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Program on Technology Innovation

The Hydrogen-Electric Energy SuperGrid

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An EPRI White Paper

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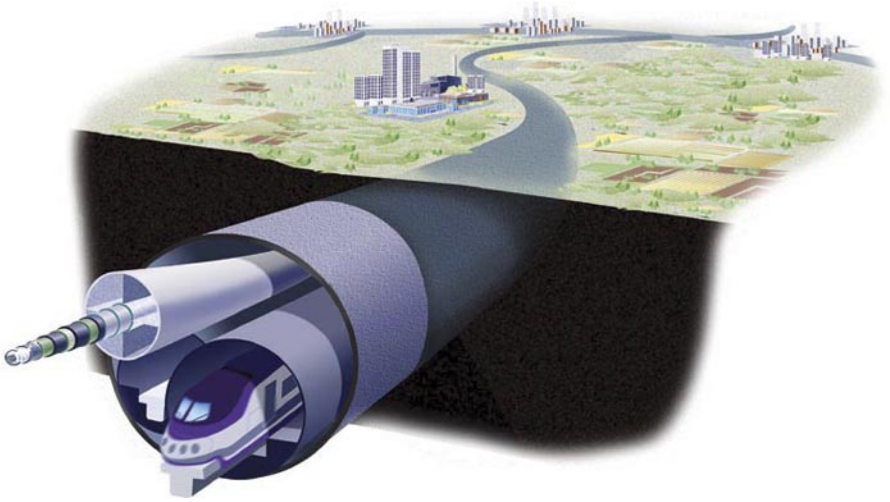
Introduction

The ultimate "holy grail" of long-range planning for national energy independence is an energy supply based on indigenous primary fuels, in an environmentally "green" system, and at an attractive cost.

The proposed SuperGrid would be a major step toward this independence goal. The system would deliver electricity and hydrogen over long distances with minimal losses.



Long-range energy planning faces several challenges and uncertainties. It is unclear today what U.S. electric and transport fuel systems will be needed 30 to 40 years from now. To date, energy planning has resulted in a mixture of programs focused on a scattering of deserving goals. A basic problem is that we don't know today how our long-range goals and priorities will shift in the coming decades.

One fundamental challenge is the ability of the country's energy systems to keep pace with growth. The continuous electrification of our homes and businesses, and a modest population growth, will result in about a 2% annual growth in electricity demand. If electrification of a fraction of our transportation becomes a reality, either directly or indirectly, the growth will be much larger. An annual growth of 2% will double U.S.

EXECUTIVE SUMMARY

To effectively supply this country's energy needs 30–40 years in the future, we must begin today to identify and implement imaginative solutions that will allow us to meet increasing demand while solving critical environmental, reliability, and security challenges.

A visionary energy system known as the SuperGrid is one such solution.

The core concept of the SuperGrid is a coast-to-coast, underground electric transmission line. Electricity would be supplied by advanced nuclear reactors, spaced along the transmission line corridor. The line would consist of a high-capacity, direct-current, superconducting power transmission cable. In addition to electricity, it would carry hydrogen supplied by the nuclear plants to cool the superconducting cable. Excess hydrogen produced by these plants would be available for commercial use in local energy markets. Load centers across the country could withdraw electric power and hydrogen as needed. The SuperGrid would supplement, not replace, the existing regional gas and electric grids now in place. The SuperGrid would produce no greenhouse gases, would use domestically derived fuel, and would be relatively invulnerable to natural or man-made catastrophic events.

While the components of the SuperGrid are feasible, each will require extensive research, development and engineering demonstration to reach the stage of commercial operation. To achieve this goal, EPRI proposes a broad-based national collaboration consisting of university engineering graduate programs, national laboratories, and the utility industry. A key feature of the program is that progressive efforts begun now will have a near-term payout in a variety of applications other than the SuperGrid, yet will advance the state of the technology so that an integrated SuperGrid system will be ready to meet the energy needs of our society by mid-century.

electricity usage by mid-century. As it has in the past, the electric utility system will find a way to meet such growth, but such forced network growth may not achieve the greatest economic and performance efficiency.

