EPRI

SuperGrid—The Next Steps

Synthesis Report Based on SuperGrid II Workshop at University of Illinois at Urbana-Champaign, October 25–27, 2004

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Technical Update, March 2005

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ABSTRACT

The "SuperGrid" represents a vision of an integrated system with the potential to play a major role in the provision of energy to the world in the latter decades of the 21st century. The core concept is a transcontinental energy spine consisting of a superconducting power transmission circuit integrated with a hydrogen pipeline and connected to nuclear power plants and other generating facilities sited in remote locations. The nuclear plants and the electricity/fuel delivery circuit would be constructed underground. Load centers across the country would withdraw power and hydrogen as needed.

SuperGrid enabling technologies include advanced nuclear plants, high-temperature superconductors, efficient thermochemical or electrolytic hydrogen production processes, and modern tunneling and underground construction methods. Motivating benefits include

- Reduced dependence on fossil fuels in the electricity, heating, and transportation sectors
- Large reductions in greenhouse gas and pollutant emissions in both the generation and consumption of energy
- Low-loss interconnections among regional networks, remotely sited nuclear plants, and remotely located renewable generating facilities
- East/west load leveling of electric power demand
- Reduced vulnerability to natural hazards and terrorism

Since the original presentation of the concept in 2001, the SuperGrid has attracted widespread attention, and it has been the subject of two national workshops. Experts have generally agreed that there are no *scientific* barriers to the system's eventual implementation. Based on discussions at the SuperGrid II workshop held in October 2004, this report provides recommendations for outreach, research, and development activities focused on the challenging design decisions that remain to be made, the formidable engineering problems that remain to be solved, and the myriad economic, environmental, and social issues that remain to be addressed.

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The following organizations and individuals are gratefully acknowledged:

- Paul Grant and Chauncey Starr developed initial visions of the SuperGrid concept and have been instrumental to its advancement.
- The Richard Lounsbery Foundation was the principal sponsor of the SuperGrid II workshop, with Jesse Ausubel, a member of the foundation's board of directors, serving as the lead.
- The University of Illinois at Urbana-Champaign hosted the SuperGrid II workshop, with Tom Overbye, a professor in the Department of Electrical and Computer Engineering, serving as the lead.

SuperGrid II attendees provided valuable technical presentations and contributed to stimulating discussions.

CONTENTS

1
INTRODUCTION

The U.S. energy future, as viewed at the outset of the 21st century, presents an array of significant challenges and uncertainties:

- The population and attendant energy needs may double by 2050.
- The price of preferred fossil fuels is increasing and will likely continue to do so.
- The availability and security of supply of these fuels may diminish.
- Environmental consequences of increased fossil fuel use—and the possible environmental, economic, and social consequences of associated greenhouse gas emissions—are of continuing concern.
- Alternative sources face barriers to their use—public acceptance in the case of nuclear power and cost, consistency, and resource location in the case of renewables.
- Vulnerability to interferences by nature and by terrorists is a heightened concern.
- System reliability is called into question by infrequent, but disruptive, cascading blackouts.

The problems, if projected beyond the United States to the rest of world, are far greater. At the same time, technology options exist, or are emerging, that address many aspects of these challenges:

- Nuclear power, if more widely accepted and used, would mitigate the cost, uncertainty, and environmental consequences of vastly expanded use of fossil fuels.
- Underground siting of nuclear plants—an idea recently receiving renewed attention—might allay public fears and provide increased security against terrorism and natural hazards.
- Hydrogen, as an energy storage and transport medium and a point-of-use fuel, might reduce fossil fuel use in the transportation sector and elsewhere.
- Hydrogen production at nuclear power plants by electrolysis or thermochemical process would provide a carbon-free energy source.
- Superconductivity is currently being considered at modest scale for utility-level power transmission.
- Underground tunneling capability is increasingly advanced as evidenced by Boston's Big Dig, New York City's Water Tunnel #3, and others.

SuperGrid—The Statement of a Vision

This confluence of challenges and technology has been noted by many observers, leading to a vision of an integrated system with the potential to play a major role in the provision of energy to the world in the latter decades of the 21st century. The vision is now known as SuperGrid.

As shown in Figure 1-1, the core concept is a transcontinental energy spine consisting of a superconducting power transmission cable integrated with a hydrogen pipeline and connected to nuclear power plants (perhaps 1,000 to 2,000 MW each) spaced along the line (perhaps 100 km apart). The nuclear plants and the electricity/fuel delivery circuit would be constructed underground. Load centers across the country would withdraw power and hydrogen as needed. The key enabling technologies include advanced nuclear plants, high-temperature superconductors, efficient thermochemical or electrolytic hydrogen production processes, and modern tunneling and underground construction methods.

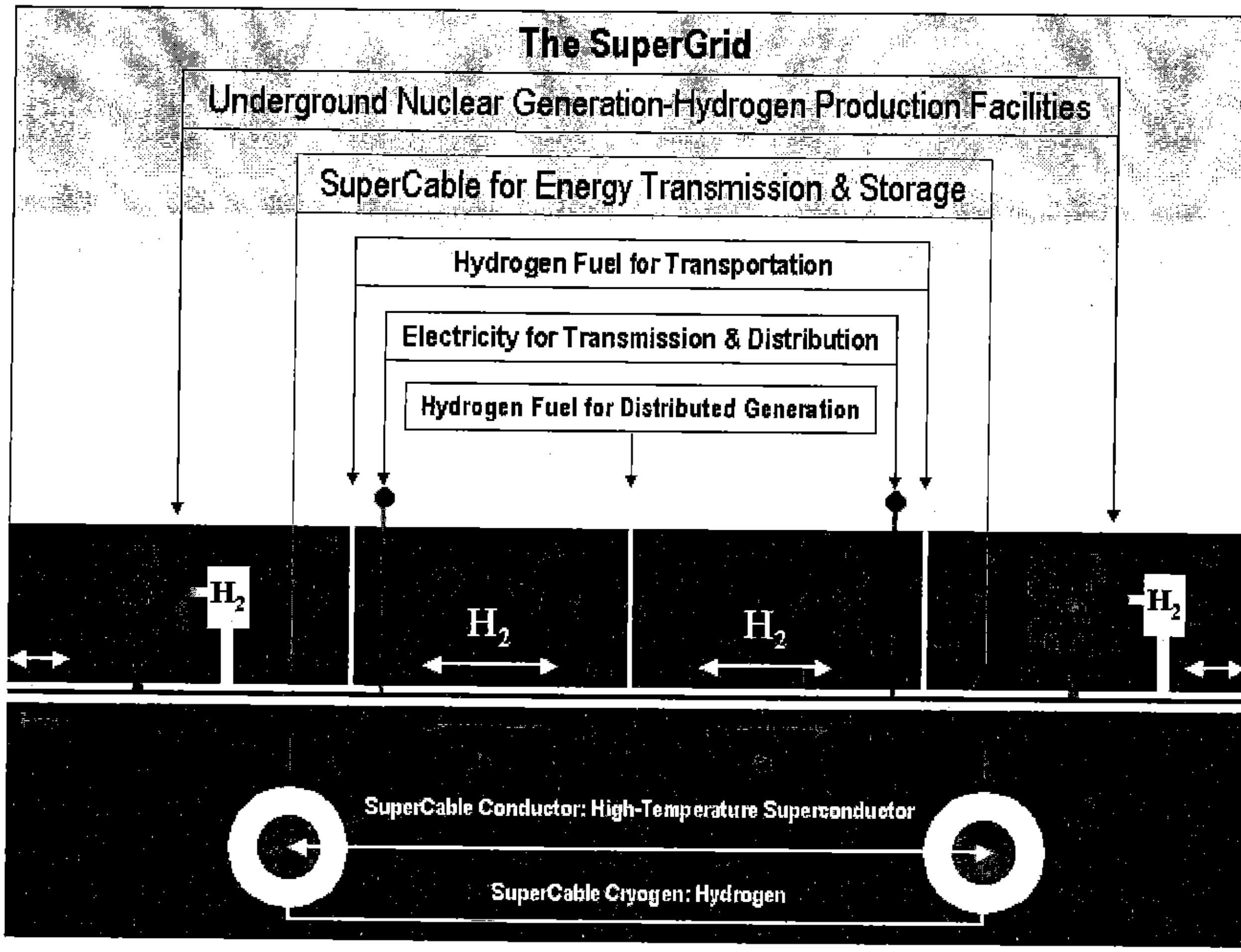

Figure 1-1
Schematic of the SuperGrid Concept

The idea was originally put forward by Grant [8] [9] as "Super City" and Starr [24] [25] as "The Continental SuperGrid." When published in *Nuclear News* and presented at an American Nuclear Society (ANS) meeting in Reno, Nevada, in November 2001, the concept was intended as a challenge to the nuclear community to engage in creative thinking and as an example of the bold and innovative approaches that will be required to meet the future energy needs of the nation and the world. Additional descriptions of the system and associated technologies can be found as long ago as 1967 by Garwin and Matisoo [6] and as recently as 2005 by Overbye [20].

