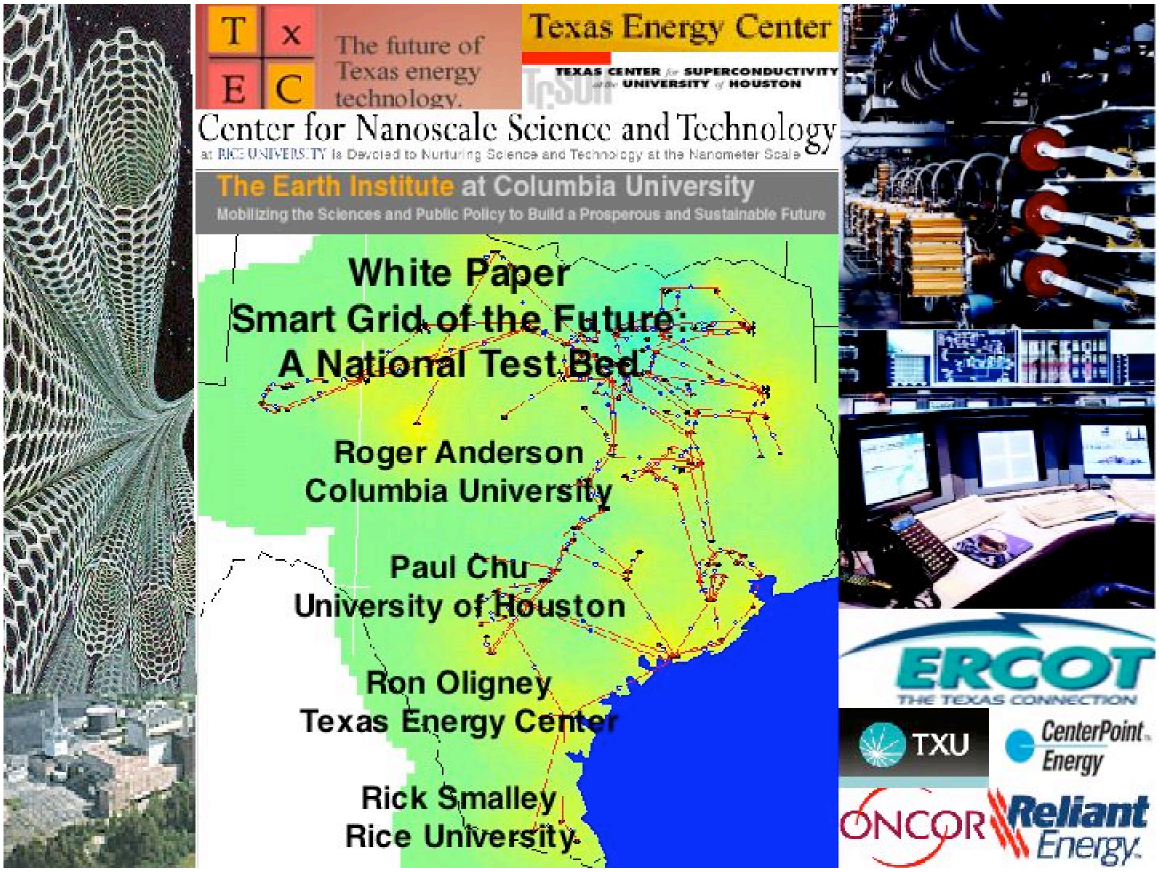
Smart Electric Grid of the Future:
A National "Distributed Store-Gen" Test Bed



New York Times, August 15, 2003: Power Surge Blacks out Northeast, Hitting Cities in Canada and 8 States; Midday Shutdowns Disrupt Millions: "It was inevitable that the first question after the lights went out was not when they would return, but whether terrorism was involved."

Wall Street Journal, August 15, 2003: Huge Power failure Hits Major Cities in U.S. and Canada. 'Cascade' of problems. No Signs of Terrorist Link: "The breadth of energy disruption suggests that some major rethinking deserves to be done about the vulnerability of America's power grid. If an accident can shut down an entire U.S. region for a day, imagine what well-planned sabotage could do."

New Jersey Star Ledger, August 15, 2003: Blackout Chokes the Northeast. Tens of Millions stranded in the Heat: "System collapsed like a house of cards. This was the largest power disruption in the history of the United States."

The Country at Risk

On August 14, 2003, smart sensors on the electric grid first detected a power surge in northern Ohio. It was caused by failure of a sequence of high voltage transmission lines in the Eastern Interconnect. The country was plunged into its worst blackout ever. What we are concerned about is not just how to keep it from happening again, but what the future grid will need to look like 10 to 20 years from now to prevent Blackouts from becoming a common occurrence as our electric power demand grows and the electric energy market changes.

This problem occurred within the complex, interconnected electric system commonly called the "Grid". Power generators were shut down and the local distribution systems of utilities like Con Edison, Keyspan, and Detroit Edison disrupted by the High Voltage AC Transmission lines. Deregulation, California's chaos, the Enron collapse, and many other economic forces over the last 10 years have orphaned this vital "Interstate Highway System of Electricity."

It is of vital national security interest that it be modernized and brought into the 21st century if we are to have any hope of preventing future disruptions of the electricity supply to the country. And next time, it may be far worse than that on August 14th, 2003. The failure detection and remediation system showed major flaws and weaknesses. The system was designed 50 years ago to automatically shut down at any sign of such a power surge. The blackout lasted several hours because each local utility had to do a "Hard Re-Boot" in computer parlance, or a "Black Start" to the energy business. It takes several hours to spin down the back up the generator turbines and much care to reestablish the matching voltages, frequencies and phases of the high voltage grid before power can be restored (several days with the nuclear plants taken off-line).

Modern computer sensing, planning and control software could have prevented the shut down in the first place by diverting power from the wave front using what are called Smart Power Controllers. These employ computer control of the electric grid's equivalent of transistors, called Thyristors, and giant capacitors to divert power from troubling congestion to underutilized grid lines. The insertion of superconducting fault current limiters to the transmission line can prevent unexpected, rapid surges of current to beyond the pre-set safe limits of the lines. Widespread use of those and far more advanced technologies will be required to create a Smart Grid of the Future. Such an advanced system will be required as demand grows steadily throughout the country over the next few years, and as we interconnect more and more with Canada and Mexico.

We saw on August 14th, 2003, that the country's economic and political well-being depends upon the energy infrastructure that we have taken so long for granted. The gallant efforts of unsung heroes at the utilities, city and state agencies have reconstituted the power of the Northeast, but at what cost? Con Edison alone spent $134 million of its own money to restore electric, gas and steam facilities disrupted by the World Trade Center attack of September 11, 2001. Who will build the Smart Grid of the Future? How is the country to meet future electricity demand while maintaining reliability and security if the current system is stressed to its limits? The Departments of Energy and Homeland Security must identify the current Transmission Grid as a threat to our national security, and fund the local and regional power generators, transmission companies, utilities and Independent Service Operators to modernize the grid, and particularly, increase the computer intelligence and Smartness of the Grid. These overburdened organizations that produce the electricity that drives our entire economy don't have the financial strength to do it themselves.

The plans for the Smart Grid of the Future must also cope with the added burden of defending against terrorist threats. The Department of Homeland Security knows all too well of our vulnerability, the nation is first dealing with larger *strategic* concerns by isolating infrastructure attacks and preventing them from spreading throughout the country. This is termed *islanding* in Homeland Defense parlance. The Islanding was successful yesterday, preventing the power wave from propagating all the way to California. But inside our "island" under attack, the city and state agencies and utilities are currently on their own for early response, as we saw yesterday.

The ultility's, ISO's and RTO's (better define them here than later) carry an enormous responsibility for the country to make sure that our energy supply has the capacity to safely deliver the extra energy that will inevitably be required in the summer of 2003 (?) and beyond. In the mean time, the country is hoping to survive the summer of 2003 (?) without further Blackouts or extensive Brownouts. And we believe the place to start is the self-contained Texas Electric Grid operated by the Electric Reliability Council of Texas (ERCOT).

Texas has been a leader in electric grid development, with its ERCOT the exemplary Independent Services Operator (ISO) in the country. ERCOT is also serving Texas as the nation's first Regional Transmission Operator (RTO). That said, Texas is also unique in that its electric grid is largely self contained, with only limited DC interconnections to Mexico, Oklahoma and Louisiana. Texas also has several of the nation's best run power companies in Reliant Energy, CenterPoint and Texas GenCo in Houston and TXU and ONCOR in Dallas.

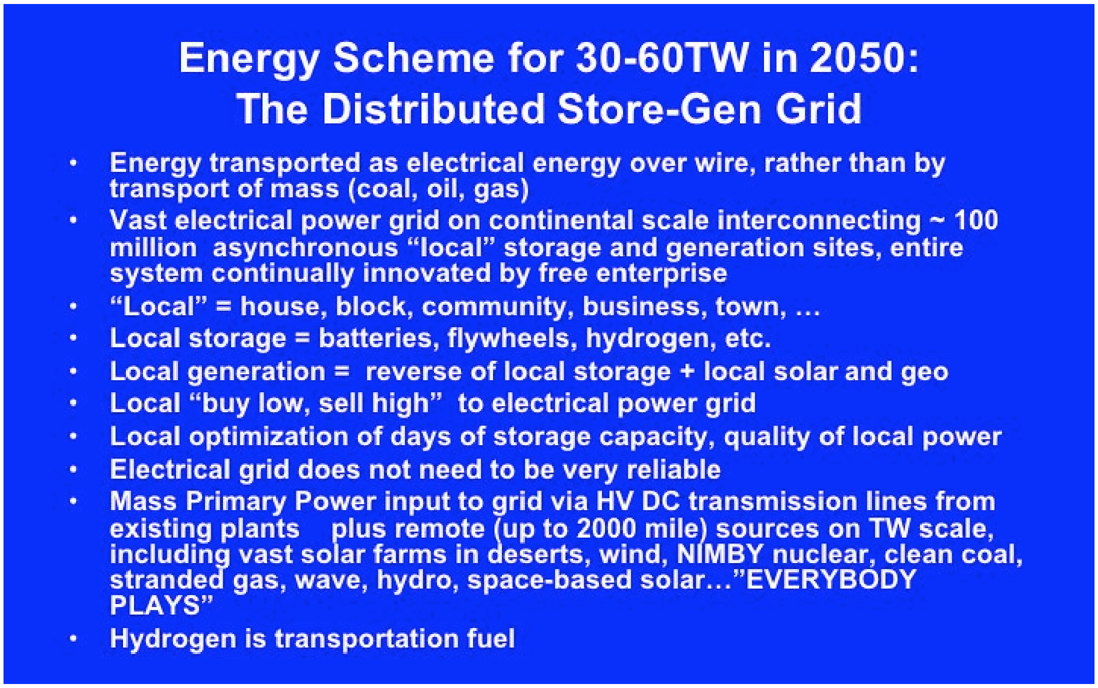
The Texas Energy Center (TxEC) has been created to continue the state's energy leadership into the 21st century, as it has been for the 20th century. TxEC's mission of leadership in energy innovation and the isolated ERCOT grid make Texas the ideal location to develop and test the Smart Grid of the Future for the nation. As Pat Woods, Chairman of FERC, has recently said, "the electric grid is the country's Interstate Highway of Power, and we'd better get on with building it." What better place to develop and test the construction components than in the self-contained, right-sized, laboratory for the national grid represented by ERCOT.

