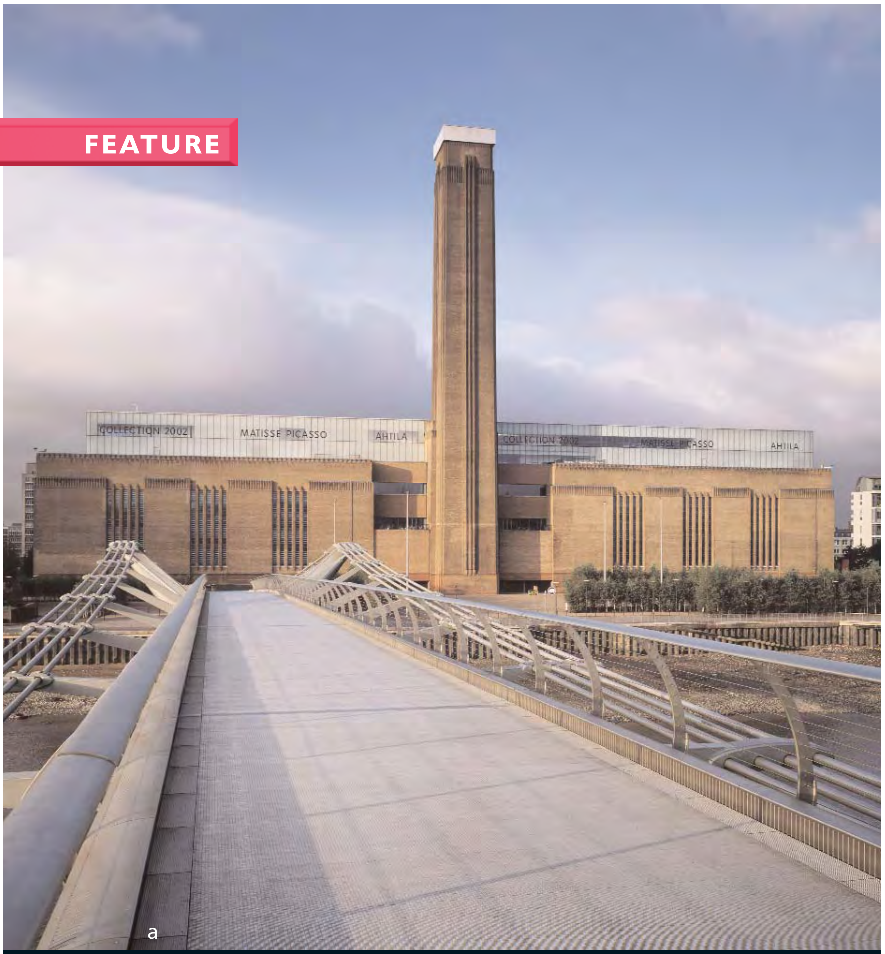
# Big Green Energy Machines

## How are we going to generate more power and decrease its impact on the environment?

By Jesse H. Ausubel



Joe Fletcher/Esto

**Figure 1. When it was built after World War II, the Bankside power station in London was conceived by its designer, Sir Giles Gilbert Scott, as a cathedral of pure energy. Closed in 1981 because of high costs, it was later converted to house a modern art collection for the Tate Gallery—viewed here across the new Millennium Bridge (a)—in which the former turbine hall acts as a covered street where works may be shown (b).**

Tate Photography

The Internet proves that to become larger, systems must become smaller. If every computer still filled the footprint of a 1960s mainframe, the Internet could never have succeeded. Miniaturizing elements from transistors to video display enabled the Internet to become pervasive and unintrusive. The elements also became less expensive, most famously in the case of chips. The shrinking of the parts in size and cost multiplied the whole in power, features, and reach.

During the 20th century, electric generators grew from 10 to 1 million kW, scaling up an astonishing 100,000 times. Yet, a power station today differs little in the space it occupies from that of 50 or 100 years ago. The Bankside power station in London, for example (Figure 1a), now a modern art gallery of the Tate Museum (Figure 1b), opened in 1953. Soaring 100 m high and occupying 3.5 hectares, Bankside provided about 200 MW at its peak. A comparable generator installed now might need 10% of the Bankside space; alternately, the site could host 10 times the power. As in the Internet, scalability and economies of scale triumph in the electric-power system.