The motivating benefits include

- A large reduction in fossil fuel use and carbon emissions in both generation and use,
- Low-loss interconnections among regional networks, remotely sited nuclear plants, and remotely located renewable generating facilities,
- East/west load leveling of electric power demand, and
- Reduced vulnerability to natural hazards and terrorism.

Since the original presentation, the concept has attracted widespread attention, and it has been the subject of two national workshops. Based on the discussions at these workshops, it has been generally agreed that there are no *scientific* barriers to the system's eventual implementation in the latter decades of the 21st century. However, challenging design decisions remain to be made, formidable engineering problems remain to be solved, and myriad economic, environmental, and social issues remain to be addressed.

The remainder of this report, intended to lay out the most critical challenges for near-term attention by EPRI and the broader energy research and development community, is organized as follows. Section 2 provides a brief summary of the overall guidance derived from the most recent workshop, SuperGrid II. Sections 3, 4, and 5 address the three main categories of recommended steps for continuing the progress toward implementation.

Additional background and explanatory materials are provided in appendices:

- Appendix A: Summary of SuperGrid I Discussions
- Appendix B: Summary of SuperGrid II Discussions
- Appendix C: Contact Information

References cited in the body of the report and in the appendices are listed in Appendix D.

2 SUPERGRID II WORKSHOP

SuperGrid II was convened in October 2004 at the University of Illinois at Urbana-Champaign (UIUC) to identify research needs in core technology areas critical to the successful implementation of SuperGrid. As was the case for SuperGrid I, the workshop was attended by experts from academic, governmental, and industrial research organizations in all the relevant disciplines. Plenary session background presentations were followed by topical breakout sessions focused on the following technical areas:

- Nuclear Power
- Hydrogen Production
- Superconducting Cable
- Power System Control
- Power System Integration
- Undergrounding
- Environment
- Construction Management

The conclusions and recommendations of the topical sessions were reported back to the full group of attendees for general comment and discussion. A complete set of the workshop presentations can be found on EPRI's website (http://www.epri.com/supergrid/default.html) [4] and in a final workshop report [20] prepared by the organizers.

This report focuses on the specific research recommendations developed at the workshop. The following subsections, "General Guidance" and "Next Steps," highlight selected topics deemed as important starting points for further work. Recommendations for subsequent work in three main topical areas are detailed in Sections 3, 4, and 5. A reasonably complete discussion of the full set of recommendations for each of these areas is found in Appendix B.

SuperGrid II—General Guidance

The point of departure for the SuperGrid II discussions was the system originally described; that is, "an integrated system consisting of nuclear generation, superconducting transmission, and the concurrent transport of electricity and hydrogen, all in underground facilities." Following extensive discussion (see Appendix B), the general consensus and guidance from the workshop emerged as follows:

1. The SuperGrid concept provides a visionary endpoint for the development and integration of a set of core technologies into a safe, clean, and reliable energy system of the future.
2. SuperGrid should be viewed not as a rigidly specified system but rather as a vision or framework within which critical core technologies will develop and a final system configuration will evolve. As was the case in the "Star Wars" concept of the Reagan Administration, the effort to create the system will be inspired by its perceived value if

successful. The effort will lead to important advances of benefit to the nation's energy future, whatever the eventual manifestation of the original concept.

3. Progress will require significant effort on many elements of the system. Therefore, widespread interest, support, and funding must be obtained from across the energy community. A critical first step should be the mounting of a systematic, organized program to publicize and promote the concept with the aim of obtaining funding for a coordinated program of engineering development.
4. To effectively and successfully achieve this end, a clear, concise and persuasive explanation of the vision must be developed that clarifies the benefits of integrating the core technologies, as well as addresses some of the obvious cost/benefit tradeoffs of co-production of electricity and hydrogen, system undergrounding, and the use of superconducting links.
5. Finally, there are many technological elements of SuperGrid that require engineering research and development. For many of these, new research activities should be initiated. Many others either are, or will be, the subject of research for reasons unrelated to SuperGrid. Examples include hydrogen production and transport, superconductivity, tunneling, power system modeling and control, power electronics devices, and many aspects of nuclear power. Researchers working in these areas should be made aware of SuperGrid and urged to include consideration of the SuperGrid concept in their initiatives.

SuperGrid II—Recommended Next Steps

At the SuperGrid II workshop, attendees offered many and varied suggestions and recommendations for moving forward along lines consistent with the general guidance summarized above. A full presentation of them is given in Appendix B. They have been organized into three categories:

1. Promotional Activities
2. Concept Development & Evaluation
3. Core Technology Research & Development (R&D)

These categories are listed in Table 2-1 and described more fully in Sections 3, 4, and 5. Subsequent sections of this report recommend next steps for achieving the following objectives:

- Create an identifiable, coordinated support group of government, academic, industrial, utility, and public interest organizations cooperating as funders, researchers, vendors, owner and operators, and advocates to advance development, acceptance, and implementation of the SuperGrid vision.
- Promote public awareness of the SuperGrid concept as an important, attractive part of the national energy system of the future.
- Influence the scope and direction of R&D in the core technology areas so that work being conducted for reasons unrelated to SuperGrid includes SuperGrid criteria, requirements, and applications in its plans and projects.

In addition, three points are noteworthy:

- It is clear that the entire list in Table 2-1 represents a body of work exceeding that which could be funded in 2005 by EPRI alone.
- The items under the heading of "Promotional Activity" were judged to be most critical and should be addressed first.
- To the extent that the successful conduct of promotional activities requires some results from work in the other two categories, initial tasks need to be selected based on funding requirements and availability, on the readiness and availability of potential contractors, and on a joint setting of priorities by EPRI staff, utility advisors, and SuperGrid collaborators.

Table 2-1
Summary of Suggested Next Steps

Area		Project/Task
Promotional Activity		Prepare promotional materials
		Visits with potential collaborators
		EPRI internal support
		SuperGrid office
Concept Development & Evaluation		Motivations/trends
		Cost-benefit analyses
		Documentation
		Roadmapping
Core Technology R&D	Nuclear Power	Review/confirm underground studies
	Hydrogen	High-pressure electrolysis
	Cable	Define cable tests (pilot; in-grid)
	Power System Control	"Grid" arrangement and system characteristics
	Power System Integration	Embedded SuperGrid system study
	Undergrounding	Assorted studies: access analyses; single- vs. multi-purpose tunnels; route selection
	Environment	"Skeptics" meetings
	Construction Management	Set up Advisory Committee; demonstration project management check list

3
PROMOTIONAL ACTIVITY

It was generally agreed that the most important step at this time is to promote awareness of and support for continuing development work on SuperGrid. This would be best achieved through a joint effort by the current promoters of the concept and could consist of the following tasks:

1. In partnership with the Lounsbery Foundation, Rockefeller University, UIUC, and others, EPRI should organize a systematic program of discussions and/or visits with potentially interested collaborating organizations for the purpose of obtaining support and cooperative funding arrangements for future efforts. Recommended initial contacts include:
   - National Science Foundation
   - National Research Council
   - National Academy of Engineering
   - U. S. Department of Energy
   - Major U.S. nuclear utilities
2. In preparation for these discussions, materials in the form of descriptive brochures, collections of technical articles, and a proposed plan of research should be prepared. A brief slide show or video with content that extends the video shown at SuperGrid II would be a useful tool in the promotional campaign.
3. The EPRI advisory structure could be used as a vehicle for disseminating information about SuperGrid, its benefits, and future development plans throughout the utility industry, which will be the primary user of the technology. Presentations to the Advisory Council, Research Advisory Committee, and Sector and Area Councils should be considered.
4. As part of EPRI's presence and activity at the Idaho National Laboratory (INL), the establishment of an on-site SuperGrid office should be considered. Given the ongoing research on advanced nuclear plant and hydrogen production processes along with the frequent visits by important members of the energy research establishment, INL represents a highly visible and potentially influential site for a coordinating activity on behalf of SuperGrid.

Additional information on promotional activities is presented in Appendix B.

