ANALYSIS OF FUTURE PRICES AND MARKETS FOR HIGH TEMPERATURE SUPERCONDUCTORS

BY JOSEPH MULHOLLAND, THOMAS P. SHEAHEN, AND BEN MCCONNELL

EXECUTIVE SUMMARY

This report presents a picture of how high temperature superconductors (HTS) may impact the national electrical system over the next 25 years. The intended purpose is to allow other analysts to make better estimates of future HTS markets. This study is limited in scope to the four most prominent users of electricity: motors, transformers, generators and transmission lines. Our intent is to focus on those technical areas in which HTS can make a significant contribution.

The analysis proceeds in several steps: First, the major electrical components of the present are examined and their associated energy losses are determined. Next, the pathway of electricity is traced through the existing grid, followed by the numerical estimates of the losses at each stage. The fraction of losses which might be mitigated by introducing new HTS devices is then determined. The percentage is small, but the economic value is large.

Using a conventional market-penetration model with parameters typical of the electric-utility industry, and estimating the amount of energy that any one HTS device saves (compared to its conventional counterpart), we arrive at a numerical value for the total national energy to be saved by introducing HTS technology. This is a function of time, spread over many years, as the new technology gradually gains market share.

By the year 2025, the sales are estimated to be approximately $1.8 billion annually, with associated annual energy savings over 10,000 Gwh. The corresponding reduction in carbon emissions for 2025 is over 1.6 million metric tons. In that year, both sales and savings are rapidly ramping upward, as more and more aging utility equipment is replaced each year. Put another way, the projected electricity savings in 2016 are enough to power the city of Rapid City, SD; but in 2025 the savings can power metropolitan Denver.

Monetary cost savings are calculated as well, using the wholesale price of electricity. This entire study is carried out assuming zero inflation, i.e., in constant dollars. However, the savings from superconductivity are offset somewhat by the high cost of manufacturing HTS wire and the cost of cryogenically cooling the HTS parts of the system.

This entire study contains frequent instances of engineering judgment, owing to the complex nature of the national electrical system. One numerical example is worked out to show how varying a seemingly minor assumption will swing the output around by 20%. Modeling of this type is inherently limited in its accuracy.

This report has been intentionally structured to make it very easy to locate assumptions and choices of numerical parameters, so that other analysts can make comparisons with calculated estimates obtained through other means.

I. PURPOSE, SCOPE AND APPROACH

The **purpose** of this study is threefold—the first objective is to develop a method of modeling that allows analysts to make estimates about the future of high temperature superconductor (HTS) technology. ["High temperature superconductor technology" describes the development of electrical conductors that have no resistance to electricity at temperatures below 77 K (-321 F). This does not include the low temperature superconductor technology, which is confined to temperatures < 20 K.] The second objective of this study is to project the savings in electric energy and estimate the monetary value associated with HTS electric power and energy savings. The final objective is to compare the monetary savings attributable to high temperature superconductors to projected costs of HTS devices, in order to refine the estimates of future HTS markets.

The **scope** of this study is also threefold. Primarily, the study addresses the use of HTS technology only for the following electrical devices:

C   Motors greater than 500 horsepower

C   Generators greater than 100 MVA

C   Transformers greater than 20 MVA

C   Transmission cables at intermediate-level voltages

More specifically, this effort calculates the savings based on the assumption that high temperature superconductors will be used in the electrical devices listed above. The span of the study covers the years 2000 through 2025. Finally, the scope of this study includes only electrical energy, sales, and HTS production in the United States.

The **approach** of this analysis is to develop data and graphs that lead to projections of the following information for the years 2000 through 2025:

C   Cost of HTS wire,

C   Amount of HTS wire required,

C   Production dollar volume versus cost,

C   Cost of cryogenic devices,

C   Sales market for cryogenic devices,

C   Sales market for HTS devices,

C   Energy savings by device, and

C   Emission savings.

Hopefully this analysis will be useful to the HTS industry in studying the sensitivity of the HTS sales markets to changes in the costs of superconducting wire and cryogenic cooling units—two factors which are critical to the competitiveness of HTS devices.

