Smart Grid: Opportunities and Challenges
Toward a Stronger and Smarter Grid

S. Massoud Amin, D.Sc.
Director and Honeywell/H.W. Sweatt Chair in Technological Leadership
University Distinguished Teaching Professor
Professor, Electrical & Computer Engineering

2009 MIT Energy Conference – Accelerating Change in Global Energy

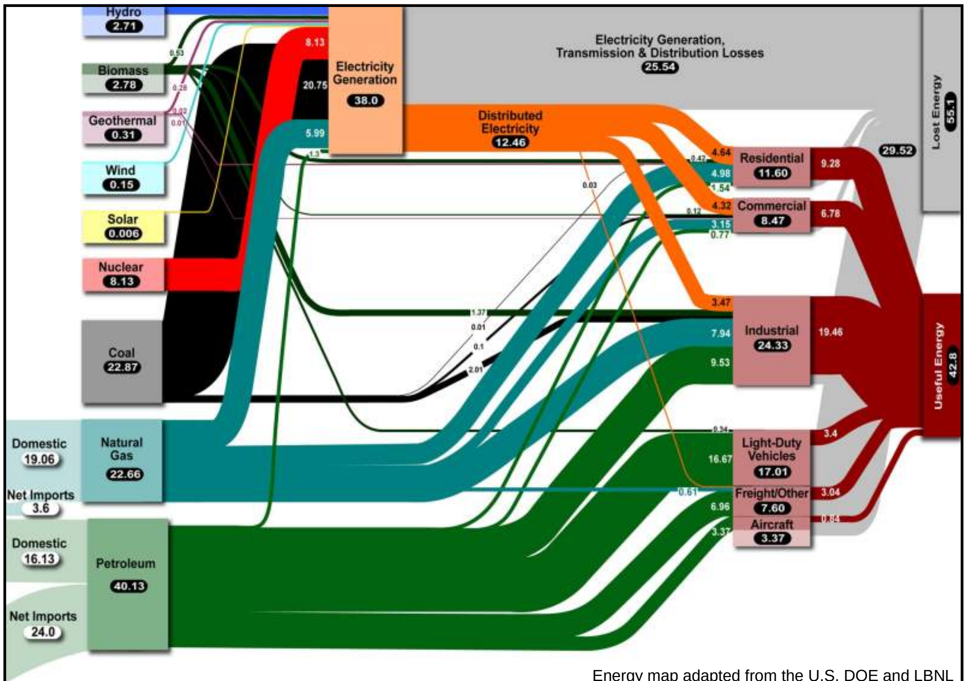
Sponsored by the Sandia National Laboratories, MIT, Cambridge, March 6th, 2009

Material from the Electric Power Research Institute (EPRI), and support from EPRI, NSF, and ORNL for parts of my graduate students' doctoral research is gratefully acknowledged

Context: Cities with 10 million people

- By 2020, more than 30 mega-cities in the now less-developed world. By 2050, nearly 60 such cities.

- Increased population creates need for more resources. World's electricity supply will need to triple by 2050 to keep up with demand, necessitating nearly 10,000 GW of new generating capacity.



Energy map adapted from the U.S. DOE and LBNL

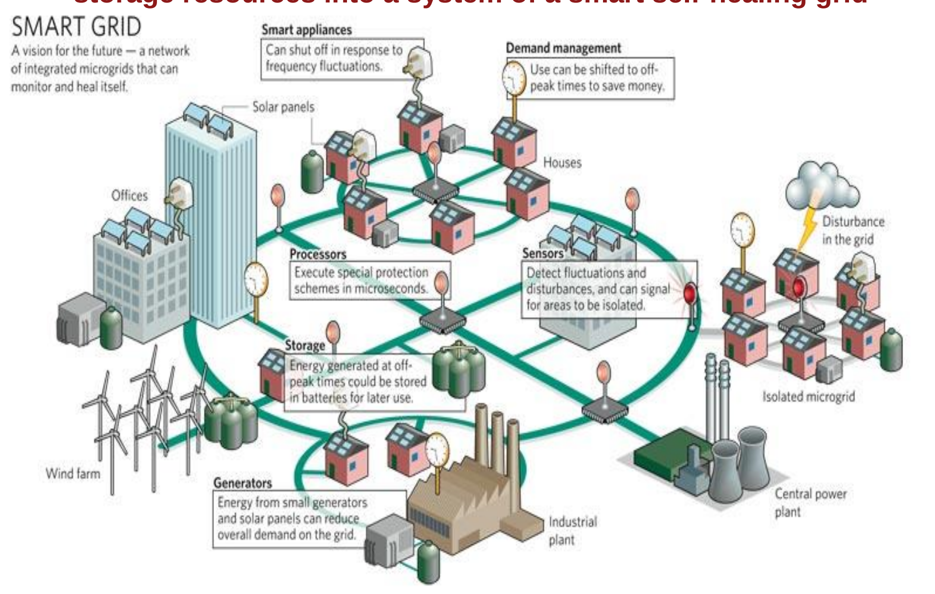
Goals and Recommendations (IEEE, Jan. 2009)

- **Building a stronger and smarter electrical energy infrastructure**
  - Transforming the Network into a Smart Grid
  - Developing an Expanded Transmission System
  - Developing Massive Electricity Storage Systems
- **Breaking our addiction to oil by transforming transportation**
  - Electrifying Transportation: Plug-In Hybrid Electric Vehicles
  - Developing and Using Alternative Transportation Fuels
- **Greening the electric power supply**
  - Expanding the Use of Renewable Electric Generation
  - Expanding Nuclear Power Generation
  - Capturing Carbon Emissions from Fossil Power Plants
- **Increasing energy efficiency**

Enabling a Stronger and Smarter Grid

- **Smart Grid Challenges/Opportunities:**
  - Infrastructure for Generation/Transmission/Distribution Systems
  - Infrastructure for Smart Customer Interface
  - Distribution Automation
  - Smart metering improves load models and profiles
  - Device monitoring and self-healing diagnostics
  - Communication infrastructure provides opportunities for monitoring and diagnostics
  - Distributed Sensing and Control
  - Alternative Smart Grid Architectures
  - Infrastructure Security: Controls, Communications and Cyber Security
  - Markets and Policy
  - Distributed generation and storage adds complexity

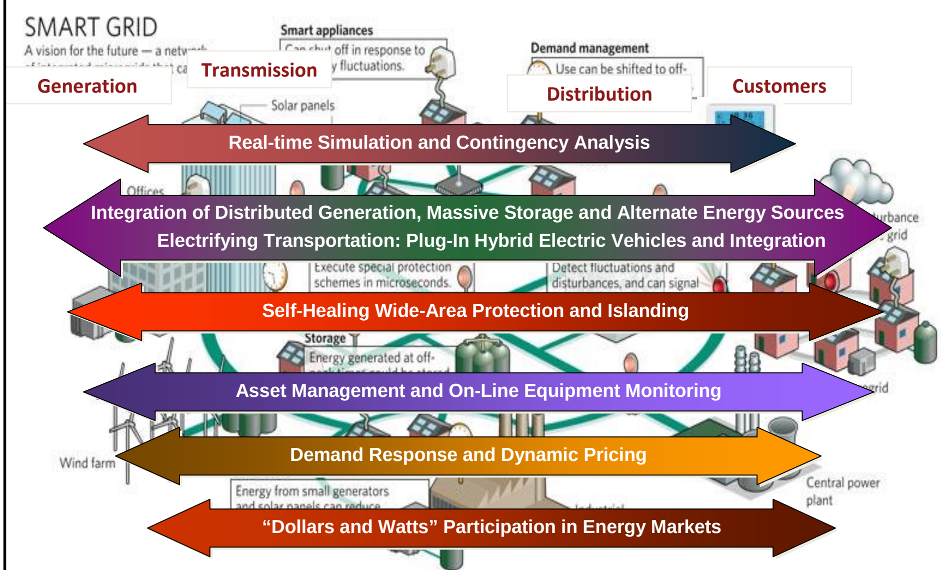
Infrastructure integration of microgrids and diverse generation and storage resources into a system of a smart self-healing grid



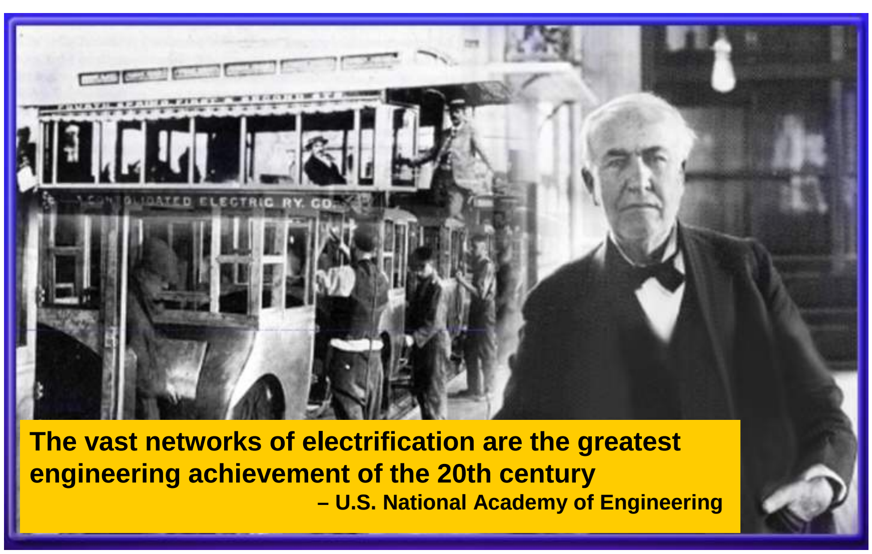
Source: Interview with Massoud Amin, "Upgrading the grid," *Nature,* vol. 454, pp. 570–573, 30 July 2008

Center for the Development of Technological Leadership
University of Minnesota Driven to Discover
Copyright © 2009 No part of this presentation may be reproduced in any form without prior authorization.

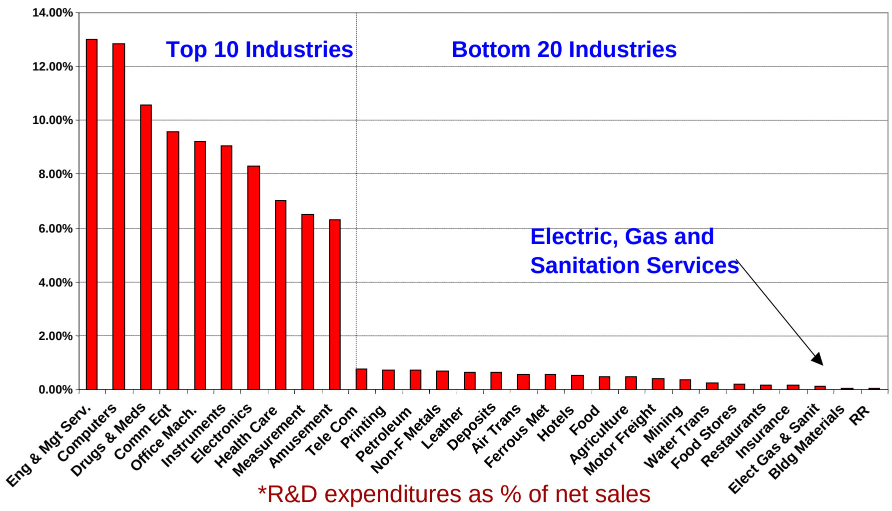
Enabling a Stronger and Smarter Grid



Transforming Society



Context: R&D Expenditures*

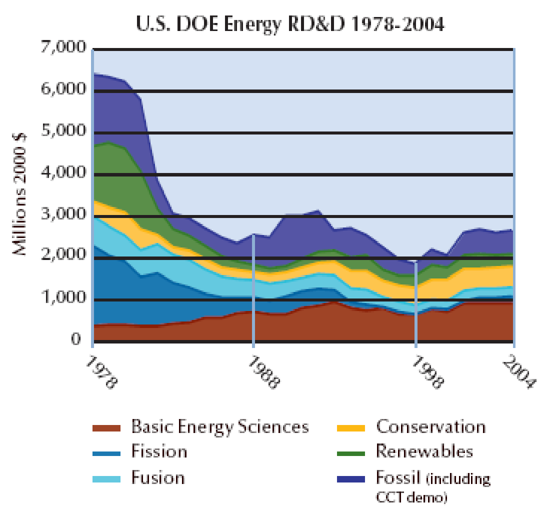


*R&D expenditures as % of net sales

Declining Public Support for Energy RD&D during the 25-years 1978-2004

- Analyses of DOE data shows that over the 25 years from FY 1978 to FY 2004, US government appropriations for ERD&D fell from 6.4B to $2.75B in constant year-2000 dollars, a nearly 60% reduction.

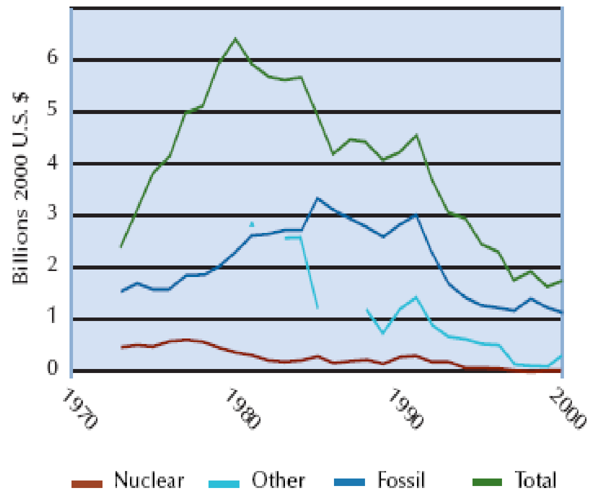
- The part of these appropriations devoted to applied energy-technology RD&D fell from $6.08 B to $1.80B.