4
CONCEPT DEVELOPMENT AND EVALUATION

Many SuperGrid II workshop participants, while acknowledging the attractiveness of the SuperGrid vision of an integrated system of core technologies, felt that the promotional activities would benefit from a clearer description of the concept. This would provide more insight into the tradeoffs between costs and benefits of several critical design decisions that would eventually need to be addressed. Therefore, it was recommended that a near-term activity be directed toward the launch of a system study to develop and evaluate a few important operating parameters of the system. Suggested tasks are the following:

1. Define the array of future energy-related problems and the attributes of SuperGrid's core technologies and define the important assumptions regarding future social, political, technological, and environmental trends that will influence the choice of preferred SuperGrid design parameters.
2. Identify a few important design choices within the defined framework of nuclear plants providing electricity and hydrogen to be delivered through major links into the existing national power grid at major load centers. These might include:
   - The relative amounts of electric power and hydrogen energy to be produced and delivered and how the ratio of these quantities might evolve over several decades.
   - The benefits of co-transport of electricity and hydrogen vs. alternative delivery schemes.
   - The benefits of placing the generation and transport facilities underground.
   - The use of superconducting links vs. more conventional transmission alternatives such as HVDC.
3. Create a planning roadmap or conduct a "scenario analysis" of alternative paths for the development of the core technologies and the consequent evolution of the SuperGrid concept. This task will complement the previous two, as conditions will change over time as population and energy demand grow, as environmental and political priorities change, and as the cost-performance characteristics of the core technologies evolve. An understanding of how changing situations will influence design choices can be used both to update the long-term vision and to choose wisely the initial steps for introducing the technology.

Additional information on concept development and evaluation activities is presented in Appendix B.

5
CORE TECHNOLOGY R&D

As noted earlier, most of the time at the SuperGrid II workshop was spent in eight topical discussion groups. Each group was charged with recommending R&D needs deemed to be of particular importance to advancing the development of SuperGrid or validating the fundamental concept. Each group produced a lengthy list of suggested topics. These are presented and discussed in Appendix B .

In the following paragraphs, one topic from each of the subject areas is selected for consideration as a near-term activity. The criterion for inclusion in this reduced set of next steps was to favor projects that provide guidance for the direction of longer-term development efforts and broader visibility for SuperGrid activity throughout the energy and R&D communities.

It is recognized that not all can be supported in this time frame, even under optimistic estimates of collaborative funding. Perhaps only one or at most two might be chosen for near-term support. However, two points are noteworthy.

The involvement of EPRI—not only as a promoter of the concept but as an active participant in the necessary R&D—was deemed by workshop participants to be critical to the success of efforts to create a supportive SuperGrid community. Therefore, the choice of the particular project is probably less important than that one be done at all.

The following eight sections correspond to the topical areas into which the workshop was organized.

Nuclear Power Plants

The development of nuclear power options—such as the advanced light water reactor (ALWR) and the high-temperature gas reactor (HTGR)—will continue apace independently of any considerations of SuperGrid, although the fact that nuclear power is the most promising carbon-free source of hydrogen is gaining increased attention. [3] [5] [14] The issue of primary importance to SuperGrid is the feasibility of constructing nuclear generation underground. The results of a conceptual study of this approach were presented at the workshop in plenary session. [17] An important next step would be a careful review and vetting of this study, including the following tasks:

- Understand the relevance of the Russian experience at Zheleznogorsk
- Revisit/update previous California Energy Commission, Swiss, Canadian, and Japanese studies
- Obtain currently credible cost estimates
- Review the assessments by the Nuclear Regulatory Commission (NRC) of undergrounding nuclear plants conducted after the Three Mile Island/Chernobyl incidents
- Review current NRC work on HTGR licensing

- Consider the options for underground cooling, specifically its effect on plant performance and cost because air cooling will probably be required

In addition, as suggested in SuperGrid I, a thorough accounting of the quantitative benefits of undergrounding should be conducted. Specific tasks would involve the following:

- Verify the postulated reduction in seismic hazards
- Estimate the reduction in security costs and insurance costs
- Consider the likely effect on public perception of acceptability
- Examine the feasibility of in situ waste disposal
- Examine the feasibility of in situ decommissioning

Hydrogen

The implementation of the SuperGrid vision and the complete realization of its substantial contribution to the de-carbonization of the U.S. energy system depend on an economical means for producing hydrogen in large quantities. [10] Much research into hydrogen production methods is currently under way. [3] [5] [28] One approach with the promise of improved economics and possible scalability to large production rates is high-pressure electrolysis. SuperGrid would benefit from increased attention to this technology. A near-term project to evaluate and, if appropriate, support the development of a high-pressure electrolysis device would be a valuable contribution. Specifically, a study would

- Review the current state of the art for electrolysis at 1,500 to 10,000 psi in work under way at Mitsubishi and Proton
- Conduct an independent thermodynamic analysis of theoretical efficiency
- Identify scaleup problems to production levels relevant to SuperGrid
- Issue a request for proposals (RFP) for a conceptual design and a plan to produce an engineering design and a plan for testing at a suitable pilot scale

Superconducting Cable

The use of superconducting cable for low-loss, long-distance transport of large amounts of electricity has been shown to be a technically and economically attractive alternative in studies spanning many years. [6] [22] In recent years, the emergence of high-temperature superconductors suitable for liquid nitrogen (LN_2) cooling has made feasible the production of limited lengths of superconducting cable. The Long Island Power Authority project presented at SuperGrid II [16] is the first transmission-class installation of superconducting cable on the U.S. power system.

A valuable near-term contribution to the advancement of SuperGrid would be the identification of opportunities for demonstrating superconducting DC cable on the existing grid. The project would not only bring out and resolve critical design and installation issues but also increase the confidence of the electricity industry in the concept and demonstrate the industry's initial acceptance of a critical element of SuperGrid to the broader energy community. The project should be designed to meet the following objectives:

- Establish intended goals of project in demonstrating
  - Successful design/cost of multi-joint cable carrying 100,000 A and 25,000 V
  - Successful integration with AC grid
  - Cost of tunneling for installation (could be surface of underground)
  - Concurrent cryogen transport
- Define precursor tests necessary for project
  - Cable design and pilot-scale lab testing
- Obtain agreement on criteria for approval of future project
- Initiate RFPs for precursor tests

Power System Control

Near-term work on power system control issues should focus specifically on problems relevant to the original SuperGrid concept of linking remote generation sources and tying together portions of the existing power grid with high-capacity DC lines. A project focused on defining the comparative benefits of a simple point-to-point "spine" as originally proposed [24] vs. a "ring" configuration with certain self-equilibrating properties as described at the SuperGrid II workshop [15] would be a useful study. Specific control issues relevant to either configuration include

- Voltage control
- Ripple suppression
- Current steering
- Fault clearing
- Blackstart
- Other large-scale dynamic behavior

Power System Integration

The breakout discussion considered issues beyond power system control, i.e., if adequate measures could be developed to enable the stable, controllable operation of a high-capacity, superconducting DC link connected to the existing AC grid, questions remain about the effects of an embedded SuperGrid element on the reliability and economy of the entire system.

A system-level analysis of the effects of placing a SuperGrid element into the existing national grid should address questions such as the following:

- What benefits will accrue to the existing system from the introduction of large baseload generating capacity and large superconducting links?
- What will be the effects on system reliability?
- What will be the effects on reliability/redundancy requirements?
- What additional sensors/models/control algorithms will be required?
- How will the economics of an open electricity market be affected?

- How does SuperGrid compare to potential competitive systems (e.g., HVDC; gas-insulated overhead lines; modular nuclear and other distributed generation) from the standpoint of T&D system integration?

The results of a near-term study to address that question would be valuable for promoting interest in and support of SuperGrid within the power industry, perhaps through a targeted workshop.

Undergrounding

Aspects of this work should be coordinated with the updating of the engineering design and cost studies recommended above for the undergrounding of nuclear plants. This study, however, would focus on the question of tunneling for the underground power transmission/hydrogen transport pipeline. Specific technology issues in designing faster, better, cheaper ways of boring tunnels is beyond the near-term scope for SuperGrid and is being addressed by others. Supplementary studies of particular benefit to SuperGrid would address issues such as the following:

- How to provide monitoring and access for inspection or repair
- Tradeoff considerations between single- vs. multi-purpose tunnels
  - Initial vs. operating cost tradeoffs among tunnels of differing sizes, e.g., single cable with personnel access, multiple cables with personnel access, combined energy and freight or passenger transport capabilities
- Methods for selecting preferred routes over long distances and variable terrain and sub-surface conditions, e.g., using survey techniques from the surface, directional drilling of pilot holes, sampling

Environmental

The general consensus of workshop attendees is that SuperGrid is "green" and hence likely to be more acceptable to environmental groups and the public at large. This belief should be tested, as a system based on significant expansion of nuclear power capacity in the form of a new reactor technology and on the widespread production and distribution of hydrogen will likely encounter significant opposition at least in the initial stages. A recommended approach is to convene a workshop of likely skeptics to address the following considerations:

- Brainstorming of any possible short-term events (accidents) and long-term events (slow releases) that might accompany the implementation of a SuperGrid system
- Detailed consideration of the life-cycle environmental issues associated with the production, use, and eventual disposal of materials involved in the construction and operation of SuperGrid
- Sociological effects related to a shift away from "small, distributed" to "big, centralized" approaches for energy supply.

