# National Energy Supergrid Workshop 2
# Final Report

**March 2005**

**SuperGrid 2 Workshop**
**University of Illinois at Urbana-Champaign (UIUC)**
**October 25-27, 2004**

**Sponsored by the**
**University of Illinois at Urbana-Champaign (UIUC)**

**With support from the Richard Lounsbery Foundation and EPRI**

**Workshop Organizers:**

**Thomas J. Overbye, UIUC**
**Chauncey Starr, EPRI**
**Paul M. Grant, W2AGZ Technologies**
**Thomas R. Schneider, TRS Energy**

**This Report is Available Online at**
**www.supergrid.uiuc.edu**

# Executive Summary

This report presents the results of the University of Illinois at Urbana-Champaign (UIUC) sponsored SuperGrid 2 Workshop (SG2), which was held October 25-27, 2004 on the UIUC campus in Urbana, Illinois. The purpose of SG2 was to formulate a technical task description of the research and development (R&D) needed to implement a visionary concept known as the "Continental SuperGrid" (or SuperGrid). As originally proposed in 2001 by Chauncey Starr, founder and emeritus president of EPRI, the SuperGrid idea calls for the creation over a time period of several decades of a continental grid delivering both electricity and hydrogen, with the electric portion of the grid utilizing superconducting, high current dc. The electric power and hydrogen would be supplied from nuclear and other source power plants spaced along the grid. Electricity would exit the system at various dc-ac taps, connecting into the existing ac power grid. The hydrogen would also exit the grid, providing a readily available, alternative fuel, for perhaps fuel-cell based automobiles, or for the storage of electricity.

The scope of this proposal is certainly ambitious. However, given its potential for significant society-wide benefits, and the societal need to transition from an energy infrastructure heavily dependent upon petroleum, it is also one that deserved serious consideration. This consideration was provided at the UIUC sponsored SuperGrid 1 (SG1) workshop, which was held on November 6-8, 2002 in Palo Alto, California. SG1 brought together about 30 technical experts from a variety of disciplines. The conclusion from SG1 was that the SuperGrid concept did appear to be technically viable and that its implementation would require no new scientific breakthroughs. However, it would require extensive R&D to move from being a visionary concept to an actual energy system. Therefore a next logical step would be the development of a more detailed, discipline specific R&D task description.

The purpose of SG2 was the development of these initial research task descriptions. To accomplish this goal SG2 brought together about 50 experts from industry, government and academia, in a variety of technical areas including electric power systems, superconductivity, hydrogen and cryogenics, geotechnical and environmental engineering, and nuclear power. Since most of the participants had not attended SG1, SG2 also provided a forum to discuss the SuperGrid concept before a larger technical audience. This report provides an overview of the SuperGrid concept, summarizes the SG2 presentations and discussions, and presents the discipline specific research task descriptions. The key findings and recommended near-term actions are as follows:

1. SG2 confirmed the finding of SG1 that no scientific breakthroughs are needed to achieve the reality of the SuperGrid, yet major technological innovations will be required to minimize environmental effects and maximize economic and societal benefits.
2. Although the role of nuclear power continues to be controversial, the SuperGrid vision is perceived as fundamentally green as it is based on technologies that emit few pollutants and that minimize the environmental impact.

3. The SuperGrid is a vision for an energy infrastructure decades in the future and not a specific implementation. Therefore it is not readily amenable to a specific “roadmap”. Rather, it will be the outcome of driving forces and trends, the result of either social forces or technological evolution. A major recommendation of the workshop is that the vision needs to be clarified and evolve along with the driving social forces and the technological developments and innovations.

4. The SuperGrid concept needs to be more thoroughly considered from an economic point of view. There is no reason scientifically that the SuperGrid could not be built. An open question is how does it compare economically to other energy delivery technologies keeping in mind that within the SuperGrid timeframe the total electric load will probably be more than double what it is today. Trying to estimate system economics decades into the future is problematic. Nevertheless, a prototype study doing a cost benefit analysis comparing underground dc superconductors with existing and likely future energy transportation technologies can and should be done.

5. The SuperGrid vision can move forward over the next few years with relatively modest funding. Much of the initial SuperGrid R&D can be accomplished through dual-use application of existing R&D projects. Nevertheless, some dedicated SuperGrid funding is required.

6. To assist in developing the vision of the SuperGrid a research community interest group should be established that serves to nurture the vision and explore its potential. An interest group or “club’ could undertake or organize future workshops and conferences and serve as an educational outreach effort to academia, industry, non-government organizations and policy makers at all levels within and outside the government as well as the general public. One objective of a public outreach effort would be to increase the public understanding of the issues related to long term sustainable energy and to increase engineers’ understanding of public preferences as it is public preferences as well as the obvious environmental and security advantages that motivate the underground siting aspects of the SuperGrid.

7. DC, high power superconducting power transmission should become a viable technology that can be integrated with the existing ac power grid. As recommended in SG1 an early demonstration of essential engineering features of the SuperGrid would be very desirable. A series of scaled experiments with superconducting dc transmission, integrated with hydrogen transport, is recommended as a first step. An integrated systems engineering experiment with hydrogen as a combined cryogen and form of energy transport at physically meaningful scales (hundreds of meters, tens of thousands of amperes and a few thousand volts) needs to be undertaken. This would be beneficial both for research and public education.

8. In addition to the above recommendations, it is recommended that a high-level committee or panel be established to further study the SuperGrid vision. The National Academy may be the most appropriate organization to undertake such a study since it could require several years with an interdisciplinary team that includes engineering and the physical sciences as well as expertise needed to assess long-term social and political issues.

# 1 Introduction

Humanity has continually pursued cheap and plentiful energy resources. For centuries the major energy resource was firewood, while for most of the last century and into the 21st century energy has come largely in the form of fossil fuels, such as oil, natural gas and coal. By providing a direct source of relatively inexpensive energy, fossil fuels currently provide much of the energy needed to run our modern economy.

But the reserves for these fuels are finite. The magnitude of these reserves, and when their production will peak and begin to diminish has been a subject for debate and discussion for at least 50 years. No one, of course, knows for sure when that day will come, or what type of price volatility and geopolitical unrest could accompany global shortages of fossil fuels. For some fossil fuels, such as coal, reserves are sufficient for many decades of usage at current rates using domestic mining (with some estimates going up to 200 years). But for others the time is growing short, with most experts predicting global oil production to peak in the next ten to twenty years. Additionally, over the last decade the effects of $CO_2$ emissions on global climate has been a subject of active debate and growing concern that such emissions need to be curtailed. Clearly the need for sustainable energy resources that afford continued growth of human prosperity and meet the expanding concern for protection of the global environment – the human habitat – has become apparent. Sustainable development and a safe human environment will require innovation beyond our current energy infrastructure.

To help facilitate this innovation, the University of Illinois at Urbana-Champaign (UIUC) with support from the Richard Lounsbery Foundation sponsored the National Energy Supergrid Workshop (SG1), which was held on November 6-8, 2002 in Palo Alto, California. The purpose of the workshop was to investigate the technical feasibility of a proposal developed by Chauncey Starr, founder and emeritus president of EPRI, to meet the nation's energy needs in the mid to later half of the 21st Century through the use of an Energy SuperGrid[1].

As originally proposed by Dr. Starr in 2001 (see Figure 1) the SuperGrid idea calls for the creation of a continental grid delivering both electricity and hydrogen, with the electric portion of the grid utilizing superconducting, high current dc. The electric power and hydrogen would be supplied from nuclear and other source power plants spaced along the grid. Electricity would exit the system at various dc-ac taps, connecting into the existing ac power grid. The hydrogen would also exit the grid, providing a readily available, alternative fuel, for perhaps fuel-cell based automobiles, or for the storage of electricity.

To provide an evaluation of this concept SG1 brought together a small group of experts from a diversity of disciplines including electric power systems, nuclear power, superconductivity and cryogenics, energy system economics, hydrogen transport, geotechnical engineering and environmental analysis. The conclusion from SG1 was that the SuperGrid concept did appear to be technically feasible and that its implementation would require no new scientific

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[1] Available online at http://www.epri.com/corporate/discover_epri/news/HotTopics/starr_NatlEnergyPlan.pdf

breakthroughs. However, it would require extensive R&D to move from being a visionary concept to an actual energy system[2].

To continue the development of the SuperGrid concept UIUC, with support from the Richard Lounsbery Foundation and EPRI, sponsored a second SuperGrid Workshop, SG2, which was held October 25-27, 2004 on the UIUC campus in Urbana, Illinois[3]. The purpose of SG2 was to formulate a technical task description of the research and development (R&D) needed to implement the SuperGrid. To accomplish this goal SG2 brought together about 50 experts from industry, government and academia, in a variety of technical areas including electric power systems, superconductivity, hydrogen and cryogenics, geotechnical and environmental engineering, and nuclear power. Since most of the participants had not attended SG1, SG2 provided a forum to discuss the SuperGrid concept before a larger technical audience. This report provides an overview of the SuperGrid concept, summarizes the SG2 presentations and discussions, and presents the discipline specific research task descriptions created at SG2.

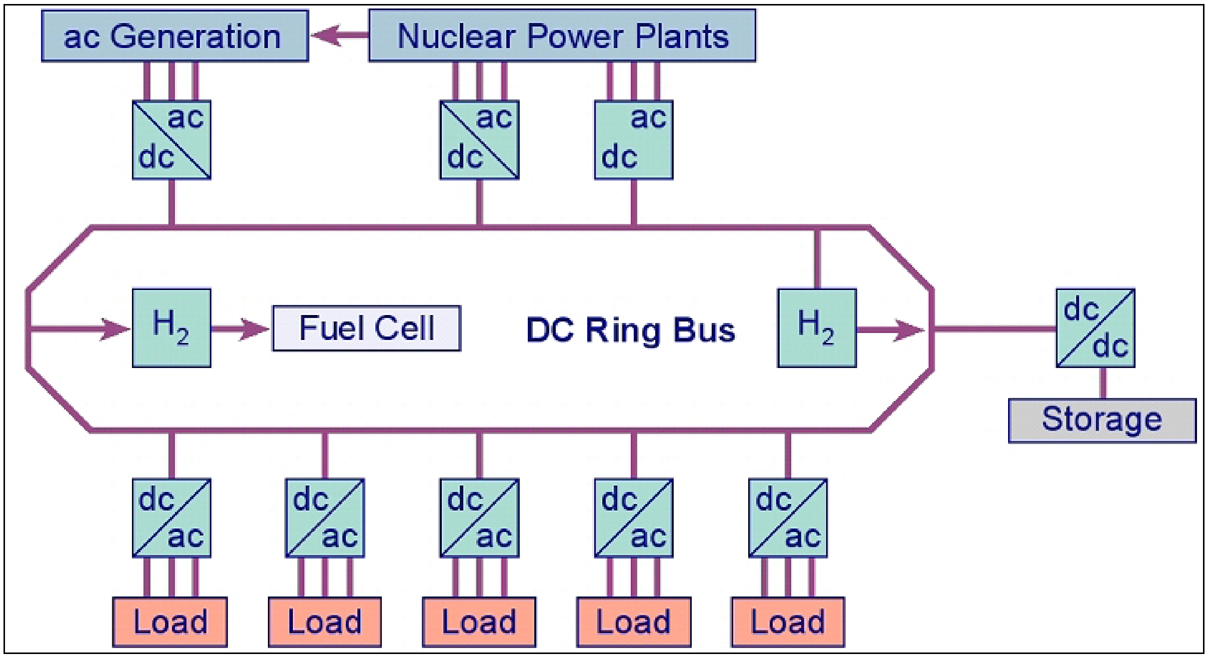

Figure 1: Original Concept for a Continental SuperGrid (Source: Chauncey Starr, EPRI)

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[2] The SG1 final report and presentations are available on-line at www.supergrid.uiuc.edu

[3] All the SG2 presentations are available on-line at www.supergrid.uiuc.edu

# 2 The Energy SuperGrid Concept

The Energy SuperGrid is a visionary concept for an enhanced, sustainable energy infrastructure to meet the country's energy needs from the middle part of the 21st century onward. To meet the goal of long-term sustainability, the SuperGrid concept assumes a significant reduction in the percentage of our energy derived from fossil fuels. To understand the need for this enhanced infrastructure it is useful to provide a brief background on U.S. and worldwide energy consumption, and to make a clear differentiation between primary energy usage and usage via an intermediate form.

