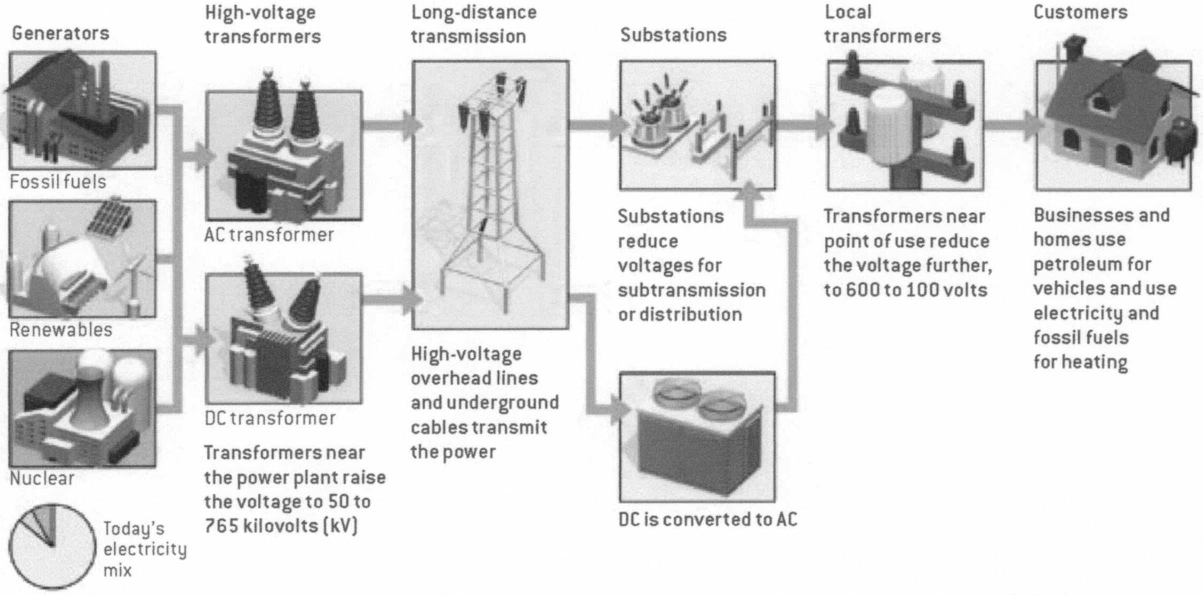
THE EVOLUTION OF A SUPERGRID

Transition to a SuperGrid would take at least a generation to complete. The evolution would inject new technologies into every level of the infrastructure: generators, transformers, power transmission and consumption.

TODAY



Transformers near the power plant raise the voltage to 50 to 765 kilovolts (kV)

High-voltage overhead lines and underground cables transmit the power

Substations reduce voltages for subtransmission or distribution

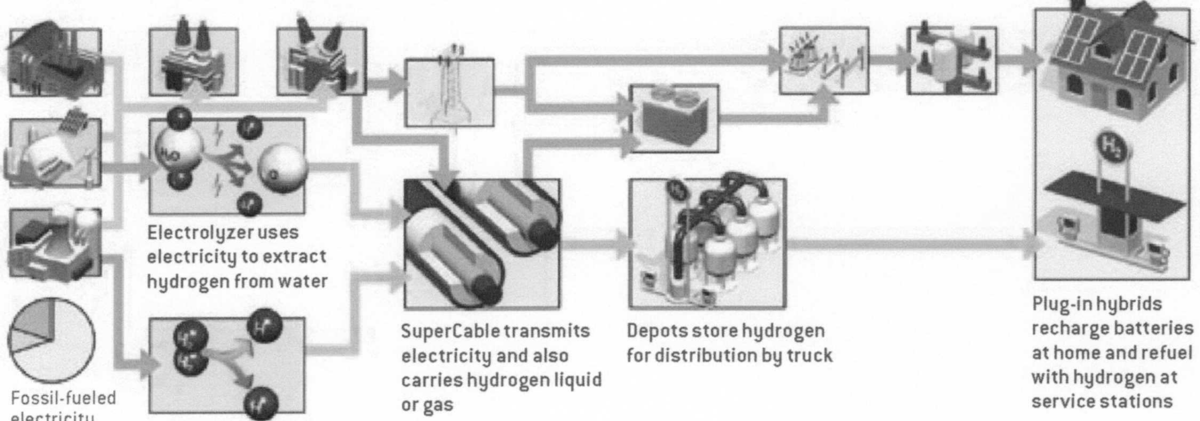
DC is converted to AC

Transformers near point of use reduce the voltage further, to 600 to 100 volts

Businesses and homes use petroleum for vehicles and use electricity and fossil fuels for heating

