platts

The McGraw-Hill Companies

Transmission & Distribution

SOURCE BOOK

www.td.platts.com

FALL 2005

brought to you by Power magazine

THE FUTURE OF TRANSMISSION

Buyers' 2006 Guide

Might "Hydricity" SuperCables eventually deliver both hydrogen and electricity?

By Dr. Paul M. Grant

Transporting large quantities of electric power over long distances via superconducting DC cables was first considered over 40 years ago by two IBM scientists. With the recent advent of long-length commercial high-temperature superconductors and the desire to move the U.S. to a hydrogen-based economy, SuperCables could revolutionize the marketing of electricity.

How to supply and configure an energy economy and infrastructure for a world of more than 10 billion inhabitants by mid-century is perhaps the principal long-range challenge facing human civilization today. A closely related challenge will be finding the most environmentally benign way to supply that energy.

A key variable in this socioeconomic equation is the extent to which Earth's remaining fossil fuel reserves can be exploited. Even though the link between observed increasing global temperature and increasing carbon dioxide emissions is debatable, all agree that such a link is plausible. With the Kyoto Protocol representing a first attempt to limit climate change, the coming decades are likely to see worldwide adoption of national carbon caps that could severely restrict the use of fossil fuels for both transportation and the production of thermal and electrical energy. One major harbinger of this trend is accelerated efforts to develop technology to displace hydrocarbons with hydrogen for fueling surface transportation. An example is California's Hydrogen Highways initiative.

But there is a downside to the hydrogen economy that must be considered. Production of sufficient hydrogen—either by electrolysis or by thermal splitting of water or methane—to displace present consumption of petroleum by automobiles and trucks in the U.S. alone would require increasing by 50% the nation's current electricity generation capacity. Given the massive amounts of CO_2 that would need to be sequestered should hydrogen be generated either directly or indirectly from fossil fuels, and given the enormous land areas needed for new biomass, wind, or solar plants that such an expansion would require, only nuclear power can feasibly enable a complete hydrogen economy.

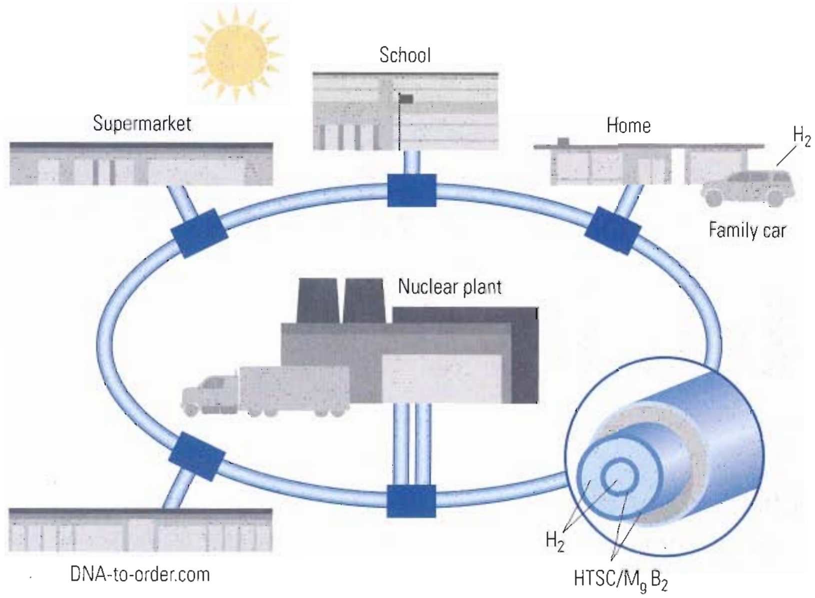
In a certain sense, hydrogen and electricity can be considered "mutually fungible." In a number of instances, each can replace or be transformed into the other—hydrogen as potential energy, and electricity as kinetic energy. However, it will be most realistic to provide both and let the end user decide. Figure 1 depicts just such a scenario on an urban scale. The electric portion of the grid would use high-current DC superconducting cables for power transmission, with liquid hydrogen as the core coolant. The electric power and hydrogen would come from nuclear and other 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, perhaps for the next generation of fuel cell–powered automobiles.