Using 2003 data provided by the U.S. Energy Information Administration, the total annual U.S. energy consumption is about 98.2 Quadrillion Btu (Quad), of which 22.7 Quad comes from coal, 22.5 Quad from natural gas, 39.1 Quad from petroleum, 8.0 Quad from nuclear and 5.9 from renewables and other sources (including hydro and wood waste). In terms of usage, practically all of the petroleum and most of the natural gas is used directly as a primary energy source for transportation (26.8 Quad), heating and cooling, and other industrial uses. Most of the remainder, including essentially all the nuclear, more than 90% of the coal and 60% of the renewables, are converted into the intermediate form of electricity (38.3 Quad), and then transmitted using the high voltage grid from the generating plants to the electric loads. Over the last 20 years (1983-2003) the growth in total U.S. energy consumption has averaged about 1.5% per year. Worldwide total energy consumption is about 415 Quad, with Figure 2 showing the breakdown by fuel type. The worldwide growth in energy consumption over the last 10 years (1992-2002) is about 1.7% per year. Figure 3 shows a plot of historical and projected energy consumption values between 1970 and 2025.

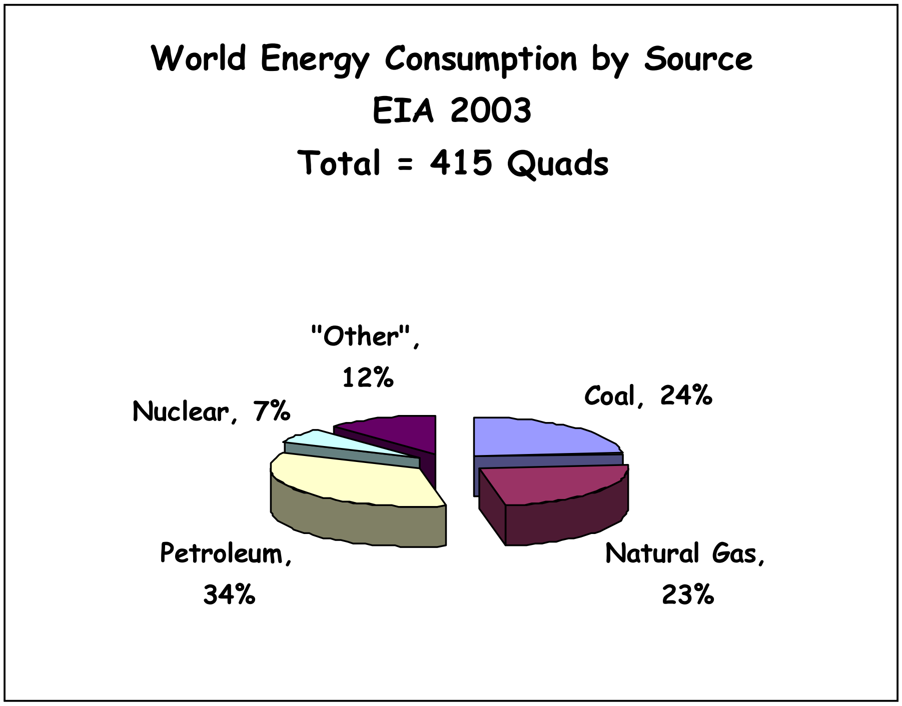


Figure 2: Worldwide Energy Consumption by Fuel Type for 2003

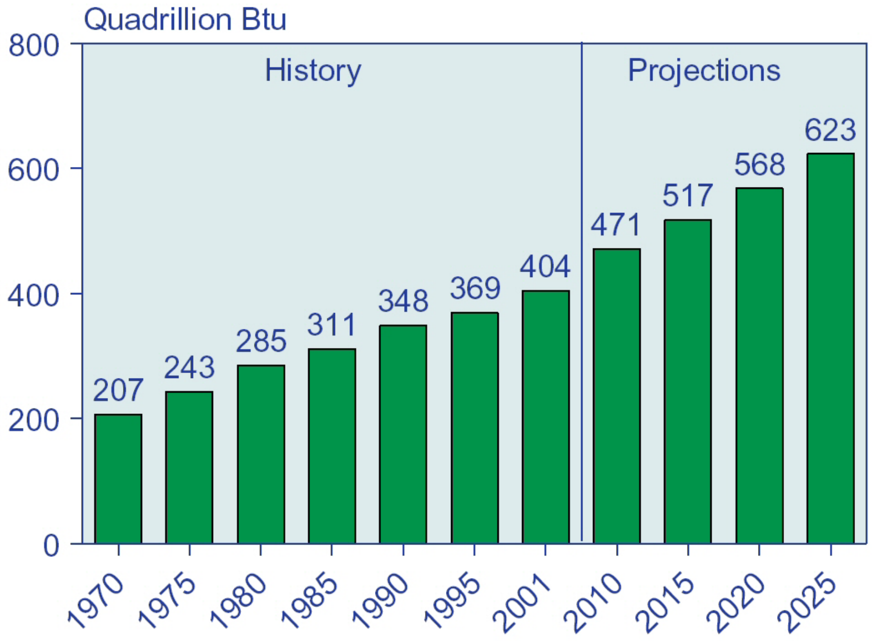


Figure 3: Worldwide Energy Consumption, 1970-2025 (Source: EIA International Energy Outlook 2004)

The SuperGrid concept addresses the questions of both where we will get our energy in the future and how we will transport it from the energy sources to the urban load centers. Assuming an annual energy growth rate of 1.5% energy usage will double in the next 50 years. But at the same time it is quite likely that petroleum and natural gas production will peak and begin to decline as reserves diminish. Therefore it is quite likely that there will need to be a significant reduction in the percentage of energy consumption derived from fossil fuels, particularly from petroleum and natural gas. Hence there will be a need both to replace this energy with alternative sources and to change how the energy is transported from its source to where it is consumed.

Currently most of the energy used in this country is transported in the form in which it is ultimately used – natural gas is transported in pipelines while petroleum products are transported in pipelines, by rail and by truck. Only about 40% of our energy (38.3 Quad) is first converted into the intermediary form of electricity and then transported via the high voltage electric power grid. But as the percentage of energy derived from petroleum and natural gas diminishes, coupled with the normal growth in total energy consumption, the amount of energy that must be transmitted in an intermediary form will rapidly grow. The only viable options for long distance energy transportation are electricity and hydrogen. Therefore it is quite probable that in 50 years the electric transmission infrastructure will need to be producing and transporting twice the amount of electric energy as today. The SuperGrid provides a vision of an environmentally friendly energy infrastructure for the middle part of the 21st century to meet this new demand in a manner in which electricity and hydrogen provide complementary means for energy transportation.

As originally proposed in 2001 the Supergrid calls for supplementing the existing high voltage electric grid using superconducting dc cables for power transmission with liquid hydrogen used as the core coolant. The electric power and hydrogen would be supplied from nuclear and other source power plants spaced along the grid. The power mix between electricity and hydrogen would be design specific, varying perhaps between 95% electric to a more even mix. Electricity would exit the system at various taps, connecting into the existing ac power grid directly in the urban load centers. The hydrogen would also exit the grid, providing a readily available, alternative fuel, for perhaps fuel-cell based automobiles. Hydrogen could also be generated locally by electrolysis using the electricity supplied by the superconducting cables.

The need for the superconducting cables arises because of the current stress on the existing ac transmission grid and the difficulty in constructing new transmission lines. In most urban areas there is little spare transmission capacity and few available right-of-ways for the construction of new lines. Replacing even some of the annual 26.8 Quad of petroleum-based transportation energy, an amount equal to about 70% of the current electricity usage, with hydrogen will require either new hydrogen pipelines or large increases in the electric transmission capacity in order to generate the hydrogen locally.

The energy pipeline concept extended to a continental scale constitutes the energy SuperGrid. The energy pipeline is perhaps the most “innovative” concept of this proposal, but does have antecedents. In the early 1970s a superconducting cable using $Nb_3Ge$ as the superconductor and hydrogen as the cryogen was the subject of study by Ted Geballe and Bob Hammond of Stanford. “Slushy” hydrogen at the time was felt to be a cheaper and more viable cryogen than helium but little attention was given then to its potential as a deliverable fuel. In 1988 with the discovery of the 125 K high temperature superconductor at IBM Almaden, several suggested the possibility of a cable cooled by methane. The energy SuperGrid incarnation of these earlier ideas proposed the use of the newly discovered superconductor magnesium diboride ($MgB_2$), or the use of a second generation of the higher temperature superconductors, with the potential for very cheap wire, as the cable conductor cooled by liquid or cold gaseous hydrogen. In principle, any of the current HTS wire embodiments would meet the engineering requirements – there is no need for any “new discoveries” in this area. Figure 4 shows a possible configuration for a supercable.

