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Program on Technology Innovation: Functional Requirements of a Hydrogen-Electric SuperGrid

Two Scenarios – SuperSuburb and SuperTie

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ABSTRACT

To effectively supply U.S. energy needs 30-40 years in the future, EPRI has proposed a unique visionary concept called the Hydrogen Electric SuperGrid. The core concept of the SuperGrid is a “continental-scale” (e.g., coast-to-coast), superconducting hydrogen-electric transmission system. Electricity and hydrogen would be supplied by advanced nuclear reactors, spaced along the transmission line corridor(s). The line would consist of a high-capacity, direct-current (dc), superconducting power transmission cable. In addition to electricity, it would carry hydrogen supplied by the nuclear plants to cool the superconducting cable. Excess hydrogen produced by these plants would be available for commercial use in local energy markets. Load centers across the country could withdraw electric power and hydrogen as needed. The SuperGrid would supplement, not replace, the existing regional gas and electric grids now in place. The SuperGrid would produce no greenhouse gases, would use domestically derived fuel, and would be relatively invulnerable to natural or man-made catastrophic events.

This report describes the results of an initial investigation into establishing the functional requirements for the key SuperGrid technologies. It includes a discussion of the current state of the respective technologies and a description of two, somewhat arbitrarily defined scenarios—for a SuperSuburb and a SuperTie. Through these scenarios, the requirements for electricity, electricity storage, hydrogen, and a cable for the SuperGrid are determined. An examination of each scenario reveals critical issues, especially with regard to the SuperCable technology, that need to be addressed whatever form the SuperGrid vision eventually takes. The methodology followed involved the use of spreadsheets that would allow other scenarios to be developed in the future.

It is important to note that all necessary technologies already exist, and that, although certainly welcomed, no new scientific discoveries or breakthroughs are needed to bring about its final realization. Significant engineering development and demonstration will be required to realize the ambitious goals set forth. An ancillary payoff from such efforts is that these could yield near-term results to meet current transmission system needs (e.g., development of a cost-effective dc superconducting transmission cable).

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1
INTRODUCTION

Overview

Long-range energy planning in the United States faces several challenges and uncertainties. One fundamental challenge is the ability of the country's energy systems to keep pace with growth. The continuous electrification of the U.S. commercial and residential sectors, and a modest population growth, will result in about a 2% annual growth in electricity demand. If electrification of a fraction of the country's transportation becomes a reality, either directly or indirectly, the growth will be much larger. An annual growth of 2% will double U.S. electricity usage by mid-century. As it has in the past, the electric utility system will find a way to meet such growth, but such forced network growth may not achieve the greatest economic and performance efficiency.

Other challenges involve environmental and reliability issues. The environmental consequences of increased fossil fuel use are of continuing concern. The ability of the national electrical grid to develop a fault-proof interconnection system has not as yet been demonstrated. Vulnerability to natural weather events, inadequate infrastructure, and malicious terrorism may increase as the system grows. Finding rights-of-way for new power lines has become a major permitting obstacle. Finding cooling water for power plants is becoming a physical obstacle. Solar and wind are intermittent and very costly and unlikely to ever supply more than 10-20% of the real end-user electrical demand.

To meet these challenges, EPRI has proposed a unique visionary concept called the SuperGrid. The core concept of the SuperGrid is a "continental-scale" (e.g., coast-to-coast), superconducting hydrogen-electric transmission system. Electricity would be supplied by advanced nuclear reactors, spaced along the transmission line corridor(s). The line would consist of a high-capacity, direct-current, superconducting power transmission cable. In addition to electricity, it would carry hydrogen supplied by the nuclear plants to cool the superconducting cable. Excess hydrogen produced by these plants would be available for commercial use in local energy markets. Load centers across the country could withdraw electric power and hydrogen as needed. The SuperGrid would supplement, not replace, the existing regional gas and electric grids now in place. The SuperGrid would produce no greenhouse gases, uses domestically derived fuel, and is relatively invulnerable to natural or man-made catastrophic events.

While the components of the SuperGrid are feasible, each will require extensive engineering research, development, and demonstration (RD&D) to reach the stage of commercial operation. To achieve this goal, EPRI proposes a broad-based national collaboration consisting of university engineering graduate programs, national laboratories, and the utility industry. A key feature of the program is that progressive efforts begun now will have a near-term payout in a variety of applications other than the SuperGrid, yet will advance the state of the technology so that an integrated SuperGrid system will be ready to meet the energy needs of our society by mid-century.

This report describes the results of an initial investigation into establishing the functional requirements for the key SuperGrid technologies. Section 2 discusses the current state of the component technologies—including nuclear, superconductivity, hydrogen, power electronics, and underground construction. To illustrate the scope of the functional requirements for a SuperGrid, Section 3 posits two broad scenarios: a SuperSuburb—a complete hydrogen and electricity, or “hydricity,” community; and a SuperTie—a nationwide intertie to facilitate diurnal balancing of electricity supply and demand. These scenarios were selected and characterized to provide the conceptual basis for calculating typical functional requirements for electricity, electricity storage, hydrogen, and a cable for the SuperGrid. It must be emphasized that this exercise is intended to be foundational, a “zero-order” view. Other scenarios are possible, and may be found even more attractive as development continues. To that end, the calculations presented in this report are supported by spreadsheets that allow changes to the defining parameters as need suggests. This report does not, however, include the spreadsheet nor document its construction.

Definition of Terms

SuperGrid

The generic description of a possible future energy system that integrates nuclear, hydrogen, and superconducting technologies to supply electricity and hydrogen without producing greenhouse gases. Possible components include advanced nuclear reactors, an underground high-capacity superconducting power transmission cable, as well as solar and biomass renewable technologies.

SuperCable

Description of an “energy pipeline” for the dual delivery of electrical and chemical power via superconducting wire (high-temperature superconductors [HTSC] or magnesium diboride, MgB_2) and cryocooled hydrogen and/or methane, in either liquid or gaseous form, either directly or using liquid nitrogen as an intermediary cryogen.

SCDC Cable

A superconducting dc cable utilizing HTSC wire and liquid nitrogen as the cryogen. The SCDC cable is currently seen as an intermediary step on the way to full implementation of the SuperCable, which would likely use hydrogen rather than nitrogen as the cryogen.

SuperSuburb

A model residential suburban community based loosely on 300,000 upper-middle-class households with total energy requirements similar to those found in Northern California.

SuperTie

A conceptual transcontinental intertie based on the SuperCable model designed to take advantage of diurnal pricing variation.

