

# **Nanotechnology and Energy: Storage and the Grid**

Science and Technology:  
Innovation to Increase Grid  
Capacity and Efficiency

# **The Challenge for the Grid Of the 21<sup>st</sup> Century**

**John Stringer**

# The Growth of the Electricity Business

- Electricity is not a fuel, it is an energy carrier.
- Edison's path, as developed by Samuel Insull, optimizing efficiency of the generation and delivery of electricity to the customer, has resulted in the very large generating stations that we are used to.
- It also resulted in the enormous, largely AC delivery network to get the electricity from the generator to the customer that we are familiar with.
- **This delivery system is what is called the grid.**

# The North American Grid

- There are three separate components of the North American Grid, called Interconnects:
  - The Eastern, covering the eastern two-thirds of the United States and Canada,
  - The Western, covering most of the rest of the two countries,
  - The Electric Reliability Council of Texas (ERCOT), covering most of Texas.

# The North American Grid

- Within each Interconnect, power flows through AC lines, so that all generators are tightly synchronized to the same 60 Hz cycle.
- The Interconnects are joined to each other by DC links.

# Bulk Electric Power Transmission

- Power transmission is between the power plant where the electricity is generated and a substation close to the location where it will be used, typically a populated area.
- The average power plant size in the U.S. in 2002 was **300 MW** (1 MW =  $10^6$  Watts)
- The installed generating capacity was 981,000 MW

# Bulk Electric Power Transmission

- If the power plants ran full time, the net annual generation would be  $8590 \times 10^6$  kWh (kiloWatt-hours).
- The actual net generation in 2002 was  $3840 \times 10^6$  kWh – **44.7% capacity factor**.
- There were  $132 \times 10^6$  ultimate customers, so the annual power consumption was **29,088 kWh per customer**.

# Bulk Electric Power Transmission

- The power is generated at voltages up to 25 kV.
- To reduce the resistive losses in the transmission of the power to the customer, it is necessary to reduce the current and hence increase the voltage.
- This favors the use of alternating current (AC), since the voltage can easily be stepped up using transformers.



# High Voltage AC Transmission

- Transmission is typically carried out with overhead conductors at voltages in the range 110 kV to 765 kV.
- The U.S. presently operates about 157,000 miles of high voltage (>230kV) electric transmission lines.
- The highest voltage line in the world is in Kazakhstan, from Ekibastusz to Kokshetau, a distance of 268 miles, at 1150 kV.

# Transmission Losses

- Losses in transmission are principally resistive, with the loss being dissipated as heat.
- Transmission and distribution losses are related to how heavily the system is loaded.

U.S.-wide transmission and distribution losses were about 5% in 1970, 7.2% in 1995 and grew to 9.5% in 2001, due to heavier utilization and more frequent congestion.

# Capacity Limits on Transmission

- The principal limitation on the capacity of a transmission line is the temperature of the line.
- **As it gets warmer, it sags.**
- In the worst case, it may contact trees or even the ground.
- **One way of increasing the capacity of the existing transmission lines would be to increase their strength to reduce the sagging.**

# Capacity Limits on Transmission

- Another limitation is the mechanical strength of the existing support structure. Conductors with higher strength-to-weight ratios for a given current-carrying capacity may increase the overall capacity of the right-of-way.

# Capacity Limits for AC Transmission Lines

<b>Voltage, kV</b>	<b>Length, miles</b>	<b>Maximum Capacity, GW</b>
<b>765</b>	<b>100</b>	<b>3.8</b>
	<b>400</b>	<b>2.0</b>
<b>500</b>	<b>100</b>	<b>1.3</b>
	<b>400</b>	<b>0.6</b>
<b>230</b>	<b>100</b>	<b>0.2</b>
	<b>400</b>	<b>0.1</b>

Data from *Transmission Planning for a Restructuring U.S. Electric Industry*, by Eric Hirst and Brendan Kirby, June 2001, prepared for Edison Electric Institute

# HVDC

- When electrical energy is required to be transmitted over very long distances, it can be more economical to transmit using Direct Current (DC) rather than Alternating Current (AC).
- The smaller losses and reduced construction cost can offset the costs of the converter stations required at each end of the line

# HVDC

- **HVDC may be the preferred option:**
  - Undersea cables – the 250 km Baltic Cable between Sweden and Germany
  - Endpoint to endpoint long-haul bulk power transmission
  - Allowing power transmission between unsynchronized AC systems
  - Connection of remote generating plant to the distribution grid.