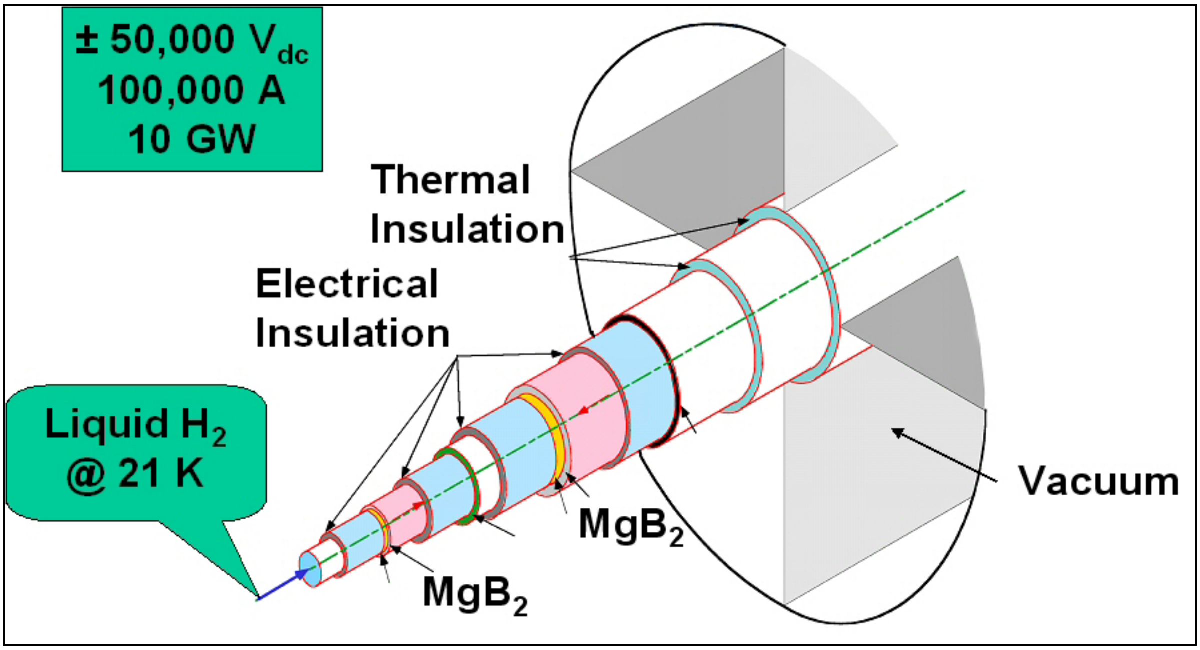


Figure 4: A Potential Design for the SuperCable (Source: EPRI)

The vision of a "Continental SuperGrid" using nuclear power was originally developed through collaboration between Chauncey Starr and Paul Grant in 2001, with the initial vision presented by Dr. Starr in November, 2001 at the American Nuclear Society (ANS) meeting in Reno. The concept was offered as an example of the kind of imaginative, "outside the box" solutions that is needed from the scientific and technical community to solve the problems of energy supply and environmental constraints anticipated over the next century. In 2002 the SuperGrid 1 Workshop, SG1, extended the original concept to encompass hydrogen and electricity, not just from nuclear, but from all sustainable energy resources with a recognition that some fossil fuels, such as coal, will continue to be important sources of energy for many decades into the future and could certainly be incorporated into the SuperGrid. SG1 conceptualized a synthesis of continuing electrification, and the evolution of hydrogen, as dual intermediate energy forms that by separating the energy resource from the utilization permits the optimization of both separately.

One of the most startling aspects of the original SuperGrid proposal was the idea of undergrounding the entire system (Figure 5). But those who deal today with financing and building regional power systems have experienced the astounding cost increments created by public and political opposition arising from the "not in my backyard" syndrome. The resulting time delays, legal processes and environmental opposition have significantly multiplied engineering estimates for building new transmission lines and generators. Undergrounding the system can remove some of these concerns. Furthermore, if deliberate sabotage and terrorism remains a significant risk undergrounding the system can result in increased system security, particularly for nuclear power plants. Underground tunneling has steadily become less costly, and worldwide demonstrations of new techniques offer the promise of continued cost reduction. Tunnels of course have a long lifetime and thus they are an opportunity for innovative public financing – like building an office structure. While there is obviously a site specific cost element, it is now also time specific. In the decades ahead undergrounding may become the least costs means of providing space for energy systems, as it is now partially the case in urban settings.

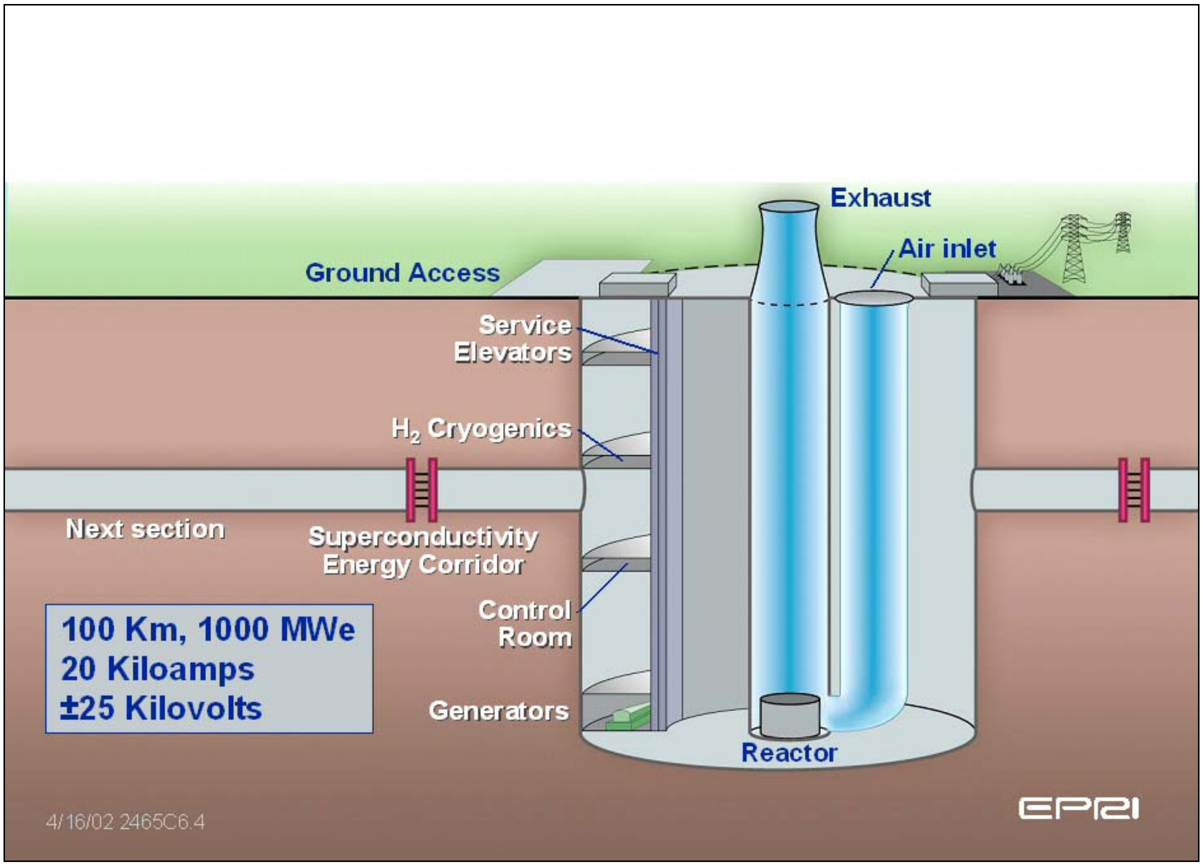


Figure 5: An Underground Section of the SuperGrid (Source: Chauncey Starr, EPRI)

# 3 Key Findings of SG2

The purpose of SG2 was to re-examine the SuperGrid concept with the goal of developing initial research task descriptions for moving the vision forward. To accomplish this goal SG2 brought together about 50 experts with expertise in a variety of different areas. Over the course of two and one half days provided a forum for them to consider the SuperGrid concept. This section summarizes the key findings of SG2, while the next section presents the discipline specific research task descriptions.

1. Overall SG2 re-confirmed the finding of SG1 that no scientific breakthroughs are needed to achieve the reality of the SuperGrid. Of course, major technological innovations will be required to minimize environmental effects and maximize economic and societal benefits.

2. The SuperGrid concept needs to be more thoroughly considered from an economic point of view. There is no reason scientifically that the SuperGrid could not be built. An open question is how does it compare economically to other energy delivery technologies such as HVDC or hydrogen pipelines. Assuming the results are favorable, such a study could be quite helpful in advancing the SuperGrid vision.

3. In the area of superconducting cables the plenary talk and breakout session both confirmed the viability of using superconductors for power transmission levels up to 10 to 20 GW. For distances of the scale envisioned for the SuperGrid only dc transmission is practical. The supercable design could be used to transport GW amounts of electricity and hydrogen or natural gas, using either the liquid hydrogen itself or liquid nitrogen in the role of cryogen. In addition the supercable itself could also be used for energy storage, with a single 12 mile, 45 cm diameter supercable having as much energy storage capacity as TVA's Raccoon Mountain pumped storage facility (the largest in the nation). The two carry-forward messages from the group were 1) studies should be done to identify opportunities for the application of supercables in the existing power grid, and 2) a prototype dc supercable should be designed, built and tested at an appropriate national lab.

4. Mike McCarthy's (American Superconductor) presentation on the LIPA high temperature superconductor (HTS) project provided a state-of-the-art description of superconducting technology. The LIPA project, which is the world's first installation of a superconductor cable in an actual grid at transmission voltages, uses superconductors operating at 138 kV, 60 Hz, 574 MVA to transmit power 660m. The take away message was the commercial use of superconductors for high power level transmission is fast becoming a commercial reality.

5. In the areas of electric power system operation and power control the plenary talks and breakout sessions confirmed that there are no fundamental constraints precluding the integration of point-to-point supercables carrying up to about 10 GW into the existing power transmission grid. Note, 10 GW is about three times the existing capacity of the HVDC Pacific Intertie. There are, of course, many technical issues that would need to be addressed for such implementations to become an engineering reality. The

implementation of a meshed network was viewed as being much more problematic. The breakout group also felt that for the SuperGrid vision to move forward it would be beneficial to perform a fairly detailed simulation of the existing North America power grid with the aim of identifying locations in which high power transmission corridors could be of benefit to the existing grid.

6. Since entire conferences and books have been devoted to the "hydrogen economy" SG2 only focused on the issues most germane to hydrogen's application in the SuperGrid. As a mechanism for energy transportation hydrogen's advantages and disadvantages over electricity arise because its energy is stored in chemical form. Since hydrogen has mass it is more difficult to transport than electricity, but has the significant advantage that its energy can be stored. Overall the group felt a more complete hydrogen system analysis is needed, to determine, for example, the best form of hydrogen to use with the SuperGrid (gaseous versus liquid, at what temperature and pressure). There is also a need for additional research in hydrogen production methods, distribution, storage and its ultimate end uses. It was also noted that there is currently significant research being undertaken by others studying the potential hydrogen economy, particularly the use of hydrogen for transportation.

7. SG2 re-confirmed that tremendous synergy exists between the SuperGrid and nuclear power, particularly with the use of high temperature reactors in nuclear parks in underground salt beds. SG2 focused on the use of underground parks to address the issues of safety, security, decommissioning and disposal. High temperature reactors have the advantage that they can be used to produce electricity or hydrogen with greater than 50% efficiency, though it is likely that any single plant would be dedicated to one use or the other. In addition, waste heat can be expelled to the air.

8. In order to keep its scope manageable SG2 did not specifically address the use of other generation technologies with the SuperGrid. While the SuperGrid could be used with just about any generation technology, it is most compatible with those technologies in which the energy source is located distant from the load. In addition to nuclear others include mine-mouth coal, wind, and natural gas field based generation.

9. Undergrounding most of the SuperGrid could significantly reduce public and political opposition to the construction of new lines. Underground construction, tunneling and micro tunneling have made great strides in the past decades, yet the potential for further technology innovation and the limits of the economics of under grounding has not been fully explored. Construction of the SuperGrid could greatly spur innovation and cost reduction in this industry.

10. While the role of nuclear power continues to be controversial, from an environmental perspective the SuperGrid is perceived as fundamentally green as it is based on technologies that emit few pollutants and minimizes the environmental impact. But as the SuperGrid vision moves forward there is a need to develop a social science research agenda.