Construction Project Management

Eventually, the installation of a SuperGrid will require a large and complex construction project. It would be useful, in the course of the preceding R&D efforts, to have an awareness of the nature of the problems likely to be encountered that might be lessened or ameliorated by informed system design and component development. To this end, a near-term effort to develop a knowledge base on the conduct of large-scale construction projects would be invaluable.

Such an effort might proceed by setting up a "project management" team of individuals with experience in large construction projects. The group could be asked to develop a management checklist containing

- A review of the likely permitting and licensing hurdles that would be required to install all or part of a SuperGrid system
- Guidance for the scheduling and budgeting process for such a project
- Guidance for the type and scale of component-level demonstrations that should be conducted to provide results of value to the estimates of cost and performance for the full-scale system
- A list of potential major roadblocks to the implementation of the system or the conduct of intermediate demonstrations

A

SUMMARY OF SUPERGRID I FINDINGS AND RECOMMENDATIONS

The first workshop to address the SuperGrid vision was held in November 2002 in Palo Alto, California, under the cosponsorship of the Lounsbery Foundation. SuperGrid I was attended by 32 technical experts with extensive background in the important technological components. The stated purpose of the workshop was to "evaluate the technical feasibility of the concept"—specifically to question and to confirm or refute the hypothesis proffered by Starr in his ANS lecture [24] that "there were no insurmountable scientific barriers" to the implementation of a SuperGrid arrangement in the 21st century.

Two days of discussions were held in seven relevant topical areas: Superconductivity, Electrical Systems, Nuclear Power, Hydrogen, Underground Construction & Tunneling, Energy Economics, System Integration, Control & Security, and Environment.

The findings and recommendations of SuperGrid I, which were presented in a workshop report [19], and can be categorized and summarized as follows:

1. The hypothesis of "no insurmountable *scientific* barriers" was supported.
2. Major engineering innovation and progress will be required in all of the related technology areas in order to fully realize the expected benefits:
   - Power generation
     - "Renewed vigor" in a nuclear energy development program to reduce costs, improve efficiency, and increase inherent safety of the entire fuel cycle
     - Continued progress in renewable options to reduce costs and improve efficiency
     - Continued progress on the efficiency of current fossil generation and electricity end use (SuperGrid need not depend on resurgent nuclear or emergent renewables for its implementation)
   - Hydrogen
     - Development not only of improved production options but also of improved transport, storage, and utilization (widespread adoption of hydrogen use is important to balancing the power/hydrogen elements of SuperGrid)
   - Power transmission and control
     - Development and commercialization of the core superconducting cable technology *plus* supporting cryogenics
     - High capacity DC transmission including all supporting elements such as converters, inverters, controllers, and control system modeling
     - Continued investigation of interaction between large DC links and the existing AC grid

- Undergrounding
  - Progress in increasing speed and reach of tunneling capability and in reducing costs
  - Fuller investigation of underground plant construction methods, risks, and costs
  - Complete accounting of the "benefits of undergrounding" (while expressing an "obvious preference" for undergrounding of generation and transmission, attendees felt that the benefits need to be quantified in order to offset the expected cost premium)
- General approach
  - Begin with scaled experiments (hundreds of meters and amperes; thousands of volts) of superconducting DC transmission integrated with hydrogen transport
  - Follow up with pilot-scale, "real world" field experiments (kilometers to tens of kilometers)

B
SUMMARY OF SUPERGRID II FINDINGS AND RECOMMENDATIONS

SuperGrid II was convened in October 2004 at the University of Illinois at Urbana-Champaign to identify research needs in core technology areas critical to the successful implementation of SuperGrid. As was the case for SuperGrid I, the workshop was attended by experts from academic, governmental, and industrial research organizations in all the relevant disciplines. Plenary session background presentations were followed by topical breakout sessions. The conclusions and recommendations of the topical sessions were reported back to the full group for general comment and discussion.

Detailed recommendations, which are provided below, are organized into three categories:

- Promotional Activities
- Concept Development & Evaluation
- Core Technology R&D

Promotional Activities

There was full agreement that SuperGrid requires widespread exposure, interest, and support across the many segments of the energy community in order to maintain even the very preliminary R&D activity necessary to advance the concept. There is an urgent need for funding beyond the resources of EPRI and the Lounsbery Foundation if any progress is to continue.

To accomplish this, several steps were recommended:

- Develop a systematic plan for contacting potential collaborators including funding sources, research groups, equipment vendors, major contract R&D organizations, utility owner/operators, environmental and public interest groups, and the media
- Prepare promotional materials to describe the concept and the core technologies, as well as the motivations for—and the benefits of—the idea
- Identify further development activities through a SuperGrid technology roadmap
- Present and propose opportunities for collaboration, funding, and other support activities
- Establish and maintain communication among a SuperGrid core group based around the workshop participants
- Develop plans to publicize SuperGrid as a safe, clean and reliable "energy system of the future" to the general public

Many specific suggestions were offered for these several steps.

Potential Collaborators

- Primary—U.S.
  - Staff of interested Congressional Committee chairs
  - U. S. Department of Energy
  - Selected National Laboratories (ORNL, LANL, INL, ANL, other)
  - National Science Foundation
  - National Research Council/National Academy of Engineering
  - Utilities
    - Senior executives of major companies
    - State ISOs
    - NERC Region staff
- Additional—U.S.
  - U. S. Department of Homeland Security
  - EPA
  - NIST
  - Academic research groups
    - Power engineering faculty (UIUC, U. Minn., U. Wisc., Cornell, U. Iowa, other)
    - Cryogenics research labs (MIT, Purdue, other)
    - Nuclear engineering departments (MIT, U. Mich., other)
    - Environmental groups (NRDC, Sierra Club, EDF, other)
    - Selected state PUCs/regulatory agencies
- International
  - World Bank
  - USAID
  - IERE
  - Asian Development Organization
  - Electricite de France
  - ESKOM

Promotional Materials

- For meetings with potential collaborating organizations
  - Introduction and support request letter
  - Slide presentations
  - Brochures
    - Concise description of system, motivations, benefits
    - Developmental path (roadmap-like description)

    - Support requirements and opportunities
  - Folder of background articles and presentations
  - Videos of core technology elements
    - Underground construction
    - Superconducting cable assembly or installation
    - Hydrogen production facility
    - Hydrogen end use (hydrogen vehicle)
- For other forums
  - Articles
    - Trade press (*Public Utilities Fortnightly*; *Power Engineering*; etc)
    - Technical society meetings
    - General—technical (*Nature*, *Science*)
    - General—less technical (*Scientific American*; *Smithsonian*; *New York Times*—Tuesday's Science section)
  - Other
    - Media spots (NOVA; NPR's Talk of the Nation—Science Fridays)
    - Visitor center models
      - Utility headquarters lobbies
      - Nuclear plant visitor centers

Concept Development & Evaluation

As noted earlier, many workshop participants expressed a need for a clearer understanding of the underlying motivation for and logic behind the SuperGrid concept. While acknowledging that the core technologies all are expected to be important contributors to energy systems of the future, they raised questions regarding the particulars of system configuration and the benefits vs. costs of some choices. It appeared that the presentation of SuperGrid as a predetermined system arrangement often led to immediate questioning of why certain choices were made or why alternate arrangements might not be preferred. The consensus of the group was that the ability to publicize and promote SuperGrid persuasively and to obtain support for it would be enhanced by a more complete review of alternate system arrangements and a clear and (where possible) quantitative evaluation of the costs and benefits of each.

To do so will require a thorough review of past concepts and current programs. Also, it must be decided whether SuperGrid is to be presented as a specifically proposed system with claimed attributes or as an inspirational vision of yet-to-be-defined attributes that suggests a path and encourages advances in certain critical technical areas. The most critical issue (much like the so-called "Star Wars" concept of the Reagan years) is not will it work, but what would you have to do to make it work; in that way, important research gets done on things that have value in many contexts.