The Even Bigger Picture

In fact, by 2050, the world will need somewhere between 30 and 60 TerraWatts (TW) of electric power. The world uses a little under 12 TW of that now, with one third of that in the United States. The Distributed Storage-Generation-Transmission-Distribution technologies of the Smart Grid of the

Future must be able to deliver that kind of power to all corners of the globe efficiently and securely. Most of this energy will be transported as electricity over wires, rather than by transport of solids and liquids (coal, oil, gas, hydrogen). Thus, we are contributing to the Electricity Economy of the future when we solve problems related to the Smart Grid.

A vast electrical power grid on continental scale, interconnecting ~ 200 million asynchronous, local (house, block, community, business, town) storage (super-batteries, flywheels, superconducting magnetic energy, hydrogen, compressed air) and generation (wind, solar, and geothermal renewables added to gas, oil, coal and nuclear will all be needed) will be even more vulnerable than today's grid. It simply must be Smart enough to overcome these weaknesses. And the entire system must be open to continual innovation by free enterprise, unlike the difficulties with R&D in the current electricity system. Perhaps most difficult of all, the Smart Grid of the Future must be built to deal with unpredictable and unreliable green power sources such as giant wind and solar farms located a thousand miles from metropolitan users.



Energy Scheme for 30-60TW in 2050:
The Distributed Store-Gen Grid

- Energy transported as electrical energy over wire, rather than by transport of mass (coal, oil, gas)
- Vast electrical power grid on continental scale interconnecting ~ 100 million asynchronous "local" storage and generation sites, entire system continually innovated by free enterprise
- "Local" = house, block, community, business, town, …
- Local storage = batteries, flywheels, hydrogen, etc.
- Local generation = reverse of local storage + local solar and geo
- Local "buy low, sell high" to electrical power grid
- Local optimization of days of storage capacity, quality of local power
- Electrical grid does not need to be very reliable
- Mass Primary Power input to grid via HV DC transmission lines from existing plants plus remote (up to 2000 mile) sources on TW scale, including vast solar farms in deserts, wind, NIMBY nuclear, clean coal, stranded gas, wave, hydro, space-based solar…"EVERYBODY PLAYS"
- Hydrogen is transportation fuel

Figure 1. The Distributed Store-Gen Smart Grid of the Future

R&D that must be integrated into a lean and efficient electrical delivery system to achieve these lofty goals includes 1) innovative fuel supply and storage (gas, oil, coal, nuclear, wind, solar), 2) new electricity generation that is efficient and environmentally neutral, 3) intelligent transmission that is capable of distributing power where it is needed more efficiently than today, and 4) distributed generation, storage, transmission and distribution at the consumer and manufacturing ends of the grid to give it stability and safety from terrorism, as well from the usual weather and mechanical outages. There is no other concerted effort anywhere in the country that we are aware of to build such a Smart Grid Test Bed for development of the new technologies and public policies, economic incentives and regulations, that will be required to produce this new electric power system. Success is essential to economic growth and vitality of America far into the future.

National Smart Grid Test Bed -- Mission Statement

Above all, the Electric Grid of the Future must be innervated with enough local and regional smarts to accommodate modernization within each of the components of the “machine”, and optimized so that it runs smoothly through the transition from the present system (largely designed 50 years ago).

Execution Plan

The breadth and scope of the Smart Grid of the Future requires that it must be a national program, but at the same time, we recognize that we must preserve the independence and autonomy of the Texas grid. Funding will begin with seed monies from the State of Texas and the Public Utility Commission, and by FY2005, will include substantial support from the Departments of Homeland Security, Energy, and perhaps the Pentagon. Though we envisage very little cost to the test bed operators, CenterPoint, ONCOR, Reliant Energy, Texas GenCo and ERCOT, we intend to design and execute the plan WITH these partners as a joint team. Our overriding objective is to secure a leadership role in the national development efforts for the Smart Grid of the Future. We will accomplish this with a 4-part Research & Development program consisting of overlapping stages:

1. Secure state and federal funding for the first operations of the project to develop the simulation capabilities to model transmission and distribution congestion, failure cascades, threats, and remediation. ERCOT will be the launch customer. New software is needed for intelligent power control & innervation to supply the brains of the Smart Grid. Simulations of congestion, planned responses, and market forces must be integrated into a system wide “learning platform” to develop the intelligence for the “brain.” We will also secure Federal R&D funding from DOE and DHS for initial test bed development and distribution of Columbia’s Decision Support Threat Simulator (DSTS) and the EPRI Solutions Distribution Engineering Workstation (DEW) to shadow ERCOT operations.
2. New power control hardware will be added to create Intelligent substations that redirect electricity flow around congestion and take actions determined by the simulations. These power controllers, cheaper thyristors, Flexible AC Transmission System (FACTS), and supervisory control and data acquisition (SCADA) systems will be added with Federal funding. We will also expand the simulation capabilities to generation, including the supply and storage of fuels.
3. New Distributed Generation and Distributed Storage capabilities will be

tested in Ft. Bend County.

4. High Temperature Superconducting Fault Limiters to Protect the Grid from Current Surges due to Natural and Human Causes
5. High Temperature Superconductor/Liguid Hydrogen (HTS/LH_2) super-energy pipelines that will provide simultaneously the clean and green electrical and chemical energy to the users will also be explored and tested.
6. The National Test Bed then becomes the first to test Nano and other advanced technologies related to transmission wires, environmental remediation, new generation technologies, electron/gas storage, and other developments we can't even imagine now related to the Smart Grid of the Future. New Quantum wires must be developed and tested, in addition to superconductors and high voltage DC lines. Nanotechnologies also offer the possibility of vast new electron storage capabilities that must be tested and connected into the Smart Grid.

In order to accomplish this mission, the Smart Grid must be able to deal with variable and unpredictable loads from green power, as well as base loads from coal and nuclear plants, and peak load from highly efficient gas co-generation facilities, plus distributed generation (DG) and distributed storage (DS) from manufacturers and consumers. New generation sources will include NIMBY (Not In My Back Yard) nuclear, clean coal, co-gen gas, hydro, wind, land- and perhaps space-based and lunar-based solar downlinks. The new Smart Grid will have to accommodate both long-distance (up to 2000 miles), high voltage AC and DC transmission and local, distributed, generation and storage.

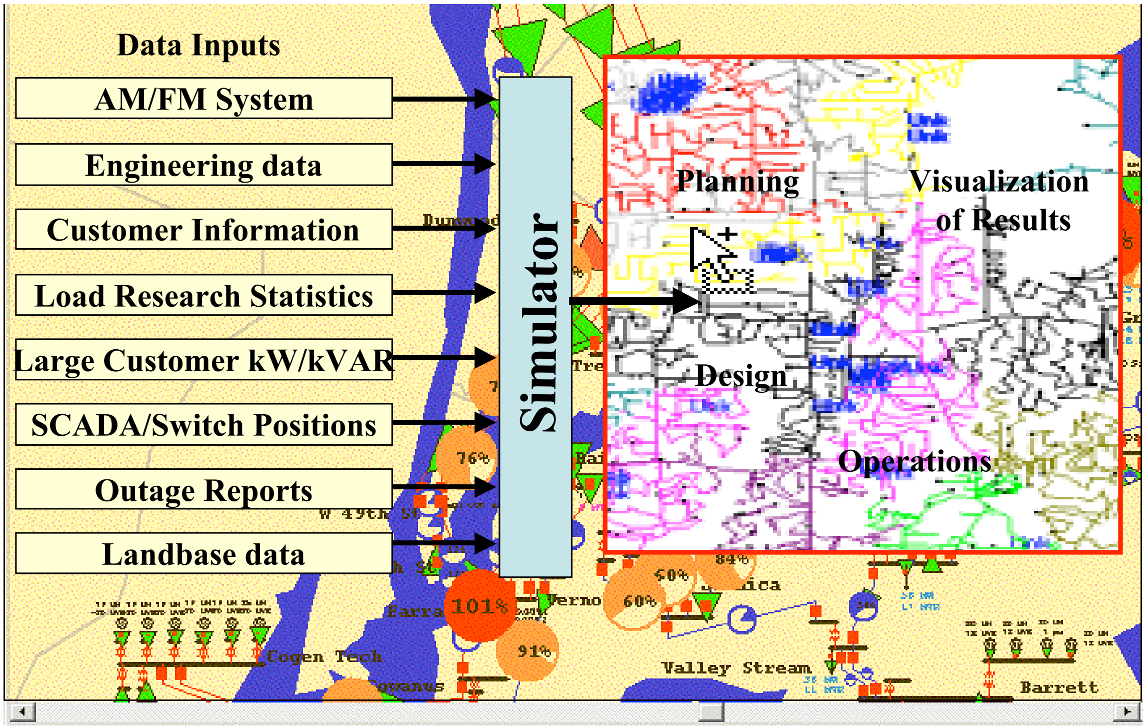
Such a "Lean Engineered" electric power system will require improved efficiency of the transmission and distribution systems (by 50% or more), if we are to keep up with and sustain economic growth in this country. The Smart Grid will use computer control systems to simulate and dispatch imperfect loads, deliver "5 9's" of quality power only when and where it is needed, and accept clean & green power without the need to build enormous new Generation, Distribution & Transmission capacity -- saving all that Capex that the industry cannot afford. And we must succeed, or the Electric Grid will become uncontrollable. The present electric grid WILL NOT WORK in the immediate future -- on any scale – local, state, national or international – as the expected new demand comes on-line! And the political backlash will be far greater than that California is currently experiencing, or the Northeast soon will.

