National Energy Supergrid Workshop Report

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Executive Summary

This report summarizes the results of the University of Illinois at Urbana-Champaign (UIUC) sponsored National Energy Supergrid Workshop, 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, for the creation of a "Continental SuperGrid" to meet the nation's energy needs in the mid to later half of the 21st Century[1].

In brief, Dr. Starr's proposal calls for the creation of an Energy Supergrid, delivering both electricity and hydrogen. The electric portion of the grid would used superconducting, high voltage 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. Electricity would exit the system at various 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.

The Energy SuperGrid concept goes beyond the vision of a future hydrogen economy, or the simple extrapolation of electrification, to a duality of a hydrogen – electricity future, *hydricity*. In this vision electricity and hydrogen become synergistic elements in the future energy infrastructure. This energy delivery grid interconnects remote sources with load centers, links regional ac interconnections and connects concentrated population centers with remote nuclear and modern renewable resources and integrates hydrogen utilization in combined heat and power facilities and hydrogen storage for mobility or transportation usage.

To provide an evaluation of this concept the workshop brought together a select 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. Over the course of two days of presentations and discussion the following findings and recommendations emerged, with the results best seen in a perspective that recognizes the need for solving the world's energy dilemma on a time scale of fifty to a hundred years.

Findings

- No scientific breakthroughs are needed to achieve the reality of the Energy SuperGrid, yet major technological innovations will be required to minimize environmental effects and maximize economic and societal benefits.
- DC, high power superconducting power transmission should become a viable technology that can be integrated with the existing ac power grid.

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[1] Available online at http://www.epri.com/attachments/273488_NatlEnergyPlan.pdf.

- Nuclear energy and the modern renewables are the only known resources that can power society for the centuries ahead when fossil fuel use will be limited as a result of either scarcity or ecological and environmental impact. However, other fuels, such as coal, will continue to be important sources of energy for many decades and could certainly be incorporated into an Energy Supergrid.

- Nuclear energy and certain of the modern renewables are inherently remote sources for energy intensive uses. As such, both require conversion to an intermediate energy form for transport to distant loads. Electricity has shown its ability to serve as an intermediate energy form and hydrogen offers the promise of being a compatible partner in a future energy infrastructure

- Distributed generation in the forms of fuel cells and other hydrogen powered engines and distributed renewables, used close to the loads, have definite applicability to complement grid supplied electricity

- The critical requirement for a secure energy infrastructure and minimization of environmental and societal impacts leads to an obvious preference for subsurface of underground siting of critical energy infrastructure elements.

- 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.

- A progressive program of experimental engineering facilities, proving engineering feasibility and identifying opportunities for improving economics, needs to be developed.

Recommendations

- 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, hundreds of amperes and thousands of volts) needs to be undertaken.

- The overall Energy SuperGrid R&D program needs to pursue several technological platforms in parallel along with a systems engineering-economics effort that integrates and cuts across the technology platforms.

- Following the practical demonstration of engineering feasibility, at what for this concept might be considered a pilot scale, a series of real world, field experiments should be pursued with physical distances of first kilometers and then tens of kilometers.

Introduction

Mankind 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 much of our energy has come 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 our reserves, and when we ultimately run out 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 300 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 consensus that such emissions need to be curtailed. Clearly the need for sustainable energy resources that afford continued growth of human prosperity and the expanding concern for 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, 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[2]. To provide an evaluation of this concept the workshop 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. This report summarizes the results of this workshop.

[2] Available online at http://www.epri.com/attachments/273488_NatlEnergyPlan.pdf.

The Energy SuperGrid Concept

In short the Energy SuperGrid is a proposal for an enhanced infrastructure to meet the energy needs of large urban areas if one assumes a drastic reduction in fossil fuel consumption, particularly petroleum and perhaps natural gas. To understand the need for this enhanced infrastructure it is useful to provide a brief background on U.S. energy consumption, and to make a clear differentiation between primary energy usage and usage via an intermediate form.

Using 2001 data provided by the U.S. Energy Information Administration, the total annual U.S. energy consumption is about 96 Quadrillion Btu (Quad), of which 21.8 Quad comes from coal, 21.5 Quad from natural gas, 38.3 Quad from petroleum, 8.2 Quad from nuclear and 6.2 from renewables (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 (26.7 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 (37.5 Quad), and then transmitted using the high voltage grid from the generating plants to the electric loads.

Significant reductions in consumption of fossil fuels will require replacement of this energy using alternative sources. However, since most options for alternative energy generation require remote locations, the energy must be transmitted using an intermediate form – electricity or hydrogen being the only two viable options. The Energy SuperGrid Workshop was organized around a vision in which electricity and hydrogen together will provide complementary energy forms for society in the 21st Century. This vision proposes a synergism between electricity and hydrogen, a synergism that was recognized thirty years ago and the insights from that period are still valid today.