Gallagher and Sagar, 2004

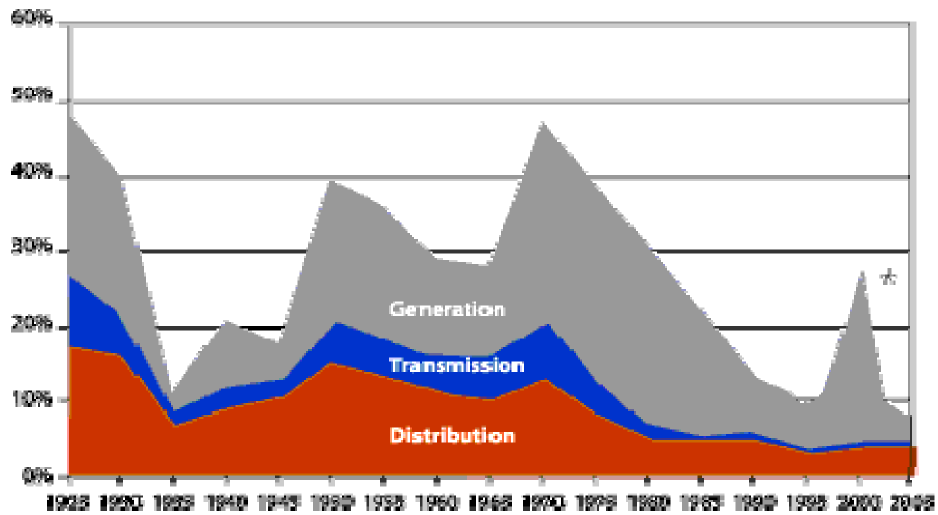
Private Sector Energy RD&D

An analysis of less complete private-sector data indicates a drop by about a factor of three in the private sector funding for the indicated purposes during the same period.



Dooley and Runci, 2004

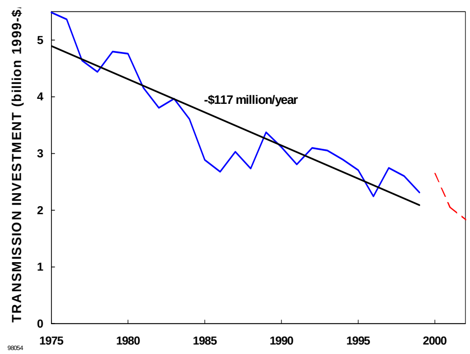
Capital Invested as % of electricity revenue



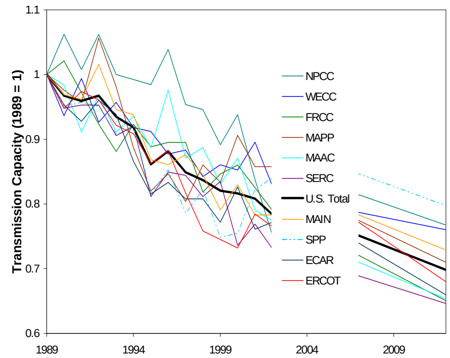
Sources: Electric Utility Industry Statistics, and 2001 Financial Review, Edison Electric Institute

Capital Invested as % of electricity revenues

Increasing Outage Events: Transmission Investment



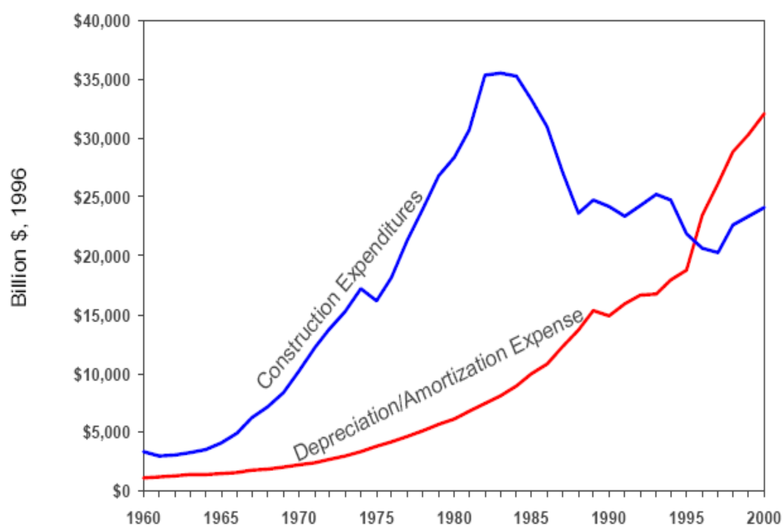
Transmission *investment* ($) since 1975



Transmission *capacity margin* in every NERC region since 1982

Transmission investment lags load growth and will remain very difficult in the future due to environmental, political, and cost issues.

Utility construction expenditures



Source: "Historical Statistics of the Electric Utility Industry" and "EEI Statistical Yearbook" - EEI

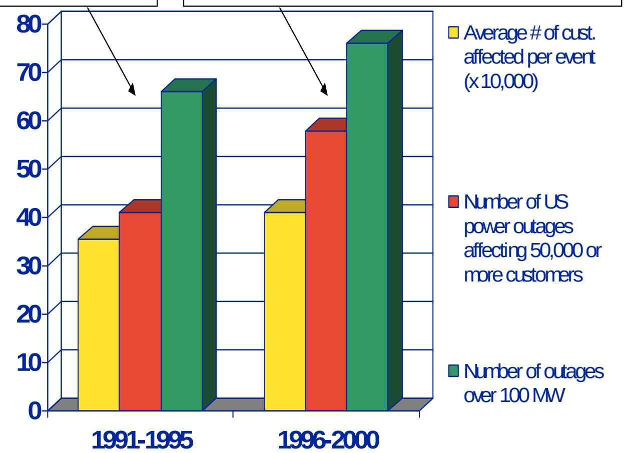
Historical Analysis of U.S. outages (1991-2000)

66 Occurrences over 100 MW
798 Average MW Lost
41 Occurrences over 50,000 Consumers
355,204* Average Consumers Dropped

76 Occurrences over 100 MW
1,067 Average MW Lost
58 Occurrences over 50,000 Consumers
409,854* Average Consumers Dropped

Increasing frequency and size of US power outages 100 MW or more (1991-1995 versus 1996-2000), affecting 50,000 or more consumers per event.

Data courtesy of NERC's Disturbance Analysis Working Group database



*Note: Annual increase in load (about 2%/year) and corresponding increase in consumers should be taken into account.

Historical Analysis of U.S. outages (1991-2005)

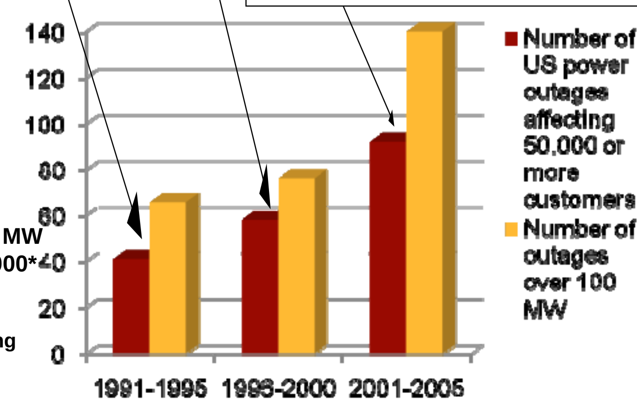
66 Occurrences over 100 MW
41 Occurrences over 50,000* Consumers

76 Occurrences over 100 MW
58 Occurrences over 50,000* Consumers

140 Occurrences over 100 MW
92 Occurrences over 50,000* Consumers

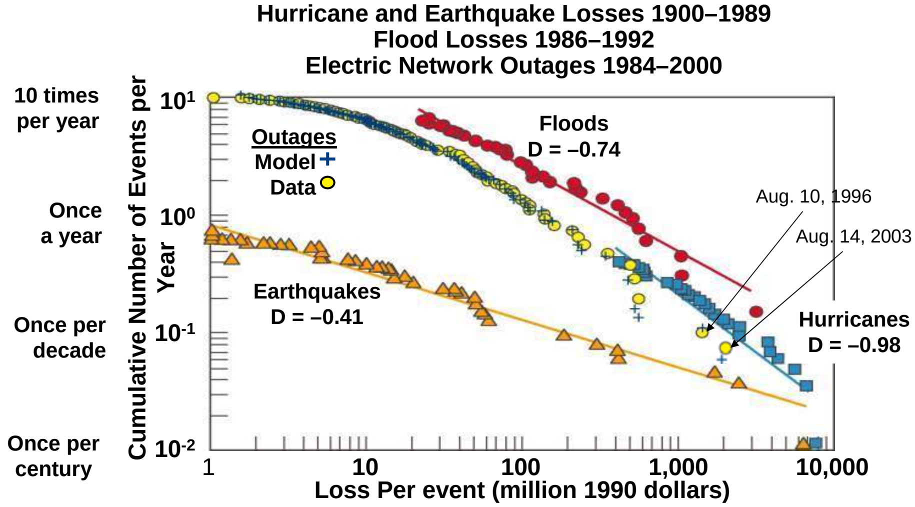
Result: Large blackouts are growing in number and severity.

***Analyzing 2006 outages:**
24 Occurrences over 100 MW
34 Occurrences over 50,000* or more Consumers
Data courtesy of NERC's Disturbance Analysis Working Group database

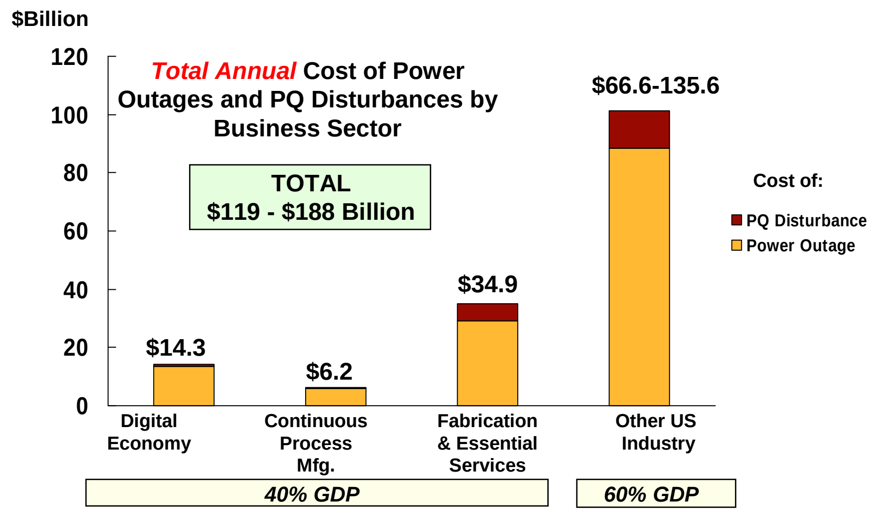


*Note: Annual increase in load (about 2%/year) and corresponding increase in consumers should be taken into account.

Power Law Distributions: Frequency & impacts of major disasters



A Toll Felt Throughout the U.S. Economy: Over $100B per year



Source: Primen Study: The Cost of Power Disturbances to Industrial & Digital Economy Companies

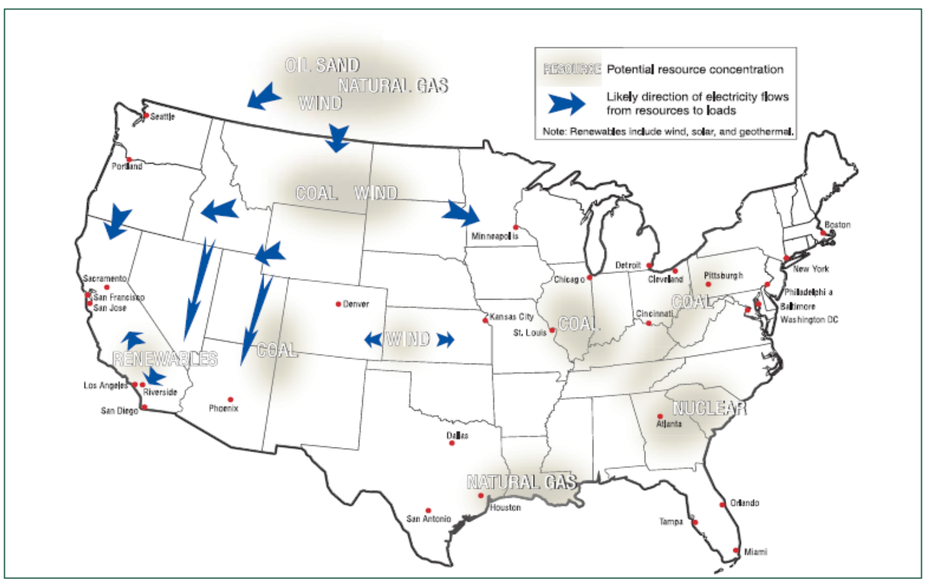
Context: Transmission investment in the United States and in international competitive markets