Costs will begin at $1 million/year, growing to $10 million/year by 2004, and it is realistic that $100 million/year, growing to >1 billion/year, must be spent nationally on this National Test Bed by 2013 if the electric grid is to be modernized in the future. The Texas Energy Center in Sugar Land will house the project. ERCOT, CenterPoint ONCOR, Reliant, and Texas GenCo. will be the Launch Customers.

Stage 1: Simulation capabilities to model transmission and distribution congestion, failure cascades, threats, and remediation.

TxEC will build a national alliance with Texas Universities and the Launch Customers. Rice, Texas A&M, the University of Houston, the Universities of Texas at Austin and Arlington are expected to participate. In addition, the Energy Research Group at Columbia University has assembled a national team that will move its development for the Texas implementation of our Decision Support Threat Simulator (DSTS) and Distribution Engineering Workstation (DEW) to the Texas Energy Center. Partners are Virginia Tech, EPRI Solutions, SMARTS, Inc., Fuld and Company, and Hawkeye Systems. SMARTS has applicable control systems for the Internet and cyber-terrorism. Hawkeye Systems is an anti-terrorism defense contractor, Fuld and Company is a competitive intelligence firm specializing in how to stay in business when under economic, political or physical threat, and Virginia Tech developed the DEW simulator.

This national team brings interested launch customers in New York with Con Edison and Keyspan and in Detroit with Detroit Edison (DTE), where we are already using DEW to simulate threats to their grids (Figure 2). However, the Northeastern power grids are very complex and not ideal for a national test bed. We naturally converged on the independence of ERCOT, and the understandability of the Houston area in particular, as the most likely national location to develop the Smart Grid of the Future in a logical way.



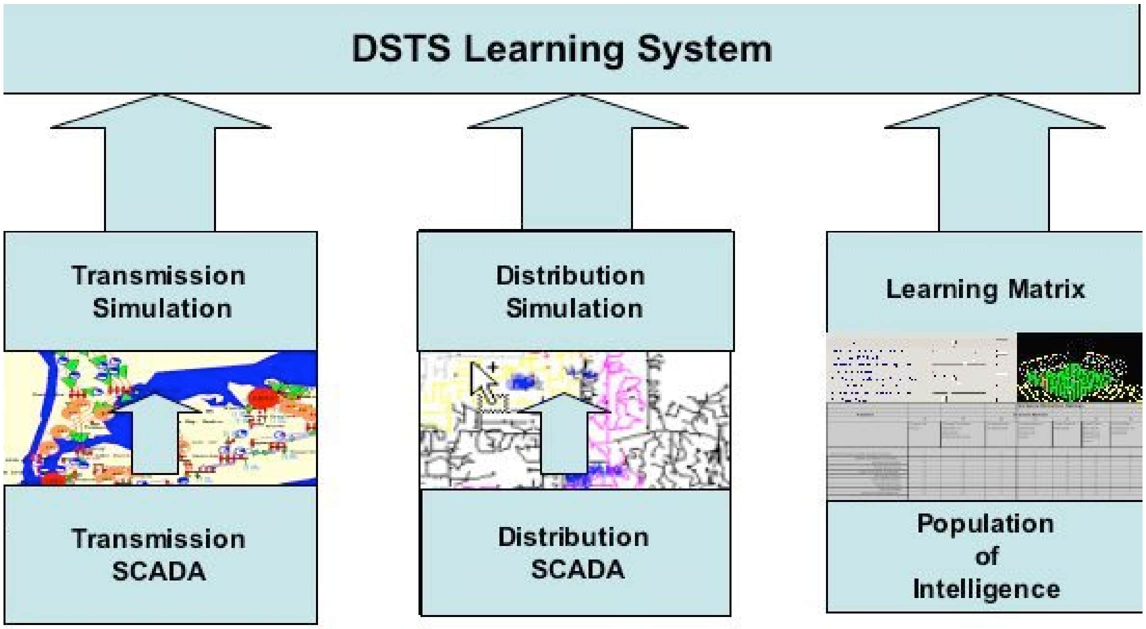


Figure 2. DSTS uses the DEW operations simulator at DTE. Appendix 1 gives a glossary of terms used here.

We will begin with additions to the simulation capabilities of the present transmission and distribution grids that companies will immediately associate with safer and more profitable operations. In an integrated infrastructure system with millions of possible failure points, good planning, operations and training require computer simulators for the electric grid that are more like those used in the nuclear and aerospace industries. The DSTS/DEW system is designed to use reinforcement learning from grid simulations to 'game-play' thousands of congestion scenarios and failure cascades resulting from weather, equipment failure, terrorism, etc. that operators must learn to deal with in the Smart Grid future, The first simulations of the ERCOT grid will be used for planning and prioritizing what, where, and how to build out our National R&D Test Bed.

DSTS focuses on critical failure-trees that are company-specific to the grid of each region (Figure 3). The cascading linkage of failure events is where the simulator becomes most powerful. Specific threat events (weather, equipment failure or human) spanning the transmission and local and company distribution networks can be analyzed and transformed into planned responses to specific “attacks” that the computer has “seen before.” The Department of Homeland Security has budgeted more than $800 million in FY 2004 for just such Infrastructure security analyses and remediation. The DSTS Learning System uses the DEW simulator to learn proper responses to asset management threats. Like learning to play chess or backgammon, the computer learning system searches for failure dependencies. Thus, operators can be trained and ready for unforeseen contingencies. The DSTS identifies and optimizes answers to the following problems impacting the grid:

- What are the new threats to the grid system?
- What are the new failure points in the grid?
- What are the new downward propagation patterns and cascading effects?
- What are the best response scenarios?

DSTS is a system which automatically and continually “learns” as it absorbs, stores, and classifies relationships among discrete runs of the simulator. It is used in conjunction with the EPRI Solutions’ DEW to prioritize and plan the restoration sequence in response to the disturbance. The DSTS learning system is initialized with "Learning Matrices" derived by scenario-playing in what are called “Table-Top” exercises. Our “war-gaming” experts pose problems and work through the solutions with grid operations experts. Rather than being out in the field, however, we electronically record the learning as the exercises proceed.

Texas ERCOT is self contained, and the Houston grid is the most direct power transmission and distribution system within Texas, with Ft. Bend Co.’s W.A. Parish power plant supplying three high voltage transmission grids into all of Houston. Failure cascade signatures need to be learned for this whole system (Figure 3).

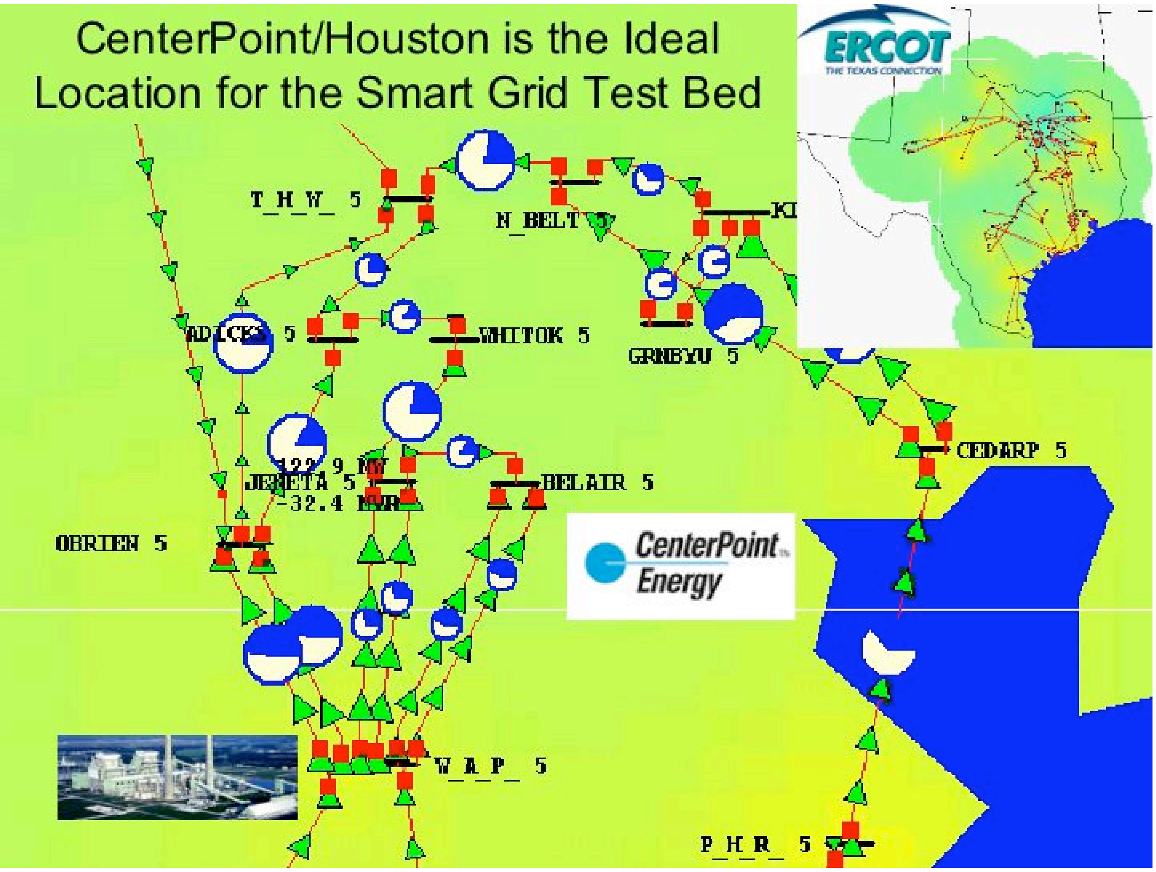


Figure 3. Texas ERCOT transmission grid has limited ties to other networks in North America through only 3 DC interconnects (to Oklahoma, Louisiana, and Mexico). The Houston high voltage transmission grid is coherent and understandable.

The Houston generation to transmission to distribution grid is owned and operated by CenterPoint, Texas GenCo, and Reliant Energy. Improvements to the Houston grid will be monitored and tracked with metrics for the duration of the project. Most of Houston's power is generated by the country's largest fossil fuel power plant at W. A. Parrish (WAP in Figure 3) and the South Texas Nuclear plant in Bay City to the southeast.