# The North American Grid

- A major problem has been emerging.
- The transmission system was not expected to be used to transfer large amounts of energy, and was not designed with this in mind.
- **Deregulation has resulted in the possibility of instabilities that can lead to major blackouts.**



# The Electric Utility Business

- The nation's electric utilities hold assets exceeding \$600 billion; with 70% invested in power plants, 20% in distribution facilities, and 10% in transmission.
- They form one of the largest industries in the U.S., approximately twice the size of telecommunications and nearly 30% larger than the automobile industry in terms of annual sales revenues.

**The Achilles Heel is the fact that supplying electricity is also extremely capital intensive, requiring far more investment per unit of revenue than the average manufacturing industry.**

**The U.S. electric enterprise is made up of over 5,000 commercial entities, both public and private.**

**The largest individual corporate market cap in the enterprise today is that of Exelon at \$32 billion. This compares with Exxon-Mobil, for example, with a market cap of \$365 billion. In fact, only about 17 electric utilities have a market equity value greater than \$10 billion.**

**As a result, the decision to invest the billion or more dollars needed to construct a major new power delivery (T&D) line is effectively an uncertainty-laden, long-term, “bet the company” decision to be avoided by most electric enterprise corporations today**

# How is Electricity Used?

# The Electric Motor

- “The introduction of electric motors revolutionized manufacturing ...by 1932 electric motors provided over 70% of all installed mechanical power in U.S. industries. The proliferation of household appliances has also been primarily due to the use of small electric motors. **Today, the ubiquitous electric motor in all its forms and sizes consumes two-thirds of all U.S. electricity production.**” (K. E. Yeager 2005).

# Consumption of Electricity in 2001 (Approximately)

- Cooling 30%
- Drives 25%
- Heating 18%
- Lighting 16%
- 'Computing' 10%

# New Issues

- Electricity is difficult to store. The grid system is essentially a ‘real time’ system.
- There is an increased interest in ‘renewable’ and distributed sources for electricity generation, most of which are variable.
- **New storage methods would have a profound impact on the electricity supply industry.**

# Storage

- Pumped water
- Compressed gas
- Thermal storage
- Mechanical (flywheels)
- Electrical (ultracapacitors)
- Magnetic (SMES)
- Electrochemical (batteries)
- Chemical (hydrogen)



# The Transformation in This Century

- “Even as the demand for power is growing, the nature of the electricity demand is undergoing a profound shift due to digital technology.”
- “In applications ranging from industrial sensors to home appliances, microprocessors now number more than 12 billion in the United States alone”.

# Improved Transmission Capacity, Grid Control, and Stability

- Transform grid into smart, electronically controlled network to increase throughput while decreasing vulnerability

# Improved Transmission Capacity, Grid Control, and Stability

## Critical Capability Gaps

- Regional/national plans for grid expansion
- **Wide-area measurement/monitoring systems**
- FACTS devices and hierarchical controls
- Post-silicon power electronics
- **Complex, interactive, adaptive controls**
- **Fully automated T&D control systems**

# Kurt Yeager: Towards the Digital Society (2005)

- “The local distribution systems that connect the power supply to each consumer are effectively a last bastion of analog, electromechanically controlled industry. This is a particularly notable paradox given the fact that the nation’s electricity supply system powers the digital revolution on which much of the current and future value depends.”