II. BRIEF DESCRIPTION OF THE ANALYSIS

The steps in preparing this analysis are enumerated below. The report is benchmarked on the 1999 National Energy Modeling System (NEMS) developed by the Energy Information Agency (EIA). The basic premise is that, on average, over the next 25 years the increase in energy consumed throughout the United States will be generated by new generators, transformed by new transformers, transmitted by new transmission lines and cables, and partially consumed by new electric motors. Some of these new devices will be made with high temperature superconductors. The amount of energy generated, transformed, transmitted and consumed by these HTS devices will be a percentage (market penetration) of the total *increase* in energy each year.   In addition, as some of the conventional devices wear out, new devices will replace them, some of which will be HTS devices. Implementing this general concept, the following steps were taken:

1. The projected electric energy sales in the United States for the years 2000–2020 were taken from the EIA *Annual Energy Outlook 2001*.

2. The *Annual Energy Outlook 2001* uses a growth rate of 1.8 percent annually. A portion of this new energy growth will be used by HTS motors and transmitted by other HTS devices when they are available.

3. Estimates of the replacement-rate for each device were made, and such replacements were considered equivalent to growth, as in step 2.   Therefore, the *energy* associated with replacement was combined with the growth in energy to establish the total energy for which HTS devices might be considered.

4. An estimate of energy-loss savings associated with typical HTS motors, generators, transformers and transmission cables were made. Engineering judgment was used to create the values listed in Appendix 1. This provided loss savings factors attributable to HTS versus conventional technology. It is important to recognize that changing these estimates (which any other analyst is free to do) will dramatically change the outcome of the model.

5. Fundamental to this model is the assumption that all *growth* in electricity will consider new technology *if it is cost-effective*. HTS technology has two important factors that dominate the determination of cost-effectiveness:

    a) HTS wire cost projections were made by extrapolating from today's R&D environment to a future commercial market.   This is the most uncertain aspect of this study.   We optimistically assumed that R&D will succeed in improving current-carrying capacity of HTS wire. Also, we employed historical data derived from the fiber optics industry and then estimated the anticipated decline from present HTS wire cost levels to a future asymptotic level of wire production costs.

    b) The cost of cryogenic coolers to support superconductivity was calculated based on estimates provided from vendors of such devices, and added to the cost of implementing HTS technology. Here again, we presumed that in the future, efficiency would increase and manufacturing costs would decline.

6. Utilizing the declining cost trajectories of both HTS wire and cryogenics, a market-penetration model for each HTS device was introduced. The parameters listed in Appendix 2 suffice to characterize the rate at which each of the new HTS devices is expected to be accepted in the marketplace.

7. The *HTS-related* eligible energy was calculated by multiplying the energy amounts described in Steps 3 and 4 by the market penetration fraction.

8. The total energy to be saved through HTS technology was derived as follows: the loss-savings factors were multiplied by the energy generated, transformed, transmitted and used by electric motors, and then multiplied by the market-penetration fractions for each device.

9. Next, the contributions from all four devices were summed to obtain the estimated total national energy savings attributable to HTS in each year.

10. Finally, the energy savings from Step 9 were multiplied by the cost of electricity per kilowatt-hour at the wholesale level to obtain the monetary value of the HTS savings.

III. EXPLANATION

In this section, we provide the details of the steps tabulated above, and we refer the reader to a number of appendices that present the methods of calculation that we used. This is done explicitly to enable the interested reader to revise our assumptions and engineering judgment, thus perhaps reaching substantially different conclusions. The methodology used in this study is robust enough to accommodate very large swings in the parameters of energy savings, manufacturing costs, and market penetration.

A. National Energy Situation

To determine the savings that may come from HTS devices, it is first necessary to determine the extent of the losses in the existing electrical grid, using conventional technology. The process of doing so has several component steps:

1. **Annual national energy use**: The projected electric energy sales and prices in the United States for the years 2000–2020 were taken from the *Annual Energy Outlook 2001*, published by the EIA. That document is both the foundation and starting point for this analysis. It has become simply "good engineering practice" to use EIA projections. In this way, controversy is avoided within the Department of Energy and calculations are done with consistency of the input data.