Stage 2: Intelligent Substations added to redirect electricity flow around congestion and take actions determined by the simulations

Every Smart Power Controller added to the transmission grid to redirect load around congestion would eliminate the need for 100 MegaWatts of new power generation in Texas. Nationally, computers operating these Power Controllers at every level of the Smart Grid would save the need to build TerraWatts of new generation through better efficiency and safety (Figure 4). Intelligent Substations are the result.

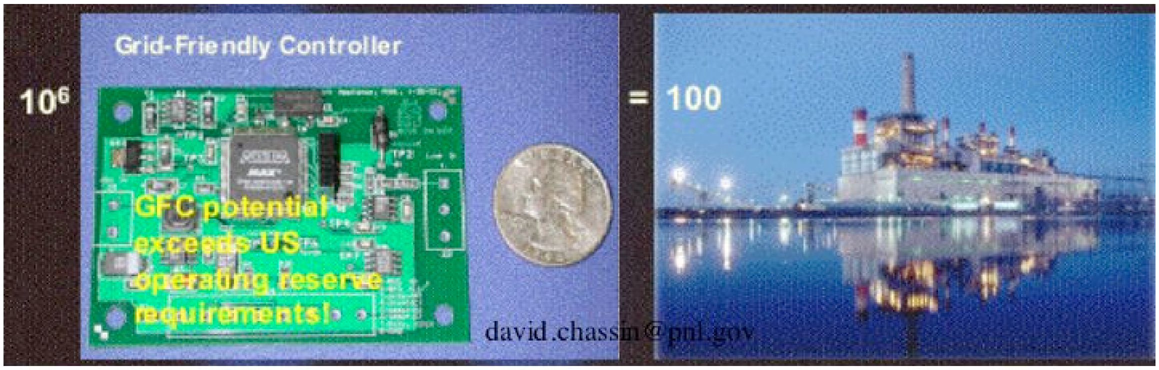


Figure 4. One million Smart Controllers can eliminate the need for 100 Gigawatts of new power plants.

Siemens has installed the world's most sophisticated high-power controller at the Marcy substation in New York, where 765,000 volt Canadian power is transformed to 345,000 volts and sent on to New York City (Figure 5). Specialized thyristor chips inside the device re-route electricity exactly where it's needed for the first time. The novel switch that holds these electric-power processors can filter and manipulate the high voltage AC flowing through the Marcy station. The immediate goal is to stabilize central New York's stressed electric grid, making it safe to divert electrons from congested to less loaded transmission lines. This is the first instance of a truly Smart Grid that allows computers to swap electricity between high-power transmission cables to relieve congestion in our overloaded national power grid. In many ways, the energy “crisis” that continues to grip California and threatens the meltdown of other key congestion points in the North American Grid is as much about getting electricity to flow where you need it—when you need it—as it is about a lack of electricity supply. The problem is that the existing network of high-power transmission lines was never meant to handle the complexity and congestion of today’s ever growing energy demands and deregulated markets.(see Appendix 2).

In addition, the transmission grid is being used for more and more long distance power transfer, a mission it is ill equipped to accomplish without congestion and difficult to control, non-linear behavior. We cannot build enough new transmission lines to keep pace with the growing power demand of the country, let alone accommodate vast new but unpredictable solar and wind power farms. It becomes imperative to build a more efficient way to re-direct electricity over long distances. In the same way that telecommunications companies have created a complex yet seamless network controlled by automated electronic switches that zap phone calls and Internet data around the world, the transmission grid must be made smart.

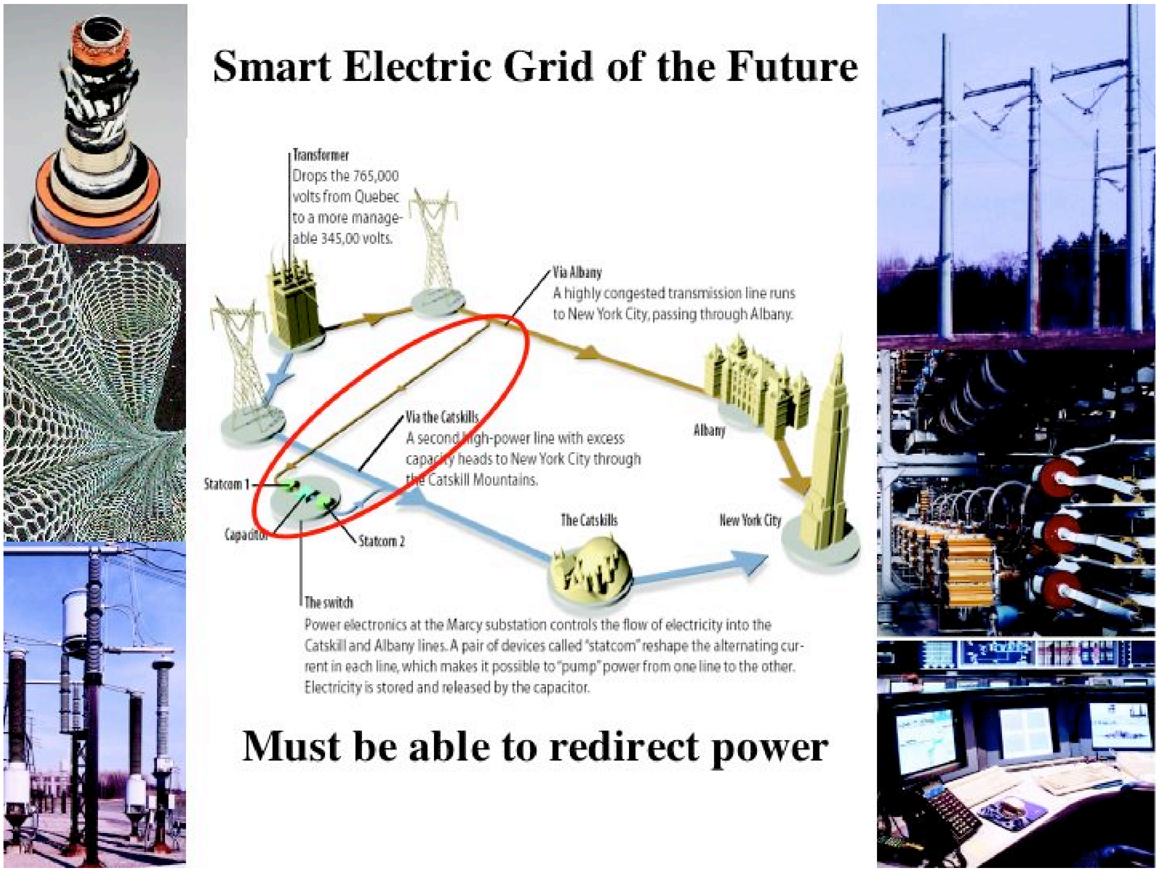
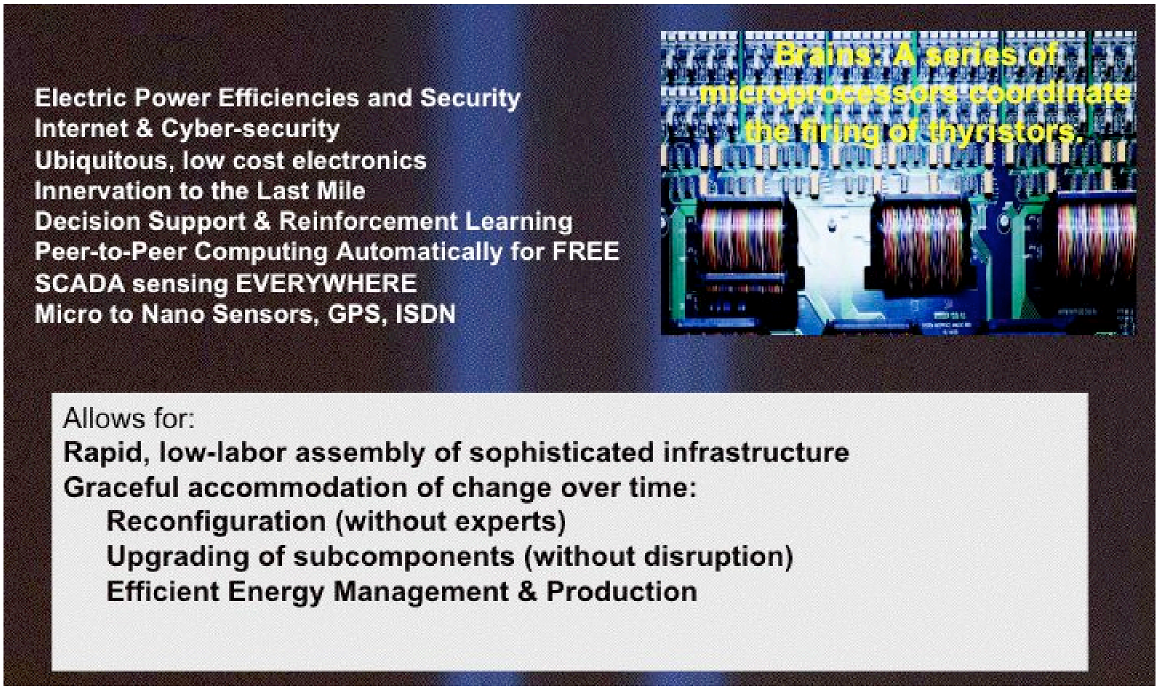


Figure 5. New technologies of the Smart Grid of the Future

Electronic control over the grid requires switches that are strong and fast enough to control electricity flow. The solution dates back to the1950s, when GE Power pioneered the thyristor. Like transistors, thyristors turn the flow of electrons through an integrated circuit on or off and divert flow to the “left or right”. Thyristors are more efficient for handling big power loads because, unlike transistors, once turned on they stay on—allowing energy to flow with little resistance. But the solid-state latch that keeps it on is thousands of times slower to switch than the transistor, limiting its ability to regulate the high-speed action of the electric grid. That began to change in the 1980s with the arrival of a speedy hybrid device called a gate thyristor, which employs its own dedicated circuit of transistors to electronically open and close the thyristor’s latch. These and other advances have enabled power electronics to be used increasingly to smooth out the flow of electricity from small-scale green power generators like solar or wind farms. These Power Controller systems will make the grid less vulnerable to voltage sags and surges that might result from terrorist attacks, as well (Figure 6).