Scale matters to the electricity consumer as well as the producer. A middle-class American household today consumes more than 100 times as much artificial illumination as did its predecessor of two centuries ago. Happily, lamps do not occupy 100 times the space. In 1800, a household would have spent 4% of its income on candles, lamps, oil, and matches, but its successor spends less than 1%. Increases in luminous efficacy and safety, as well as lower fuel cost, allowed light to spread.

Affordable electric power contributed as much as any technology to lifting human well-being in the 20th century. Mobility afforded by the internal combustion engine contributed hugely too. Electric power and mobility both depend on primary energy (see *The Industrial Physicist*, February 2000, pp. 16–19). During the 21st century, global primary energy demand will likely grow from the present 13 TW to 50 or even 100 TW. One cause is chips going into 1,000 objects per capita, or 10 trillion objects, as China and India log into the game. A second is that all people continue to expand their travel range, thereby increasing access to jobs, education, and enjoyment. Let us assume a big increase in efficiency and a slower population growth. A mere 1.5% yearly growth in total energy demand during this century, about two-thirds of the rate since 1800, would multiply demand for primary energy over fourfold between 2004 and 2100.

If size and power—of individual machines or the system—grow in tandem, the use of materials, land, and other resources would be unacceptable. Technologies succeed when economies of scale form part of their conditions of evolution. I seek an energy system that is 5–10 times as powerful as the present system but fits within or, better, reduces its present footprint, a system of engines big in power and green in impact.

Size helps control emissions and the use of materials, because one big plant releases no more emissions than many small plants, and emissions from one plant are easier to collect. Society will not close the carbon cycle, for example, if it must collect emissions from millions of microturbines. I will share two visions for big green energy machines suiting the 21st century: the zero-emission power plant (ZEPP) and the Continental SuperGrid.

## The ZEPP

The ZEPP is a supercompact, superfast, superpowerful turbine putting out electricity and carbon dioxide ($CO_2$) that can be sequestered. Investments by energy producers will make methane (natural gas) overtake coal globally as the lead fuel for making electricity over the next two to three decades. Methane tops the hydrocarbon fuels in heat value, measured in joules per kilogram, and thus lends itself to scaling up. Free of sulfur, mercury, and other contaminants of coals and oils, methane is the best hydrocarbon feedstock.

Although methane produces about half the $CO_2$ per unit of energy of coal, it still yields this greenhouse gas. Even in 2020, we may need to dispose of an amount of carbon from methane equal to nearly half of today's carbon emissions from all fuels, and later, methane use might cause about 75% of total $CO_2$ emissions. So prevention of climate change must focus on methane.

Can we find technology consistent with the evolution of the energy system to dispose economically and conveniently of the carbon from making electricity? The practical means is the ZEPP. The basic idea is a gas power plant operating at very high temperatures and pressures, so we can bleed off the $CO_2$ as a liquid and sequester it.

Big energy use means powerful individual ZEPPs, because the size of generating plants grows even faster than total use. Plants grow because large is cheap, if technology can cope. For many technologies, a tenfold larger scale shrinks unit costs by two-thirds.

Analysis of the history of power plants shows that their maximum size has grown in intense spurts. In the United States, one growth pulse centered in 1929 quickly expanded plants from a few tens of megawatts to about 340 MW. After a period of plant-size stagnation, a pulse centered in 1965 quadrupled the maximum size to almost 1,400 MW. The world pattern closely resembles the U.S. experience. For reference, New York now draws more than 12,000 MW on a hot summer day. The stagnation of maximum power-plant size for the past few decades should not narcotize today's engineers. Growth of electricity use in the next 50 years could quadruple maximum plant size again to more than 5,000 MW.

