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A Power Grid for the Hydrogen Economy

Cryogenic, superconducting conduits could be connected into a "SuperGrid" that would simultaneously deliver electrical power and hydrogen fuel

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On the afternoon of August 14, 2003, electricity failed to arrive in New York City, plunging the eight million inhabitants of the Big Apple--along with 40 million other people throughout the northeastern U.S. and Ontario--into a tense night of darkness. After one power plant in Ohio had shut down, elevated power loads overheated high-voltage lines, which sagged into trees and short-circuited. Like toppling dominoes, the failures cascaded through the electrical grid, knocking 265 power plants offline and darkening 24,000 square kilometers.

That incident--and an even more extensive blackout that affected 56 million people in Italy and Switzerland a month later--called attention to pervasive problems with modern civilization's vital equivalent of a biological circulatory system, its interconnected electrical networks. In North America the electrical grid has evolved in piecemeal fashion over the past 100 years. Today the more than $1-trillion infrastructure spans the continent with millions of kilometers of wire operating at up to 765,000 volts. Despite its importance, no single organization has control over the operation, maintenance or protection of the grid; the same is true in Europe. Dozens of utilities must cooperate even as they compete to generate and deliver, every second, exactly as much power as customers demand--and no more. The 2003 blackouts raised calls for greater government oversight and spurred the industry to move more quickly, through its Intelli-Grid Consortium and the Grid-Wise program of the U.S. Department of Energy, to create self-healing systems for the grid that may prevent some kinds of outages from cascading. But reliability is not the only challenge--and arguably not even the most important challenge--that the grid faces in the decades ahead.

A more fundamental limitation of the 20th-century grid is that it is poorly suited to handle two 21st-century trends: the relentless growth in demand for electrical energy and the coming transition from fossil-fueled power stations and vehicles to cleaner sources of electricity and transportation fuels. Utilities cannot simply pump more power through existing high-voltage lines by ramping up the voltages and currents. At about one million volts, the electric fields tear insulation off the wires, causing arcs and short circuits. And higher currents will heat the lines, which could then sag dangerously close to trees and structures.

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It is not at all clear, moreover, how well today's infrastructure could support the rapid adoption of hybrid vehicles that draw on electricity or hydrogen for part of their power. And because the power system must continuously match electricity consumption with generation, it cannot easily accept a large increase in the unpredictable and intermittent power produced from renewable wind, ocean and solar resources.

We are part of a growing group of engineers and physicists who have begun developing designs for a new energy delivery system we call the Continental SuperGrid. We envision the SuperGrid evolving gradually alongside the current grid, strengthening its capacity and reliability. Over the course of decades, the SuperGrid would put in place the means to generate and deliver not only plentiful, reliable, inexpensive and "clean" electricity but also hydrogen for energy storage and personal transportation.

Engineering studies of the design have concluded that no further fundamental scientific discoveries are needed to realize this vision. Existing nuclear, hydrogen and superconducting technologies, supplemented by selected renewable energy, provide all the technical ingredients required to create a SuperGrid. Mustering the social and national resolve to create it may be a challenge, as will be some of the engineering. But the benefits would be considerable, too.

Superconducting lines, which transmit electricity with almost perfect efficiency, would allow distant generators to compensate for local outages. They would allow power plants in different climate regions to bolster those struggling to meet peak demand. And they would allow utilities to construct new generating stations on less controversial sites far from population centers.

For moving tens of gigawatts over hundreds of kilometers, perfect conductors are a perfect fit.

SuperGrid connections to these new power plants would provide both a source of hydrogen and a way to distribute it widely, through pipes that surround and cool the superconducting wires. A hydrogen-filled SuperGrid would serve not only as a conduit but also as a vast repository of energy, establishing the buffer needed to enable much more extensive use of wind, solar and other renewable power sources. And it would build the core infrastructure that is a prerequisite if rich economies are to move away from greenhouse-gas-emitting power plants and vehicles.

A New Grid for a New Era
A continental supergrid may sound like a futuristic idea, but the concept has a long history. In 1967 IBM physicists Richard L. Garwin and Juri Matisoo published a design for a 1,000-kilometer transmission cable made of niobium tin, which superconducts at high currents. Extraordinary amounts of direct current (DC) can pass resistance-free through such a superconductor when the metal is chilled by liquid helium to a few degrees above absolute zero. The scientists proposed a DC cable with two conductors (made of superconducting wire or tape) that together would carry 100 gigawatts--roughly the output of 50 nuclear power plants.