The Energy Supergrid proposal 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. 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. In most urban areas there is little spare transmission capacity and few available right-of-ways for the construction of new lines. Replacing the annual 26.7 Quad of petroleum-based transportation energy, an amount equal to more than 70% of the current electricity usage, with hydrogen will require either new hydrogen pipelines or large amounts of electric energy to generate the hydrogen locally. The SuperGrid proposal addresses both issues through its subterranean electric/hydrogen "energy pipeline."

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, today’s global climate change issue not yet having arisen. 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 proposes the newly discovered superconductor magnesium diboride (MgB_2), or the 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.

The vision of a “Continental SuperGrid” was first outlined in a presentation by Dr. Starr at the 2001 American Nuclear Society (ANS) meeting in Reno, Nevada, with nuclear power as the primary energy source. 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. The Energy SuperGrid Workshop 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. The Workshop 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.

Acknowledging that today there is routine use of hydrogen in the chemical and petrochemical industries, a transition to hydrogen is envisioned which does not require radical abandonment of existing infrastructures but an evolutionary transition. Perhaps hydrogen powered vehicles, with either IC or fuel cell engines, will be the first major departure from business-as-usual in end uses, and underground superconducting electric power cables the first step in the energy pipe element of the SuperGrid.

If deliberate sabotage and terrorism remains a significant risk, many of the major elements of the SuperGrid could be placed underground or subsurface, easing the problem of protection and increasing security. Certainly such underground siting would be required in many urban areas. At the same time, the distributed energy components also add to the robustness and reliability of the Energy SuperGrid.

In the Workshop, Dr. Starr added to his original concept, the vision of electrified transportation and hydrogen fueled electrified cars and trucks, a picture of a futuristic “all electric” energy system takes shape. All “electric” here is in the sense that in most situations the primary resource is converted first to electricity and then to hydrogen as needed. Alternatives where hydrogen might be predicted directly also exist, in the broadest sense the Energy SuperGrid combines the vision of the "Hydrogen Economy" with a futuristic vision of continued electrification. The exact blend being determined not by government planning but by the relative evolution and revolutions of technology. If a hydrogen-fueled motor gradually replaces the gasoline and diesel fueled internal combustion engine, the reduction of U.S. dependence on oil imports might radically change U.S. foreign policies and commitments.

The Energy SuperGrid is then a future vision that shifts the nature of both American domestic energy policy and foreign policy. At this very early stage in the conceptual development of this future vision, virtually all important performance parameters and design features are not yet specified and will only emerge with time as the conceptual development continues and as the vision is tested against engineering realities.

Yet this futuristic vision is seductive as it merges the previously apparently competing views of hydrogen and electricity and permits an evolutionary introduction of the new technology. Such a grand vision and large-scale energy system would require a commensurately large national investment. The costs of such an infrastructure could well reach the order of $1 trillion over 50 to 100 years, at an average rate of perhaps $10 billion a year using a combination of public and private funding. Staggering as these quantity are, it is well within the range of practical investments as the combined electric, natural gas and petroleum industries combined annual revenues approach $1,000 Billion.

Benefits of the Energy SuperGrid

What would be the benefits of the Energy SuperGrid? Will they justify a large national investment? In the history of technology, social structure has been significantly altered on a century time scale by the slow diffusion of new technological developments; for example, the steam engine, electricity, wire and wireless communication, internal combustion engine, jet engine, microprocessor, internet, etc. These are all enablers of technologies that led to social change. In a more modest way, a demonstrated SuperGrid might result in such change. The future energy sources will be a mix of old and new options. The SuperGrid concept may be a stimulant for new options. In opening remarks at the Workshop, Dr. Starr enumerated possible outcomes that may provide motivational background that flow from the operational character of the SuperGrid.

Minimizes virtual distance between source and load with a no-loss expandable power line.

On a large enough scale, the SuperGrid minimizes the distance constraint most notably between the east and west coasts. On a smaller scale it could connect regional transmission networks. It would thus provide a back-up supply for regional outages due to weather extremes, and similar unpredictable events. On a local scale, it permits the renewables to provide a SuperGrid feed that uses the time-load-flattening of the grid to compensate for renewable local and diurnal variations.

Hydrogen production by large-scale electrolysis.

The Energy SuperGrid supports the hydrogen energy cycle through large-scale hydrogen production by electrolysis, and large-scale hydrogen-based energy storage. An open technical question is the mix of gas pressure, and of normal or cryogenic temperatures. The energy pipeline may at times be only a gas pipe and at other times only an electric transmission cable. The extent to which electricity and hydrogen are mixed in the energy pipeline is a design variable to balance between providing cryogenic cooling to the superconductor and providing gaseous fuel. Growth of the hydrogen cycle will shape these operational decisions and the design parameters.

Energy storage and distribution with hydrogen gas.

Gas pressure and the phase change of gas to liquid provide energy storage. Such storage capability, combined with fuel cells, may allow electricity networks to shift to a delivery system approximating the commodity characteristics of oil and gas, away from the present instant matching of supply to demand. Storage also significantly enhances the role of intermittent sources such as solar and wind. For example, storage increases the stability of time-sensitive energy prices, both temporally and spatially. This may modify the economic market power of electricity suppliers.