Country	Investment in High Voltage Transmission (>230 kV) Normalized by Load for 2004–2008 (in US$M/GW/year)	Number of Transmission-Owning Entities
New Zealand	22.0	1
England & Wales (NGT)	16.5	1
Denmark	12.5	2
Spain	12.3	1
The Netherlands	12.0	1
Norway	9.2	1
Poland	8.6	1
Finland	7.2	1
United States	4.6 (based on representative data from EEI)	450 (69 in EEI)

Source: IEEE PES, 2006

Center for the Development of Technological Leadership | University of Minnesota Driven to Discover

Context: New patterns in power delivery



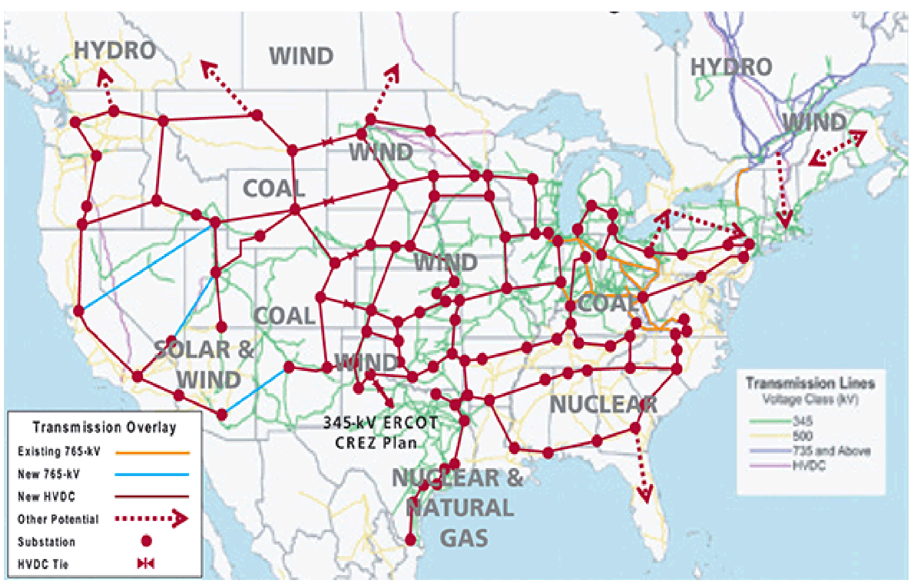
Map adapted from the U.S. DOE National Electric Transmission Congestion Study

Center for the Development of Technological Leadership | University of Minnesota Driven to Discover

Context: New patterns in power delivery

- More efficient to move electrical power through the transmission system than to ship fuels the same distance;
- Transition from fossil fuel-based power generation to fluctuating energy sources such as wind, sun, and wave power introduces challenging demands on the storage, dispatch, operation and integration with the power grid;
- Integration of energy resources and demands will require interconnected transmission network, a **Smart Grid,** that is:
  - **Intelligent:** autonomous digital system identifies surges, outages
    → **Predictive** rather than reactive, to prevent emergencies
  - **Resilient:** "self-healing" and adaptive - instantaneous damage control
  - **Reliable:** dynamic load balancing
  - **Flexible:** accommodates new off-grid alternative energy sources
  - **Interactive** with consumers and markets
  - **Optimized** to make best use of resources and equipment
  - **Integrated**, merging monitoring, control, protection, maintenance, EMS, DMS, marketing, and IT
  - **Secure:** less vulnerable to attacks and destabilizers

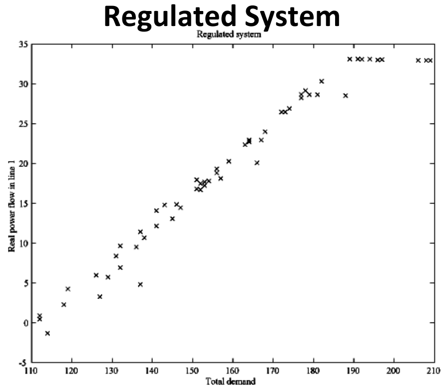
Enabling a Stronger Grid



Map adapted from the U.S. DOE National Electric Transmission Congestion Study

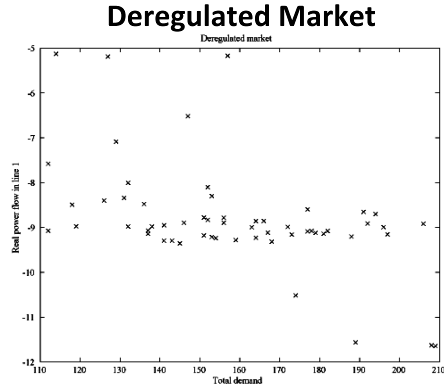
Context: New Challenges

Regulated System



- Economic dispatch
- Strong correlation between power flow and demand

Deregulated Market



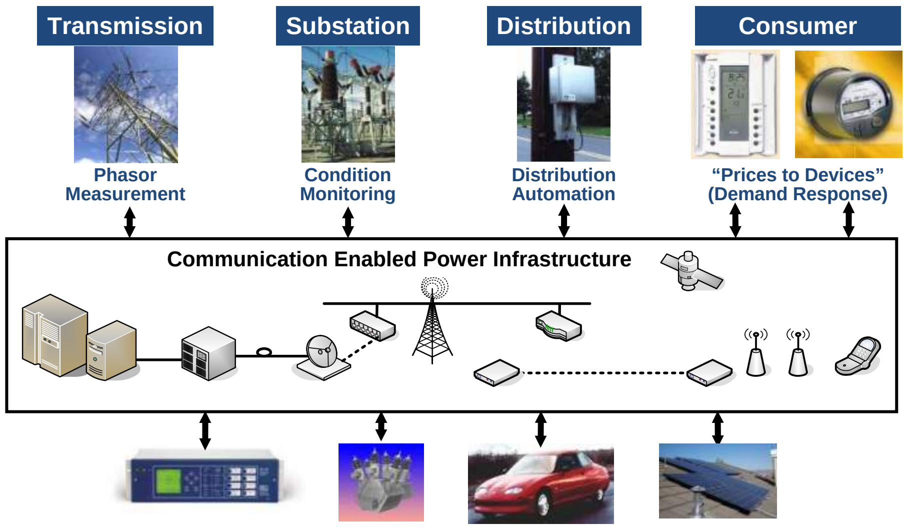
- Market-based dispatch
- Poor correlation between power flow and demand

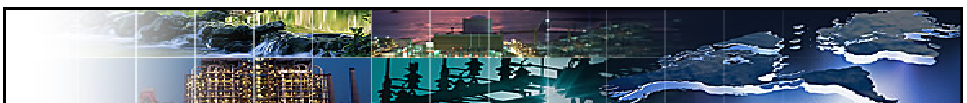
Source: EPRI/DOD Complex Interactive Networks/Systems Initiative (CIN/SI)

Definition: Self Healing Grid

- **What is "self healing"?**
  - A system that uses information, sensing, control and communication technologies to allow it to deal with unforeseen events and minimize their adverse impact …
- **Why is self healing concept important to the Electric Power Grid and Energy Infrastructure?**
  - A secure "architected" sensing, communications, automation (control), and energy overlaid infrastructure as an integrated, reconfigurable, and electronically controlled system that will offer unprecedented flexibility and functionality, and improve system availability, security, quality, resilience and robustness.

Smart Grid – Exchanging Information Seamlessly Across the Enterprise





The Infrastructure Challenge

Will today's electricity supply system be left behind as an industrial relic of the 20th century, or become the critical infrastructure supporting the digital society, a smart self-healing grid?

What are we doing about it?

Overview of my research areas (1998-2003):

Initiatives and Programs I developed and/or led at EPRI

1999-2001	Y2K2000-present	2002-present	2001-present
EPRI/DoD Complex Interactive Networks (CIN/SI)	**Enterprise Information Security (EIS)**	**Infrastructure Security Initiative (ISI)**	**Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)**
Underpinnings of Interdependent Critical National Infrastructures Tools that enable secure, robust & reliable operation of interdependent infrastructures with distributed intelligence & self-healing	1. Information Sharing 2. Intrusion/Tamper Detection 3. Comm. Protocol Security 4. Risk Mgmt. Enhancement 5. High Speed Encryption	**Response to 9/11 Tragedies** 1. Strategic Spare Parts Inventory 2. Vulnerability Assessments 3. Red Teaming 4. Secure Communications	1. Self Healing Grid 2. IntelliGrid™ 3. Integrated Electric Communications System Architecture 4. Fast Simulation and Modeling

Recent Directions: EPRI/DOD Complex Interactive Network/Systems Initiative

"We are sick and tired of them and they had better change!"
Chicago Mayor Richard Daley on the August 1999 Blackout

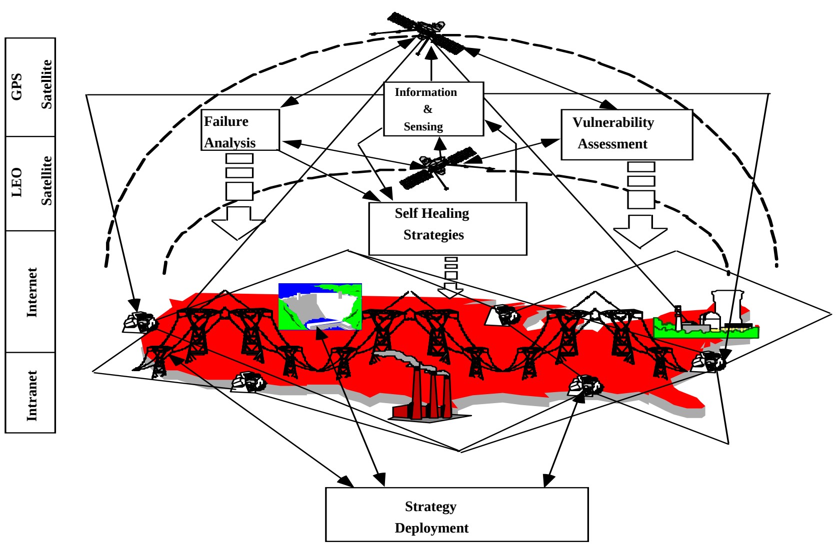
Complex interactive networks:

- *Energy infrastructure*: Electric power grids, water, oil and gas pipelines
- *Telecommunication:* Information, communications and satellite networks; sensor and measurement systems and other continuous information flow systems
- *Transportation and distribution networks*
- *Energy markets, banking and finance*

1999-2001: $5.2M / year — Equally Funded by DoD/EPRI

Develop tools that enable secure, robust and reliable operation of interdependent infrastructures with distributed intelligence and self-healing abilities

Complex Interactive Networks



Center for the Development of Technological Leadership | University of Minnesota Driven to Discover
Copyright © 2009 No part of this presentation may be reproduced in any form without prior authorization.

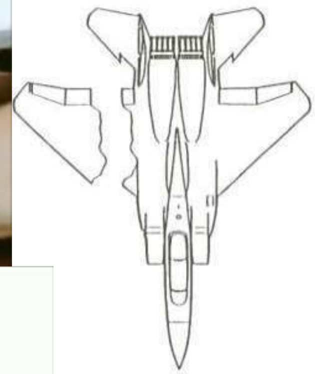
CIN/SI Funded Consortia

108 professors and over 240 graduate students in 28 U.S. universities were funded: Over 420 publications, and 24 technologies extracted, in the 3-year initiative

- U Washington, Arizona St., Iowa St., VPI — Defense Against Catastrophic Failures, Vulnerability Assessment
- Purdue, U Tennessee, Fisk U, TVA, ComEd/Exelon — Intelligent Management of the Power Grid
- Harvard, UMass, Boston, MIT, Washington U. — Modeling and Diagnosis Methods
- Cornell, UC-Berkeley, GWU, Illinois, Washington St., Wisconsin — Minimizing Failures While Maintaining Efficiency / Stochastic Analysis of Network Performance
- CMU, RPI, UTAM, Minnesota, Illinois — Context Dependent Network Agents
- Cal Tech, MIT, Illinois, UC-SB, UCLA, Stanford — Mathematical Foundations: Efficiency & Robustness of Distributed Systems

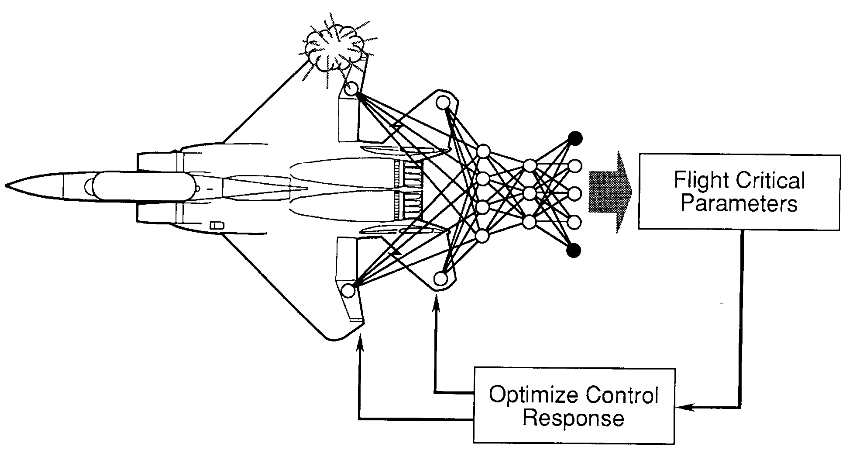
Background: The Self Healing Grid

Saving systems from collapse: The Case of the Missing Wing (1983-1997)



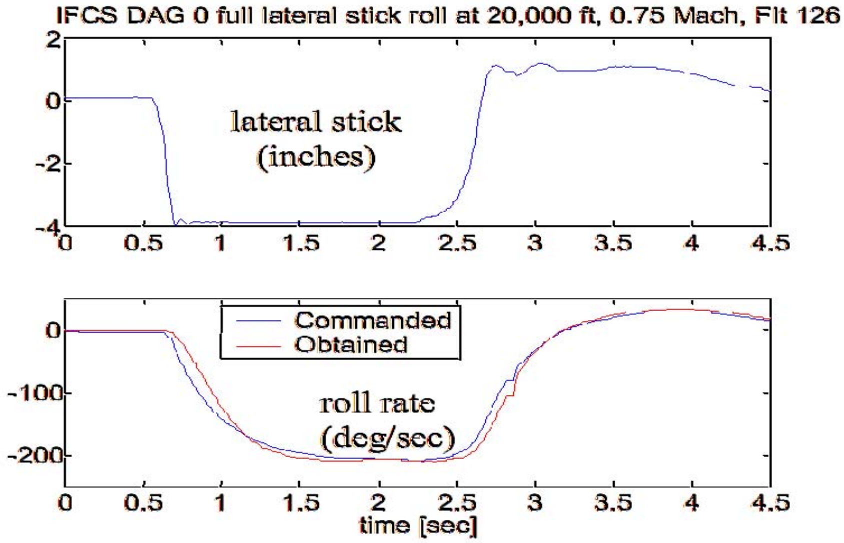
NASA/MDA/WU IFCS: NASA Ames Research Center, NASA Dryden, Boeing Phantom Works, and Washington University in St. Louis.

