Sustainable Electric Power Systems in the 21st Century: *Requirements, Challenges and the Role of New Technologies*

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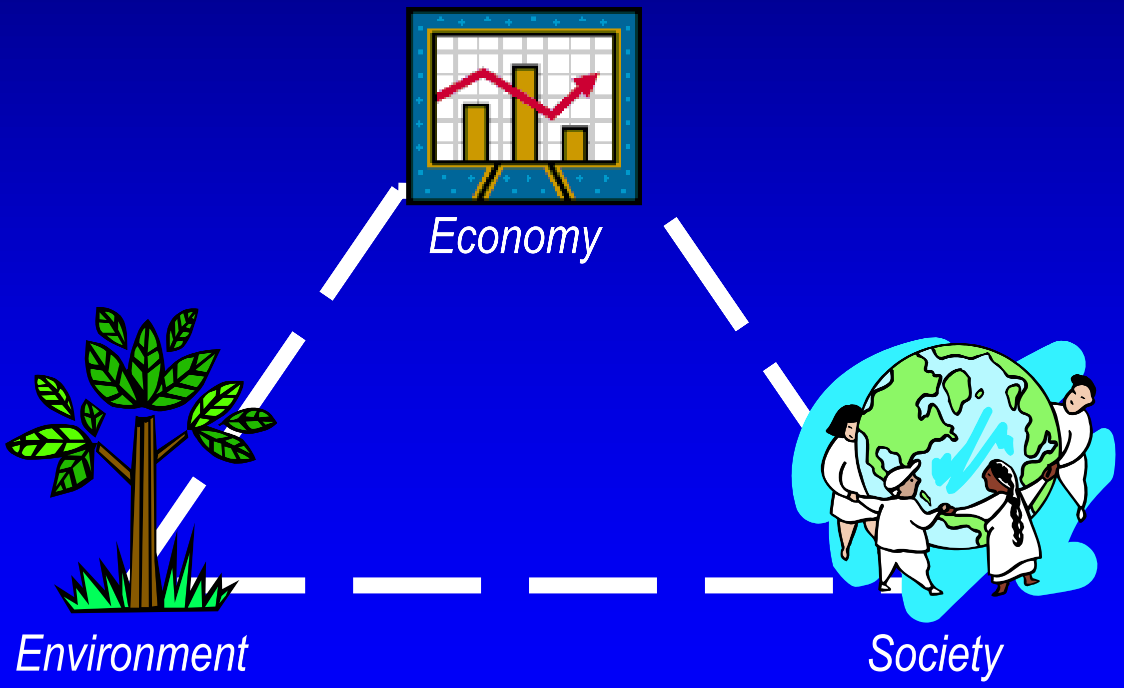
Power Systems in the 21st Century

- The electric power industry:
  - humble beginning in the 1880s; grown into one of the largest industries
- Has done a very good job of meeting the energy needs of the 20th century:
  - electricity has become a basic necessity in modern society
- Has had an adverse impact on the natural environment
- Industry now undergoing major restructuring
  - shift from monopolistic to competitive structure
  - new economic and social pressures
- Need to refocus business so as to meet energy needs of society in a way that leads to long-term "sustainability"

Sustainability

Involves balancing economic growth and social progress with the preservation of the natural environment



Sustainability of Power Systems

- Business practices have to be built on "three pillars" of sustainability:
  - environmental sustainability
  - economic sustainability
  - social sustainability
- Our challenges, therefore, are to:
  - produce, transmit and utilize energy in an environmentally responsible manner
  - reduce cost by improving business practices and operating efficiency
  - enhance reliability and quality of power supply

Environmental Sustainability

We need to:

- Integrate "green thinking" into our way of life and business practices
- Minimize the environmental impact of power plants as well as all other equipment
- Maximize resource conservation
  - leads to environmental as well as economic sustainability
- Utilize electricity/energy in an efficient and smart manner !

Environmental Concerns Related to Power Generation

- Greenhouse gas emissions, global warming issues and local emissions
- Increasing dependence on renewable sources
- Significant increase in the use of natural gas and bio-fuels
  - What is the best form of their use?
- Opportunities for clean coal technologies
- Revival of nuclear option

The general trend would be towards a "carbon-free electricity / hydrogen energy economy" !

The Gazette Newspaper
Colorado Springs, June 10, 2004

Power-plant pollution deaths tallied

COX NEWS SERVICE

AUSTIN, Texas • Air pollution from coal-fired power plants causes about 24,000 premature deaths a year nationwide, a study indicates.