Provides optimal application of nuclear power.

Nuclear power was assumed as the base case in the original concept. Nuclear is particularly attractive as an energy source for hydrogen due to the low incremental costs of the fuel. The SuperGrid provides an ideal application of its low cost fuel and its operational reliability at a constant power level. The nuclear plants can be run at constant power and produce hydrogen whenever the demand for electricity is lower than the plant output capacity. Within the next half century, the national demand for electricity is very likely to double or even triple if a significant portion of the energy used for transportation is transmitted by electricity. Nuclear has demonstrated its value by currently providing 20% of the U.S. electricity supply. The SuperGrid provides a platform for adding nuclear power to the future supply mix. These benefits would also apply to our large hydroelectric sources, but these are unlikely to grow. Obviously solar, wind, and other renewables would fit in the future, but for a variety of reasons may be limited both functionally and economically. All avoid greenhouse gas emissions and are independent of depletion fossil fuels.

Expands electrical solid-state power control.

From an electrical engineering view, many existing solid-state control configurations need to be explored for the management of a superconducting direct current system that requires very stable current and load adjustment by variable voltage. All this is feasible today, but the scale needed raises fresh requirements for converters and inverters. The historic competition between alternating and direct current systems at the local level may once again arise. The SuperGrid supports either choice. The competitive merits have yet to be explored.

Underground energy corridor and facilities.

Undergrounding the grid and the nuclear power plants is an intuitive choice. Its obvious disadvantage is cost of tunneling and underground construction. Less obvious, but very substantial may be the advantages of underground siting. These advantages may include reduced vulnerability to attack by nature, man or weather -- greater public acceptability due to physical removal from interference with normal surface activity. Undergrounding may reduce rights-of-way disputes, and reduce surface congestion, which is bound to grow; -- and finally, real and perceived reduced public exposure to real or hypothetical accidents. Thus official regulatory approvals may be less time consuming. Time delay to settle rights-of-way and public safety concerns is a very costly element of transmission line projects, so such savings may be large. Cumulatively, all these indirect benefits may be large enough to compensate for the additional costs of undergrounding the SuperGrid.

Common use of long-distance tunnels.

Separable from the Energy SuperGrid, but a possible valuable dual use, would be the eventual common use of the energy pipeline tunnels with underground high-speed transportation system using maglev propulsion. A common tunnel for energy and transportation is a speculative concept if a combustible fuel is transported in the common tunnel. For electricity and transportation systems it is technically feasible and well founded today.

Discussion of Workshop Presentations

Formal presentations were made during the workshop on many of the various technologies and technology platforms essential to the Energy SuperGrid. Each of these individual topics is discussed briefly in this section. For the purposes of this exposition, the order has been changed and some comments and information that was presented has been reorganized to better reflect the consensus of the Workshop. The actual workshop agenda is provided in Appendix A of this report, while a list of participants is provided in Appendix B.

Nuclear and Renewable Resources.

The original Energy SuperGrid concept was proposed as a future powered by nuclear energy. The workshop brought forward the role of modern renewables and "distributed energy resources." Distributed energy is any energy resource located at or near the point of energy utilization. In this context some renewables are suitable for distributed utilization near the load while others may be better sited at remote locations. Some workshop participants also emphasized the continued role for coal as a significant energy source.

Currently commercial nuclear reactors and other nuclear reactor design approaches that are not currently commercial such as Helium cooled reactors; avoid emissions of greenhouse gases and dependence on fossil fuels. Experimental "pebble-bed' reactors that use graphite encapsulated nuclear fuel have been proposed and demonstrated at experimental reactors. In the U.S, a variant of this technology was demonstrated in the early 1970's and a 300 MW reactor was constructed and operated. Such reactors brought to full commercial use, promise increased energy efficiency and fully passive safety in case of a loss of coolant.

Although many details of the engineering and operational details of such advanced nuclear power plants need to be fully developed, no scientific breakthroughs are needed and prototype units could be engineered and built today.

Of the renewable technologies, wind turbines are closest to economic competitiveness and are commercially available today. Yet, this energy resource is most significant in areas remote from load centers. Photovoltaics, on the other hand, can readily be located, as part of or on building, however, photovoltaics is still a future technology with respect to the economics of energy production.

In the mid-term, between now and 2050, both renewables and nuclear will become increasingly attractive technologies as the technical and economic challenges of both are reduced through further research and experimentation. Both categories of energy resources can be classified as non-polluting and "carbon free', yet both have radically different drawbacks and challenging economics.

What emerged from the discussion of nuclear power was the realization that the major issues with respect to safety can, and are, addressed by the new design paradigm of inherent, passive cooling in event of a loss of engineered coolant. The real issue for nuclear power is one of perception of the public and the excessive expense for more safeguards. These conclusions are relevant to both plant safety and waste storage and disposal. The economics of nuclear depends strongly on an educated public and a higher level of scientific literacy. Concerns over global warming, or the exhaustion of fossil fuels, are but additional arguments in favor of expanded use of nuclear.

