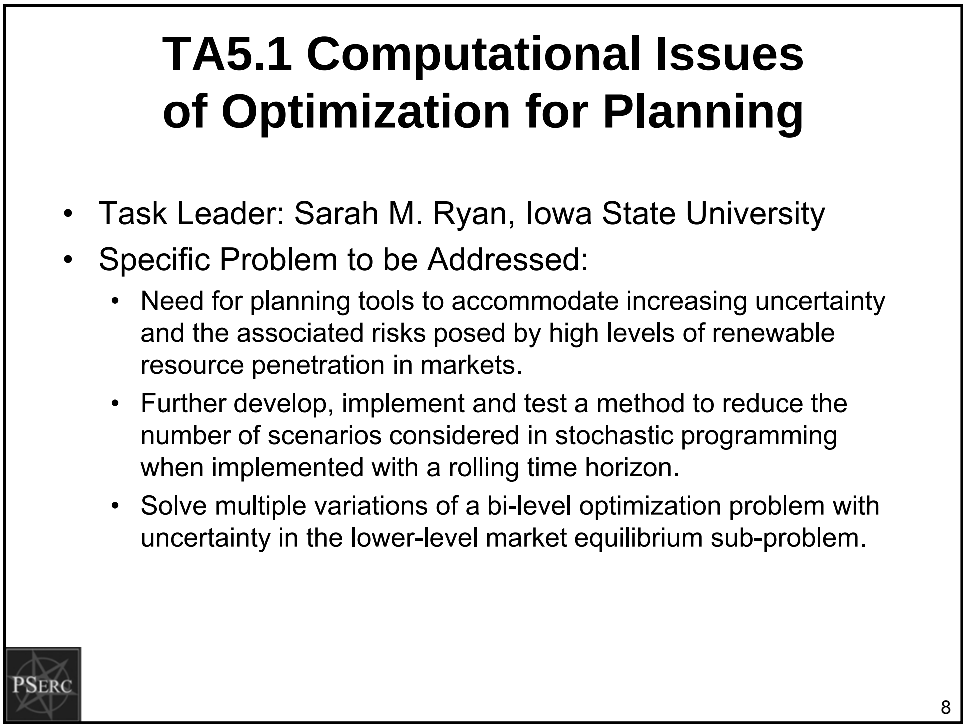
| Technology | Time Scale | Space Scale | Opportunities |
|---|---|---|---|
| **Sensing** | | | |
| Intelligent Distributed Sensor Networks | sec, min | T/D | Ubiquitous low-cost sensing<br>Energy harvesting-powered |
| Intelligent Electronic Devices | us – min | T/D | Synchronized event recording<br>Operational @ non-oper. data<br>Customizable applications |
| Smart meters | sec, min, hour | Customer | Consumer-in-the-loop enabler<br>Enhanced restoration |
| **Data Management** | | | |
| Common Models | - | T/D | Seamless data exchange |
| Data Mining | all | all | Learning from the load<br>Behavior Discovery |



# Technologies and Opportunities

| Technology | Time Scale | Space Scale | Opportunities |
|---|---|---|---|
| **Decision Making** | | | |
| Data Analytics | min, hour | all | System discovery |
| Hierarchical control | sec, min, hour | Utility, microgrid, customer | Coordinated control<br>Increased operational range<br>Increased reliability and economy |
| Model-less phasor measurement security apps. | ms-sec | Wide-area ISO, utility, microgrid | Increased wide-area awareness<br>Enhanced reliability |
| Rolling Time Stochastic Optimization | LT Planning | ISO, utility | Efficient scenario analysis<br>Increased benefits from assets<br>Optimal expansion planning |
| Decision-Making Frameworks | all | all | Develops formalisms for decisions<br>Ensures objectives can be met. |

TA5



# TA5.1 Computational Issues of Optimization for Planning

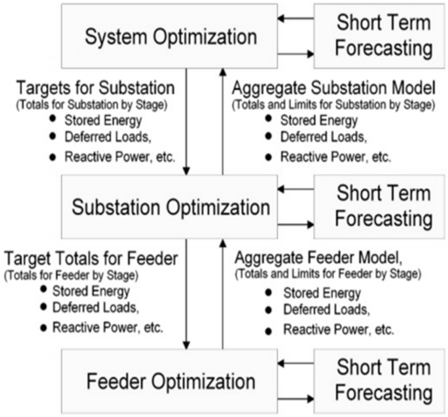
- Task Leader: Sarah M. Ryan, Iowa State University
- Specific Problem to be Addressed:
  - Need for planning tools to accommodate increasing uncertainty and the associated risks posed by high levels of renewable resource penetration in markets.
  - Further develop, implement and test a method to reduce the number of scenarios considered in stochastic programming when implemented with a rolling time horizon.
  - Solve multiple variations of a bi-level optimization problem with uncertainty in the lower-level market equilibrium sub-problem.