Other challenges involve environmental and reliability issues. The environmental consequences of increased fossil fuel use are of continuing concern. The ability of the national electrical grid to develop a fault-proof interconnection system has not as yet been demonstrated. Vulnerability to natural weather events, inadequate infrastructure, and malicious terrorism may increase as the system grows. Finding rights-of-way for new power lines has become a major permitting obstacle. Finding cooling water for power plants is becoming a physical obstacle. Solar and wind are intermittent and very costly and unlikely to ever supply more than 10–20% of the real end-user electrical demand.

In the face of these challenges, what is needed is an imaginative long-range vision of our national energy future.

Vision

The SuperGrid concept is a visionary energy system that combines subsystems known today to meet many of the above challenges. The feasibility of the SuperGrid subsystems has been considered at two national workshops and deemed achievable, although each subsystem requires extensive research, development, and demonstration (RD&D) to reach the stage of engineering demonstration.

The core concept of the SuperGrid is a coast-to-coast, underground electric transmission line, consisting of a high-capacity, direct-current (dc), superconducting power transmission cable. Electricity would be supplied by advanced nuclear reactors, spaced along the transmission line corridor. In addition to electricity, the nuclear plants would supply hydrogen needed to cool the superconducting cable. Excess hydrogen produced by these plants could be available for commercial use by local industrial consumers. Load centers across the country could withdraw electric power and hydrogen as needed. The SuperGrid would supplement, not replace, the existing regional gas and electric grids now in place.

(See the sidebars for more detail on each of the subsystems.)

SuperGrid is environmentally “green.” It utilizes the applied science knowledge of superconductivity to implement large power-carrying capacity over long distances. The power transmission will be in underground tunnels for reduced vulnerability. These tunnels are also intended to carry liquid hydrogen, both as refrigerant and fuel.

Hydrogen would come from a chemical catalytic process or from high-temperature electrolysis of water (other methods may become attractive in the future—see sidebars). The hydrogen produced can be stored in the pipeline, providing the equivalent of many millions of kilowatt hours of storage, convertible to electricity on demand. The balance between electricity and hydrogen can be adjusted as the end-use mixture develops. The flexibility would allow for a continental east-to-west load leveling of electric power demand arising from the three-hour time difference across the country’s time zones.

Electricity can come from any source, but SuperGrid is proposing dedicated nuclear power plants spaced along the SuperGrid, augmented by other nearby nuclear plants as necessary to support increased demand for electricity along the SuperGrid. Nuclear plants are proposed for SuperGrid for a number of reasons, including:

- Demonstrated high levels of safety, environmental protection, and reliability. Nuclear plants don’t produce greenhouse gases or other environmental pollutants.
- Low cost. With indigenous, stable, and low-cost fuel supplies, nuclear energy enjoys the lowest production costs in the United States today. Increased environmental controls on fossil fuels would give nuclear energy further cost advantage.
- Capacity to expand rapidly as an energy supply option for application in all regions of the country—a prerequisite for support of a nationwide SuperGrid. Technologies are available that would allow nuclear plants to operate virtually anywhere in the United States, including arid regions with minimal cooling water supplies.

Because of their unique ability to efficiently produce hydrogen, the proposed high-temperature gas-cooled nuclear plant designs, being evaluated by the “Generation IV” Program of the U.S.

Department of Energy (DOE), are the logical choice for the dedicated plants in this application. Advanced Light Water Reactors located nearby would serve as backup supplies for additional electric power.

RD&D

The challenge that the SuperGrid system faces is the RD&D required to move from evident feasibility to demonstrated commercial operation. The staging of progressive steps in the SuperGrid during the coming three decades will be shaped by the engineering of its subsystems, and the RD&D of its more advanced components.

The key hurdle to be overcome will be the cost-effective design of long-distance, underground dc superconducting cables. Such cables will interconnect widely-spaced conventional alternating current (ac) electrical distribution substations, using electronic interface equipment (ac/dc converters) to change the direct current flowing in the cable to alternating current used by consumers.