Goal: Optimize controls to compensate for damage or failure conditions of the aircraft



NASA/MDA/WU IFCS

Intelligent Flight Control System: Example – complete hydraulic failure (1997)



Accomplishments in the IFCS program

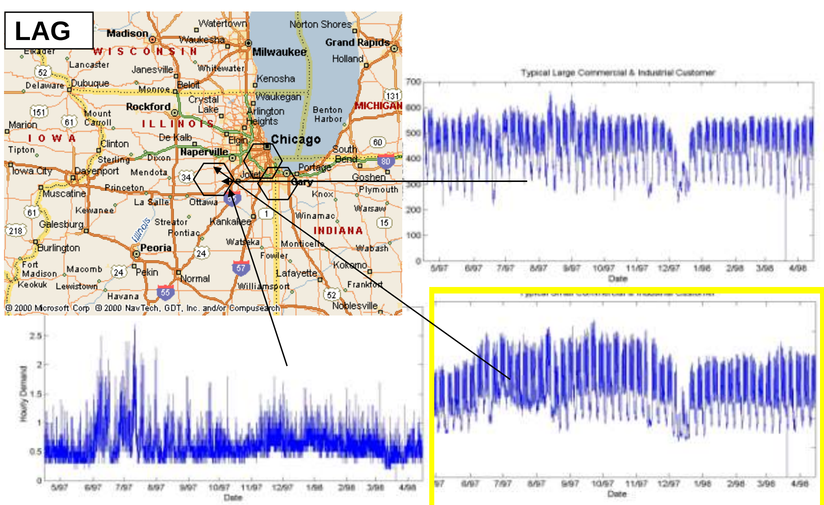
- The system was successfully test flown on a test F-15 at the NASA Dryden Flight Research Center:
  - Fifteen test flights were accomplished, including flight path control in a test flight envelope with supersonic flight conditions.
  - Maneuvers included 4g turns, split S, tracking, formation flight, and maximum afterburner acceleration to supersonic flight.
- Stochastic Optimal Feedforward and Feedback Technique (SOFFT) continuously optimizes controls to compensate for damage or failure conditions of the aircraft.
- Flight controller uses an on-line solution of the Riccati equation containing the neural network stability derivative data to continuously optimize feedback gains.
- Development team: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University.

Self-healing Grid (1998-present)

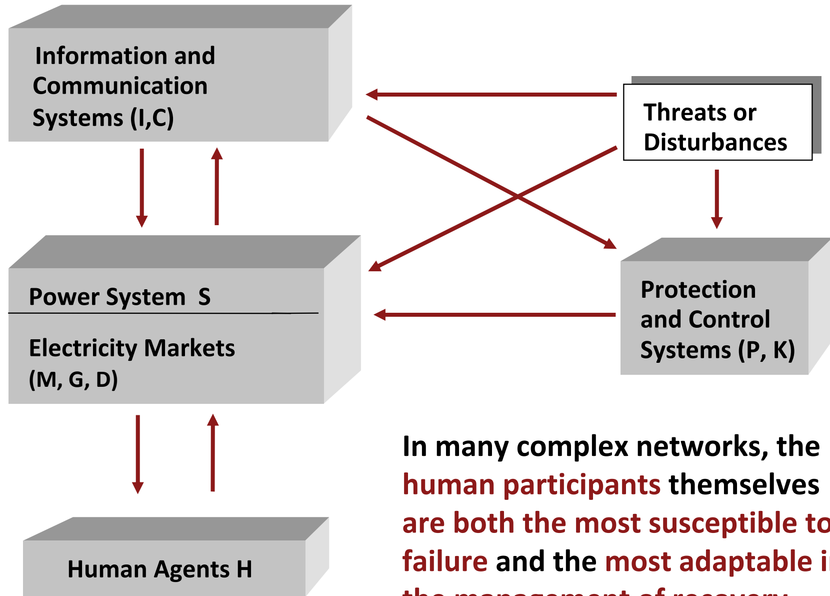
Building on the Foundation:

- Anticipation of disruptive events
- Look-ahead simulation capability
- Fast isolation and sectionalization
- Adaptive islanding
- Self-healing and restoration

Local area grids (LAG)



Integrated Sensing, Protection and Control



In many complex networks, the human participants themselves are both the most susceptible to failure and the most adaptable in the management of recovery.

"… not to sell light bulbs, but to create a network of technologies and services that provide illumination…"

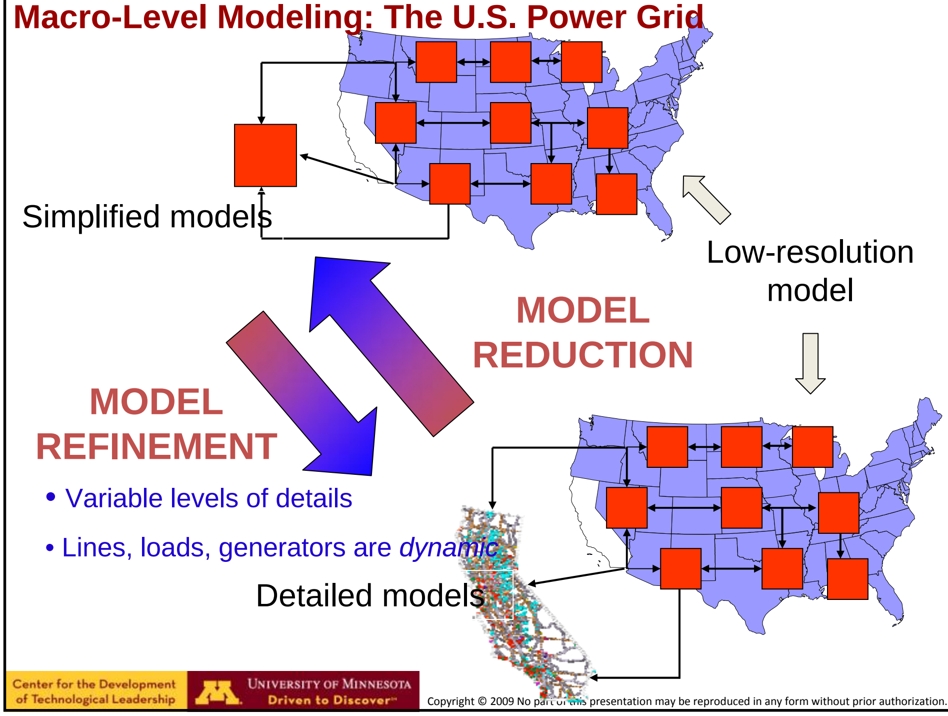
The Energy Web:

"The best minds in electricity R&D have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming - and interconnected with everything else."

-- Wired Magazine, July 2001

http://www.wired.com/wired/archive/9.07/juice.html

Macro-Level Modeling: The U.S. Power Grid

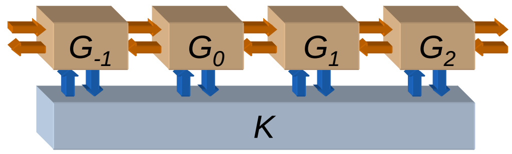


Look-Ahead Simulation Applied to Multi-Resolution Models

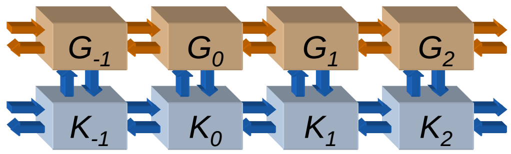
- Provides faster-than-real-time simulation
  - By drawing on approximate rules for system behavior, such as power law distribution
  - By using simplified models of a particular system
- Allows system operators to change the resolution of modeling at will
  - Macro-level (regional power systems)
  - Meso-level (individual utility)
  - Micro-level (distribution feeders/substations)

