Our Nation's Energy Infrastructure:

Toward Stronger, more Secure and Smarter Grid

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Context: Cities with 10 million people

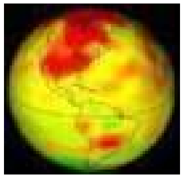
- By 2020, more than 30 mega-cities in the now less-developed world. By 2050, nearly 60 such cities.

- 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.

What Lies Ahead?

The world faces enormous challenges and opportunities – here is one person's list of the top 10

1. **ENERGY (carbon-free)**
2. WATER
3. FOOD
4. **ENVIRONMENT**
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

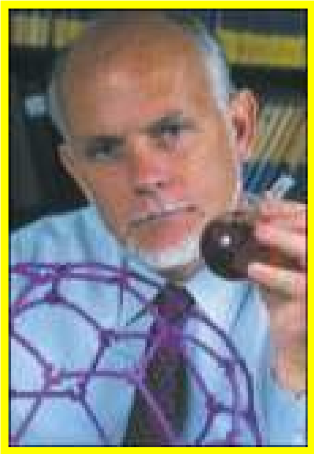


Rick Smalley, Rice U.

(1943-2005)

Nobel Prize 1996

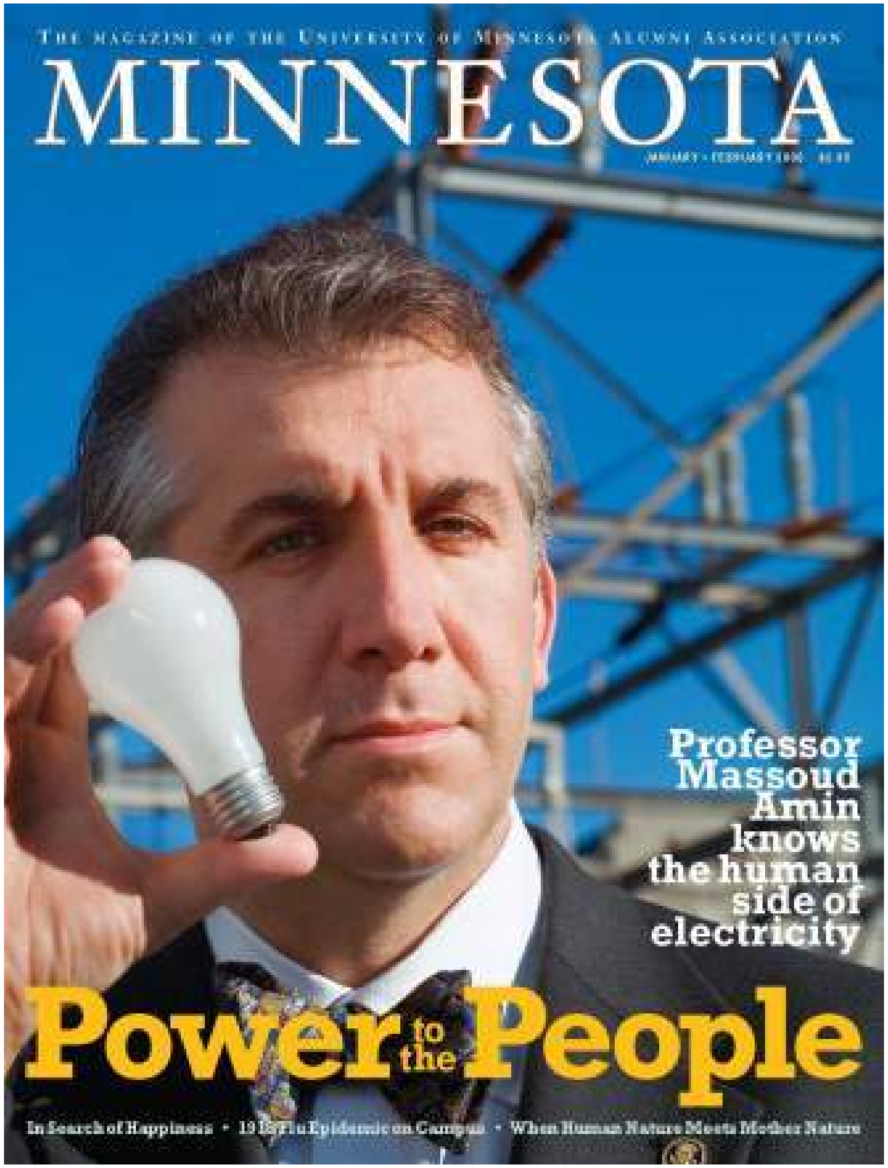
"CIVIC SCIENTIST"



Observations on electrification, economic development, and societal transformation

My father at the Mayo Clinic (pictured in Lake City, Minnesota on January 2, 1952)

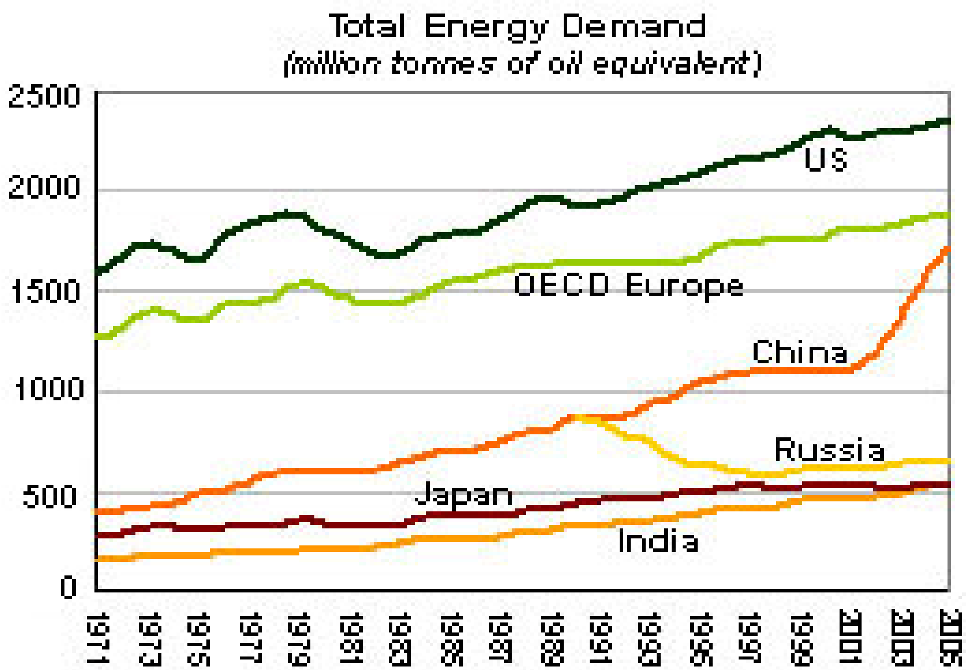
Near Persepolis, Iran, March 1967

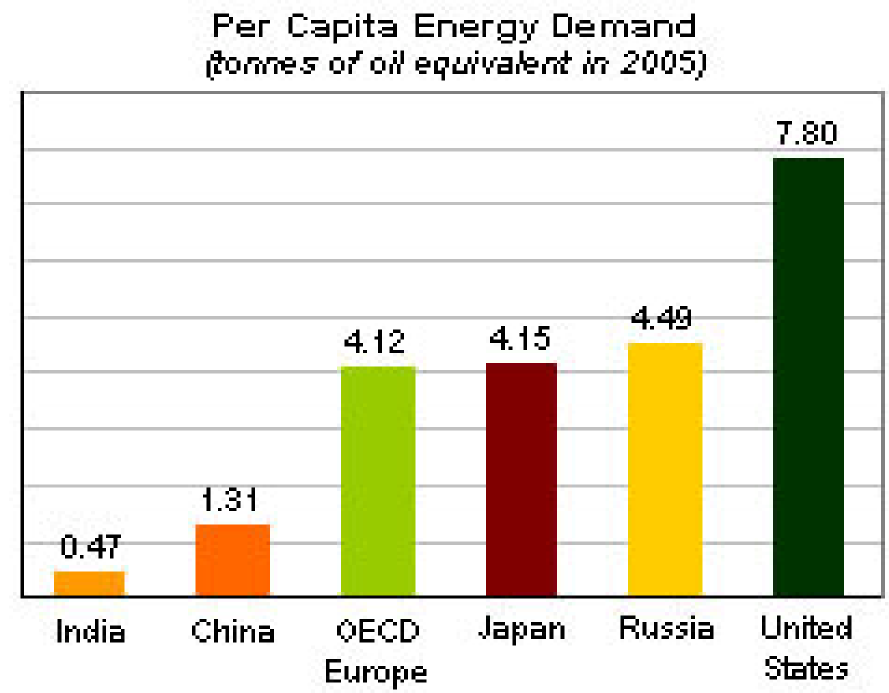


Minnesota, January 2005

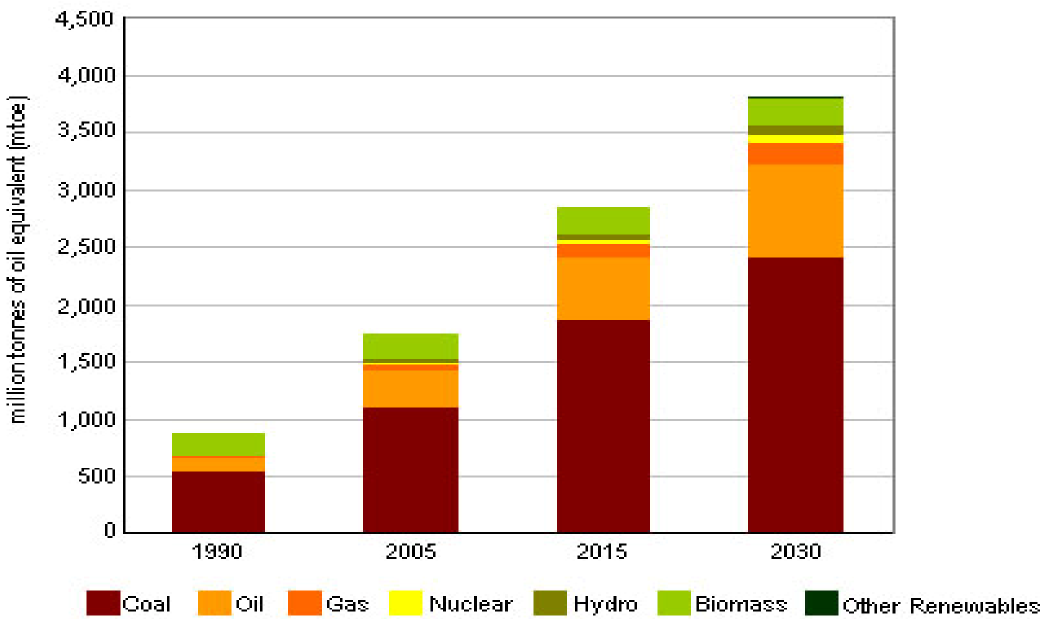
Energy Demand

Source: http://earthtrends.wri.org/updates/node/274





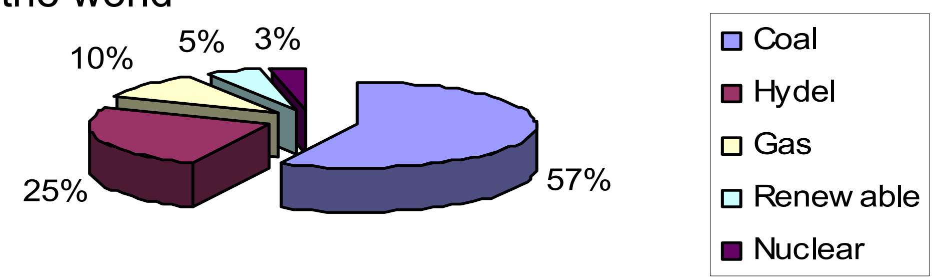
China's Energy Growth



India's installed Capacity

122 GW; 5th largest generation capacity in world

T & D network of 5.7 million circuit km – 3rd largest in the world

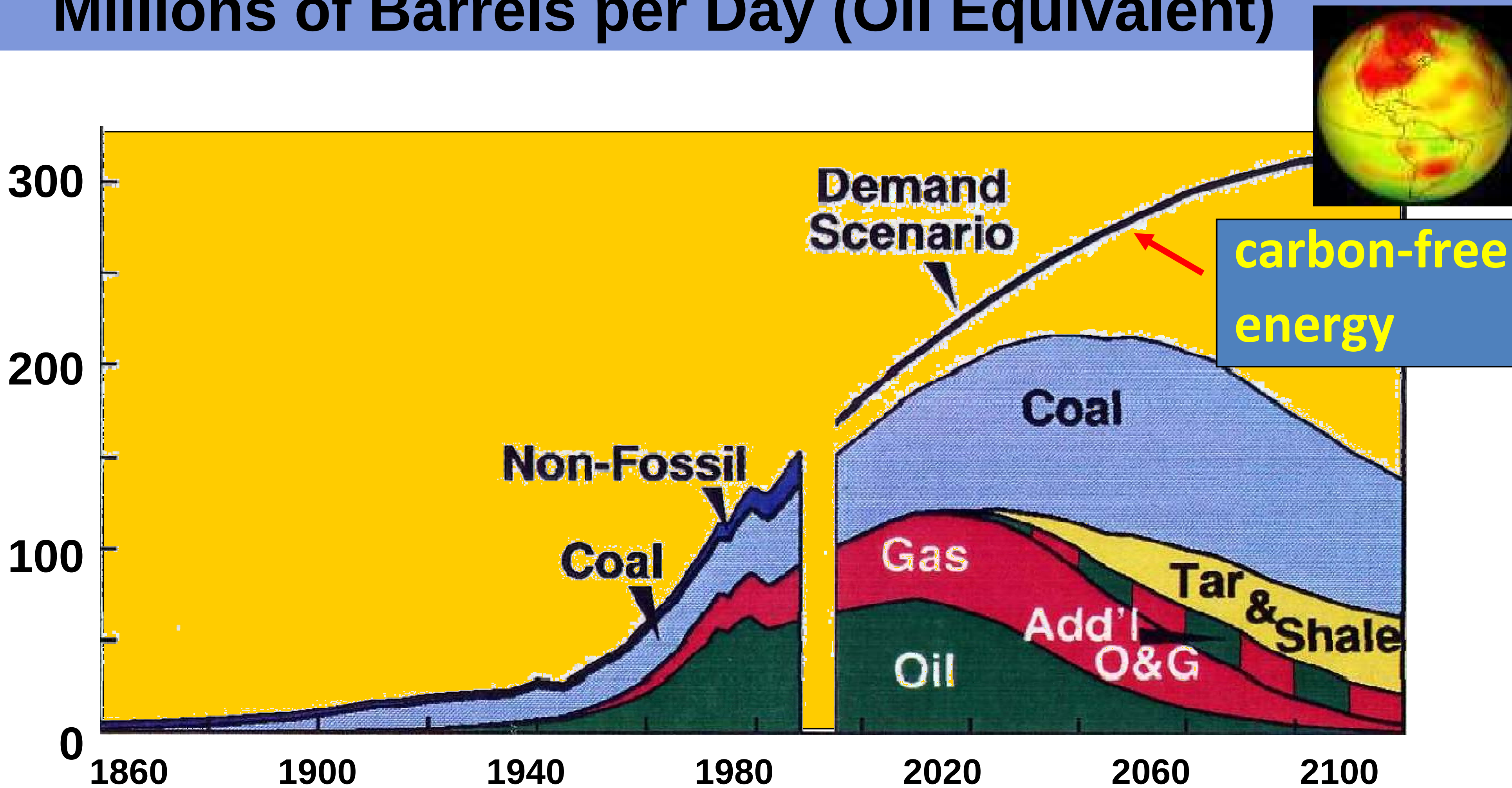


Low per capita consumption at 606 units -- less than half of China

World Energy

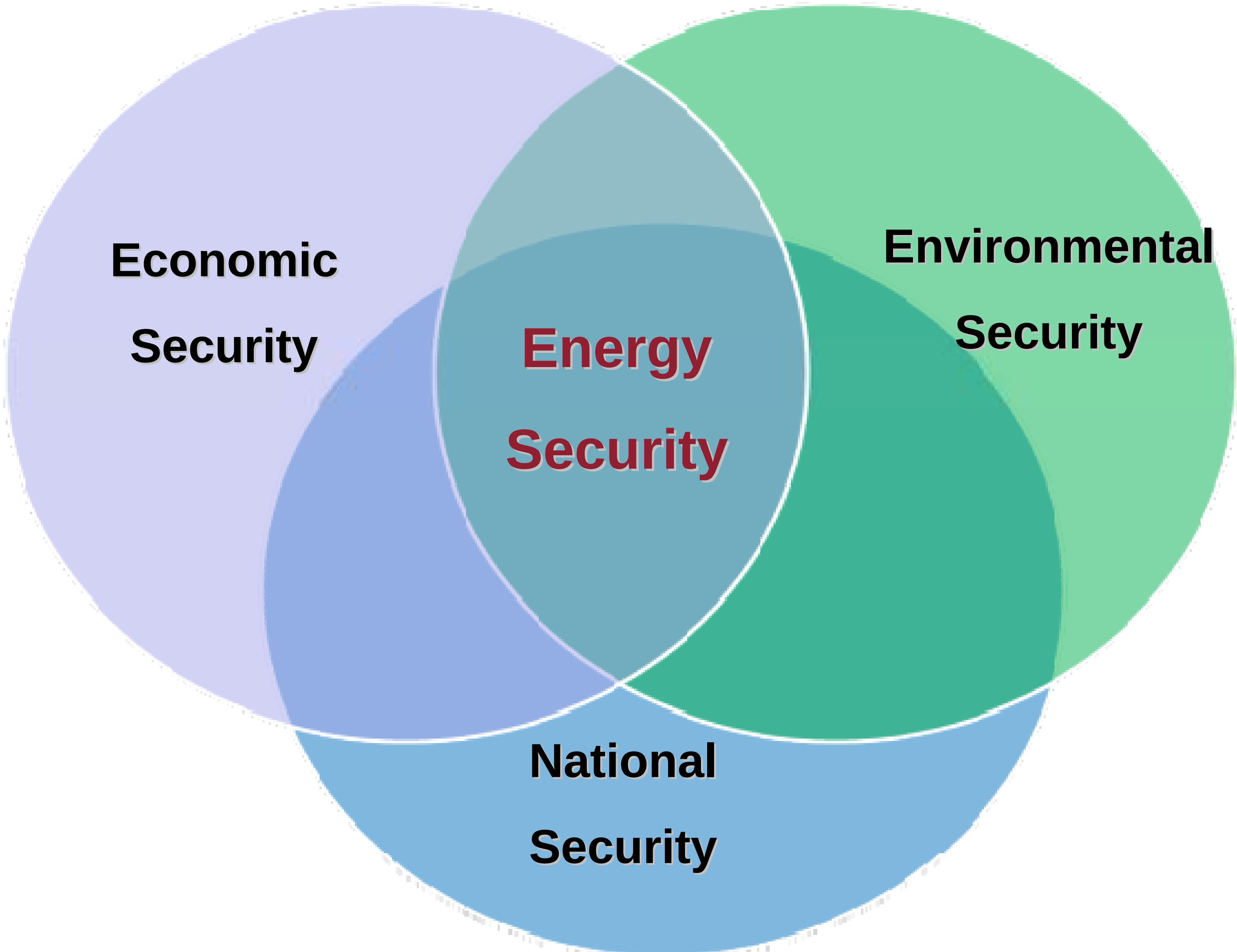
Rick Smalley, Rice U.

Millions of Barrels per Day (Oil Equivalent)



Source: John F. Bookout (President of Shell USA) ,"Two Centuries of Fossil Fuel Energy" International Geological Congress, Washington DC; July 10,1985. Episodes, vol 12, 257-262 (1989).