    Rate of electricity sales increase: The EIA electricity forecast data escalates at approximately a 1.8 percent annual growth rate. Consequently, the difference in electricity generation from one year to the next is quite easy to calculate, and this is used to estimate the potential market for electrical devices, whether superconducting or not. Beyond 2020, we used a simple

escalation factor of 1.8% annually. It was assumed that all this energy was eligible for HTS devices. Later in the analysis, this amount was multiplied by market-penetration factors.

2. **Energy losses in the *conventional* electrical grid**: Once again we used the *Annual Energy Outlook 2001* database to determine the losses in the U.S. electric system. These losses were then distributed among the various components of the electric grid and determined on both a *marginal* and *average* basis (i.e., *power* and *energy* basis). We employed certain engineering judgments to develop this analysis, which is presented in Appendix 3.

    To properly distinguish between the *peak* and *average* losses, one absolutely essential preliminary is to recognize the diurnal variation in demand for electricity. We must distinguish between the i^2R *losses* and the *no-load losses* associated with transmission and distribution of electricity. To treat this distinction carefully, it is important to understand the *load factor* and the *load duration curve*, which characterizes the relationship between peak and average power consumption, as illustrated in Appendix 4 and further refined in Appendix 3.

    Appendix 3 is of central importance to this entire study. There we trace the progress of electric power and energy through the consecutive stages of transmission and distribution (including transformers in the path), and arrive at an estimate of the total losses in the U.S. utility system. Through a very careful accounting of the losses at each step via spread-sheet analysis, we are able to calculate both *instantaneous* power and *total energy* losses. The outcome of Appendix 3 is a rather accurate national accounting of the losses customarily incurred by utilities.

3. **Losses relevant to HTS**: Next, the "domain" of electricity relevant to high temperature superconductivity was constructed, by restricting attention to that fraction of the electricity that can plausibly be impacted by HTS devices. Appendix 5 presents those calculations. We are careful there to specify the assumptions about HTS applicability clearly, thus allowing the reader to construct alternate estimates.

To study how individual HTS devices might have an impact, we proceeded as follows: first, the flow of electricity through the several different devices of interest in this study was traced, in accord with standard engineering methods, utilizing values of efficiency (which depend on size, etc.) and other parameters obtained from manufacturer's specifications. Appendix 1 enumerates the key energy-related parameters of each device in our model.

To apply this method to the entire national electric system, it is very important to use accurate models of system components, in order to obtain accurate estimates of the power used (and hence of the savings that are possible). For example, it is known that very large electric motors usually operate at 97 percent efficiency, whereas small horsepower motors are typically in the 91−93 percent range. We analyze the potential savings associated with large motors in Appendix 6. Continuing at such a level of detail, Appendix 7 discusses the possible savings in generators. Appendix 8 presents efficiency data for transformers of various sizes. Appendix 9 is similar, looking at the details of losses in conventional transmission lines, including the effects of variations in load discussed in Appendix 4.

Some examples will help to explain the importance of engineering judgment in this study:

1. To estimate losses in transformers, we start with the premise (reflecting utility experience) that between the initial generation of electricity and the final use in homes, buildings or factories, there are up to six transformers, each of which in turn suffers small losses. However, only the ones operating at high voltages are of interest for superconductivity, since the lower-voltage transformers in the distribution stages would not be cost-effective if they were superconducting. In order to make a reasonably accurate estimate of the losses of interest (i.e., superconductivity-eligible), we have applied engineering judgment regarding the power characteristics through those transformers that are especially suited for HTS technology.