Big ZEPPs require transmitting immense mechanical power from more powerful generators through a large steel axle rotating as fast as 3,000 rpm. The way around

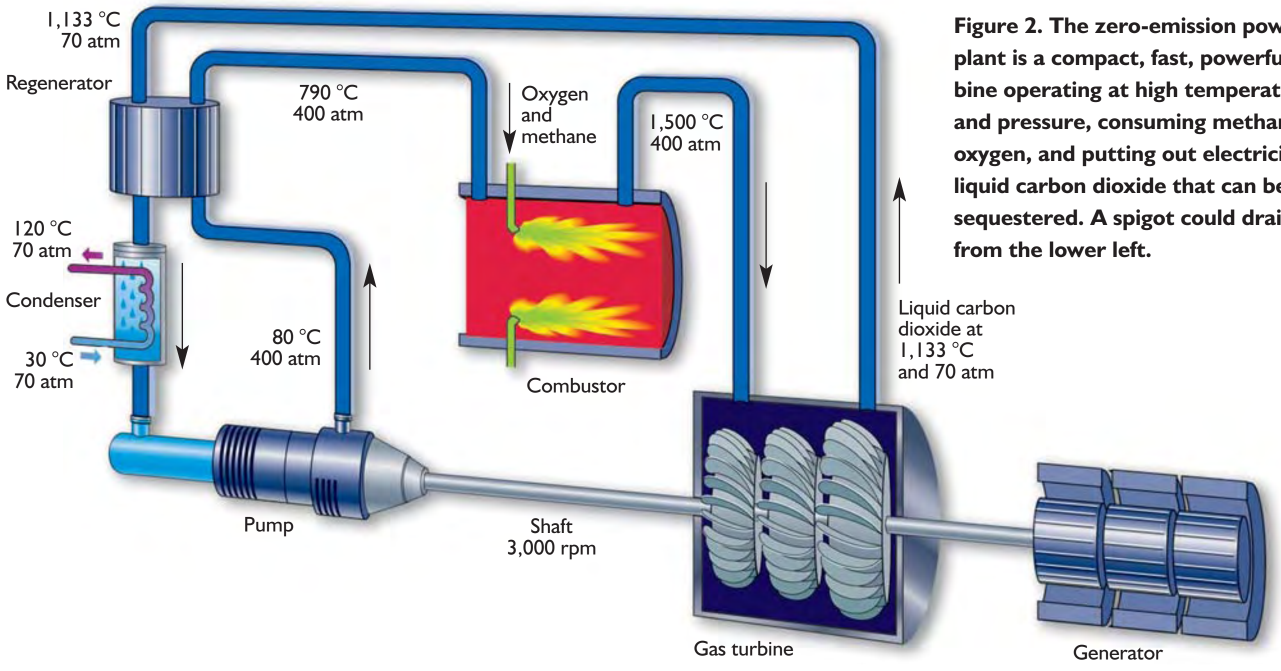


**Figure 2. The zero-emission power plant is a compact, fast, powerful turbine operating at high temperature and pressure, consuming methane and oxygen, and putting out electricity and liquid carbon dioxide that can be sequestered. A spigot could drain $CO_2$ from the lower left.**