The Energy Nexus
What we've learned from Energy Crises



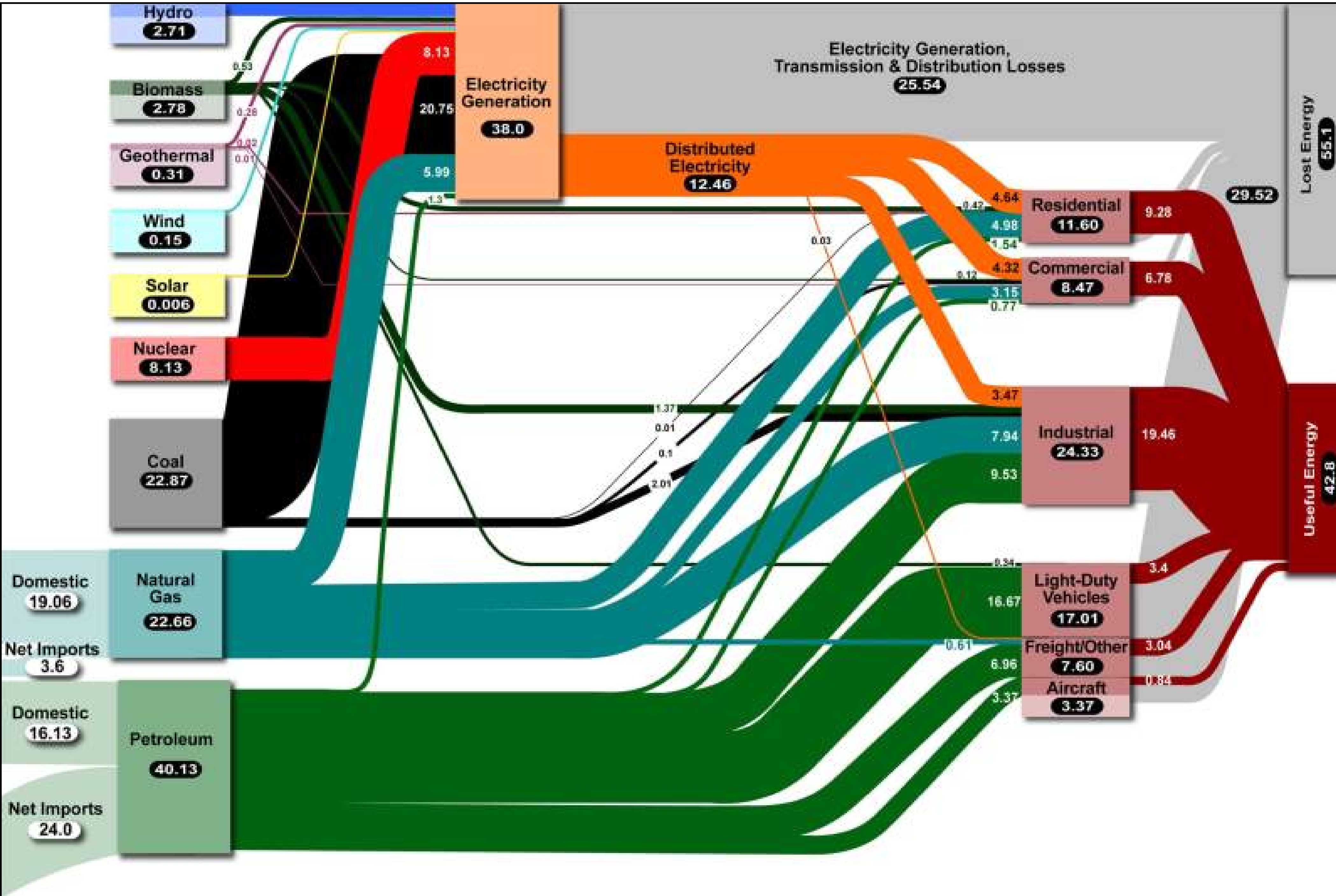
Source: RAND

Poll

- **Question:** What is your background?

  Answer: (please choose one)

  - Utility
  - Product/Service Provider
  - Government
  - Non-Profit/University
  - Other



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

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Poll

- **Question:** **What do you see as pathways forward to transform our infrastructure in the next 2 to 5 years?**
- **Answer:**

  - Energy efficiency

  - Greening of electric supply

  - Electrification of transportation

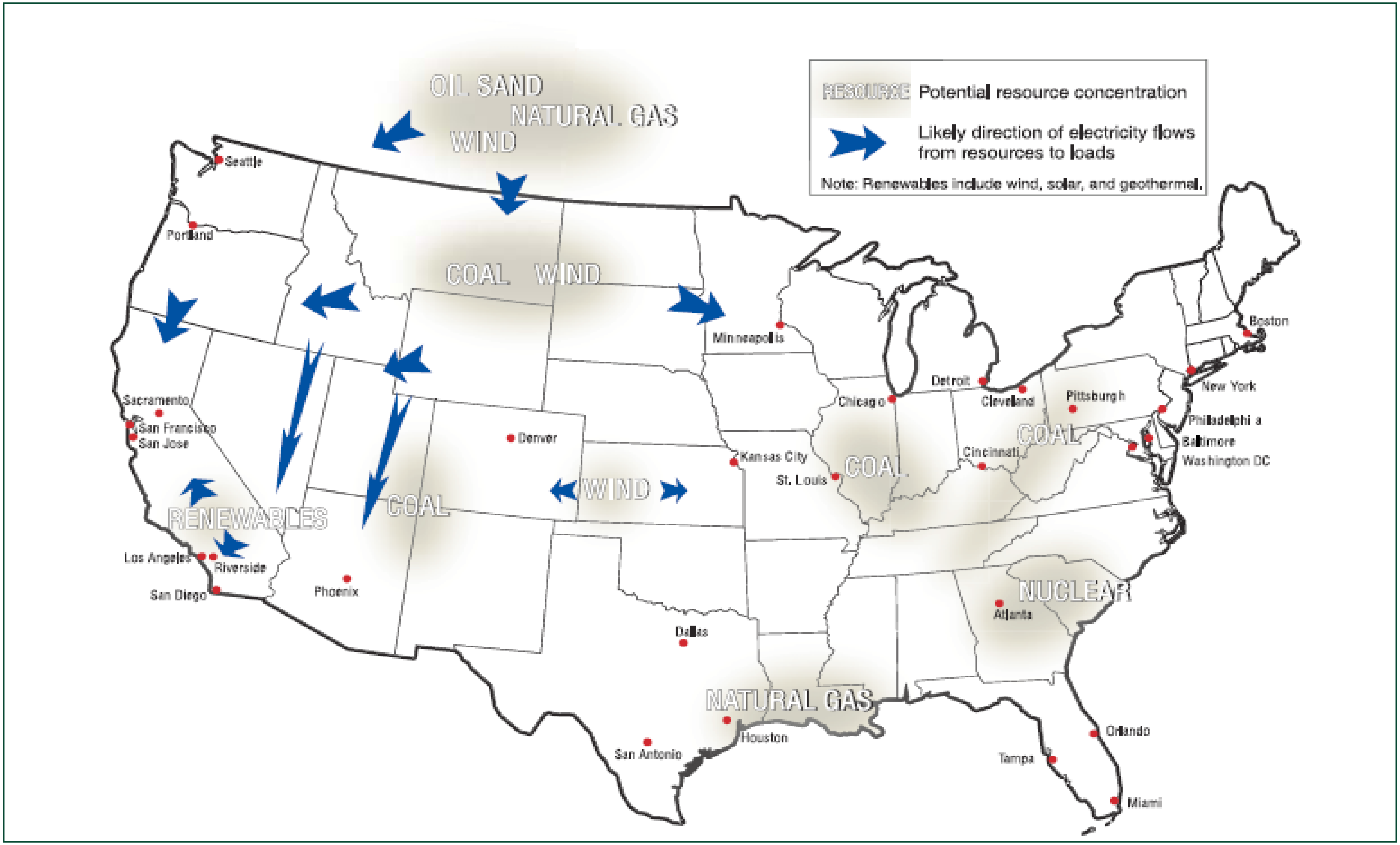
  - Building stronger smarter electrical energy infrastructure

Goals and Recommendations

- **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**

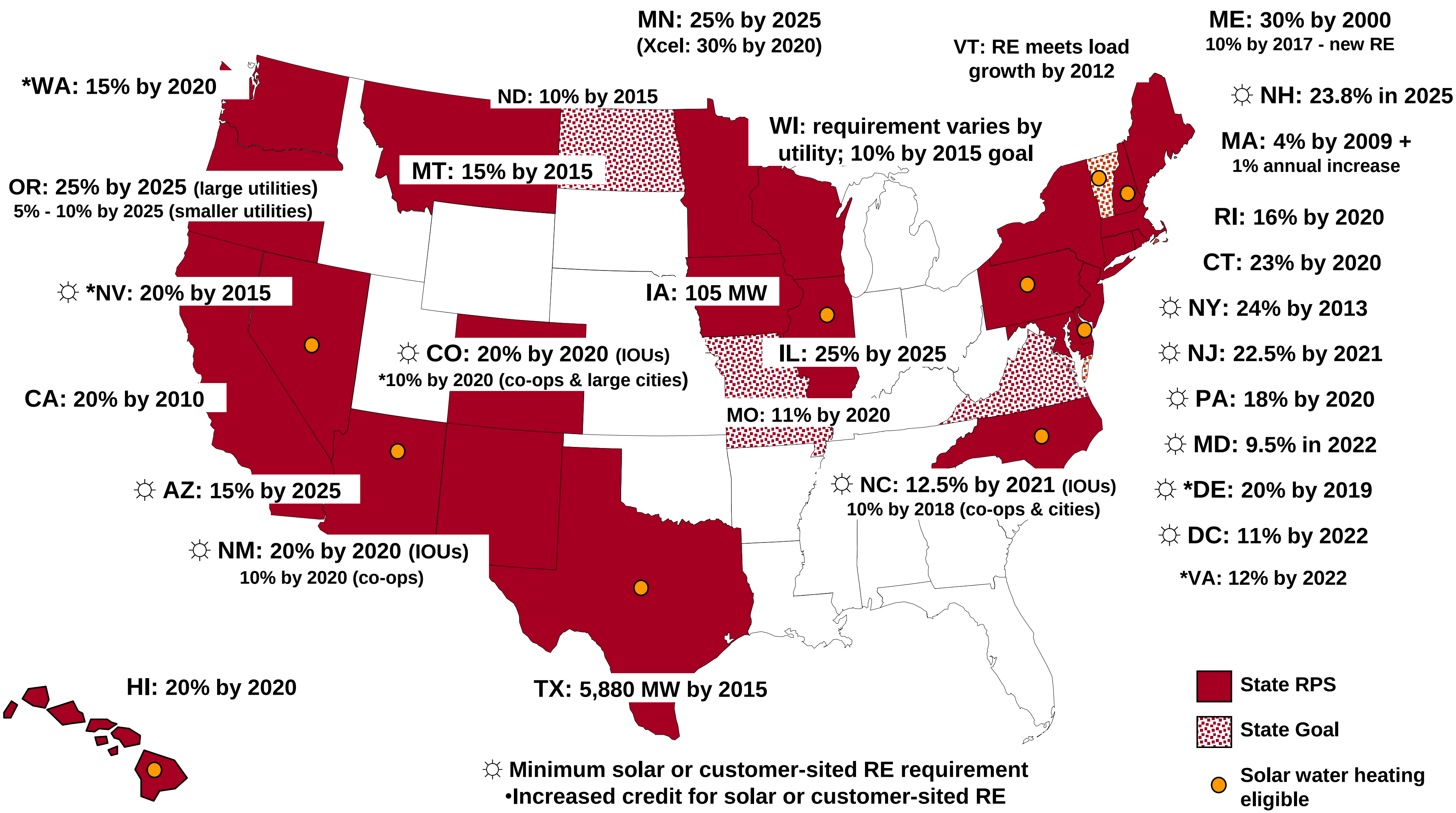
Source: M. Amin's briefing at the Congressional R&D Caucus, March 26, 2009, and IEEE Energy Policy Committee, 2009

Context: New patterns in power delivery



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

Renewables Portfolio Standards



Information courtesy of the Department of Energy

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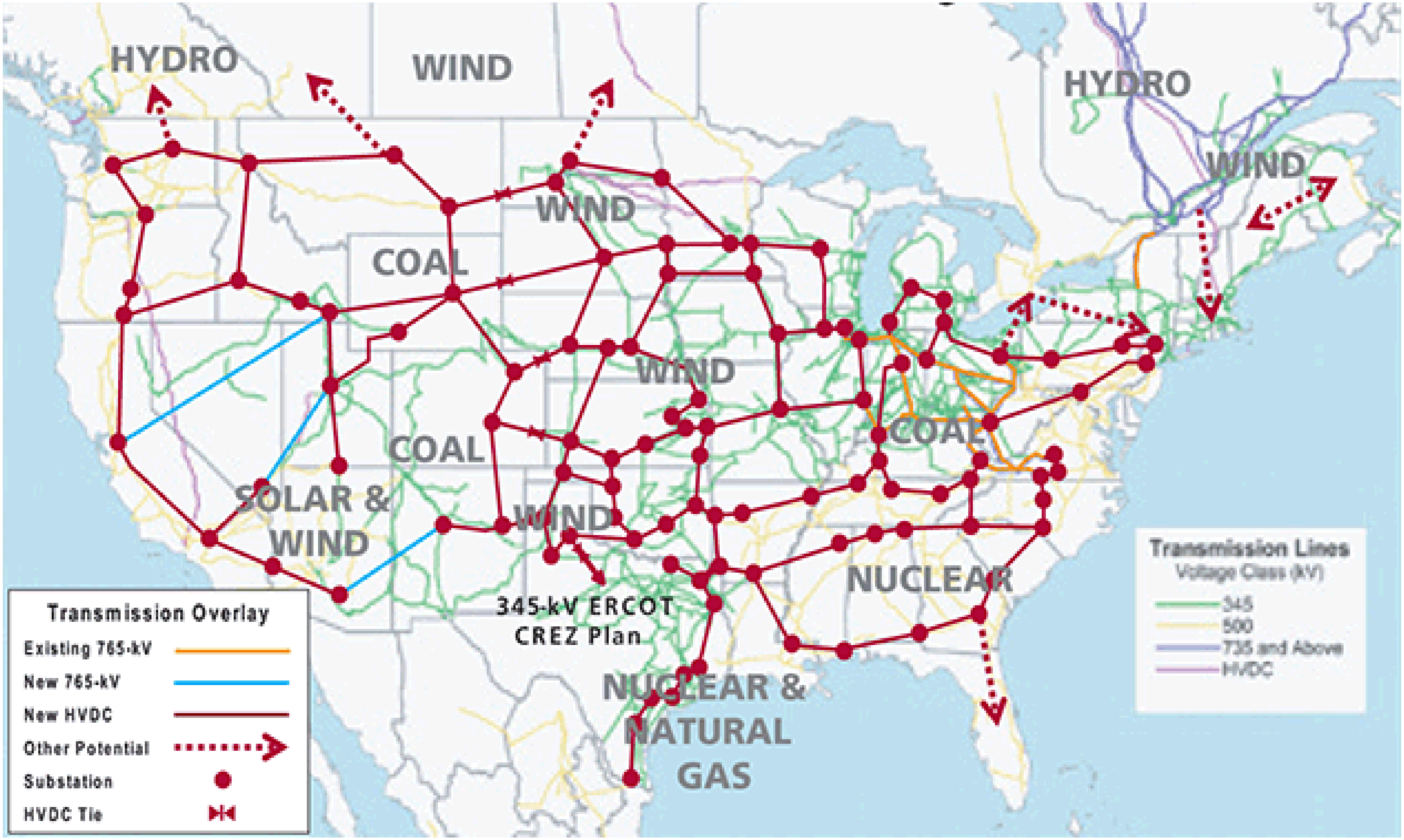
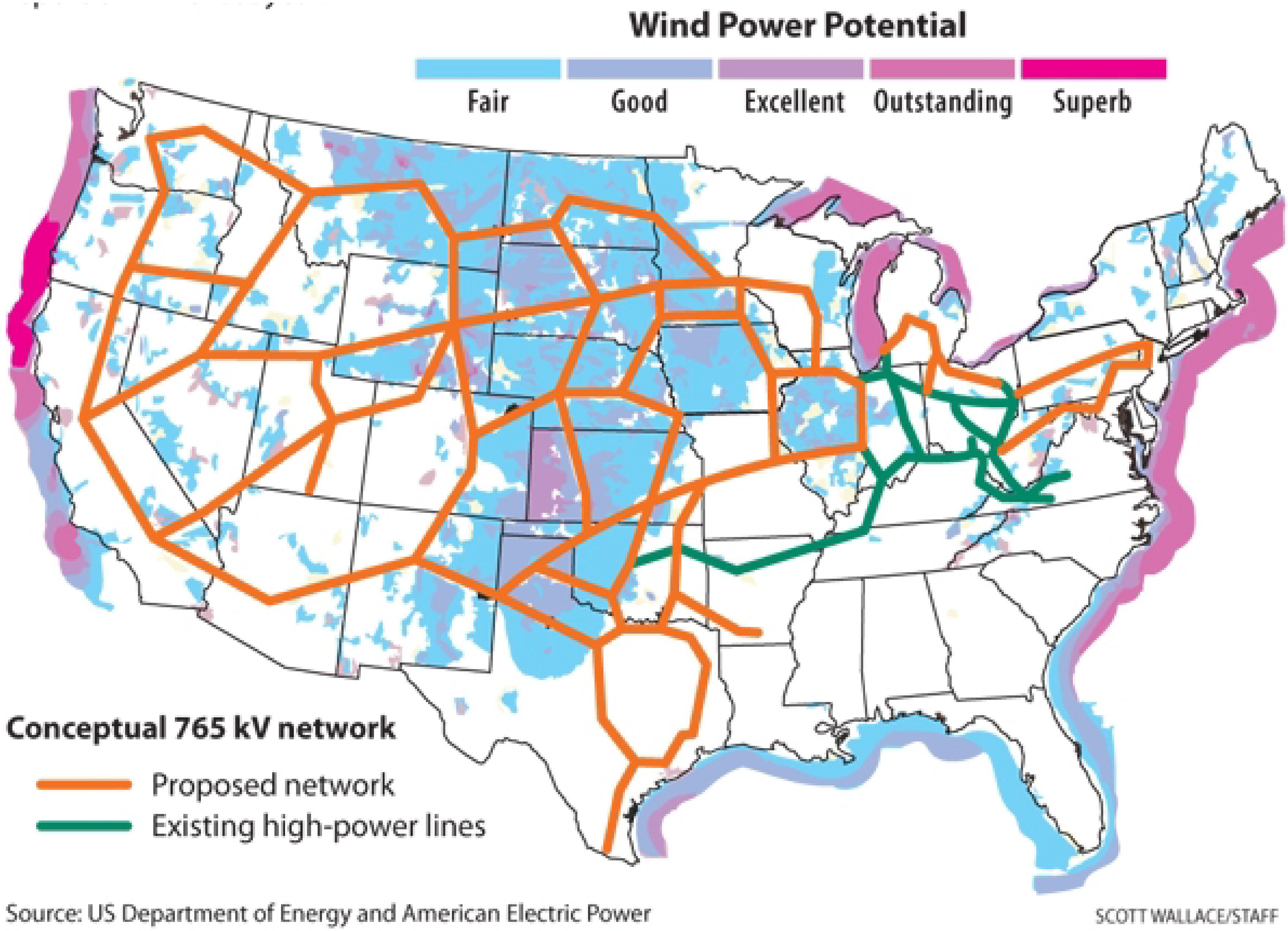
Enabling a Stronger Grid