Each of the advanced subsystems of SuperGrid requires RD&D, starting now and spread over several decades, so as to be operationally available when our national electricity grid will realistically be ready to absorb them. The time-clock for major use of new energy options runs in half-century units. This suggests that time is available for the SuperGrid RD&D to match end-use needs that will have grown to challenge our power systems in 30–40 years.

An important aspect of the SuperGrid concept is that its integration achieves new efficiencies. Equally, the development of each of the subsystems has application in a variety of future options other than SuperGrid. Examples include: the routine production and handling of hydrogen for energy storage; a large hydrogen distribution system; the reliable use of superconductivity for high-power transmission; low-cost undergrounding and tunneling techniques; the environmental benefits of nuclear power, including its spent fuel handling; and electrical control of mixed dc/ac systems that can smoothly mesh with existing local and regional networks.

Role in National Energy Planning

We propose that national strategy planning include support for demonstrations of the subsystems that are not currently commercially available. If we do nothing, the capital commitment pressures on our electrical utilities will produce an “in-the-box” expansion of today’s proven systems, as is already happening. These commercial plants provide defensible real-time choices, but will leave us with patchwork capital commitments for the coming half-century. This is not the equivalent of long-range planning. Tweaking our present systems will not achieve the long-range environmental and performance goals that we must meet.

If there is to be an effectively sophisticated direction of technical policy, it will have to come from engineering and the energy community. We cannot expect leadership on century-long planning from our government political process or market-based processes alone. The historical lesson is that the electrical utilities must be committed and active in long-range planning.

Management and Administration

The scale and duration of RD&D suggest that SuperGrid will need a multi-stakeholder collaboration. This White Paper seeks to initiate such collaboration. A collaboration of three principal groups is proposed: (1) university engineering graduate programs; (2) national laboratory hardware development and pilot plant demonstrations; and (3) utility industry trials of subsystems in plant operations.

Fortuitously, an initial framework has recently been created by the DOE in the formation of the new Idaho National Laboratory, or INL (merging Idaho National Engineering and Environmental Laboratory and Argonne National Laboratory-West). INL, which became official in February 2005, has been given the responsibility for managing collaborative projects such as the SuperGrid. Battelle Energy Alliance (which includes the Electric Power Research Institute) has the contract to administrate its operation.

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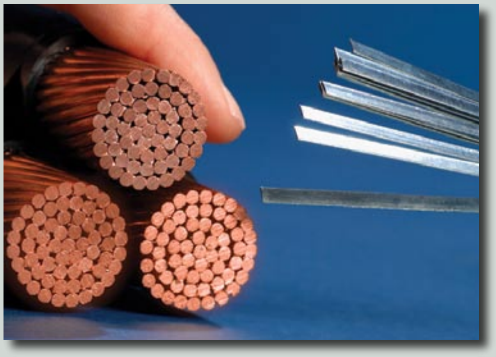
SuperGrid Components

The SuperGrid concept is an assembly of advanced engineering options intended to be used together—their integration has the potential to achieve valuable synergies—or as subsystems that could also be employed individually in other advanced power systems.

Superconducting Cable

At the heart of SuperGrid is the "SuperCable," a superconducting power transmission cable with the additional capability to transport and store hydrogen. The passage of electric current in usual conductors such as aluminum and copper produces heat and energy loss because the electrons responsible for the current continually "rub" against the atoms of the metal. A superconducting material, on the other hand, under certain circumstances is able to carry electricity without any resistance, and, in principle, would prove ideal to use for the lossless transmission of electric power.



Copper Wire and Superconductors (photo courtesy AMSC)

The phenomenon of superconductivity was discovered in the early twentieth century, and, in fact, several prototype superconducting power cables were built and successfully tested in the 1970s and 1980s. The principal difficulty facing widespread deployment of such cables at the time was the necessity to cool superconductors to temperatures near absolute zero in liquid helium (4.2 K) in order for them to have lossless properties. Today, superconductors are used primarily for powerful magnets in MRI machines and large particle physics laboratories.