Electric Power Efficiencies and Security
Internet & Cyber-security
Ubiquitous, low cost electronics
Innervation to the Last Mile
Decision Support & Reinforcement Learning
Peer-to-Peer Computing Automatically for FREE
SCADA sensing EVERYWHERE
Micro to Nano Sensors, GPS, ISDN

Brains: A series of microprocessors coordinate the firing of thyristors.

Allows for:
Rapid, low-labor assembly of sophisticated infrastructure
Graceful accommodation of change over time:
  Reconfiguration (without experts)
  Upgrading of subcomponents (without disruption)
  Efficient Energy Management & Production

Figure 6. Linkage between Future electric grid and innervation

The electric grid was originally interconnected to increase reliability and reduce cost. Interconnection means the most expensive generators can be kept off if others—even a thousand kilometers away—can fill the need more cost-effectively. However, without smarts, the transmission grid can transmit disturbances, making the whole system harder to control. Fluctuations propagate around the grid non-linearly, knocking out transformer sub-stations in waves. And the higher the voltage, the more dynamically unstable. Because high-power transmission is so unstable, operators must often limit a line’s load to as little as 60 percent of its ultimate thermal capacity.

Power electronics combined with a Smart control system can reclaim this lost capacity using programmable processors that patch over a surge or sag within a small fraction of a second. The present state-of-the-art is to manually adjust a transformer or trip automatic breakers that sense a disturbance and drop whole segments of the transmission grid off line. This, in turn, sends power through neighboring circuits amplifying the non-linear behavior of the system.

This Power Controller hardware was first installed in 1995 by the EPRI and Siemens at a TVA site in northeast Tennessee. Siemens and ABB have recently sold three more commercial power processors to the Oklahoma, Arkansas and western Texas utility "Central and South West". Meanwhile, Mitsubishi Electric recently installed one in Vermont (Figure 7) and is engineering the first of four units destined for San Diego Gas and Electric.

Figure 7. In 2001, Vermont Electric Power Co. installed a Mitsubishi Electric Power Products STATCOM system at its Essex substation to combat voltage instability and power quality problems (Appendix 2).

By making it safe to draw hundreds of extra megawatts from distant sources over existing transmission lines, San Diego's devices will help overcome the shortage of local power generation that has left power companies throughout California vulnerable to outages and price swings. These systems are only the first primitive steps in power control electronics. The installation at Marcy represents the first attempt at major CONTROL for the grid. Of the two 345,000-volt transmission lines that run south from Marcy to New York City, the eastern one that skirts Albany and runs down the Hudson Valley is over capacity and heavily congested, whereas the other that runs through the Catskill Mountains to the west before it heads for Manhattan is underutilized.

A pair of devices called “statcom’s” reshape the AC in each line, which make it possible to “pump” power from the one line to the other. Electricity had to be stored and released by large capacitors. Believe it or not, this was the first time actual power flow was take off one line and put onto another line by computer controlled power processors in America.

The dearth of investment in transmission over the last 20 years -- combined with on-again, off-again deregulation and restructuring of the power industry -- has left the U.S. transmission system in a state of confusion and relative instability. Since the transmission boom of the late 1960s and early 1970s, construction of new transmission facilities has lagged behind both the construction of new generation and growth in peak power demand. This disconnect has led to the present concerns with bottlenecks and congestion in certain parts of the country and general transmission system instability nationwide. One possible fix for the overburdened transmission system is the application of Flexible AC Transmission System (FACTS) technology. FACTS is a combination of solid-state switches and computerized automation that enable nearly instantaneous customized control of power flows, far faster than traditional electromechanical switches."

FACTS technology is supplied in the United States by such companies as ABB, ALSTOM T&D, Mitsubishi Electric Power Products, and Siemens Power T&D. The devices can be used to move power along transmission lines from one point to another in a very precise way, to help stabilize the transmission system after a disturbance, to relieve or even eliminate congestion, to tie grids together, to integrate distributed generation resources into the grid and to combat the phenomenon of loop flow. But, despite its potential to provide a much-needed boost to the transmission system, adoption of FACTS technology has been less than rapid in the United States because of its cost. But cost is a relative issue. While FACTS may be expensive compared with mechanically switched capacitor banks, cost becomes less of a barrier when one compares a FACTS implementation with the construction of new transmission lines.

FACTS relies heavily on semi-conductor switches which are 50 percent of the cost. In the future, breaker-switched capacitors that have always worked in the past will NOT work in the faster, more complex grid of the future. Unfortunately, in the Northeast, we are getting to that point very quickly. If there has ever been a region in urgent need of FACTS and Smart Grid technology, it is the Northeast Interconnect. Concerns about transmission capacity have been well-publicized the last three years, with ISO’s New England and New York periodically warning of the potential for blackouts in that part of the country due to congestion constraints. The serious outage of August, 2003 makes the need even more urgent. The whole country surely realizes that we have been given a warning shot, and we had better act on bringing not just stability to the grid, but modernization as well.

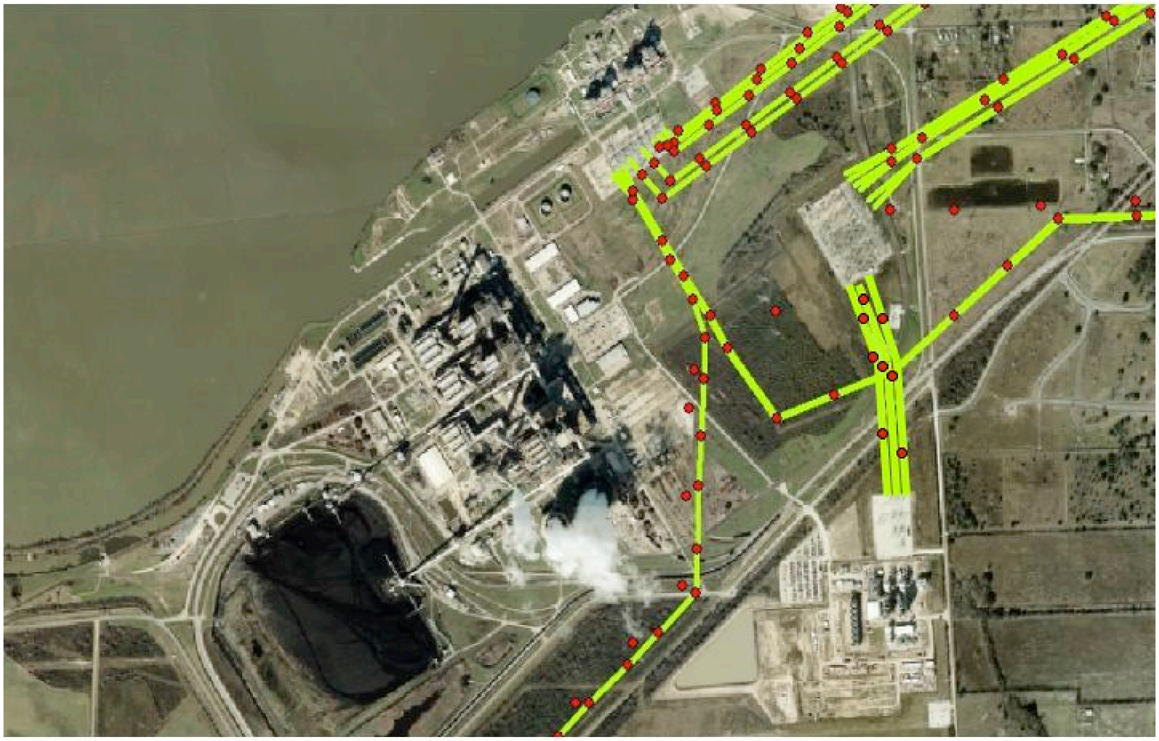
While critically important for the power short Northeast, the Marcy and FACTS test is not a well controlled experiment in Smart Grid development because of the complexity of the inter-ties in the Northeast. Texas ERCOT, the TXU ONCOR grid in Dallas/Ft. Worth, and the CenterPoint grid in the West Houston area, and particularly Ft. Bend County, offer much more controlled environments for such testing.

The problem is costs. The power controller hardware is big, heavy and expensive. Its costs must be dropped by a factor of ten to make it an economically viable choice for the entire grid. A perfected HTS/FCL will provide an inexpensive and effective alternative. Nanomaterials promise a new generation of power controllers that are cheaper, stronger and lighter than today's "prototypes", but we must begin now to learn how to add such devices to the Smart Grid of the Future using funds provided by the Federal government.

Stage 3: Adding Distributed Generation and Distributed Storage

Fort Bend County where the Texas Energy Center is housed is fortunate to have both the country's largest fossil fuel plant (Parrish) and the most modern co-gen gas fired power plant (Brazos Valley Energy) right across the railroad tracks from each other. They both connect into two large 360 KV and one 125KV transmission lines. There are 4 substations also. We intend to include these facilities into the foundation of our test bed.