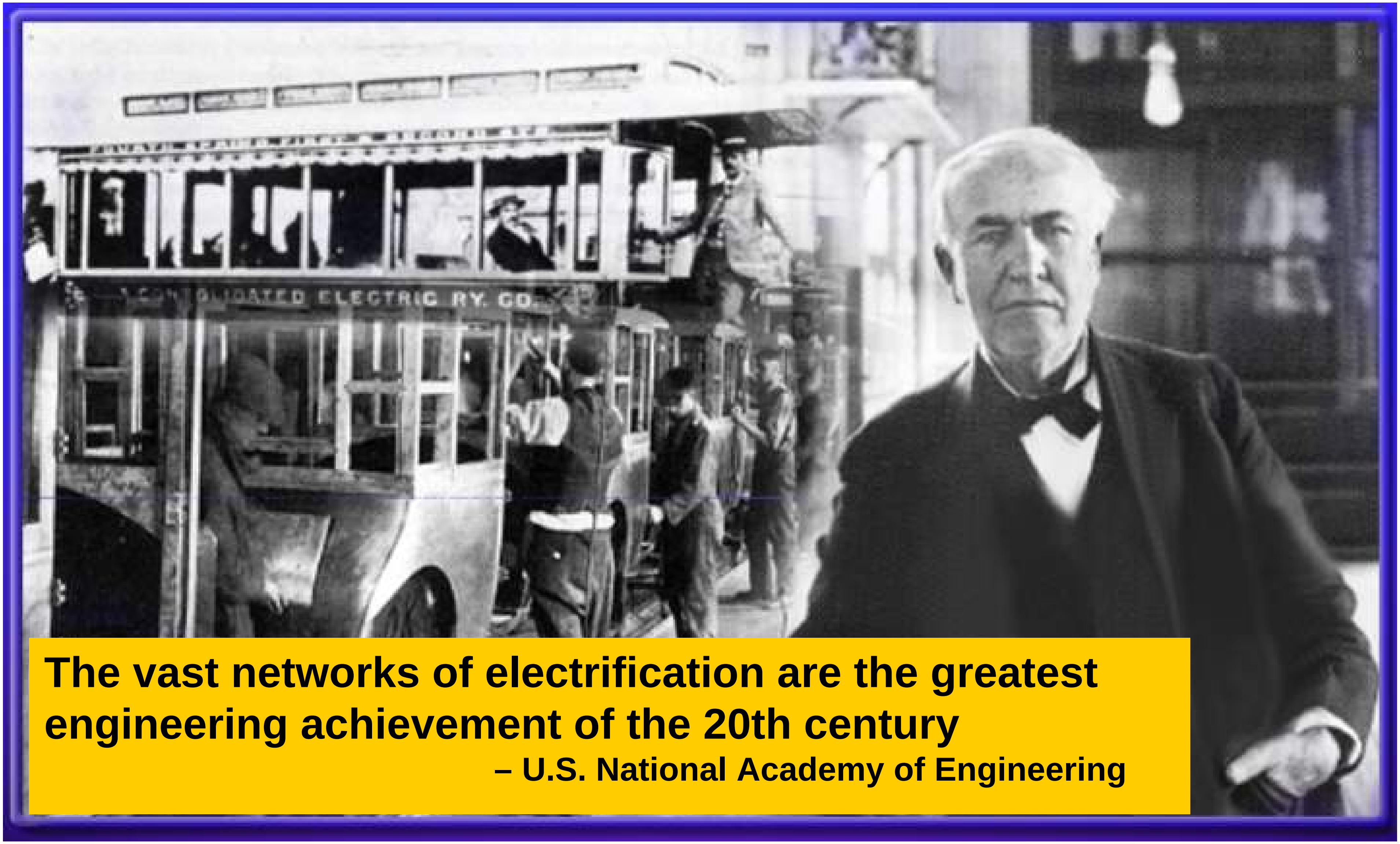


Map adapted from the U.S. DOE National Electric Transmission Congestion Study

AEP 765 KV PLAN



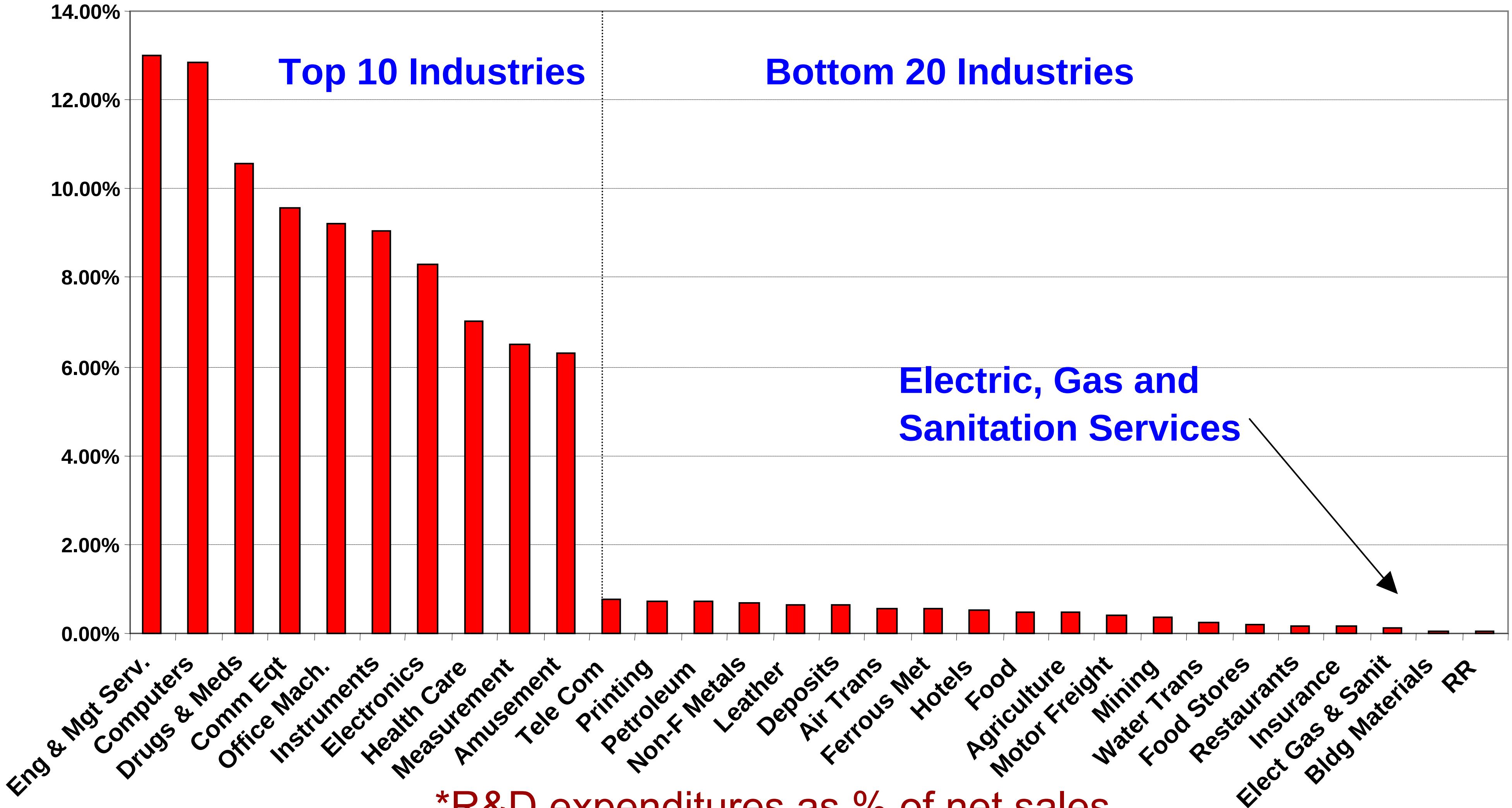
Transforming Society



The vast networks of electrification are the greatest engineering achievement of the 20th century

– U.S. National Academy of Engineering

Context: R&D Expenditures*



*R&D expenditures as % of net sales

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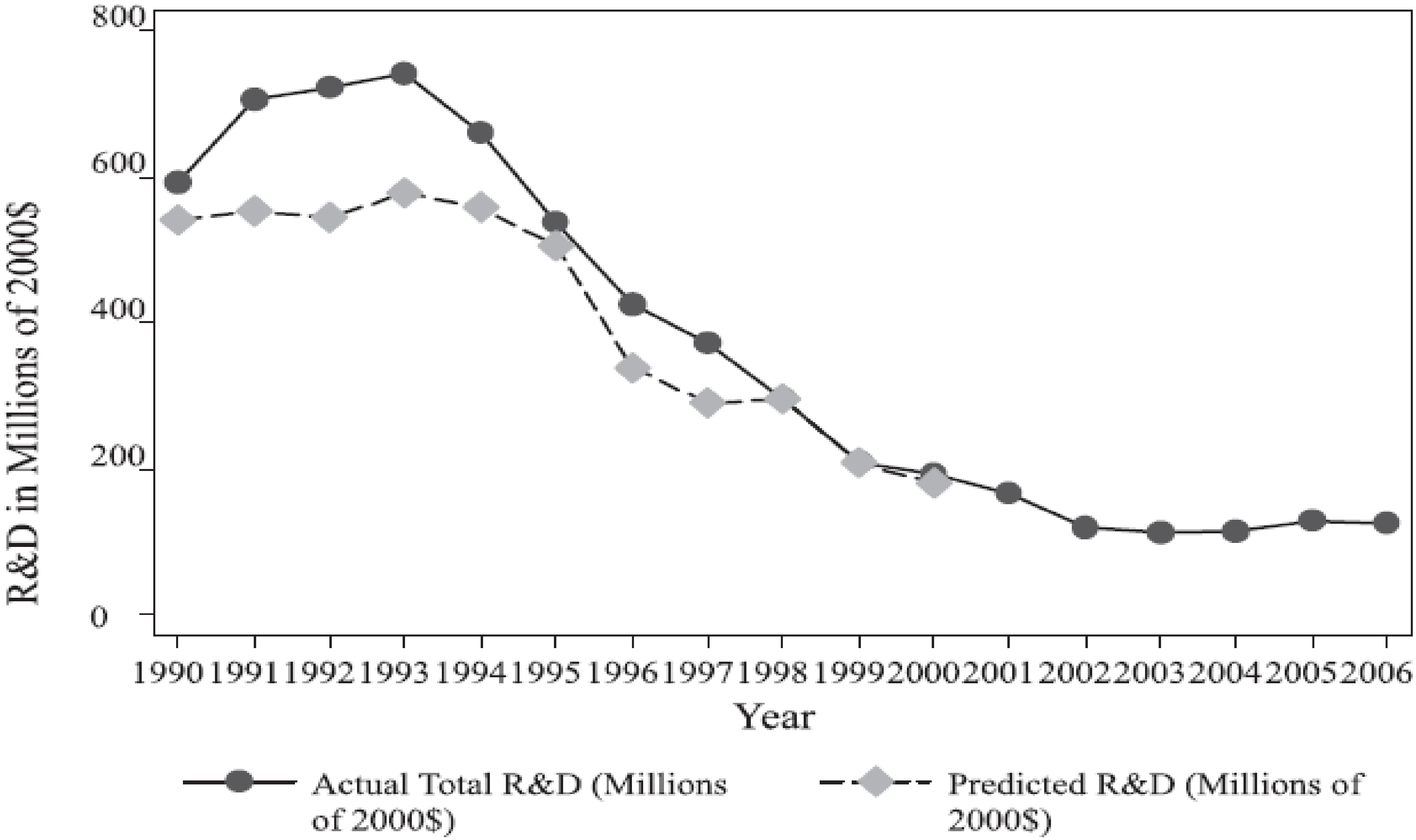
U.S. Electric Utilities R&D: 1990-2006

Annual R&D in the lowest rates of any major industrial sector with the exception of the pulp and paper



Source: "Powering Progress: Restructuring, Competition, and R&D in the U.S. Electric Utility Industry," by *Paroma Sanyal and Linda Cohen, The Energy Journal*, Vol. 30, No. 2, 2009

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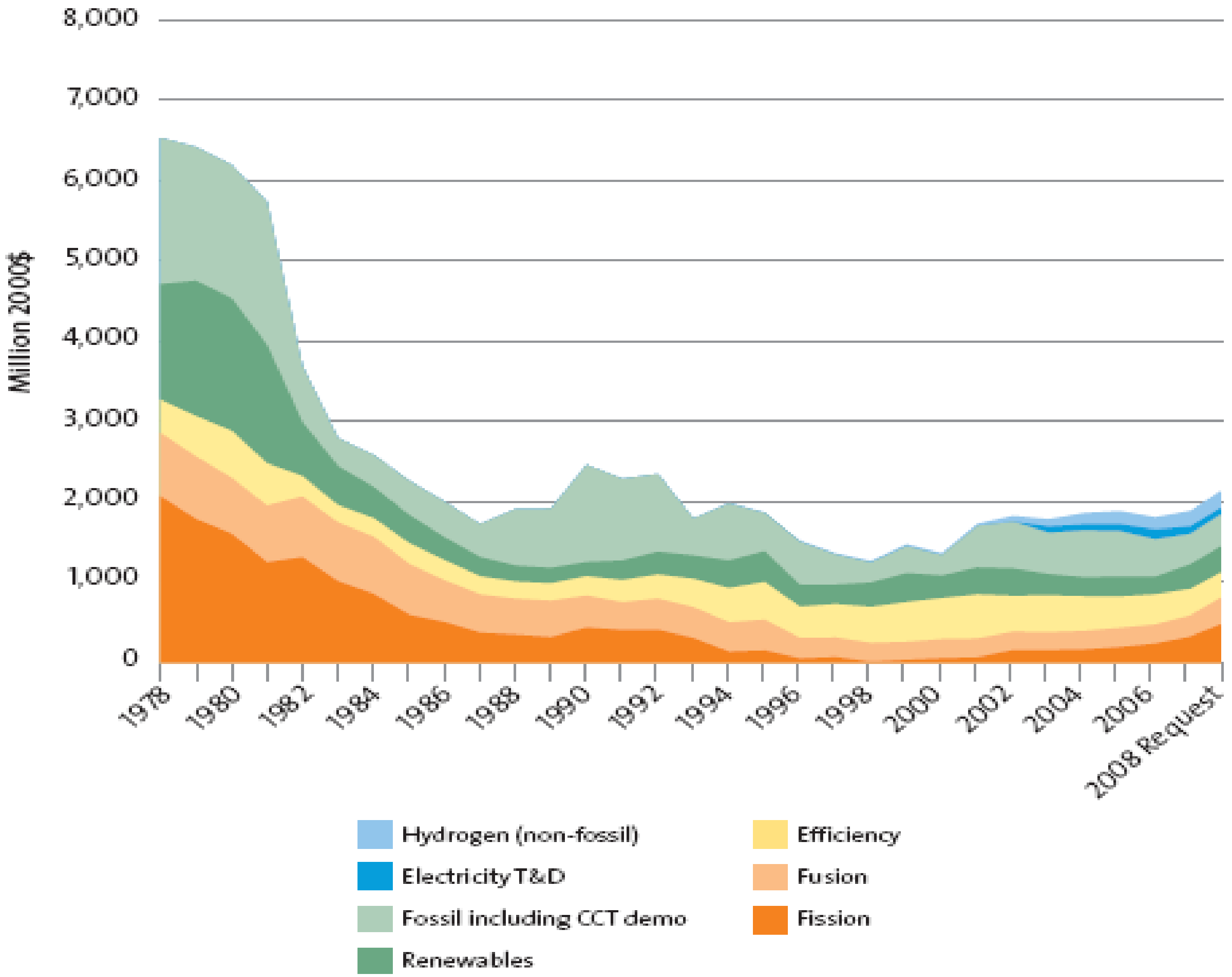
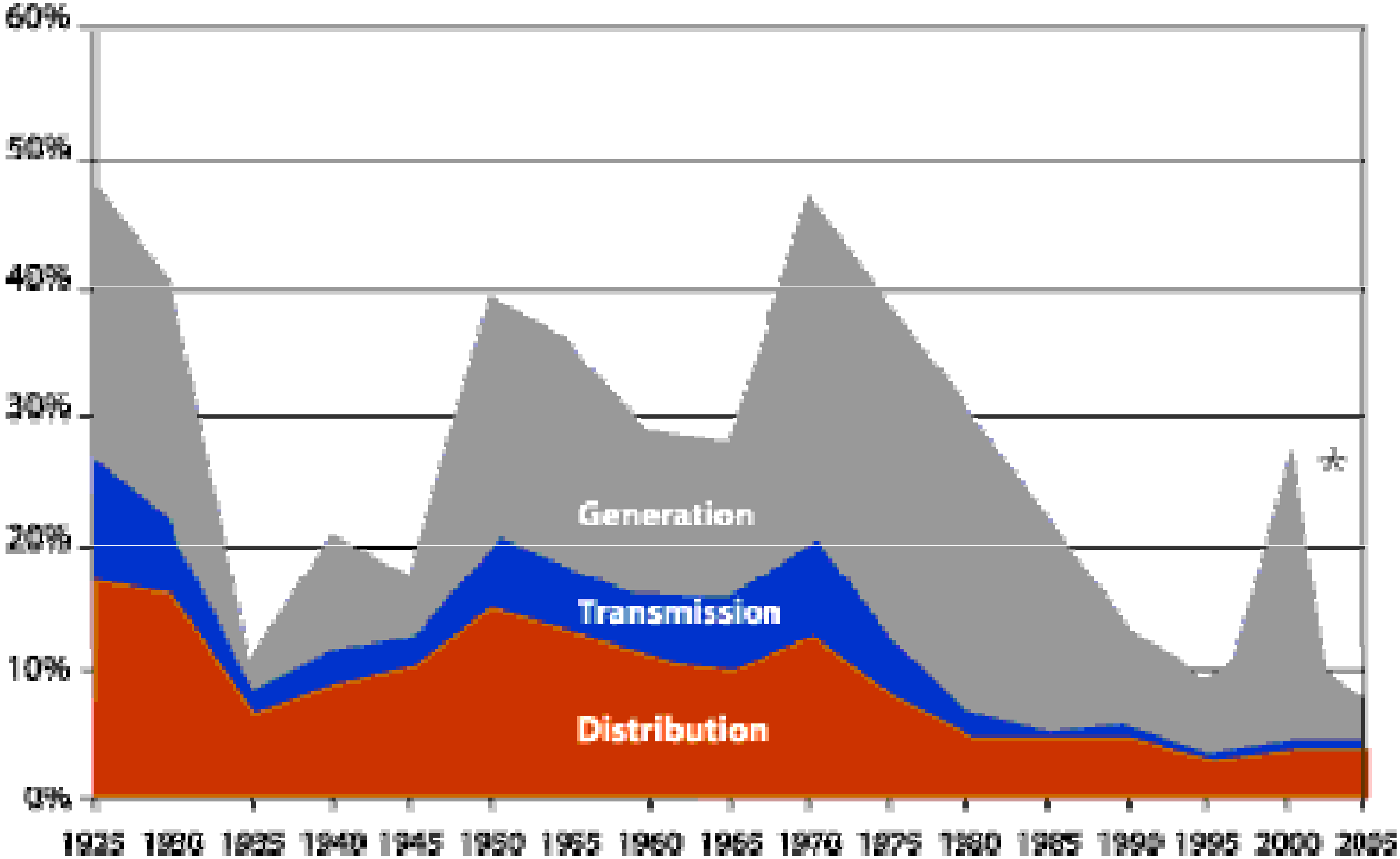
U.S. DOE ENERGY RD&D: Real Spending FY 1978–FY2008



Source: Gallagher, K.S., A. Sagar,D. Segal, P. de Sa, and J.P. Holdren. 2007. DOE Budget Authority for Energy Research, Development and Demonstration Database. Energy Technology Innovation Project. John F. Kennedy School of Government, Harvard University.

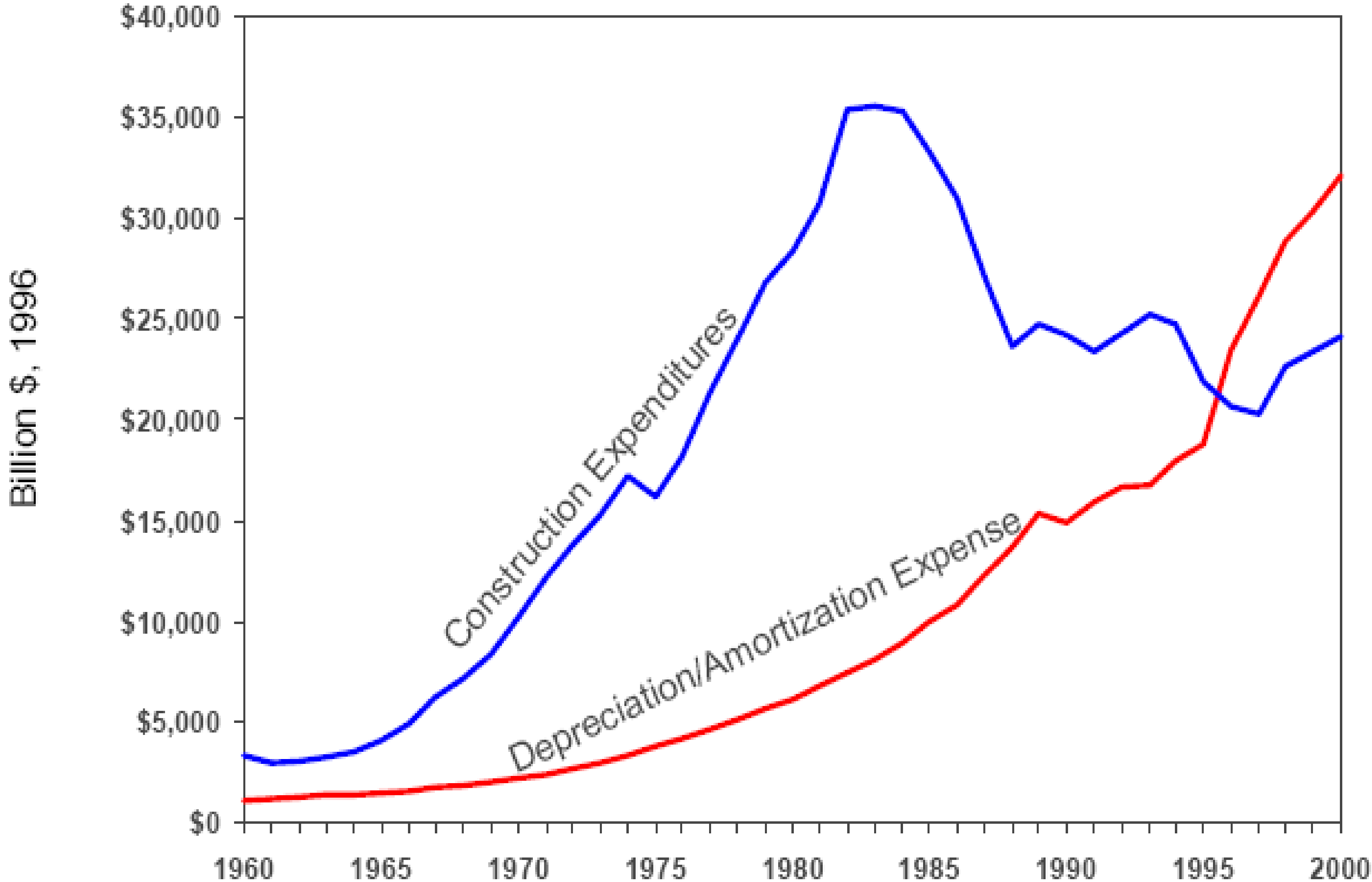
Capital Invested as % of electricity revenue



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

Capital invested as % of electricity revenues

Utility construction expenditures



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

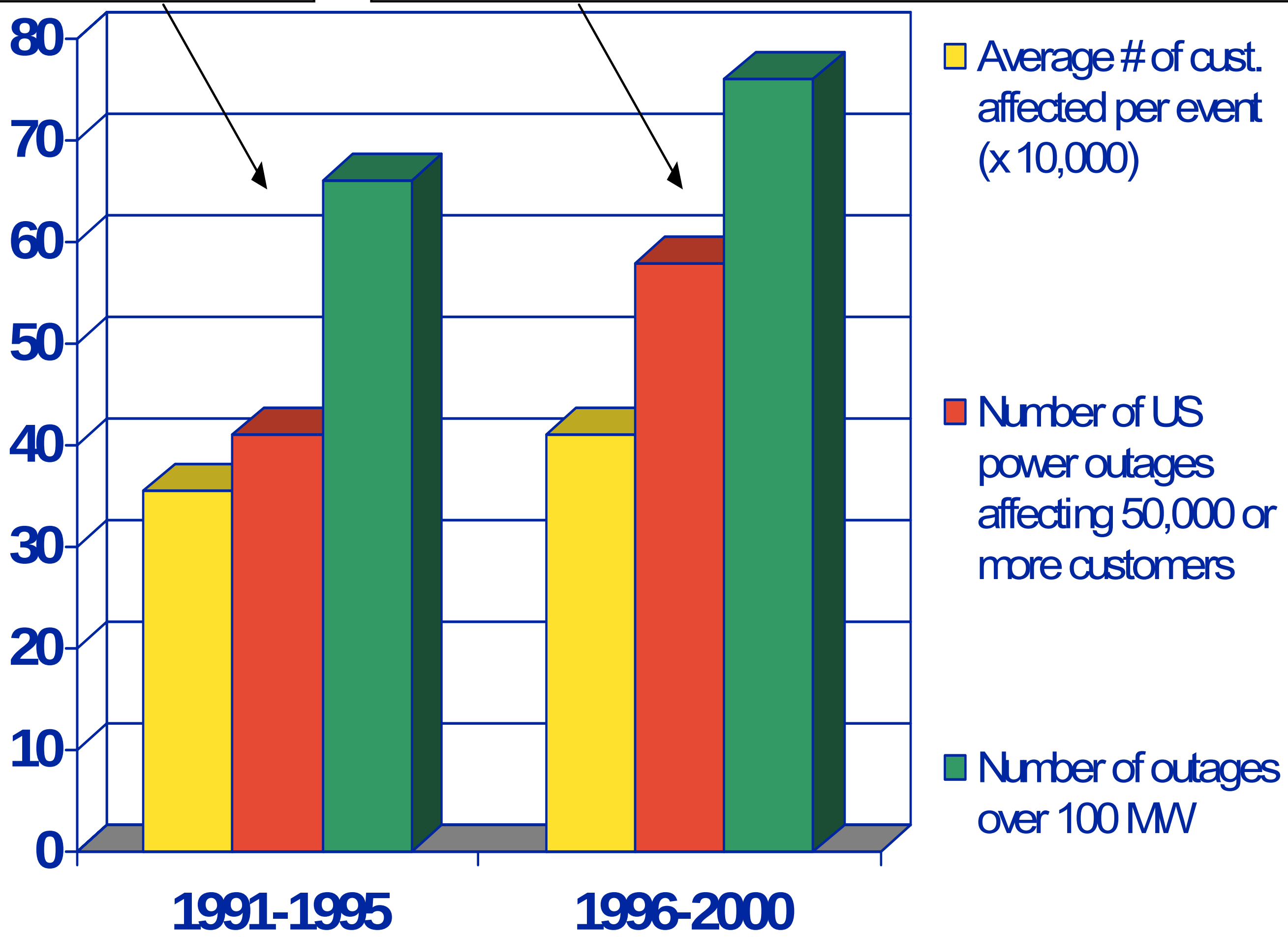
Historical Analysis of U.S. outages (1991-2000)

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.