However, in 1986, a Nobel Prize-winning discovery was made by two IBM scientists of a new class of superconductors, which would work at temperatures well above 100 K. These higher temperatures permit the use of much more efficient and less costly refrigerators. Moreover, simpler and easier-to-handle cooling fluids, such as liquid nitrogen (or hydrogen), can now be employed to operate superconducting transmission cables. More than a dozen prototype projects are presently under way worldwide, and insertion of superconducting cables into the grid by utilities is expected by the end of this decade.

Direct and Alternating Current Flow

Electric power is the product of current (the flow of a given number of electrons) times voltage (the "pressure" on the electrons). Since electrification began, there have been two methods of transmitting power over wires from its point of generation to its point of use: by "direct current" or by "alternating current." Direct current (dc) flows in a constant magnitude driven from a constant voltage, and was applied by Thomas Edison to "light up" downtown New York City in the 1880s. However, in the absence of an economical means to increase the voltage, increasing loads require an increasing current flow. In a dc circuit, losses are proportional to the square of the current, so increasing currents soon lead to significant loss of power along the lines—power that never reaches the customer. That was the situation in Edison's day, so dc power transmission did not catch on.

The modern electric power system installed worldwide was invented by Nikola Tesla, at about the same time as Edison's efforts. It employs alternating current, (ac), which continuously changes its magnitude and polarity and is driven by a voltage of changing magnitude and polarity at regular intervals (in the United States, this is 60 times a second). Ac has the advantage that power flow can easily be controlled by raising and lowering its voltage through a device called a transformer, also invented by Tesla. Thus, more power can be sent at the same current, keeping the heat losses the same, simply by raising the voltage with a transformer.

However, there are limits in distance for ac power transmission as well. The continuous charging and discharging of an ac underground cable, as the voltage goes back and forth, limits their practical distance to 15–30 miles. And, over very long distances of several hundred miles, even high-voltage overhead ac transmission lines have significant electromagnetic losses.

In such circumstances, a return to dc becomes attractive. Fortuitously, over the past 50 years, semiconductor switching devices have been devised that can change high ac voltage into high dc voltage, and vice versa. However, these "ac/dc converters" add significant expense, and "high-voltage dc transmission (HVDC)" is only employed when it is the least-cost solution, such as transmission from remote hydroelectric generation sources.

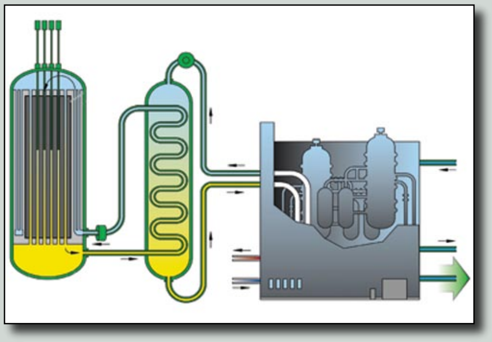
As mentioned, superconductors have the advantage of carrying enormous amounts of current without losses. This property only exists for dc. For ac, there are small losses arising from the motion of internal magnetic fields. Even so, these losses are three to four times less in a superconducting cable than for a copper cable of the same physical size, thus making ac superconducting cables practical for new and replacement urban underground transmission systems.

ABB's HVDC Valve (photo courtesy ABB)

On the other hand, at the power levels and corridor distances envisioned for SuperGrid, low-voltage, high-current dc (and thus truly lossless) cables provide the most practical and efficient means for electricity transmission, and will more than justify and offset the cost of the ac/dc converter stations required.

Nuclear Plants

The proposed generation source for the SuperGrid is a series of high-temperature nuclear power plants capable of generating electricity and hydrogen. Such plants may be based on any of a variety of advanced nuclear technologies under consideration by industry, under safety review by the Nuclear Regulatory Commission, or under DOE investigation. Due to the high capital cost of large power reactors, the plants will likely take advantage of design standardization, including the option for modular construction. These units are anticipated to have greater simplicity of design, economy of mass production, and reduced siting costs.