11. SG2 did not address the issue of the ultimate cost of the SuperGrid. Since the SuperGrid is concept for a future energy infrastructure, to be built over several decades, it is not even clear what components of the concept should be included in a cost estimate. Just the supercables themselves? The supercables with the new generation? The supercables, new generation and a new "hydrogen economy" load infrastructure? Plus any cost figures would need to be compared to the net societal costs of the alternatives, numbers that are fraught with uncertainty (e.g., the cost of a barrel of oil in 2030, the ultimate societal cost of $CO_2$ emissions). Finally, any cost estimates need to be placed in the context of the current U.S. annual energy costs (greater than \$700 billion using 2000 EIA figures), costs that are sure to rise. Nevertheless, as mentioned previously the costs of using the supercables should be compared to other energy delivery technologies.

# 4 Discipline Specific Research Agendas

A key part of SG2 was to have the supergrid concept considered by various discipline specific working groups. The disciplines considered were 1) superconducting cables, 2) electric power system control, 3) electric power system integration, 4) hydrogen, 5) nuclear, 6) underground construction and tunneling, and 7) environmental engineering. The workshop agenda included plenary overview talks given by experts in each of these disciplines, two sets of parallel, discipline specific breakout sessions, followed by times for plenary reports by the breakout groups and discussion. Each breakout group was charged with developing the discipline specific research agenda needed for moving the supergrid concept forward. The results for each session are given below. Note, the results form the power system control and electric power system integration groups have been combined in this report.

## 4.1 Superconducting Cables

The plenary talk on superconducting cables was given by Paul Grant who also chaired the breakout sessions. In the plenary, Grant focused on the physics of practical superconductors and their limitations, pointing out that zero resistance is only theoretically possible under direct current conditions, and even then is susceptible to thermal dissipation given inevitable rectification ripple and requirements to periodically excite and de-energize the cable. As a rule of thumb, under steady state operation, cables constructed using presently available commercial HTSC wire and tape offer 3-5 times more capacity at 60 Hz and 100-500 at 0 Hz at 77 K (the boiling point of liquid nitrogen) than cryoresistive copper held at the same temperature. In his plenary, Grant also outlined several designs for the supercable component of SuperGrid for the combined transport in gigawatt amounts of electricity and hydrogen or natural gas, with either liquid hydrogen itself or liquid nitrogen in the role of cryogen. A design of a supercable transporting natural gas is shown in Figure 6. For distances of the scale envisioned for the SuperGrid, only dc transmission is practical from a loss point of view on GW power levels, operating in the range 20-25 kV and 100 kA to take full advantage of the superconducting properties. It was emphasized that the physics of superconductors will require a new paradigm for management of power flow on such a cable, one under which line voltage is varied at constant current to accommodate time variations of supply and load, the exact opposite to the operation of the present conventional transmission system. A sidebar discussion was held regarding the opportunity to use the cryogenic infrastructure required by superconductivity to also cool the power electronic devices and thus expand their window of operation.

The breakout sessions revealed many of the workshop attendees were unaware of the history and currently advanced state of high temperature superconducting cables. Mike McCarthy of American Superconductor gave a review of the upcoming Long Island Power Authority cable project, thus demonstrating cable designs, cryogenic support and splice/joint issues are well in hand, and that the existing DOE superconductivity partnership initiative between industry, utilities and national laboratories have the resources to address a wide variety of other superconducting power applications. Research areas peculiar to the supercable will involve rigid vs. flexible design, transportation to the site, and challenges of on-site construction somewhat in common with natural gas pipelines. In addition, the high dc current levels and associated magnetic fields and resultant mechanical stresses will present new issues outside the present scope of the DOE program.

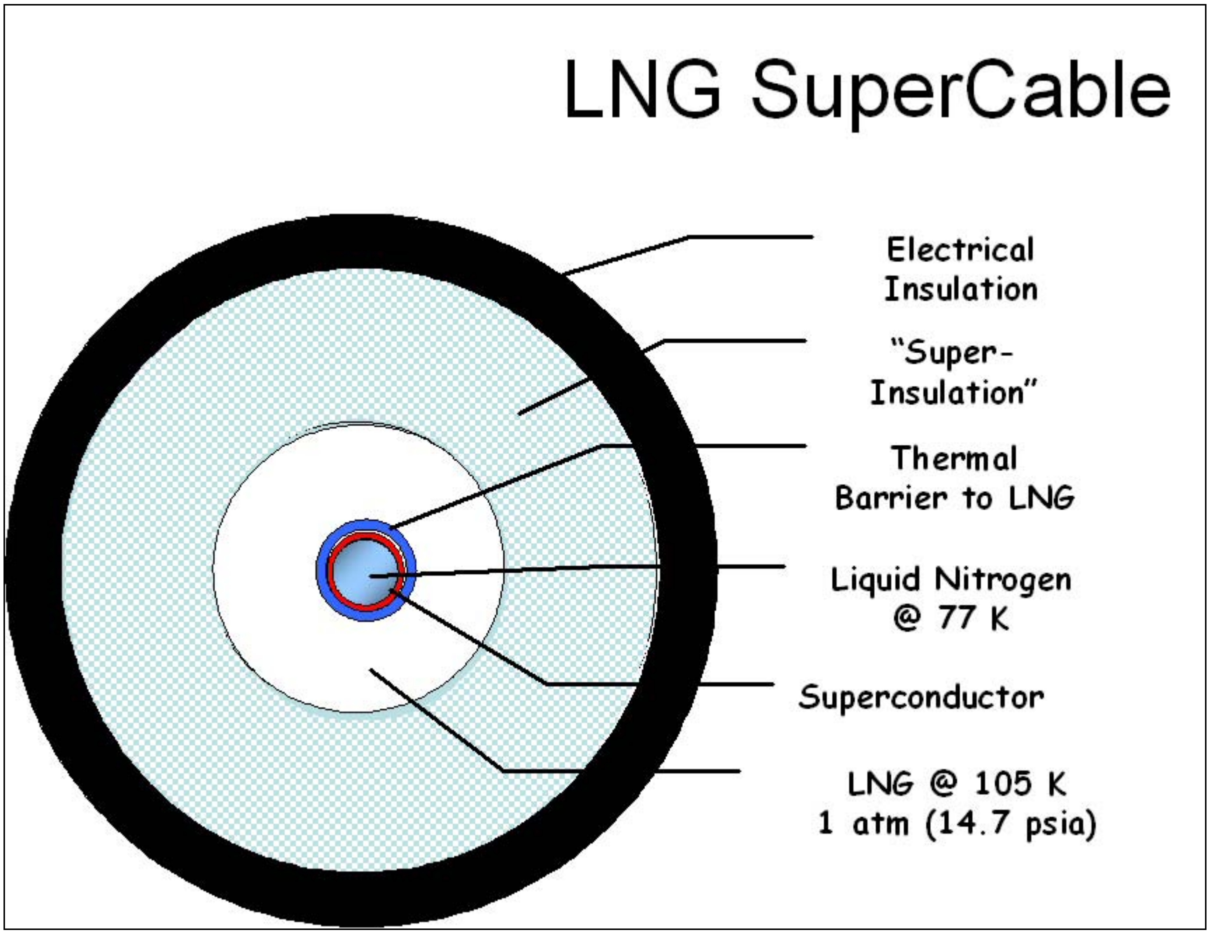


Figure 6: A "Hybrid SuperCable using Natural Gas as the Cryogen (Source: SG2 Presentation by Paul Grant)

In 1993, an EPRI report prepared under the leadership of Robert Lasseter of the University of Wisconsin (an SG2 participant) pointed out the likely occurrence of instabilities in a meshed network (grid) of generation and load points connected by very low impedance (possibly zero!) conductors. Suppression of such instabilities would require the judicious and dynamic insertion of current limiters thus partially defeating the advantages offered by superconductivity, and that a ring or spoke topology would be more appropriate. This issue rose again during the breakout sessions, and it was generally agreed that initial deployment of dc superconducting cables as prelude to the SuperGrid would be point-to-point or back-to-back applications. The carry-forward message was that opportunities for such application should be sought out to relieve constrained transmission corridors as identified in the DOE's National Transmission Grid Study, and teams should formed under industry leadership with DOE to design, build and test a short prototype HTSC dc cable at an appropriate national laboratory in anticipation of an eventual demonstration effort at a suitable field location on the grid as previously described.

## *4.2 Electric Power System Control and Integration*

The plenary talk in power system control was given by Robert Lasseter (University of Wisconsin-Madison) while the breakout group was chaired by Phil Krein (UIUC). The plenary talk in electric power system integration was given by Robert Thomas (Cornell University) while the breakout group was chaired by Peter Sauer (UIUC). Because of substantial overlap these two areas have been combined.

The overall feeling of the electric power systems control and integration breakout groups was the initial research agenda in this area could be started with a relatively modest financial commitment. While several million per year for the first few years would be ideal, smaller amounts could be used to jump start the effort. Also, much of this research could have dual use of solving both existing challenges and challenges associated with the supergrid. The initial research agenda tasks should include the following.

### 1. Scoping study addressing the need for a super-conducting grid

If the vision is to move forward a scoping study should be performed to look at the cost-benefit analysis of using superconducting dc cables compared with other transmission technologies, such as traditional HVDC links and newer ac technologies. The breakout group noted that the power levels envisioned for the supergrid conductors, 10 GW, was only 2 or 3 times greater than the capacity of existing transmission lines such as the Pacific Intertie.

### 2. Perform a fairly detailed simulation of the existing North America power system

It the vision is to move forward a study is needed to show tangible benefits for adding high power transmission corridors to the existing grid. This study could be thought of as a more detailed follow-up to the study done by DOE in its National Transmission Grid Study. This study could begin by doing an hourly security constrained Optimal Power Flow (OPF) simulation of the existing North American power grid with the transmission system represented using a “dc power flow” type model. This study would establish the economic prices for power in the different regions of the country (i.e., bus locational marginal prices [LMPs], with the results iteratively benchmarked with the actual bus LMPs (where available). Such a study would have benefit irregardless of the SuperGrid effort. Then, the SuperGrid specific portion of the study would seek to identify locations where high power transmission corridors with perhaps new generation could be shown to have significant economic benefit. Of course the assumed system conditions, such as load levels and fuel prices, could be adjusted to simulate different hypothesized future scenarios. These studies could also look at the benefits of tying together the Eastern, WECC and ERCOT systems (part of the original SuperGrid proposal). Later studies could also include the impacts of substantial amounts of energy storage (via hydrogen). Assuming the results of such a study are positive, they could be quite helpful in selling the SuperGrid concept.

### 3. Develop appropriate power system models for the supergrid elements

In order to perform the necessary studies looking at the impact of the supergrid on the existing grid, appropriate power system models for the SuperGrid components need to be developed. The model detail will, of course, vary based upon the study objective. For example, in the studies envisioned above in Task 2 the supergrid elements could be represented as constant power devices, with perhaps a need to consider power ramping constraints (e.g., MWs per minute). In longer term studies the reliability of the elements would need to be considered and the duration of each outage (cooling down a supercable could take days). In shorter term studies, such as transient stability and short circuit studies more detailed models would be needed. For analyzing the power control interactions, which would model kHz level switching actions, full switch-based models would be needed. This task will certainly need to be iterative with the research being done to develop the superconductors themselves.