Today's electricity mix

10 YEARS AFTER SUPERGRID CONSTRUCTION BEGINS



Electrolyzer uses electricity to extract hydrogen from water

Thermal cracker uses heat from power plant to extract hydrogen

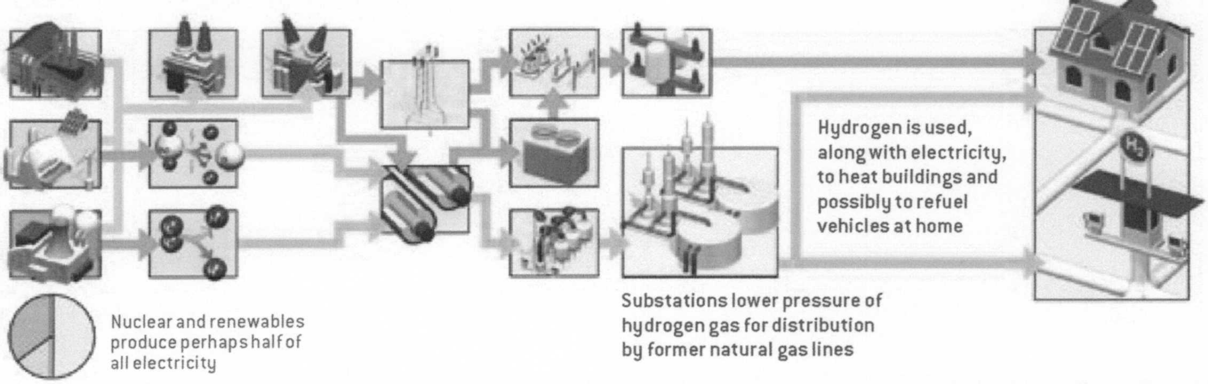
SuperCable transmits electricity and also carries hydrogen liquid or gas

Depots store hydrogen for distribution by truck

Plug-in hybrids recharge batteries at home and refuel with hydrogen at service stations

Fossil-fueled electricity begins to decline

25 YEARS AFTER SUPERGRID CONSTRUCTION BEGINS



Hydrogen is used, along with electricity, to heat buildings and possibly to refuel vehicles at home

Substations lower pressure of hydrogen gas for distribution by former natural gas lines

Nuclear and renewables produce perhaps half of all electricity

SLIM FILMS

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 SuperCable—that can drastically reduce the cost of moving energy over long distances.

SuperCables

FOR THE ELECTRICITY PART of the SuperGrid, 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. Superconductors 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

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

THE AUTHORS

PAUL M. GRANT worked for IBM for 40 years, starting in 1953 at age 17 as a pinsetter at the company bowling alley. After earning a Ph.D. in physics at Harvard University, he joined the San Jose Research Laboratory, where he participated in the discovery of high-temperature superconductivity. From 1993 to 2004, Grant was a science fellow at the Electric Power Research Institute (EPRI), which was founded by ***CHAUNCEY STARR*** in 1973. Starr, a 1990 recipient of the U.S. National Medal of Technology, did early research on cryogenics, managed the atomic energy division of Rockwell International, co-founded the American Nuclear Society, and was president of EPRI for more than a decade. ***THOMAS J. OVERBYE,*** who holds the Fox Family Professorship in Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign, contributed to the official investigation of the 2003 North American blackout.

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 SuperCable 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 SuperCable 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 SuperCables would provide sufficient capacity to transmit all the power generated by the giant Three Gorges Dam hydroelectric facility in China.

Because a SuperCable 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 SuperGrid 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 SuperGrid 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 SuperGrid 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 SuperCable 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.


PUMP-FILLED LAKE atop Raccoon Mountain in Tennessee stores enough potential energy to create 32 gigawatt-hours of electricity when drained through its hydroelectric dam. Every 70 kilometers of SuperCable would store an equivalent amount of energy in the form of hydrogen.

TENNESSEE VALLEY AUTHORITY

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. SuperGrid 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 [*see illustration on opposite page*]. By smoothing out fluctuations in demand, the low-loss grid could help reduce the need for new generation construction.

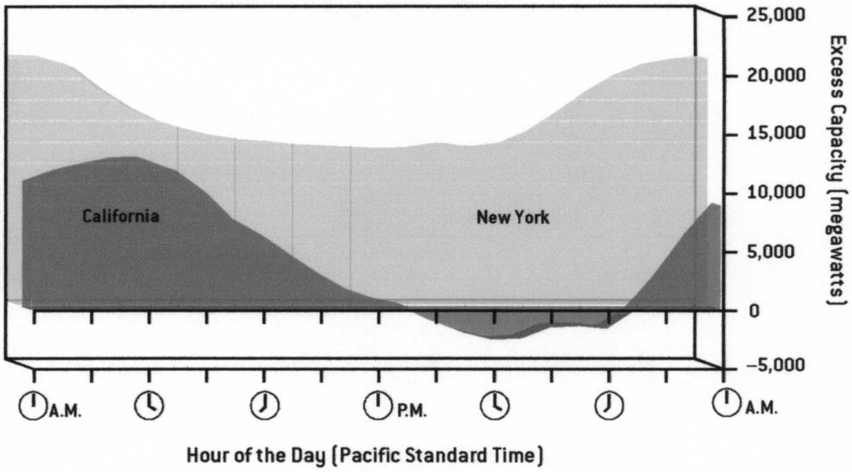
The SuperGrid could go a long way, too, toward removing one of the fundamental limitations to the large-scale use of inconstant energy from wind, tides, waves and sunlight. Renewable power plants could pump hydrogen onto the grid, rather than selling electricity. Alternatively, baseline generators could 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 SuperCables into the existing power grid will pose. The largest of these is what to do if a SuperCable 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 SuperCable. 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 SuperCable 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.