Ichihara, Tokyo Electric Power/Ian Worpole

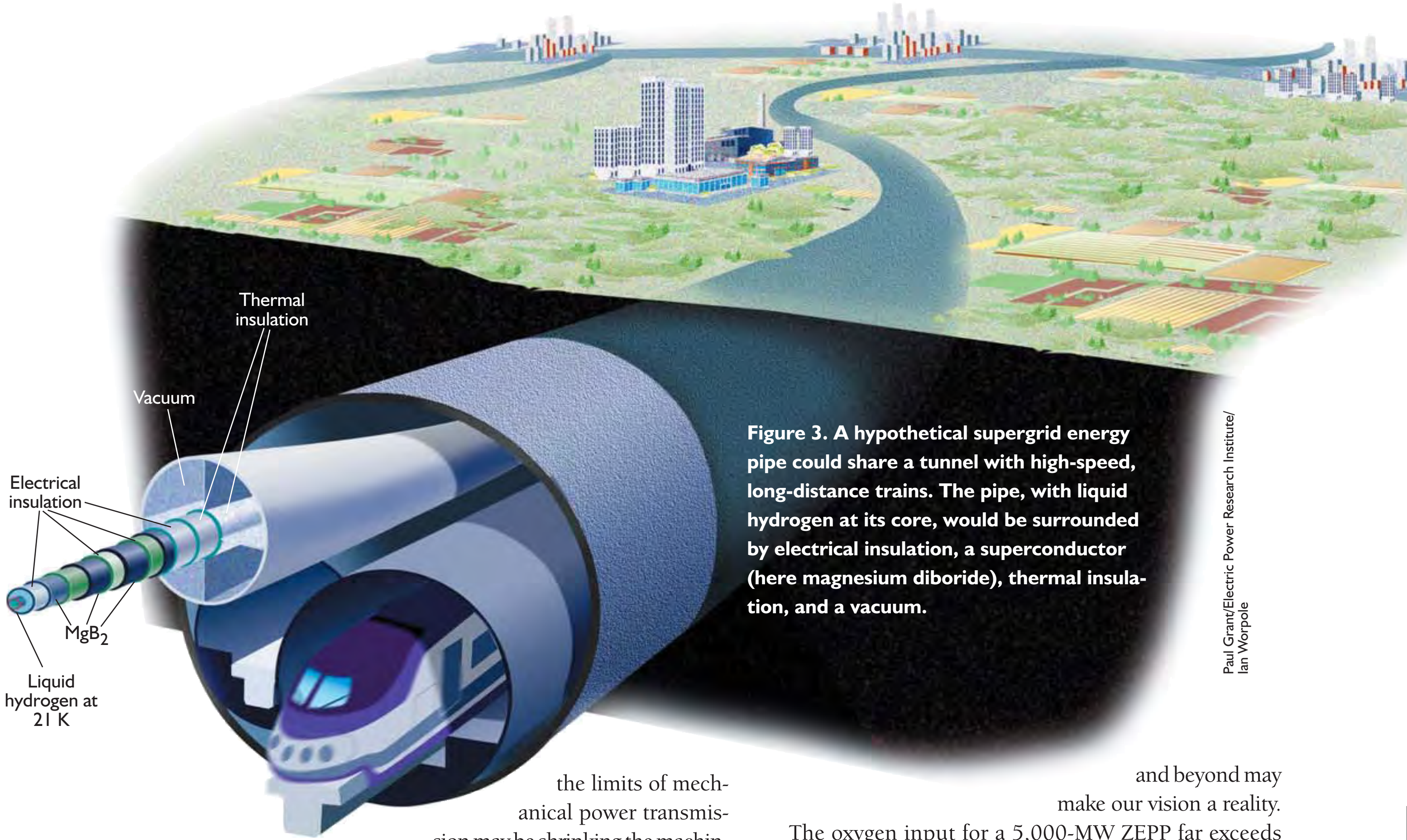


**Figure 3. A hypothetical supergrid energy pipe could share a tunnel with high-speed, long-distance trains. The pipe, with liquid hydrogen at its core, would be surrounded by electrical insulation, a superconductor (here magnesium diboride), thermal insulation, and a vacuum.**

Paul Grant/Electric Power Research Institute/
Ian Worpole

the limits of mechanical power transmission may be shrinking the machinery. Begin with a very-high-pressure $CO_2$ gas turbine where fuel burns with oxygen. The pressure needed ranges from 40 to 1,000 atm, at which $CO_2$ would be recirculated as a liquid and bled out. A simple configuration offered by colleagues from Tokyo Electric Power shows the major components (Figure 2).

A more developed design might circulate oxygen and add methane when needed by local injection to make expansion almost isothermic. Dual cycles, maximum capacity, and changes in temperature in the regenerator with such dense gases all need to be imaginatively considered by physicists and engineers in a grand concourse of designs.

Fortunately for transmitting mechanical power, the high pressures shrink the machinery in a revolutionary way and so permit the turbine to rotate very fast. The generator could then also turn very fast, operating at high frequency, and appropriate power electronics would slow the generated electricity to 60 cycles.

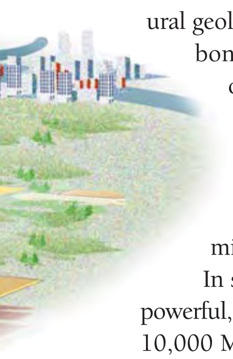
An envisioned temperature of 1,500 °C will probably require using new ceramics now being engineered for aviation. Problems of stress, corrosion, and cracking will arise at the high temperatures and pressures, and need solutions. Developing power electronics to slow the cycles of the alternating current also raises questions. Although the needed electronics are beyond today's state of the art, power electronics is still young—meaning expensive and unreliable—but the art of the year 2020 and beyond may make our vision a reality.