# Method and Deliverables

- **Methods:** Scenario reduction in stochastic programming using a rolling time horizon.
- **Achieved**: Demonstration of scenario reduction method for generation expansion in a small system. Solution of at least two versions of the bi-level optimization model.
- **Final**: Comprehensive test of new scenario reduction heuristic against other methods in realistic-sized generation expansion problems. Full case study of bi-level optimization on a realistic system to demonstrate scalability.

# TA5.2 Hierarchical Probabilistic Coordination and Optimization of DERs and Smart Appliances

- Task Leader: A. P. Meliopoulos, Georgia Tech
- Problem to be Addressed
  - Need to integrate smart grid technologies, renewables, smart appliances, PHEVs, etc. into an optimized system of systems that can mitigate the effects of uncertainties.
- Quantification of:
  - a) Resulting savings,
  - b) Impact on GHG emissions
  - c) Shifts in primary fuel utilization.



# Method and Deliverables

- **Methods:** Hierarchical stochastic optimization and control
- **Achieved:** Simulation results for a typical system that quantifies the savings in fuel costs, shifting of primary fuel utilization, and reduction in greenhouse emissions.
- **Final:** A hierarchical optimization model and results from case studies.

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# TA5.3 Real-Time PMU-Based Tools for Monitoring Operational Reliability

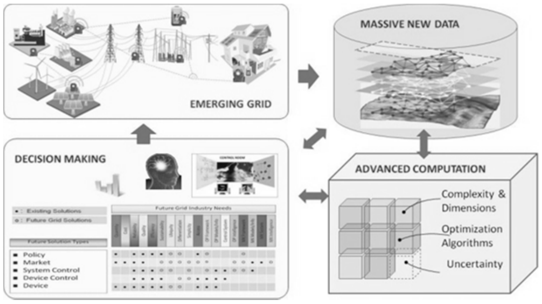
- Task Leader: Alejandro D. Dominguez-Garcia, University of Illinois
  Collaborators: Peter W. Sauer, University of Illinois
- Specific Problem to be Addressed
  - Need for real-time PMU-based tools for helping operators with operational reliability issues:
    1. System loadability monitoring,
    2. Transient stability analysis, and
    3. Real-time line model and equivalent parameter updating.
  - Develop recursive-filtering techniques for appropriately handling of phasor measurement data and estimating the parameters of interest.

# Method and Deliverables

- **Methods:** Prob. 1 & 2: PMU data alone without assuming any knowledge of the system topology. Prob. 3: Individual transmission model.
- **Achieved:** PMU data filtering algorithms and theory of model-less loadability monitoring.
- **Year 2:** Line model and equivalent updating algorithms based on PMU data.
- **Final:** Feasibility of performing transient stability using PMU measurements on certain monitored lines.

# TA5.4 Decision-Making Framework for the Future Grid

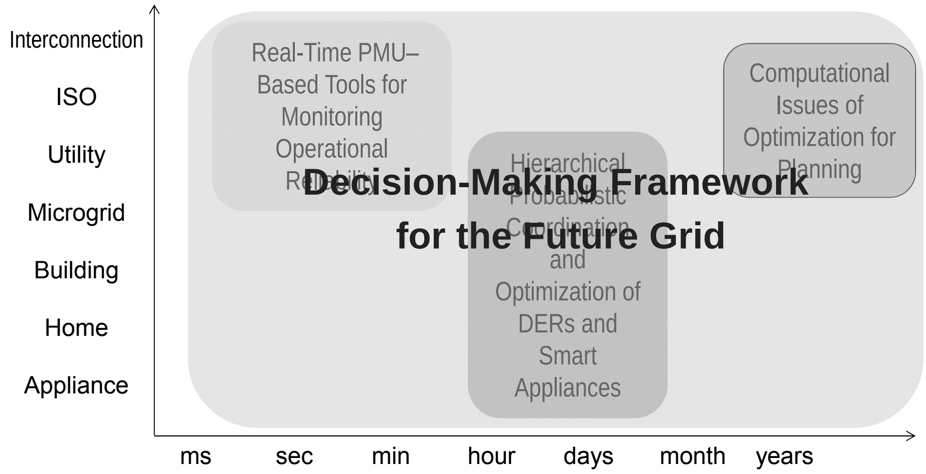
- Task Leader: Santiago Grijalva, Georgia Tech
- Specific Problem to be Addressed
  - Characterize emerging decision processes at new spatial and temporal scales.
  - Identify new decision makers and address decision complexity.
  - Identify gaps and technological needs for effective decision-making.