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CURRENT STATUS OF SUPERGRID COMPONENT TECHNOLOGIES

Nuclear

The generation of electricity via nuclear fission has a long and varied history. As often happens with the development of any new technology, unforeseen problems arise as that technology is deployed in society. In the case of nuclear power, given the immense amount of energy involved and the radioactive nature of the process, these problems have the potential for serious and disastrous consequences when they emerge through nuclear power plants. One might argue that the worst nuclear power plant accidents that could happen have already happened—Three Mile Island and Chernobyl—and the lessons learned thereafter have made nuclear power perhaps the safest of any large-scale industrial process. This increased safety factor is even more ensured by newer designs such as the Generation IV high-temperature gas-cooled reactors. Expelling their waste heat directly into the air also eliminates many siting issues associated with lower-temperature reactors, which must be located near thermal heat sinks such as large bodies of water. The Generation IV reactors also have a property that is quite crucial to the SuperGrid vision—the ability to produce either electricity or hydrogen with equal thermal efficiency.

Superconductivity

For the electricity portion of the SuperGrid, where we need to move gigawatts (GWs) hundreds of miles, perfect conductors would be ideal. In 1911, just such materials, called superconductors, began to be discovered. However, they also posed several problems—in order to have no electrical resistance, they had to be cooled to near absolute zero by liquid helium. Moreover, they could only carry moderate amounts of current, and resistance reappeared when the superconductors were subjected to fairly small magnetic fields. It took more than 50 years to synthesize and develop practical superconductors that could be made into wires and magnets. A number of prototype power devices—motors, generators, transformers, and cables—were constructed and successfully tested in the 1960s and 1970s, but the cost and unreliability of the refrigeration infrastructure prevented utility application. Other than in the powerful magnets used for laboratory research, medical magnetic resonance imaging, and devices used to focus the collision of fundamental particles to explore the frontiers of the Big Bang, superconductors have not had major commercial deployment.

The year 1986 reawakened old dreams to use superconductivity for the lossless transmission of electric power. Two IBM scientists, Georg Bedorz and Alex Mueller, who were to go on to win the 1987 Nobel prize in physics, found a class of copper oxide ceramics that are superconducting at the unheard of temperature of 30 K. This achievement was followed shortly by the discovery of a compound of similar type with a transition temperature of 91 K, well above the “Holy Grail” temperature of 77 K, the boiling point of liquid nitrogen readily obtainable from the air. Today’s record temperature is 135 K, but the practical “high-temperature” superconductors (HTSC) used for wire have critical temperatures in the range 90–110 K.

The ensuing 20 years have witnessed many prototype and demonstration projects, including the construction and operation of HTSC ac cables, using wire and tape based on these new materials. However, there are major disadvantages to using superconductivity for ac. Superconductors are, by well-established physical principles, not perfect conductors at any frequency other than zero (dc). Nonetheless, even at 50–60 Hz, superconductors are some 200 times less resistive than copper at the same temperature. At present, a number of cable demonstrations exist or have been completed worldwide—all ac and below 345 MW in transmission capacity.

However, our vision is to augment the existing electric grid with a set of SuperCables, where each would be used to “wheel” on the order of 5 GW worth of electrons with as close as possible to zero resistance and line loss for distances of up to several hundred miles. This could only be done through a dc superconducting transmission line, operating at perhaps ±50 kV and carrying 50 kA. The SuperCable will use liquid hydrogen (21 K), as both cryogen and chemical power delivery agent, to cool a superconducting core transmitting electricity from a central nuclear production plant. The superconducting wire material can be any of those presently under development or actually available, including that made from the recently discovered magnesium diboride, superconducting at 39 K.

Hydrogen

A little over 170 years ago, Michael Faraday, considered the father of modern experimental physics, discovered that water could be decomposed into hydrogen and oxidation under passage of an electric current. Within three years, inspired by Faraday’s finding, William Grove, a British jurist and amateur scientist, determined this reaction was in fact reversible. Hydrogen and oxygen could be combined to produce water and electricity—thus inventing what today we call a fuel cell. In a certain sense, a fuel cell can be thought of as a kind of battery that is continuously being recharged by feeding in hydrogen and oxygen. This uniquely fungible property of electricity and hydrogen opens up the possibility of storing large amounts of electricity as hydrogen, and would be one of the most significant residual benefits of moving to a transportation system based on hydrogen as fuel. We will exploit this “equivalence” as fundamental to the SuperGrid Initiative.

Fuel cells remained a relatively obscure technology until the 1950s when more efficient electrolytes were developed, and they were used as the primary electric power source in the Apollo Command Module throughout the 1960s and 1970s. Attention has since focused on this technology for use in hydrogen-powered hybrid vehicles as a result of concern over carbon emissions and desire for energy independence from foreign suppliers. We should note that a fuel cell is not a “heat engine,” as is the Otto cycle internal combustion gasoline motor, and thus not subject, in principle, to constraints imposed by the Second Law of Thermodynamics on the latter. The theoretical upper limit on internal combustion engines is some 50%, and the best of today’s automobiles can achieve the low 30s. Nevertheless, a fuel cell is far from lossless, and present units convert only 60% of the chemical potential of hydrogen into electric power. Added to these losses are those resulting from conditioning the direct current output for the electric motor drive chain, a process that is about 80% efficient. Thus, a hydrogen fuel cell hybrid can be expected to derive about 50% of the energy that went into producing the hydrogen in the first place. With improvements in fuel design, this number could reach the mid-60s in the future.

While we will probably never need to completely replace all hydrocarbons used in transportation, replacing even a modest percentage would require staggering amounts of hydrogen. Part 2 of the SuperGrid concept envisions an energy economy that uses energy delivered in the form of hydrogen and electricity (“hydricity”) with fuel cells and electrolysis used as a pollution-free means of interchange. The delivery of hydrogen to fueling stations (gas pumps) is one of the principal challenges that any “hydrogen economy” has to face. For this challenge, the SuperGrid vision offers an attractive solution: create much of the hydrogen with the Generation IV high-temperature reactors and then transport it with the electricity.

Power Electronics

Exploring the design and operation of appropriate power electronics and systems to control the “electricity portion” of the SuperCable in a point-to-point model will be an important component of the vision. Power electronics, especially in the form of FACTS (Flexible ac Transmission System) has been well established for more than five decades in the case of HVDC transmission, and is now under application to ac transmission to supply reactive power support. Current silicon power device characteristics and performance will be sufficient for the SuperGrid, especially if the operating voltage level will permit the use of the more common Insulated Gate Bipolar Transistors (IGBTs), rather than specialized Gate Turn-off Thyristors (GTOs). Also an important consideration would be transfer of capacity from the SuperCable to existing overhead lines, should that prove required during operation of initial demonstrations, which are likely to utilize existing overhead rights of way. One relatively unknown area is controlling and dissipating faults under very high dc current conditions; investigation and pursuit of a solution must be a major component of SuperGrid.

