The Energy SuperGrid

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Abstract: Provision of sufficient, clean and affordable energy to sustain both a rising world population and its aspirations to the highest standard of living is the major challenge facing this generation and others to follow throughout the 21st century. We define "clean" as not only implying zero emission fuel for transportation and generation of electricity, but provided in the least eco-invasive manner possible. We propose as a vision to meet this challenge, an Energy SuperGrid, comprising a symbiosis of nuclear, hydrogen and superconducting technologies.

Keywords: Nuclear, Hydrogen, Superconductivity

Introduction: the Problem

According to the DOE International Energy Outlook 2004, world energy consumption is expected to grow from its present level around 400 quads per annum to well over 600 by 2025, a greater than 50% increase.[2] Moreover, many predict human population levels to approach 10 billion by mid-century with global industrialization rates far outpacing those of the United States. As the world aspires to reach an American standard of living, IEO 2004 predicts the present energy consumption rate, 215 quads per year in the industrialized nations and 185 in emerging countries, to evolve toward 270 to 330, respectively. How to supply and configure the energy economy and infrastructure for such a world is perhaps the principal long-range challenge facing human civilization at the dawn of this new century. A major component of the challenge will be to attain this goal in the most environmentally benign and least eco-invasive manner possible.

A principal uncertainty in this social equation is the extent to which the earth's remaining fossil fuel reserves can be exploited. Even though the possible link between observed increasing global temperature and concomitant increasing carbon dioxide emissions (currently at 6,000 MMTCE/year and expected to reach 10,000 by 2025) remains controversial, all agree that such a link is at least physically plausible, and the coming decades are likely to see an internationally agreed upon "no regrets" policy adopted severely restricting or eliminating the use of fossil fuels for both transportation and the production of thermal and electrical energy. One major harbinger of this trend is the concentrated effort globally to develop technology to displace hydrocarbons with hydrogen for surface transportation fuel. We have argued that the production of sufficient hydrogen to displace present consumption of petroleum in automobile and truck vehicles in the United States alone, either by electrolysis or thermal splitting of water or methane would require additional power production equivalent to doubling the nation's current electricity generation capacity.[3] Given the massive amounts of CO_2 to be sequestered should hydrogen be generated either directly or indirectly from fossil fuels, and the enormous land areas needed for biomass, wind or solar required in its place, it was concluded that only nuclear power could feasibly enable a complete hydrogen economy.

SuperGrid: the Solution

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 kinetic. However, it will be most realistic to provide both and let the end user decide the choice to employ. Figure 1 depicts just such a scenario on an urban scale, where both hydrogen and electricity are produced centrally in a nuclear power plant, supplemented by roof-top solar photovoltaics and the combustion of waste biomass, and distributed throughout the community via a "SuperCable" conveying cryogenic hydrogen and electricity using superconducting wires refrigerated by the former.[4,5]

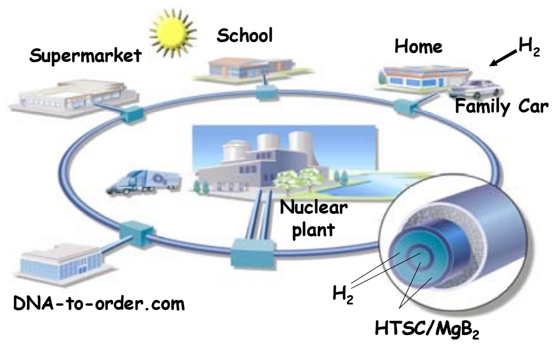

Fig.1 Vision concept of an urban community whose complete energy infrastructure comprises electricity and hydrogen generated by nuclear fission and solar roof power distributed through a SuperCable ring bus[4]

This urban concept was subsequently expanded to include the vision of a "Continental Energy SuperGrid," a nationwide network of nuclear power plants linked by such SuperCables,[6] and was further addressed in a workshop organized to explore the engineering feasibility of various aspects of the SuperGrid, including the topics of system stability, reliability and physical security, which concluded such a project, despite its immense scale and cost, could in principle be carried out using present or soon to be available technology.[7]

Nuclear Power: Heart of the SuperGrid

Above we made the assumption that continued combustion of fossil fuels as the primary power source for transportation and electricity generation would prove unacceptable in the long term, either due to carbon emission elimination, or depletion of natural resources.

In addition, we held society would require its energy infrastructure to minimally invade the ecology and environment, preserving as much natural habitat as possible, concluding that only nuclear fission power can accommodate both goals.

A few simple examples will suffice to show why sequestration and massive deployment of renewable energy have to be ruled out as sources of baseline power.