Garwin and Matisoo were exploring what might be possible, not what would be practical. It would not make sense to inject that much power into one point of the grid, and liquid helium is a cumbersome coolant. But their ideas inspired others. In the following decades, short superconducting cables were built and tested to carry alternating current (AC) in Brookhaven, N.Y., and near Graz, Austria, with the latter operating connected to the local grid for several years.

Ten years after the discovery of high-temperature superconductivity, a technical study by the Electric Power Research Institute (EPRI) concluded that with liquid nitrogen as a coolant, a five-gigawatt DC "electricity pipe" could compete economically with a gas pipeline or conventional overhead lines for transmission distances of 800 kilometers or more. Two of us (Grant and Starr) developed the idea further in papers that explored how ultracold hydrogen--either liquid or supercritical gas--might both chill the superconducting wires and deliver energy in chemical form within a continental-scale system. In 2002 and 2004 the third author (Overbye) organized workshops at which dozens of experts detailed a plan for a 100-meter pilot segment, precursor to a 50-kilometer intertie between existing regional grids.

It is important to develop prototypes soon, because existing electrical grids are increasingly reaching the point of maximum loading--and, as the blackouts indicate, occasionally exceeding it. As total generating capacity in the U.S. has risen by almost a quarter in the past five years, the high-voltage transmission grid has grown in size by just 3.3 percent. Yet society's appetite for energy continues to grow rapidly: the U.S. Energy Information Administration forecasts that by 2025 annual energy use in the U.S. will hit 134 trillion megajoules (127 quadrillion BTUs), over a quarter greater than it was in 2005.

The rising demand poses two problems: where to get this new energy and how to distribute it. Fossil fuels will probably still supply a large fraction of our energy 20 years from now. But global competition for limited petroleum and natural gas resources is intense, and even mild production shortages can send prices skyrocketing, as we have seen in the past few months. Concern over greenhouse warming is leading to other constraints.

If we have an opportunity to move away from our dependence on fossil fuels, clearly we should take it. But fully exploiting nonfossil energy sources, including wind, solar, agricultural biomass and in particular advanced nuclear power, will require a new grid for this new era. To distribute trillions of kilowatt-hours of extra electricity every year, the U.S. grid will have to handle roughly 400 gigawatts more power than it does today.

The current infrastructure can be enhanced only so far. New carbon-core aluminum wires can be stretched more tautly than conventional copper wires and so can carry perhaps three times as much current before sagging below safe heights. And U.S. utilities will take advantage of provisions in the 2005 Energy Act that make it easier to open new transmission corridors.

But high-voltage lines are already approaching the million-volt limit on insulators and the operating limits of semiconductor devices that control DC lines. AC lines become inefficient at distances around 1,200 kilometers, because they begin to radiate the 60-hertz power they carry like a giant antenna. Engineers will thus need to augment the transmission system with new technologies to transport hundreds more gigawatts from remote generators to major cities.

Next-Generation Nuclear

One of our goals in designing the SuperGrid has been to ensure that it can accept inputs from a wide variety of generators, from the smallest rooftop solar panel and farmyard wind turbine to the largest assemblage of nuclear reactors. The largest facilities constrain many basic design decisions, however. And the renewables still face tremendous challenges in offering the enormous additional capacity required for the next 20 years. So we built our concept on a foundation of fourth-generation nuclear power.

The 2005 Energy Act directed $60 million toward development of "generation IV" high-temperature, gas-cooled reactors. Unlike most current nuclear plants, which are water-cooled and so usually built near large bodies of water--typically near population centers--the next-generation reactors expel their excess heat directly into the air or earth.

In newer designs, the nuclear reactions slow down as the temperature rises above a normal operating range. They are thus inherently resistant to the coolant loss and overheating that occurred at Chernobyl in Ukraine and Three Mile Island in Pennsylvania [see "Next-Generation Nuclear Power," by James A. Lake, Ralph G. Bennett and John F. Kotek; *Scientific American*, January 2002].

Like all fission generators, however, generation IV units will produce some radioactive waste. So it will be least expensive and easiest politically to build them in "nuclear clusters," far from urban areas. Each cluster could produce on the order of 10 gigawatts.