Superconductivity

With the discovery of new superconducting materials in 1986, a new world of possible engineering applications of superconductors has opened. The question today is not if new superconductors will be available, but when will they be commercial and at what price and performance.

The leading U.S. firm has declared its Bismuth based superconductor as commercial and has recently demonstrated the first long length (ten meters) of production for a second generation superconductor. An alternative material, magnesium diboride (MgB_2), has shown promise and is some where in between in its state of development.

The critical differences between these materials are performance at higher temperatures and their manufacturing cost. For cable applications, both of the higher temperature copper oxide materials can be operated at liquid nitrogen temperatures while MgB_2 probably needs to operate at the temperature of liquid hydrogen.

The operating temperature makes a significant difference in the energy spent in cooling the cable system. It also makes a difference as to the potential synergism between superconducting cable and the transport of hydrogen. The original concept has the hydrogen being transported as a liquid that also serves as a coolant for the superconductor. If the superconductor can be cooled at liquid nitrogen temperatures, the need for liquid hydrogen is eliminated and the two intermediate energy forms could also be uncoupled in the “Energy Pipeline”.

Electric Power

From the perspective of electric power systems, what is the energy SuperGrid? The SuperGrid is a high capacity transmission network “overlay” over the existing electric grid. It would interface to the high voltage ac network only at the high voltage substations, but with very high levels of power being interchanged between the two. Hence the SuperGrid would have a significant impact on the current grid, with the interactions between the two an area for future study.

Of course the historical basis for the high voltage ac transmission grid remains intact. That is, sustainable resources remote from the primarily urban electric load centers require high voltage transmission. Some generation economies of scale lead to the need for regional sharing of power plants. Reduced transportation costs of high voltage dc provides an alternative to siting electric generators near the load centers and can combined with economies of scale in transmission (“coal by wire”) to make remote siting of power plants feasible.

The arguments that support the continental scope of the SuperGrid concept are straightforward. The SuperGrid can enable national-level competition, eliminate or greatly reduce market power, eliminate transmission bottlenecks or reduce the impact of bottlenecks and increase system reliability. The SuperGrid concept places emphasis precisely where it is needed, since little new transmission is being built today. There are economies of scale and lumpiness in the physical infrastructure of electric power. Markets don’t work well in these cases and market failure in construction of new transmission facilities translates into a tragedy of the commons.

The impacts, both negative and positive, of the addition of an Energy SuperGrid on the operation and planning of the current grid will require further study. Since the 1960’s some limited point to point dc transmission has been utilized in the North American electric power network, but at power levels below that envisioned for the SuperGrid. In some cases it has been used to benefit in the long distant transmission of power between regions. In other cases it has been used to connect neighboring systems while uncoupling these same systems “electro-magnetically”. A dc link between two ac systems can be operated to uncouple the two ac networks and avoid certain engineering complexities that would otherwise occur if the link was ac. DC links can also be used to preciously control the flow of power on the regional interconnection. With ac the power will flow as dictated by the normal rules of physics that dictate the power flows on ac networks. A dc link can be controlled independent of these laws of physics and precise control maintained over the power flows, now dictated by the contractual relationship and scheduled power by the operators.

In the perspective described above, the use of isolated dc links within a large ac system and between ac systems can be considered a mature technology that is well understood and engineered. However, the Energy SuperGrid raises new engineering questions since it could incorporate many dc links, each potentially having multiple inputs and outputs, and would incorporate lossless dc superconductors. Although the basic engineering of such a system was presented at the workshop, no real system operating at high voltages and power levels using lossless dc has actually been built.

A major challenge to the concept of the Energy SuperGrid is experimental verification and development of the engineering details of the power electronic interfaces and control systems for the dc SuperGrid. The consensus is that while no new scientific breakthroughs are required and the engineering fundamentals of ac to dc control are well known, there are still detailed engineering needs which need to be addressed. These engineering issues are one of the larger open engineering questions associated with the Energy SuperGrid.

In addition to these system issues for the large-scale dc and ac networks, there is the issue of distributed generation (DER). DER can offset local adequacy constraints. Grid security may also be enhanced through proper design and operation of DER. Safety considerations can be properly addressed and local voltage support, stability enhancement planning takes on a whole new dimension with DER. Hydrogen could provide the fuel for this DER. Grid utilization factors may decrease or increase. Indeed a major challenge is development of design and planning tools that can accommodate the simultaneous operation of the dual electric and hydrogen system.

At another level, the addition of a network of large power interregional dc links and grids may greatly relieve congestion on the existing ac system and permit precise control of regional transfers of power for economic benefit.

Hydrogen

Entire conferences and books have been devoted to the “hydrogen economy” since the late 1960’s when energy futurists first proposed the use of hydrogen, produced by electrolysis of water using electricity from nuclear plants. Today’s focus is on electricity from renewables, yet the original approach of nuclear electrolysis of water is still valid.