2. Transmission lines illustrate the range of variations quite well. Other authors [see, for example, L.R. Lawrence, *High Temperature Superconductivity: The Products and Their Benefits,* July 1998] consider only *underground transmission* cables, which currently amount to less than 200 miles in the United States. (*Distribution* cables accumulate to much greater length, but they are not at issue here.) Limiting the potential HTS market to so small a portion of transmission lines obviously reduces the calculated savings. We concur that conservative estimates are an appropriate way to acknowledge the risk-averse nature of utility decision makers, but we believe that approach is too limited; we consider transmission lines in the voltage range 69 kV–161 kV eligible for HTS technology. It is particularly noteworthy that overhead transmission line costs are extremely high for conventional technology because of the cost of right-of-way. HTS offers great savings here, because of the much smaller "footprint" associated with superconducting cables. However, HTS cables pay a high price for their associated cryogenics.

Nevertheless, to allow others to make their own assumptions, Appendix 5 states clearly how the calculations proceed for various scenarios about which transmission lines might be superconducting.

3. In the same way, again recognizing the requirement that any device must be cost-effective or it will never be built, we considered only electric motors over 500 horsepower as candidates to become HTS motors. This restricts the amount of electricity in motors to only 29 percent of the total national electricity flowing through motors [Xenergy Corp., *United States Industrial Electric Motor Systems Market Opportunities Assessment*, December 1998]. Appendix 10 presents this very simple calculation.

Clearly, limitations of this type lead to a lower estimate of losses (and hence of possible savings), but in our judgment, this gives a more accurate (albeit conservative) estimate of the likely future savings from HTS technology.

B. Market for HTS Devices

We assumed that all new equipment (i.e., whatever is needed to support expansion of total electricity consumption) will use new technology wherever it is commercially advantageous, i.e., cost-effective. Moreover, we estimated the rate of retirement of old equipment based on the historical experience of electric utilities and major users of electrical equipment. Lifetimes of 30 years or more are common in utility applications. However, we anticipated that not all aged equipment would be replaced, and this modification is discussed in Appendix 11. When replacement occurs, it will be done with "best available technology," where "best" includes weighting for the relative cost of competing devices.

In this way, the percentage market penetration by new technology will be faster than either the growth rate or the replacement rate alone. In order to represent this transition quantitatively, we used standard S-shaped market penetration models, the mathematics of which are presented in Appendix 2. There are four parameters in any such formula, chosen by the modeler:

C year in which new technology starts to make inroads;

C rapidity of market penetration;

C time until 50 percent of the market is captured; and

C fraction of the total market eventually captured.

For the four cases of interest here (transformers, transmission cables, generators and motors) we present specific numerical estimates of these parameters in Appendix 2. The parameters given in Table 2-1 are among the most important in this entire study, for they specify the individual market penetration curves for each HTS device. Figure 1 displays our four distinct market penetration curves for the four HTS devices. Evidently, market penetration is very slow at first, (until wire costs and cryogenic costs come down), but eventually motors and transformers penetrate to nearly the same levels; cables and generators asymptotically reach a smaller fraction of their available markets.

Perhaps the most important point to note in Figure 1 is that market penetration has nearly reached "saturation" by 2025, the outer limit of this study.

When making the decision whether to buy a more expensive device (higher first cost), the value of the future stream of savings must be brought back to its *net present value* [Franklin Stermole, *Economic Evaluations and Investment Decision Methods,* 1974]. This requires a particular numerical choice of a discount rate. For utilities, this is customarily taken to be 7 percent with zero inflation assumed [OMB Standard]. (This entire study is carried out in non-inflated dollars.) For industrial customers—the typical buyers of motors—the opportunity cost of money is higher, set at 10 percent here; this has a mildly retarding effect on the market penetration by motors.

There is a crucial "chicken and egg" effect that affects the market penetration model. If very few HTS devices are built, their cost will be very high, they will not be cost effective, and penetration will be negligible. As discussed in Section C, the cost will drop with increasing demand and more production. In carrying out this study, we chose not to write a sophisticated routine to model the slippage of the market penetration curves. Rather, we manually adjusted the parameters in Appendix 2 (underlying Figure 1) to produce a self-consistent picture of the way HTS devices would enter the real (and evolving) market

The results in Part IV of this report indicate that sales of HTS devices (i.e., market penetration) remain small until 2015. That is because the performance of wire changes only slowly with advances in R&D and manufacturing experience, and reaches an asymptotic value in 2015.