It is well known that the electrical and thermal transport properties of all semi-conducting materials are enhanced at low temperature. It is thus worth investigating utilizing the same refrigeration infrastructure necessary to support superconductivity operation to optimize performance of the power electronic devices. However, off-the-shelf “junction transistors,” such as silicon IGBTs and GTOs, are designed for ambient operation and become inoperable at cryogenic temperatures due to “freeze out of minority carriers.” Design and construction of prototype devices with “junction doping profiles,” which will support highly efficient and fast switching at low temperatures, may prove a very useful adjunct to power control in the SuperGrid.

Underground Construction

The SuperCables themselves would mostly be located underground, an approach that could significantly reduce public and political opposition to the construction of new lines. The larger capacity of the SuperCables relative to existing ac lines would help to make undergrounding more cost-effective. Underground construction, tunneling, and micro-tunneling have made great strides in the past decades, as demonstrated by Boston’s “Big Dig,” and New York City’s Water Tunnel #3. There is under construction a 10.4-kilometer, 14.4-meter-diameter hydroelectric tunnel on the Canadian side of the Niagara River, 140 meters below ground at a cost of $600 million dollars using an automated tunnel-boring machine (TBM). Studies completed at Fermilab several years ago focusing on construction of an 800-kilometer, 3-meter-wide, 150-meter-deep circumferential tunnel to house a proposed 200 TeV hadron collider suggested its cost might well be below $1000 per meter. Still, the potential for further technology innovation and the limits of the economics of undergrounding have not been fully explored. Construction of the SuperGrid could greatly spur innovation and cost reduction in this industry.

3

FUNCTIONAL REQUIREMENTS FOR A SUPERGRID

The general scope of the functional requirements for a SuperGrid can be best illustrated through several examples, or "scenarios." However, such scenarios represent a "zero-order" approach, and any actual embodiment will entail an immense engineering and construction undertaking, with many specific details unique to the particular project. In this report we will describe two extreme scenarios—the SuperSuburb, a complete hydrogen and electricity, or "hydricity," community, and the SuperTie, a nation-spanning intertie to facilitate diurnal balancing of electricity supply and demand. Although neither is strictly a "Continental SuperGrid," as originally conceived, an examination of each reveals critical issues, especially with regard to the SuperCable technology, that need to be addressed whatever form the SuperGrid vision eventually takes. Calculations and results for the two scenarios were obtained from spreadsheets, allowing researchers in future studies to devise alternative and perhaps quite different scenarios.

In discussing the functional requirements for these two scenarios, the present report takes for granted the existence of appropriate nuclear and hydrogen generation technologies and power electronic infrastructure. In addition, this document does not directly address the infrastructure necessary to implement the adjunct solar roof and urban biomass renewable energy technology that may be required to supplement the principal base load energy production. However, all these areas require attention and development within the overall SuperGrid initiative and EPRI is developing a research plan to address them.

SuperSuburb

To understand the functional requirements, we will consider how the SuperGrid vision could address the total energy requirements of a large, upper-middle-class American residential community located in a moderate climate such as found throughout California, the Southwest, and the Southern states. To determine individual residential energy requirements, we will use the 2005 statistics for gas, electric, and transportation energy consumption for one household, which we will call the "Common Household Equivalent (CHE)." The household's monthly gas and electric usage is plotted in Figure 3-1.

Electricity Requirements

Note that we have used kilowatt-hour units for gas consumption in anticipation that each residence in SuperSuburb will be an "all-electric house." That is, electricity will supply all household "thermal" requirements that gas often satisfies such as heating, cooking, hot water and fabric dryers, in addition to its usual application for lighting and appliance operation. The principal domestic chemical energy used will be in the form of hydrogen replacing petroleum as the family transportation fuel of choice. However, Figure 3-1 displays a marked variation throughout the year in gas consumption strongly correlated with season, whereas electricity usage is far more uniform. Given the desire, especially for nuclear power plants, to generate baseline power at as constant a level as possible throughout the year, there is an implication that a form of electricity storage needs to be provided if electricity is to take over the task of household heating. We will assume this electricity storage is to be implemented through hydrogen generation and storage at facilities within SuperSuburb and its timely release as electricity when required. We will assume that the hydrogen independently co-generated at the nuclear plant farm will be used as baseline fuel for the personal vehicle fleet of the residents of SuperSuburb, and to serve as cryogen to support the transmission of electricity via superconductivity over the SuperCable.

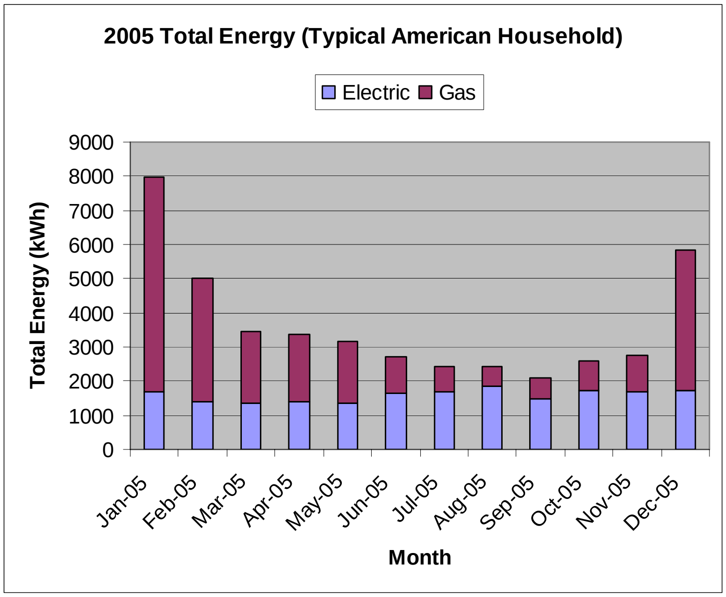


Figure 3-1
2005 Natural Gas and Electricity Consumption by Month for One American Household. (A common energy unit (kWh) is employed.)

The statistical properties of the data displayed in Figure 3-1 are summarized in Tables 3-1 and 3-2.

Several observations can be made. Note, for electricity, the standard deviation is only around 11% of the average monthly consumption, whereas for gas this number is nearly 85%. Moreover, the gas usage deviation is heavily skewed away from a Gaussian mean, and its kurtosis value indicates the distribution has a “peakiness” character, which can also be observed in Figure 3-1. Therefore, a principal design challenge is to ensure sufficient baseline generation at the nuclear plant with appropriate sizing of the electrical portion of the SuperCable, and at the same time provide enough hydrogen “reverse fuel cell – storage” capacity in SuperSuburb to “load-level” seasonal heating fluctuations.