# The Transformation in This Century

- These digital devices are highly sensitive to even the slightest disruption in power (an outage of less than a fraction of a single cycle can disrupt performance), as well as to variations in power quality due to transients, harmonics, and voltage surges and sags.
- “ ‘Digital quality power’ with sufficient reliability and quality to serve these growing digital loads, now represents about 10% of total electrical load in the United States, for example. **It is expected to reach 30% by 2020.**”

- “Keeping the lights on 99.97% of the time is simply not good enough. That still means the average consumer doesn’t have power for 2.5 hours a year. **In today’s impatient, increasingly computerized world that is more than just a nuisance.**” (KEY).

# Creation of the Infrastructure for a Digital Society

- Develop technology to meet the energy needs of a digital society, power the modern economy, and integrate energy users and markets

## Critical Capability Gaps

- Integration of DC microgrids into grid architecture; integration of transmission grid with automated distribution grid
- Commercial high-temperature superconducting technology

# Creation of the Infrastructure for a Digital Society

- Control of electromagnetic interference; hardening of end-use devices
- Resolution of technology/policy issues at “last mile” convergence of telecom/electricity systems
- Integrated electricity, communications, gas, and water corridors; undergrounding



# Improved Power Quality and Reliability for Precision Electricity Users

- Enhance the capability of transmission, distribution, and end-use systems to reduce the number and severity of power quality disturbances

# Improved Power Quality and Reliability for Precision Electricity Users

## Critical Capability Gaps

- Interconnection standards and integration guidelines for distributed resources
- Technologies for short-duration ride-through capability
- Backup generation and storage systems
- DC microgrids to meet clean power requirements
- Power quality solutions on the customer side of the meter

# The Objectives of the New Century

- Digitally controlling the power delivery network by replacing today's relatively slow electromechanical switching with **real-time, power-electronic controls**.
- Integrating communications to create a dynamic, interactive power system as a new “mega-infrastructure” for real-time information and power exchange. Through advanced information technology, **the system would be ‘self-healing’**.
- Automating the distribution system to meet changing consumer needs:

# The Objectives of the New Century

- Reduce the number of consumer interruptions.
- Improve system fault anticipation.
- Achieve faster restoration.

# The Objectives of the New Century

- Integrating distributed energy resources.
- The new system would also be able to seamlessly integrate an array of locally installed, distributed power generation units (such as fuel cells and renewables) as power system assets.
- **Unfortunately, today's electrical distribution system, architecture, and mechanical control limitations prohibit, in effect, this enhanced system functionality.**