The study, prepared by Abt Associates, a U.S. Environmental Protection Agency's consultant on air pollution impact, found that 22,000 of those deaths, along with many nonfatal heart attacks and tens of hundreds of thousands of asthma attacks, could be prevented by requiring power plants to install currently available pollution control technology.

But revisions to federal pollution control rules favored by the Bush administration would reduce deaths far less — by about 10,000 per year in 2020 — than the limits a bipartisan group of senators proposed in 1999, the study concluded. Abt, based in Cambridge, Mass., released a similar study in 2000 before multiple medical studies linked power plant pollutants with increased risk of cancer and heart attacks.

Unveiled in cities across the nation Wednesday, the study was commissioned by a coalition of environmental groups known as Clear the Air. Paid for by the Pew Charitable Trusts, it was reviewed and embraced by a number of organizations with scientific or medical credentials, including Physicians for Social Responsibility, a 1985 Nobel Prize winner.

"The scientists in our headquarters office believe this is sound science and should raise alarm bells," said Lisa Doggett, an Austin family practice doctor who helped organize the physician group's Austin chapter, which released the study in Austin along with the Texas Public Interest Research Group.

"The evidence, from groups such as the American Academy of Pediatrics, is growing that pollution from power plants can be a significant cause of health problems, such as cancer and heart attacks, in addition to asthma attacks," said Doggett, daughter of U.S. Rep. Lloyd Doggett. "Between 10 and 20 percent of my patients (at the People's Community Clinic) suffer from asthma or a respiratory disease."

Statewide, the pollution from coal-fired power plants causes 144 lung cancer deaths each year, the study found.

Technology Drivers that will Help Meet Future Energy Needs

- Technological advancement and cost reduction, combined with novel applications of renewable energy technologies
  - Bio-energy**
  - Solar energy
  - Geothermal
  - Ocean energy **
  - Wind energy
- Energy Storage
  - advanced batteries
  - hydrogen

Technology Drivers (cont'd)

- Distributed Energy Technologies
  - Fuel cells, Microturbines
  - installed at points of consumption to reduce peak demand, reduce transmission costs, and improve power quality and security
- Technologies for complementary use of electricity and hydrogen as energy carriers

Ocean Energy

- Forms of ocean energy
  - tidal current energy: tides, currents, thermal, salinity gradient
  - wave energy
- Receiving much attention
  - many pilot projects worldwide
  - recent project at Vancouver Island using a novel turbine design:
    - friendly to aquatic life
  - potentially a large primary energy source: clean and cheap
- Typical costs
  - capital costs = $1000/kW to $2000/kW; energy costs = $0.35/kWh
- Integration with existing power systems presents technical challenges
  - not an insurmountable problem

Fuel Cells

- First demonstrated in 1839 by William Grove
  - combines hydrogen with oxygen from air to generate electricity with water and heat as by-products
- Hydrogen may be supplied from an external source, or generated inside fuel cell by reforming a hydrocarbon fuel
- Used to power tractors since 1959; used by NASA in the 1960s
- Recent advances have reduced cost and size dramatically
- Wide range of potential applications
  - source of electric power in different sizes: micro fuel cells for laptops to large units connected to power grids
  - automobiles: fuel cell vehicles

The key device in the complementary use of electricity and hydrogen !

Typical Operating Characteristics of Fuel Cells

Type/Electrolyte	Efficiency	Temp	Capacity
Proton Exchange Membrane	30-35%	180°F	5-250 kW
Phosphoric Acid	35-40%	400°F	50-200 kW
Potassium/Lithium Carbonate	45-57%	1200°F	250 kW-30 MW
Solid Oxide	45-50%	1800°F	3 kW- 3 MW

- **Emissions** (lbs/MWh):

	NOx	SO_2
Fossil fuel plant	4.20	9.21
Microturbine	0.29	0.00
Carbonate fuel cell	0.013	0.00

Fuel Cells (cont'd)

- With co-generation, a carbonate or solid oxide fuel cell can achieve an efficiency of 60% to 70%
  - Can generate electricity directly from a hydrocarbon fuel by reforming the fuel inside to produce hydrogen
  - this compares with efficiency of 35% for coal plants and 40% for gas turbines

- Examples of fuel cell applications for power generation using bio-fuels:

  (a) waste from dairy processing plant (City of Tulare, California)

  (b) waste byproduct of beer brewing process (Sierra Nevada Brewing Co.)