Objectives

- State clearly the motivation for such a system
- Call attention to current technological trends that suggest the plausibility of such a system
- Explore, quantify (where possible), and compare the merits/flaws of alternative concepts

Motivations

- Sustainability
  - Reduced use of nonrenewable fuels
  - Reduced emissions (all kinds)
- Environmental
  - Reduced CO_2 emissions (also SO_x, NO_x, etc.) in generation and in end use (H_2 vehicles)
  - Reduced infrastructure intrusion (plants/cables no longer visible; plants remotely located)
- Economic
  - Reduced transmission loss
  - Protection against fossil fuel price increases
  - Form of large-scale storage
  - Improved system utilization—East-West leveling
  - Linking of remote (renewable) sources to distant load centers
- Energy reliability
  - Reduced dependence on foreign sources
  - Resistant to natural hazards
  - Resistant to terrorist disruption
  - Reduce cascading failures (blackouts)
  - Supplement local shortages (brownouts)
- Systemic
  - Improved public acceptance
  - Easier siting
  - Alternative to adding conventional lines to existing infrastructure
- Geopolitical
  - Freedom from foreign dependence
  - An element in "global electrification"

Core Technologies

- Generation
  - Nuclear—LWR vs. HTGR
    - regulatory environment

- Renewables—"eco-invasiveness" vs. remote location
  - effect of variable capacity
- Fossil—role in SuperGrid

- Hydrogen
  - Production—electrolysis vs. thermochemical
    - at generation site or at load center
    - amount as fraction/multiple of electrical energy produced
  - Transport—as gas, liquid, slush (pressure, temperature)
    - use as cryogen for superconductor or not
- Cable
  - spine vs. ring vs. mesh
  - superconducting vs. conventional
  - DC vs. AC
  - H_2 cooled vs. other (N_2, LNG)
- Undergrounding
  - nuclear plant—cost vs. benefits
  - cable—underground vs. surface (enclosed "vault") vs. overhead
    - underground tunnel vs. trench

Core Technology R&D

The workshop was organized into seven topical areas, each with a breakout panel. An eighth area, "Construction Management," was introduced in a special plenary presentation, and each of the seven panels addressed the subject to some extent. The previous "Promotional Activity" and "Concept Development & Evaluation" sections of this appendix represent a reasonably consistent view across the seven panels on the needs in these areas. The following subsections summarize the results of each individual breakout session and the special plenary discussion, providing a description of the topical area and recommendations for specific technical issues that merit R&D attention.

Area 1: Nuclear Power Generation

Nuclear power generation is one of four core technologies in the SuperGrid concept. Its use as the source both of electric power and of energy for the generation of hydrogen provides the major displacement of fossil fuels, reduction in greenhouse gas emissions, freedom from dependence on foreign fuel sources, and protection against continuing price increases. Although solar, wind, hydro, and biomass could all be said to provide the same benefits, nuclear plants are favored for their siting flexibility, constancy of output, greater flexibility for the choice of hydrogen generation methods, proven reliability, and lower cost. The issues of spent fuel disposal and public acceptance of the technology in the United States remain open questions.

The technology of nuclear power is well established. Currently, it accounts for 18% of the global electricity supply. Furthermore, it is currently experiencing a rebirth as the generation option of choice in many places in the world and, more recently, as a viable option for future U.S. deployment:

- Thirty U.S. reactors have been granted license extensions—most recently Exelon's Dresden and Quad Cities plants
- Worldwide, 27 plants are currently under construction; 18 of them in Asia.
- Local authorities in Port Gibson, Mississippi, have gone on record as supporting the construction and operation of a new nuclear plant at Entergy's Grand Gulf power station.
- The United States and nine other countries are conducting a program (Gen IV) to support the R&D required to bring fourth-generation nuclear power to commercialization before 2030.
- In "The Economic Future of Nuclear Power" from the University of Chicago, nuclear power was judged "economically competitive" and declared beneficial as "an emission-free way to produce hydrogen..."

The items requiring attention are well known. They are safety and waste disposal. Extensive effort has been directed toward the development of inherently safe, passive systems. The question of spent fuel containment, transport, and permanent interment remains a contentious issue. Activity in these areas is under way worldwide and will continue in the absence of any consideration of SuperGrid.

SuperGrid reintroduces the idea of constructing nuclear power plants underground—a concept that has been discussed since the early days of nuclear power for the purpose of allaying public fear of nuclear accidents. It fits well with the larger SuperGrid concept, in which the superconducting DC cable/hydrogen pipeline will also be preferably placed underground.

Topics for Further Consideration

The issues related to nuclear power generation of particular interest to SuperGrid are those specifically related to

1. The integration of power generation with hydrogen production, and
2. The costs and benefits of underground construction and operation.

Integration with hydrogen production. This topic was studied in detail by EPRI. [3] [5] The study was based on a variety of alternative HTGR configurations with closed gas-turbine power conversion cycles. Hydrogen production methods considered were conventional electrolysis, methane splitting, steam methane reforming and thermochemical water splitting using the sulfur-iodine (S-I) process, and high-temperature steam electrolysis.

Development work in this area is under way, with significant amounts of funding from both government and private sources. This work will continue with no specific relationship to SuperGrid. However, the scale of SuperGrid will require hydrogen production rates of up to 300,000 lb/hr, which are quite large by comparison to normal industrial or individual end-use applications. The suitability of candidate processes for scaleup of several orders of magnitude is an important criterion for SuperGrid considerations, and existing projects should be encouraged to assess possible technologies on that basis. It has been suggested that high-pressure electrolysis may have important efficiency advantages, although this remains to be firmly established. Work in that area would be a valuable extension of current research for SuperGrid applications.

Costs/benefits of undergrounding. A conclusion of SuperGrid I was that the underground siting of nuclear power plants was "obviously preferable." While this may be true, this conclusion is based largely on the intuitive notions that underground plants would be more acceptable to the public and less vulnerable both to natural hazards and to terrorist attack.

There are three areas to investigate further:

1. What is the impact on construction and operating cost of undergrounding?
2. What regulatory issues of public safety (NRC), worker safety (OSHA), or environmental protection (EPA) may arise?
3. Can the expected benefits of undergrounding be confirmed and realized?

At least one nuclear plant has been constructed underground, at a location in Central Siberia. The plant was identified at the SuperGrid II workshop as a facility of the Mining and Chemical Combine, Zheleznogorsk, Krasnoyarsk, Kray. [17] Additional current information on the facility is available at the Bellona Foundation's website. [1] While it appears that the environmental impacts of the plant and reprocessing facility on the surrounding area have been severe, it has been suggested that this is due primarily to inadequate management practices and not to any fundamental problem with the underground location of the plant. [7]

Additionally, a number of engineering studies have been performed, mostly in the 1970s in the United States, Canada, Switzerland, and Japan. As summarized at the SuperGrid II workshop, the results from those studies were "mostly positive," concluding that there were "no insurmountable problems" and the approach was "...feasible from the viewpoints of construction practice, schedule, and cost penalty." [17] Nonetheless, the reported construction cost penalties ranged from 11 to 60%, depending on rock type and depth. As a result, with the slowdown in new plant licensing and construction at that time, the approach was not pursued.

More recently, a study at the Los Alamos National Laboratory (LANL) extended the approaches of the earlier studies to consider construction in salt deposits and to co-locate several plants as an "underground power park." [17] The LANL study appears to be primarily conceptual in nature, but it raises the possibility that the costs could actually be *less* than those for surface sites. This possibility is based on a number of potential savings, including the following:

- Reduced decommissioning costs with in situ decommissioning and disposal
- Reduced transportation costs with co-located storage and disposal facilities
- Reduced excavation costs in salt as compared to granite
- Reduced facility cost through the elimination of containment structure
- Reduced reactor costs through the use of a modular rector
- Minimized site costs for successive reactors
- Reduced security costs
- Reduced insurance costs

Suggested next steps include the following:

1. It would be useful to have up-to-date and credible information on the Russian experience at the "Mining and Chemical Combine" facility. [1]

2. The cost estimates developed in the earlier U.S., Canadian, Swiss, and Japanese studies should be reviewed and updated.
3. The LANL salt-bed location study should be vetted and, if necessary, the engineering and economic assumptions reviewed and confirmed by experienced architect/engineering firms.
4. If the premise of the study is confirmed, a geological survey should be conducted to determine the location and "capacity" of suitable salt-bed sites in the United States and perhaps elsewhere in North America.
5. A review of possible operating practices and procedures at a combined underground power generation/hydrogen production/waste storage facility should be carried out, along with the following studies:
    - A review of existing probabilistic risk analyses to determine where they may need to be modified to apply
    - A review of applicable regulations from NRC, OSHA, EPA, and other involved agencies to see which regulations might be relaxed (as hypothesized in the "reduced cost assumptions"), which might be modified, and what new regulations might be expected
6. As was also suggested in SuperGrid I, a "thorough accounting" of the benefits of undergrounding should be performed:
    - A methodology should be developed and applied to test the assumption that underground nuclear plants will find greater acceptance by the public, by environmental groups, and by siting authorities.
    - A vulnerability analysis should be conducted to test the assumption that underground plants will be less vulnerable to natural hazards and terrorist attack. It is not entirely obvious, for example, that an underground plant would always be less subject to the risk of earthquake damage than a surface plant.