Sensing and Control Strategies

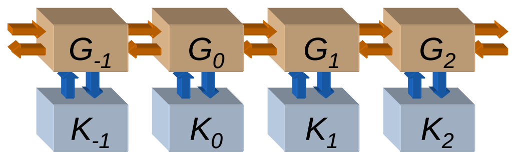
- Centralized



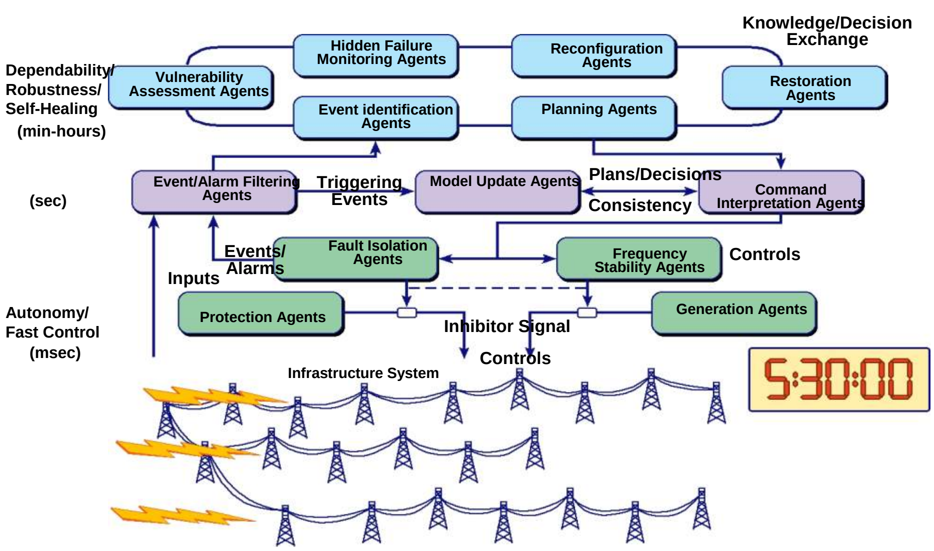
- Distributed



- Perfectly decentralized

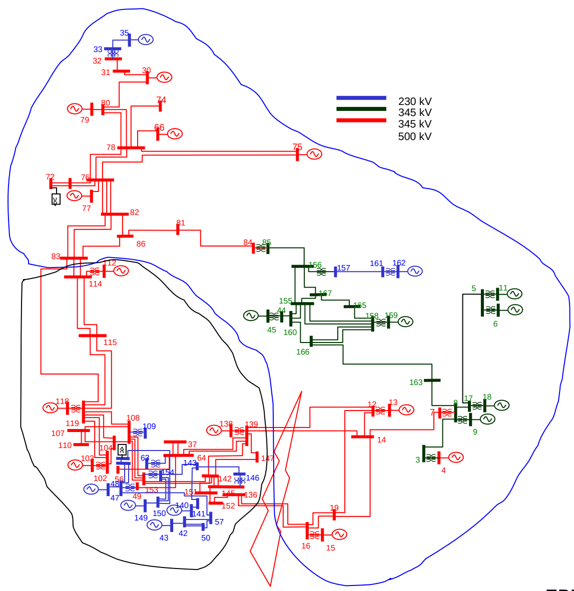


The Self-Healing Grid



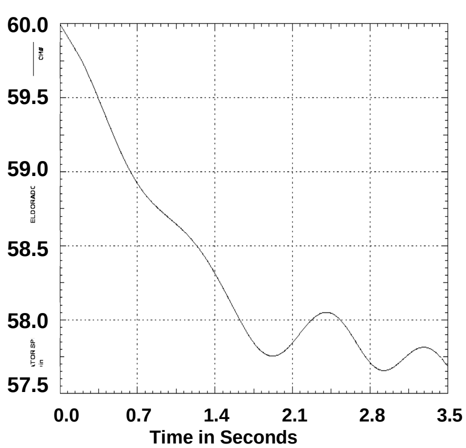
EPRI/DoD CIN/SI Initiative

The Self-Healing Grid

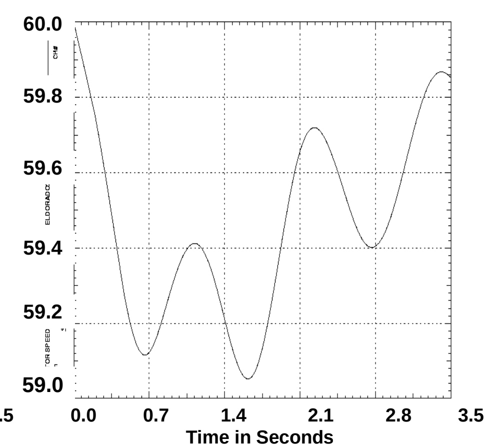


EPRI/DoD CIN/S Initiative

Adaptive Islanding

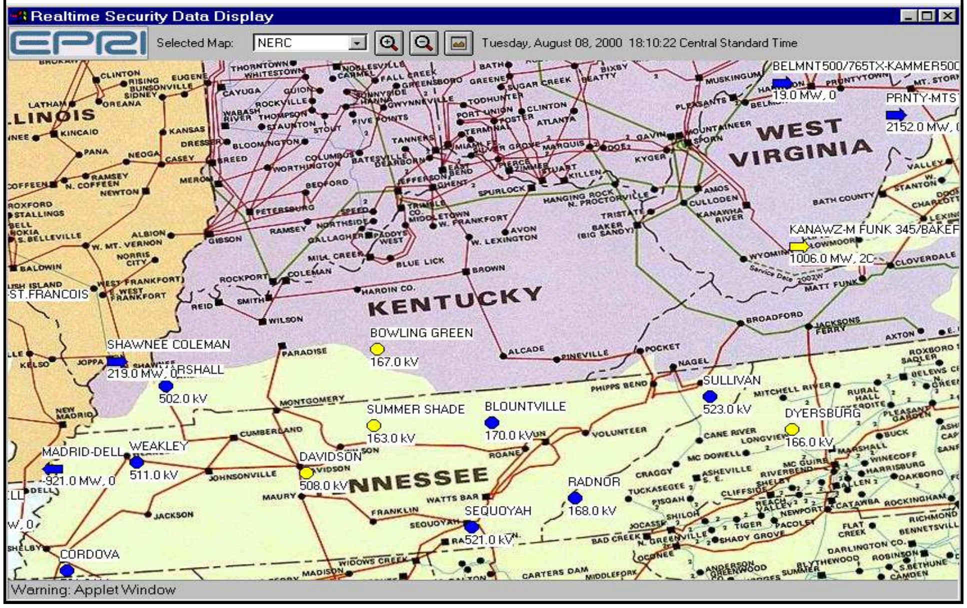


Past Scheme

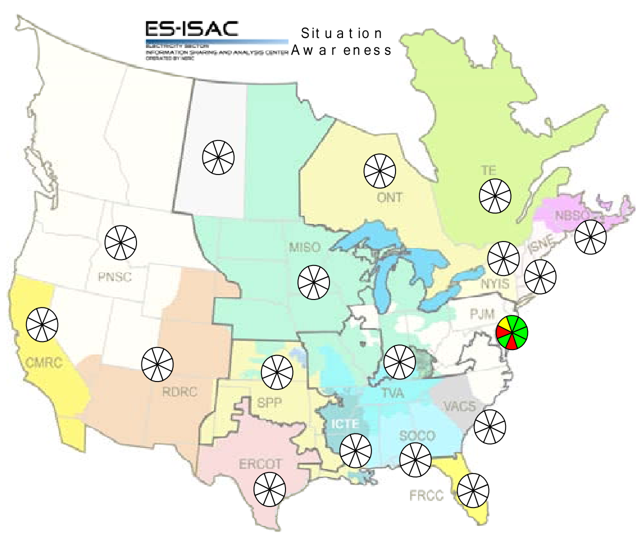


New Scheme

EPRI's Reliability Initiative-- Sample Screen of Real-time Security Data Display (RSDD)

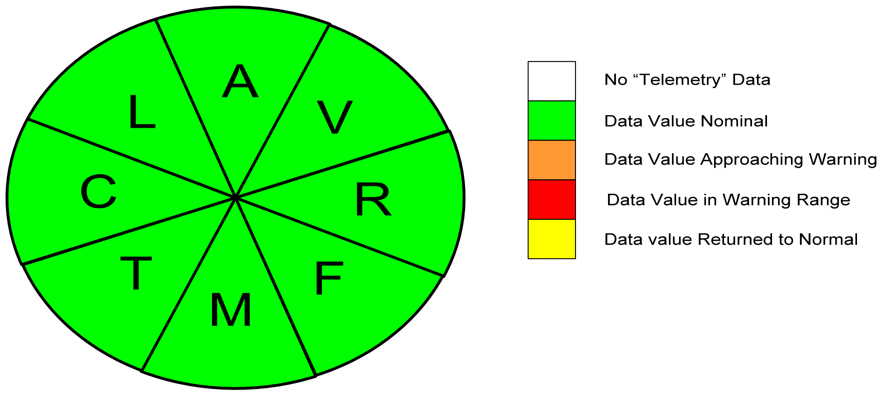


Situation Awareness Tool (SAT)



Source: NERC

Situation Awareness Tool (SAT)



A – ACE
L – Deviation from Forecasted Load
C – Reserve Real-power Capacity
V – Voltage Deviation from Normal
R – Reserve Reactive-power Capacity
M – Text Message
T – Transmission Constraint
F – Frequency

Source: NERC

Prioritization: Security Index

General

1. Corporate culture (adherence to procedures, visible promotion of better security, management security knowledge)
2. Security program (up-to-date, complete, managed, and includes vulnerability and risk assessments)
3. Employees (compliance with policies and procedures, background checks, training)
4. Emergency and threat-response capability (organized, trained, manned, drilled)

Physical

1. Requirements for facilities (critical list, inventory, intrusion detections, deficiency list)
2. Requirements for equipment (critical list, inventory, deficiency list)
3. Requirements for lines of communications (critical list, inventory, deficiency list)
4. Protection of sensitive information

Cyber and IT

1. Protection of wired networks (architecture analysis, intrusion detection)
2. Protection of wireless networks (architecture analysis, intrusion detection, penetration testing)
3. Firewall assessments
4. Process control system security assessments (SCADA, EMS, DCS)

Context: IT interdependencies and impact

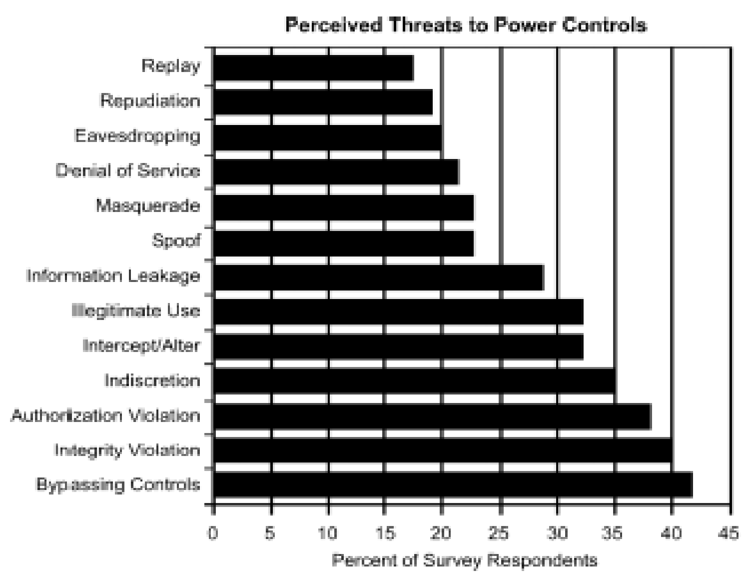
Dependence on IT: Today's systems require a tightly knit information and communications capability. Because of the vulnerability of Internet communications, protecting the system will require new technology to enhance security of power system command, control, and communications.

Increasing Complexity: System integration, increased complexity: call for new approaches to simplify the operation of complex infrastructure and make them more robust to attacks and interruptions.

Centralization and Decentralization of Control: The vulnerabilities of centralized control seem to demand smaller, local system configurations. Resilience rely upon the ability to bridge top--down and bottom-up decision making in real time.

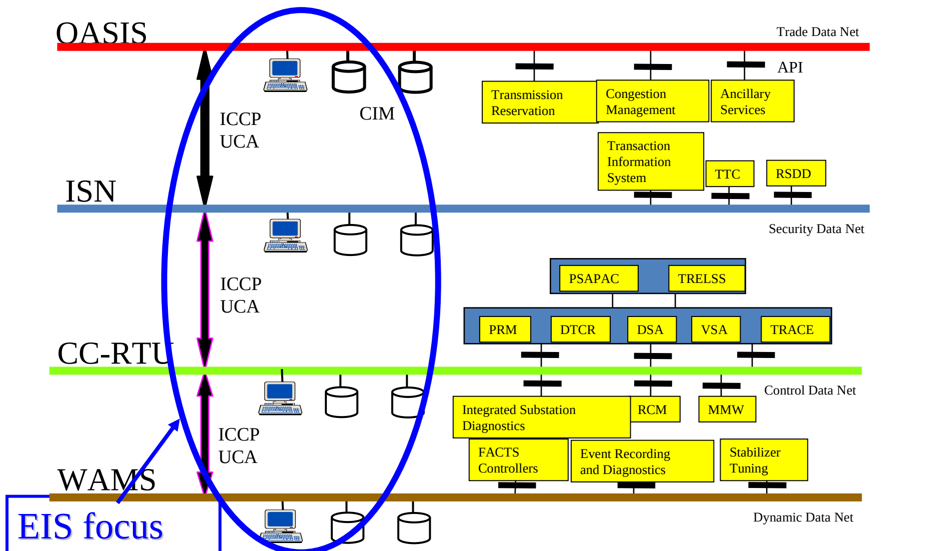
Assessing the Most Effective Security Investments: Probabilistic and dynamic assessments can offer strategic guidance on where and how to deploy security resources to greatest advantage.

Cyber Threats to Controls

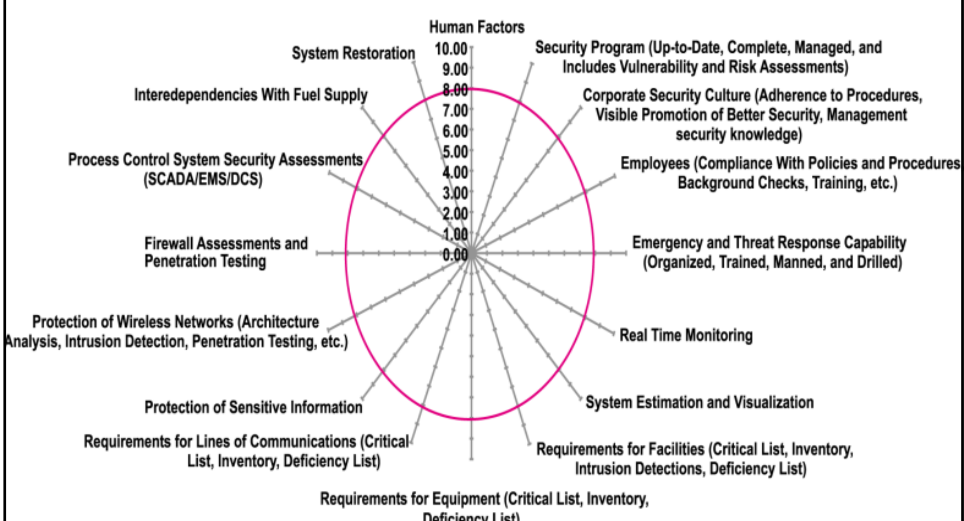


Source: *EPRI, Communication Security Assessment for the United States Electric Utility Infrastructure*, EPRI, Palo Alto, CA: 2000. 1001174.