Table 3-1
2005 CHE Energy Consumption Statistics

Energy (kWh)	**Electricity**	**Natural Gas**	**Total**
Annual Total	18,894	24,882	43,776
Monthly Average	1575	2073	3648
Standard Deviation	174	1747	1748
Skewness	-0.15	1.51	1.69
Kurtosis	-1.57	1.88	2.42

Note: Statistically, “skewness” is the “tail distance” away from the mean of a distribution of observations (positive to the right, negative to the left) and is a measure of the “safety factor” required for annual load leveling. “Kurtosity” is the flatness (minus) or “peakiness” (plus) of the distribution.

Table 3-2 restates the energy data of Table 3-1 in terms of power delivered on a monthly basis—that is, the average energy divided by the number of seconds in a month, in order to obtain a rough estimate of the source generation and storage margin that SuperSuburb will require.

Table 3-2
2005 CHE Power Requirements Based on Monthly Time Interval

Power (kW)	**Electricity**	**Natural Gas**	**Total**
Monthly Mean	2.16	2.84	4.99
Standard Deviation	0.24	2.39	2.39
Mean + STD	2.39	5.23	7.39
Mean - STD	1.92	0.45	2.60

Electricity Storage-as-Hydrogen Requirements

The CHE requires an average monthly power delivery of essentially 5 kW, but with a large, almost 50%, deviation. Because all SuperSuburb residential power will derive from a large nuclear facility, an attempt to “load follow” will be undesirable and impractical. However, to deliver constantly only the average will inevitably result in shortfalls during the colder seasons. Thus, a “safety factor” must be applied that is by necessity empirical, whereby enough excess electricity is generated during the warm months to store as hydrogen for re-conversion to electricity and heating during the cold. Calculations performed in the course of this study suggest that a base load rate 20% higher than the monthly mean, 6 kW per CHE, will be sufficient, and would result in a need for facilities to store a maximum energy slightly in excess of 6000 kWh per CHE, which includes a 30% penalty (arbitrary, based on “best-case” practical conversion technology) on the round-trip electricity-to-hydrogen-to-electricity. (This energy need not necessarily be stored at the CHE site.) The hydrogen storage infrastructure required is given in Table 3-3.

Table 3-3
Baseline Electric Power and Energy Storage Requirements per CHE in SuperSuburb

Baseline Power (kW)	Energy Stored (kWh)	Hydrogen Mass Equivalent (kg)	Volume as Liquid (21 K, 14.7 psia) (cube edge in meters)	Volume as Gas (300 K, 2000 psia) (cube edge in meters)
5.99	6129	187	1.38	2.63

Observe that the volume per CHE to be provided for hydrogen storage for simply load-leveling monthly fluctuations is dramatically substantial. If stored as high-pressure gas, the equivalent of around five 1000-gallon standard residential storage tanks would be required (if stored as liquid, a single 500-gallon tank would suffice, but refrigeration support would be required). On top of the basic volume requirement, a reversible fuel cell and water supply must be added. These considerations suggest a central "utility" facility, analogous to a substation, would be more practical than on-site at the household.

Note that scenarios other than the "all-electric house" with hydrogen employed for leveling electricity supply and demand and transportation are possible and perhaps even more desirable. For example, hydrogen could be used instead of electricity for space heating and cooking as well as for transportation. The SuperCable itself can be employed for storage of hydrogen rather than on-site storage tanks in SuperSuburb. By reversing the flow of hydrogen in one of the monopoles of SuperCable, a reservoir of hydrogen would be maintained that would at the same time be "tappable" and provide the cryogenic conditions necessary to sustain superconductivity. Finally, a variant of SuperCable, whereby supercritical hydrogen gas at varying pressure and a constant temperature of 77 K (sufficient to operate present HTSC wires and tapes) provides an alternative method for the storage and release of hydrogen energy.

Hydrogen for Transportation Requirements

This section explores the requirements for replacing gasoline with hydrogen throughout SuperSuburb and the delivery capacity of the SuperCable that would be necessary to support its supply. As mentioned earlier, all transportation-targeted hydrogen will be produced at SuperSuburb's nuclear farm with the dual purpose of acting as cryogen to support the electricity portion of the SuperCable in transit. The demand is assumed to be more or less constant and independent of season, since the fuel will be used for transportation, not heating. Table 3-4 contains CHE background data for the estimate.

Table 3-4
CHE Transportation Energy Consumed

Miles/Year	DOE H_2 Mileage (kWh/mile)	H_2 Daily Mass Consumption (kg)	SuperCable H_2 Delivery Power (kW)
30,000	0.76	1.91	2.61

Note: The CHE mileage estimate may be too conservative. The table data reflect only two vehicles. Many American households may have more than two vehicles.

Table 3-5 provides data on the scope of the delivery needed to supply SuperSuburb with sufficient transportation hydrogen, including "steady-state H_2 station storage" for a normalized household population density of CHEs.

Table 3-5
Number of CHEs per H_2 Station and Individual Station Capacity

US Households (2005)	Number of Stations (1998)	Households per Station	Turnover Rate (days)	H_2 Mass (kg)	Liquid "cube" (meters)	Gas "cube" (meters)
75,000,000	187,000	401	3	2298	3.2	6.1

Note: The data in Table 3-5 were derived from the U.S. Census Bureau and various retail gas station associations. The household number is roughly that of unattached single-family dwellings nationwide. The actual number of gas stations has declined slightly from 1998. The "turnover" rate— that is, the number of day's supply at each station—has anecdotal origins.

Table 3-6 provides estimated data on the gross power delivery to satisfy the residential and personal transportation needs of any given size SuperSuburb. In this case the example used is a community of 300,000 residences, a number slightly greater than contained in San Jose, California, the nation's 10th largest city. Table 3-6 summarizes the results of calculations performed using data from Tables 3-3 through 3-5.

Table 3-6
Baseline Electric and Hydrogen Power Needs of a "San Jose" SuperSuburb of CHEs

CHE Households	Base Electric Power (MW)	Electricity to be Stored as H_2 (tonnes)	Base H_2 Power (MW)	H_2 Stations
300,000	1798	56,104	782	748

Again note the substantial storage capacity that this embodiment of SuperSuburb requires to load-level fluctuations in electric household heating demand, on the assumption that the nuclear plant runs continually 24 hours a day, 7 days a week, 365 days a year. For "centralized" storage on the capacity scale of SuperSuburb's hydrogen "gas" stations, some 25,000 such locations would be necessary. It should be noted that this estimate does not include commercial or industrial energy consumption. Table 3-6 represents a large residential suburban community.