### 4. Utilize the models from Task 3 to perform more detailed studies focusing on the interaction between the supergrid and the existing grid

Whereas Task 2 would focus on the system level benefits of the SuperGrid, Task 4 would focus more on studies looking in detail at the impact of the SuperGrid with the existing grid. For example, using the models developed in Task 3 to perform detailed transient stability or short circuit studies.

### 5. Development of high current circuit breakers and sensors

As currently envisioned the SuperGrid will have current levels at least an order of magnitude greater than existing in the power grid. Managing these currents will require new sensors and new circuit breakers. Also, newer sensors might allow for increased intelligent system control.

### 6. Interaction between the SuperGrid and power markets

As envisioned the SuperGrid could have a very positive impact on existing power markets by adding large amounts of price-sensitive load. For example, substantial amounts of electricity may be used for the production of fuels for transportation use, such as hydrogen or methanol. Because the end product is storable there is inherent flexibility in the electric usage associated with its production, allowing the load to be seen as price sensitive – run the production when the price is low, and curtail it when the price rises. In addition, the SuperGrid adds substantial amounts of new energy storage with the hydrogen stored within the superconducting pipeline. The ability to transfer large amounts of power long distances could also have very positive impacts. However, the market implications of such a system need to be researched. Research is also needed to investigate the impact the large, SuperGrid-sized contingencies could have on existing power markets.

### 7. Continued research in the modeling and analysis of large systems

The SuperGrid could potentially create a single, integrated North America power system. The group felt continued research into the modeling of such large systems would be beneficial, looking into issues such as better power flow/optimal power flow algorithms, better contingency analysis tools, improved transient stability tools, etc.

### 8. Investigation of converter optimized generation

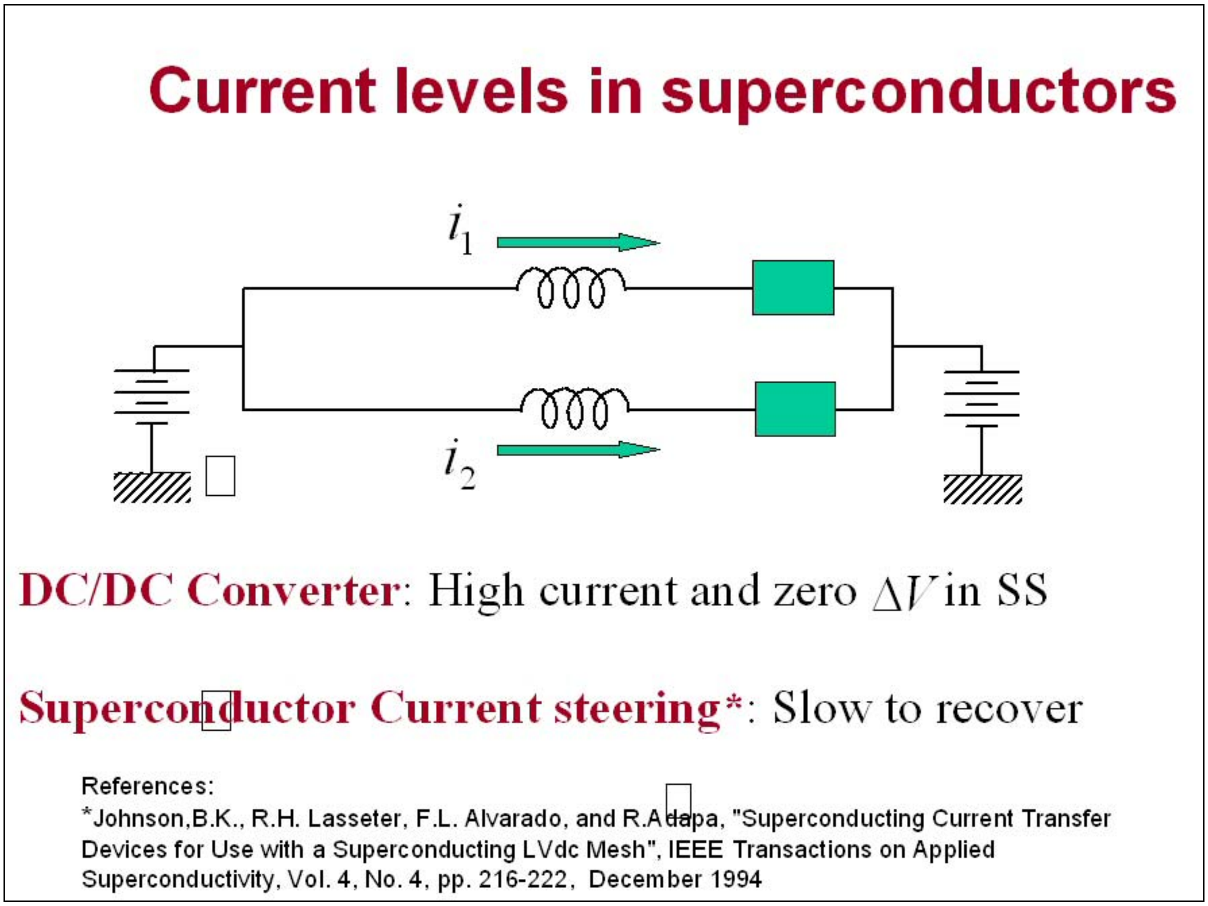
Currently practically all of the electric energy used in this country is generated using 60 Hz synchronous machines, with the frequency dictated by the need to operate in synchronism with the 60 Hz grid. However, if the generators are strictly connected to the dc SuperGrid then there is no longer a 60 Hz requirement and no longer even a requirement to use synchronous machines. Research is needed to determine the best machine designs and operating frequency for machines that are always directly connected to the supergrid via rectifiers.

### 9. Distribution level reliability and power quality aspects of the supergrid

While the SuperGrid is designed for bulk power transmission, it is certain to have impacts on the end customers connected to the distribution system. Research is needed to determine the positive and negative aspects of these impacts.

### 10. Investigation of superconducting dc grids

Initially, the SuperGrid will probably consist of point-to-point transmission corridors. Eventually, however, it may be desirable to create an actual dc superconducting network. But there are some fundamental difficulties associated with creating and operating these networks. For example, consider a simple network problem in which a second dc line is added in parallel to an initial line. With a traditional HVDC system in steady-state the amount of current flowing on each conductor is a function of the relative resistance values for each lines. During the insertion of the second line, the current in the second line will ramp up to its steady-state value according to it’s L/R time constant, and the voltage drop across the first line. For a traditional transmission line this ratio is quite small, less than say 0.05, resulting in a rapid convergence to the steady-state current. But in a superconductor, with its extremely low R, the time constant is quite large, and the voltage drop across the parallel line is essentially zero. Therefore when the new line is inserted its current will almost remain at zero (Figure 7). Research is needed to determine the best means for developing networked superconducting dc systems.



**Current levels in superconductors**

**DC/DC Converter**: High current and zero $\Delta V$ in SS

**Superconductor Current steering***: Slow to recover

References:
*Johnson,B.K., R.H. Lasseter, F.L. Alvarado, and R.Adapa, "Superconducting Current Transfer Devices for Use with a Superconducting LVdc Mesh", IEEE Transactions on Applied Superconductivity, Vol. 4, No. 4, pp. 216-222, December 1994

Figure 7: Problems with Current Control in Parallel Superconductors (Source: SG2 Presentation by Robert Lasseter)

## 11. Research and Development of Advanced Power Electronics

Advanced power electronics will be needed for hardware control functions in the SuperGrid. The challenges differ from those in conventional systems by several orders of magnitude. As a result, fundamental breakthroughs will be needed in switching device technology to meet SuperGrid needs. In general terms, higher voltages and lower currents are preferred for hardware control in a power grid. High currents by themselves pose extreme challenges. The largest present devices can switch a few thousand amperes rapidly. The extension to 100,000 A or more in a broad power grid is unclear and will require intensive research efforts.

To place the issues in perspective, it is useful to compare controls in terms of system base impedance. For example, a 500 kV power system intended to deliver 5 GW has a base impedance of 500 Ω. Hardware control elements in such a system must have impedance levels on the order of 0.1% per unit to avoid unacceptable power losses and to make interconnections and physical layout manageable. With a 500 Ω base value, 0.1% per unit is 0.5 Ω. This level can be achieved with today's technology. It also means that sensitivity to details such as interconnect inductances and stray capacitances is not a major factor in design and operation. Incremental improvements can further reduce losses and enhance reliability.

A possible SuperGrid system, operating at about 10 kV and intended to deliver 5 GW has a base impedance of 0.02 Ω. Hardware control elements must have impedances on the order of tens of microohms to meet a 0.1% per unit target. Since the target level is more than four orders of magnitude lower than present high-power devices, there are extensive research needs to create basic new technologies and achieve the result. Consider, for example, that 1 m of wire has enough inductance at 60 Hz to generate impedance of 0.002 Ω -- already 10% of the base impedance. This is an example of why a SuperGrid system must operate at dc. Even transients at 1 Hz generate large relative voltage drops along short runs of wire at these low impedance levels.

### 12. Suppression of Ripple and Noise

A related problem is that of ripple and noise in the nominal dc system. In a conventional HVDC power system, the high base impedance level means that filter circuits are relatively straightforward to implement. Impedances on the order of ohms can deflect away high-frequency ripple generated by the rectification process and mitigate interaction with nearby communication systems. At the low impedance levels of the supergrid, it is a much more difficult challenge to implement an effective filter. In addition, the very high currents mean that any residual ripple still generates significant magnetic fields that can couple into adjacent circuits. Research will be needed on low-impedance active and passive filtering, and also on propagation of ripple and noise in low impedance systems, in support of the development of a supergrid.

In principle, extreme low impedances can be achieved by parallel connection of large groups of higher-impedance devices. In practice, the gain from such an arrangement is limited by interconnection impedances and related issues associated with layout and fast switch operation. The challenges of ultra-low-impedance devices, low-impedance interconnects, and fast synchronized switching of large arrays of parallel devices are vast and will require major advances from many research groups.

### A Vision Forward

When asked to consider how to move the vision forward the group felt that 1) the investor owned utilities (IOUs) were unlikely to fund the initial work in this area, and 2) the first two research tasks need to be done to demonstrate a tangible benefit to the project. All agreed on the need to move towards a sustainable energy infrastructure, but there was not agreement that the use of superconductors was needed to achieve this goal.

## *4.3 Hydrogen*

Hydrogen research and development is an extremely broad subject and only a portion of the full range of issues could be addressed in the workshop breakout sessions. In particular the workshop did not seek to address the many issues associated with the end uses of hydrogen in the residential, commercial and transportation sectors.

Hydrogen has been an integral part of energy technology for more than a century. Mixed with carbon monoxide it was widely used in North America throughout the first half of the 20th Century. This mixture, known as town or coal gas, was displaced as a result of the discovery and development of large-scale natural gas resources and the construction of the extensive natural gas pipeline system that continues to deliver natural gas throughout North America.

Today hydrogen is used in the chemical, petrochemical, pharmaceutical and materials processing industries as well as other sectors but the wide-scale use of town gas in residential and commercial sectors has been replaced by natural gas and electrification of many end-use applications.