Texas GenCo Coal Plant - 4 GW



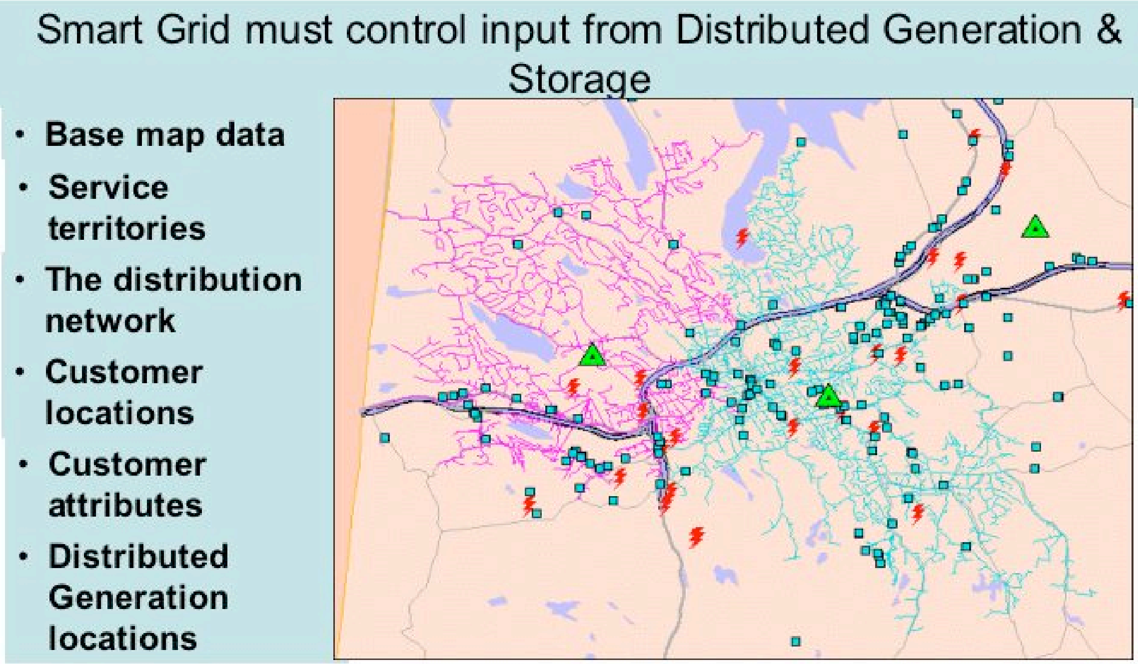
Brazos Valley Power Co-Gen Gas Plant - 659 MW

End-use efficiency improvements affect both supply and demand concurrently. Efforts at the National Test Bed will be directed toward optimizing end-use energy under a “systems” approach, whereby a combination of demand reduction, local storage and self-generation options can accommodate the increased demand for electric service at the consumer end of the grid. It must be possible for a manufacturing facility owner to participate in a utility load-shedding program if the facility can continue operating selected equipment using distributed generation, thereby reducing peak electric demand with no loss in productivity. Now, he must shut down, disconnect, then restart his DG as emergency power. Then, when the power comes back, he must shut down again and reconnect to the grid. This is a technical problem of matching voltage, phase and frequency between the grid and the DG that the Smart Grid can solve. The deployment of a dc interconnect can provide a relief to such an impasse.

The effects of expanding gas facilities to support gas-fired DG technologies and its impacts on natural gas supply and pricing are also a worry. In comparison between DG and centralized station power plants, DG has lower thermal efficiency and higher emissions of pollutants. If the central station power plants are remote, however, how much of the electricity is lost over the transmission system before it reaches the point of use? How does this plant’s total costs, including line losses, compare to the total costs of a DG unit located near the point of use and how will the Smart Grids change the economics of the above?

Distributed Generation (DG) and Storage (DS) must then be added to prop up the far edges of the distribution network, which is especially vulnerable to energy fluctuations at its terminus. Not only will these power controllers, together with DG and DS make the network more efficient, they will enable a new level of Smart control over the transmission grid, allowing controllers to operate "toll roads" to providing revenue sources that could attract the private capital badly needed to upgrade and maintain the long-distance transmission system.

DG and DS must be integral parts of the energy system of the future, providing consumers and energy providers with safe, affordable, clean, reliable, and readily accessible energy services. However, there are significant problems connecting to DG and DS to the grid, and better intelligence on the grid side is required. DG regulatory proceedings have clearly identify the lack of grid interconnection capabilities as THE primary barrier to entry to date (Figure 8).



Smart Grid must control input from Distributed Generation & Storage

- **Base map data**
- **Service territories**
- **The distribution network**
- **Customer locations**
- **Customer attributes**
- **Distributed Generation locations**

Figure 8. All categories at left must be understood before potential DG (red lightning bolts) and candidates for DS (green triangles) can be easily connected into the distribution grid via Plug-and-Play hardware.

DG Grid Interconnection Technical issues are:

- Can the interconnection be made more user-friendly to the end-use consumer?
- Can a substantial amount of DG be interconnected in both radial and networked distribution systems?
- Are there safe, reliable and cost-effective interconnection solutions?
- Can interconnection solutions be deployed in a timely manner?
- Can engineering studies for interconnection be eliminated, standardized, or streamlined?

- How to certify DG unit compatibility with end-use equipment and other DG equipment?
- Can qualified interconnection systems be certified so that they may be installed with minimal field-testing?

Energy storage technologies produce no net energy but can provide electric power over short periods of time. They are critical to correct voltage sags, flicker, and surges, that occurs when utilities or customers switch suppliers or loads. They are mostly used today as uninterruptible power supply (UPS).

Examples of Storage Technology Developments are:

Battery Storage: Utilities typically use batteries to provide an uninterruptible supply of electricity to power substation switchgear and to start backup power systems. However, there is an interest to go beyond these applications by performing load leveling and peak shaving with battery systems that can store and dispatch power over a period of many hours. Batteries also increase power quality and reliability for residential, commercial, and industrial customers by providing backup and ride-through during power outages. The standard battery used in energy storage applications is the lead-acid battery. A lead-acid battery reaction is reversible, allowing the battery to be reused. There are also some advanced sodium/sulfur, zinc/bromine, and lithium/air batteries that are nearing commercial readiness and offer promise for future utility application.

Conventional and Superconducting Flywheels: A flywheel is an electromechanical device that couples a motor generator with a rotating mass to store energy for short durations. Conventional flywheels are "charged" and "discharged" via an integral motor/generator. Flywheel design involves creating a flywheel out of a lightweight, yet strong composite fiber. This wheel is then levitated on conventional magnetic or superconducting bearings and spun at speeds exceeding 100,000 rpm.Magnets are imbedded within the flywheel structure that allow the flywheel to act as a rotor of a three-phase brushless DC motor/generator.In the conventional flightwheel, the wheel is supported by the repulsive force generated by an externally controlled field, whereas in the latter, by the inherend properties of the HTS with no need of external field and thus saves energy. The use of a stator winding around the flywheel rotor allows for brushless electromagnetic transfer of angular momentum to and from the flywheel. This transfer of angular momentum is the same transfer of energy that occurs electrochemically in a conventional battery. Present research into composite materials show the possibility that flywheel energy storage could approach energy density levels that are ten times that of lead-acid batteries. The motor/generator draws power provided by the grid to spin the rotor of the flywheel. During a power outage, voltage sag, or other disturbance the motor/generator provides power. The kinetic energy stored in the rotor is transformed to DC electric energy by the generator, and the energy is delivered at a constant frequency and voltage through an inverter and a control system. Traditional flywheel rotors are usually constructed of steel and are limited to a spin rate of a few thousand revolutions per minute (RPM). Advanced flywheels constructed from carbon fiber materials and magnetic bearings can spin in vacuum at speeds up to 40,000 to 60,000 RPM. The flywheel provides power during period between the loss of utility supplied power and either the return of utility power or the start of a sufficient back-up power system (i.e., diesel generator). Flywheels provide 1-30 seconds of ride-through time, and back-up generators are typically online within 5-20 seconds. A 10Wh HTS flywheel prototype is being developed by Boeing in partnership with DoE.

Superconducting Magnetic Energy Storage (SMES): Superconducting magnetic energy storage systems store energy in the field of a large magnetic coil with direct current flowing. It can be converted back to AC electric current as needed. Low temperature SMES cooled by liquid helium is commercially available. High temperature SMES cooled by liquid nitrogen is still in the development stage and may become a viable commercial energy storage source in the future. A magnetic field is created by circulating a DC current in a closed coil of superconducting wire. The path of the coil circulating current can be opened with a solid state switch which is modulated on and off. Due to the high inductance of the coil, when the switch is off (open), the magnetic coil behaves as a current source and will force current into the capacitor which will charge to some voltage level. Proper modulation of the solid-state switch can hold the voltage across the capacitor within the proper operating range of the inverter. An inverter converts the DC voltage into AC power. SMES systems are large and generally used for short durations, such as utility switching events.

Supercapacitors: Supercapacitors (also known as ultracapacitors) are DC energy sources and must be interfaced to the electric grid with a static power conditioner, providing 60- Hz output. A supercapacitor provides power during short duration interruptions and voltage sags. By combining a supercapacitor with a battery-based uninterruptible power supply system, the life of the batteries can be extended. The batteries provide power only during the longer interruptions, reducing the cycling duty on the battery. Small supercapacitors are commercially available to extend battery life in electronic equipment, but large supercapacitors are still in development, but may soon become a viable component of the energy storage field.

Compressed Air Energy Storage (CAES): Compressed air energy storage uses pressurized air as the energy storage medium. An electric motor-driven compressor is used to pressurize the storage reservoir using off-peak energy and air is released from the reservoir through a turbine during on-peak hours to produce energy. The turbine is essentially a modified turbine that can also be fired with natural gas or distillate fuel. Ideal locations for large compressed air energy storage reservoirs are aquifers, conventional mines in hard rock, and hydraulically mined salt caverns

Developers and manufacturers of Distributed Energy Resources (DG + DS) are looking for ways to combine technologies to improve performance and efficiency of distributed generation equipment. Several examples of hybrid systems include: the solid oxide fuel cell/gas turbine hybrid system, which can provide electrical conversion efficiencies of 60 to 70%. They rely on the principle that fuel cell efficiency and reaction speed will improve when the fuel-cell stack operates above atmospheric pressure. By operating the fuel cell stack at 4 atmospheres or higher, it is possible to integrate the fuel cell with a gas turbine. In this hybrid arrangement, the gas turbine compressor is used to pressurize the fuel cell, then the hot exhaust from the fuel cell stack, which still contains 50% of the fuel's energy (as unreacted fuel and waste heat), is fed back into the turbine, combusted and expanded to extract more energy. Energy recovered from a recuperator is used to help heat inlet air for the fuel cell stack and the compressor. Several companies are working to develop Sterling engine/solar dish hybrid systems. These kinds of hybrid systems are small, with typical outputs in the range of about 5 to 25 kW . This size makes dish/Stirling hybrids ideal for stand-alone or other decentralized applications, such as replacement of diesel generators. Larger dish/Sterling plants with outputs of 1 to 20 MW could be developed to meet moderate-scale grid-connected applications. Dish/Stirling hybrids can also be designed to run on fossil fuels for operation when there is no sunshine. Wind turbines can be used in combination with energy storage and some type of backup generation (i.e., reciprocating engine, turbine, or fuel cell) to provide steady power supply to remote locations not connected to the grid. Reversible fuel cells combined with local hydrogen storage will need nano materials to make it anywhere near economically practical. Also, flywheels are being combined with IC engines and microturbines to provide a reliable backup power supply. The energy storage device provides ride-through capability to enable the backup power supply to get started. In this way, electricity users can have an interruption-free backup power supply. We wish to offer a test bed for all of these systems.