A SuperCable for SuperSuburb

Generation and delivery to the SuperSuburb of the quantity of power identified in Table 3-6 are the next tasks, consistent with the nuclear, hydrogen, and superconductivity symbiosis at the core of the SuperGrid initiative and vision. These steps are shown in Figure 3-2. Specific SuperCable power delivery and dimensional parameters are listed in Tables 3-7 and 3-8. Calculations were made using this data and the concept of the cable shown in the schematic cross-section in Figure 3-3.

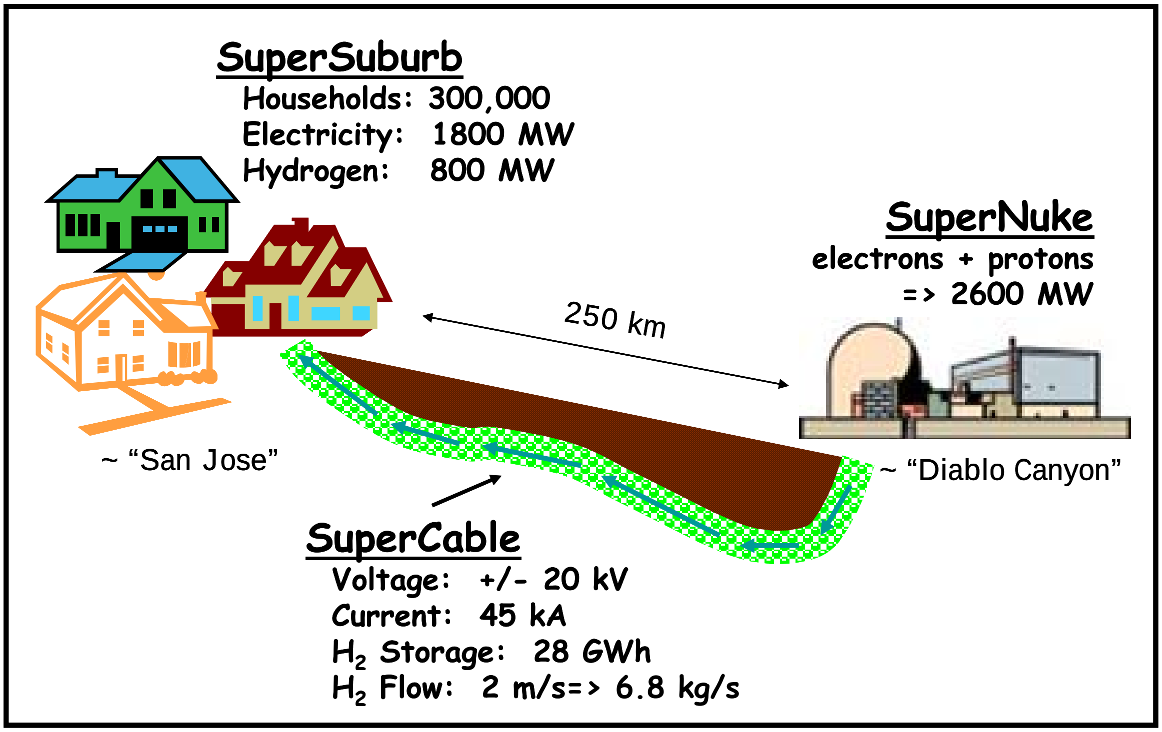


Figure 3-2
Conceptual Depiction of SuperSuburb and its Power Supply

Table 3-7
SuperSuburb SuperCable Monopole Physical Parameters (See Figures 3-2 and 3-3.)

Operating Current Density, J (A/cm^2)	**t_{SC} (cm)**	**Hydrogen Flow Rate (m/s)**	**D_{H2} (cm)**	**Maximum Magnetic Field (T)**
15, 000	0.05	2	17.5	0.10

Table 3-8
SuperSuburb SuperCable Monopole Minutia and Costs

HTSC Tape Parameters							
Width (mm)	**Thickness (mm)**	**Length (m)**	**Total No. Tapes**	**Tape Req'd (km)**	**Approx. No. Splices**	**Tape C/P ($/kA×m)**	**HTSC Cost (M$)**
4	0.25	800	~300	~80,000	~100,000	50	591

It is remarkable that a layer of superconducting tape only 0.5 mm thick, surrounding the liquid hydrogen transport tube 17.5 cm (nearly 7 inches) in diameter, comprising an annulus of about 3 cm^2 in area, is sufficient to carry 45 kA of electric current. Presently available "Generation I" high-temperature superconducting (HTSC) tapes from American Superconductor have operational current densities on the order of 17,000 A/cm^2 at 77 K in tapes nominally 0.25 mm thick and 4 mm wide available in continuous lengths up to 800 meters. Inasmuch as the operating temperature will be around 21 K, our choice of operating current density is very conservative. About two layers of tape will be sufficient, but splices will be needed every kilometer or so, and these may present a difficult issue. Table 3-8 summarizes these details.