# Method and Deliverables

- **Methods:** Complex systems, formal informatics mapping methods, information flow, agent-based simulations, gap analysis.
- **Achieved:** Categorized list of new decisions, data requirements, and layered architecture.
- **Y2:** Data, computation, and analytical gaps.
- **Final:** Critical decision points and processes.
- Automated, machine-learned and human decisions.
- Massive data and computation module interfaces.
- Demonstration for 3 areas: transmission investment, restoration, and consumer management.

# TA5 Summary



# Conclusions

- Research Priorities
  - Enhanced stochastic optimization algorithms
  - Distributed computational framework under a cyber-physicals systems (CPS) formalism.
  - Distributed power system control algorithms
  - Access to realistic test data
  - Availability to benchmark software

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# Panelist Comments
# Technology Session 6: Computational Challenges

### Alejandro Dominguez-Garcia, University of Illinois at Urbana/Champaign

Simulation Challenges

1. Representation of continuous and discrete dynamics behavior in transient and midterm stability analysis
2. Representation of uncertainty (probabilistic/unknown-but-bounded) across different spatial and temporal scales
3. Characterization of tight interaction between cyber layer (sensing, control, communication) and physical layer (generation, transmission, distribution)

Real-Time Monitoring and Control Challenges

1. Distributed architectures/algorithms for information processing and decision making
2. Measurement-based approaches to real-time monitoring with minimal reliance on system models
3. System-wide self-healing mechanisms fully adaptable to system operating conditions

### Brian Gaucher, Smart Energy Program Manager, IBM

1. **Data:** Unprecedented scale, volume and speed of data, to be analyzed and optimized across domains with uncertainty in near real-time. Includes new data mining, pattern recognition, anomaly detection, prediction and analytics
2. **Mixed/cross domain analytics:** Mixed transmission, distribution and cross domain analysis with the ability to address optimized use of prediction, forecasting and storage for e.g., Distributed Energy Resources
3. **Real-time dynamic analytics:** Development of dynamic real-time AC Optimal Power Flow and modeling for stability analysis, state estimation, (N-x) contingency analysis
4. **Oversight/automation:** Secure, reliable efficient systems, will require broad, deep and 'real-time' oversight, w/ feedback control with increased automation driven by the shrinking timescales and complexity
5. **Visualization:** New visualization is needed to enable operators ‘easy’ Wide Area Situational Awareness to intuitively act upon events within the human time scale
6. **Computational**
    - New approaches to ‘real-time’ physical modeling
    - Improved solution to prescriptive/stochastic optimization (LP, IP, MILP, MINLP…) and machine learning for energy systems
    - SG Virtual Power Grid (VPG) and Energy “Nervous System”

**Kip Morison, Chief Technology Officer, BC Hydro**

1. **Management and value extraction from big data**: Conventional SCADA data is now being augmented by high volumes of often disparate data from smart meters, PMUs, numerous intelligent devices, and other sources from the environment and social sources. Advanced technologies, including analytics will be required to manage this data and to use it to achieved utility strategic objectives.
2. **Risk-based planning and operational tools**: Deterministic planning and operations has been the mainstay of utility operation. Given the growing complexity of systems due to deployment of smart-grid technologies (distribution automation in particular) combined with a higher penetration of distribution generations will require the development of advanced risk-based tools using probabilistic techniques.
3. **Advanced real-time dynamic security assessment tools**: This domain includes many sophisticated technologies today, but advances in computation will be needed to deal with larger system modes, the need to assess more scenarios, and to utilize new inputs such as PMU data. It is expected that new hardware architectures will be needed (some distributed systems have scaling limitations) and algorithms (speed and modeling).
4. **Optimization tools:** The use of optimization is limited in today's utility operation (optimum powerflow and some control tuning are some of the few examples). Two significant factors are driving the need for new optimization computational capabilities 1) the need for coordination and optimization of the widespread use of "smart-grid" controls (such as VVO or FLISR) and 2) the need to optimize many aspects of system operation and planning in order to defer capital needed for new or replacement infrastructure.

**Sarah Ryan, Iowa State University**

Need for tractable computational models and methods that include:

| Element | Dimensions in short-term operations | Dimensions in long-term planning |
|---|---|---|
| Uncertainty | Day-ahead forecasts of renewable generation, availability of dispatchable resources, and demand | Technology development, fuel costs, climate change, demographics, and macroeconomics |
| Distributed decisions on supply and demand | Generator offers and price-sensitive demand bids in wholesale markets | Investments in generation and transmission, consumer technology adoption and responses to incentives |
| Decision-making stages | Forward, day-ahead, and real-time markets | Adaptation to realizations of uncertain elements and decisions by other actors |

# Workforce Development

## Meeting the Educational Challenge of the Smart Sustainable Grid

**Chanan Singh**

Texas A&M University

Future Grid Forum
June 27-28, 2012
Washington D.C.