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

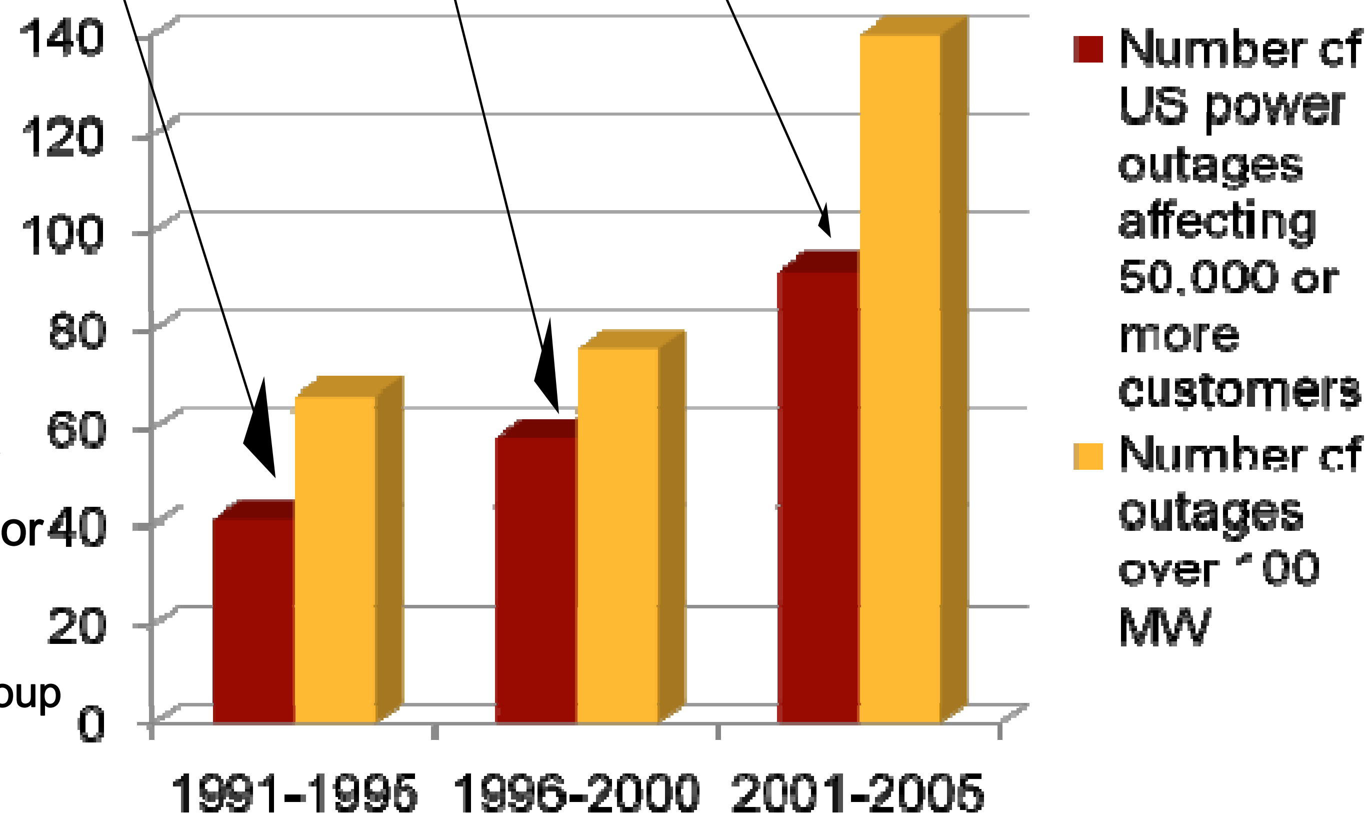
66 Occurrences over 100 MW
41 Occurrences over 50,000* Consumers

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.

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

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

EPRI/DoD Complex Interactive Networks (CIN/SI)

Underpinnings of Interdependent Critical National Infrastructures

Tools that enable secure, robust & reliable operation of interdependent infrastructures with distributed intelligence & self-healing

Y2K2000-present

Enterprise Information Security (EIS)

1. Information Sharing
2. Intrusion/Tamper Detection
3. Comm. Protocol Security
4. Risk Mgmt. Enhancement
5. High Speed Encryption

2002-present

Infrastructure Security Initiative (ISI)

Response to 9/11 Tragedies

1. Strategic Spare Parts Inventory
2. Vulnerability Assessments
3. Red Teaming
4. Secure Communications

2001-present

Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)

1. Self Healing Grid
2. IntelliGrid™
3. Integrated Electric Communications System Architecture
4. Fast Simulation and Modeling

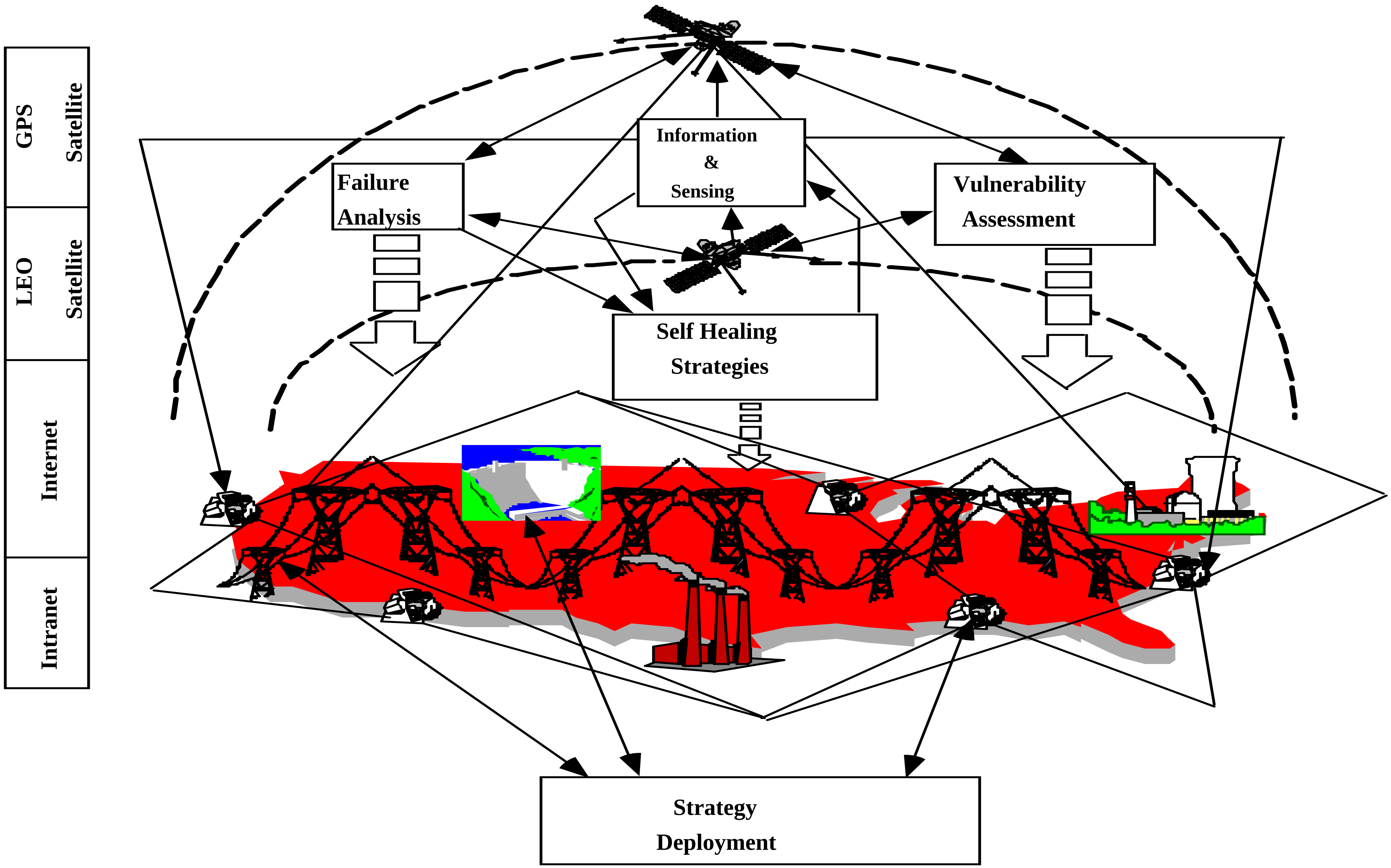
Recent Directions: EPRI/DOD Complex Interactive Network/Systems Initiative (1998-2002)

Complex interactive networks:

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

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

Complex Interactive Networks



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
- Purdue, U Tennessee, Fisk U, TVA, ComEd/Exelon
- Harvard, UMass, Boston, MIT, Washington U.
- Cornell, UC-Berkeley, GWU, Illinois, Washington St., Wisconsin
- CMU, RPI, UTAM, Minnesota, Illinois
- Cal Tech, MIT, Illinois, UC-SB, UCLA, Stanford

- Defense Against Catastrophic Failures, Vulnerability Assessment
- Intelligent Management of the Power Grid
- Modeling and Diagnosis Methods
- Minimizing Failures While Maintaining Efficiency / Stochastic Analysis of Network Performance
- Context Dependent Network Agents
- Mathematical Foundations: Efficiency & Robustness of Distributed Systems

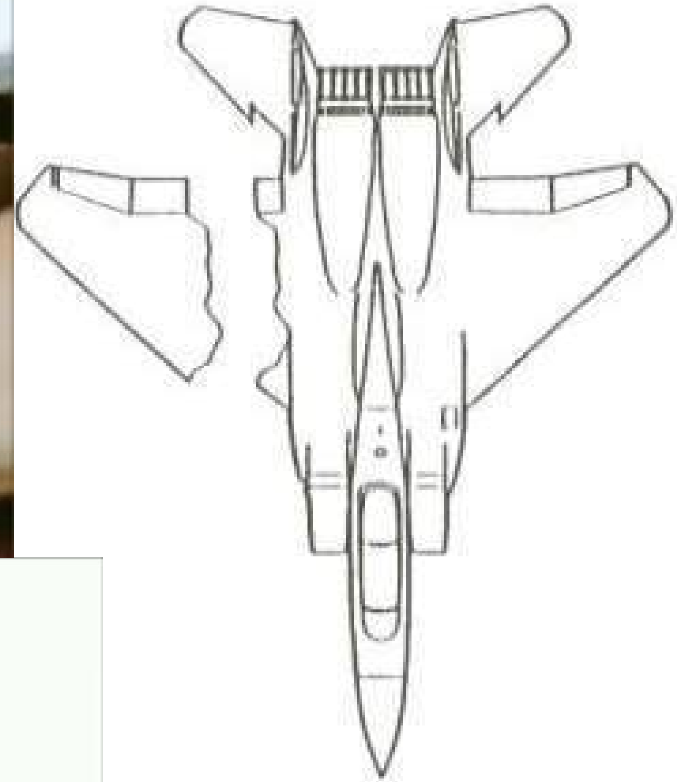
Definition: Self-Healing ("Smart") Grid (1998-present)

- **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.

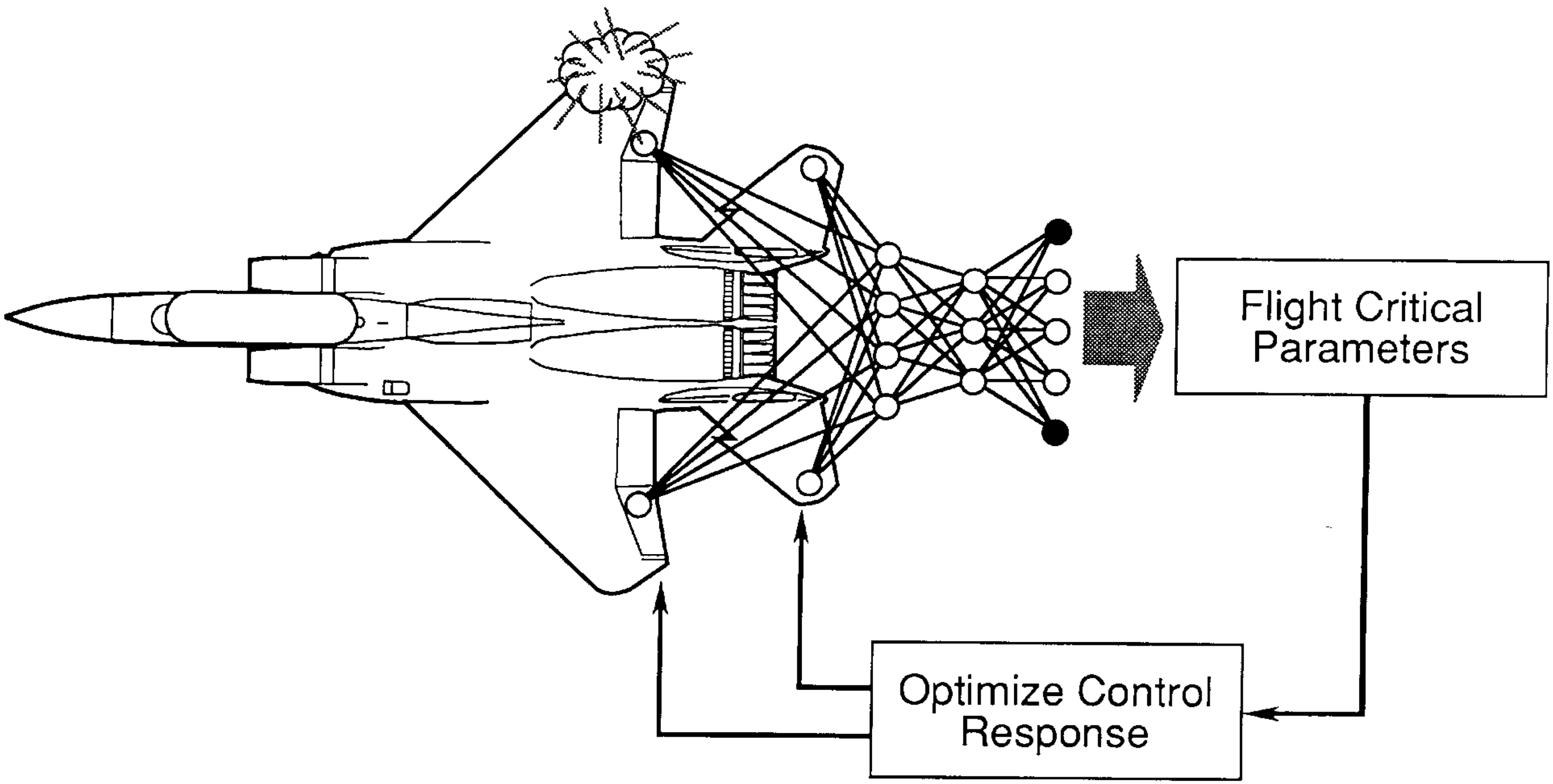
Background:
The Self Healing Grid

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



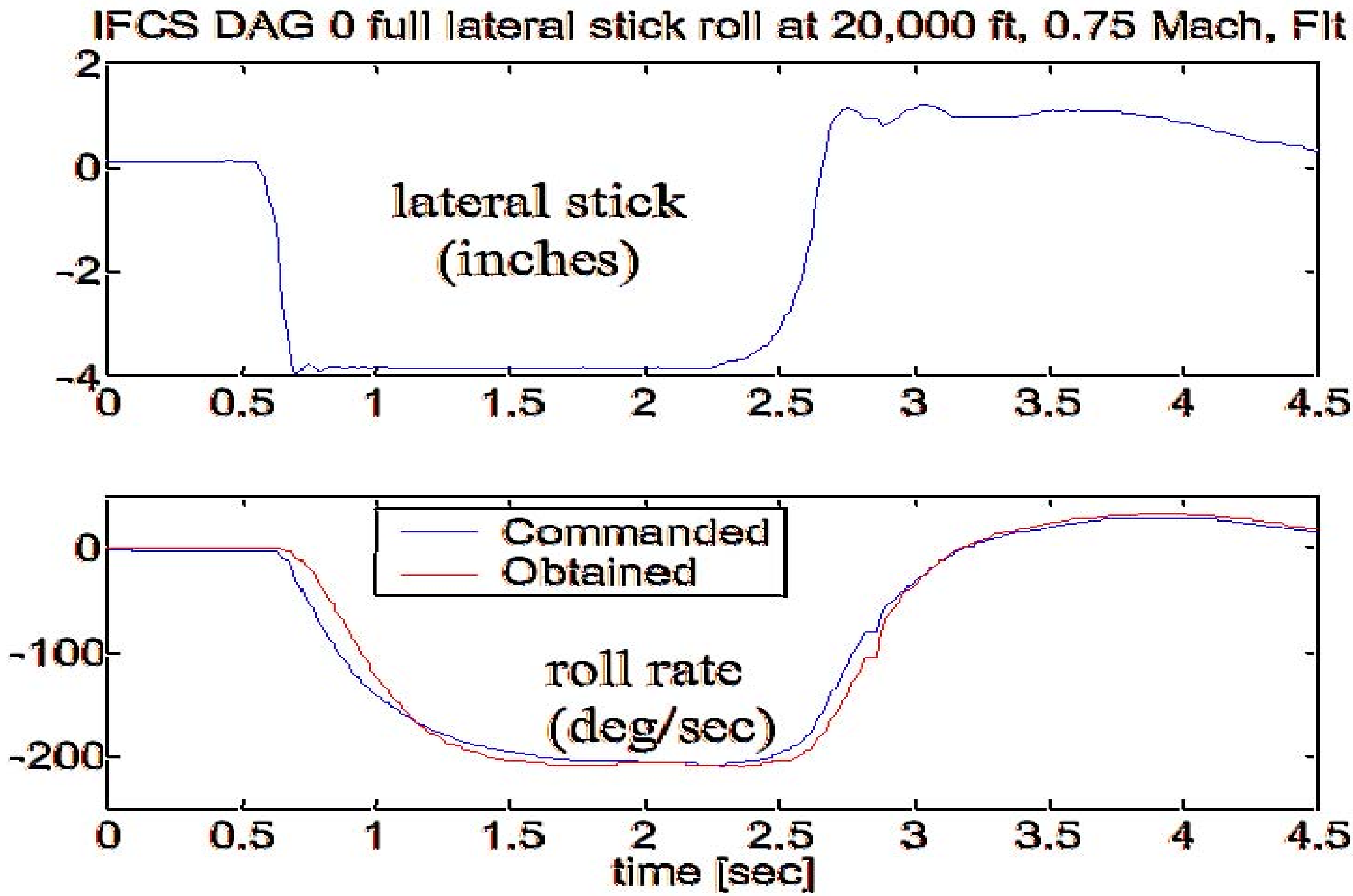
NASA/MDA/WU IFCS: NASA Ames Research Center, NASA Dryden, Boeing Phantom Works, and Washington University in St. Louis.