The underlying principle is simple and almost too obvious to mention – energy stored in chemical form is more compact in volume and weight then other forms for storing electric energy. Further if atmospheric oxygen is used to recombine the hydrogen into water the engineering and cost penalties of carrying the oxygen are eliminated and the hydrogen and atmospheric oxygen combine to form water, a closed, environmentally “benign” fuel cycle.

The workshop discussions revealed that hydrogen is in widespread use as a chemical feedstock and the engineering details of pipeline transmission and storage of hydrogen for stationary and chemical feedstock uses is a well established engineering reality. Furthermore, internal combustion engines have been run on hydrogen. Fuel cells for the electrochemical conversion to electricity have been in use for decades. The missing elements are not scientific feasibility but economic commercialization.

The overall sense from the workshop was that the use of hydrogen is today limited by the competition from conventional fossil fuels, which remain cheaper than the hydrogen alternative. It is fully expected that the hydrogen technology will come into use as scarcity or environmental constraints limit the use of fossil fuels and in particular, diesel and gasoline. Still major R&D investments remain to improve technical performance and reduce capital costs while improving energy conversion efficiencies.

For mobile or transportation fuels, hydrogen does create a particular challenge. Hydrogen exists as a gas, except at extreme pressures or cryogenic temperatures. Consequently, hydrogen is not the ideal chemical storage media for autos and truck applications where the volume and weight requirements are most severe. Cryogenic liquid hydrogen can be used, but with a consequent penalty in the energy needed for producing the cryogenic liquid hydrogen. New materials and means of storing gaseous hydrogen are under development and adequate storage densities may be achievable through these new methods using new materials.

Underground Construction and Tunneling

The workshop was treated to 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.

It surfaced that exploring the potential future prospects for this technology is a critical issue and could greatly alter the future economics of the underground portions of the SuperGrid. Little coordinated research seems underway and the evolution of the technology appears to come about very incrementally.

Environment

The environmental issues facing the Energy SuperGrid were presented in a comprehensive review and inventory. This underground aspect of the concept is of paramount importance and two distinct issues drive underground siting of the concept: minimization of environmental and aesthetic impacts, and increased security and reliability.

The consensus in the discussion of the environmental impacts is that there do not appear to be any new elements or environmental issues that have not been addressed in other projects of various types. Indeed, the sense is that the undergrounding of significant portions of the SuperGrid will ameliorate many environmental issues. Additionally, the emphasis on “carbon free” energy resources responds directly to the current concern over global climate change.

However, both of the energy resources, nuclear and modern renewables have environmental drawbacks or negative features. With nuclear it is the well known and understood challenge of nuclear waste and the public perception of plant safety. With the renewables it is the land area requirements to capture the diffuse energy resource, typically, land area requirement that in a global sense is not excessive but on a local level can lead to opposition or engineering difficulties and poor economics.

The Energy SuperGrid will require new assessment procedures that effectively address cradle to grave considerations over large spatial and long temporal scales. To meet the environmental assessment needs, we will need a technology development process for environmental effect/impact analysis that is as advanced as the scientific and engineering supporting the SuperGrid.

Energy Economics

The workshop presentations and discussion of economics was, of necessity, quite general and non-specific. Indeed, at this early stage in the development of the concept it may be premature to subject the concept to a strict scrutiny of engineering or energy economics. What is expected is that as scarcity and environmental constraints become more important the economics of the concept will improve. Similarly as the engineering development and research proceeds economics will improve.

A major issue in the workshop was the necessity of the subsurface or undergrounding of the nuclear power plants and SuperGrid itself. The sense was since this may add significantly to the cost, the environmental, reliability and security benefits needed to justify this expense need to be carefully examined. Yet it may be that this becomes not an engineering requirement but a social decision. Society has endorsed major engineering decisions long before the economics were proven. Such was the case of the New York City Subway, transcontinental railroads and the Interstate highway system.

Priority Issues Identified in Wrap-up Session

A principle conclusion of the workshop was that the vision rests on a set of technologies and technology platforms, and advancement in any or all of these technologies will make the concept more appealing. The final session of the workshop was a combination of a brainstorming session to identify the major issues of highest priority and a survey of R&D issues. Obviously these two tasks overlap and hence are not completely separable. The discussion and critical views on the most important issues are discussed briefly below. The full treatment of these issues will await a more detailed study of the vision and conceptual development of the essential elements of the Energy SuperGrid. The result of the survey of the participants on R&D issues is listed in Appendix C. A full exposition of all of these R&D issues will be the subject of a future Roadmapping.

Vision

The Vision as articulated in its original form needs to be broadened and developed in greater detail as is very general and preliminary. Future development of the vision and the various elements and alternatives are needed. A first step was taken in the workshop. With the inclusion of modern renewables and distributed generation from hydrogen into the vision the workshop took a first step in this direction.

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.