A short history of superconductivity

Almost immediately after superconductivity was discovered in 1911, scientists proposed applying the phenomenon to electricity transmission and distribution. Superconducting wires and cables held the promise of carrying direct current without loss. However, the early superconductors were primarily elemental metals whose superconducting properties disappeared in the presence of even moderate currents and magnetic fields. Furthermore, the superconductors' operational need for

1. The grid of the future?

In this conceptual drawing, an urban community's entire electricity supply comes from a nuclear plant and rooftop photovoltaic panels. The nuclear plant also generates hydrogen, which is distributed along with the electricity by a SuperCable ring bus.



Source: Dr. Paul Grant

large amounts of liquid helium was a major barrier to their development and use. It wan't until the post–World War II discovery of "hard" superconducting alloys capable of sustaining practical levels of current, the ability to manufacture long wire lengths of these materials, and the availability of efficient helium liquefaction equipment that any proposal to use superconductivity for electricity transmission could be taken seriously.

In 1967, Richard Garwin and Juri Matisoo of IBM published a paper proposing the construction of a 100-GW, 600-mile, superconducting DC transmission line based on the then newly discovered type II compound, Nb3Sn. The line would have to be refrigerated along its entire length by liquid helium at 4.2 Kelvin (K). At the time, it was thought that remote nuclear power plant farms or hydroelectric plants would supply a major portion of growing national electricity demand, and that "high power bandwidth" superconductor cable transmission at near-zero loss would become economical. In principle, Garwin's and Matisoo's idea presaged many aspects of the "SuperCable" concept.

In the 1970s and early 1980s, more studies on the feasibility of both AC and DC superconducting cables appeared, and two watershed AC superconducting cables were built and successfully tested at Brookhaven, N.Y., and Graz, Austria. The latter cable actually provided live grid service for several years. In 1975, a report assembled by Stanford University and the U.S. National Institute of Standards and Technology (NIST) examined the use of "slush hydrogen" at 14K as cryogen for a cable using Nb3Ge with a transition temperature near 20K as the superconductor. However, no attention was given to the use of hydrogen as an energy agent itself.

The discovery of high-temperature superconductors (HTSCs) in 1986 and the development of practical HTSC tape and wire in the early 1990s gave rise to the idea at EPRI that an HTSC DC "electricity pipeline" cooled by liquid nitrogen could compete economically with conventional high-voltage DC transmission lines or gas pipelines for the task of transporting energy over distances greater than 120 miles.

Although today several prototype HTSC cables are being demonstrated and tested worldwide, all of these projects envision AC applications at T&D voltage levels of 66 kV and above. But the major advantage of superconductivity is its ability to transport large DC currents at relatively low voltage. Superconductors are lossless conductors only under constant-current conditions. When current levels fluctuate, heat-producing hysteretic losses occur, and they require additional cryogenic capacity to remove ambient thermal inleak to the cable. Moreover, the use of lower voltages reduces dielectric stress and improves cable reliability and longevity.

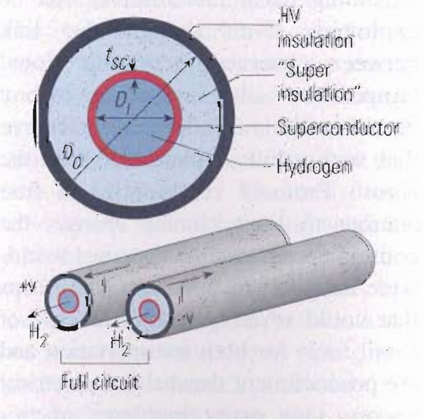
A preliminary design

Perhaps the most important design issue for the SuperCable involves the absolute and relative amounts of hydrogen and electric power to be delivered. As a first-order analysis, assume the peak demand of a typical home is 5 kW. To service a community of 200,000 households, a SuperCable would have to deliver 1,000 MW_e via superconductors and 1,000 MW_t via flowing hydrogen for heating and cooking.

Figure 2 depicts the essential physical characteristics and cross section of a basic SuperCable and a circuit based on

2. SuperCable

This SuperCable cross section and schematic for one pole of a bipolar circuit are roughly to scale.