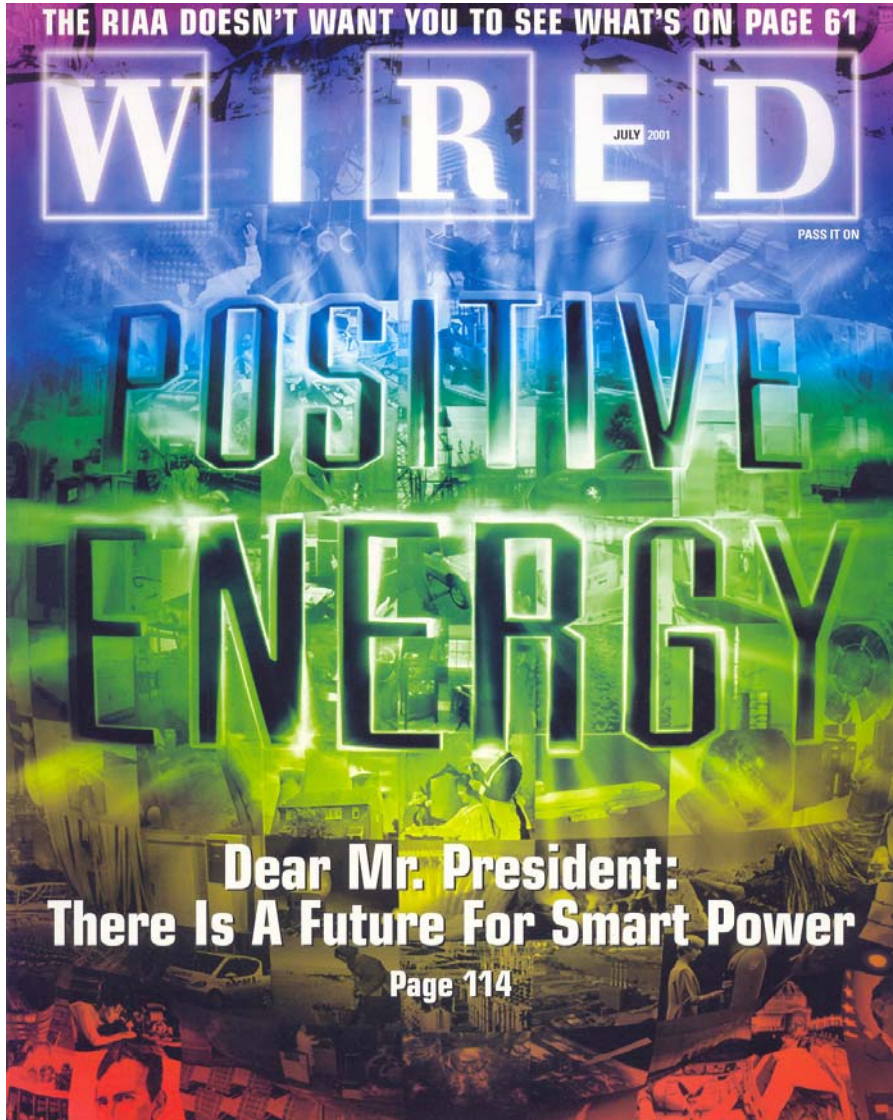
# The Objectives of the New Century

- Increased ability to deliver varying ‘octane’ levels of reliable, digital grade power
- **Increased functional value for all consumers** in terms of metering, billing, energy management, demand-response, among others
- **Transforming the meter into a consumer gateway** that allows price signals, decisions, communications, and network intelligence to flow back and forth through the two-way energy/information portal.

# Enabling Technology

- Sensors for real-time monitoring and complex network control
- Electronic power flow control
- Real-time dispatch of distributed resources
- Interference-free power line communications
- DC microgrids for premium power services

# 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. Call it **The Energy Web**





# Something Really New!

- In a paper he presented to the November 2001 Winter Meeting of the American Nuclear Society, EPRI's founder, Chauncey Starr, proposed a radically new approach which would solve several problems.
- **This is the Continental Supergrid.**