Field prototype experiments

Some of the technology platforms needed to implement the full vision of a North American Energy SuperGrid are already in commercial use while others are at early stages of development. A series of logical, scale-up experiments should be proposed and high value early applications of the various elements of the SuperGrid sought to accelerate future implementation at commercial scale.

Role of hydrogen fuel for distributed and mobile generation

The two intrinsic characteristic of hydrogen most often quoted by advocates is its inherent storability and clean combustion, with water as the only byproduct. This is contrasted with electricity and the pollution caused by its generation from fossil fuels. Indeed, the storage of electricity is difficult, indeed it requires the conversion of electricity to another from and later re-conversion to electricity for most uses.

However, hydrogen is not a primary energy resource itself; it needs to be either extracted from a fossil fuel such as hydrocarbon or electrolyzed from water using electricity. In some cases the conversion of electricity to hydrogen and back to electricity makes sense, in other cases the electricity is best used directly or stored in another form such as a battery. Each particular case requires its own engineering performance/coast trade-off.

Based on the current understanding of the competition between these energy forms it seems obvious that hydrogen will be more useful in some applications and electricity more useful in others. That is, these energy forms complement rather than compete with each other.

Synthesis and integration of future electricity – Hydrogen Economy: “Hydricity”

Advocates of the “Hydrogen Economy” are creating an artificial divide between future electrification and the use of hydrogen as an alternative energy form. Neither electricity nor hydrogen are primary energy resources. Rather each is an intermediate energy form with very different characteristics. Both are energy forms that can be “zero emission” at the point of use. Hydrogen may emit limited emissions at the point of production and use, depending on the conversion technology used. By seeking a synthesis between these two forms of energy in routine societal use, the best features of both can be utilized.

Grand Challenge Project

With the success of the early experimental projects in hand, a “Grand Challenge” project should be identified. This project should be bold and directed at an early realization of the vision in a particular site-specific application where the benefits would be large and the challenge realistic and achievable. A budget in the hundreds of millions will be necessary to show practical application at a scale that will convince the skeptical.

Findings and Recommendations

The general findings and recommendations from the workshop are presented below. However, these items must be interpreted within the workshop perspective of looking at addressing energy needs on a time scale of fifty to a hundred years. With this timeframe as a premise the following can be drawn from the workshop deliberations.

Findings

- No scientific breakthroughs are needed to achieve the reality of the Energy SuperGrid, yet major technological innovations will be required to minimize environmental effects and maximize economic and societal benefits.
- DC, high power superconducting power transmission should become a viable technology that can be integrated with the existing ac power grid.
- Nuclear energy and the modern renewables are the only known resources that can power society for the centuries ahead when fossil fuel use will be limited as a result of either scarcity or ecological and environmental impact. However, other fuels, such as coal, will continue to be important sources of energy for many decades and could certainly be incorporated into an Energy Supergrid.
- Nuclear energy and certain of the modern renewables are inherently remote sources for energy intensive uses. As such, both require conversion to an intermediate energy form for transport to distant loads. Electricity has shown its ability to serve as an intermediate energy form and hydrogen offers the promise of being a compatible partner in a future energy infrastructure
- Distributed generation in the forms of fuel cells and other hydrogen powered engines and distributed renewables, used close to the loads, have definite applicability to complement grid supplied electricity
- The critical requirement for a secure energy infrastructure and minimization of environmental and societal impacts leads to an obvious preference for subsurface of underground siting of critical energy infrastructure elements.
- 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.
- A progressive program of experimental engineering facilities, proving engineering feasibility and identifying opportunities for improving economics, needs to be developed. This program needs to be developed within the framework of a set of alternative future scenarios – akin to a technological roadmap, yet providing flexibility in redefinition of specific goals and the future balanced blending of electrification and hydrogen infrastructures appropriate for a research effort that may span a century

Recommendations

- 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, amperes and thousands of volts) needs to be undertaken.

- The overall Energy SuperGrid R&D program needs to pursue several technological platforms in parallel along with a systems engineering-economics effort that integrates and cuts across the technology platforms. These parallel path R&D efforts include:

  - Development and commercialization of essential superconducting technology
  - Large capacity dc electric transmission, including all of the supporting technologies such as ac-dc conversion, control systems, cryogenics, etc.
  - Continued investigation of the interaction between the existing ac transmission grid and the proposed SuperGrid.
  - Development of improved hydrogen production, transmission, storage and utilization as an alternative energy form for transport and storage
  - Continued focus on highly efficient electrification of the current direct fossil fuel utilization and continued improvements in efficiencies of the use of electricity.
  - Renewed vigor in a nuclear energy development program focused on a significant step forward in efficient resource utilization and reduction in capital costs while increasing the inherent safety of the entire fuel cycle.
  - Continued support for research in renewable energy to assure achievement of future cost reductions and improvements in efficiency of resource utilization.
  - A focused program on rapid and economic construction of tunnels and underground space to yield significant rewards in lowering costs.
  - Full accounting of the benefits of undergrounding facilities that may balance the obvious cost premium with high value from security and reliability. This is true for siting of major energy conversion facilities as well as for the "energy pipelines" of electricity and hydrogen.