  (c) biogas produced from food waste (Tokyo Super Eco Town)

  (d) biogas from water treatment plant (Point Loma Water Treatment Plant, San Diego, CA)

- Environmentally friendly alternative power generation source that can potentially yield lower cost electricity
  - non-combustion, non-mechanical power generation process
  - lower fuel and maintenance costs

Hydrogen Energy

- Hydrogen is an energy carrier
  - not a primary energy source
  - similarity with electrical energy
- Complementary use of electricity and hydrogen
  - hydrogen ideal for energy storage
  - offers more flexibility for transportation and use
- Hydrogen can be:
  - used just like conventional fuels, or
  - reacted with oxygen in a fuel cell to produce electricity (more efficient)
- The two most abundant hydrogen-containing compounds:
  - water (H_2O)
  - hydrocarbon fuels (H_xC_y), such as: oil, coal, natural gas and biomass

Hydrogen Economy

- Significant changes in the energy field tend to occur at the turns of centuries
  - early 1800s - the rise of steam
  - early 1900s - the rise of electricity
  - early 2000s - the dawn of hydrogen age?
- Interest in hydrogen energy is not new !
- What are the major drivers leading to hydrogen economy now?
  - environmental concerns
  - technological developments
- Challenges to the use of hydrogen
  - reduction in cost of production
  - safe storage at the required high pressure
  - availability of appropriate primary energy source

Formation of Hydrogen Infrastructure

- Production of hydrogen from hydrocarbons
  - reforming natural gas, methane, biomass, ...
  - development of decarbonization technologies
  - coal gasification: longer term, high potential option
- Production of hydrogen from water, using electrolysis
  - attractive in systems with surplus electricity and limited storage capability
- Development of renewable electric power resources for distributed hydrogen production: small hydro, solar, wind, wave

Formation of Hydrogen Infrastructure (cont'd)

- Development of hydrogen fuelling / supply stations
- Development of high pressure hydrogen storage and transportation technologies
  - hydrogen has low energy density
  - needs to be stored and transported at high pressure
- Hydrogen storage: high capacity and cyclable
  - containers for storage of compressed hydrogen
  - metal hydrides, ceramics and conducting polymer

Role of Electric Utility in Enabling the Hydrogen Economy

- Hydrogen and electricity are readily exchangeable
  - form an ideal "energy currency pair"
- Hydrogen and electricity will dominate the transportation and energy delivery systems of the 21st century
  - will link low-impact energy sources to end-users
- Electric utilities are well positioned to be key enablers of the hydrogen economy by producing, distributing and selling hydrogen to markets in:
  - transportation (limited involvement so far: electric trains and street cars)
  - industrial supply
  - portable power
  - stationary power

Powertech Lab's Hydrogen 700 Project

- Cooperative project sponsored by six automobile manufacturers
- Powertech has been facilitating development of 700 bar (10,000 psi) hydrogen storage systems for fuel cell vehicles
  - lightweight and safe storage system
  - performance tests on storage tanks, regulators, solenoid valves, pressure relief devices
  - safety and performance tests include:
    - hydraulic pressure cycling
    - exposure to temperature and environmental extremes
    - vibration
    - bonfire and gunfire
  - ISO 15869 standard for compressed hydrogen storage for vehicles

Powertech's Compressed Hydrogen Infrastructure Program (CH_2IP)

- Multi-year program initiated in 2001 to demonstrate the technical feasibility of hydrogen infrastructures for transportation and power generation markets
- Funded by the Canadian Government and several industrial partners:
  - BC Hydro, Stuart Energy, BP, Shell Hydrogen, Chevron Texaco, BOC, Dynetek, JFE Container
- Design and construction of high pressure hydrogen fuelling stations
  - first 700 bar station in the world for fast-filling of hydrogen
- Lightweight mobile trailers for transporting hydrogen at 875 bars
- Supported testing 700 bar vehicle safety standards for hydrogen fuelling stations


BChydro
BCHydroGEN
Powertech
Stuart
Powertech
BCHydroGEN
Ford
fuel cell vehicle
zero emissions

B.C. Hydrogen Highway's Integrated Waste Hydrogen Utilization Project (IWHUP)

- Three-year, $17 million project led by Sacré-Davey Engineering and Powertech Labs, with 8 other organizations
- Involves capturing and purifying by-product hydrogen vented to the atmosphere at ERCO's electrochemical sodium chlorate plant in North Vancouver
- Facilities to initially produce up to 20 kg/hr of pure 6250 psig hydrogen
  - ultra high-pressure transportable hydrogen storage systems
  - mobile hydrogen fuelling station to create Hydrogen Infrastructure for light-duty vehicles
  - hydrogen is initially being used to fuel 8 internal combustion engines converted to run on H_2
- Enough waste hydrogen (600 kg/hr) from the plant to fuel 20,000 vehicles

Future of Distributed Generation (DG)