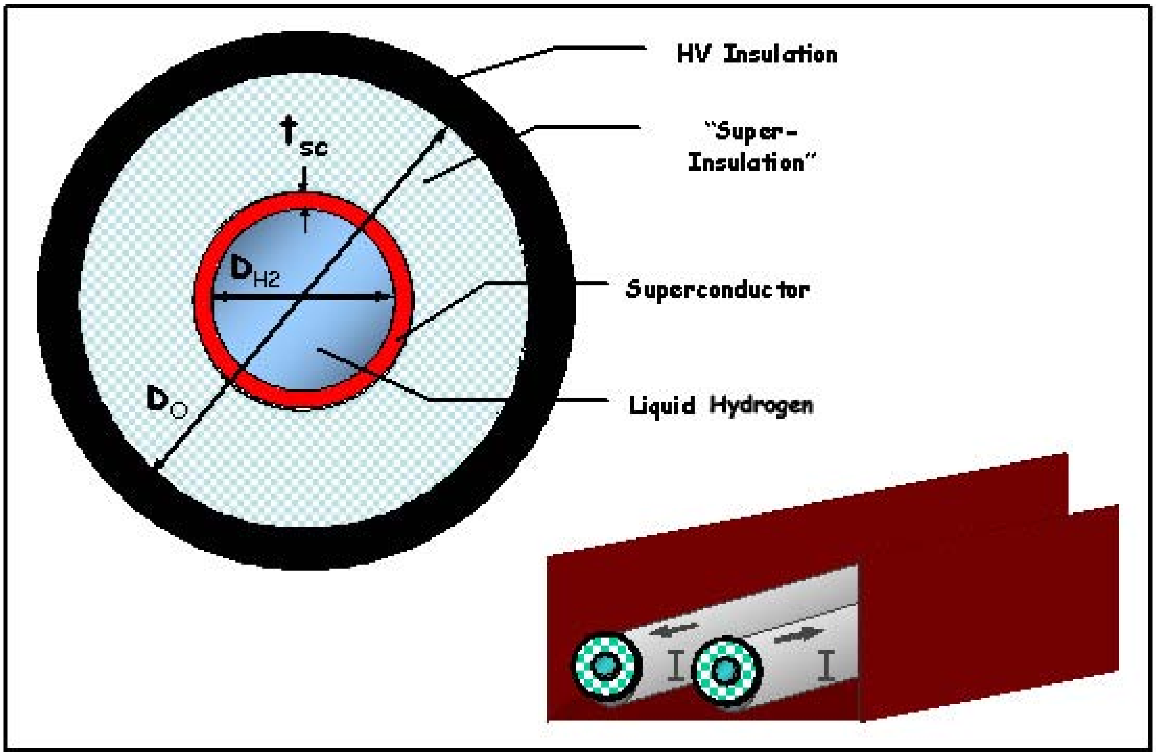


Figure 3-3
The Monopole SuperCable. (Note that this embodiment requires two units.)

These numbers are based on data and costs obtained for Generation I HTSC Tape from American Superconductor Corporation as of early 2006. The total tape required for the 250-km SuperCable specified in Figure 3-2, some 160,000 km, represents approximately two years production at American Superconductor's (AMSC's) Devens, Massachusetts, facility.

Table 3-9 indicates that radiation heat in-leak is the largest thermal load on the SuperCable, followed by fluid (LH_2) flow friction (addenda losses are estimates of other losses, such as support thermal conduction, ohmic losses from HTSC joints [trivial], etc.). However, it is important to note that hysteretic losses from ripple go as the third power of the rms current at 360 Hz, and thus increase rapidly if filtering is inefficient. For example, if the ripple is at 3% of 45 kA, it dominates other sources, and the total heat load almost triples.

Table 3-9
SuperSuburb SuperCable Monopole Thermal Loss Budget Based on Specifications and Dimensions from Figures 3-2 and 3-3 and Table 3-7 (All units in W/m.)

Radiation	Flow Friction	Addenda Loss	1.0 % Ripple	Total
0.70	0.49	0.20	0.09	1.48

Table 3-10 contains performance and cost data in support of the refrigeration infrastructure necessary to service the SuperCable, and Table 3-11 provides a summary of the expected “payback period” associated with the incremental cost and benefit of a superconducting cable that has lower losses than conventional transmission lines. The cost is almost negligible compared to that shown in Table 3-8 for HTSC wire (at 50 $/kA×m). Even so, under the assumptions detailed in Table 3-11, these additional costs over and above conventional power delivery systems can be recovered in a reasonably short time.

Table 3-10
SuperSuburb SuperCable Monopole Refrigeration Requirements Based on Specifications and Dimensions from Figures 3-2 and 3-3, and Tables 3-7 and Table 3-9

Temperature Rise (K/km)	Total Rise for 250 km SuperCable (K)	Permissible Rise Prior to Re-Cool (K)	Total Number of Cooling Stations Required
0.045	11	1	11

Station Spacing (km)	Cooling Power per Station (kW)	Cost of Heat Uplift ($/kW)	Per Station Cost (K$)	Total Station Cost (M$)
22.25	32.9	5	164	1.85

Table 3-11
SuperSuburb SuperCable Economic Factors. (Note that the capital equipment costs from Tables 3-8 and 3-10 have been doubled to reflect that two monopoles are actually in service.)

Cost of Electricity ($/kWh)	Line Losses in Conventional Transmission (%)	Annual Value of Losses on 1800 MW Transmission Line (M$)	Additional Capital Costs for HTSC and Refrigeration (M$)	FRB Discount Rate (%)	Period for ROI (Years)
0.05	5 %	39.4	1185	5.5 %	18

While an 18-year payback may not be “attractive” in today’s utility business, when viewed from a social benefit perspective, it is not unreasonable. For example, the implied reduction in carbon emissions due to these line loss savings provides a “social” return on investment that is not only attractive but, for some points of view, imperative.

Throughout this analysis, it has been assumed that converter costs for both conventional HVDC and the SuperCable would be roughly the same. Furthermore, it has been assumed that the SuperCable would be permanently evacuated, and the cost has been included for re-pressurization (pumping) of the liquid hydrogen in the $/W calculation for heat up-lift. An additional concept deserving future consideration is one where the cryogen is liquid nitrogen and the hydrogen is co-transported as high-pressure supercritical gas at 77 K.

At this time, an engineering economy analysis has not been attempted to determine the value of hydrogen delivered to SuperSuburb. Its value compared to the present “relatively low” cost of oil, coal, and methane cannot be assessed at the present time due to uncertainties in government support of the “hydrogen economy” to encourage completely carbon-free alternatives. One may consider a possible future follow-on addendum to these current functional requirements to focus on such issues. Part of that effort might look at alternatives to the “all-electric” household scenario. For example, if nuclear-generated electricity is really cheap, why not generate just electricity delivered subsequently to SuperSuburb for local hydrogen production? Such an alternative would require new nuclear power technologies much more capable of “load following” than available presently.

Finally, only one of several differing SuperCable designs has been considered—namely, the simplest possible, two monopole “room temperature dielectric” cables in the same right-of-way. For this design, the force between adjacent cables separated by 1 or 2 meters arising from their respective magnetic fields is likely manageable. Of more concern is the magnitude of the “perpendicular” field on the mutual degradation of superconducting properties, which could be substantial. These issues are left for future investigation.

SuperTie

It has long and often been conjectured that, should a two-way, high-capacity, east-west “electricity pipeline” exist, it would be possible to take advantage of the diurnal load-demand cycle to move power bi-directionally in response to market and pricing signals. Indeed the high-voltage direct-current (HVDC) portion of the Pacific Intertie is used in an analogous seasonal cycle to move power back and forth between Southern California and Oregon/Washington in response to variations in hydroelectric capacity in the latter two states. The concept of a “Continental SuperTie” is depicted in Figure 3-4.

The SuperTie SuperCable design follows from Figure 3-3, with about twice the amount of HTSC tape added to achieve 10 GW. This barely changes the physical dimensions of the SuperSuburb SuperCable, and the SuperTie will be assumed to have equivalent hydrogen transport properties.