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



NASA/MDA/WU IFCS

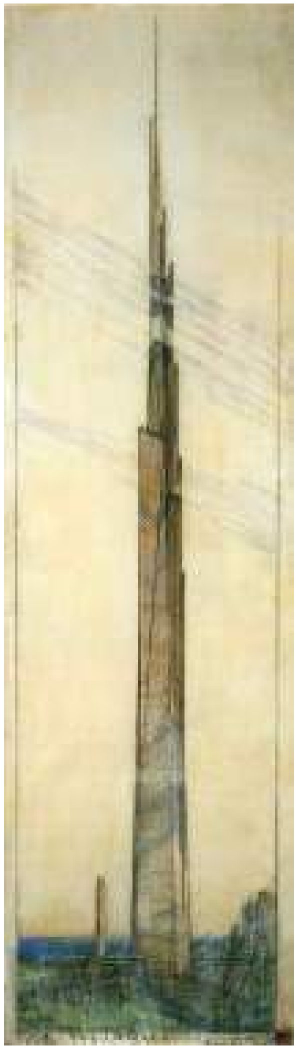
Intelligent Flight Control System: Example – complete hydraulic failure (1997)



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.

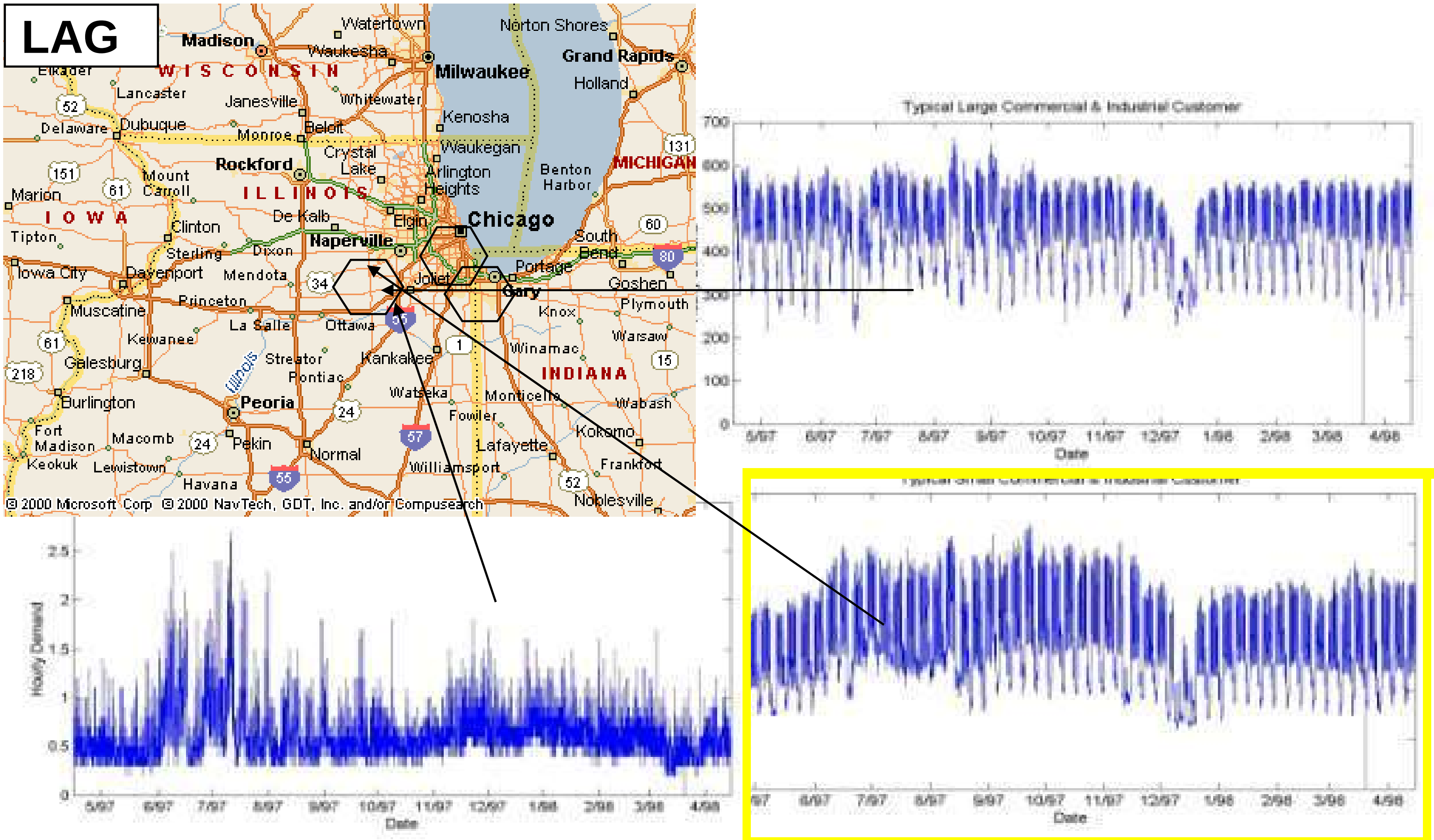
Self-healing Grid (1998-present)



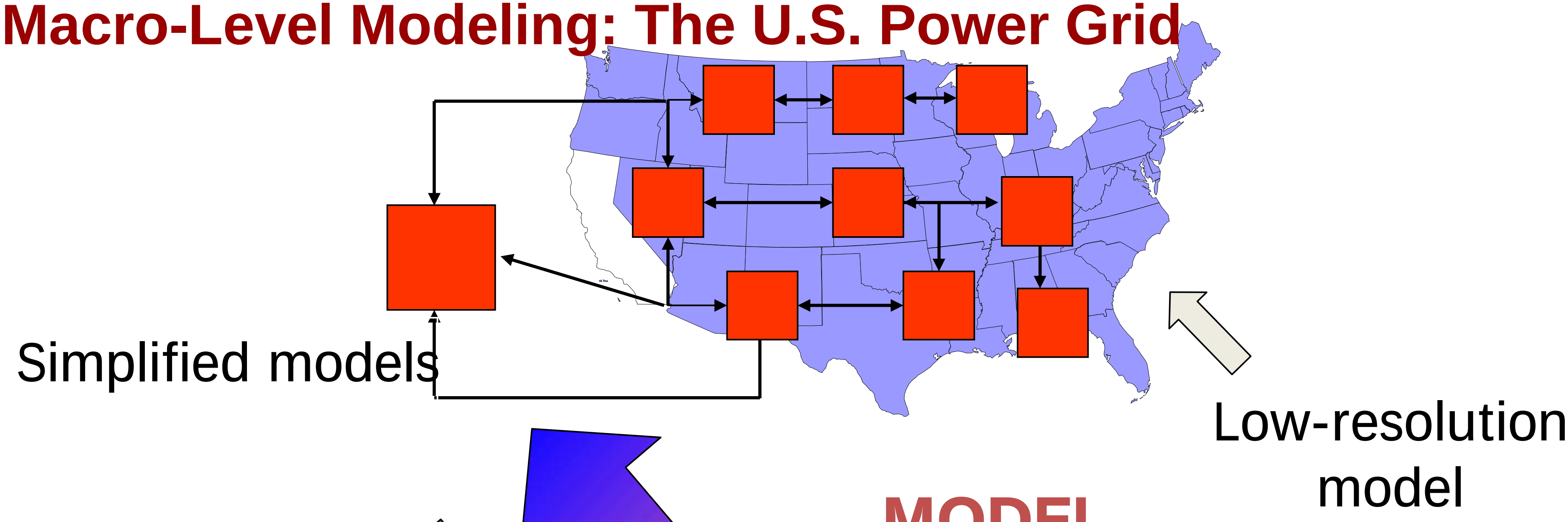
Building on the Foundation:

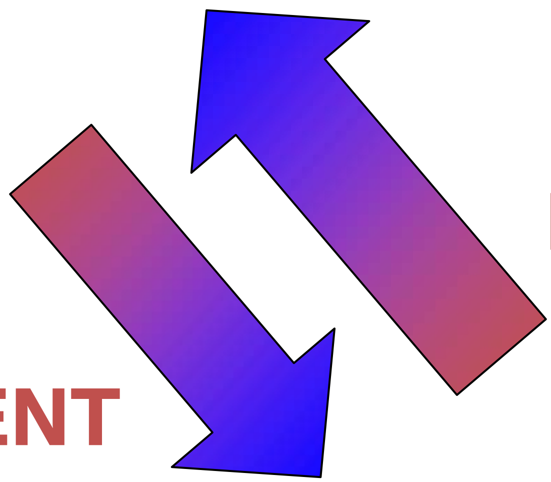
- Anticipation of disruptive events
- Look-ahead simulation capability
- Fast isolation and sectionalization
- Adaptive islanding
- Self-healing and restoration

Local area grids (LAG)

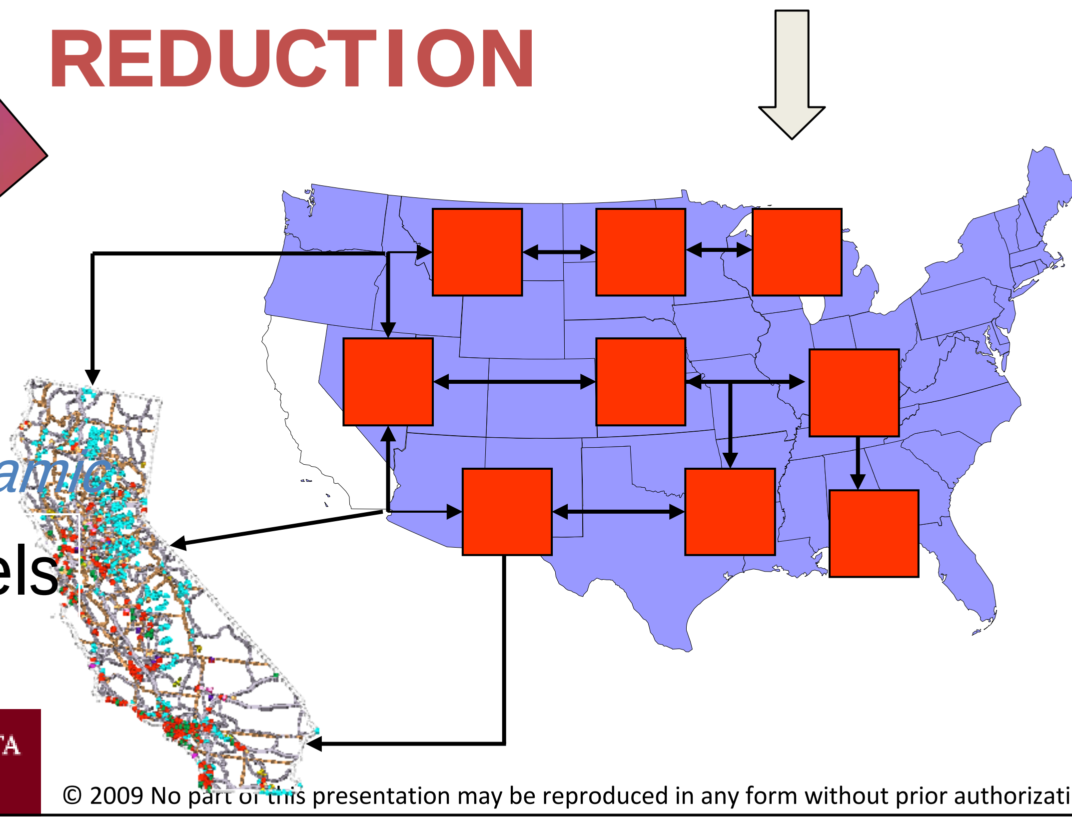


Macro-Level Modeling: The U.S. Power Grid





- Variable levels of details
- Lines, loads, generators are *dynamic*

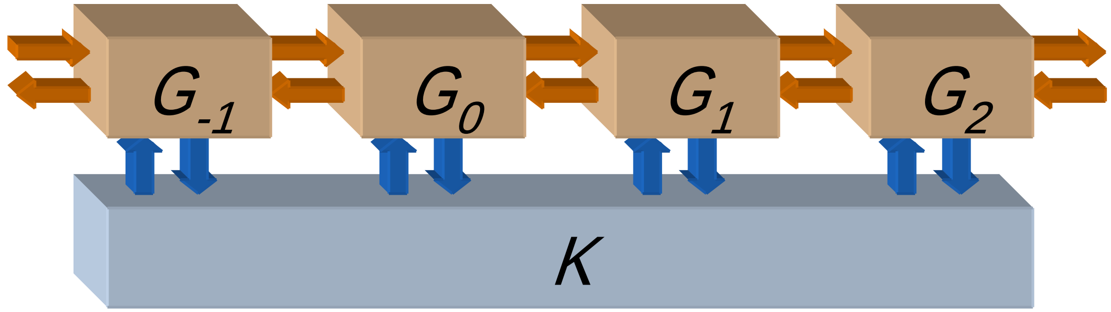


Look-Ahead Simulation Applied to Multi-Resolution Models

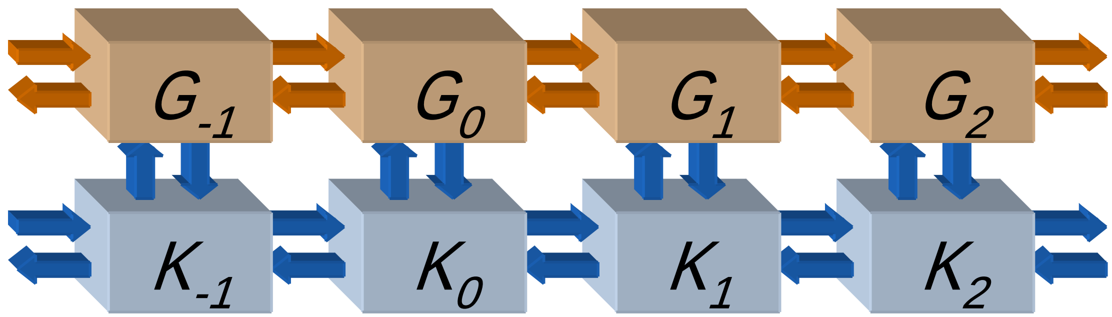
- Provides faster-than-real-time simulation
  - By drawing on approximate rules for system behavior, such as power law distribution
  - By using simplified models of a particular system
- Allows system operators to change the resolution of modeling at will
  - Macro-level (regional power systems)
  -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