Source: Dr. Paul Grant

Table 1. Nominal SuperCable parameters enabling delivery of 1,000 MW_t of hydrogen

Hydrogen power (MW_t)	Cryostat tube diameter (inches)	Hydrogen flow rate (ft/sec)	"Equivalent" electrical current density (A/in^2)
1,000	6	11.1	1,825

Source: Dr. Paul Grant

Table 2. Superconductor current density and annular wall thickness enabling delivery of 1,000 MW_e, given the parameters of Table 1

Electric power (MW_e)	Voltage	Current	HTSC current density (A/in^2)	Annular wall thickness (inches)
1,000	± 5,000 V	100,000 A	161,300	0.033

Source: Dr. Paul Grant

Table 3. SuperCable's potential energy storage capacity vs. that of existing systems

Facility	Capacity (GWh)
Raccoon Mountain (TVA)	32
Alabama Electric Cooperative's McIntosh compressed-air energy storage (CAES) plant	20
250-mile SuperCable circuit (with 6-inch-diameter tube)	33

Source: Dr. Paul Grant

it. Note that each "cable" delivers half of the total hydrogen power. Tables 1 and 2 contain estimates of the physical dimensions and superconductor material performance needed to achieve the target 1,000 MW capacities for both hydrogen and electricity.

Finally, it is interesting to consider hydrogen in the SuperCable acting not only as a cryogen and an energy delivery agent, but also as a possible electricity storage medium. For example, suppose that in the circuit in Figure 2 the liquid hydrogen is circulated through both "poles" (rather than flowing unidirectionally in each), with only small amounts tapped off for delivery, leaving most of the hydrogen available for conversion to electricity.

In such a configuration, a 250-mile SuperCable circuit would store the equivalent of TVA's Raccoon Mountain reservoir (the largest pumped-storage hydro unit in the U.S.) with a considerably smaller footprint (Table 3). The big caveat here is that the "round-trip efficiency" of reversible fuel cells has yet to be determined. Of course, not all of this hydrogen would be immediately available, and a reserve supply—probably stationed at the "recooling booster" stations the SuperCable requires every 5 to 15 miles—would be needed to maintain a sufficient amount of hydrogen for cryogenic purposes. A nationwide development of SuperCable infrastructure could enable the long-sought-after "commoditization" of electricity through its storage as liquid hydrogen, thereby revolutionizing electricity markets.

Technical obstacles remain

Leaving aside for the moment the frictional energy released by the viscous flow of liquid hydrogen, the principal losses from the SuperCable would be radiation from the surrounding ambient environment and the replenishment of the recooling booster stations with hydrogen to maintain design temperatures in the SuperCable. But on a practical basis, the level of ripple induced in a DC line by rectification and imperfect filtering of an AC generation source also could become a serious issue.

For example, even if the ripple factor were only 1%, at 100,000 amps there will exist a 1,000-A (rms) current whose heat production will have to be dealt with. Moreover, managing supply/load variations will require constant current control by changing the voltage level. Energizing and de-energizing the electrical system of the SuperCable must be handled with great care—a well-known challenge with persistent-current superconducting magnets. Finally, heat in-leak due to thermal conduction from the ambient environment can be neglected if the vacuum level between the inner cryostat and outer high-voltage insulation sheath can be kept below 10^{-5} torr. Each of these technical issues will undoubtedly be the subject of more research and development.

The SuperCable is, of course, a highly speculative concept, even though currently available superconducting materials suggest the concept is technically feasible right now. Yes, there are many difficult engineering issues that remain to be addressed. Among them are:

- How to accommodate the substantial forces between two monopole cables created from the magnetic fields surrounding the flow of 100,000-A currents.
- Determining what sort of power electronics infrastructure is required to maintain the lowest possible ripple factor.
- Figuring out how to manage load/supply variations at constant current.

But, with the potential benefits so great for human civilization, it behooves the worldwide engineering community to marshal its considerable resources in the service of seeking answers to these questions. ■

The author would like to acknowledge the support, encouragement, and inspiration provided over the years by many colleagues at EPRI—especially its founder, Dr. Chauncey Starr.

*—**Dr. Paul M. Grant** is an IBM research staff member emeritus and an EPRI science fellow (retired), and now holds an appointment as visiting scholar in applied physics at Stanford University. He is also an independent energy consultant and can be reached at w2agz@pacbell.net or www.w2agz.com.*