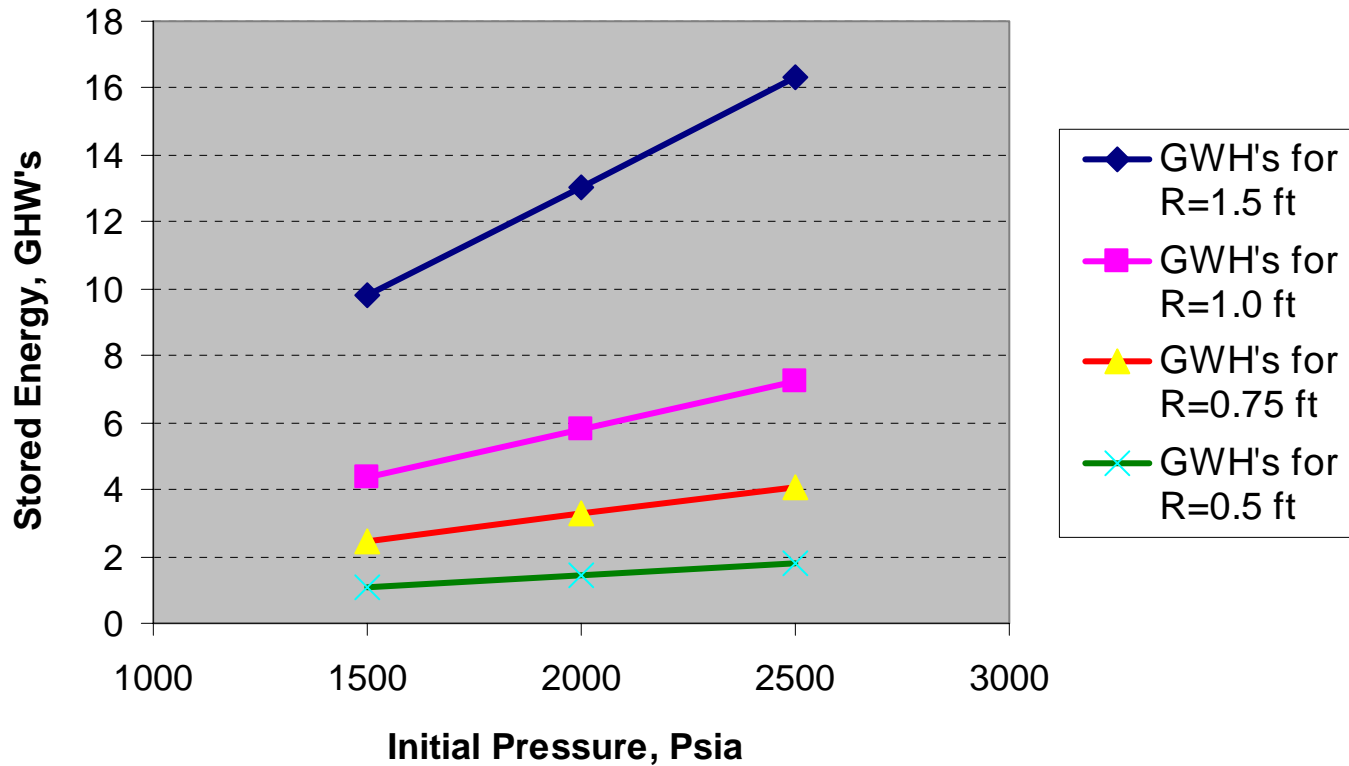
# Continental Supergrid

- The electric part of the Supergrid would be a DC superconducting line, using liquid hydrogen as the coolant.
- The electricity would be supplied to the Supergrid by power plants situated along it – because it is superconducting, the locations don't matter.

# Continental Supergrid

- The Supergrid would feed the conventional grid through DC to AC converters at appropriate locations.
- The hydrogen would also leave the Supergrid, and be replenished; the effect of this would be to provide a **continental hydrogen pipeline grid.**