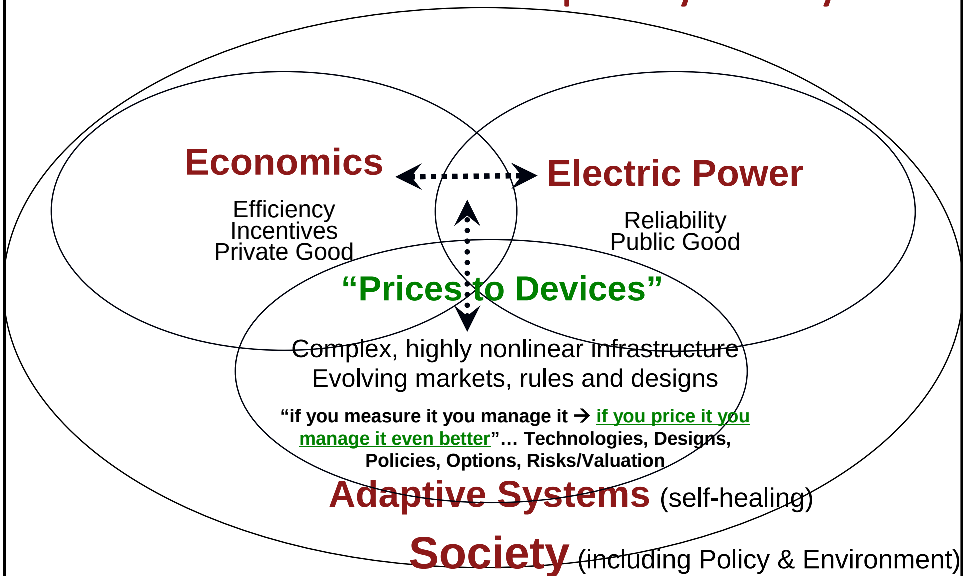
Information Networks for On-Line Trade, Security and Control



Assessment & Prioritization: A Composite Spider Diagram to Display Security Indices



Energy Infrastructure, Economics, Efficiency, Environment, Secure Communications and Adaptive Dynamic Systems



EPRI/DOD Complex Interactive Networks Initiative

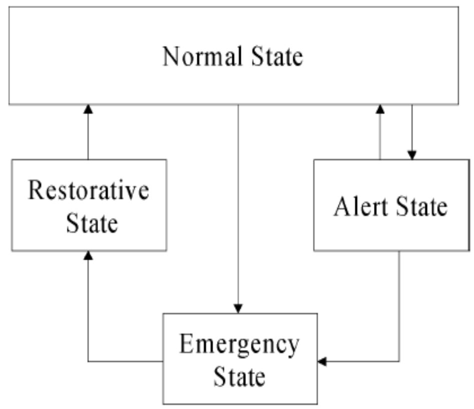
- Overall results (theoretical and applied) for increased dynamic network reliability and efficiency:
  - ❖ Identification, characterization and quantification of **failure mechanisms**
  - ❖ *In Silico* testing of devices and policies in the context of the whole system-- the grid, markets, communication and protection
  - ❖ Fundamental understanding of interdependencies, **coupling and cascading**
  - ❖ Development of **predictive** models
  - ❖ Development of prescriptive procedures and **control strategies** for mitigation or/and elimination of failures
  - ❖ Design of **self-healing and adaptive** architectures
  - ❖ Trade-off between **robustness and efficiency**
- Extracted the most promising technologies for testing with real data and further development.
- However many challenges and opportunities persist →

Understanding Complex Dynamical Systems

… Systems' operations, mathematical foundations, and guidance on how to measure and adapt to disturbances:

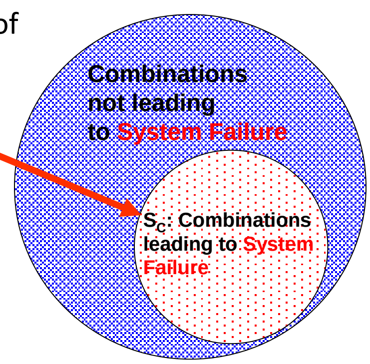
System is characterized as having multiple states, or "modes," during which specific operational and control actions/reactions are taking place:

- ***Normal mode:*** economic dispatch, load frequency control, maintenance, forecasting, etc.;
- ***Alert mode:*** red flags, precursor detection, reconfiguration and response;
- ***Emergency/Disturbance mode:*** stability, viability, and integrity -- instability, load shedding, etc.;
- ***Restorative mode:*** rescheduling, resynchronization, load restoration, etc.



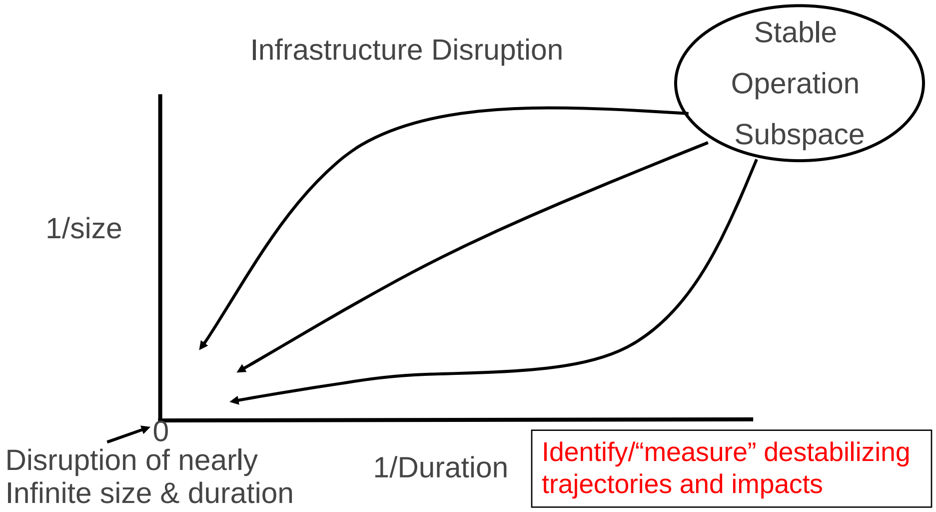
Another Persisting Challenge

- Enhancing Reliability and Security of Network Operation via quantification of the system state and its "direction/ speed/momentum" toward a major failure
- Making Network Availability (quick restoration) a key requirement
- Introducing Quality of Service as an additional constraint
- Ultimately, enabling operators to act more efficiently and with greater confidence in difficult (sometimes unclear, unexpected or even conflicting) circumstances



Which trajectories lead to catastrophic failures?

An Assessment Methodology

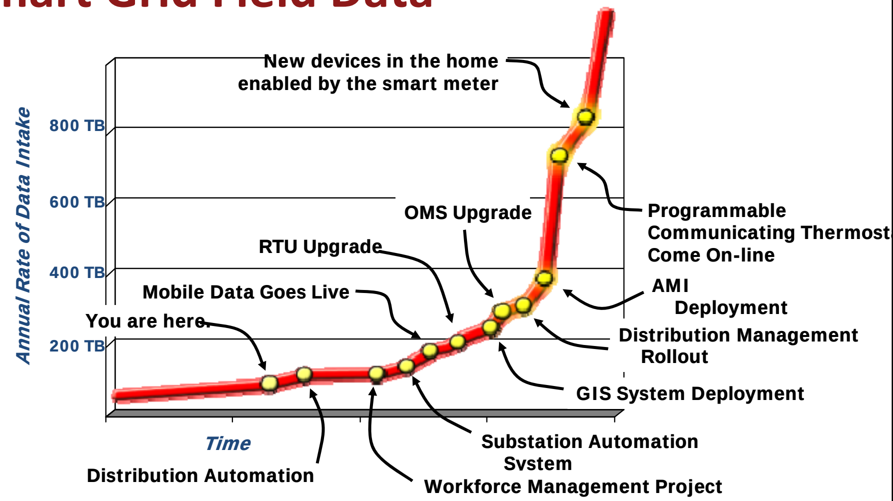


Identify/"measure" destabilizing trajectories and impacts

Foresight

Renewables/infrastructure integration,
Electrification of transportation

Smart Grid Field Data

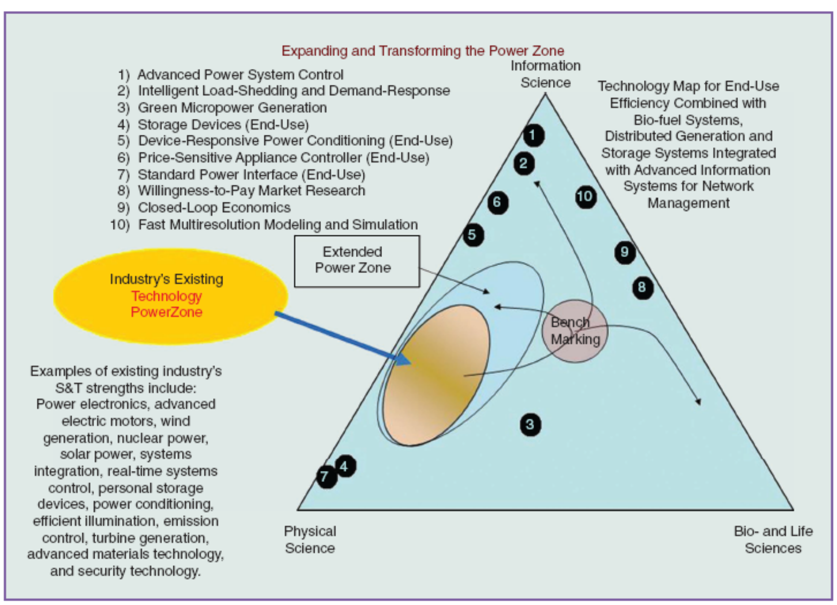


Tremendous amount of data coming from the field in the near future - paradigm shift for how utilities operate and maintain the grid

Source: EPRI

One of my research areas: S&T Assessment, Scan & Map

(April 2005-Feb 2006; Galvin Electricity Initiative)



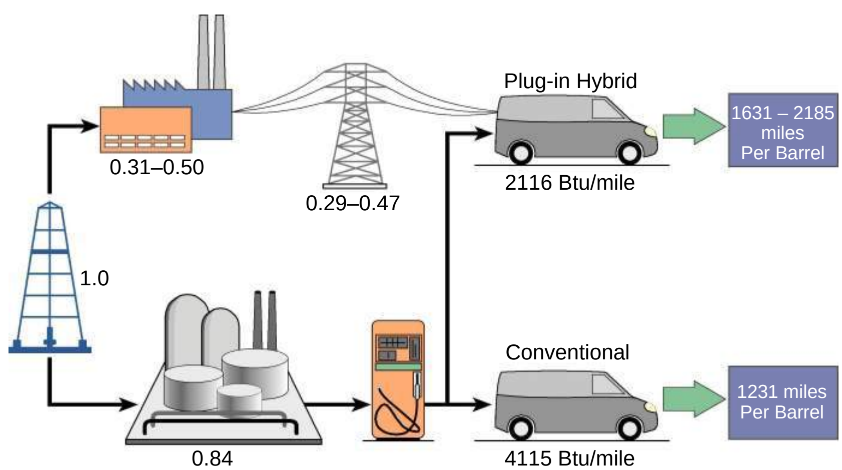
- “***Wind power could blow electric grid:*** Utilities and developers are poised to more than quadruple the amount of wind power in the Northwest, but a study shows the electric grid might not be able to handle it all, *The Oregonian* reported. The federal Bonneville Power Administration said in its assessment it has space on the grid to add only one-third of the planned 4,716 megawatts without additional power lines, the newspaper reported. A total of 6,000 megawatts of wind would supply about 8% of the Northwest's electricity needs, according to the BPA report. "A resource isn't very valuable unless you can deliver it," Elliot Mainzer, a transmission manager with the power agency, told *The Oregonian*. Bringing lines from the current grid to new wind farms costs up to $3 million a mile…”

CNNMoney.com
A Service of CNN, Fortune & Money

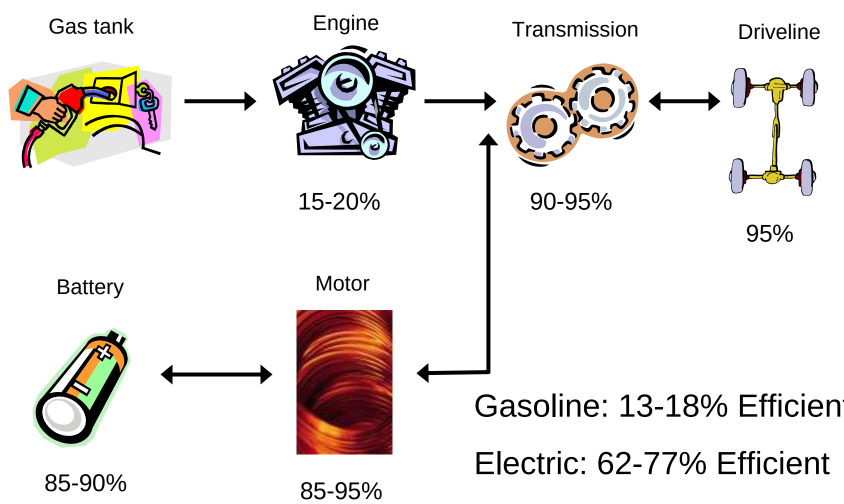
(July 22, 2008)

- ***“GM, utilities team up on electric cars:*** Partnership aims to tackle issues that will crop up when electric vehicles are rolled out… General Motors Corp. has joined with more than 30 utility companies across the U.S. to help work out electricity issues that will crop up when it rolls out new electric vehicles in a little more than two years.”