It is estimated that simply to displace present US daily consumption of gasoline with electrolytically manufactured hydrogen would require the addition of 400 GW of continuously available power to national electricity production.[3] To give this number some perspective, some 500 800-MW coal plants or 20 20-GW Three Gorge hydroelectric facilities would have to be constructed.

In terms of the foreseen efficiencies of two popular renewable options, the wind resources needed would occupy about 130,000 km^2 of land area (roughly the size of New York State) and photovoltaic solar nearly 20,000 km^2 or the entire country of Denmark, and these estimates assume 100% availability. Realistic diurnal generation by each of these renewable technologies seldom exceeds 25% on average, so the land mass required would quadruple.

Biomass does not fare much better. To supply 400 GW by biomass in the US, one would have to put land area equal to size of the state of Nevada…the 7th largest in the country…under agricultural production, and also require even more energy to produce the necessary fertilizer. Carbon dioxide sequestration on a scale to capture emissions from 400 gigawatts worth of coal plants would require enormous underground reservoirs or oceanic dispersal with uncertain environmental consequences.

Given these environmental and ecological impediments to fossil and renewable resources, only nuclear fission power can rationally be considered, and even here the prospect is daunting. Four hundred 1-GW light water reactors or 50 8-GW clusters of plants the size of Tokyo Electric Power's Kashiwazaki Kariwa facility would have to be built. However, the power density of Kashiwazaki Kariwa is an astounding 1800 watts/m^2, including all support facilities, temporary "waste" storage and enclosed wildlands, as compared to 10 – 100 watts/m^2 for wind and solar when actually generating at peak capacity. Thus 400 GW of electricity could in principle be produced on a total land area equivalent to that of metropolitan San Francisco. With the emerging high temperature helium gas cooled reactor technology with passive resistance to meltdown, most future nuclear generation could be safely and conveniently placed underground.

SuperCables: Arteries of the SuperGrid

Superconducting Cables

Almost immediately after its discovery in 1911, superconductivity and superconducting wires, with their ability to carry direct current without loss, were proposed for electricity transmission and distribution cable application. However, the early superconductors were primarily elemental metals whose superconducting properties disappeared under even moderate currents and magnetic fields. Furthermore, the necessity to supply large amounts of liquid helium for their operation was a major, if not overwhelming, barrier. Not until the discovery of "hard" superconducting alloys such as NiTi and Nb_3Sn capable of sustaining practical levels of current in the years following World War II, the ability to manufacture long wire lengths of these materials, and the increasing availability of efficient helium liquefaction equipment, could transmission of electricity via superconductivity be seriously considered.

In 1967, Richard Garwin and Juri Matisoo at IBM published a paper proposing the construction of a 100 GW, 1000 km, dc superconducting transmission line based on the then newly discovered type II compound, Nb_3Sn, refrigerated throughout its entire length by liquid helium at 4.2 K.[8] At the time it was thought remote nuclear power plant farms or hydroelectric facilities would provide a major portion of the then burgeoning national demand for electricity, and that the "high power bandwidth" transmission at near zero loss available from deployment of superconducting cables would become economical. In principle, their idea presaged many aspects of the SuperGrid 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, NY, and Graz, Austria, the latter actually undergoing live grid service for several years.[9] At least two reports published during this period explored the joint use of hydrogen with superconducting wires for electricity transmission. Bartlit, Edeskuty and Hammel considered an energy transmission line employing low temperature superconductors cooling by liquid helium with liquid hydrogen serving as a heat shield, the hydrogen to be delivered eventually as rocket fuel for NASA.[10] In 1975, a report assembled by Stanford University and NIST examined the use of "slush hydrogen" at 14 K as cryogen for a cable using Nb3Ge with a transition temperature near 20 K as the superconductor;[11] however, no attention was given the use of hydrogen as an energy agent itself.

Following on the discovery of high temperature superconductors in 1986 and the appearance of practical tape and wire in the early 1990s, Schoenung, Hassenzahl and Grant revisited the work of Garwin and Matisoo in light of these new events, and concluded that an HTSC dc "electricity pipeline" cooled by liquid nitrogen could compete economically with conventional high voltage dc transmission lines or gas pipelines for distances greater than 200 km.[12] Although today several prototype HTSC superconducting cable demonstrations are planned or actually undergoing test worldwide, all target ac applications at transmission and distribution voltage levels at 66 kV and greater, we must emphasize that the major advantage of superconductivity is the ability to transport very large dc currents at relatively low voltage. Only under constant current conditions are superconductors perfect conductors, otherwise heat-producing hysteretic losses occur requiring additional cryogenic capacity above and beyond that to remove ambient thermal in-leak to the cable. Moreover, the use of lower voltages will reduce dielectric stress and improve cable reliability and extend lifetime.