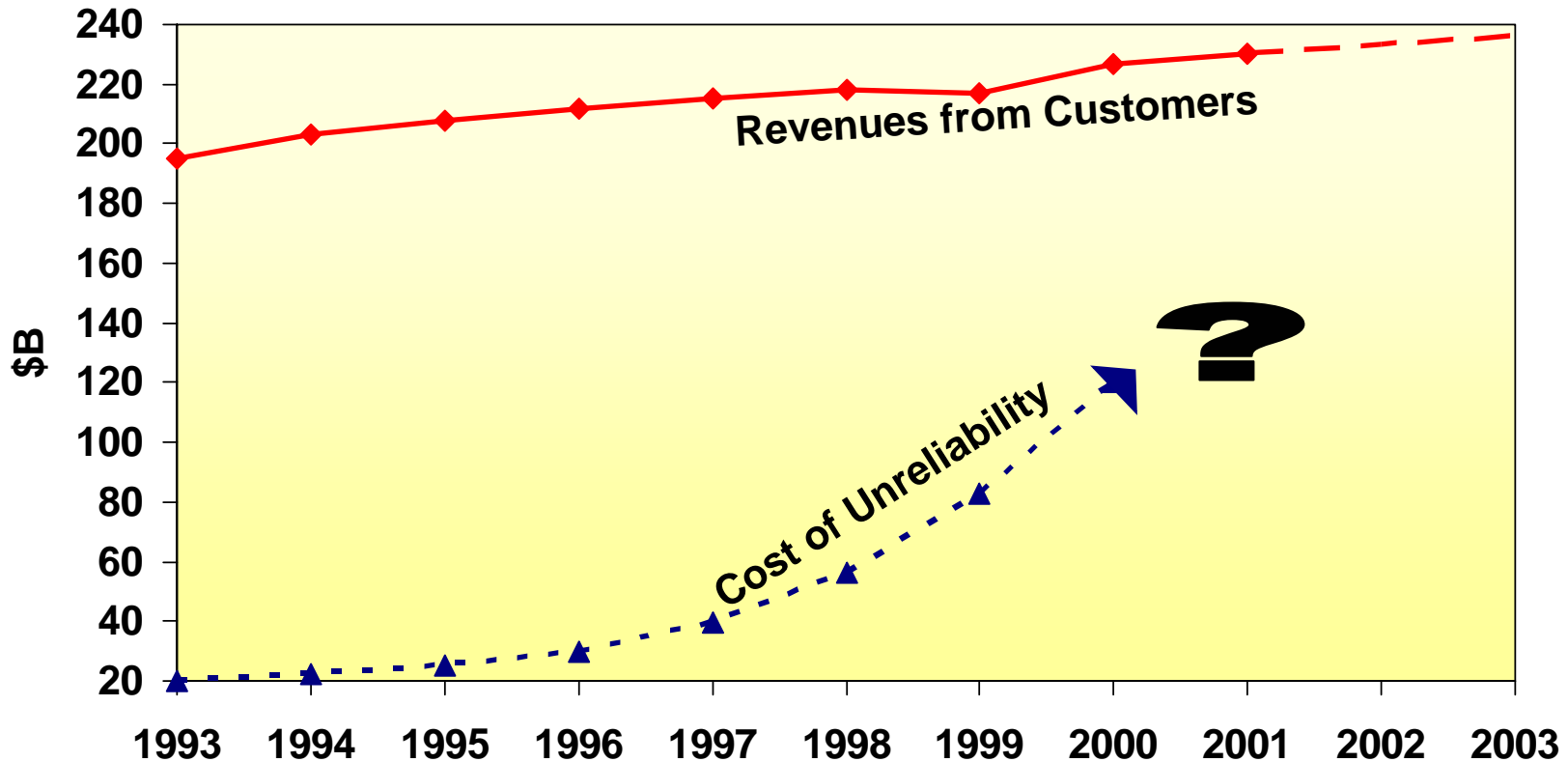
## GWH's Stored In 300 Mile Hydrogen Pipeline, From 10% Increase In Pressure Level (Electrolyzer Eff.= 0.9, and Pipeline Radius = R)



*The pipeline can store a tremendous amount of energy by operating between two different pressure levels.*



# The Real Price of Electricity Service



# Transformative Elements

**Enable a Seamless, Self-Healing  
Power Delivery System**

**Deploy Power Flow Control  
Technologies**

**Integrate Local  
Computational Agents**

**Deploy Sensors and  
Communications**



# A Descriptive Framework

Increase the Efficiency and Value of Electricity

Transform the  
functionality of  
the power delivery  
infrastructure

Enable digital  
economy

Revolutionize  
the value of  
electricity services

Enable the  
monitoring and control  
of power  
systems in  
real time

Increase  
the control  
and capacity  
of power  
delivery  
systems

Enhance the  
performance of  
digital devices

Enable connectivity  
and enhance  
end-use

Integrated Energy and Communication  
System Architecture

# U.S Utility Data

	<b><u>1968</u></b>	<b><u>1985</u></b>	<b><u>2002</u></b>
<b>Ultimate Customers (million)</b>	70	101	132
<b>Net Generation (<math>10^9</math> kWh)</b>	1,436	2,545	3,841
<b>Installed Generating Capacity (<math>10^3</math> MW)</b>	310	712	981
<b>Average Power Plant Size (MW)</b>	85	227	300
<b>Circuit Miles of High-Voltage Line* (<math>10^3</math> miles)</b>	425	605	730
<b>Residential Service Price (¢ per kWh – 1983\$)</b>	7.1	6.8	6.8

\*22,000 volts and above