Full Fuel Cycle Efficiency Comparison



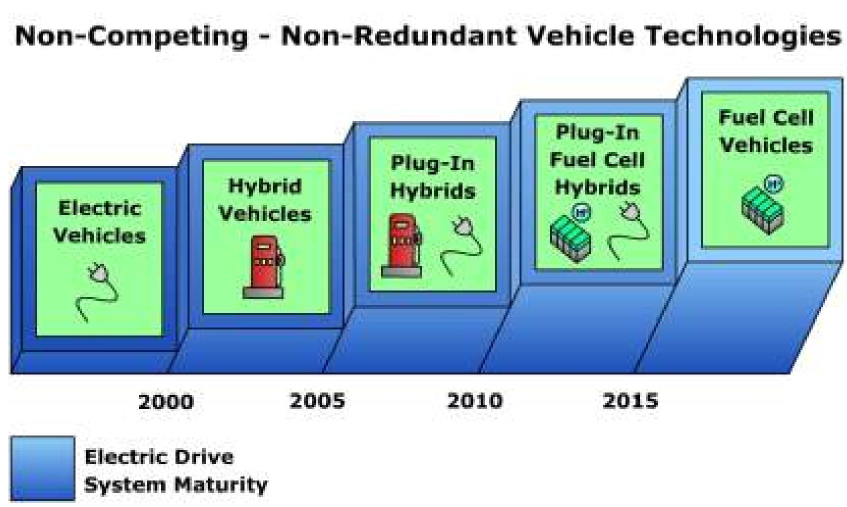
Hybrid Vehicle Efficiency



Gasoline: 13-18% Efficient

Electric: 62-77% Efficient

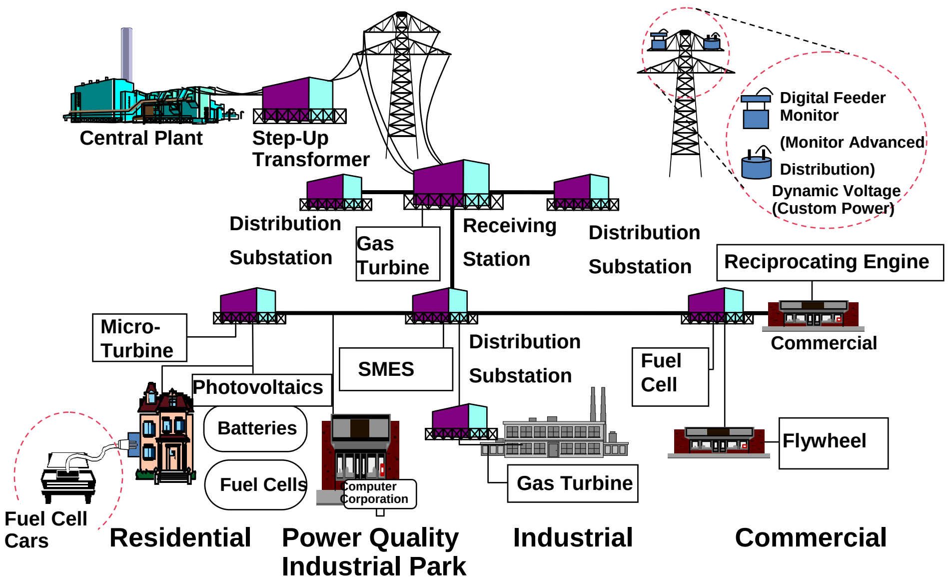
Market Transformation of Electric Drive Vehicles



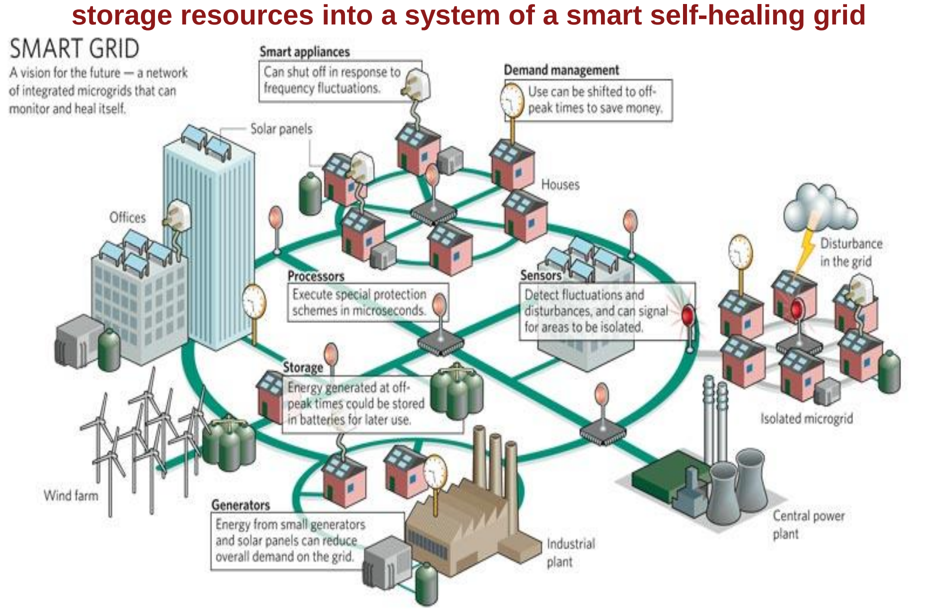
Source: EPRI

Center for the Development of Technological Leadership
University of Minnesota Driven to Discover℠
Copyright © 2009 No part of this presentation may be reproduced in any form without prior authorization.

Our Goal…Enabling the Future

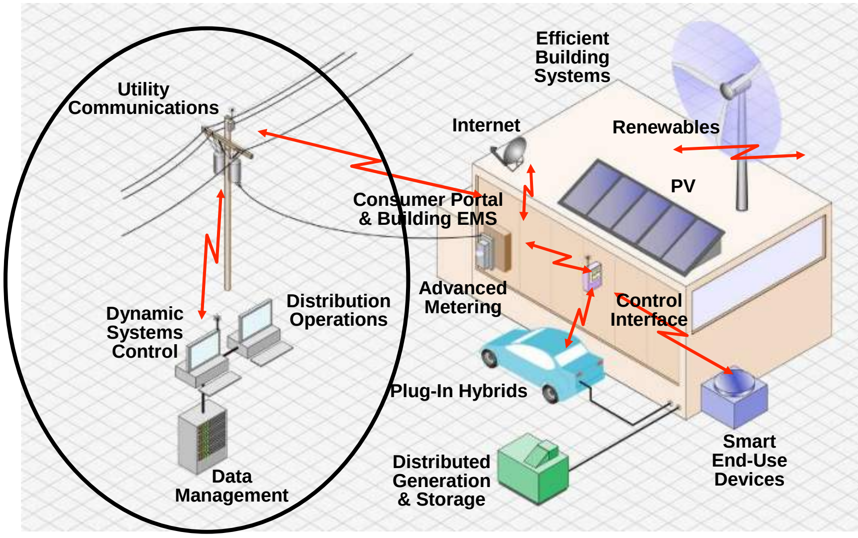


Infrastructure integration of microgrids and diverse generation and storage resources into a system of a smart self-healing grid



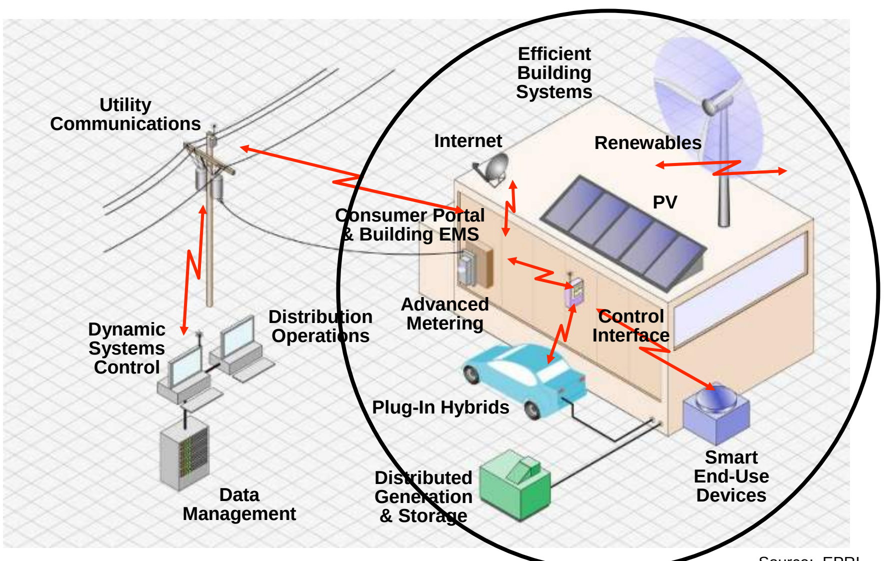
Source: Interview with Massoud Amin, "Upgrading the grid," *Nature,* vol. 454, pp. 570–573, 30 July 2008

Smart Grids and Local Energy Networks



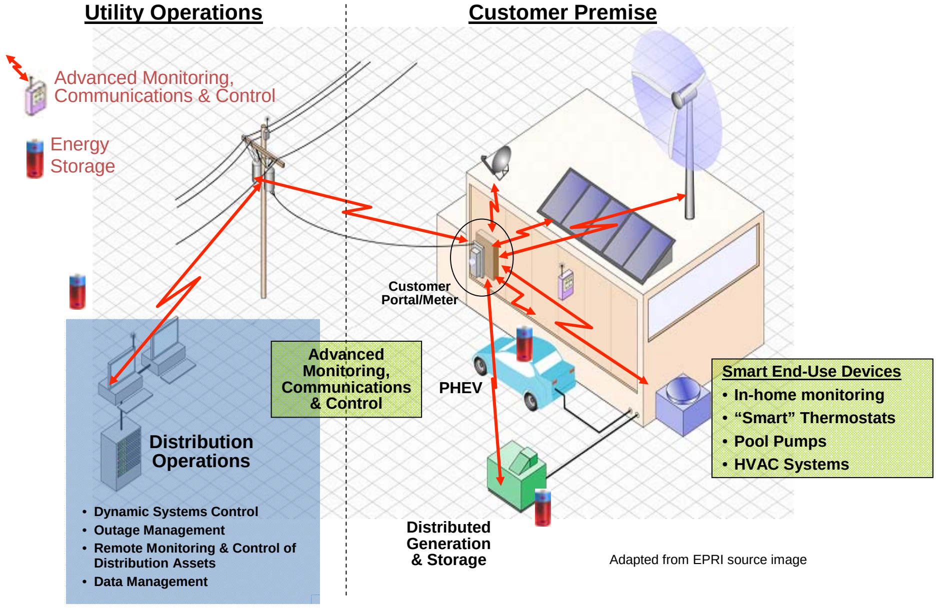
Source: EPRI

Smart Grids and Local Energy Networks

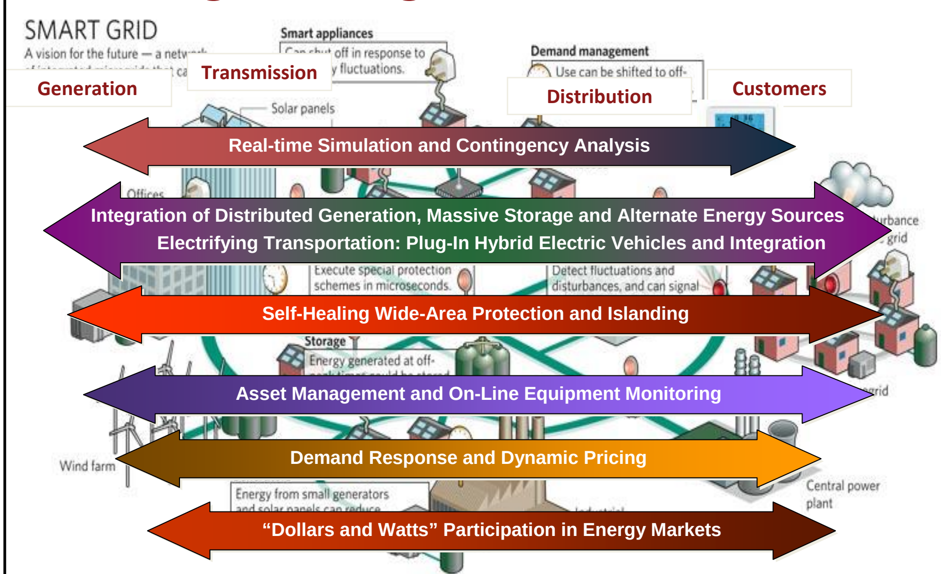


Source: EPRI

Distribution Operations of the Future



Enabling a Stronger and Smarter Grid



Enabling a Stronger and Smarter Grid

- **Smart Grid Challenges/Opportunities:**
  - Infrastructure for Generation/Transmission/Distribution Systems
  - Infrastructure for Smart Customer Interface
  - Distribution Automation
  - Smart metering improves load models and profiles
  - Device monitoring and self-healing diagnostics
  - Communication infrastructure provides opportunities for monitoring and diagnostics
  - Distributed Sensing and Control
  - Alternative Smart Grid Architectures
  - Infrastructure Security: Controls, Communications and Cyber Security
  - Markets and Policy
  - Distributed generation and storage adds complexity

Center for the Development of Technological Leadership

University of Minnesota Driven to Discover

Bottom Line:

"Only three things happen naturally in organizations:
friction, confusion and underperformance.
Everything else requires leadership."