The major source of hydrogen is from processing of natural gas (methane) and as a by-product of petroleum refining. Only a small portion of hydrogen used in North America is currently produced by the electrolysis of water using electricity. In general large-scale production by electrolysis is not economic relative to methane reforming. In some areas cheap hydroelectric power has been used, but cheap electricity is now scarce in North America. A rather interesting niche market for large-scale use of hydrogen is in the launch of the Space Shuttle where the second stage Jupiter missile is fueled by a mixture of liquid hydrogen and liquid oxygen. Significant technology development and actual experience with cryogenic hydrogen production, storage and handling comes from this program.

As a consequence of this extensive history of industrial uses, some aspects of hydrogen's production, delivery (transportation and distribution), storage and utilization is well understood, although the knowledge is not widespread and many have an impression that the idea of using hydrogen is new and unproven.

The idea of using nuclear energy as an energy resource and hydrogen as an energy carrier became popular in the 1970's and was explored extensively by systems researchers and futurists in that decade. Public opposition to nuclear energy and the increased perception of risks placed these future concepts in obscurity until the concern over climate change emerged in the 1990's. The concept of a hydrogen economy is again at the forefront when the future of energy in the 21st Century is discussed.

From the breakout sessions, and subsequent discussions, a few critical issues emerged that are perceived as having priority for the development of the SuperGrid vision.

### 1. Complete Systems Analysis

As hydrogen is absent from wide-scale use outside of limited industrial and niche applications, a complete systems analysis of the uses of hydrogen is needed. An explicit example is a trade-off analysis to determine if liquid or gaseous hydrogen is 'best' or most appropriate to the SuperGrid.

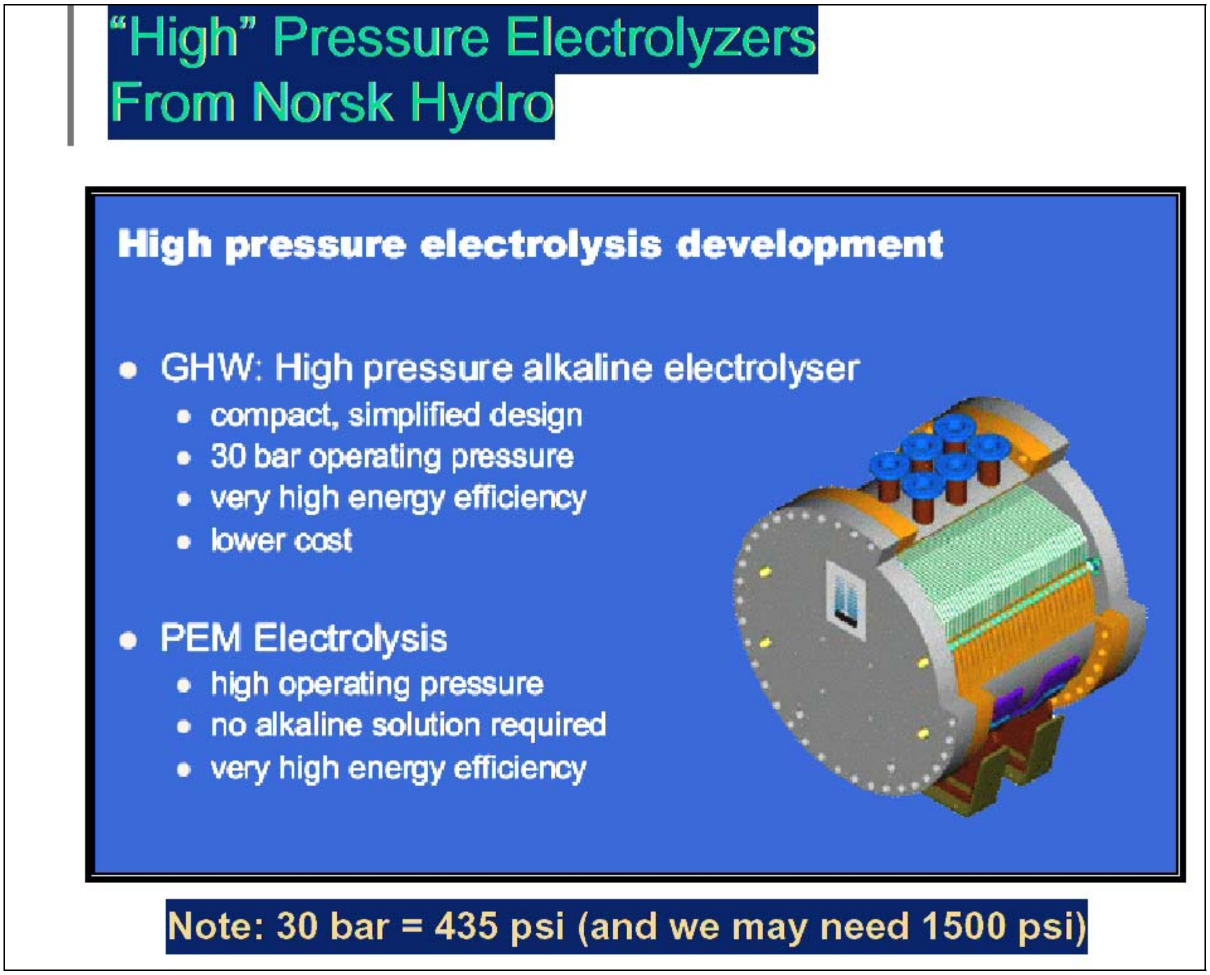
The goal of this research element is to determine if liquid or gaseous hydrogen is preferred. This trade-off analysis should be performed, at a minimum, as a function of type of superconductor used, technology available, economics, safety and para vs. ortho hydrogen content.

Specific results of the research would include: a) determine specifications for hydrogen phase, temperature, pressure, flow-rate, and estimate cost of equipment, determine overall efficiency, and develop tradeoff curves/tables and b) experimentally determine/verify performance of hydrogen cooled superconductors that use gas versus liquid phases of hydrogen.

## 2. Hydrogen Production

Hydrogen production methods will have to be developed and tested that produce hydrogen for large scale, medium scale, and small scale systems to match the varying scales of the resources, which may range from distributed solar and wind energy resources to nuclear. There are two alternative methods for hydrogen production from nuclear energy; these are electrochemical, through electrolysis (Figure 8) and thermochemical through the use of heat and a catalytic reaction. Electrolysis has been in wide spread use for many decades, yet there are opportunities for increasing efficiency and reducing capital costs. Thermochemical conversion is a different matter and is generally at the laboratory level with the exception of the old coal gas process and steam reforming. Electrochemical processing offers the advantage of proven technologies while thermo-chemical processing offers the promise of improved economy of scale. Initial studies do not indicate an efficiency advantage of one over the other.

The goals of this research topic are to determine/develop, and test preferred designs for the production of hydrogen. R & D needs include a basic effort to determine designs for each production method above, its efficiency, cost, and maintenance requirements. There is also a need to look into carbon dioxide capture and sequestration for situations where hydrogen is produced from fossil fuels. Additional issues such as hydrogen separation and purification through advanced membrane separation processes need to be explored.



“High” Pressure Electrolyzers
From Norsk Hydro

**High pressure electrolysis development**

- GHW: High pressure alkaline electrolyser
  - compact, simplified design
  - 30 bar operating pressure
  - very high energy efficiency
  - lower cost
- PEM Electrolysis
  - high operating pressure
  - no alkaline solution required
  - very high energy efficiency

Note: 30 bar = 435 psi (and we may need 1500 psi)

Figure 8: State-of-the-Art High Pressure Electrolyzers (Source: SG2 Presentation by Robert Schainker)

## 3. Hydrogen Piping And Distribution Equipment And Components

The goals of this research are to determine or develop, and test preferred designs for hydrogen piping and distribution equipment/components including materials selection. Large-scale transmission and distribution of hydrogen gas is a well-developed technology and for the most part the necessary experience and standards exist for the engineering of full-scale systems. Examples of the R&D needs include:

- assessment of existing pipelines experience and economics.
- materials research starting with the assessment of design, performance and maintenance issues of liquid and gas piping and distribution systems, and
- materials research to lower costs and assure long-term reliability under taken with a specific look at the following areas, at a minimum:  imbrittlement, seals, valves, joints, coatings.
- development of automated leak detection and location methods/devices.

## 4. Hydrogen Storage

The goals of this research are to determine/develop, and test preferred designs for hydrogen storage applicable to all aspects of the SuperGrid vision. The R&D needs for hydrogen storage fall into two broad categories. First, assess existing and proposed large-scale hydrogen storage methods applicable to the SuperGrid as a delivery system (i.e., low temperature hydrogen gas and hydrogen liquid storage methods, which need to be focused on the SuperGrid pipes used as the storage medium by operating the pipes at about a 10%+ increase/decrease over their nominal piping pressure). There is also a need to address hydrogen storage needed for SuperGrid startup and maintenance activities. Second, the development of storage for specific end uses. This topic merits a separate research workshop. It is worth noting that DOE spent about $30 million in Fiscal Year 2004 on storage related to vehicle applications.

## 5. SuperGrid Environmental and Social Issues and Training

It is now well understood that all new major projects need to address environmental, social and public acceptance issues in the earliest stages of concept development. The objective of this work is to assure that the design and engineering incorporates environmental impact, social and public acceptance issues from the very beginning and throughout development and commercialization. Research and development needs include: a) strategy for addressing these topics for each of the R&D phases, and b) training of research professionals and students on the importance of addressing these issues and assuring that concern for these issues be a part of the SuperGrid development process.

## 6. Industrial Use of SuperGrid Hydrogen

Although the uses of hydrogen range from the very large-scale uses to personal transportation, the discussion focused on two specific research and development needs for the large scale uses; a) develop/evaluate the benefits of major SuperGrid transmission lines to oil/gas refineries, chemical, pharmaceutical plants and other large scale industrial users with the objective of altering the SuperGrid design to be sure these potential uses/applications are economically and technically attractive and b) explore/develop the opportunity for commercial use of oxygen from hydrogen electrolysis and alter/update design of high-pressure electrolysis to take advantage of this additional commercial application of the SuperGrid.

## 7. Operational Issues Of The SuperGrid

In concept development and early engineering studies, operational issues need to be considered including start-up and shutdown issues under normal and emergency conditions, from the hydrogen perspective. (Note: this effort needs to be done on the superconductor and many other components of the SuperGrid as well.) Specific R&D projects could include:

- Assess/evaluate start-up/shut-down time and equipment needed, both for the first time and other times. This may impact the design of the SuperGrid in significant ways if start and/or normal shutdown time periods are too long (e.g., months?).

- Assess/evaluate start-up and shut down issues associated with emergency conditions (e.g., grid outages that cause SuperGrid elements to be put into a forced outage, and SuperGrid outages that will send transients onto the local grid). These events need to include vacuum system failures, inverter failures, ground faults, internal short circuits (from the superconductor through the hydrogen cryogen), piping failures, superconductor failures, lightning strikes, earthquakes, etc.). This effort needs to include a complete failure modes and effects analyses.

Based on the results of tests of critical components that would impact normal and emergency outages, the design of the SuperGrid will likely change in important ways not originally expected.