Figure 1 Market Penetration Curves
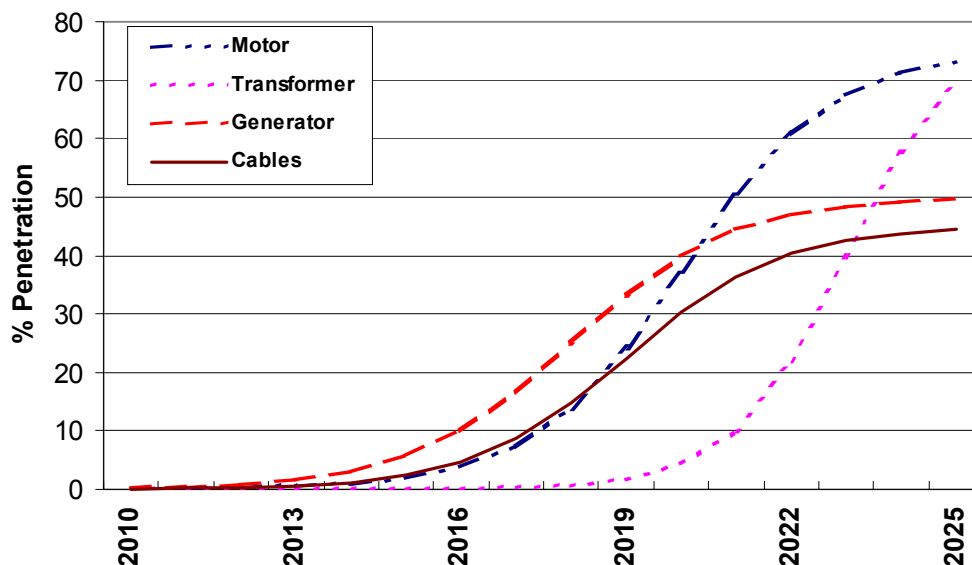
C. Cost of HTS Devices

Estimating the future cost of producing HTS wire is known to be very difficult. The experience of the semiconductor industry is embodied in *Moore's Law*, wherein price-per-unit has fallen by many orders of magnitude over time. However, *Moore's Law* is too optimistic for realistic cases of HTS applications, because the size of one unit does not shrink as it has for semiconductors. Obviously the distance between cities does not decrease, and so diminishing size cannot be a route to lowering cost. It was judged that the declining cost-per-unit experience of the fiber-optics manufacturers (summarized in Appendix 12) was a much more appropriate means of modeling the plausible future decline in manufacturing costs for HTS wire. Today we are still in the R&D stages, so our starting point is only a rough guess. Consequently, there is more uncertainty associated with the HTS cost projections than with any other step of this entire analysis. To enable the interested reader to revise such estimates by using his own values, the pathway to our HTS wire cost estimates is carefully spelled out in Appendix 13.

Every superconductor comes with a "cryogenic penalty," made up of both operating costs (energy) and capital equipment costs.   At the present time, the "baseline" is the cost of liquid nitrogen, but that is considered unreliable by many utilities, and furthermore, electric motors are planning to operate well below 77 K, so further cooling is mandatory there.

The efficiency of any refrigerator determines how severe will be the "cryogenic penalty" for an application. In Appendix 14, we present an optimistic outlook for the efficiency of cryogenic systems of the future. Manufacturers and vendors of cryogenic equipment have stated that with

large increases in demand, the cost per device will drop. There is historical evidence to support this assertion, as described in Appendix 15. Based on these two appendices, estimates have been made of the additional cost to refrigerate each of the four applications.

D. Energy Savings

The savings from each new HTS device were determined. For example, Appendix 6 traces the path of energy (and the associated dollar costs) through a 1160 hp (865 kW) electric motor. For each of the four new HTS devices, there is considerable uncertainty in estimating potential savings because of two major wild cards today:

C   future HTS wire cost (and current-carrying capacity) is unknown; and

C   we can only make rough guesses at what the dollar penalty for refrigeration will be when these devices are installed in the real world.