W. WAYT GIBBS

CONTINENT-WIDE SUPERGRID could help avoid brownouts and overloads by allowing operators to shift huge amounts of power over long distances. On a hot summer day, for example, demand for electricity in California (*red*) can exceed the state's active generating capacity for several hours. But generators in New York State have surplus capacity (*green*), so they can make up the deficit.

Probably the best way to secure SuperCables 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.

SuperCables 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 SuperGrid, and to clarify the costs, participants in the 2004 SuperGrid workshop proposed constructing a one-kilometer-long SuperCable 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 SuperGrid. 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 SuperGrid effort. But one can judge the ultimate benefits: a carbonless, ecologically gentle domestic energy infrastructure yielding economic and physical security.

MORE TO EXPLORE

National Energy Planning for the Century. Chauncey Starr in *Nuclear News*, Vol. 45, No. 31, pages 31–35; February 2002. Available at **www.w2agz.com/SG%20-Bibliography.htm**

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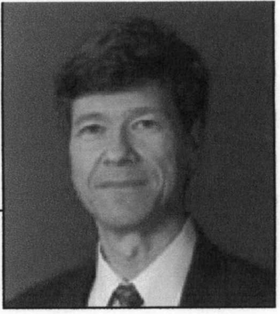
Proceedings of the 2002 and 2004 SuperGrid conferences are available at **supergrid.uiuc.edu**

Sustainable Developments



ARNOLD ADLER

Ecology and Political Upheaval

Small changes in climate can cause wars, topple governments and crush economies already strained by poverty, corruption and ethnic conflict

By JEFFREY D. SACHS

Careful study of the long-term climate record has shown that even a minor shock to the system can cause an enormous change in outcome, a nonlinear response that has come to be called "abrupt climate change." Less well recognized is that our social and economic systems are also highly sensitive to climate perturbations. Seemingly modest fluctuations in rainfall, temperature and other meteorological factors can create havoc in vulnerable societies.

Recent years have shown that shifts in rainfall can bring down governments and even set off wars. The African Sahel, just south of the Sahara, provides a dramatic and poignant demonstration. The deadly carnage in Darfur, Sudan, for example, which is almost always discussed in political and military terms, has roots in an ecological crisis directly arising from climate shocks. Darfur is an arid zone with overlapping, growing populations of impoverished pastoralists (tending goats, cattle and camels) and sedentary farmers. Both groups depend on rainfall for their livelihoods and lives. The average rainfall has probably declined in the past few decades but is in any case highly variable, leaving Darfur prone to drought. When the rains faltered in the 1980s, violence ensued. Communities fought to survive by raiding others and attempting to seize or protect scarce water and food supplies.

> **Public debates tend to neglect powerful ecological effects because we focus on politics.**

A drought-induced famine is much more likely to trigger conflict in a place that is already impoverished and bereft of any cushion of physical or financial resources. Darfur was also pushed over the edge by ethnic and political conflict, with ambitious, violent and unscrupulous leaders preying on the ethnic divisions. These vulnerabilities, of course, have not been unique to Darfur. Several studies have shown that a temporary decline in rainfall has generally been associated throughout sub-Saharan Africa with a marked rise in the likelihood of violent conflict in the following months.

Africa is certainly not alone in experiencing the linkages of climate shocks and extreme social instability. Rainfall shifts associated with El Niño cycles have had similarly catastrophic consequences. The massive 1998 El Niño produced huge floods off the coast of Ecuador, which destroyed a considerable amount of export crops and aquaculture. That led to a failure of loans to Ecuador's already weak banking system, which in turn helped to provoke a bank run, an unprecedented economic collapse and eventually the ouster of the government. Halfway around the world the same El Niño caused an extreme drought in Indonesia, coinciding with Asia's massive financial crisis. Indonesia's drought and resulting food shortage contributed to financial and political destabilization and to the end of President Suharto's 31-year rule. As in Ecuador, the short-term economic collapse was by far the largest in Indonesia's modern history.

Climate skeptics who ask impatiently why we should care about "a degree or two" increase in the global mean temperature understand neither the climate nor the social and economic systems in which we live. Both climate and society are subject to great instability, nonlinear responses and high unpredictability. Climate changes may influence storms, droughts, floods, crop yields, disease vectors and much more, well beyond what the current "average" forecasts suggest. And the resulting ecological effects, especially on societies already facing hunger or financial and political fragility, can be enormous and dire. Our public debates tend to neglect these powerful effects because we focus on politics and only rarely on the underlying environmental pressures.

Once we recognize the ecological risks to our economic well-being and even to our national security, we will begin to look much harder for practical approaches to mitigating the pressures that our global society is now placing on the earth's ecosystems. We will then need to increase our preparations for the intensified shocks that are surely on their way. The intertwined strategies of mitigation and adaptation will be the topics of future columns. SA

Jeffrey D. Sachs is director of the Earth Institute at Columbia University and of the U.N. Millennium Project.