Balance between Hydrogen and Electricity Power Delivery

Perhaps the most important design issue for the SuperCable surrounds both the absolute and relative amounts of hydrogen and electric power to be delivered. In a total "hydricity economy," such questions remain to be socially and economically settled, and much of the answer will depend on other means to transport hydrogen and the end use it will receive. Will the latter be as thermal energy, transportation fuel or energy storage, or, as is likely, a combination of all three and in what proportion? For purposes of our preliminary design discussion, we will employ the principle of "greatest social transparency," or "least interference" with current individual energy consumption customs. That is, we will simply assume hydrogen as a domestic energy agent will completely supplant current consumption of hydrocarbons (natural gas, LPG or heating oil) and household electricity demand will remain more or less the same. Hydrogen for transportation will assumed to be distributed independently. The typical California residential household (such as the author's) consumes roughly equal amounts of electricity and thermal energy in the form of natural gas annually. We will assume the peak demand at any given time to be 5 kW equivalent for each, we will configure a SuperCable to deliver 1000 MWe via superconductors and 1000 MWt via flowing hydrogen to service a community of 200,000 households (even though utilities design for much larger local capacity, e.g., wire size a split phase 200 ampere service for ~ 50 kW, transmission and generation capacity are probabilistically determined on the assumption only a small number of consumers will actually need this amount of power at any given time!).

Figure 2 outlines the essential physical characteristics and cross-section of a basic SuperCable circuit. Note that each "cable" delivers half the total hydrogen power.

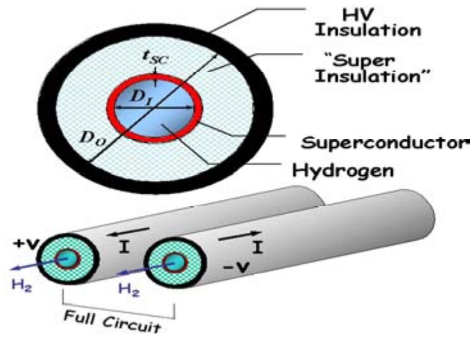

Fig. 2 SuperCable cross-section schematic (roughly to scale) for one pole of a bipolar circuit.

Engineering and thermal property calculations show the above power delivery capacities for nominal SuperCable dimensions for D_I = 15 cm (the liquid hydrogen transporting inner tube with flow rate around 3.5 m/s) and D_O = 20 cm using presently available commercial high temperature superconductors can be readily achieved.[13]

Storage of Electricity as Hydrogen in the SuperCable

Finally, it is interesting to consider hydrogen in the SuperCable of these dimensions acting not only as a cryogen and an energy delivery agent, but as a possible medium for storage of electricity in addition. For example, suppose in the circuit in Fig. 2, the liquid hydrogen circulated through both "poles," rather than flowing unidirectionally in each, with only small amounts tapped off for delivery, and most left for future conversion back to electricity (this scenario implies LH_2 "buffering tanks" be located appropriately along the length of the circuit to assure enough would be continuously available for cryogenic purposes). Table I compares a possible SuperCable energy storage circuit configuration with two large existing pumped hydro and compressed air energy storage (CAES) facilities in the United States.

Table1 Comparison of potential storage capacity of the supercable with conventional systems

Facility	Capacity (GWh)
Raccoon Mountain (TVA)	32
Alabama CAES	20
400 km SuperCable Circuit D_I = 15 cm	33

Thus a 400 km SuperCable circuit would store the equivalent of TVA's Raccoon Mountain reservoir, the largest pumped hydro unit in the US, with a considerable smaller footprint, and the caveat that the "round trip efficiency" of reversible fuel cells is yet to be determined. Of course, not all this capacity would be immediately available, and a reserve supply, probably stationed at the 10 – 20 km "recooling booster" stations mentioned before, will be necessary to maintain a sufficient amount for cryogenic purposes. A nationwide development of SuperCable infrastructure could enable the long-sought "commoditization" of electricity through its storage as liquid hydrogen and thus revolutionize electricity markets.