Remote siting will make it easier to secure the reactors as well as to build them. But we will need a new transmission technology--a Super-Cable--that can drastically reduce the cost of moving energy over long distances.

SuperCables

For the electricity part of the Super-Grid, where we need to move tens of gigawatts over hundreds of kilometers, perfect conductors are a perfect fit. Although superconducting materials were discovered in 1911 and were fashioned into experimental devices decades ago, it is only quite recently that the refrigeration needed to keep them ultracold has become simple enough for industrial use. Super-conductors are now moving beyond magnetic resonance imaging scanners and particle accelerators and into commercial power systems.

For example, the DOE has joined with power equipment manufacturers and utilities to produce prototypes of superconducting transformers, motors, generators, fault-current limiters and transmission cables. Other governments--notably Japan, the European Union, China and South Korea--have similar development programs. Three pilot projects now under way in the U.S. are demonstrating superconducting cables in New York State on Long Island and in Albany and in Columbus, Ohio.

These cables use copper oxide-based superconducting tape cooled by liquid nitrogen at 77 kelvins (-196 degrees Celsius). Using liquid hydrogen for coolant would drop the temperature to 20 kelvins, into the superconducting range of new compounds such as magnesium diboride [see "Low-Temperature Superconductivity Is Warming Up," by Paul C. Canfield and Sergey L. Bud'ko; *Scientific American*, April 2005].

All demonstrations of superconducting cables so far have used AC power, even though only DC electricity can travel without resistance. Even so, at the frequencies used on the current grid, superconductors offer about one two-hundredth the electrical resistance of copper at the same temperature.

The Super-Cable we have designed includes a pair of DC superconducting wires, one at plus 50,000 volts, the other at minus 50,000 volts, and both carrying 50,000 amps--a current far higher than any conventional wire could sustain. Such a cable could transmit about five gigawatts for several hundred kilometers at nearly zero resistance and line loss. (Today about a tenth of all electrical energy produced by power plants is lost during transmission.)

A five-gigawatt Super-Cable is certainly technically feasible. Its scale would rival the 3.1-gigawatt Pacific Intertie, an existing 500-kilovolt DC overhead line that moves power between northern Oregon and southern California. Just four Super-Cables would provide sufficient capacity to transmit all the power generated by the giant Three Gorges Dam hydroelectric facility in China.

Because a Super-Cable would use hydrogen as its cryogenic coolant, it would transport energy in chemical as well as electrical form. Next-generation nuclear plants can produce either electricity or hydrogen with almost equal thermal efficiency. So the operators of nuclear clusters could continually adjust the proportions of electricity and "hydricity" that they pump into the Super-Grid to keep up with the electricity demand while maintaining a flow of hydrogen sufficient to keep the wires superconducting.

Electricity and Hydricity
The ability to choose among alternative forms of power and to store electricity in chemical form opens up a world of possibilities. The Super-Grid could dramatically reduce fuel costs for electric- and hydrogen-powered hybrid vehicles, for example.

Existing hybrids run on gasoline or diesel but use batteries to recover energy that otherwise would go to waste. "Plug-in" hybrids that debuted last year use electricity as well as gas [see "Hybrid Vehicles," by Joseph J. Romm and Andrew A. Frank; *Scientific American*, April]. BMW, Mazda and others have demonstrated hydrogen hybrids that have two fuel tanks and engines that burn hydrogen when it is available and gasoline when it is not. Many automakers are also developing vehicles that use onboard fuel cells to turn hydrogen back into electricity by combining it with oxygen.

Even the most efficient automobiles today convert only 30 to 35 percent of their fuel energy into motion. Hydrogen fuel-cell hybrids could do significantly better, reaching 50 percent efficiencies with relative ease and eventually achieving 60 to 65 percent fuel efficiencies.

Replacing even a modest percentage of petroleum-based transportation fuels would require enormous amounts of both hydrogen and electricity, as well as a pervasive and efficient delivery infrastructure. The Super-Grid offers one way to realize this vision. Within each nuclear cluster, some reactors could produce electricity while others made hydrogen--without emitting any greenhouse gases.