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# The Backdrop

- A smart grid with heavy penetration of variable energy sources, integrated microgrids, central and distributed energy storage and distributed communication and computational technologies allowing smarter utilization of resources and consumer participation.
- Greater emphasis on reliability, resilience to physical and cyber-attacks, as well as emergence of new loads and generation operating conditions make monitoring, control and protection of electricity grid challenging.
- These factors, together with emphasis on markets, result in a higher uncertainty in the planning and operation of future energy systems.

# Workforce for this Grid?

- Workforce needs will happen at various levels : skilled workers, engineers, managers.
- Our concern is with the engineering workforce needed to:
  - design, construct and operate the future grid.
  - to produce innovative ideas and transformative changes to integrate clean and sustainable energy sources.
- *Relevant education of this workforce is critical to the success of the future grid*.

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# Channels to Education

- All research activities as a part of this initiative as well as others in this area will contribute, to some extent, to the development of the workforce through participation of graduate students in the research projects.
- Education through this channel is deep but relatively speaking more narrowly focused.
- The scope of this thrust is education of a much wider audience as well as giving a more comprehensive view to those engaged in research on particular topics.

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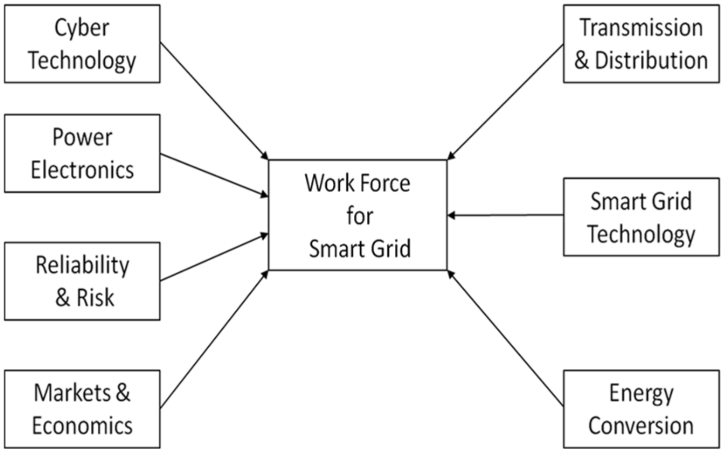
# State of Art

- The most common source of engineering workforce is the BSEE degree programs where the students take 3 to 4 courses in power systems or a combination of power systems and power electronics.
- The next level is the MSEE: the students can take more courses in their area of interest and have more depth.
- The highest level is the PhD: the students get more knowledge as well as develop evaluation abilities.
- Evaluation level (Bloom’s Taxonomy) is the highest level of understanding which allows the individual to argue and debate alternatives and to evaluate arguments.
- Successful orchestration of the smart grid needs workforce at all the three levels in different proportions.

# What is Needed?



Cyber Technology

Power Electronics

Reliability & Risk

Markets & Economics

Work Force for Smart Grid

Transmission & Distribution

Smart Grid Technology

Energy Conversion

# Challenges to this Vision

- U.S. universities tend to give a broad based education to the students at the BSEE level.
- This is expected to open more opportunities and lifelong learning capabilities to the graduates.
- At the BSEE level, the power curriculums need to compete with other specializations and general education requirements for their share of credit hours.
- Power related courses therefore need to design their education within these constraints.

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# Challenges

- In the environment of restricted hours available, the struggle between the depth and breadth of coverage is always a problem.
- In addition in most schools the pace and rigor of the course is typically geared towards the average student.
- Most of the power system related programs are small and have access to only a narrow set of specialties.
- Even in the larger programs, the expertise of faculty is determined by the research they engage in. Therefore expertise for all the needed technologies may not be available.

# Challenges

- Evolution of the future grid is fast-paced and the key technologies are in constant flux. Therefore, the curriculum and training to develop the workforce also needs to be fast-paced, flexible and able to quickly adapt to rapid technological developments, while simultaneously ensuring solid foundation in the fundamentals.
- The interdisciplinary expertise required for smart grid technologies, including measurements, communication, computing, and control, make the required education and training more challenging.
- In addition the students need to be able to work in interdisciplinary teams.