Area 2: Hydrogen

The second major technology element in the SuperGrid concept is hydrogen. It enters the picture in several ways:

- An alternative end-use fuel, primarily for vehicles
- The cooling medium for the superconducting cable
- An energy storage and transport mechanism

It would be produced at the generating plant when the need for electricity is low, transported to load centers through the "SuperCable," stored until needed both in the cable itself or at hydrogen storage depots near load centers, and then converted back to electricity in a distributed generation network or burned as fuel in vehicles or stationary burners.

The hydrogen component of the system was viewed during SuperGrid I as being reasonably well in hand. Hydrogen was considered to be in routine use in chemical and petrochemical plants. It was stated that pipelining and storage were well established, and that the fuel could be burned in engines or in fuel cells. Its perceived benefits of cleanliness at the point of use and protection against future scarcity of fossil fuel led to the expectation of an evolutionary progression into increasing use as the price (primarily of fuel cells) declined. No specific technical projects were discussed or recommended other than the general guidance of continuing to "improve performance," "reduce cost," and "increase conversion efficiency."

At SuperGrid II, five areas were considered important for additional attention:

1. Hydrogen production processes
2. Hydrogen transport in pipelines
3. Hydrogen storage
4. The future evolution of hydrogen end use
5. Public perception of hydrogen safety

Hydrogen Production

The primary questions for hydrogen production were

- Selection of preferred processes
- Coordination of hydrogen production with the nuclear power cycle
- Scale-up of production equipment to the sizes relevant to SuperGrid
- Overall cost reduction

Hydrogen production is currently the subject of intensive R&D. The U.S. Department of Energy's Energy Efficiency and Renewable Energy (EERE) program [28] and the National Energy Technology Laboratory (NETL) [18] give overview summaries of the programs. The processes of interest to SuperGrid are categorized as on the "Centralized Production Pathway" and include the thermochemical processing of fossil fuels or biomass feedstocks and the thermochemical splitting or electrolysis of water. Under "Other Production Pathways," the coproduction of hydrogen, heat, and power at power parks (similar to the production element in SuperGrid) is being considered.

Much of the effort is being carried out at the National Laboratories (INL, NETL, NREL, LLNL, LANL, ORNL and others) and at a variety of academic centers (e.g., U. of Colorado, Iowa State, UC Berkeley *et al.*) and industrial centers (e.g., Praxair, GE, Air Products, TIAX, LLC, Westinghouse Savannah River Labs).

Over 125 thermochemical processes are known and have been at least cursorily reviewed. The two currently receiving the most attention are the sulfur-iodide (SI) and calcium-bromine (Ca-Br) processes. Both are described in some detail, along with preliminary cost estimates, in recent EPRI reports. [3] [5] Both are being studied in conjunction with HTGRs as the energy source. Issues to be considered are those of scaleup of capacity to production rates suitable for integration into the SuperGrid system.

Hydrogen Transport and Pipeline Development:

Work on the design, materials selection, and construction of hydrogen pipelines (and hydrogen storage facilities) has been going on for more than 40 years. Much of the work has been supported by the USDOE [27]. A summary of work at Sandia National Laboratories [21] notes the existence of extensive materials research characterizing the degradative effects of hydrogen on materials of construction, the search for modifications in composition and microstructure to improve performance, and work on a 24-m-long demonstration pipeline. Existing operational pipelines are characterized as "expensive" and using "conservative designs and materials." An important extension of current research would be to study effects at expected pipeline pressures up to 34 MPa (~5,000 psi).

At SuperGrid II, the discussion of hydrogen transport was directed to the consideration of hydrogen pipelines integrated with power transmission in the form of the SuperCable. The following specific issues were identified:

- Selection (as part of a larger system evaluation study) of the preferred state (gas, liquid, slush), pressure, and temperature of the hydrogen in the pipeline
- Materials problems for the lines, valves, joints, and other components
- Scaleup to line capacities (sizes) relevant to SuperGrid
- Consideration of the use of existing networks (in the LANL presentation, it was noted that "gaseous hydrogen ≠ natural gas" and "any component subjected to mechanical loads in a gaseous hydrogen environment is potentially susceptible to hydrogen effects")
- Monitoring and maintenance

Hydrogen Storage

A similarly large body of work exists on hydrogen storage. A cursory web search yields thousand of citations including references to periodic USDOE program workshops [27]. Recent advances have been reported [14], and the field should be expected to advance rapidly. The storage questions are similar to those for the pipelines:

- Selection (as part of a larger system evaluation study) of the preferred role of storage in the SuperGrid concept, including location and capacity of the storage elements
- Type of storage such as pressurized gas, liquid, metal hydrides, or adsorbed hydrogen
- Materials for tankage and related components

Hydrogen End Use

In order to understand how SuperGrid might be brought into service, it is necessary to have some notion as to how the use of hydrogen as an end use energy source will develop. Issues of interest include the following:

- Understanding of likely growth profiles of hydrogen
  - Expansion of existing use in chemical and petrochemical plants
  - Vehicle fuel
  - Other stationary thermal applications
  - Distributed power generation

Public Perception

Hydrogen suffers in some quarters from the perception that it is dangerous and difficult to manage properly—the so-called Hindenburg syndrome. USDOE and LANL have been working on "Codes and Standards for the Hydrogen Economy," focusing on an "analysis of unintended hydrogen release scenarios." [21] This concern must be addressed, in conjunction with similar perceptions of nuclear power, if SuperGrid is to find enthusiasm and acceptance with the environmental community and the public.

Area 3: Superconducting Cable

Superconductivity, the other core technology in the SuperGrid concept, has long held the promise of long-distance, loss-free transport of electric power. Garwin and Matisoo performed a serious analysis of the prospect in 1967 [6], but at that time liquid helium cooling was required for the original 4 K superconductors. The prospect became more achievable with the discovery of higher-temperature superconductors with higher critical currents and magnetic fields and the possibility of liquid nitrogen cooling. In recent years, design studies, laboratory testing, and in-grid demonstrations have been conducted. [2] One project of note is the installation of what will be the world's first "transmission-level" superconducting cable at the LIPA East Garden Substation. The cable schematic is shown in Figure B-1. The design and operating specifications are as follows:

- AC
- 138kV/2400A ~ 574 MVA
- 610 m long
- Six 1612 kV terminations
- One 161 kV splice (for test; not required for grid installation)

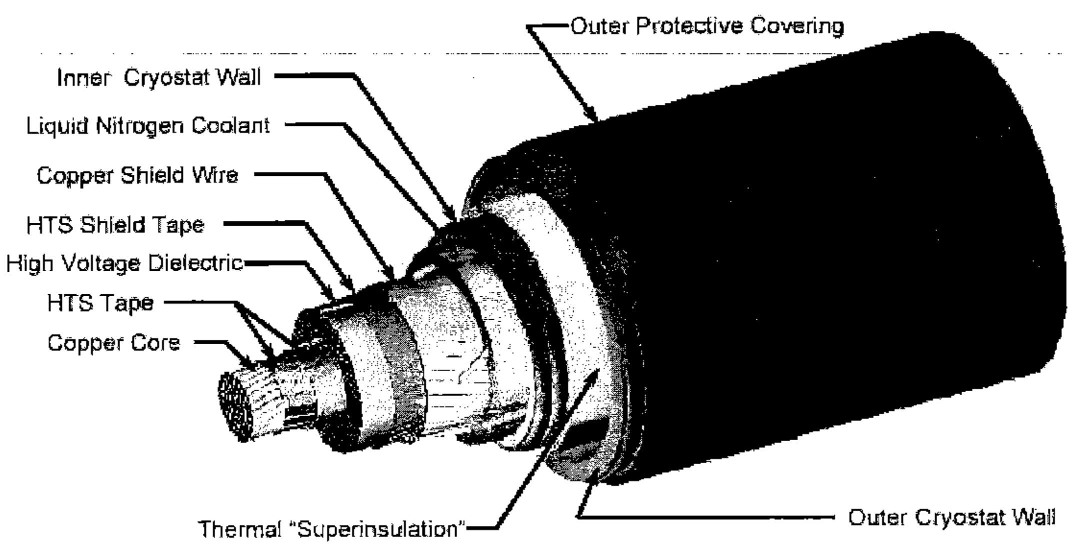

Figure B-1
LIPA Cable Schematic (presented by American Superconductor at SuperGrid II)

SuperGrid applications will require a significant advances in the technology, including the following:

- DC rather than AC
- Use of hydrogen as the cryogen coolant
- Concurrent transport of hydrogen down the cable

- Significantly longer runs of cable

A sketch of the SuperCable power transmission/hydrogen transport concept is shown in Figure B-2.