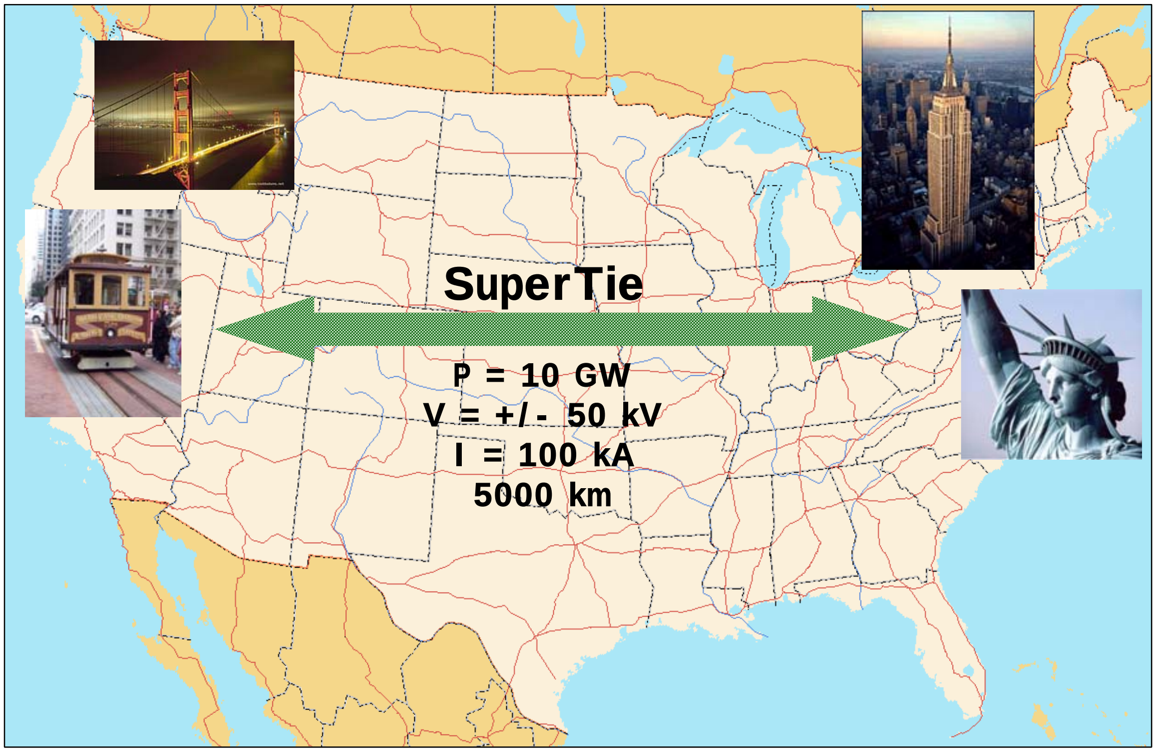
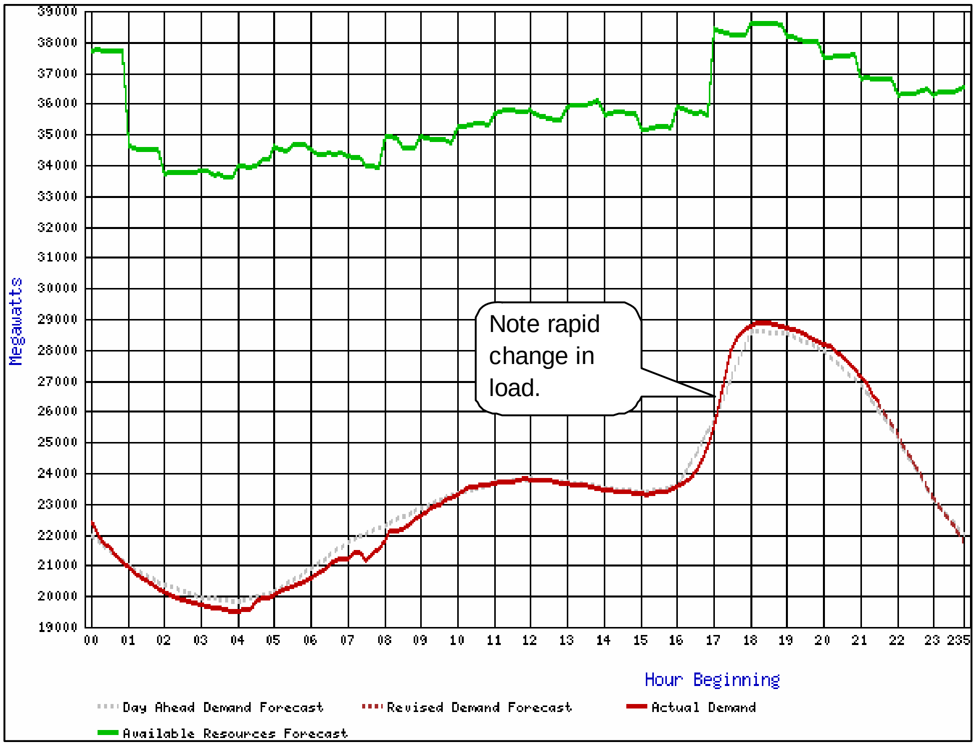


Figure 3-4
The Continental SuperTie

Whereas SuperSuburb addressed an electricity scenario in which power flowed constantly in one direction only, a situation ideally suited for the use of superconducting cables, SuperTie will transport very large amounts of time-varying currents including at least two sign changes per day. Type II superconductors, to which HTSC materials belong, are not perfect conductors under such conditions, experiencing hysteretic losses on cycling arising from physical phenomenon similar to that found in transformers with ferromagnetic cores. This is the source of loss to heat caused by ripple and is the reason why HTSC ac cables are limited in capacity compared to dc. Thus it becomes necessary to examine in some detail the effect of large variations in current in the SuperTie.

In this case, the fundamental model for the western United States is assumed to be the diurnal variation of power demand on a typical day in California shown in Figure 3-5.

We next assume a similar daily variation for the eastern United States, displaced three hours forward in time relative to California. The difference between the two demand curves reflects qualitatively the likelihood of power flow reversal and relative transfer magnitudes as a consequence of resultant price signaling and market response. It should be emphasized that, should a SuperTie exist or be built, its traffic will reflect particular market models in place at the time. Here it is merely assumed that when regional demand is lower in one part of the country than in another, prices will drop and attract transmission of power to an area where demand is higher. What is important here is to examine the spectral components of even this crude model in order to determine if any of the components results in intolerable hysteretic losses.