The oxygen input for a 5,000-MW ZEPP far exceeds the output of the largest present oxygen plant, but cryoseparation could provide it. A cryogenic plant located near a ZEPP introduces a bonus, because superconductors need the cold. Companies already sell small motors wound with high-temperature superconducting wire that halve the size and weight of a conventional motor built with copper coils and also halve electrical losses. Colleagues at Tokyo Electric Power calculate that ZEPP plant efficiency could reach 70%, well above the 55% peak of gas turbines today (Figure 4).

At high pressure, waste carbon is already liquid and, thus, easily handled. Opportunities for storing $CO_2$ will join access to customers and fuel in determining plant locations. Because most natural gas travels through a few large pipelines, these pipelines are ideal sites for ZEPPs.

Underground caverns such as those that once held coal, oil, and gas deposits are logical places to sequester $CO_2$. The logic is encouraged by fact. On a small scale, $CO_2$ already profitably helps tertiary recovery of oil. In regions such as Texas, extensive systems pipe $CO_2$ for geologic storage in depleted oil fields for potential reuse in nearby fields. The past 20 years have proven the feasibility of $CO_2$ storage. Commercial enterprises now store, without leaks, more than 30 million tons per year for enhanced oil recovery.

The challenge lies in going to a large scale. The present annual volume of $CO_2$ from all sources is about 15 $km^3$, or 500 times what the oil industry now uses. Nat-



ural geological traps only occasionally contain hydrocarbons, so one can extend storage to the voids that oil and gas prospectors routinely find. Grasping another opportunity, one could use aquifers in silicate beds to move the waste $CO_2$ to the silicates, where chemical processes would turn it into carbonates and silica that remain stable for millions of years.

In short, the ZEPP vision is a supercompact, superpowerful, superfast turbine: 1–2 m in diameter, potentially 10,000 MW or double the expected maximum demand, 30,000 rpm, putting out electricity at 60 cycles and $CO_2$ that can be sequestered. ZEPPs the size of a locomotive, or even an automobile, and attached to gas pipelines, might replace the carbon-emitting antique power plants now cluttering our landscape.

I propose introducing ZEPPs in 2020 and a fleet of 500 5,000-MW ZEPPs by 2050. Recall that the world built today's fleet of some 430 nuclear-power plants in about 30 years. ZEPPs, together with another generation of nuclear-power plants in various configurations, can stop the $CO_2$ increase in the atmosphere around 2050 in the range of 450–500 ppm—about one-quarter more than today—without sacrificing energy consumption. ZEPPs merit billions of dollars in R&D, because the plants will form a profitable industry for those who can capture the expertise to design, build, and operate them.

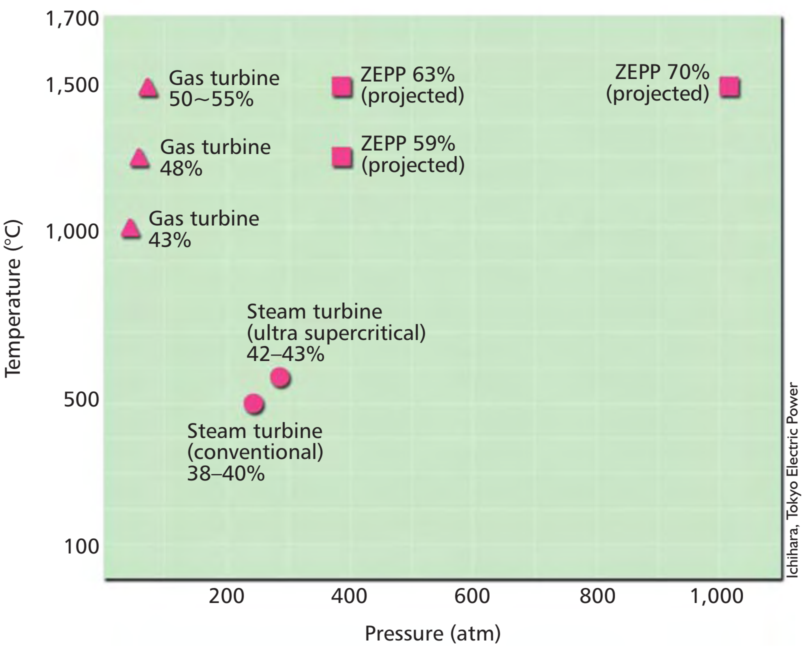
Like the jumbo jets that carry a big fraction of passenger-kilometers, compact ultrapowerful ZEPPs could be the workhorses of the energy system in the middle of the century. Yet, power companies could insert ZEPPs into densely settled regions such as eastern China without much change to the footprint of the energy system.