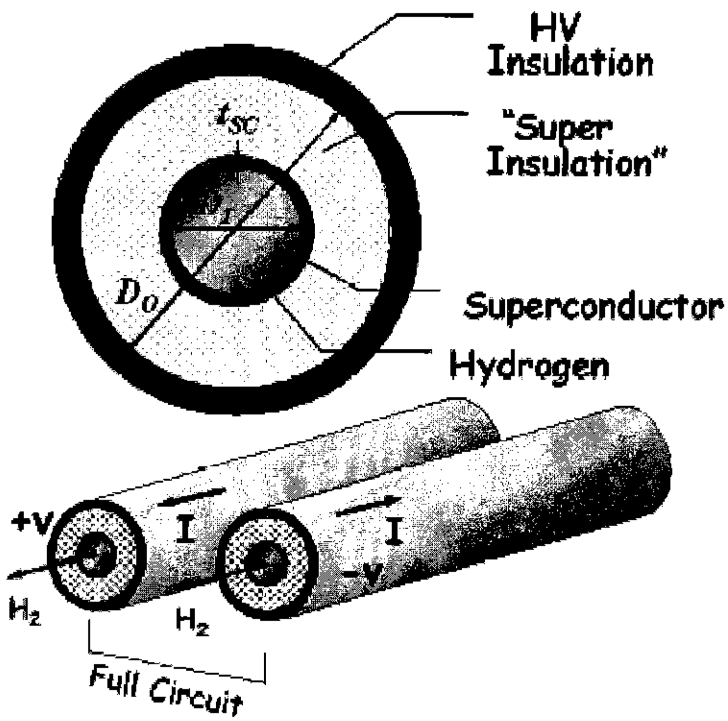

Figure B-2
SuperCable Schematic (presented by P.M. Grant at SuperGrid II)

Research Issues

There are a number of design issues to be worked out in the development of the SuperCable. Initial specifications require a selection of a general design target including

- Cable capacity
  - Electric power and relative amount of hydrogen transport
  - State of hydrogen—liquid, gas, slush, p, T

Given a chosen design target, important design questions include

- Voltage-current tradeoffs
- Interface with AC grid
- Ripple suppression
  - Filters
- Cable configuration
  - Pipe lengths and diameters

- Rigid vs. flexible
- On-site manufacturing
  - Conductor winding
  - Vacuum (sealed or pumped?)
- Cold vs. warm dielectric
- Joints
  - Superconducting
  - Welded
  - Expansion (bellows)

- Construction for magnetic field forces
- Splices (zero resistance?)
- Cryogenic alternatives
  - Pulse tubes
  - "Cryobreaks"

Approach to Development

It was recommended that SuperCable development be approached in three steps.

- Laboratory pilot test
  - 10- to 100-m cable
  - perform at suitable national laboratory
- Small-scale demonstration
  - 1-km cable
- Operating link demonstration
  - ~ 10-km cable
  - install in existing grid bottleneck

The complexity of the demonstration can be adjusted for the several steps as a function of the level of technical confidence and the available budget at the time. Choices would include

- Selection of cryogen—N_2, LNG, H_2
- Function—with or without concurrent cryogen transport
- Location—underground or surface

Area 4: Power System Control

Existing power transmission and distribution systems take the form of highly interconnected networks with hundreds of generators and millions of loads. The control functions are applied to the current at essentially constant voltage. The advantages to the system, in addition to the ease of changing voltage with transformers, include the presence of multiple paths and the consequent redundancy for getting power to the user. The disadvantages are that the systems have losses and are susceptible to uncontrolled power paths leading to unnecessary losses or to system congestion over some links.

The advantage—in the form of reduced "antenna" losses—of DC over AC transmission over long distances or in underground or undersea links has long been recognized. The introduction of large-scale DC links has become common in recent years on the Northwest Intertie from hydro sources in Washington into Northern California, at Three Gorges in China, at Furukawa in Japan, and elsewhere.

The idea integral to SuperGrid extends this evolution to the use of superconducting DC transmission at large scale to provide loss-free transport of power from remote generation resources to load centers. While some relatively short-length superconducting lines have been and are being installed into utility systems (Detroit Edison, LIPA), to date they have all been AC links to avoid the additional complexity of integration of a DC line with the AC grid. The extension of the technology to long-distance, high-current superconducting DC raises system integration and control issues that require R&D:

- Superconductors require constant current in order to be completely loss-free. Therefore, a *voltage* control methodology must be developed.
- Control of superconducting meshes or networks is difficult. Some sort of current steering methodology is required.
- The benefits of the proposed system require going to high currents. Therefore, the control elements must be devices with very low impedance; these are far from the current state of the art.
- The very high surge voltages (L(di/dt)) that would accompany faults on very high current lines must be handled.
- No satisfactory DC circuit breakers currently exist.
- Single lines carrying high power present "contingency analysis" problems to system planners requiring large redundancy to be built into the system.

A number of references on the control of superconducting power systems are available. [12] [13] [26]

Research Issues

Research recommendations from the SuperGid II power system control panel are difficult to categorize. It was the general opinion that "from a power control perspective, superconducting lines do not add benefits compared to HVDC lines." Much of the attitude appeared to stem from a concern that a superconducting *network* or *mesh* would be exceedingly difficult to control if it were superconducting. However, this was not the proposed arrangement; the misunderstanding may have stemmed from the use of the term "Super<u>Grid.</u>" However, some of the suggestions appear to be relevant to the general question of high-current superconducting links:

- DC circuit breakers
- Efficient DC/AC/DC conversion
- Tap interaction
- Conventional devices at cryogenic temperatures

- Fault management
- General question of system modeling with a large, superconducting DC component embedded in the larger system

Area 5: Power System Integration

A lengthy discussion was presented of the transmission and generation expansion planning and system operating considerations. This was done to provide a context of an existing, large-scale operating system into which SuperGrid would have to be introduced as an alternative to the construction of additional, conventional transmission lines. The primary points emphasized were that reliability and economy were the overriding considerations, and that the existing analysis and optimization tools for AC power flows and for contingency analysis and simulation have been developed and tuned for the existing system. While these points are self-evident, they frame the concerns and research issues in the area of power system integration.

The introduction of SuperGrid, assuming it is DC, will be viewed by planners as the addition of large amounts of baseload generation at discrete points in the grid. This will introduce issues of

- Loss of high-density corridors on contingency
- System protection (if DC) in the absence of DC circuit breakers
- Integration of low-impedance cables (if AC)
- Requirement for load-following capability in the form of supplementary conventional generation or grid-level storage or distributed resources with associated storage

Research Issues

Primary system-level questions were identified as follows:

- How does the introduction of SuperGrid into the existing system affect system dynamics and control?
- How do you optimize a mixed traditional/superconducting system? (Apparently, there are current issues at BPA with the Pacific Intertie that would be expected to be more severe with SuperGrid elements.)
- What are the market implications of SuperGrid?
- How do large SuperGrid contingencies interact with locational marginal pricing markets, and how do planners hedge against them?
- Will the introduction of SuperGrid improve or degrade the reliability and operating characteristics of the existing grid?

Additional issues include the following:

- System modeling tools will be required.
- Contingency analysis tools for systems with large amount of DC do not exist but will be required.
- The interaction of SuperGrid with other generation sources will require study.

- The benefits/drawbacks of tying together widely separated (Eastern, WSCC, ERCOT) regions must be considered.
- New, fuller understanding of system dynamics is required.
- L(di/dt) characteristics of superconductors limit their dynamic response.
- Inertia requirements on the AC system must be considered.
- Component issues must also be addressed:
  - High current DC sensors
  - DC circuit breakers
  - Combined H_2 and electric substation design and operation

Next Steps

The power system integration panel, along with the power system control panel, made the strongest assertion about the need for "a value statement that articulates what SuperGrid is all about." They also posed the question, "Why does the existing grid need the SuperGrid?"