Note rapid change in load.

Figure 3-5
Daily Variation in Electricity Supply and Demand in California on Sunday, 8 January 2006. (Vertical axis units in megawatts and horizontal in hours starting at midnight. The top line denotes power available statewide and the bottom line indicates actual consumption. Data from the California Independent System Operator (CalISO) database.)

Figure 3-6 reflects the difference in diurnal consumption between an east coast and west coast “California” separated by 5000 km in distance and three hours in time. On the particular day chosen, shown in Figure 3-5, there would have been four instances of change of current direction, and the most rapid swing found was 10 A/s between 5 and 6 PM, east coast time, occurring when the lights are coming on in New York and demand (and cost) is still low in San Francisco. CalISO publishes demand and supply data on an hourly basis, and casual inspection of Figure 3-6 would suggest 10 A/s is the fastest change that would be observed on a continuous basis. Compare this number with a “sawtooth” ripple of 1% on 100 kA at 360 Hz, which is about 720,000 A/s, and it is unlikely that “power trading” fluctuations are going to be much of a problem. In any event, a Fourier analysis may be done of the time series shown in Figure 3-6, and an estimate made of the losses for the major spectral components. See Figure 3-7 for results of such an analysis.

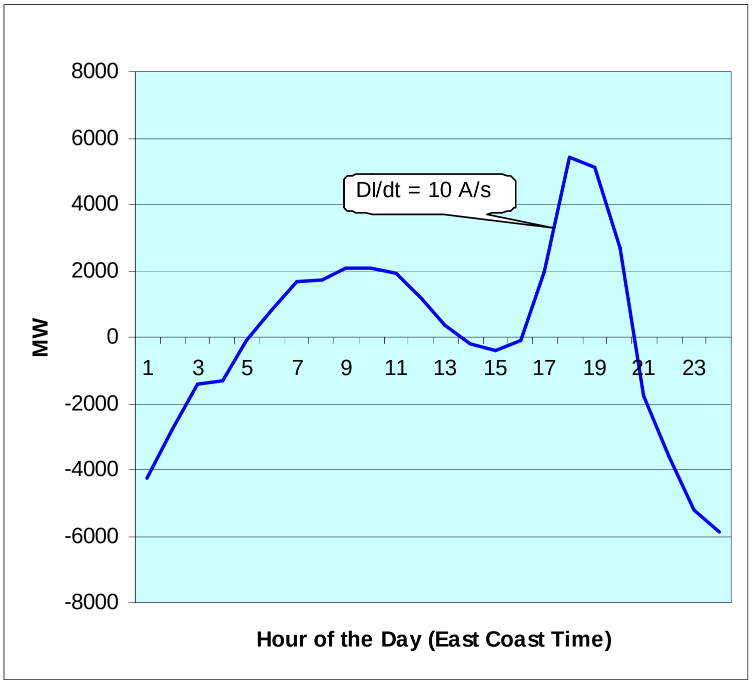


Figure 3-6
Qualitative Variation in Power Flow Magnitude and Direction from West to East throughout the Day. (Actual behavior will depend on particular market employed.)

In order to analyze the loss from each harmonic, the "Bean Model" is employed for hysteretic dissipation for Type II superconductors in the limit that the peak current is on the order of the critical current, which is taken as 15 kA/cm^2. This equation is:

$$W_H(n) = 2 \times 10^{-9} I_n^2 f$$

Here $W_H(n)$ is the hysteretic loss in watts/cm for harmonic n, I_n the amplitude in amperes of the nth harmonic and f its frequency in hertz. Results for the first four largest harmonics are given in Table 3-12.

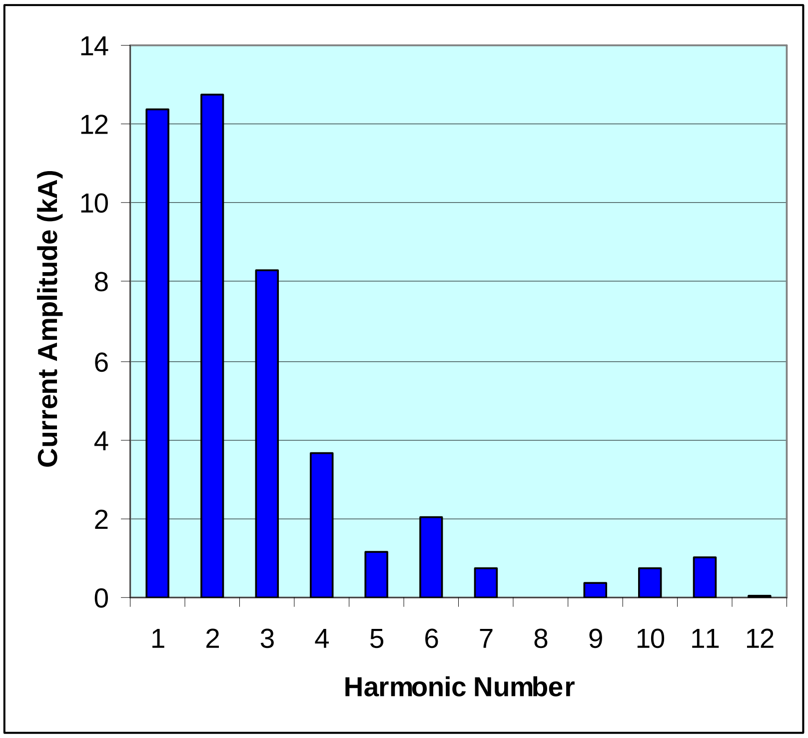


Figure 3-7
Absolute Value of Each Fourier Component of the Time Series Shown in Figure 3-6. (Power has been converted to current using +/- 50 kV as the SuperTie voltage.)

Table 3-12 clearly demonstrates that a high-capacity HTSC SuperTie SuperCable would have no difficulty supporting a trading scenario based on our “Two California” model. At most, the total power dissipation during one 24-hour period on the entire 5000-meter SuperTie would be in the 8-9 kW range, easily sustained. In fact, if a worst-case scenario is assumed, setting an upper limit of hysteretic loss of 1 W/m, reversing the entire 100-kA capacity of the SuperTie, the Bean Model predicts that this could be accomplished in slightly over two hours.

Table 3-12
SuperTie Diurnal Harmonic Content for a Period of 24 Hours. (Data from Figure 3-7)

Harmonic, n	**I_n (kA)**	**f (μHz)**	**W_H (kW/5000 km)**
1	12.4	11.6	1.8
2	12.8	23.2	3.8
3	8.31	34.7	2.4
4	3.67	46.3	6.2
Total			8.7

A
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