## Continental SuperGrid

Let me introduce a second, even bigger green energy machine, the Continental SuperGrid, to deliver the preferred energy carriers, electricity and hydrogen, in an integrated energy pipeline. The fundamental design involves wrapping a superconducting cable around a pipe pumping liquid hydrogen, which provides the cold needed to maintain superconductivity (Figure 3). The SuperGrid would not only transmit electricity but also store and distribute the bulk of the hydrogen ultimately used in fuel-cell vehicles and generators or redesigned internal-combustion engines.

Although methane is a good energy carrier, hydrogen is better environmentally. Its combustion yields only water vapor and energy. In the 1970s, journalists called hydrogen the Tomorrow Fuel, but critics worried that hydrogen would remain forever on the horizon, like fusion energy. For hydrogen, tomorrow is now today.

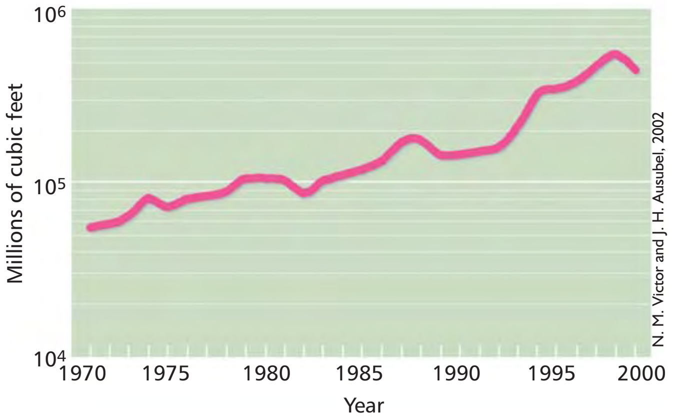
Long used as a rocket fuel and in other top-performance market niches, hydrogen is now a thriving young industry. World commercial production in 2002 exceeded 40 billion cubic feet per day, which is equal to 75,000 MW if converted to electricity. U.S. hydrogen production, about one-third of the world's output, more than tripled between 1990 and 2000 (Figure 5). More than 16,000 km of pipeline worldwide transports hydrogen gas for big users, and pipes at 100 atm extend up to 400 km, for example, from Antwerp, Belgium, to Normandy, France. But the SuperGrid scale is orders of magnitude larger.



Ichihara, Tokyo Electric Power

**Figure 4. The efficiency of power generation increases with operation at higher pressures and temperatures.**

Continental means coast-to-coast—for example, across the 4,000 km of North America, making one market for hydrogen and electricity. Superconductivity solves the problem of energy loss from power lines, and a continental scale increases efficiency by flattening the electricity-load curve, which still follows the sun. High capacity means 40,000–80,000 MW. The cable would carry dc and might look like either a spine or a ring. Power converters would connect the dc SuperGrid at various points to existing high-voltage ac transmission substations. SuperGrids should thrive on all continents. A continental



N. M. Victor and J. H. Ausubel, 2002

**Figure 5. Production of hydrogen in the United States, 1971–1999, on a semilog scale.**

system might cost about $1 trillion, or $10 billion per year for 100 years, to build, operate, and maintain.

The long road to the SuperGrid should begin with a compelling demonstration. I propose that within three years, the United States build a flexible 100-m "Supercable"—a 3-cm-diameter pipe for 1-m/s hydrogen flow inside a 10-cm-diameter overall pipe whose superconducting wire carries 5,000 V, 2,000 A, and 10 MW dc, demonstrating constant current under variable load and a low ripple factor.

Technical choices and challenges abound—in cryogenics and vacuums, power-control and cable design, and dielectric materials under simultaneous stress from low temperatures and high fields. Still, within 10 years, we could build and operate a 10–20-km segment that solves an actual transmission bottleneck. And by midcentury, we could have the first SuperGrid consisting of some 40 100-km-long sections integrated with nuclear plants of several thousand megawatts supplying the grid with electricity and hydrogen.