Some research directions were suggested to address both existing system challenges and to confront anticipated challenges associated specifically with SuperGrid:

- Better modeling methods for larger systems and multi-terminal DC systems
- Consideration of breaking up the existing grid into smaller islands with DC interties

Additional topics specifically related to SuperGrid issues included the following:

- Conceptual designs and functional requirements determination of alternative sizes and arrangements of SuperGrid concepts (as discussed in "Concept Development & Evaluation")
- Vulnerability assessment of the future grid with and without the introduction of SuperGrid
- Development of credible grid models with embedded SuperGrid along with examination of a variety of demonstration problems (initial work on system architecture, modeling, and simulation)
- Establishment of a utility industry group of experienced, active power system professionals to assist in the evaluation of alternative concepts and to aid in the eventual introduction of SuperGrid into the existing system

Area 6: Undergrounding

An interesting review of evolving tunneling technology was provided at the workshop. The general conclusion was that tunnels of essentially any required diameter and length could be dug through nearly any terrain given sufficient time and budget. No significant breakthroughs in the form of increased tunneling speed or cost reductions were anticipated in the near future. Over a period of several decades, they may, of course, occur. Research to improve the state of the art is clearly beyond any reasonable scope of the SuperGrid project; if the field is to advance, it will be done by others for reasons unrelated to SuperGrid.

Nonetheless, the SuperGrid community should stay current on state-of-the-art tunneling technology in order to make informed decisions about design directions including

- The value vs. cost of undergrounding the cable links
- The value and cost of full-length access for inspection and maintenance
- The tradeoffs of multiple-use (large) vs. single-use (small) tunnels

Some aspects of the subject are closely related to the more general issue of project construction management discussed below.

Next Steps

It would be useful to make the tunneling community aware of the existence of the SuperGrid activities. At full scale, SuperGrid would potentially be a very large project and would generate attention and interest in the industry. This awareness could be achieved by the establishment of a "Tunneling Advisory Group" made up of active, industry experts. This could achieve the following beneficial results:

1. The industry, if aware of tunneling requirements special to the SuperGrid situation, might direct a portion of their development effort to address specific issues, such as the following:
   - Exceptionally long runs
   - Tunneling through highly variable terrain
   - Need for easy access for cable inspection, maintenance, and repair
2. The SuperGrid community could be made more aware of those geologic characteristics that make tunneling more difficult and expensive, such as the following:
   - Non-uniform ground
   - Presence of soil-rock interfaces
   - High groundwater pressure
   - Oil and gas deposits
   - Caverns and faults
   - High permeability zones
3. SuperGrid construction efforts would benefit from knowing more about the nature of the tunneling industry, in which a few small firms compete for a few high-risk projects. Project RFPs often get few bids, particularly for non-standard situations. Special contractual arrangements paying attention to appropriate means of risk allocation and risk minimization would be valuable.
4. Increased tunneling industry support for—along with public awareness of—the need for advanced or innovative technologies might attract government support for R&D efforts aimed at SuperGrid requirements.

Area 7: Environment

A review of the SuperGrid concept from the viewpoint of environmental professionals was provided. The issues discussed included the following:

- Hydrogen

- Safety concerns over the possibility of fires or explosions from either small, continuous leaks or sudden, massive releases
- Pipelines
  - Effects of installation on wildlife in critical areas
  - Locational issues such as avoidance of transportation corridors or existing power corridors
- Manufacturing
  - Mining or extraction of materials
  - Production processes as, for example, of $MgBr_2$ wire
- Water
  - Consumption of water to produce hydrogen
  - Increased humidity (greenhouse effects) of vastly increased hydrogen use
- Air quality
  - Reduction of CO_2, SO_2, NO_x, and other emissions compared to alternative supply and end use options

The general consensus was that the balance of potential environmental effects appeared to be a positive benefit from the substitution of SuperGrid for conventional electric power and vehicle fuel supply.

Next Steps

The primary suggestions from the environmental panel were more along the lines of economics and public behavior than of environmental science or engineering:

- To determine the economic incentives for the SuperGrid concept
- To explore the effects (for good or for ill) on population patterns by potentially encouraging a centralized, "mega-city" distribution rather than a more decentralized one
- To conduct a cradle-to-grave accounting of the environmental risk and effects of the manufacturing, operation, and eventual disposal of the system in comparison to alternative systems
- To conduct a careful assessment of the likelihood and consequences of hydrogen leakage
- To revisit the question of electric and magnetic field effects in the SuperGrid context.
- To encourage the awareness of SuperGrid among the environmental organizations and the public in the earliest stages of R&D
- To convene a National Research Council committee to develop an environmental research plan for SuperGrid in comparison with other technologies

Area 8: Construction Project Management

It is clear that even an initial implementation of SuperGrid at commercial scale would require a very large, coordinated engineering/construction effort even after the scientific and related component engineering problems were solved. The scoping, organization, and eventual management of such a project is beyond the competence and capability of most of the R&D

community, falling in the purview of the architect/engineering world. An understanding of what would be involved in the full-scale installation process is valuable to the present R&D effort for two reasons: (1) to understand the effect of system design and configuration decisions on the feasibility and difficulty of eventual implementation; and (2) to structure pilot and initial demonstration projects so as to provide the most useful information to the engineering construction and management process for system design and installation at commercial scale.

Construction Challenges

A description of the challenges facing SuperGrid in the construction phase from the viewpoint of an experienced manager of large projects was presented at the workshop. [23] It is noteworthy that the presentation ended with a citation of the Trans-Alaskan pipeline and North Sea oil and gas recovery as examples of formidable construction challenges that were successfully met and an assertion for the SuperGrid concept: "It can be done!"

The analysis assumed that all of the component technologies and methods were demonstrated and available and that no *scientific* uncertainties remained. The project considered was at a "demonstration" scale suitable for the resolution of construction issues—specifically, to build a section of SuperGrid of sufficient size to demonstrate "constructability" by

- Confirming permit requirements and timelines
- Benchmarking cost and schedule estimates
- Identifying specific obstacles and any need for specialized equipment or methods

The demonstration project contained the critical elements of the SuperGrid concept, including underground generation, hydrogen production, vacuum and refrigeration capability, AC/DC/AC conversion, grid interconnection, substations, control rooms, and instrumentation for monitoring and data acquisition. For this project, size and capacity were specified as follows:

- Transmission/transport length: 20 to 30 km
- Superconducting cable: 10 to 15 segments (~ 2 km long)
- Electrical capacity: 500 MW; 25 kV; 20 kA
- Hydrogen capacity: TBD

A cost range of $50 to $150 million ($2 to $5 million per mile) was estimated.

The project would take place in four phases

1. Conceptual design and rough order of magnitude (ROM) budget estimate
2. Detailed design
   - Refined budget
   - Schedule
   - Pre-qualify contractors
3. Contract award and construction
4. Commissioning
   - Startup/testing

- Review and validate cost and schedule estimates
- Monitor operation for 1 year
- Develop/check-out maintenance problems

The project would provide information on the following critical issues:

1. Obtaining rights-of-way for underground cables
2. Public acceptance of the concept
   - Public information elements to be included from the beginning
3. Permitting—hundreds of jurisdictions and agencies likely to be involved
4. Choice of conduit concepts
   - Single vs. multiple use
5. Choice of tunnel vs. trench vs. aboveground vault
   - Full access will be required at the demonstration stage for inspection, monitoring, repair, and maintenance
6. Cable design and installation
   - Identify any remaining scaleup problems
   - Field vs. shop fabrication
   - Placement methods to avoid damage
7. Generation options
   - Non-nuclear at demonstration stage, e.g., underground gas turbine or diesel
   - Use existing facility
8. Hydrogen production
   - Scale-up of modular packaged units
   - Determine if undergrounding is necessary

Research Issues

A number of specific questions were identified that should be addressed in the near term in order to set the preliminary requirements and scope for the construction planning:

- System issues
  - Hydrogen capacity
  - Hydrogen production
  - Practical, cost-effective module sizes and capacity
  - Power conversion and control equipment
- Component issues
  - Hydrogen production technology
  - Hydrogen module capacity
  - Number and types of cable joints and splices (to determine field assembly, connection, and testing requirements)

- Special tooling or equipment for handling superconductors
- Instrumentation and leak detection
- Design issues for maintainability

- Other issues
  - Identify likely range of permit requirements and timelines
  - Establish acceptable range of soil parameters for buried cable
  - Evaluate hydrogen greenhouse effect

Next Steps

Recommended steps to be undertaken during these early stages of system R&D focused on the following issues:

- Obtaining the advice of an experienced construction advisory group in the review and evaluation of "pre-conceptual" designs
- Establishing a forum for information exchange between the construction advisory group and the research groups
- Collecting background information on major undergrounding projects

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