Appendix 1 presents our engineering judgment about the relevant parameters associated with the four HTS devices. Furthermore, Appendix 1 presents life-cycle cost data for the various HTS devices expressed in terms of a suitable unit.

The total HTS-related energy savings as a function of time were constructed in this way: at this point we had the total energy flowing through each device category, the degree of market captured by HTS versions of them in any given year (Figure 1), and the average HTS energy savings of each device. From there it was a straightforward step to multiply the three together, sum them for each year, and thus obtain a total annual energy savings attributable to HTS for each device category.

Once the total annual electricity savings were in hand, it was a very simple multiplication to convert that to price, or *monetary value* of electricity saved. The cost of electricity was taken directly from the National Energy Model prepared by the EIA. The industrial electricity price was used because it best reflects the cost of electricity saved by HTS cables, transformers, generators and motors.

As a final step, the savings in electricity were scaled proportionately to reduce the amount of coal being burned, and hence to reduce the amount of emissions of the three gases: CO_2, NO_x and SO_2.

IV. **TYPICAL RESULTS**

To illustrate how this entire procedure works as a unit, we ran the model for one case using specific numerical entries (assumptions) for many parameters. The entire point of this exercise is to show clearly that any other analyst can modify those numbers and obtain different results.

There are four appendices devoted to making that possible: Appendix 16 describes the basic assumptions, and expands on section III above. Appendices 17, 18 and 19 are detailed guides to the exact location of various numbers on the linked spreadsheets (known as *Assumptions, Database* and *Results* within the *Excel* program). The user will find that most of what is likely to be changed is located on the *Assumptions* spreadsheet – that is where the analyst's engineering judgment is most

significant. Some EIA data is presented on the *Database* spreadsheet; again, the analyst with a different electricity growth model is free to change it.

A. HTS Markets

Projections of future market sizes for HTS materials and devices are of great interest to people in the HTS manufacturing sector. HTS materials include the HTS wire and associated cryogenic equipment. The HTS devices are the motors, transformers, generators, and electric cables that are made from HTS components. Table 1 presents our estimates of the market for HTS devices. As described in the preceding section, the many parameters, assumptions and engineering judgments employed throughout this study come together in the computational model to produce these results.

As discussed in several appendices, we chose one size of a device to represent the entire category. For example, the 65 MVA transformer is the "unit of measurement" for transformers as they enter the market. Recognizing that not all transformers (or motors, etc.) are the same size, we let the *number* of each device be a continuous variable, not restricted to integer values. Thus if there are 2.6 units of a device sold in its first year in the market, that means there is an assortment of actual sizes manufactured, such that the total adds up to 2.6 times the standard unit. Using generators as an example, 1.83 x 300 MVA = 550 MVA, which might be made up of two 200 MVA generators and one 150 MVA generator.

It is noteworthy that the first device to enter the market is not the greatest energy saver. Although cables get a head start, generators catch up quickly. By contrast, motors remain comparatively small in total sales, because only very large motors (> 500 hp) participate in the transition to HTS technology.

B. HTS Wire Cost

Each HTS device requires a certain amount of HTS wire; summing all these requirements produces an estimate of the magnitude of the HTS wire-manufacturing market. For the number of devices comprising the market estimated above, the projected amount of HTS conductor to be produced is shown here in Figure 2.

The cost of HTS wire is generally described by a figure-of-merit measured in dollars per kiloamp-meter ($/kA-m). This figure-of-merit is dependent on two parameters: first, the maximum amount of current the HTS wire will conduct; and second, the manufacturing cost per meter of wire. Both of these parameters are expected to improve as a result of advances in manufacturing techniques. Figure 3 presents our estimate of the relationship between the production of HTS wire and the cost per meter. This graph is based on experience in the optical fiber field, which is described in Appendix 12. Both vertical and horizontal axes are in arbitrary units.

Consequently, the actual cost of making HTS wire is expected to decrease as more tape is produced and manufacturing technology improves over the years. Figure 4 results from combining Figures 3 and 2; it shows the projected cost of HTS wire on a $/m basis over the time frame of this study.