Nuclear power fits with the SuperGrid because of its low cost of fuel per kilowatt-hour and operational reliability at a constant power level. High-temperature reactors with coated-particle or graphite-matrix fuels promise a particularly efficient and scalable route to combined power and hydrogen production. Currently, hydrogen comes mostly from steam reforming of methane. To spare the chores and costs of carbon capture and sequestration, hydrogen must eventually come from splitting water, and the energy to make the hydrogen must also be carbon-free. Large-scale production of carbon-free hydrogen using nuclear energy should begin around 2020.

Thermochemically, high-temperature nuclear plants could nightly make hydrogen on the scale needed to meet the demand of billions of consumers (see *The Industrial Physicist*, February/March 2002, pp. 22–25). Nuclear-energy production is inherently 10,000 or even 100,000 times as compact as producing energy from hydrocarbons and, thus, scalable. Like ZEPPs, high-temperature reactors could be 5,000–10,000 MW. Thus, the acreage for power parks and even the number of plants need differ little from those of today.

Operating 24 hours a day, the plants would double basic efficiency of the electric-power industry's capital stock, which today is geared to peak demand—about twice the level of baseload but unused half the time. The latent hydrogen-storage capacity of the SuperGrid, combined with fuel cells or other new engines, may allow electrical networks to shift to a delivery system more like those of oil and gas, and away from the present, costly, instant matching of supply to demand.

For ultimate safety, security, and aesthetics, we should put the SuperGrid, including its cables and power plants, underground. Although costly, building underground reduces vulnerability to sabotage or natural disaster, accidents, right-of-way disputes, and surface congestion. Since 1958, Russia has operated underground reactors in Siberia. The SuperGrid multiplies the chances of siting reactors that produce hydrogen far from cities.

Eventually, magnetically levitated trains (maglevs), propelled by linear motors of superconducting magnets, could share the tunnels, moving at high speed in low-pressure tubes from one edge of a continent to another in 1 h. The maglevs would spread the infrastructure cost over multiple uses.

The magic words for the SuperGrid are hydrogen, superconductivity, zero emissions, and small ecological footprint, to which we add high-temperature reactors, energy storage, security, reliability, and scalability. The prize is that the SuperGrid pipe could carry 5 to 10 times the power of a cable today within the same diameter.

## Conclusion

Small is beautiful when small also means powerful and inexpensive, like the machinery of the Internet. The energy system requires economical green ideas big in power yet small in impact.

Solar and the so-called renewables are not green when considered on the large scales required. A single 1,000-MWe nuclear plant equates to prime farmland of more than 2,500 $km^2$ producing biomass, a wind farm occupying 750 $km^2$, or a photovoltaic plant of about 150 $km^2$ together with land for storage and retrieval. Although a present natural-gas combined-cycle plant uses about 3 metric tons of steel and 27 $m^3$ of concrete per average megawatt electric, a typical wind-energy system uses 460 metric tons of steel and 870 $m^3$ of concrete. Solar and renewables in every form require masses of machinery to produce many megawatts. They lack efficiencies and economies of scale. Like low-yield farming, to produce more calories, solar and renewables multiply in extent, linearly. Unlike the Internet, solar and renewables cannot become much smaller as they become much larger. Thus, they will grow little.

Fortunately, hot new technologies like ceramics, as well as cool ones like superconductors, make possible big, truly green energy machines. ZEPPs and SuperGrids can multiply the power of the system 5–10 times while shrinking it in a revolutionary way.

## Further Reading

Electric Power Research Institute. *High-Temperature Gas-Cooled Reactors for the Production of Hydrogen: An Assessment in Support of the Hydrogen Economy;* report no. 1007802; EPRI: Palo Alto, CA, 2003.

Overbye, T.; Starr, C., conveners. *Report of the National Energy Supergrid Workshop*; Palo Alto, CA, Nov. 6–8, 2002; available at http://www.energy.ece.uiuc.edu/SuperGridReportFinal.pdf.

Peterson, P. F. Will the United States Need a Second Geologic Repository? *The Bridge* **2003**, *33* (3), 26–32.

Yantovskii, E. I. *Energy and Exergy Currents*; Nova: Commack, NY, 1994; 183 pp.

### BIOGRAPHY

**Jesse H. Ausubel directs the Program for the Human Environment at The Rockefeller University in New York (ausubel@rockefeller.edu). This article is based on his presentation at the Millennium Technology Prize Symposium in Espoo, Finland, June 14, 2004. Thanks to C. Marchetti.**