By transporting the two together, the grid would serve both as a pipeline and as an energy store. For example, every 70-kilometer section of Super-Cable containing 40-centimeter-diameter pipes filled with liquid hydrogen would store 32 gigawatt-hours of energy. That is equivalent to the capacity of the Raccoon Mountain reservoir, the largest pumped hydroelectric facility in the U.S.

By transforming electricity into a less ephemeral commodity similar to oil or natural gas, the new grid could allow electricity markets to tolerate rapid swings in demand more reliably than they do today. Super-Grid links crossing several time zones and weather boundaries would allow power plants to tap excess nighttime capacity to meet the peak electricity needs of distant cities. By smooth-ing out fluctuations in demand, the low-loss grid could help reduce the need for new generation construction.

The Super-Grid could go a long way, too, toward removing one of the fundamental limitations to the large-scale use of inconstant energy from wind, tides, waves and sunlight. Renewable power plants could pump hydrogen onto the grid, rather than selling electricity. Alternatively, baseline generators could monitor the rise and fall in electrical output from these plants and might be able to use electrolysis to shift their electricity/hydricity blend to compensate.

Charging Ahead
No major scientific advances are needed to begin building the SuperGrid, and the electric utility industry has already shown its interest in the concept by funding a SuperGrid project at EPRI which will explore the numerous engineering challenges that integrating Super-Cables into the existing power grid will pose. The largest of these is what to do if a Super-Cable fails.

The grid today remains secure even when a single device, such as a high-voltage transmission line, fails. When a line sags into a tree, for example, circuit breakers open to isolate the line from the grid, and the power that was flowing on the wire almost instantaneously shifts to other lines. But we do not yet have a circuit-breaker design that can cut off the extraordinary current that would flow over a Super-Cable. That technology will have to evolve. Grid managers may need to develop novel techniques for dealing with the substantial disturbance that loss of such a huge amount of power would cause on the conventional grid. A break in a SuperCable would collapse the surrounding magnetic field, creating a brief but intense voltage spike at the cut point. The cables will need insulation strong enough to contain this spike.

Safely transporting large amounts of hydrogen within the Super-Cable poses another challenge. The petrochemical industry and space programs have extensive experience pumping hydrogen, both gaseous and liquid, over kilometer-scale pipelines. The increasing use of liquefied natural gas will reinforce that technology base further. The explosive potential (energy content per unit mass) of hydrogen is about twice that of the methane in natural gas. But hydrogen leaks more easily and can ignite at lower oxygen concentrations, so the hydrogen distribution and storage infrastructure will need to be airtight. Work on hydrogen tanks for vehicles has already produced coatings that can withstand pressures up to 700 kilograms per square centimeter.

Probably the best way to secure Super-Cables is to run them through tunnels deep underground. Burial could significantly reduce public and political opposition to the construction of new lines.

The costs of tunneling are high, but they have been falling as underground construction and microtunneling have made great strides, as demonstrated by New York City's Water Tunnel Number 3 and the giant storm sewers in Chicago. Automated boring machines are now digging a 10.4-kilometer-long, 14.4--meter-diameter hydroelectric tunnel beside the Niagara River, at a cost of $600 million. Recent studies at Fermilab estimated the price of an 800-kilometer-long, three-meter-wide, 150-meter-deep tunnel at less than $1,000 a meter.

Super-Cables would carry many times the power of existing transmission lines, which helps the economic case for burial.

But the potential for further technology innovation and the limits imposed by the economics of underground construction need more exploration.

To jump-start the Super-Grid, and to clarify the costs, participants in the 2004 SuperGrid workshop proposed constructing a one-kilometer-long Super-Cable to carry several hundred megawatts. This first segment would simply test the superconducting components, using liquid nitrogen to cool them. The project could be sponsored by the DOE, built at a suitable national laboratory site, and overseen by a consortium of electric utilities and regional transmission operators. Success on that prototype should lead to a 30- to 80-kilometer demonstration project that relieves real bottlenecks on today's grid by supplementing chronically congested interties between adjacent regional grids.

Beyond that, price may largely determine whether any country will muster the political and social will to construct a Super-Grid. The investment will undoubtedly be enormous: perhaps $1 trillion in today's dollars and in any case beyond the timescale attractive to private investment. It is difficult to estimate the cost of a multidecade, multigenerational Super-Grid effort. But one can judge the ultimate benefits: a carbonless, ecologically gentle domestic energy infrastructure yielding economic and physical security.