Very-High Temperature Reactor—An Advanced Nuclear Reactor (courtesy U.S. DOE)

Among the developing technologies, one promising design is the High Temperature Gas-cooled Reactor (HTGR), which is being developed in several countries outside the United States, including South Africa, China, Germany, Great Britain, Japan, and Russia (Grant 2002, p. 23). The recent passage of the Domenici-Barton 2005 Energy Act provides authorization for an HTGR development program at the Idaho National Laboratory (INL). HTGRs use hot (800–900°C), high-pressure helium gas heated by passage through the fissile core to drive either a turbine connected to an electric generator, or a process heat plant capable of generating hydrogen. These plants have important passive safety features. They can be designed to dissipate excess heat by passive convection and conduction to the surroundings, and a pyrolytic graphite and silicon carbide shell protects the elements to temperatures up to 1600°C.

Hydrogen

Hydrogen has been produced and used for industrial purposes for more than 100 years. Much research into hydrogen production methods is currently under way. Policymakers and the technical community are exploring approaches to use hydrogen as an energy carrier that complements electricity. Both hydrogen and electricity are clean at the point of use, are easily converted to one another, and can be derived from a variety of domestic energy sources.

In the SuperGrid, hydrogen could play three roles: as a cooling medium for the superconducting cables, as an alternative end-use fuel (primarily for vehicles), and as an energy storage and transport medium. Hydrogen would be produced by using some of the electricity from the nuclear plants, when the need for electricity is low, to electrolyze water into hydrogen and oxygen. (Because of the large electricity requirements of electrolysis, today's methods of hydrogen production mostly use natural gas and chemical cycles that produce carbon dioxide (CO_2) as a byproduct. However, the high temperature available from an HTGR can be used to thermally split the water molecule, thus providing hydrogen without producing CO_2. INL is exploring a "hybrid" HTGR design that would make both electricity and hydrogen.) The hydrogen would be transported to load centers through the SuperCable, either in liquid or as cooled high-pressure gas, stored until needed both in the cable itself or at hydrogen depots near load centers, and then converted back to electricity in a distribution network or burned as a fuel in vehicles or stationary burners.

The ratio of electricity to hydrogen is adjustable to end-use demand (energy is delivered via the SuperCable to the end-user as either electricity or hydrogen—or both—in a ratio that accommodates the end-user's need).

Undergrounding

Locating the SuperGrid underground would enhance public acceptance, avoid right-of-way issues, and reduce vulnerability to lightning, wind, and terrorist attacks.

Historically, installing underground transmission systems has been costly, and used only in urban areas where overhead lines are not possible. However, in the past 30 years, power companies seeking to install overhead power systems have also begun to incur large cost increases due to permitting requirements and public and political opposition. The resulting time delays, legal processes, and environmental opposition have significantly multiplied engineering estimates. Such indirect costs may increase with time. In contrast, the public has been increasingly accepting of the additional costs of underground power delivery given its clear environmental and aesthetic value.

Underground tunneling has steadily become less costly, and worldwide demonstrations of new techniques offer promise of continuous cost reduction. Tunnels, of course, have a long lifetime, and thus offer an opportunity for innovative public financing—like building a subway or bridge. This obviously is a site-specific cost element, with a civic investment component. In the decades ahead, undergrounding may become the least-cost means of providing space for energy delivery systems, as it now does in many urban utility settings. This may also eventually become the case for nuclear power plants as well. A recent review of both old and new ideas on undergrounding such facilities has been published in *Nuclear News* (Myers and Elkins 2004). Expanding on their concept will require significant advanced construction engineering R&D in order to bring about its realization.

Cutter Head of State-of-the-Art Tunneling Machine (photo courtesy E. Cording, University of Illinois–UC)

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EPRI web site: http://www.epri.com/supergrid/default.html

UIUC web sites on national SuperGrid Workshops—I and II:
http://www.supergrid.uiuc.edu/sg1
http://www.supergrid.uiuc.edu/sg2

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Together…Shaping the Future of Electricity

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