Stage 4: High Temperature Superconducting Current Limiters to Protect the Grid from Current Surges due to Natural and Human Causes

"Fault-currents," which are momentary spikes many times greater than the normal operating current, occur due to falling power lines, lightening, and/or short-circuits in the load. Fault-currents result in power surges, power sags, or even power outage, degrading the quality of power. In our technologically oriented society, progress is closely coupled to the demand for more electric power with higher quality. As the electric power systems grow and become more interconnected, fault-currents happen more frequently. Fault-currents cause lost power, impaired equipment, and/or scrambled information. The ever increasing use of computers and other microelectronics whose sensitivity to power irregularity grows with their enhanced sensitivity aggravates the situation. The conventional way to avoid fault-currents by reconfiguring the power system is costly and often leads to less operational flexibility and reliability. A device known as a "fault-current limiter" (FCL) or a "current-surge suppresser" will limit this unwanted current surge and protect the electric power system. So far, all FCL's have either cost or performance limitations due to the limitations of materials and refrigeration. The FACTS can perform similar function as FCLs, but with serious cost impediment even though relative, as discussed in Stage 2.

The very fundamental principle of limiting or controlling the current to impose variable impedance in series with the power system has been known for as long as Ohm's law. A FCL will limit the unwanted current surge by raising the impedance under fault-current conditions. An ideal FCL should therefore possess the following characteristics:

- zero or very small impedance under normal operation, with very low energy loss

- very large impedance under fault conditions, sufficient to limit the current surge to protect the power system and equipment

- short response time to the fault-currents, enough to prevent damages to the power system and equipment

- short recovery time, to normal operation on the cessation of fault-currents, to ensure the rapid restoration of power

- high reliability over a long period of time

- compact, simple and low-weight design

- low cost in construction and operation

There are three general categories of FCL's, depending on the nature of the impedance. They are resistive, resistive/inductive, and inductive with impedances being, purely resistive, combined resistive/inductive, and purely inductive, respectively. A purely resistive FCL is preferable since it makes the circuit less inductive. As a result, it reduces the fault-current peak and enables the current zero crossing to take place within the first half of the cycle, making the fault-current limiting more effective.

Unfortunately, until now, no FCL's have been commercially practical due to either their cost or performance limitations. For instance, semiconducting FCL's using the thyrister technology, also known as FACTS as discussed in Stage 2, are costly and consume an unacceptable amount of power during normal operation. The superconducting FCL's employing the conventional low-temperature superconducting materials are cost prohibitive because of the bulky design and the associated refrigeration for operation at ~ - 460° F.

Several concepts of FCL's, taking advantage of some superior properties of HTS have been advanced in the last few years. However, most of them are still just "paper" concepts that have just being constructed and to be tested ,because of the various problems due to materials and design. ABB of Switzerland is the leader in pursuing the commercial development of HTS FCLs. We at the University of Houston, the home of the first liquid nitrogen HTS, have proposed a design to alleviate part of the HTS-element fabrication problems. operating in the simplest resistive mode among all types of FCL concepts. The working principle and scaling at low rating have been demonstrated. Unfortunately, we failed at scaling it up to certain power due to materials. With the impressive advancement made in coated HTS conductors, we believe that the time is ripe for us to carry out the scale-up prototype testing at the National Test Bed at TxEC after preliminary scale-up development is completed at the Texas Center for Superconductivity at the University of Houston in partnership with several industrial partners by examining the dynamics and control of the switching, the tailoring of the HTS materials needed, the heat-management during switching, and packaging of the device.

Stage 5: High Temperature Superconductor/Liquid Hydrogen Super-Energy Highway to Large Amount of Clean and Green Energy to Meet the Need of the Sustainable Energy Economy of the Future

Superconductivity is the property of a class of materials known as superconductors, whose resistance to electricity becomes zero when cooled to below their transition temperature T_c. Such property disappears when the current density through the superconductor exceeds a critical value J_c and the magnetic field experienced by the superconductor is greater than the critical value of H_c. The profound implication of superconductivity in the energy industry was recognized immediately after its discovery in 1911. Unfortunately, the T_c of the compounds, called low temperature superconductors (LTSs), found in the ensuing decades had stayed at 23 K (-418 F), rendering LTSs for energy transmission impractical, due to the lack of any practical coolant. However, the discovery of the so-called high temperature superconductors (HTSs) in 1987 with a T_c above 77 K, the boiling point of liquid nitrogen, drastically changed the situation and brought the HTS-cables for energy transmission over long distance at negligible energy loss closer to reality. In the past 15 years, many new HTS compounds have been discovered. The T_c has been raised to 134 K at ambient and 164 K under high pressure. Kilometer lengths of HTS-tapes have been successfully made using the BSSCO ($Bi_2Sr_2Ca_2Cu_3O_8$) compound employing the powder-in-tube tape-drawing technique followed by repeated thermo-mechanical treatments. Various prototype devices have been constructed and tested using the BSCCO tape (Figure 9).

Figure 9. High temperature Superconducting cable installation, switchyard, and control room from Southwire.

However, in terms of the robustness of their superconducting properties, none can surpass the YBCO ($YBa_2Cu_3O_7$)-series, in spite of their lower T_c of 93-96K compared with the 115 K of BSSCO. This is because J_c of YBCO at 77 K is higher than that of BSCCO, especially in the presence of a magnetic field. As a results, DoE started a few years ago has focused their HTS-cable efforts on YBCO-coated conductors, in order to exploit the full potential of HTSs. The YBCO-coated conductor comprises an atomically aligned YBCO films on a specially prepared flexible metallic substrate. Until very recently, only short lengths of a few centimeter YBCO coated conductors could be prepared due the complexity in processing. However, progress made in the U.S., Japan and Germany in the last 12 months has been exceedingly impressive. YBCO coated conductors with good performance of lengths more than 100 m has been achieved. The opportunity now of successful deployment of HTS coated conductors for electric power transmission has never been brighter, albeit several obstacles are yet to be overcome.

The Smart Grid should be energetically efficient, economically competitive, environmentally friendly, technologically advanced, safe and secured to transmit massive amount of energy to fuel our economy. Recent national roadmap workshops and proceedings have all pointed to the important role of HTS in meeting such goals. -- see www.energetics.com/electric.html --

A HTS coated conductor will not only transmit mass amount of electricity with practically zero energy loss but also improve power quality. Given the enhanced transmission capacity, it will provide greater stability for the grid to avoid overload without constructing additional generation plants and transmission lines.

The idea to combine the superconducting cable with the cryogenics together to form the power transmission line is not new. The proposed versions are (1) LTS (Nb_3Sn, T_c=18 K) /LHe (T_b=4.2 K) proposed by Garwin and Matisoo in the early 60's, (2) LTS (Nb_3Al-Ge, T_c=21.3 K) /LH_2(T_b=20.3 K) by Matthias in the late 60's, (3) HTS (YBCO, T_c =93 K)/LN_2 (T=77 K) by Chu in 1987, HTS (HBCCO, and (4) T_c=164 K under pressure)/LPG (T_b=~160's K) by Chu and Grant in 1994. While all seem to be possible, versions (2) and (4) are not practical because the the low J_c, due to the closeness of T_c and the boiling boint of different liquid coolants T_b. The Founding President of the Electric Power Research Institute proposed a transmission system that combines the benefits of HTS cables and liquid hydrogen by using liquid hydrogen to cool the transmission cables to deliver the clean and green energy simultaneously in electrical and chemical form. The liquid hydrogen used to keep the HTS transmission system operative will be produced at the generation site initially from fossil fuels or other means and will be used along the way for transportation for cars. The synergistic advantages of the two environmentally desirable secondary energy sources are thus fully exploited. A city power by such a HTS/LH_2 SuperEnergy Highway has been envisaged by Grant of EPRI as shown in Figure 11.

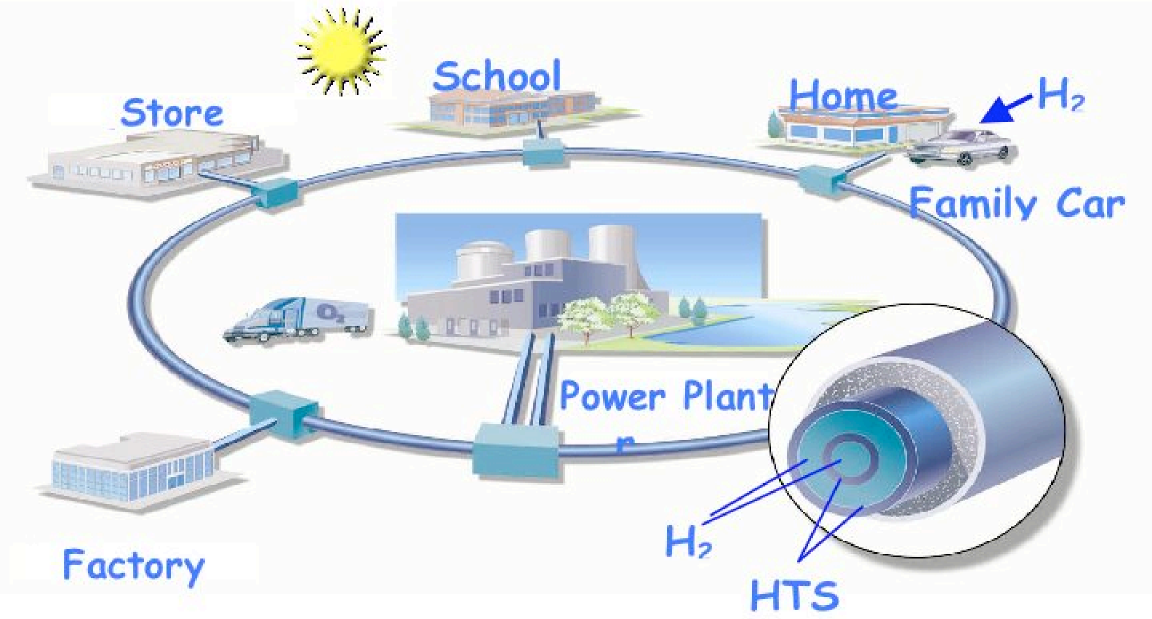


Figure 10. The Super Energy Highway from EPRI.