Table 1   Projected Market for HTS Devices (Thousands of Dollars)

Year	Motors	Transformers	Generators	Cables	Total
2011	228	0	6,926	4,117	11,270
2013	956	0	24,710	14,405	40,071
2015	4,025	243	83,634	48,335	136,236
2017	15,399	1,451	227,535	135,001	379,386
2019	50,968	9,353	445,693	318,844	824,857
2021	108,429	56,081	592,904	488,783	1,246,196
2023	148,770	222,277	656,499	570,326	1,597,872
2025	164,072	390,964	675,656	586,284	1,816,975

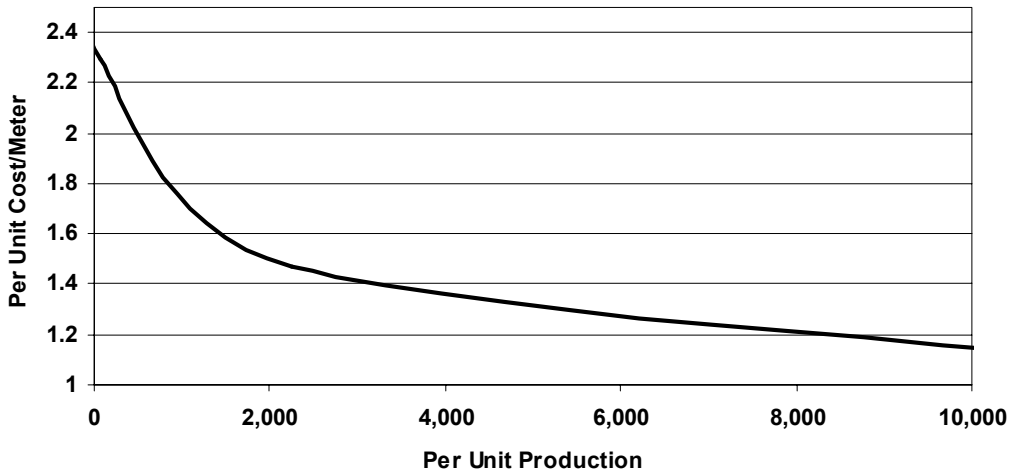## Figure 2   Future HTS Wire Requirements
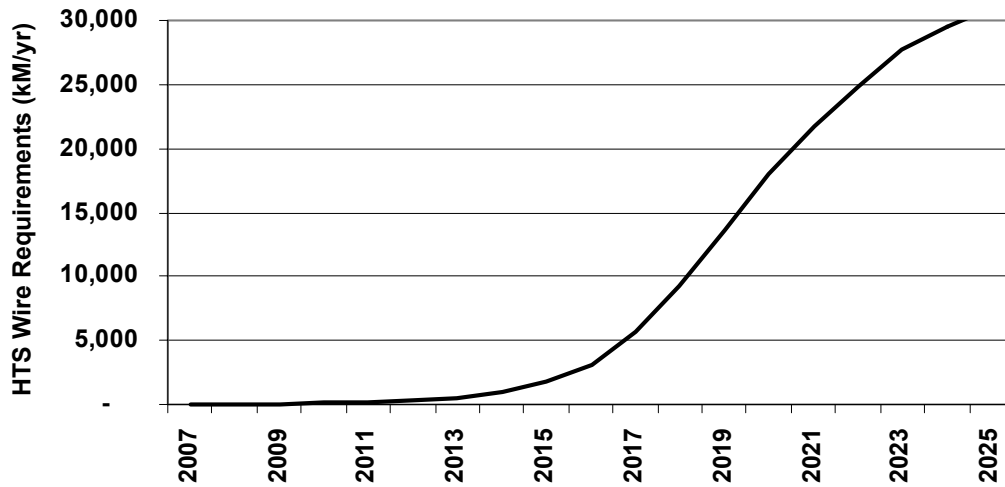
Figure 3   HTS Per Unit Cost Curve

At the same time that manufacturing cost-per-length is going down, current carrying capacity is going up. Over the past few years, researchers have increased the current carrying capacity of HTS wire at the rate of about 75 Amps per year [1997-99 DOE Wire Development Workshops]. In this study, we have assumed that trend will continue until 2015 when it reaches 1,000 Amps for a 1 cm wide tape. This is approximately the maximum current carrying capacity that can be expected from second-generation coated conductor HTS tape with both sides coated [Dean Peterson and Steve Foltyn, Los Alamos National Laboratory]. This anticipated increase in maximum current carrying capacity will help drive down the figure of merit cost, measured in $/kA-m. By combining this trend with the $/meter curve of Figure 4, Figure 5 illustrates how this figure of merit is expected to decrease over the next two decades as production increases.