- Offer significant economic, environmental and security benefits
- DG becoming increasingly cost competitive !
- A study conducted by World Alliance for Decentralized Energy (WADE) compares the costs of future capacity development using a rigorous model for the U.S.:
  - 5.8 cents/kWh vs 8.9 cents/kWh for conventional central generation
- Reduction of transmission costs in most cases

Future of Distributed Generation (cont'd)

- DG will significantly reduce greenhouse gas emissions
- Less vulnerable to natural calamities and acts of terrorists
  - ice storm (Quebec and Eastern Ontario)
  - hurricane (France, U.S.)
  - earthquakes
  - sabotage
  - power grid blackouts (2003 blackouts in North America and Europe)
- Protection and controls for DG should be designed so that the units continue to operate when isolated from the power grid

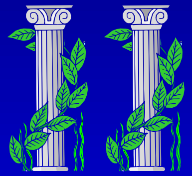
Other Aspects of "Greening of the Electric Power Business"

Minimizing the environmental impact of all equipment, not just generation.

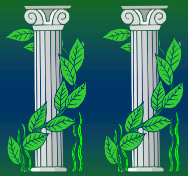
The following projects at Powertech Labs serve as examples:

- **Sulfur hexaflouride (SF_6) gas assessment and reclamation:**
  - reduction of emission of an extremely potent greenhouse gas
- **PCB in solids destruction plant**
  - disposal of PCB contaminated fluorescent light ballast potting compound using sodium dispersion process: a non-thermal environmentally benign process
- **Environmentally friendly transformer oil:**
  - vegetable-based oil as alternative to mineral-based oil; biodegradable and non-toxic to fish

Social Sustainability



Social Sustainability

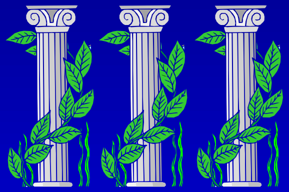


- Equity of customer access
- Ethical business practices*
- Governance and control

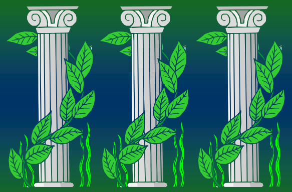
- Occupational safety and control
- Employee development

- Community development
- Partnerships/Networking*
- Support for universities and basic research*

Economic Sustainability



Economic Sustainability



- Efficiency, economy and service quality
  - More important in the new environment
- Efficiency and economy achieved by
  - More effective use of individual equipment and the integrated power system
- Service Quality
  - Need to have an infrastructure that will support the reliability and service quality demands of a digital economy
- An increased focus will be on providing a "higher value service"