The HTS materials to be used for the HTS/LH_2 SuperEnergy Highway are YBCO and MgB_2. To operate the HTS at the LH_2 boiling point of 20.3 K greatly enhances current carrying capacity of the power cable as well as relaxes the stringent requirement on the processing cost of HTS coated conductors. Work at the Texas Center for Superconductivity at the University of Houston recently has focused their attention to investigate the issues, from HTS materials to hydrogen generation, transportation, storage and safety and their synergy, related to the deployment of such a SuperEnergy Highway. A prototype HTS/LH_2 SuperCable will be constructed and tested at the National Test Bed at the Texas Energy Center which is located at a location with the major components needed for such an on-site-test, i.e. the electric power companies and the hydrogen generation and handling facilities.

Stage 6: America's First NanoGrid – Quantum Transmission Wires for the National Smart Grid Test Bed.

We have a long way to go before we have the design for a Smart Grid that can move TeraWatts (TW) from one side of the continent to another. Our ultimate plan is to produce the test bed for a Smart Grid for North America that would be a distributed store-gen grid with 50% or more of the primary power coming from remote sources such as 1TW from solar in the western deserts, and 1 TW each from remote nuclear plants such as near Hanford in Washington state, and clean coal plants in Wyoming. A quantum wire revolution in transmission lines is needed before this is practical.

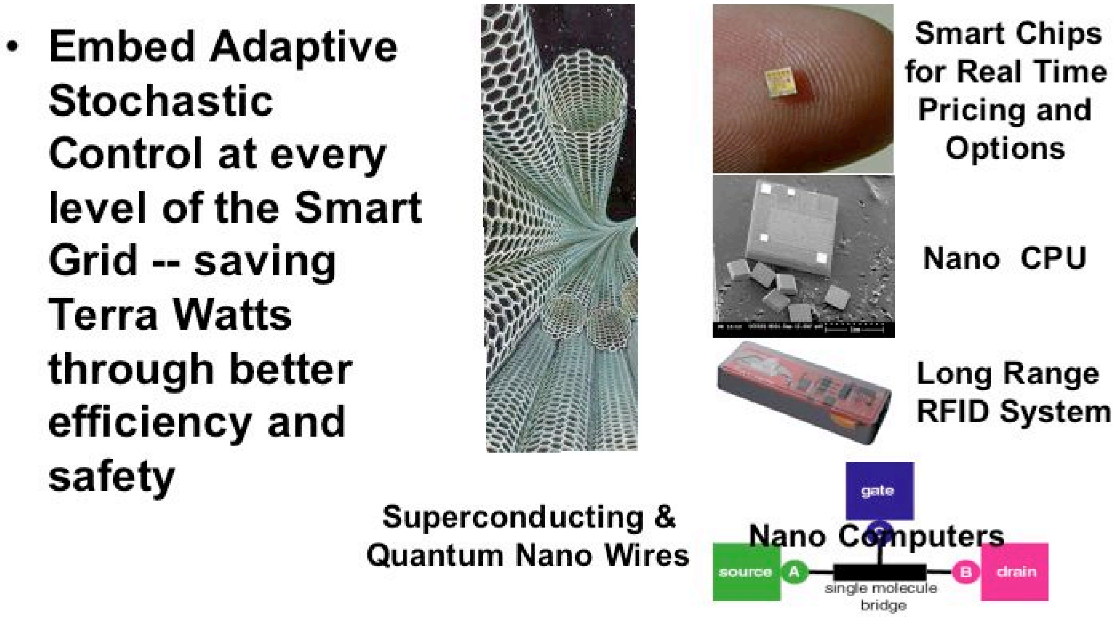
The Texas Energy Center proposes to have a major role in this revolution, It will be at least 5 years before a quantum wire power cable is ready to test in a Smart Grid test bed, but these quantum wires have to be tested I some real grid. It might as well be here in Texas. And there is at least 5 years of hard work to get the Grid to the intelligence level required to usefully test the quantum wires in the first place.

Currently, new types of transmission lines in development can carry three to five times as much electricity as copper lines. If they work, they promise to relieve congestion on the nation's old and overtaxed power grid. A ceramic-coated superconductor tape or wire developed by Los Alamos could be produced at a price competitive with copper within two years. The wire can transmit electric current with virtually no resistance if it is chilled by liquid nitrogen to minus 320 degrees Fahrenheit. Without resistance, a superconductor wire can carry more current than conventional copper wire, a factor that can reduce the cost of electricity production, storage, transmission and use, scientists say. So far, the wire manufacturers -- American Superconductor Inc. in Westborough, Mass., and SuperPower Inc. in Schenectady, N.Y. -- have produced the wire only in 10-meter lengths. They expect to produce 1- kilometer lengths in about two years.

Superconductor cables, which must be kept cold, can replace copper only if the power lines are buried. The cost of burying power lines makes this technology practical only in densely populated areas. New Nano technologies that will be important beyond 5 years out include (Figure 11):

- High current cables (superconductors and/or quantum conductors) with which to rewire the electrical transmission grid
- Batteries and super Capacitors -- revolution to improve by 10-100x distributed generation (DG) applications.
- Nanoelectronics to revolutionize sensors and power control devices
- Storage -- a revolution in light weight materials for high pressure storage tanks , flywheels, hydrogen conversion
- DG Fuel cells -- a revolution to drop cost by 10 to 100x
- Nanotech lighting to replace incandescent and fluorescent lights
- Photovoltaics -- a revolution to drop cost by 10 to100x

Quantum wires (QW) will have the electrical conductivity of copper at one sixth the weight and it will be stronger than Kevlar. They can perhaps be spun into polypropylene-like wire and used for the transmission grid of the future. These Fullerene nanotude arrays should form a “super-material” of extreme strength, light weight, high temperature resistance, unidirectional thermal conductivity (electrons just fit into each tube, and so have only one place to go). It will take the Center for NanoScale Science & Technology at Rice and other nano centers at least 5 years to develop methods to produce QW in great enough purity, in large enough amounts, and cheaply enough to spin continuous fibers into QW.



- **Embed Adaptive Stochastic Control at every level of the Smart Grid -- saving Terra Watts through better efficiency and safety**

Figure 11. Plenty of room at the bottom, according to Richard Feynmann describing nanotechnology opportunities.

While increasing energy demands are putting more and more stress on the nation's long-distance power transmission network, cities are suffering their own version of electric gridlock with what is called the Distribution Network; the lower power AC grid that ultimately delivers power to homes, offices, and manufacturing sites. In many locations in every major city in America, distribution lines are fast reaching capacity and are literally burning up. Superconducting cables could safely triple the power moving through existing conduits, avoiding the need to dig up the streets. Detroit Edison has installed at its Frisbie substation the country's first underground superconducting power cable, made by American Superconductor and built by Pirelli, the worlds larges producer of power cables, That cable, when kept cold, can transmit electricity with near perfect efficiency. The Frisbie demonstration is the first commercial applications of high-temperature superconductors for the Distribution grid. These ceramics transmit AC with nearly zero resistance at temperatures as high as -139 °C (the materials can be cheaply cooled to that temperature using liquid nitrogen). In contrast, conventional copper cables dissipate as much as 20 percent of the power they carry because of resistance, and that lost power escapes as heat. This limits just how much power can flow before the cable melts. However, DTE are continuing to have major problems with leaky cryostats -- they can't keep the cable cold for very long before some leak appears and shuts them down.

Smart Grid of the Future research at the TxEC will be coordinated with fuel cell and hydrogen developments also being pursued. We will need extensive use of affordable, reversible fuel cells combined with local hydrogen storage, likely with the nanotech revolution to make the whole system practical and affordable.

Smart Grid Risk Table

Risk	Mitigation
Does not scale to National grid.	The simulation part is known and proven to scale. There are means to deal with scaling problems with reinforcement learning and SCADA. Fast and scalable fault signature vectors are required for problem detection mapping.
Not enough people resources	We are also working with the first-adapter utilities that have already implemented some major components of the Smart Grid, including simulators and SCADA.

Unable to generate sufficiently Test Bed for advanced products	There must be multiple experimental stages, and each will be successively more directed and complex.
New unproven approaches with major development risks	Our team has extensive experience in innovation in the energy business, and has implemented systems with Lean efficiencies in oil and gas and Internet fault management. In addition, the last several years of the project will address real problems that arise during the Test Bed development.

Appendix 1: Glossary of DSTS and DEW terms

Decision Support Threat Simulator

The system that we are proposing is system for helping operators make optimal asset management decisions and training against threats. Our system is also known as an **adaptive aiding system**. It does not take action itself, but aids operators in making decisions. In doing, so it also trains operators and can be used offline for this purpose. It is based on a grid simulator, in this case the simulator in DEW, and also a computer **learning system** that learns from experience gained by simulations of scenarios.

Decision Support System

A computer based system to aid in helping operators make optimal decisions.

Learning System

A computer based system that learns from experience presented to it. In our case we use an “online” type of learning called **reinforcement learning** that learns as it goes along online. Algorithmically, reinforcement learning is a stochastic adaptive control algorithm, hence “online”, and a type of **dynamic programming**.

Dynamic Programming

Dynamic programming is a computer algorithm that optimizes sequential decisions over time. It also incorporates uncertainty about the future in its choice of decisions.

Learning Matrices

These are a matrix representation for knowledge. They are a generalized form of a artificial neural network. Two matrices chained together can represent a two layer neural network. When the learning system is discovering the “plant” or, in our case the grid, it is adapting the weights in these matrices. The sources of adapting in our system are:

1) The simulator
2) Online operations in shadow mode
3) Initial learning captured from desktop exercises which are useful to guide the initial learning by the learning system

Codebooks
An efficient and compact form of a **Learning Matrix** used in the Smarts inCharge product (see http://www.smarts.com). We intend to explore its use to deal with scaling problems of the learning system.

Self-healing Grid
A self-healing grid is one capable of automatically sensing, isolating and instantaneously responding to power system disturbances, while continually optimizing its own economic as well as operational performance Our system can be viewed as a variant of this concept that keeps the operators involved in the optimization of asset management and the maintenance of the system to be self healing.

Appendix 2: Additional Intelligent Sub Station References

Integrated Substation Diagnostics: New Monitoring System to Enhance Substation Maintenance
Smart Substations: Condition Monitoring: Interim Progress
Transformer Expert System, XVisor: A Practical Statistical Evaluation of Transformer Failure Predictions
Proceedings: Tenth EPRI Substation Equipment Diagnostics Conference