Sensing and Control Strategies

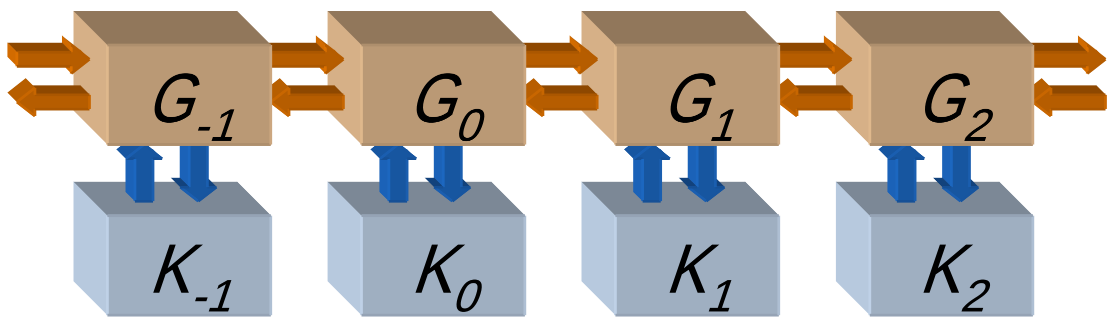
- Centralized



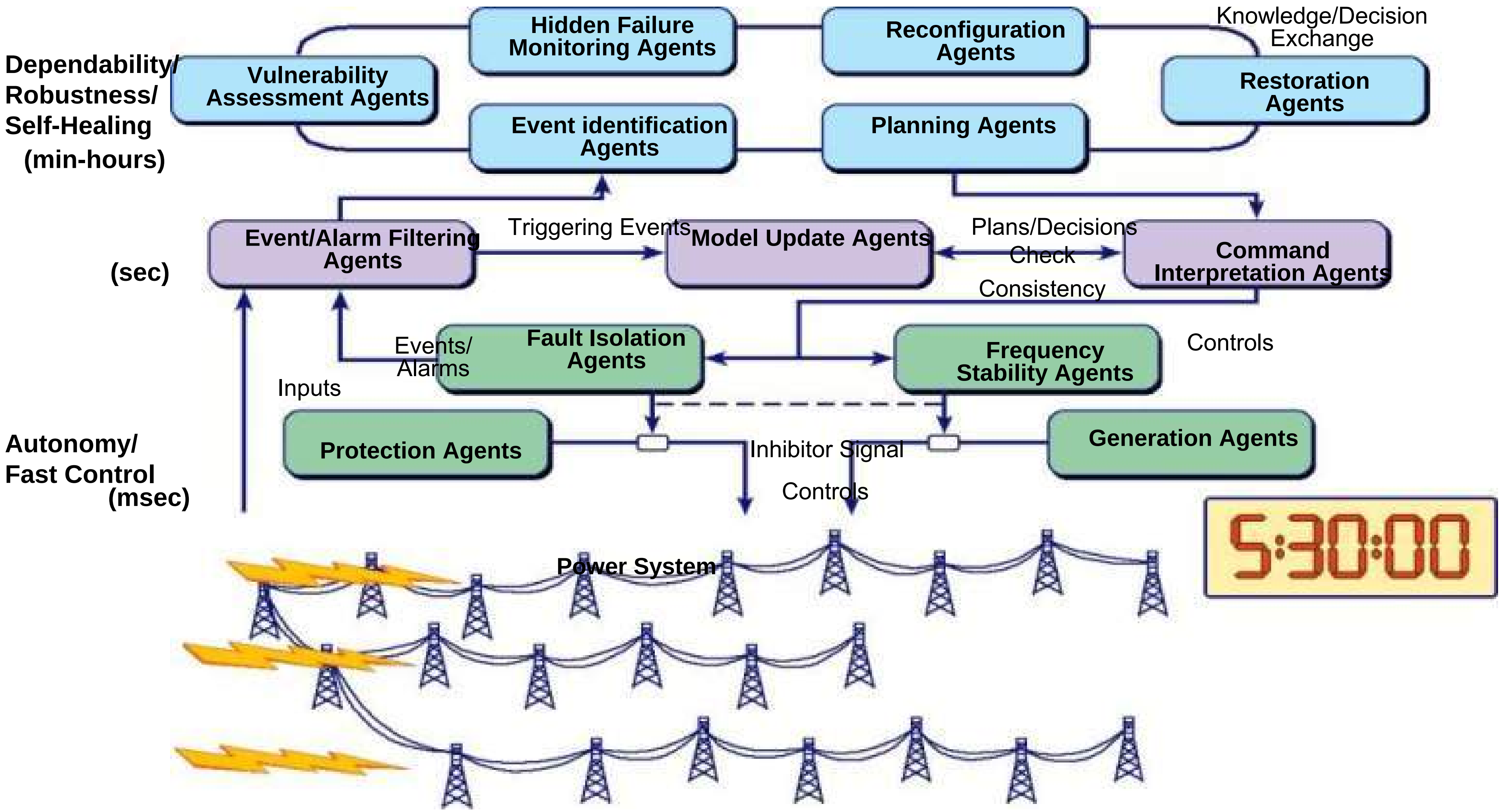
- Distributed



- Perfectly decentralized

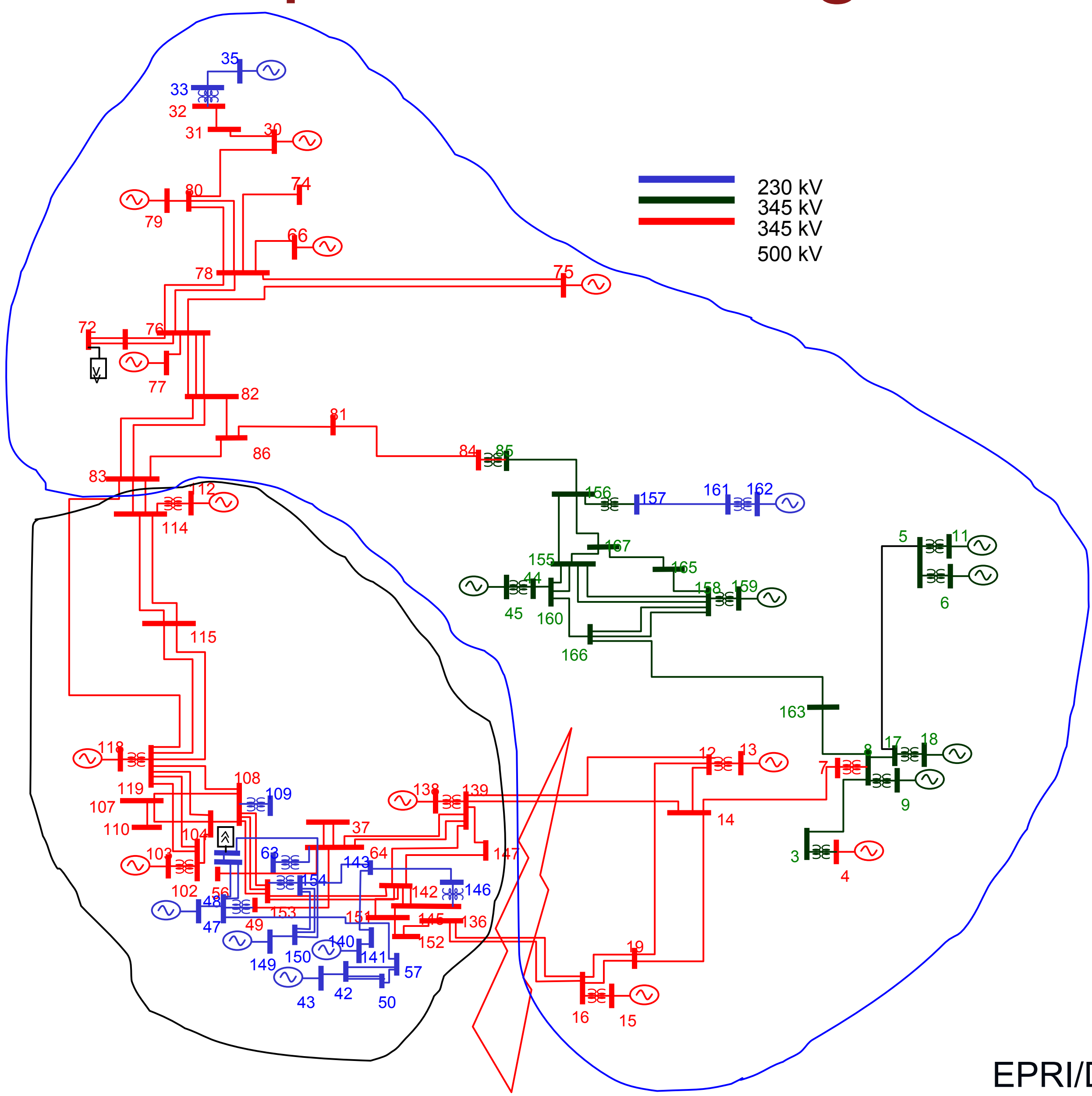


Background: The Self-Healing Grid



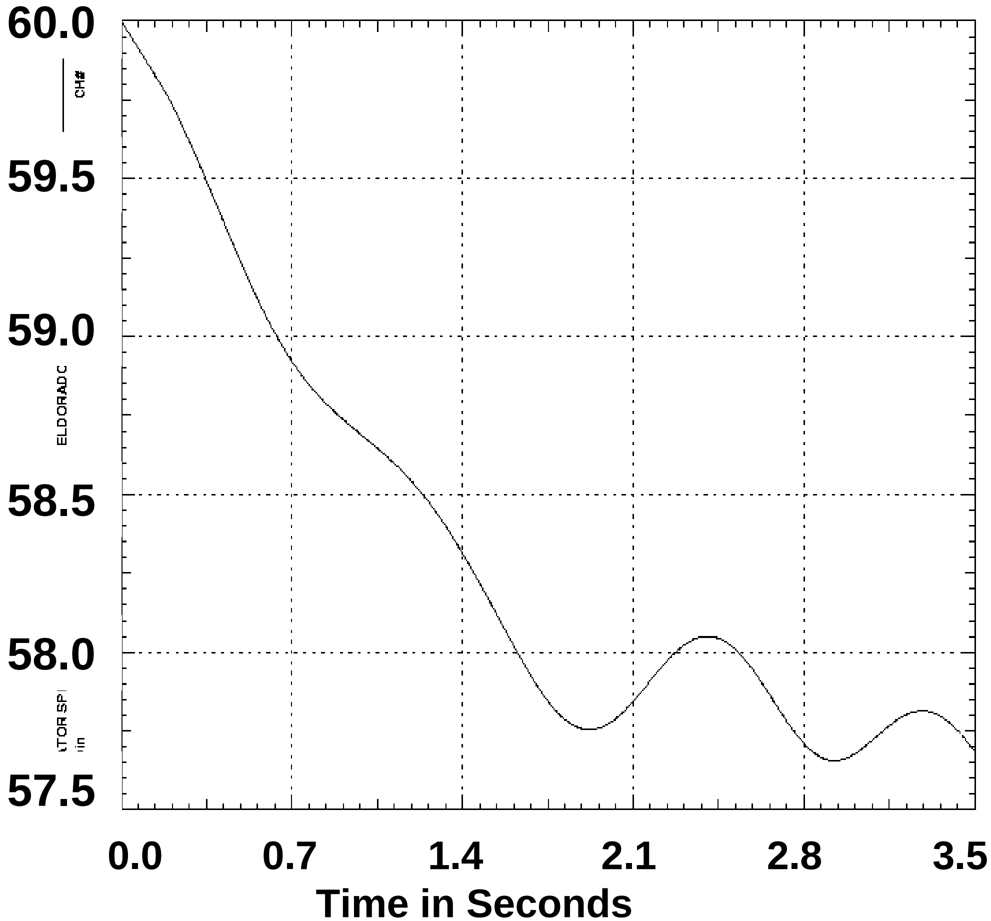
EPRI/DoD CIN/S Initiative

Background: The Self-Healing Grid
Intelligent Adaptive Islanding

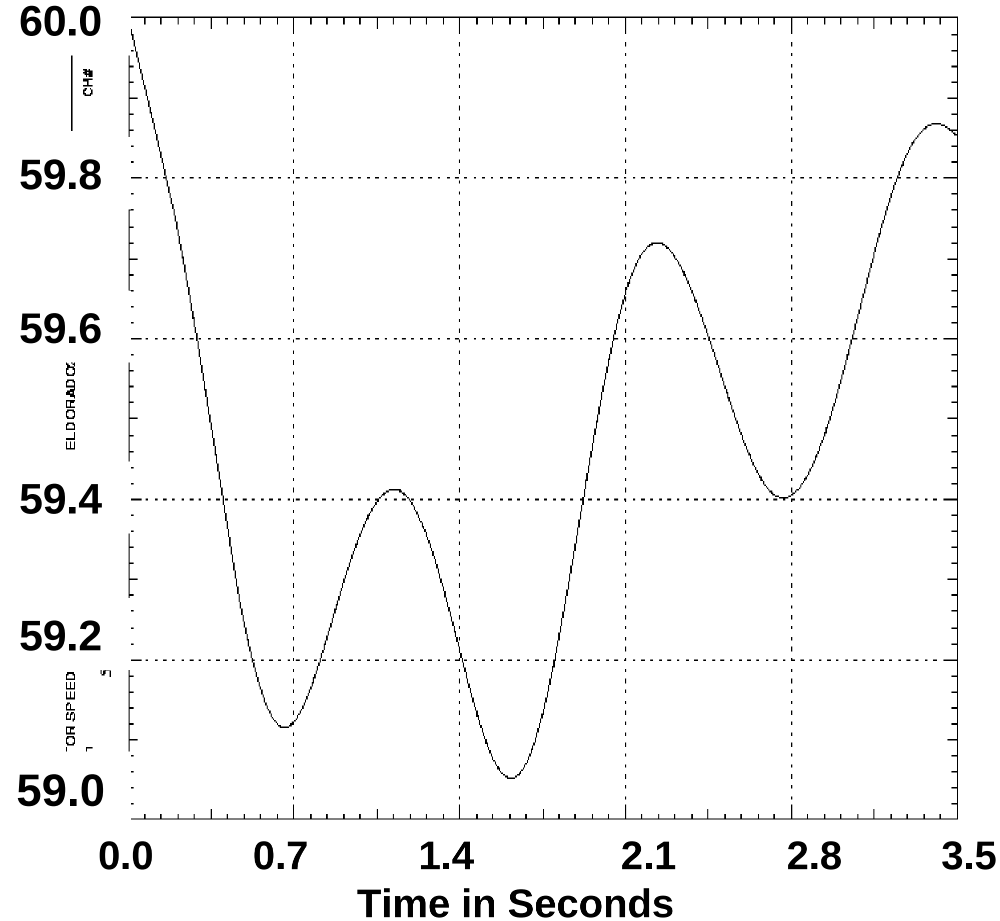


EPRI/DoD CIN/S Initiative

Background: Simulation Result

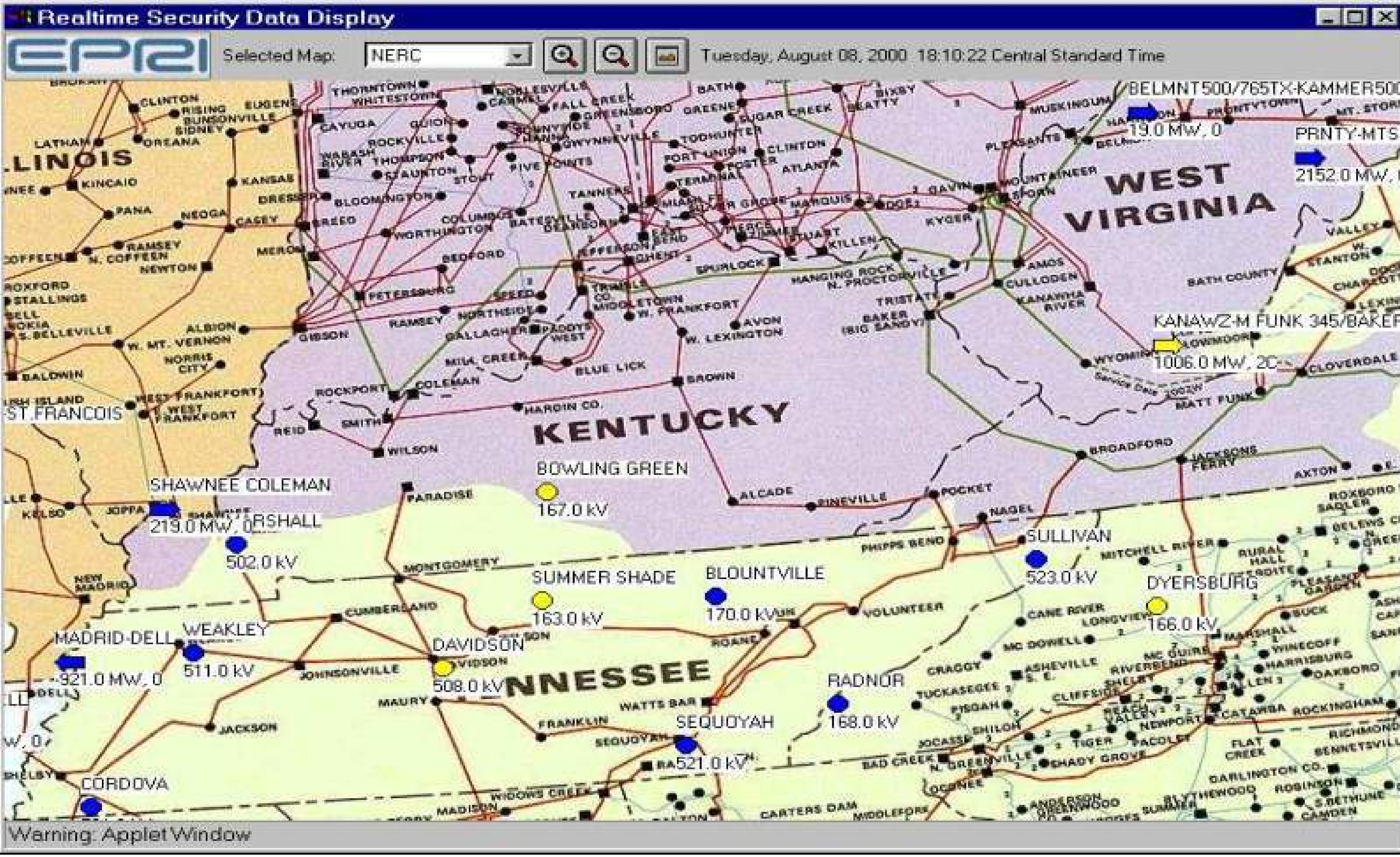


Past Scheme



New Scheme

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



Critical System Dynamics and Capabilities

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

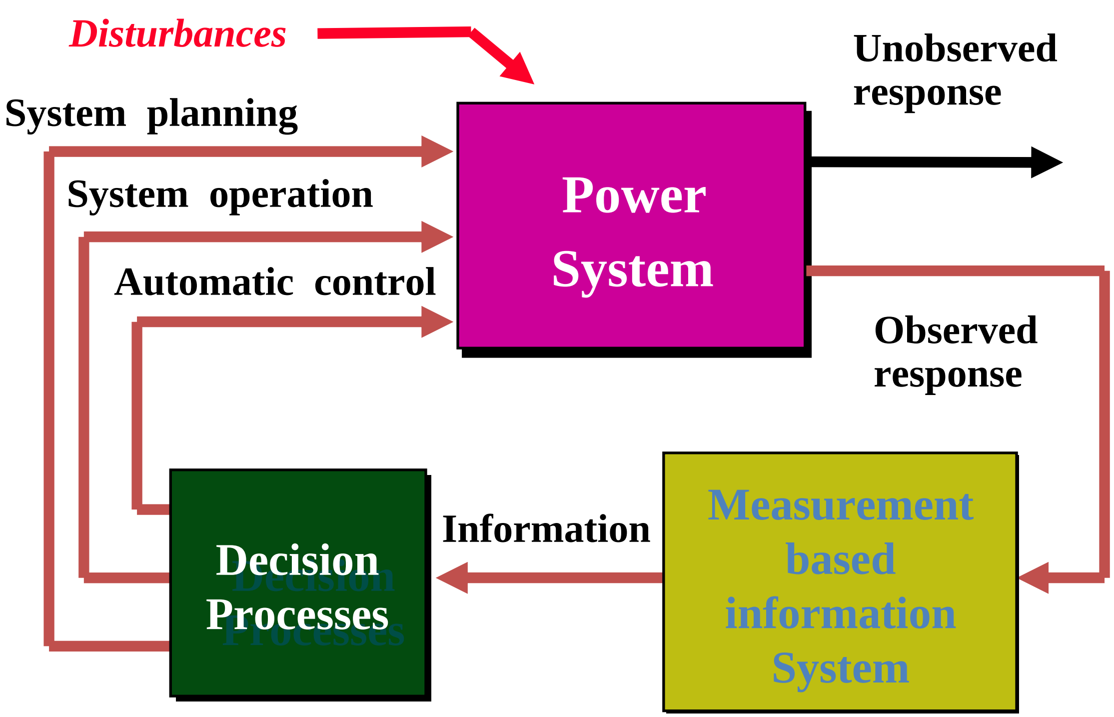
re·sil·ience, *noun,* 1824:
The capability of a strained body to recover its size and shape after deformation caused especially by compressive stress;
An ability to recover from or adjust easily to misfortune or change

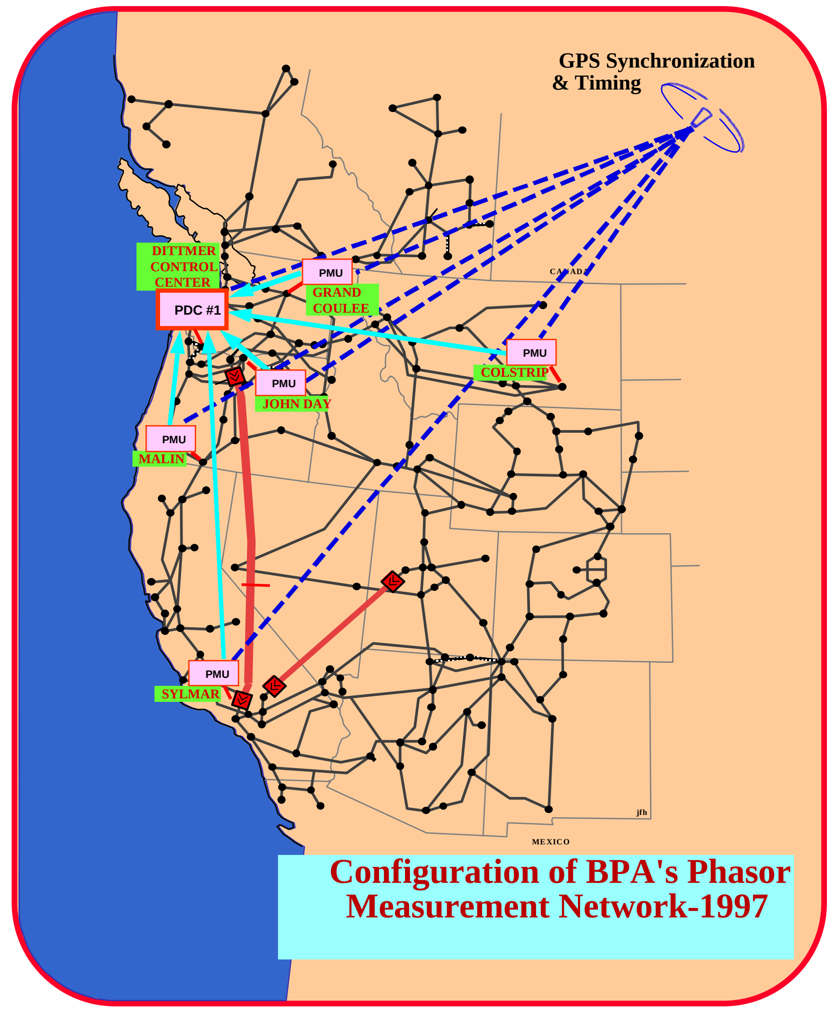
Resilience enables "Robustness": A system, organism or design may be said to be "robust" if it is capable of coping well with variations (internal or external and sometimes unpredictable) in its operating environment with minimal damage, alteration or loss of functionality.

Wide-Area Measurement System (WAMS)

Integrated measurements facilitate system management

"Better information supports better - and faster - decisions."





Configuration of BPA's Phasor Measurement Network-1997

Source: DOE/EPRI WAMS project-- BPA & PNNL, 1998

Additional Damping with Wide Area PSS Based on Autonomous and Robust Controller Concepts

System oscillations - between areas (the system is being asked to do what it was never designed for, large-scale inter-area transfers)

- Increasing interconnection of power systems
- Power system deregulation
- The number of local PSSs is saturated
- Developing wide area measurements technologies
- Apply robust controller design concepts

Power System Diagnostics and Control: Enhanced Real Time System Operation

- Several generations of dynamic recording devices (DFRs, DSRs, PMUs) deplored in power systems (WSCC, NY, NE, AEP)
- Currently, recorded data mostly used for recreating disturbance events and validating models and their parameters
- Use data to:
  1. identify the type and location of disturbances
  2. determine whether multiple events have occurred
  3. assess the impact of disturbances on system
  4. monitor whether the system is adequately damped
  5. evaluate the needs for immediate control actions or retuning control algorithms
  6. identify/detect precursors to sabotage and tamper

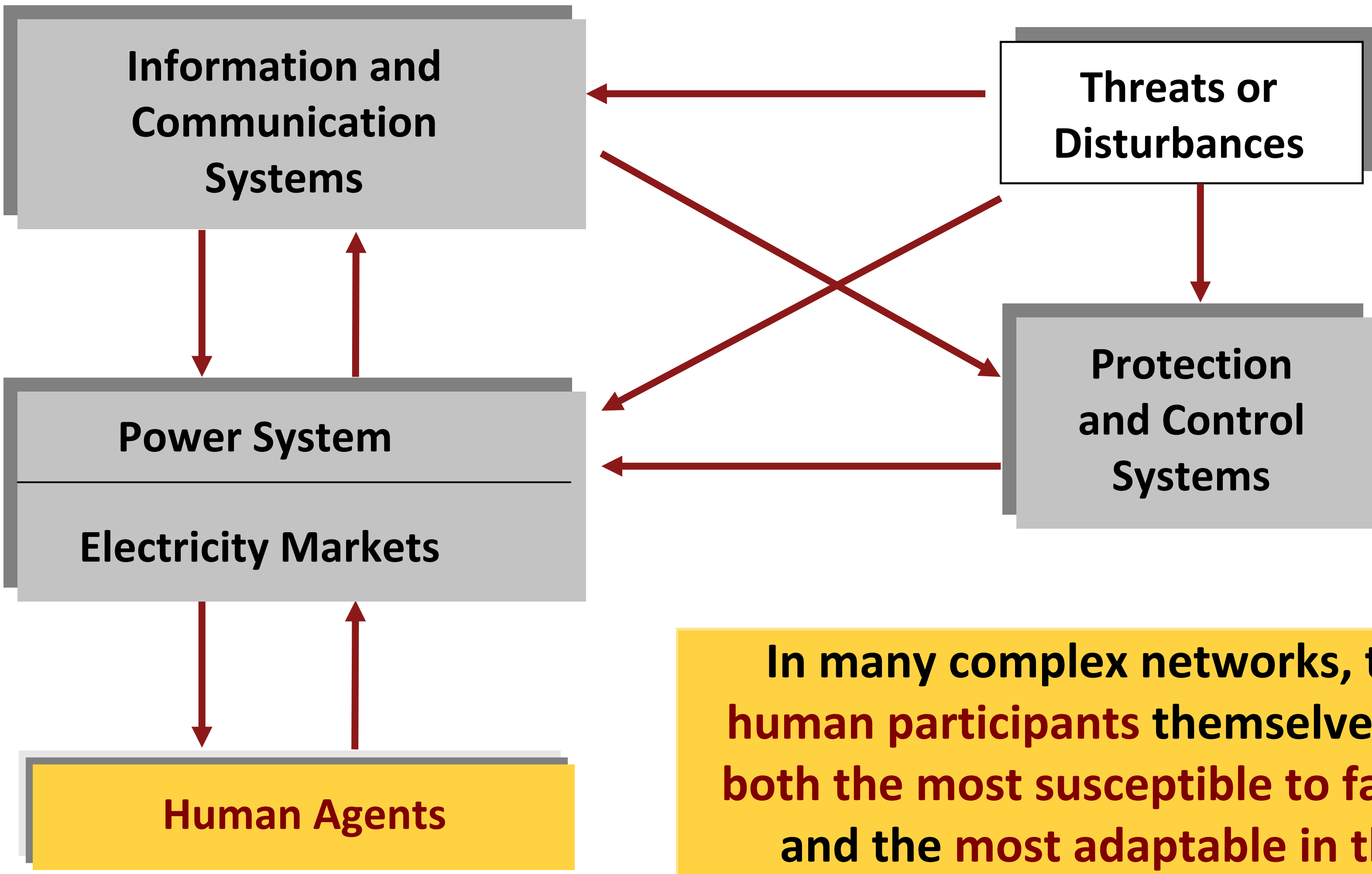
Communication Requirements (Feb. 2002)

Power System Tasks	Bandwidth Requirement	Current Response Time
Load Shedding (Local Decision)	**Low**	**Seconds**
Adaptive Relaying (e.g., Blocking relay)	**Low**	**Not Available**
Hierarchical Data Acquisition and Transfer	**High**	**Seconds (e.g., 2-12 seconds / scan for RTUs)**
Line / Bus Reconfiguration	**Low**	**Minutes (manual)**
Control Devices (e.g., FACTS, Transformer,…)	**Medium**	**Seconds (by manual)**
Fault Event Recorder Information	**Medium**	**Minutes**
Generator Control	**Low**	**Seconds**
Strategic Power Infrastructure Defense & Coordination with Control Centers (EPRI/DoD CINSI)	**High**	**Not Applicable**

Communication Requirements (Feb. 2002)

Type of relay	Data Volume (kb/s)		Latency	
	Present	Future	Primary (ms)	Secondary (s)
Over current protection	160	2500	4-8	0.3-1
Differential protection	70	1100	4-8	0.3-1
Distance protection	140	2200	4-8	0.3-1
Load shedding	370	4400	0.06-0.1 (s)	
Adaptive multi terminal	200	3300	4-8	0.3-1
Adaptive out of step	1100	13000	Depends on the disturbance	

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.