-- Peter Drucker

Enabling a Stronger and Smarter Grid:

- Broad range of R&D including end-use and system efficiency, electrification of transportation, stronger and smarter grid with massive storage
- Sensing, Communications, Controls, Security, Energy Efficiency and Demand Response *if architected correctly* could assist the development of a smart grid
- Smart Grid Challenge/Opportunity areas include:
  - Distributed Control
  - Grid Architectures
  - Cyber Security

Selected References

Downloadable at: http://umn.edu/~amin

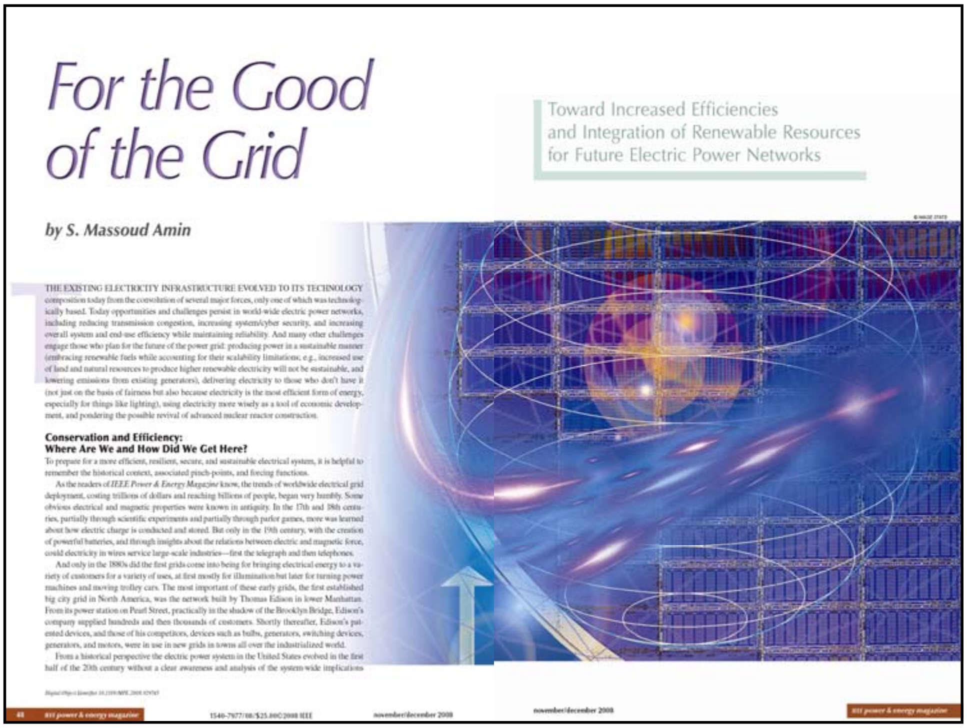
"For the Good of the Grid: Toward Increased Efficiencies and Integration of Renewable Resources for Future Electric Power Networks," IEEE Power & Energy, Vol. 6, Number 6, pp. 48-59, Nov/Dec 2008

"The Electric Power Grid: Today and Tomorrow," MRS Bull., Vol. 33, No. 4, pp. 399-407, April 2008

"Preventing Blackouts," Scientific American, pp. 60-67, May 2007

"Powering the 21st Century: We can -and must- modernize the grid," IEEE Power and Energy Magazine, pp. 93-95, March/April 2005

"North American Electricity Infrastructure: Are We Ready for More Perfect Storms? ," IEEE Security and Privacy, Vol. 1, no. 5, pp. 19-25, Sept./Oct. 2003



For the Good of the Grid

Toward Increased Efficiencies and Integration of Renewable Resources for Future Electric Power Networks

by S. Massoud Amin

THE EXISTING ELECTRICITY INFRASTRUCTURE EVOLVED TO ITS TECHNOLOGY composition today from the convolution of several major forces, only one of which was technologically based. Today opportunities and challenges persist in world-wide electric power networks, including reducing transmission congestion, increasing system/cyber security, and increasing overall system and end-use efficiency while maintaining reliability. And many other challenges engage those who plan for the future of the power grid: producing power in a sustainable manner (embracing renewable fuels while accounting for their scalability limitations; e.g., increased use of land and natural resources to produce higher renewable electricity will not be sustainable, and lowering emissions from existing generators), delivering electricity to those who don't have it (not just on the basis of fairness but also because electricity is the most efficient form of energy, especially for things like lighting), using electricity more wisely as a tool of economic development, and pondering the possible revival of advanced nuclear reactor construction.

Conservation and Efficiency: Where Are We and How Did We Get Here?

To prepare for a more efficient, resilient, secure, and sustainable electrical system, it is helpful to remember the historical context, associated pinch-points, and forcing functions.

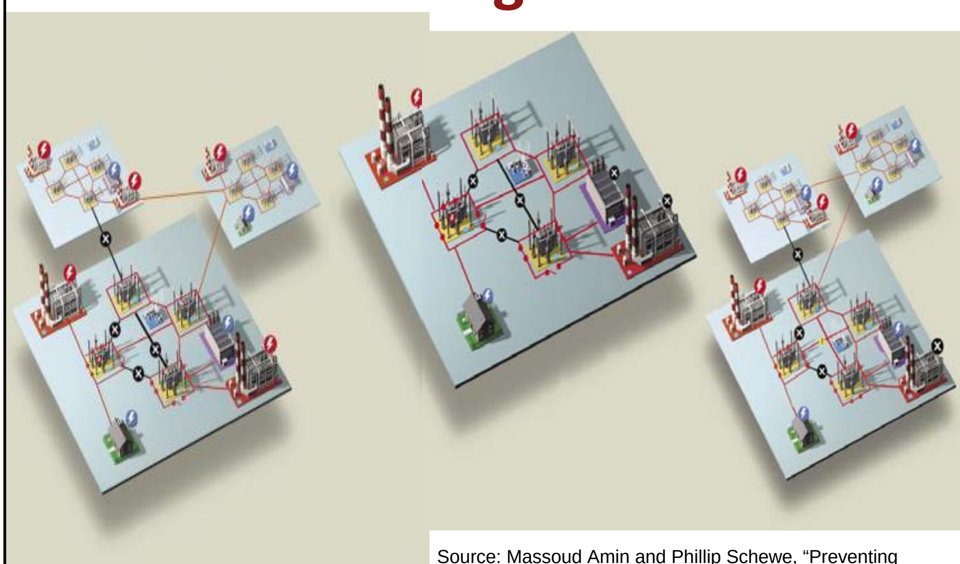
As the readers of *IEEE Power & Energy Magazine* know, the trends of worldwide electrical grid deployment, costing trillions of dollars and reaching billions of people, began very humbly. Some obvious electrical and magnetic properties were known in antiquity. In the 17th and 18th centuries, partially through scientific experiments and partially through parlor games, more was learned about how electric charge is conducted and stored. But only in the 19th century, with the creation of powerful batteries, and through insights about the relations between electric and magnetic force, could electricity in wires service large-scale industries—first the telegraph and then telephones.

And only in the 1880s did the first grids come into being for bringing electrical energy to a variety of customers for a variety of uses, at first mostly for illumination but later for turning power machines and moving trolley cars. The most important of these early grids, the first established big city grid in North America, was the network built by Thomas Edison in lower Manhattan. From its power station on Pearl Street, practically in the shadow of the Brooklyn Bridge, Edison's company supplied hundreds and then thousands of customers. Shortly thereafter, Edison's patented devices, and those of his competitors, devices such as bulbs, generators, switching devices, generators, and motors, were in use in new grids in towns all over the industrialized world.

From a historical perspective the electric power system in the United States evolved in the first half of the 20th century without a clear awareness and analysis of the system-wide implications

48 ieee power & energy magazine 1540-7977/08/$25.00©2008 IEEE november/december 2008 november/december 2008 ieee power & energy magazine

Smart Self-Healing Grid



Source: Massoud Amin and Phillip Schewe, "Preventing Blackouts," Scientific American, May 2007

Bigger picture: challenges…

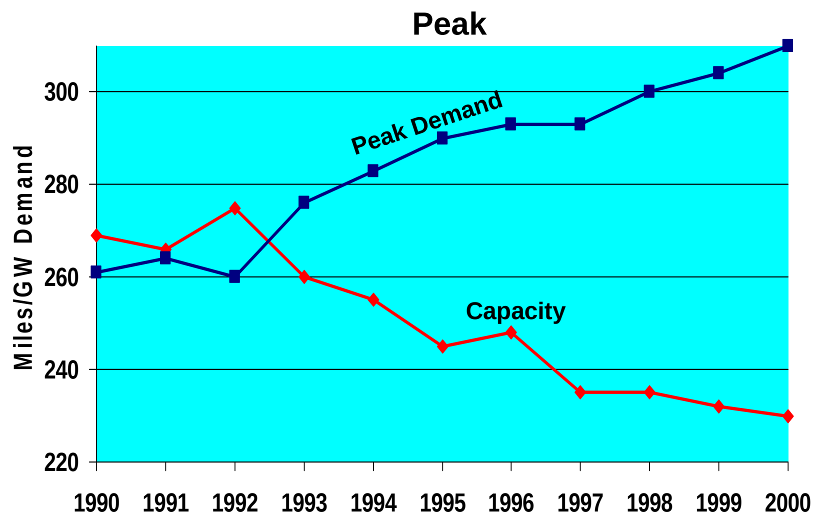
- Development of advanced Computers, Communications, & Control networks overlay the power network,
- Knowing what is happening- Satellite-based WAMS
- Understanding what constitutes a problem- Dynamic Stability Analysis, visualization tools
- Understanding the “true” dynamics soon enough to do something about it- Faster analysis, look-ahead simulation,...
- Determining what actions could solve the problem- Contingency plans, and risk management
- Implementing the solution- Control devices/systems; alternate path options

… require basic research to develop fundamental solutions…

- Intelligent sensors as elements in real-time data base; sensor interface to multi-resolutional models? Metrics?
- Increased dependence on information systems (e.g., software as the glue among various subsystems/tasks)
- Dependability/robustness is the key; V&V remains a big challenge
- Effect of market structures, distributed generation, other new features on above issues
- Designing/Evolving a robust system - Complexity, distributed sensing, control and adaptation

Center for the Development of Technological Leadership
University of Minnesota Driven to Discover℠
Copyright © 2009 No part of this presentation may be reproduced in any form without prior authorization.

Transmission Capacity vs. Demand

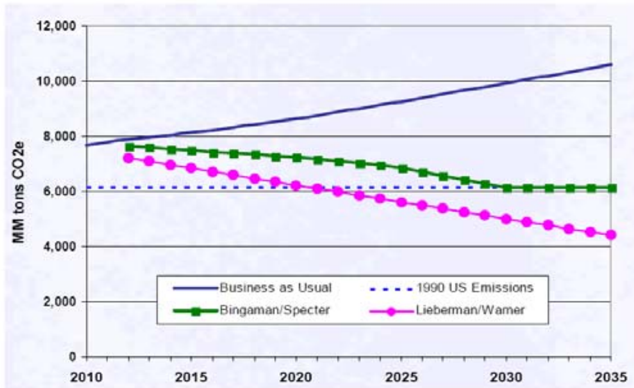


Related on-going R&D include

- EPRI: Intelligrid, Fast Simulation and Modeling
- Initiatives at several utilities, including Xcel, AEP, Austin Energy, ISOs, etc.)
- Energy Bill passed in December 2007: Title XIII Smart Grid, Sections 1301 -1309
  - Establishes a statement of policy supporting modernization of the grid; authorizes a biennial status report and survey of barriers to modernization
- US Department of Energy: Gridwise, Modern Grid, Next Generation Grid Initiatives
- University of Minnesota Center for Smart Grid Technologies
- Smart Grid Newsletter

...coupled with emerging environmental programs

US GHG Emissions and Proposed Cap-and-Trade Programs



Business as usual emissions based on US Energy Information Administration projections

Meeting either objective will require improvements in supply-side emissions and reduction in consumption.

Summary of numbers: Direct Spending

Total Direct Spending for Renewable Energy and Energy Efficiency: The bill provides \$16.8 billion in direct spending for renewable energy and energy efficiency programs over the next ten years.

Grid Development: The bill provides \$4.5 billion to modernize the nation's electricity grid with smart grid technology. The bill increases federal matching grants for the Smart Grid Investment Program from 20% to 50%.

R&D, Demonstration Projects: The bill provides \$2.5 billion for renewable energy and energy efficiency R&D, demonstration and deployment activities.

Federal Power Marketing Administrations: The bill provides \$6.5 million for capital investments by certain federal power marketing administrations in electric power transmission systems.

Advanced Battery Grants: The bill provides \$2 billion for grants for the manufacturing of advanced batteries and components. This includes the manufacturing of advanced lithium ion batteries, hybrid electrical systems, component manufacturers, and soft-ware designers.

Defense Energy and Efficiency Programs: The bill provides \$300 million to the DOD for the purpose of research, testing and evaluation of projects to energy generation, transmission and efficiency. The bill provides an additional \$100 million for Navy and Marine Corps facilities to fund energy efficiency and alternative energy projects.

Study of Electric Transmission Congestion: The bill requires the Secretary of Energy to include a study of the transmission issues facing renewable energy in the pending study of electric transmission congestion that is due to be issued in August 2009.

M. Amin's summary of the stimulus plan funding for Smart Grid

Summary of numbers: Tax Incentives

Three-Year Extension of PTC: The bill provides a three-year extension of the Production Tax Credit (PTC) for electricity derived from wind facilities through December 31, 2012, as well as for geothermal, biomass, hydropower, landfill gas, waste-to-energy and marine facilities through December 31 2013.

Investment Tax Credit (ITC) Accessible to All Renewable Energy: The bill provides project developers of wind, geothermal, biomass and other technologies eligible for the PTC, the option of instead utilizing the 30% ITC that previously only applied to solar and other clean technology projects.

Advanced Energy Manufacturing Credits: The bill provides $2 billion worth of energy related manufacturing investment credits at a 30% rate. These credits apply to projects creating or retooling manufacturing facilities to make components used to generate renewable energy, storage systems for use in electric or hybrid-electric cars, power grid components supporting addition of renewable sources, and equipment for carbon capture and storage (CCS).

Plug-in Electric Drive Vehicle Credit: The bill increases the tax credit for qualified plug-in electric drive vehicles for the first 200,000 placed in service. The base amount of the credit is $2500. Batteries with at least 5 kilowatt hours of capacity have a credit of $2917. The credit is further increased by $417 for every kilowatt hour in excess of 5 kilowatt hours, but cannot exceed $5000.The credit is allowed to be taken against the alternative minimum tax.

Macroeconomic Rationale

1. Endogenous growth models - theoretical support for domestic technology creation

2. Y = f(R, K, H), where:

   Y = GDP

   R = R&D

   K = physical capital

   H = human capital

3. <u>GDP growth</u>: a) Velocity and proportion of R, K, H, and
   b) available and affordable energy: determinants of success