Summary and Conclusions

In this paper, we have presented both a technical and societal vision for satisfying the growing energy requirements of an increasingly industrialized world. We maintain such a concept is technically feasible right now without having to anticipate future and problematic discoveries of new materials. Still, a very large number of engineering issues remain to be addressed; e.g., how to accommodate the substantial forces between between two monopole cables created from the magnetic fields surrounding the flow of 100 kA currents…would a coaxial design serve better? How do we handle the high voltages and disperse the current generated under fault condions? What sort of power electronics infrastructure is required to maintain the lowest possible ripple factor and manage load/supply variation at constant current? And then, there are a myriad of energy use variables that are really societal and economic determinants, such as the division in the deployment of electricity versus hydrogen alluded to before and the safety problems relevant to distributing and using hydrogen.

Finally, we have left discussion of what is most certainly the paramount issue surrounding the SuperGrid until last. In terms of sustainability, depending on choice of recycling and reprocessing technology, there exist 300 – 800 years of reserves to maintain and advance nuclear power as the Heart of the SuperGrid. To implement these technologies, the world needs to confront the possible diversion of nuclear materials to weapons of mass destruction.[14, 15] International laws and institutions must be established that control and vigorously enforce use of actinide materials for peaceful purposes only from minehead, through recovery and breeding, to eventual disposal, and prevent diversion to rogue nation weapons programs. Only then can be realized the vision the fathers of the atomic age foresaw and desired, a world where 'atoms for peace' would prevail, creating a clean energy source independent of any geographically accidental richness of fossil reserves. Perhaps that would be the greatest legacy left by the SuperGrid to future generations.

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Appendix: Nomenclature

One quad equals one quadrillion (10^{15}) Btu (British thermal unit), or 3×10^{11} kilowatt-hours. On average, one quad per year is enough to power about three New York Cities. MMTCE denotes million metric tonne carbon equivalent, and HTSC denotes "high temperature superconductors," defined as those metals with a transition temperature above 30 K. The use of the terms "hard" or "type II" are equivalent descriptions of practical superconductors.

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BIOGRAPHY

Paul M. Grant was born in Poughkeepsie, NY, on May 9, 1935. He holds a BSEE degree from Clarkson University and the AM and PhD degrees in Physics from Harvard University. His undergraduate and graduate education was underwritten by the IBM Corporation whose employ he entered in 1953 at age 17.

His early career with IBM was as a technician and system programmer on Project SAGE, the world's first supercomputer and prototype for NORAD. During college, he returned to work summers at IBM on thin magnetic film memory development, silicon epitaxial film growth and laser spectroscopy. His PhD thesis addressed the optical properties of semiconductor thin films.

Upon completing graduate school, Dr. Grant was posted to the IBM San Jose Research Laboratory where he pursued a variety of basic research studies on the physical properties of magnetic semiconductors, organic and polymer metals, and high temperature superconductors and participated in the initial development of laboratory automation software and systems. His IBM career also included management and divisional executive staff responsibilities to evaluate IBM's printer, storage and display technologies.

In addition, he served a two-year sabbatical as IBM Visiting Professor of Materials Science at the National University of Mexico.

In 1993, Dr. Grant retired from IBM to accept a position as Science Fellow at EPRI where he oversaw a variety of exploratory studies on wide bandgap semiconductors and power applications of superconductivity, and served as a consultant to EPRI's executive management and utility membership on a broad range of energy science issues. He retired from EPRI in early 2004 to undertake a variety of personal and professional interests.

Dr. Grant has published over 100 papers in scientific peer-reviewed journals, as well as numerous articles on science and energy issues in the popular press and interviews on television which have earned him several awards as a science writer and commentator. He is a co-inventor on the international base patent for high temperature superconductivity and consults regularly with the US Department of Energy on power applications of superconductivity. Dr. Grant is a Fellow of the American Physical Society and sits on the Executive Committees of the Society for Industrial Physics and Education.

DOE Activities

- Reviewer of DOE Office of Electric Transmission and Distribution (OETD) National Laboratory programs in HTSC power applications.
- Advisor (along with Paul Chu) to Jimmy Glotfelty, OETD Director, on technology issues involving HTSC and FACTS. We helped write the 2003 presentation to the Office of Management and Budget for 2004 appropriations.
- Co-managed with DOE the EPRI/Pirelli cable project, the first prototype superconducting cable in the US.
- Co-managed with DOE the Detroit Edison Frisbie substation demonstration.
- Reviewer of project proposals received by OETD for support (e.g., dc HTSC cables, very low impedance ac cables).
- Often DOE asks me, as a private citizen, to explore "delicate issues" of interest to the Department. For example, I was asked to meet with Sumitomo executives and assure them they could participate in the US Superconductivity Partnership Initiative without facing "political" barriers. These negotiations led to the present "Albany Cable" project. Likewise, I pursued, on behalf of OETD, the question whether American Superconductor would consider being prime contractor for the LIPA cable project.