Smart Grid Concept
and
Enabling Technologies

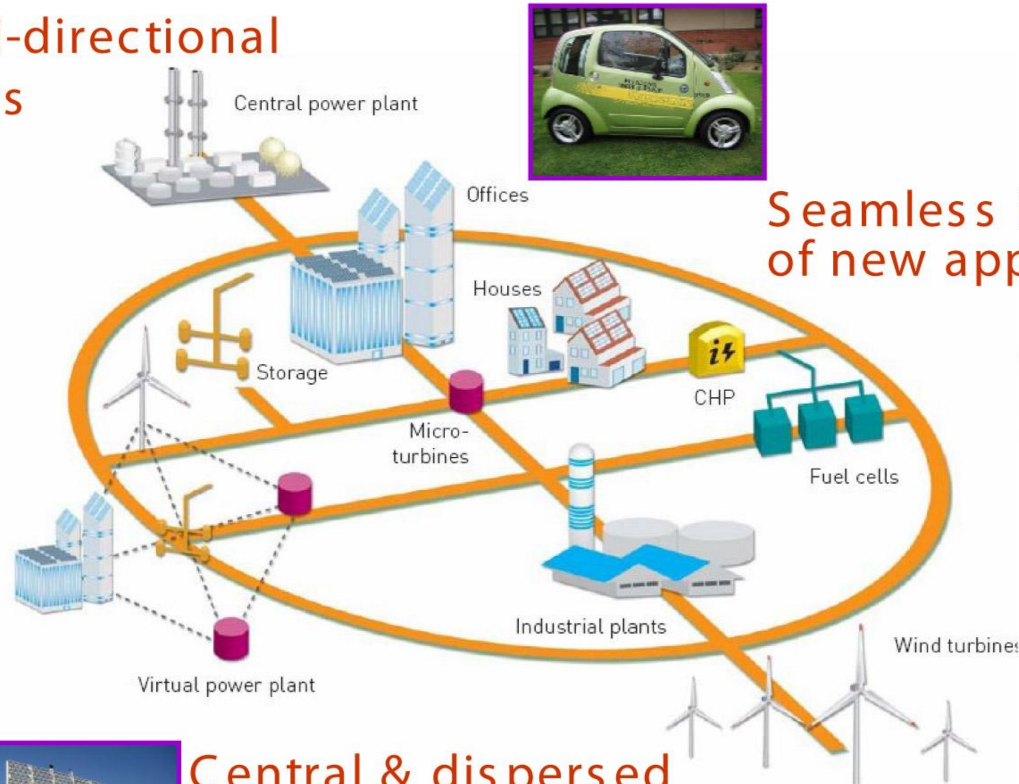
Smart Grid

- A Smart Grid is an electricity network that intelligently integrates the actions of all users connected to it: generators, transmission equipment and consumers to efficiently deliver sustainable, economic and secure electricity supplies.

- A Smart Grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies to:
  - better facilitate the integration of generators and storage devices of all sizes and technologies;
  - allow end consumers to play a part in optimizing operation of the system;
  - significantly reduce the environmental impact of the total electricity supply system; and
  - deliver enhanced levels of reliability and quality of power supply.

Smart Grid: the more internet-like grid

Multi-directional flows



Seamless integration of new applications

End user real time Information & participation

Central & dispersed intelligence

Central & dispersed sources

Smart materials and power electronics

COURTESY OF JOHN SCOTT, KEMA

Smart Grid: Goals & Objectives

- Effectively engaging consumers/end users in optimizing overall power system performance
- Enhancing efficiency of power system operation and reduction of capital costs
- Enhancing security, reliability and quality of power supply
- Enabling distributed energy sources
- Enabling electric vehicles/transportation

Smart Grid Enabling Technologies

- Robust, Reliable and Secure high speed communication systems
- "Intelligent" electronic devices, monitors and algorithms for online condition assessment and taking corrective actions

Smart Grid Application Domains

1. Implementation of Advanced Metering Infrastructure: Load Management
2. Integration of Distributed Resources and formation of Microgrids
3. Effective use of equipment: Condition assessment, performance enhancement and life extension
4. Enhancement of Integrated Power System Performance

Advanced Metering Infrastructure

- Smart Meters:
  - Allow consumers to track their energy use and participate in load-shaping strategy and energy-savings program
  - Reduction in the expense of online meter reading
- Real-time pricing/hour ahead emergency pricing with *"Home Energy Dashboard"*
  - Time-of-use-pricing provides a financial incentive for consumers to shift some electricity usage from on-peak periods to off-peak periods
- Direct Load Control (?)
- Electric and Plug-in Hybrid Vehicles
  - Reduction of fueling costs
  - Load shaping

Distributed Resources and Microgrid

- Smart Grid technology will facilitate integration of distributed resources:
  - Distributed Generation: solar; microturbines; fuel-cells using hydrocarbon fuels
  - Energy Storage Devices: large batteries (VRB); hydrogen (electrolyzer, fuel cell)
  - Plug-in Hybrid Vehicles: reserve generation and frequency regulation

- With increase in Distributed Energy sources and ability to communicate with various distributed resources, formation of Microgrids has become a reality

Examples of R&D Work Addressing Enhancement of Effective Use of Individual Equipment

Technologies for More Effective Use of Equipment

Much of the power system infrastructure and assets are 35 to 50 years old.

The following technologies contribute to more effective use of equipment, operating efficiency and reliability:

- Automated pro-active monitoring systems for maintenance and prevention of failures
- "Intelligent systems" technology for equipment diagnostics
- New technologies for dynamic equipment rating
- New technologies for assessment of remaining life
- Improved methods of life extension, uprating and efficiency enhancement
- Reliability-based asset management

On-Line Monitoring of Transformers

- Catastrophic failures are costly
  - replacement costs, revenue loss, environmental impact
- On-line monitoring/condition assessment based on:
  - a) monitoring oil to detect condition of insulation
  - b) frequency-response characteristics using system perturbations
- Intelligent systems software for analyzing measured data and identifying any impending problems and transmitting the information to control centers
- Early detection of incipient faults
- Prevent unscheduled outages and costly catastrophic failures

On-Line Transformer Oil Conditioning and Life Extension

- Transformer oil/paper ages with time and temperature
- Aging accelerated by moisture, acids, impurities and contaminants
- Condition of paper determines life of transformer
- Continuously remove accelerants from oil to retard aging process
- Extends life of transformers by at least 10%