- Following the practical demonstration of engineering feasibility, which for this concept might be considered a pilot scale, a series of real world, field experiments should be pursued with physical distances of first kilometers and then tens of kilometers.

Appendix A: Workshop Agenda

Wednesday, November 6

Session 1	**Overview and Concept**
14:00-14:45	Overview Presentation (Chauncey Starr)
14:45-15:45	Discussion
15:45-16:15	Break
Session 2	**Superconductivity**
16:15-16:45	Overview Presentation (Paul Grant)
16:45-17:45	Discussion

Thursday, November 7

Session 3	**Electrical**
08:30-09:00	Overview Presentation (Fernando Alvarado)
09:00-09:45	Discussion
Session 4	**Nuclear**
09:45-10:15	Overview Presentation (Jim Stubbins)
10:15-10:45	Break
10:45-11:30	Discussion
Session 5	**Hydrogen**
11:30-12:00	Overview Presentation (Bob Schainker)
12:00-12:45	Discussion
Session 6	**Underground**
13:45-14:15	Overview Presentation (Ed Cording)
14:15-15:00	Discussion
Session 7	**Energy Economics**
15:00-15:30	Overview Presentation (George Gross)

15:30-16:00 Break

16:00-16:45 Discussion

Session 8 System Integration/Control/Security

16:45-17:15 Overview Presentation (Bob Lasseter)

17:15-18:00 Discussion

Friday, November 8

Session 9 Environmental

08:30-09:00 Overview Presentation (Ed Herricks)

09:00-09:45 Discussion

09:45-10:15 Break

Session 10 Future Research Directions

10:15-10:45 Overview Presentation (Tom Schneider)

10:45-11:30 Discussion

Appendix B: Workshop Participants

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Appendix C: R&D Issues Identified by Workshop Participant Survey

Programmatic

- SuperGrid vision and concept is major innovation in thinking about energy delivery and transmission. Concept needs to be developed further to become a credible approach. Need to explore order of magnitudes of energy flows, security and reliability and possible benefits to justify program and make vision more realistic. Program strategy that incorporates near-term small-scale implementation – experimentation and demonstration is desirable.
- Assemble high-level coordinating group to facilitate development of a National Program to start the planning of a National SuperGrid Program
- Propose and gain federal funding of SuperGrid Program. May focus on coordination of multiple program elements ongoing at DOE and elsewhere.
- Explore potential for kWh tax for funding of advanced research and SuperGrid
- Undertake a survey of best locations of various scale demonstrations in US. An example would be to Consider a demonstration project across SF Bay
- Develop a communications plan that should be focused on how to establish support for concept.
- Keep rail transit and Maglev separate from SuperGrid concept as this time as rail is difficult to justify in and of itself.

Roadmapping

- The SuperGrid concept is a long-term vision, which needs roadmaps with a long-term perspective for development and implementation. The SuperGrid concept also needs to be integrated into broader view of society and the economy in2050.
- The Roadmapping needs to study the trade-off between electricity and hydrogen in the SuperGrid concept. As the concept and many elements of the individual technologies are in early stages of development, the Roadmapping needs to be more "Lewis and Clark" and less "Cooks tour".

Systems

- Study reliability and the technical and economic characteristics of SuperGrid, new tools to visualize and analyze this concept on a systems level will be needed and could provide information to address the spatial and temporal scale of SuperGrid. Develop tools and data to "vision" the future of SuperGrid and its evolution over time. Understanding social-technical dynamics – how to incorporate new ideas into current practice New modeling techniques to address the social dynamics may be helpful in examining a concept targeted at 2050 and beyond.
- Further development of conceptual approach and rough estimates or targets for economics and engineering design. Parametric analysis of Super rid technical and economics is needed. Examine the potential benefits of hybrid superconducting -- conventional ac system. Parameters to explore include needed storage, proportion of

superconducting dc to conventional ac, robustness and reliability criteria. Develop basic engineering parameters such as total flows of hydrogen needed, energy transfer capability of various hydrogen pipe designs etc.

- Investment incentives for energy infrastructures need to be examined and new business model developed as the current deregulation has brought investment in delivery infrastructure to a very low level.
- Reliability and security needs evaluation and cost/benefit. The benefit may well be larger than anticipated at this early stage. Physical security, benefits and value as well as estimates of differences between conventional systems and SuperGrid
- Examine electricity – hydrogen alternatives in a scenario process and take approach of flexibility for alternative outcomes of scenarios. Balance between electricity and hydrogen needed in society. Substitutability of electricity and hydrogen and relative size of hydrogen and electricity "pipes"
- Systems control will be needed to effectively integrate the SuperGrid into existing networks. Concepts to cover include adaptive sharing of power, network robustness and hierarchical control techniques.
- Superconducting transmission with nitrogen cooling and separate hydrogen pipelines is major alternatives as is a hydrogen only pipeline with distributed generation.
- Detailed study of an overlay of high power SuperGrid on conventional system
- Comparison of technical and economic trade-off for above ground installation vs. underground Energy SuperGrid, again the benefits need to be explored carefully as there may be social benefits that need to be internalized or accounted for in new ways.