# Opportunities

- Collectively, the universities in the PSERC provide a broad spectrum of expertise. This allows a rare opportunity to tap this resource for text books and course material to meet the interdisciplinary needs of education.
- Advances in e-learning technologies, and ubiquitous access to high speed internet provide a tremendous opportunity to address the above challenges.

# What Can We Do?

- We can act as an enabling agent.
- Our objective is to develop a collection of educational material, books as well as notes, on relevant topics and on background topics required to understand these concepts, and make them available to those interested.
- This will make it possible to teach a variety of subjects as the availability of such material facilitates offering such courses.
- Through this process of collective and collaborative wisdom, cutting-edge research and insightfulness can be made accessible to practicing engineers, researchers and students.

# What are We Doing?

- The issues of breadth and depth need to be balanced.
- Also we need to consider the current gaps in the education of the existing workforce.
- The nature of audience, whether these are school going graduates, working engineers or other energy professionals also needs to be considered.
- We need to utilize the e-learning technologies to provide an as up-to-date education as possible.
- After careful thinking, six specific tasks have been undertaken for this thrust. Some educational materials will be focused on providing the breadth and the others on depth in needed areas.

# What are We Doing?

- Tasks focused on covering the breadth of the topics needed:
  - PSERC Academy: A Virtual Library of Thousand Short Videos
  - Smart Grid Education (on Synchrophasors ) for Students and Professionals
  - Energy Processing for Smart Grid Technology
- Tasks focused on depth:
  - Educational Tools for Reliability Modeling and Evaluation of the Emerging Smart Grid
  - Course in Energy Economics and Policy Critical
  - Infrastructure Security: The Emerging Smart Grid

# PSERC Academy

- Not focused on any particular topic but rather provides a mechanism for disseminating rapid advances in an efficient manner.
- The vision is to develop, over a period of 3-5 years, hundreds or even thousands of online videos ranging from introductory material to advanced topics.
- Delivered using a range of methods from simple lectures and derivations of equations to sophisticated multi-media delivery.
- Meant to evolve over time, based on user and expert feedback, changing needs and learning technologies.

## Smart Grid Education about Synchrophasors

- Industry-wide projects are creating a need to educate emerging engineers about synchrophasor fundamentals.
- An excellent book already published on the subject but we recognize a need for more elaborate instructional material.
- A group of authors has engaged in development of instructional materials to:
  - Develop comprehensive educational package that will reach out to educators, students, practicing engineers, managers, legislators, and public officials;
  - Write a text book and prepare a set of presentations that may be used for instruction.

## Energy Processing for Smart Grid

- Fundamentals of electric machines and transformers , modeling of renewable energy such as wind and solar resources while accounting for variability.
- Ability to model and analyze power electronics building blocks of inverters or converters.
- Ability to understand real time measurements using phasor measurement units (PMU), smart meters and consequently use the measurements to perform real time stability, power flow and optimal power flow of the grid under different contingencies.

## Reliability Modeling and Evaluation of the Emerging Smart Grid

- Educational material developed through this task will provide the target audience with the state of the art tools for modeling and analysis of reliability of this complex cyber-physical system.
- This material will be useful for those who need to use these tools as well as those who want to do further research.
- They will be able to use this knowledge to make tradeoffs between reliability, cost, environmental issues and other factors as needed.

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## Energy Economics and Policy

- The goal is to provide a deep understanding into the economic and technological drivers that led to the regulatory policies and market institutions that have dominated the electricity industry over the last century.
- From such a base, one can explore how advances in both technology and economic policy have made possible new market designs and helped to spur increased wholesale trade.
- A complete view of the potential role of the future grid within the energy sector must also consider the economic characteristics that permeate the energy industries.

# Critical Infrastructure Security

- Design and development of a new smart grid course focused on cyber-security.
- Key areas of research focus include designing an interdisciplinary course; locating and creating course materials; teaching in efficient manner and disseminating course material to be adopted by other educational institutes.
- Has four components: smart grid operation and control; communication; data management and computing; and basics of cyber-security.

# Concluding Remarks

- Education is an enabling and empowering force.
- It provides knowledge, understanding, and insightfulness to understand problems and situations and make decisions.
- It also empowers the workforce to make further innovations to serve the power systems industry.
- Education can serve the workforce involved in the management and operation of existing technology as well as spur the progress to higher levels of accomplishment in the smart grid, through providing insightful and holistic viewpoints.

# Concluding Remarks

- The work done throughout this thrust will thus have a transformative and disruptive influence on the orchestration of the smart grid.
- Work is going on six topics to yield quality educational material.
- With time more topics may need to be addressed and the current ones updated. So resources need to be found to continue this effort.