In-Situ Profiling (Hydraulic Smoothing) of Hydro Turbines to Increase Efficiency

- Water passage surfaces become hydraulically rougher due to cavitation erosion, sand erosion, and corrosion
  - contributes to energy loss
- Turbine smoothing areas: penstock, spiral case, stay wanes, wicket gates, turbine runner blades and crown, draft tube
- Penstock and spiral case suffer from corrosion
  - hydraulic smoothing achieved by using innovative coatings
- Turbine runner components suffer from cavitation damage
  - efficiency increased by restoration of cavitated surface to its original profile

In-Situ Profiling of Hydro Turbines (cont'd)

- Automated system for profiling of turbine components:
  - Computational Fluid Dynamics (CFD) model for various turbine parts
  - Abrasive water jet cutting system to profile various turbine components
  - 3-D profiler to examine profile of turbine parts and compare with CFD model
  - Robotic system integrating water jet cutting and 3-D profiler
- Expected increase in efficiency:
  - 4% to 5%
- Reduced maintenance costs

Performance of Integrated Power Systems: Challenges and Solutions

Effective Use of Integrated Power Systems: <u>Challenges</u>

- **Reliable, secure and efficient operation presents many challenges in a competitive "market" environment**
  - **many entities with diverse business interests**
  - **system expansion and operation driven by economic drivers**
  - **inadequate transmission and infrastructure enhancements**
- **Power systems are physically very large complex systems**
  - **cover large geographic areas: *continental power grids***
  - **millions of devices requiring harmonious interplay**
  - **exhibit <u>complex modes</u> of instability**

Power System Security

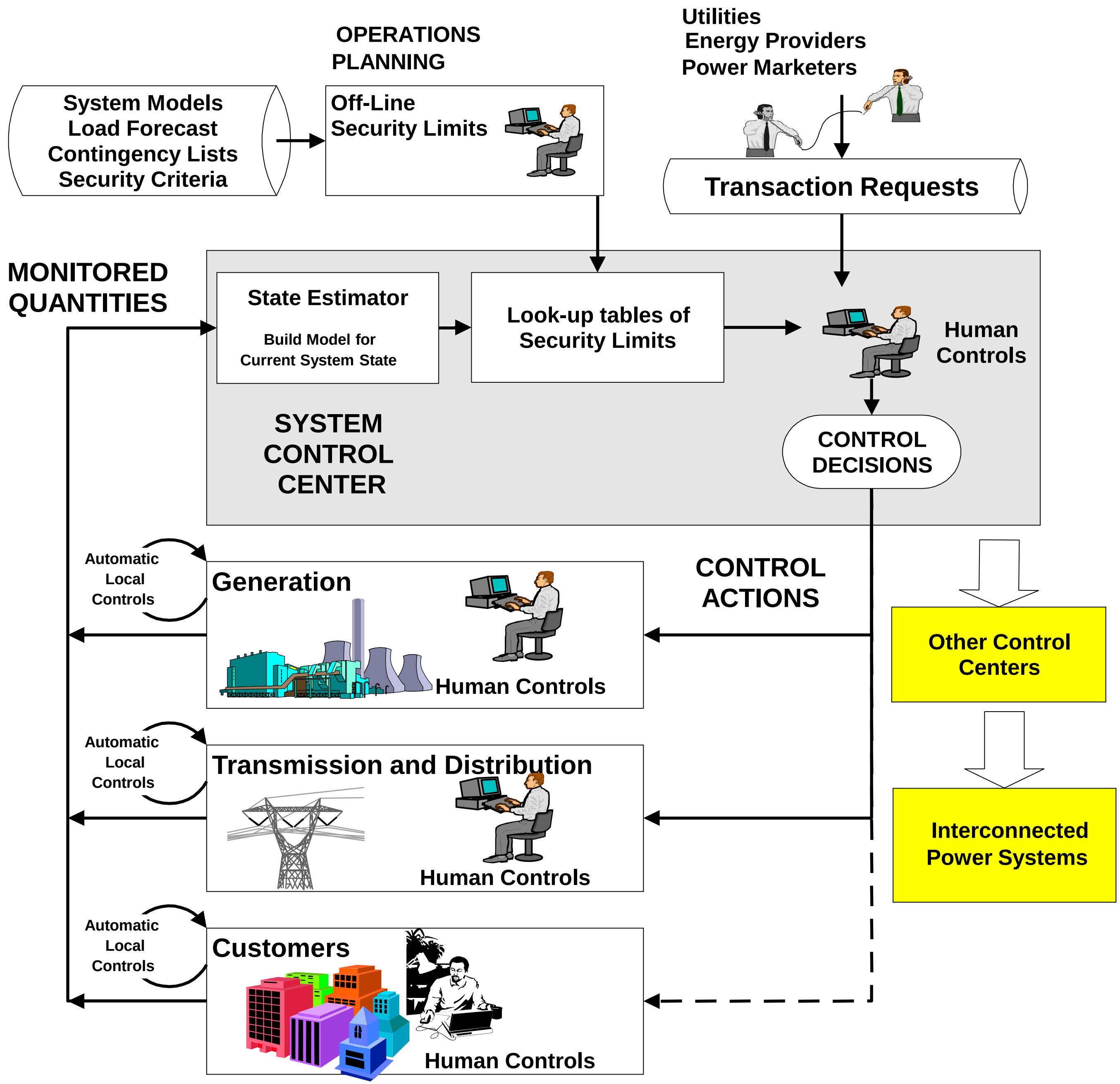
- Major concern since the infamous 9 November 1965 blackout of Northeast US and Ontario
- Presents new challenges in the present environment
- We had several wake up calls recently
  - August 14, 2003 blackout of NE U.S.A. and Ontario
  - August 28, 2003 blackout of South London and Northwest Kent
  - September 28, 2003 blackout of Italy
  - September 23, 2003 blackout of South Sweden and Eastern Denmark
  - August 13, 2004 blackout of Australian States: Queensland, NSW, Victoria