The Emerging Smart Grid or Energy Web:
A Complex Adaptive Infrastructure System

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

"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."

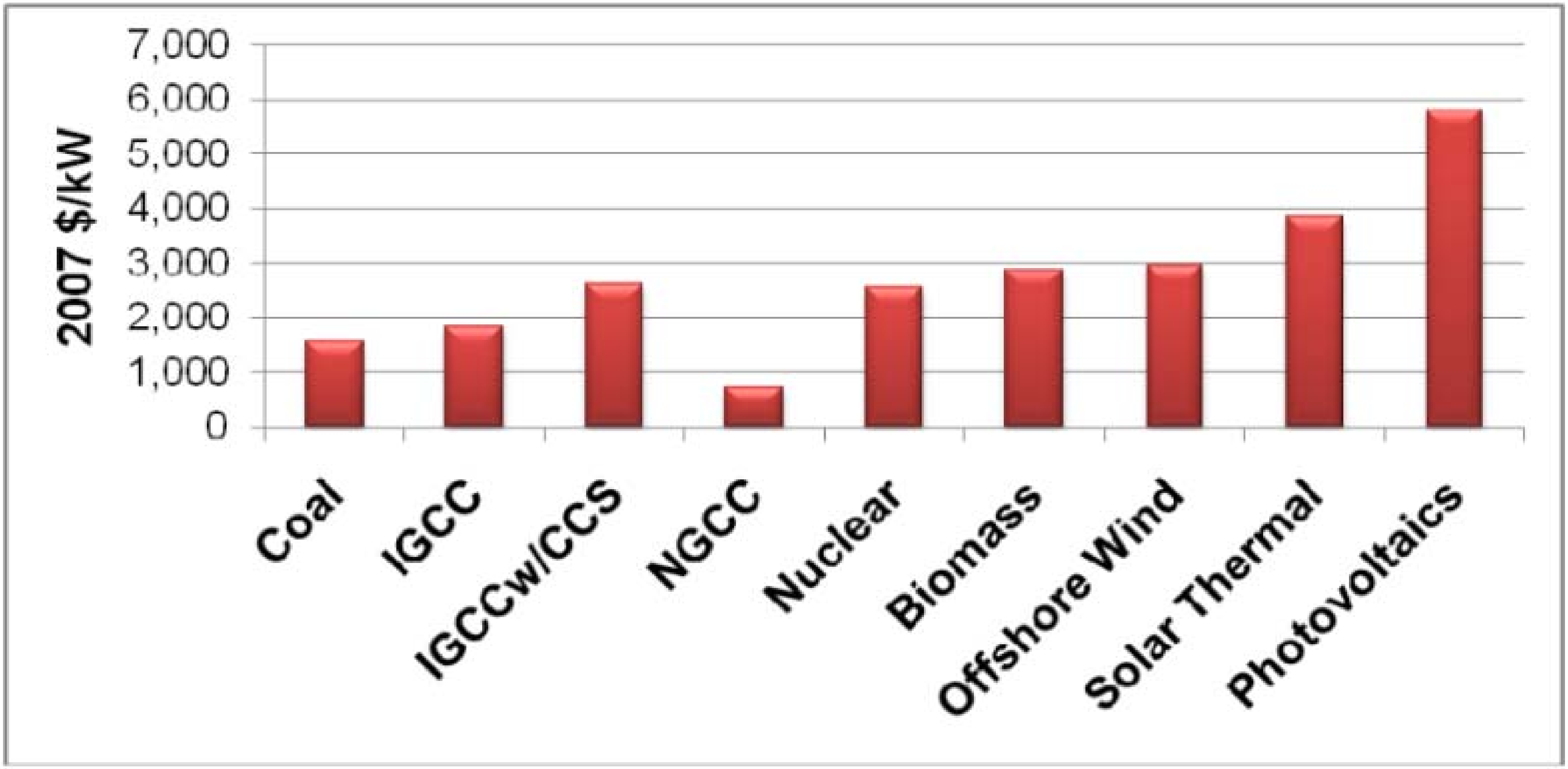
-- Wired Magazine, July 2001
http://www.wired.com/wired/archive/9.07/juice.html

Foresight

Renewables/infrastructure integration,
Electrification of transportation

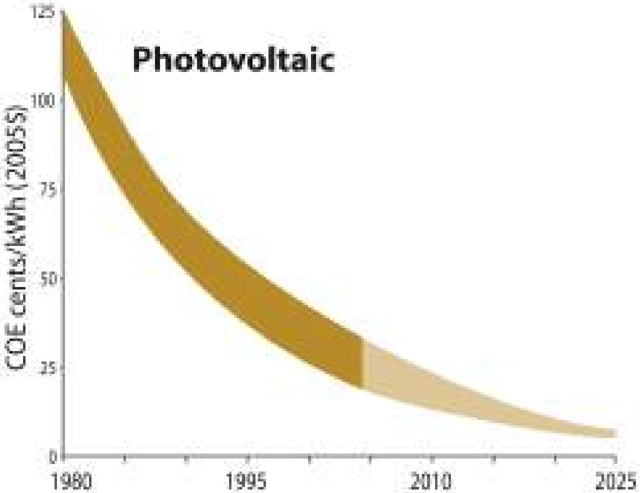
Estimated Costs of New Electric Generation

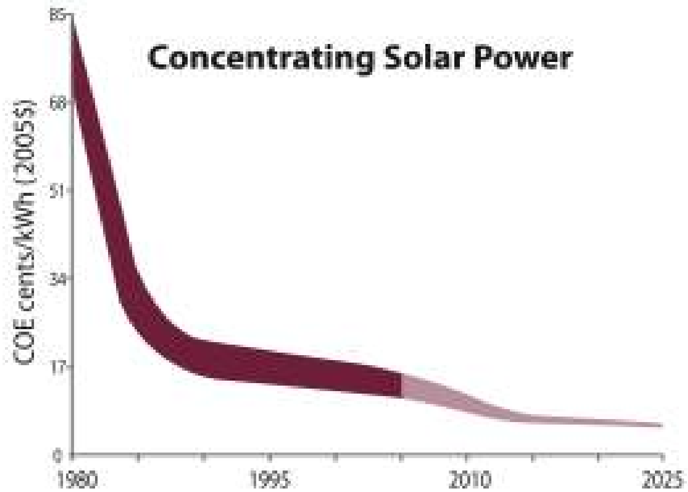
(Sources: U.S. Energy Information Administration and Management Information Services, Inc, 2008)

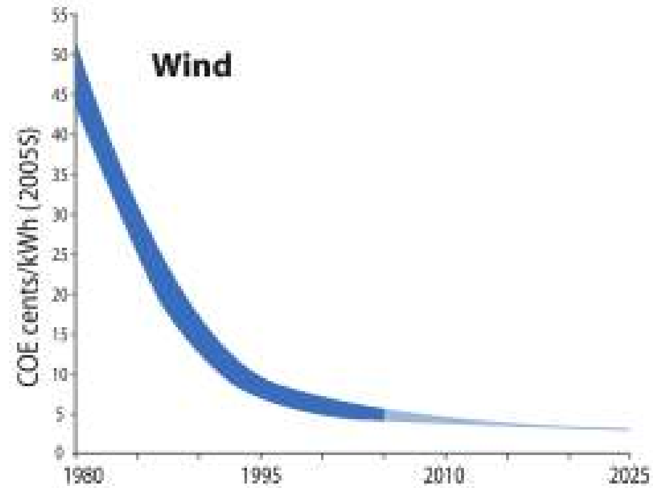


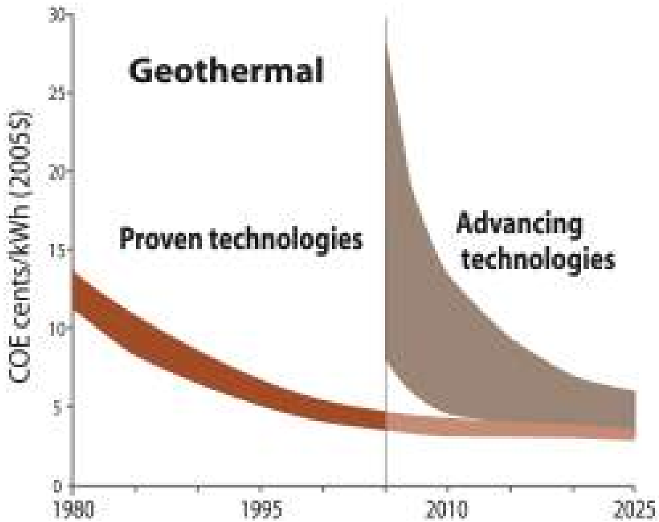
Renewable Energy Cost Trends

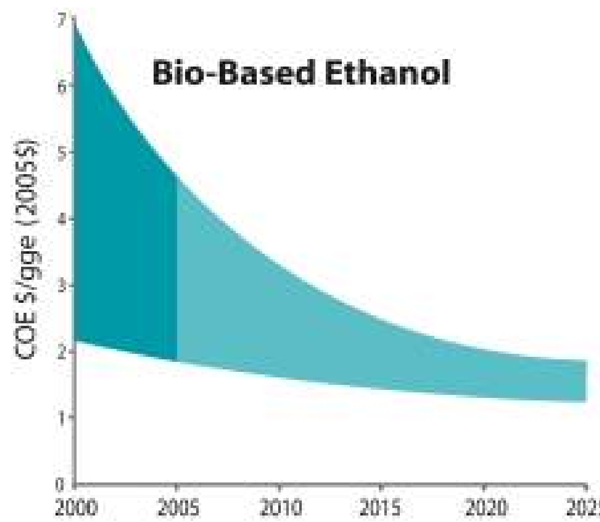
Levelized cost of energy in constant 2005$[1]









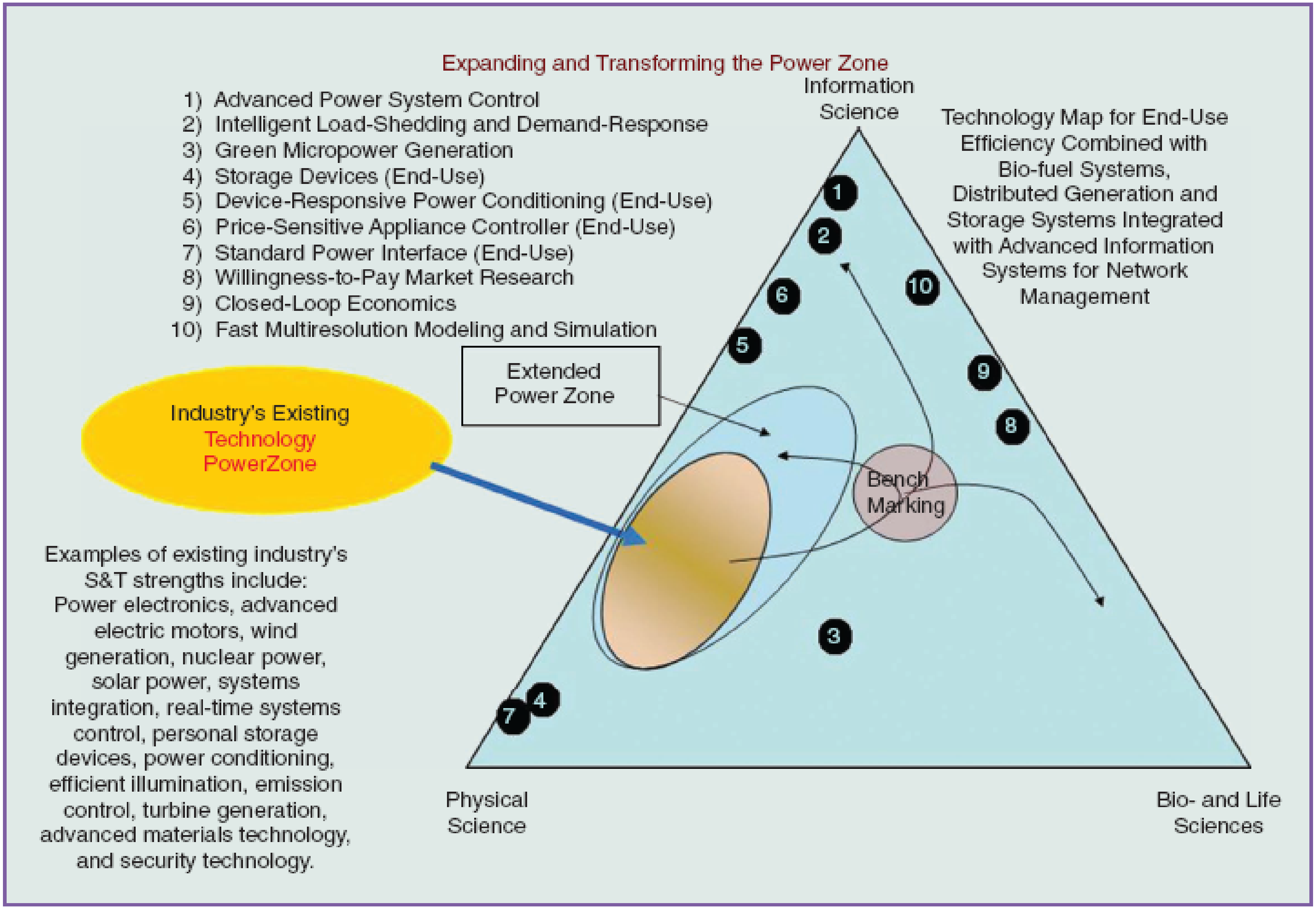


Source: NREL Energy Analysis Office (www.nrel.gov/analysis/docs/cost_curves_2005.ppt)

[1]These graphs are reflections of historical cost trends NOT precise annual historical data.

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

(April 2005-Feb 2006; Galvin Electricity Initiative)

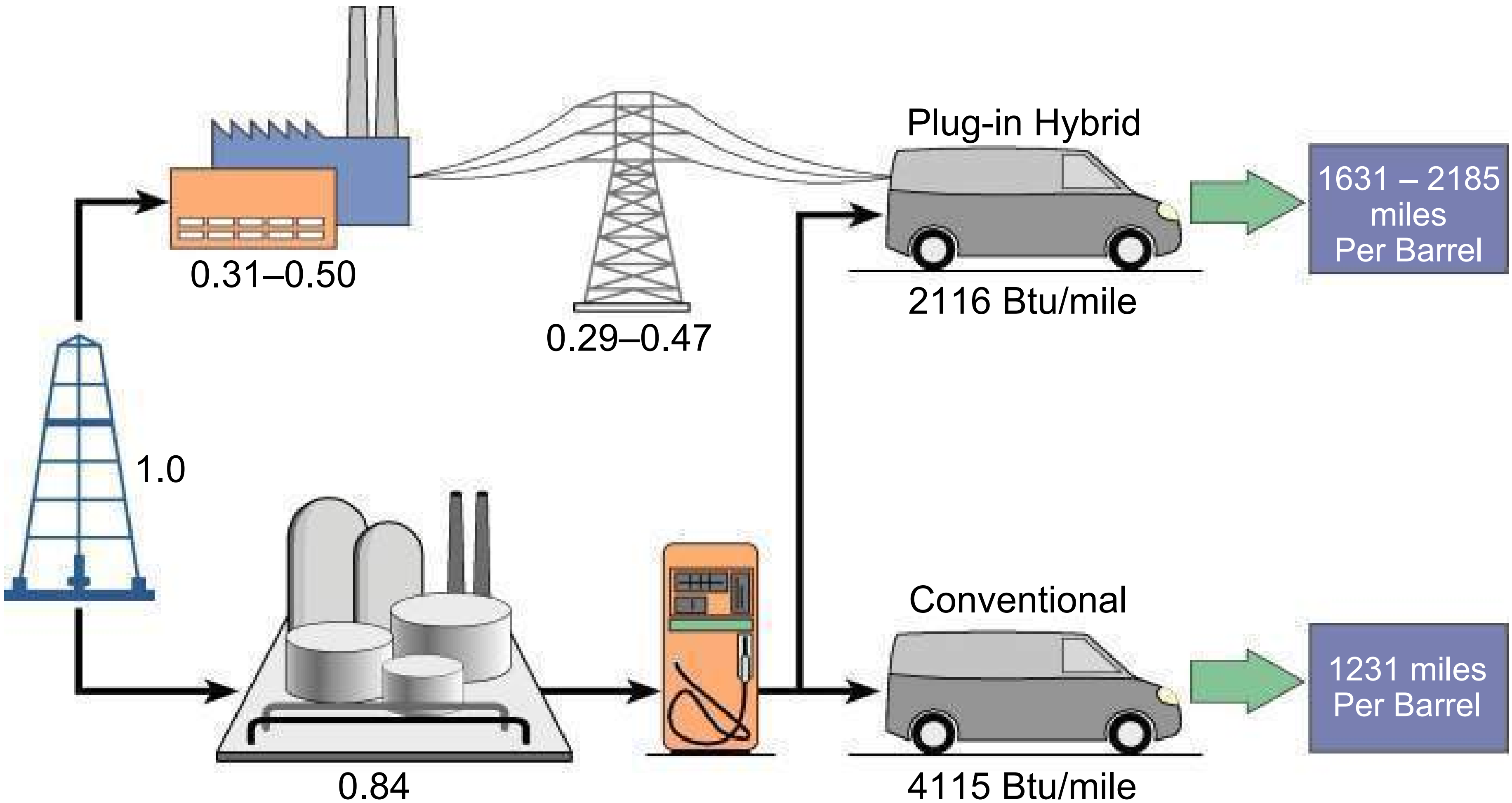


- "***Wind power could blow electric grid:*** Utilities and developers are poised to more than quadruple the amount of wind power in the Northwest, but a study shows the electric grid might not be able to handle it all, *The Oregonian* reported. The federal Bonneville Power Administration said in its 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…"