## 4.4 Nuclear

The plenary talk in nuclear was given by Wes Myers (Los Alamos National Laboratory) while the breakout group was chaired by James Stubbins (UIUC). The plenary talk underscored the synergy between the supergrid concept and nuclear power, particularly the use of underground nuclear parks. Commercial nuclear power continues to be a major source of electric energy, with reactors producing about 20% of the electric energy used in the U.S., and about 18% of the electric energy used elsewhere in the world. Nuclear generated electricity is expected to continue at this level or possibly expand in the future. Reactors have a major advantage over many other energy systems that the do not generate greenhouse gases, which is consistent with the move toward hydrogen as a replacement energy source for carbon-based fuels. Domestically, there have been 23 license extensions approved by the NRC, 19 more under review, while more are expected. In addition, there are currently 27 reactors under construction around the world, with 18 of those in Asia. Domestically, however, there continues to be a lack of new construction, driven primarily by concerns about the financial risks arising from an untried approval system for new construction, start-up and operation. Also, reactor safety and waste management continue to concerns, although perhaps of less importance than in the recent past. Technical and economic evaluations by companies in response to DOE’s Nuclear Power 2010 Program, however, indicate a decision to construct new nuclear power plants might be forthcoming. The focus on underground nuclear parks was specifically to address these types of concerns about safety and security. It would also provide a mechanism for verifying the stability of underground installations which would help support the development of nuclear waste repositories.

To address these issues the use of underground nuclear parks was presented, especially if located in underground salt beds (Figure 9). Salt has remarkable containment qualities and also has well-known mechanical, chemical, and thermal properties. Some of the advantages of locating reactors in salt include 1) reduced decommissioning costs through the use of in-situ decommissioning and disposal, 2) reduced transportation costs by co-locating the storage and disposal facilities, 3) lower initial excavation costs compared to granite, 4) lower facility costs through the elimination of the containment structure, 5) lower reactor costs through the use of modular reactors, 6) increased expansion flexibility, and 7) lower security costs. Such an underground nuclear park could consist of an array of high-temperature (>900° C) reactors that could be used for either electricity and/or hydrogen production. Such a design is very synergistic with the supergrid concept since its remote location would require a high capacity energy transmission system. Of course, more convention reactor designs could also be used with the supergrid.

Concerning the development of an initial research agenda, the group felt that most of the technical issues associated with the development of the next generation reactors have already been identified and described in-depth in the Generation IV roadmap, with the lead concept being the development of a high temperature reactor that can be used both electricity and hydrogen production at greater than 50% energy conversion efficiency. It is likely that any single plant would likely be dedicated to one use or the other. In addition to the advantages of high temperature reactor systems for efficient energy production and to support thermal-chemical hydrogen production systems, they have the added advantage that their waste heat can be expelled to air, eliminating many siting issues associate with lower temperature reactors which must be located near larger thermal heat sinks such as large bodies of water. Nevertheless, the system and economic issues associated with these reactors, particularly when they are coupled into an integrated electricity-hydrogen infrastructure, have not been addressed nearly as well as the technical issues. The group felt that nuclear parks were readily compatible with scaling up to the 10 GW power levels envisioned in the supergrid.

Last, the group expressed concern that human resources in the nuclear area are in need of attention. The potential market for personnel is much larger than the current or near future supply of trained nuclear engineers. This could be a significant factor with a desired rapid revitalization of the nuclear power industry as may be required for the supergrid.

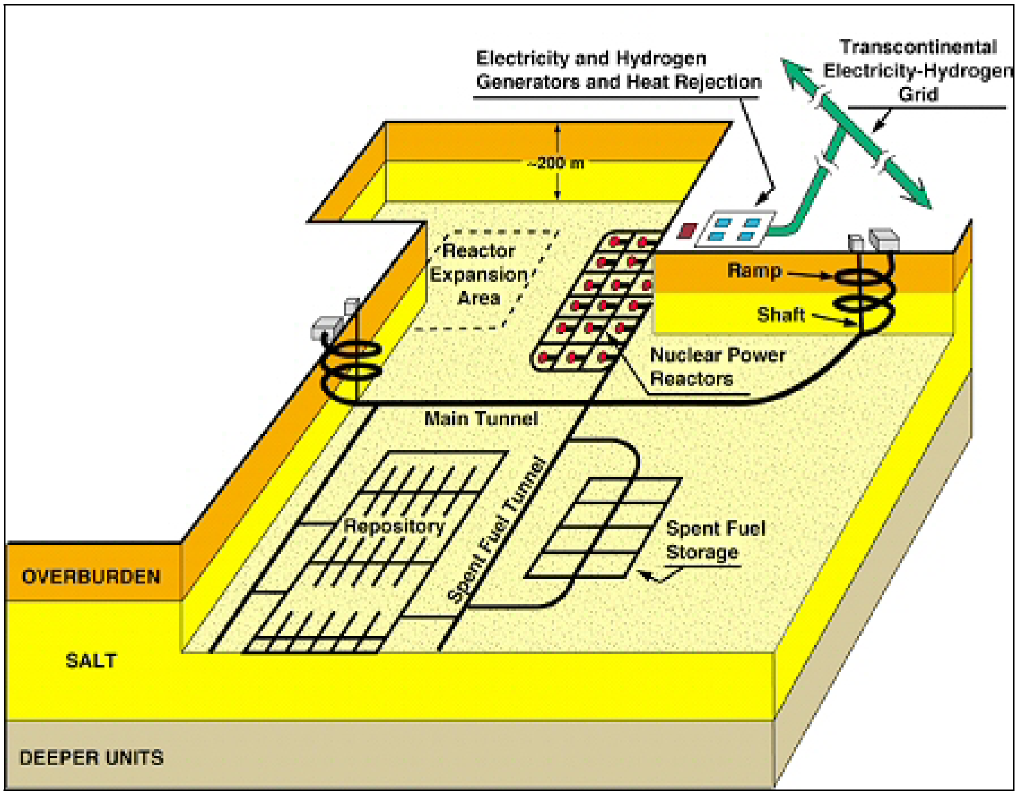


Figure 9: Concept of an Underground Nuclear Park in a Shallow, Massive Salt Deposit (Source: SG2 Presentation by Wes Myers)

## 4.5 Underground Construction and Tunneling

In the underground construction and tunneling area Ed Cording (UIUC) gave the plenary talk and chaired the breakout group. The plenary talk provided a thorough and in-depth review of the state-of-the-art of tunneling. While some aspects of this family of technologies have changed little in basic characteristics, major advances have been made in reducing labor requirements and greatly increasing speed and the safety of tunnel boring for diameters in the 15-20+ feet. Indeed tunneling boring machines have altered the economics significantly and large-sale projects can now be addressed that would have been to daunting in past years. However, the technology has evolved incrementally and there is not a clear understanding of the ultimate potential for increasing speed and reducing costs. Each tunnel-boring machine is designed for the specific conditions of the project that it will tackle. Tunneling, and particularly micro-tunneling with diameters of between two to four feet, have been aided by technology developed originally for vertical and horizontal drilling for oil and gas resources. But the full potential of these new innovations have not yet been fully exploited. Rough estimates for tunneling are now about $50 to $100 per foot for trenching (e.g., fiber optic conduit), $200/ft for pipe jacking or directional drilling, $500/ft for 2 to 4 foot diameter micro tunnels, $1500/ft for optimum-size tunnel boring machine (TBM) tunnels, and $3000/ft for larger TBM tunnels. Most of the supergrid would probably consist of micro-tunnels.

Given the tremendous scope of the supergrid, and the need to construct large amounts of underground tunnels, a project of this magnitude has the potential to significantly increase the industry tunneling capabilities. Currently the tunneling industry consists mostly of small engineering firms and contractors that do not have the financial resources to take significant risks – each project must stand on its own. There has been no government research funding. Also, there are very few bidders on large (+$200 million) tunnel contracts.

The goal of the research associated with tunneling for the supergrid is to reduce the tunnel costs, and to reduce the environmental/societal disruptions associated with constructing the tunnels. Overall the three ways to reduce tunnel costs are to 1) increase the advance rate, 2) reduce crew sizes, and 3) reduce contractor risk. Therefore in order to decrease the ultimate tunneling costs associated with the supergrid the initial research projects need to provide funds for developments that support innovations by the machine manufacturers, contractors and tunnel designers, while minimizing contractor risk. To decrease disruptions tunneling with longer runs needs to be used as opposed to trenching and open excavation. Some specific initial research and development topics are:

1. Since a major source of risk in a tunneling project is not accurately known the underground conditions, better methods exploration are needed.
2. Better access to the cutter face for repair to reduce risk to crew and schedule.
3. Better construction monitoring and sensing.
4. Techniques for reduced ground loss.
5. Improved construction of the tunnel lining.
6. Improved contractor practices to provide true incentives for decreased costs and adherence to the schedule.

## *4.6 Environmental Engineering*

The plenary talk in the environmental engineering area was given by Wayland Eheart (UIUC) while the breakout group was chaired by Edwin Herricks (UIUC). Since there is already a large body of literature looking at the environmental effects of the different electric power generation technologies (e.g., nuclear, coal, wind), the environmental engineering breakout group was asked to consider the environmental effects of the supergrid itself, without explicit consideration of the energy sources. Therefore the discussion focused on the supergrid pipelines, with the assumption the pipelines would be carrying both electricity in superconductors cooled to low temperatures and hydrogen.

Fundamentally the group viewed the supergrid concept as being “green” (i.e., environmentally friendly). The key issue then is how to get to this green future. Still, there were a number of issues that needed to be considered. The most pressing research needs were viewed as being in the areas of economics and public behavior. Concerning economics, what are the costs and tradeoffs associated the supergrid, and what incentives are needed to move wary from the existing environmentally unfriendly technology. Also, what are the economics of the supergrid compared to competing energy technologies. Concerning public behavior, the group felt strongly that there needs to be a social science research agenda. For example, how will the supergrid affect public behavior? Will more abundant, lower cost energy result in an increasingly decentralized population resulting in increase urban sprawl?

Aside from these larger questions there is a research need to focus on the cradle to grave analysis of each of the technology components in the supergrid. Some specific research topics include

1. What new materials are needed for the supergrid? What are the environmental risks caused by their manufacturing, use and disposal?
2. Where does the water come from associated with the hydrogen production? While the quantities of water needed might be relatively low, their use could have an environmental impact if the energy sources are located in arid or semi-arid regions.
3. What are the environmental impacts of constructing and maintaining the supergrid energy pipelines. In remote areas access roads will need to be created for construction and maintenance. Locating the pipeline underground eliminates some environmental concerns, such as unsightliness and impact on wildlife migration routes.

4. What are the implications of $H_2$ pipelines, particularly when they transverse heavily populated areas. Since there are currently less than 500 miles of $H_2$ pipelines worldwide, there is not much experience with managing large $H_2$ pipeline networks. What are the likely material impacts from long-term exposure to high pressure hydrogen?
5. What the are worst case failure scenarios? While the total electric energy stored in a superconducting cable itself is relatively low ($1/2\ L\ I^2$ , so about $10^{10}$ joules for a 100,000 amp, 1 H line = 2 tons of TNT), an uncontrolled failure could still cause substantial localized damage. What are the implications of a hydrogen leak? While hydrogen is not very toxic, it is flammable. There would be no disposable costs since the hydrogen would quickly dissipate into the atmosphere. Also, what would be the implications if a leak occurred at a river or lake crossing?
6. If large amounts of hydrogen were produced by electrolysis, this would result in lots of really cheap $O_2$. This could have some very positive environmental effects, such as more cost effective sewage treatment, better industrial waste treatmenta, and even dispersed (household level) sewage treatment.