Technologies for Effective Use of Power Systems

- Improved system design and operation
  - robust, coordinated control design
  - improved protective relaying
  - on-line security assessment
- Improved emergency controls
  - defense against "extreme contingencies"
  - "self healing" systems
- Intelligent controls
- Real-time system monitoring and control
- Integrated information technology (IT) solutions
  - support complete business processes

Power System Control

- Overall control functions highly distributed
  - several levels of control
  - involve complex array of devices
- Human operators provide important links at various levels
  - acquire and organize information
  - make decisions requiring a combination of deductive, inductive, and intuitive reasoning
- Intuitive reasoning allows quick analysis of unforeseen and difficult situations and make corrective decisions
  - most important skill of an operator


OPERATIONS
PLANNING
Utilities
Energy Providers
Power Marketers
System Models
Load Forecast
Contingency Lists
Security Criteria
Off-Line
Security Limits
Transaction Requests
MONITORED
QUANTITIES
State Estimator
Build Model for
Current System State
Look-up tables of
Security Limits
Human
Controls
SYSTEM
CONTROL
CENTER
CONTROL
DECISIONS
Automatic
Local
Controls
Generation
Human Controls
CONTROL
ACTIONS
Other Control
Centers
Automatic
Local
Controls
Transmission and Distribution
Human Controls
Interconnected
Power Systems
Automatic
Local
Controls
Customers
Human Controls

Intelligent Control of Power Systems

- Future power systems more complex to operate
  - less structured environment
- Role of human operator becoming increasingly complex
- Current automatic controls do not have
  - "human-like" intelligence
- Add intelligent systems to conventional controls at various levels
  - learn and make decisions quickly
  - process imprecise information
  - provide high level of adaptation