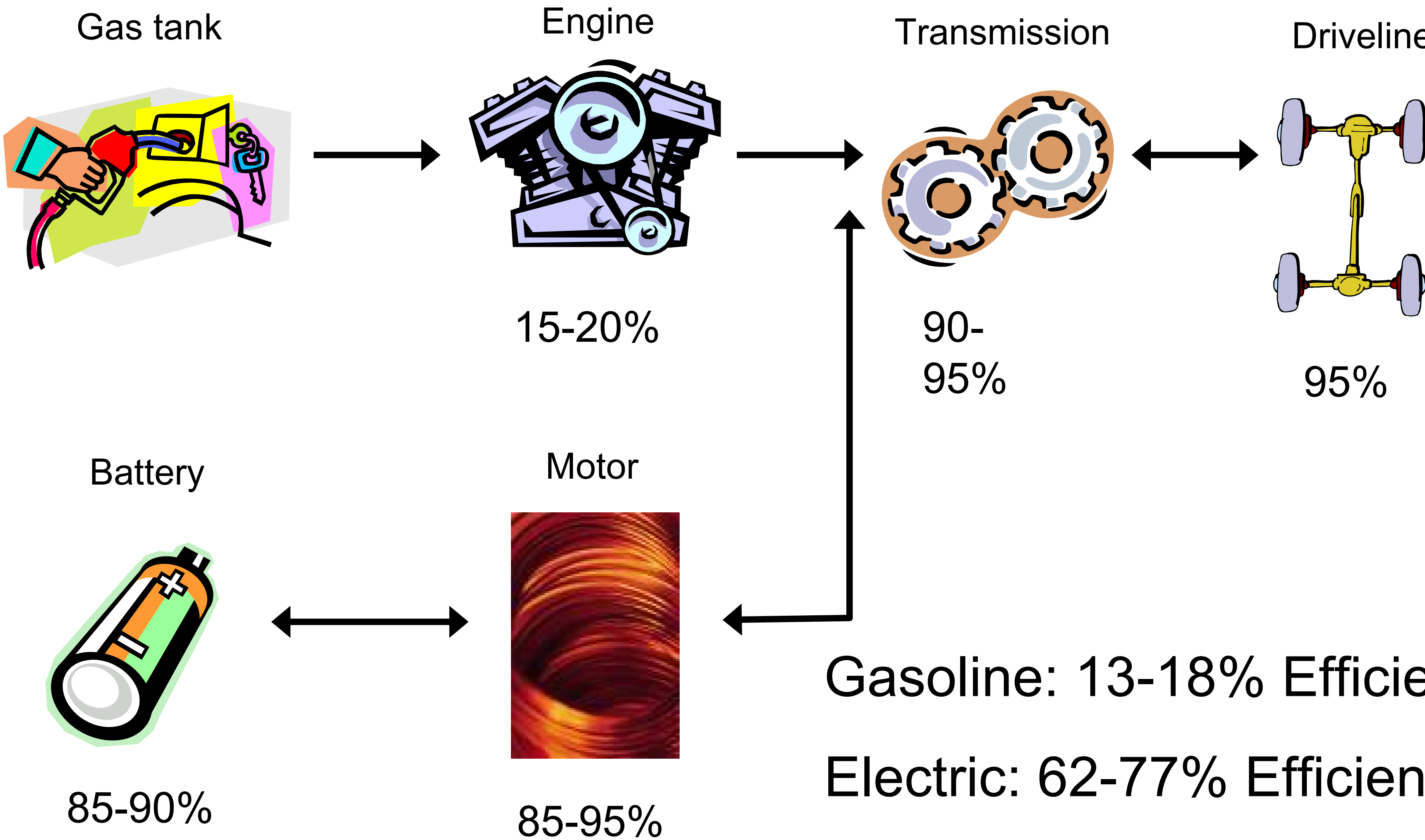
(July 22, 2008)

- "***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

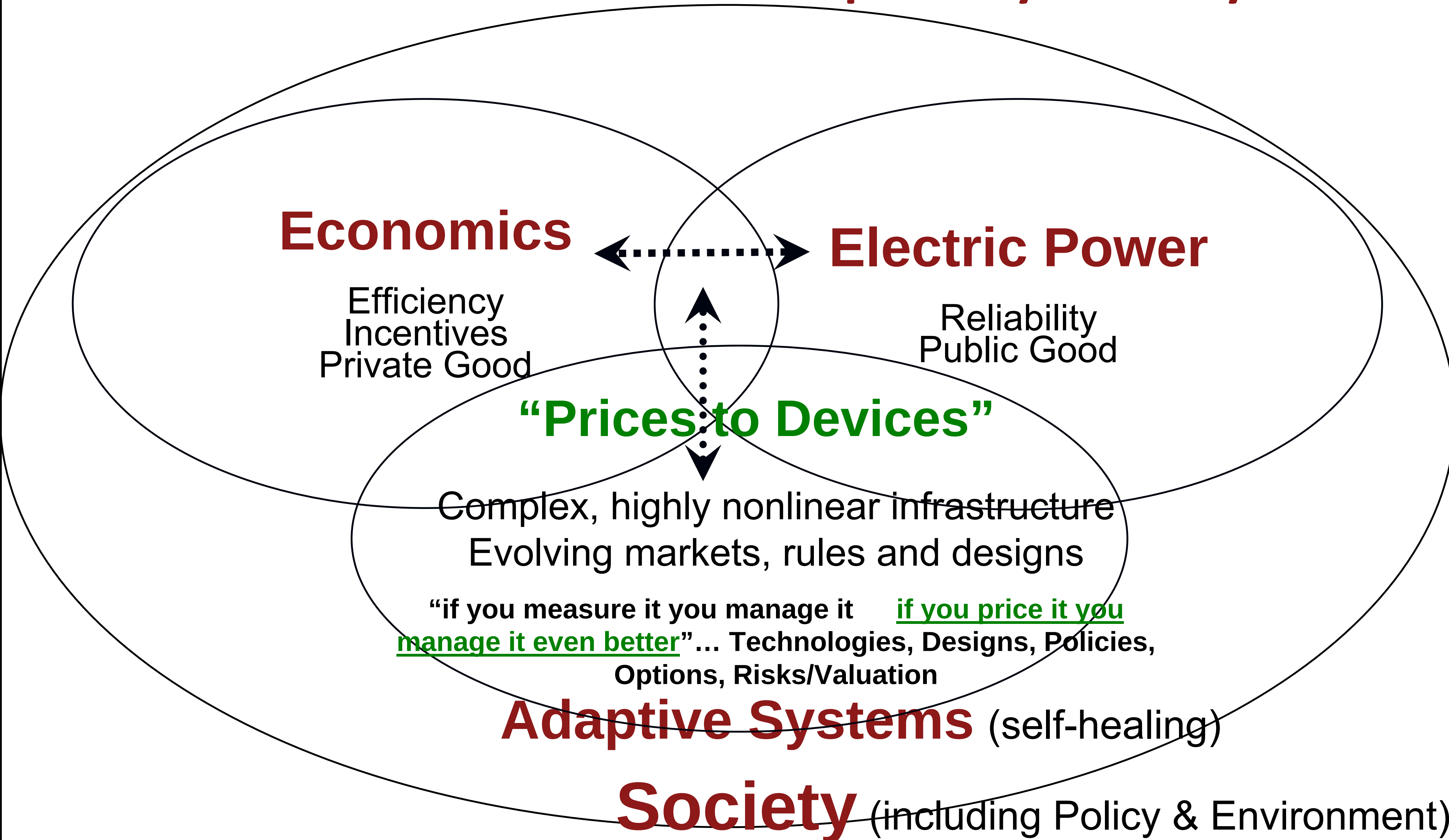
Electric: 62-77% Efficient

Bi-directional Interface for Plug-In Hybrids

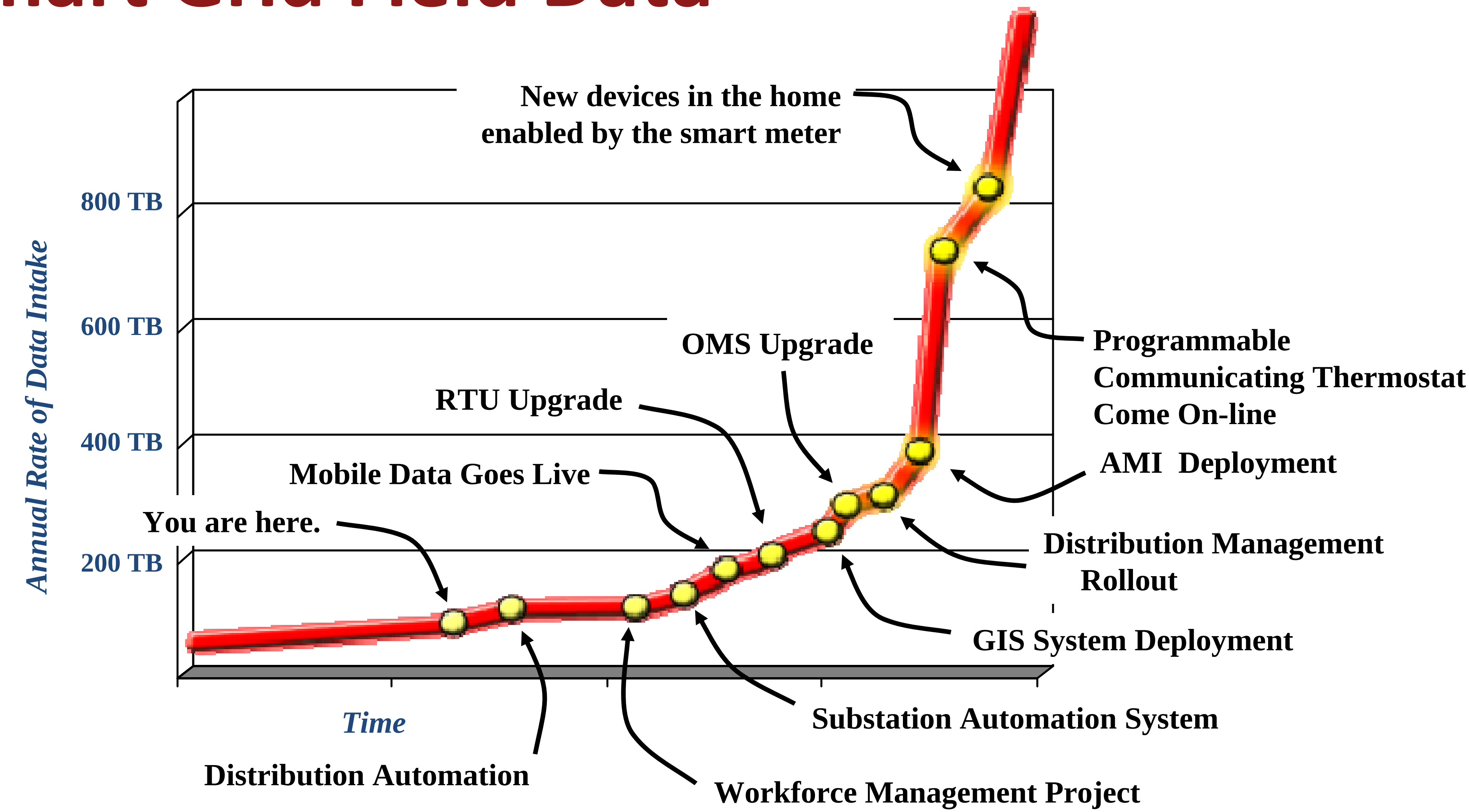
Charger for GM's EV1 was based on the Minnesota Rectifier topology.

Smart Grid

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



Smart Grid Field Data

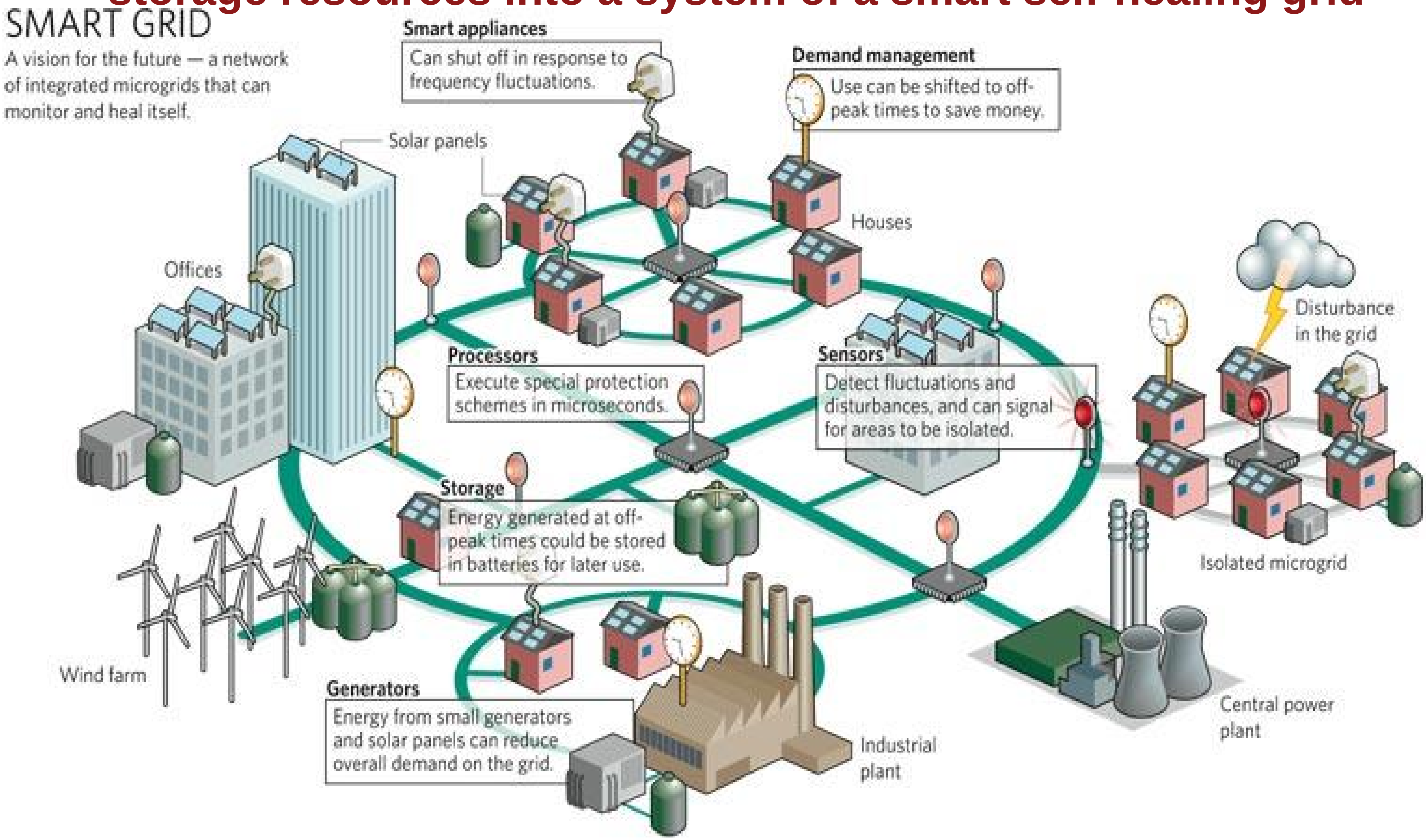


Tremendous amount of data coming from the field in the near future - paradigm shift for how utilities operate and maintain the grid

Source: EPRI

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

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.

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.

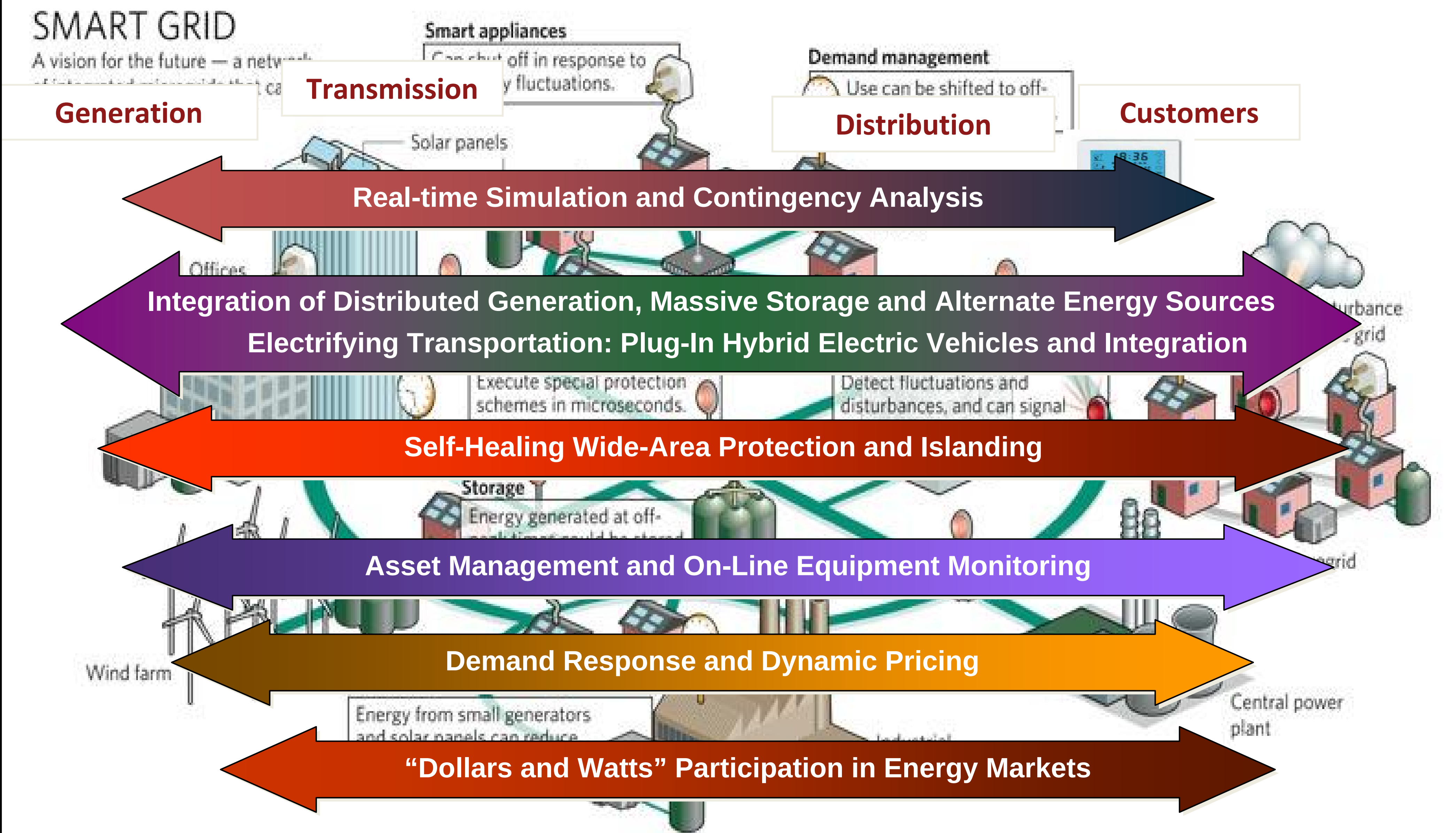
Advanced Energy Manufacturing Credits: The bill provides $2 billion worth of energy related manufacturing investment credits at a 30% rate. These credits apply to projects creating or retooling manufacturing facilities to make components used to generate renewable energy, storage systems for use in electric 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.

Related on-going R&D include

- EPRI: UCA, CIN/SI, Intelligrid, Fast Simulation and Modeling
- Initiatives at several utilities, including Xcel, AEP, Austin Energy, SCE, PG&E, ISOs, and also in companies including GE, Honeywell, IBM, Siemens, etc.
  - Austin Energy journey as an example:
    - Delivering SG1.0 (power plant - transmission, distribution - meter - customer info/bill and back) by August 2009 for 1 million consumers, 43,000 businesses, 440 square miles, 500,000 devices, and 100 terabytes.
    - Planning SG 2.0 (SG 1.0 integration to Smart Appliances, Distributed Generation, Storage, and Plug-in Hybrid EVs - EVs) via the Pecan Street Project - www.pecanstreetproject.org
- 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 and Modern Grid Initiatives
- University of Minnesota Center for Smart Grid Technologies

Enabling a Stronger and Smarter Grid



Observations

- Critical importance of **consumer empowerment** and end-to-end system modernization
- If the transformation to smart grid is to produce real strategic value for our nation and all its citizens, our goals must include:
  - To seamlessly integrate and optimize electricity supply and demand,
  - To enable every building and every node to become an efficient and smart energy node.
- Considerable effort is focused on interstate transmission, on incremental improvements and maintaining the regulated monopoly service status-quo to avoid stepping on states' rights.
  - This will inevitably undermine most of the real smart grid value by continuing the business as usual of the past, rather than for enhancing the reliability, efficiency, security and quality of consumer services.

Policy, Science and Technology Must Support This Transformation: Recommendations

- Establish the “Smart Grid” and “self-healing” interdependent infrastructure security & protection as national priorities
- Authorize increased funding for R&D and demonstrations of the “Smart Grid”, and interdependency R&D, resilience/security
- Revitalize the national public/private electricity infrastructure partnership needed to fund the “Smart Grid” deployment

M. Amin’s briefing at the U.S. Congressional R&D Caucus (www.researchcaucus.org) on March 26, 2009

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

M. Amin's briefing at the U.S. Congressional R&D Caucus (www.researchcaucus.org) on March 26, 2009


LEADERSHIP

Bottom Line:

"Only three things happen naturally in organizations:

friction, confusion and underperformance.

Everything else requires leadership."

-- Peter Drucker

We have a bright future if we challenge the best minds and marshal their talents…

- Albert Einstein once said that "compounded interest is the most powerful force in the universe":
  - "250 year reserves of coal" will shrink very quickly even at 2-3% growth rate per year.
- Advanced Nuclear and renewable resources:
  - Solar - Wind -Geothermal
  - Ocean/Wave energy -- Waste to energy
  - Agricultural, incl. soy/corn, sugar (e.g., Brazil)
    - Biodiesel, cellulosic, ethanol, methanol, biomass
  - Hydrogen from renewables (longer term)
    - will it require more energy to produce?
- Broad range of R&D including end-use and system efficiency, electrification of transportation, stronger and smarter grid with massive storage, and with security built-in.

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

…The Future is Bright…

Courtesy FPL Energy

Q&A

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Professor, Electrical & Computer Engineering
University Distinguished Teaching Professor

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

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May others benefit
from your lead.
Thank you