# 5 Recommendations for Moving Forward

The last session of the workshop focused on developing recommendations for moving forward. These included the following.

### Vision

The SuperGrid is a vision for an energy infrastructure decades in the future and not a specific implementation. Therefore it is not readily amenable to a specific "roadmap." The vision as articulated in its original form and in SG1/SG2 needs to be broadened and developed in greater detail. Future development of the vision and the various elements and alternatives are needed.

### Funding for Concept Development

An early task is to develop more specific conceptual designs for the implementation of the vision to guide the exploration of alternatives among the fundamental features. A "scooping" study should be commissioned and undertaken with full exploration of the critical engineering and economic parameters. As some of the technologies are unproven, and others are mature technologies whose future use is little understood, a search for cost and performance targets to guide a major R&D program is considered a rational and practical approach at this early stage of development. Targets and breakeven costs could be developed in the parametric study of various scenarios implementing the vision.

### Laboratory Scale Experiments for Superconducting Cables

Initial laboratory scale experiments with current and voltage levels of perhaps 100 amps and a few thousand volts, with dc cable runs of tens to hundreds of meters are needed. The practical electrical, cryogenic and power electronic components and systems integration would be best developed in a experimental environment rather than in a single "demonstration" project. The development of an experimental program at one of the national laboratories is a logical first step.

### Community Building

To assist in developing the vision of the SuperGrid a research community interest group should be established that serves to nurture the vision and explore its potential. An interest group or "club' could undertake or organize future workshops and conferences and serve as an educational outreach effort to academia, industry, non-government organizations and policy makers at all levels within and outside the government as well as the general public. One objective of a public outreach effort would be to increase the public understanding of the issues related to long term sustainable energy and to increase engineers' understanding of public preferences as it is public preferences as well as the obvious environmental and security advantages that motivate the underground siting aspects of the SuperGrid.

### Lift Public Understanding of Long-Term Energy Needs

There is a need for increased public, political and engineering support for long-term energy research. Ways to raise this support include magazine and newspaper articles, papers in trade magazines, and perhaps TV shows.

## High Level Study

In addition to the above recommendations, it is recommended that a high-level committee or panel be established to further study the Supergrid vision. The National Academy may be the most appropriate organization to undertake such a study since it could require several years with an interdisciplinary team that includes engineering and the physical sciences as well as expertise needed to assess long-term social and political issues.

# Appendix A: SuperGrid Workshop 2 Agenda

**Sunday, October 24 (Levis Faculty Center, UIUC Campus – Third Floor)**

| | |
|---|---|
| 7:00 PM | Vans leave Hampton Inn for Levis Faculty Center |
| 7:30 - 9:00 PM | Public Lecture: "**Big Ways to Decarbonize the Energy System,"** by Jesse Ausubel, Rockefeller University |

**Monday, October 25 (Levis Faculty Center – Fourth Floor, Room 407)**

| | |
|---|---|
| 7:45 – 8:15 AM | Vans Leave Hampton Inn for Levis Faculty Center |
| 8:00 – 8:30 AM | Registration/Continental Breakfast |
| 8:30 – 8:45 AM | Welcome and Overview – Tom Overbye UIUC |
| 8:45 – 9:30 AM | Supergrid Vision – Chauncey Starr, EPRI (via videotape) |

**Technical Plenary Session**: Overviews of the Supergrid by discipline, with each presentation 15 minutes followed by 15 minute questions/discussions; chaired by Tom Overbye.

| | |
|---|---|
| 9:30 – 10:00 AM | Supercable – Paul Grant (EPRI retired) |
| 10:00 – 10:30 AM | Power Control – Bob Lassester (Univ. Wisconsin) |
| 10:30 – 11:00 AM | Break |
| 11:00 – 11:30 AM | Power System Integration – Bob Thomas (Cornell) |
| 11:30 – 12:00 | Hydrogen – Robert Schainker (EPRI) |
| 12:00 – 1:00 PM | Lunch on Levis Third Floor |
| 1:00 – 1:30 PM | Nuclear – Wes Myers (Los Alamos National Lab) |
| 1:30 – 2:00 PM | Underground Construction/Tunneling – Ed Cording (UIUC) |
| 2:00 – 2:30 PM | Environmental Engineering – Wayland Eheart, UIUC) |
| 2:30 – 3:00 PM | Break |
| 3:00 – 5:00 PM | Parallel breakout sessions by disciplines, with each breakout group charged with developing list discipline specific research topics. The focus of these breakout sessions is on the scientific/technical challenges to implementing the supergrid (i.e., the "what" question).<br>The breakout groups, with moderators are:<br>**Supercable** (Paul Grant),<br>**Power control** (Phil Krein),<br>**Power system integration** (Pete Sauer),<br>**Hydrogen** (Robert Schainker),<br>**Nuclear** (Jim Stubbins),<br>**Underground construction/tunneling** (Ed Cording), |

| | |
|---|---|
| | **Environmental engineering** (Ed Herricks) |
| 5:00 – 5:45 PM | Return to Hampton Inn via bus/vans (optional) |
| 5:45 PM | Bus/vans leave the Hampton Inn and Levis for Kennedy’s |
| 6:00 – 9:00 PM | Reception at Kennedy’s followed by dinner |

### Tuesday, October 26 (Levis Faculty Center – Fourth Floor, Room 407)

| | |
|---|---|
| 7:45-8:15 AM | Vans leave Hampton Inn for Levis Faculty Center |
| 8:00 – 8:30 AM | Continental Breakfast |
| 8:30 – 8:50 AM | Campus Welcome, College of Engineering Dean David Daniel |
| 8:50 – 10:15 AM | Reports by each of the breakout groups; chaired by Tom Overbye |
| 10:15 – 10:45 AM | Break |
| 10:45 – 12:00 | General Q&A and discussion with a focus on integration issues and challenges; chaired by Paul Grant. |
| 12:00 – 1:00 PM | Lunch on Levis Third Floor |
| 1:00 – 1:45 PM | Talk by Craig Smith (DMJM) “Supergrid Construction Challenges” |
| 1:45 – 4:30 PM | Reconvene **breakout sessions** with the same moderators. However, the focus of the breakout sessions on Tuesday switches from being purely technical to addressing the more practical challenges to implementing the supergrid. Questions for discussion include who does what, where, when, how much will it cost, and what are the organizational and institutional challenges that need to be overcome to get the research done. |
| 2:30 to 3:00 PM | Break Refreshments available in 407 |
| 4:30 – 5:00 PM | Return to Hampton Inn via vans |
| 5:45 PM | Vans leave the Hampton Inn to Grainger Library |
| 6:00 PM | Reception at Grainger Engineering Library followed by dinner |

### Wednesday, October 27 (Levis Faculty Center – Fourth Floor, Room 407)

| | |
|---|---|
| 7:45-8:15 AM | Bus Leaves Hampton Inn for Levis Faculty Center |
| 8:00 – 8:30 AM | Continental Breakfast |
| 8:30 – 10:00 AM | Reports by each of the breakout groups; chaired by Jesse Ausubel |
| 10:00 – 10:30 AM | Break |
| 10:30 – 11:30 AM | Workshop wrap up and where do we go from here, Jesse Ausubel |
| 11:30 AM | Adjourn |
| 11:30 – 12:30 PM | Lunch (box lunches available to eat at Levis or to take with you) |

# Appendix B: SuperGrid Workshop 2 Participants

Jesse Ausubel
Rockefeller University
ausubelATrockefellerDOTedu

Balu Balachandran
Argonne National Lab
baluATanlDOTgov

Patrick Chapman
UIUC
plchapmaATuiucDOTedu

Paul Chu
University of Houston
cwchuATuhDOTedu

Ron Chu
Exelon
ronDOTchuATexeloncorpDOTcom

Ed Cording
UIUC
ecordingATuiucDOTedu

Steinar Dale
Florida State University
daleATcapsDOTfsuDOTedu

Ben Damsky
EPRI
bdamskyATepriDOTcom

Peter Dickson
MWH Global
peterDOTaDOTdicksonATmwhglobalDOTcom

Deepak Divan
Georgia Tech
deepakDOTdivanATeceDOTgatechDOTedu

Steven Eckroad
EPRI
seckroadATepriDOTcom

Wayland Eheart
UIUC
weheartATuiucDOTedu

Ian Grant
TVA
isgrantATtvaDOTgov

Paul Grant
W2AGZ Technologies
wzagzATpacbellDOTnet

Steven Harper
UIUC
srharperATuiucDOTedu

Ed Herricks
UIUC
herricksATuiucDOTedu

Henry Huang
Pacific Northwest Lab
zhenyuDOThuangATpnlDOTgov

Marija Illic
Carnegie Mellon University
milicATeceDOTcmuDOTedu

Allan Jacobson
University of Houston
ajjacobATuhDOTedu

Brian Johnson
University of Idaho
bjohnsonATeceDOTuidahoDOTedu

Tom Kay
Exelon
thomasDOTkayATexeloncorpDOTcom

Bud Kehrli
American Superconductor
bkehrliATamsuperDOTcom

Vladimir Kogan
AEP
vikoganATaepDOTcom

Phil Krein
UIUC
kreinATuiucDOTedu

Jason Lai
Virginia Tech
laijsATvtDOTedu

Bob Lasseter

University of Wisconsin-Madison
lasseterATengrDOTwiscDOTedu

John Maulbetsch
Maulbetsch Consulting
maulbetsATixDOTnetcomDOTcom

Michael McCarthy
American Superconductor
michaelmccarthyATamsuperDOTcom

Romeu Murariu
MWH Global
romeuDOTmurariuATusDOTmwhglobalDOTcom

Wes Myers
Los Alamos
wmyersATlanlDOTgov

Robert Neilson
INEEL
rmnATinelDOTgov

Tom Overbye
UIUC
overbyeATuiucDOTedu

Phil Overholt
DOE
philipDOToverholtAThqDOTdoeDOTgov

Henryk Piekarz
Fermilab
hpiekarzATfnalDOTgov

T.S. Gopi Rethinaraj
UIUC
rethanarATuiucDOTedu

Angus Rockett
UIUC
arockettATuiucDOTedu

Ben Russ
General Atomics
benDOTrussATgatDOTcom

Layla Sandell
EPRI
lsandellATepriDOTcom

Pete Sauer
UIUC
sauerATeceDOTuiucDOTedu

Robert Schainker
EPRI
rschainkATepriDOTcom

Jurgen Scheffran
UIUC
scheffraATuiucDOTedu

Tom Schneider
TRSEnergy
trsenergyATaolDOTcom

Clifford Singer
UIUC
csingerATuiucDOTedu

Craig Smith
DMJM
craigDOTsmithATdmjmDOTcom

Finis Southworth
INEEL
finATinelDOTgov

Jim Stubbins
UIUC
jstubbinATuiucDOTedu

Bob Thomas
Cornell University
rjt1ATcornellDOTedu

Deborah Thurston
UIUC
thurstonATuiucDOTedu

Harold Weinstock
AFOSR
haroldDOTweinstockATafosrDOTafDOTmil

Alan Wolsky
Argonne National Lab
awolskyATanlDOTgov

Don Wuebbles
UIUC
wuebblesATuiucDOTedu