Energy Pipe

- Need to do conceptual designs of nodes in electric and hydrogen connections, terminations, splices etc.
- Electrical engineering systems needs to examine scale of Energy Pipe relative to system security and reliability
- Research and development of the integrated hydrogen transport, cryogenic and electrical properties for conditions anticipated in the Energy Pipe will be a significant engineering challenge.
- Develop necessary coatings, materials, grounding systems, splices for cables and joints for cables, piping and terminations for both gas and electric.

Superconductors

- Superconductor progress has opened the path for the SuperGrid. We should expect the unexpected and anticipate further advances and breakthroughs that will lead to system level improvements.
- Demonstration of cost effective manufacture of HTS cables is needed early in the program, but effective manufacturing cost projection may be possible even without full manufacturing capabilities in place.
- Critical design issue is the choice between hydrogen cooling and nitrogen cooling in both temperature and liquid and gas. This also reflects the uncertainty over the choice of the superconductor. These design choices should not be made too early.
- Control of superconductor networks with multiple terminals

- Lab tests of DC superconducting loops interacting with control systems and multiple energy inputs and output locations exploring alternative concepts of monitoring and control of DC loops.
- Develop a 1000 MW demonstration project

Hydrogen

- Hydrogen is a major subject of investigation with a modest government program and considerable private sector funding. The subject is very large and includes production, transportation and utilization. It could not be dealt with in sufficient depth in the workshop.
- Investigate DTE concept of Power Hydrogen. Investigate DOE funding of Hydrogen programs. Hydrogen application focus may be on transportation. Consider test of Hydrogen/superconductor mini grid and the hydrogen-electricity interface.
- Design and develop high-pressure electrolyzer and compatible fuel cell for use with SuperGrid. Hydrogen production techniques today are well understood, but the technology is expensive. R&D on technology for production of Hydrogen, cost, efficiency, feasibility)
- Hydrogen as a transportation fuel is a major theme of the proponents of the "hydrogen economy". Commercial demonstration of fuel cells or IC engines for mobile applications is needed/
- High-density (by both volume and weight) storage of hydrogen is a major challenge for transportation applications in personal vehicles.
- Cost, safety, security of tunnels with cryogenic hydrogen, etc
- Exploration of possible benefits and pitfalls of thermo-chemical hydrogen production

Renewables

- Photovoltaics are high priority with high efficiency, long life, low cost and distributed on buildings.
- Wind power is generally considered as commercial technology but is still more expensive then alternative fossil fuel systems.

Nuclear

- Alternative waste disposal and fuel processing approaches for large-scale use of nuclear merit renewed R&D. Include complete nuclear fuel cycle and waste management and reprocessing
- Design and demonstration of affordable nuclear plant designs is needed. Fail safe and cost effective nuclear is essential
- Development and licensing of standardized plant design is crucial to future economics.

Environment

- Complete exploration of environmental issues and minimization of environmental impacts.
- Implications of hydrogen use vs. Co2 emissions

- Water issues, supply, water table etc.
- Proactive investigation of environmental issues with community

Electric Power

- Topology of SuperGrid system needs to be examined in conjunction with integration into conventional systems. This will require significant extension of existing tools and computer models.
- R&D on electric energy storage with low cost, high efficiency and a desirable charge/discharge characteristic remain a continuing need.

Tunneling

- Under grounding is not obviously an essential feature and is a high cost element, especially if maintenance and access are needed and redundant "energy piles' are needed for reliability and security. Experimentation and demonstration more easily carried out with above ground facilities.
- Small diameter tunneling seems nearly economic but reliability may require large man accessible diameter tunnels. Small diameter (up to four feet?) rapid tunneling with small crew and low cost techniques is currently practiced over relatively short distances. Tunneling and escalation techniques with small crew and ability to deal with rock and soils below water table are critical to lower costs. Need robust designs and long life in machines for boring and tunneling. Link with new drilling techniques in oil and gas production. Cost reductions and development of low cost approaches may well be possible, the full potential of the technology and future costs is not well developed. Long distances at low cost is essential development objective
- Evaluate lower cost smaller diameter tunnels where needed as an alternative to large diameter tunnels. Depend on distributed sensors along tunnel facility as substitute for human inspection. Utilize advanced communications and sensors to pinpoint location of problems. Utilize robotics for maintenance and repair. Utilize vertical tunnel access to make necessary repairs when needed.

Power Electronics

- Control of large network of superconducting loss-less lines. (Stability, frequency, short circuits) with multiple terminals is as yet an untested technology. This requires early experimental development and testing of control concepts.
- Developments of high power electronics for ac/dc interfaces with lower cost, low losses, very high power, and modular construction.