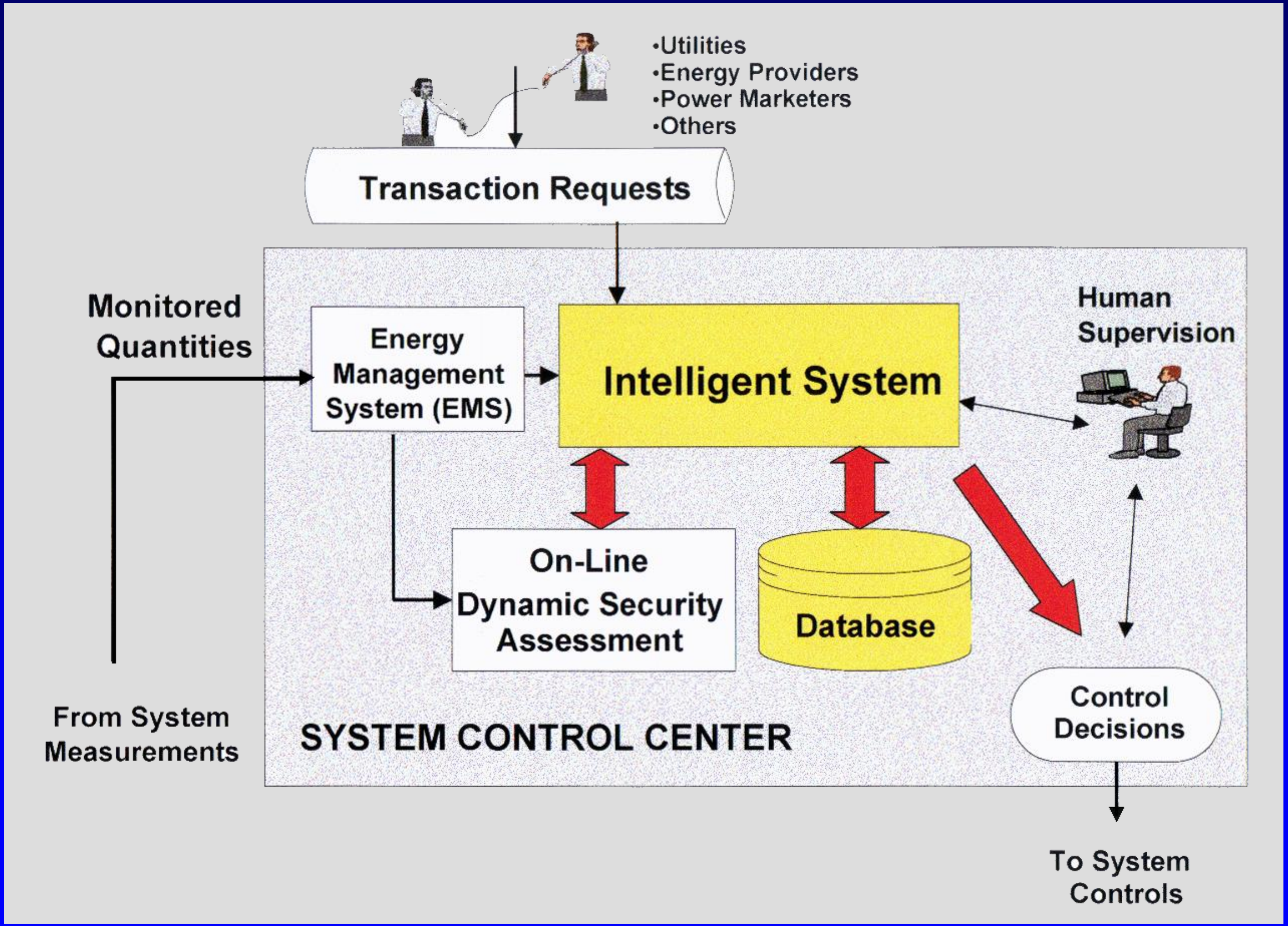
Wide Area Monitoring and Control

- Advances in communications technology have made it possible to
  - monitor power systems over a wide area (WAMS)
  - remotely control many functions (WACS)
- Research on use of multisensor data fusion technology
  - process data from different monitors, integrate and process information
  - identify phenomenon associated with impending emergency
  - make intelligent control decisions
- A fast and effective way to predict onset of emergency conditions and take remedial actions
- The ultimate "self-healing" power system !

Future Trends in On-Line Dynamic Security Assessment using *Intelligent Systems*

- Knowledge base created using simulation of a large number of cases and system measurements
- Automatic learning, data mining, and decision trees to build knowledgebase for intelligent systems
- Fast analysis using a broad knowledge base and automatic decision making
- Provides new insight into factors and system parameters affecting stability
- More effective in dealing with uncertainties and large dimensioned problems
- At Powertech, we completed a PRECARN project for power system security assessment using intelligent systems technology: POSSIT

DSA Using Intelligent Systems



"Smart Use" of Electricity/Energy

- Enormous opportunities exist for "smart" use of power leading to efficiency, economy and conservation
- Examples of "smart use" of power:

(a) "Buildings for Sustainability"

- David and Lucile Packard Foundations Los Altos Project
- "Living Building": designed to use of renewable "clean" energy generated locally, minimal reliance on the grid, efficient use of energy

(b) "Better Buildings through Integrated Intelligent Systems"

- Project commissioned by Industry Canada, coordinated by Continental Automated Buildings Association (CABA) and PRECARN
- Reduced energy consumption and greenhouse gas emissions, improved safety and security of occupants, and reduced life cycle costs

(c) BC Hydro "Power Smart" program

Sustainable Power Systems in the 21st Century

Concluding Remarks

- Challenge is to produce electricity that is:
  - greener, cheaper, reliable and of higher quality
- Greater dependence on distributed energy technologies and renewable energy technologies
- Increased emphasis on the development of "smart grids"

Smart Grid Initiatives

Concluding Remarks (cont'd)

- While current smart grid initiatives largely tend to focus on smart meters and load shaping strategies, we are likely to see more technology –rich initiatives in the long run

- To achieve the end goals, a unified vision of the road to smart grid is needed by all entities involved: various utilities, government agencies and related power system organizations