C. Cryogenic Refrigeration

The impact of cryocoolers on the future competitiveness of HTS devices is critical. The 1999 benchmark cost of a medium-sized cryogenic refrigeration unit was about $60,000/kW$_{cold}$ at 77K. The cryocooler manufacturers assure the HTS developers that the price of refrigeration will come down as the demand increases and more units are produced [*Cryogenics Needs of Future HTS Electrical Power Equipment*, Workshop Proceedings, July 22, 1998]. For the projected number of HTS devices expected to appear in the years ahead, the projected number of refrigerators is shown in Figure 6.
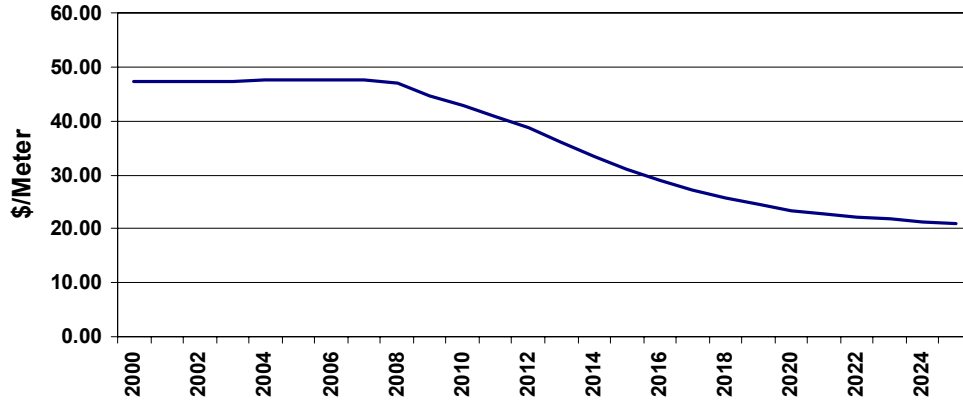
Figure 4   HTS Wire Cost ($/Meter)

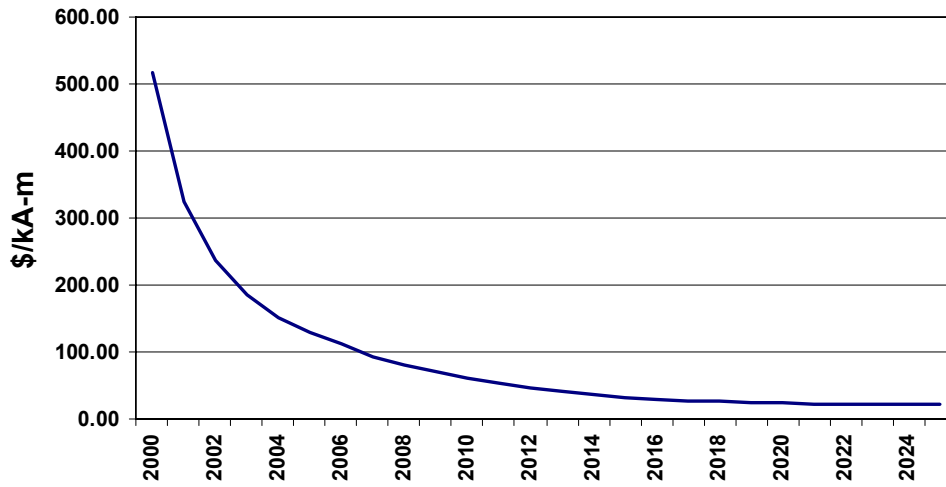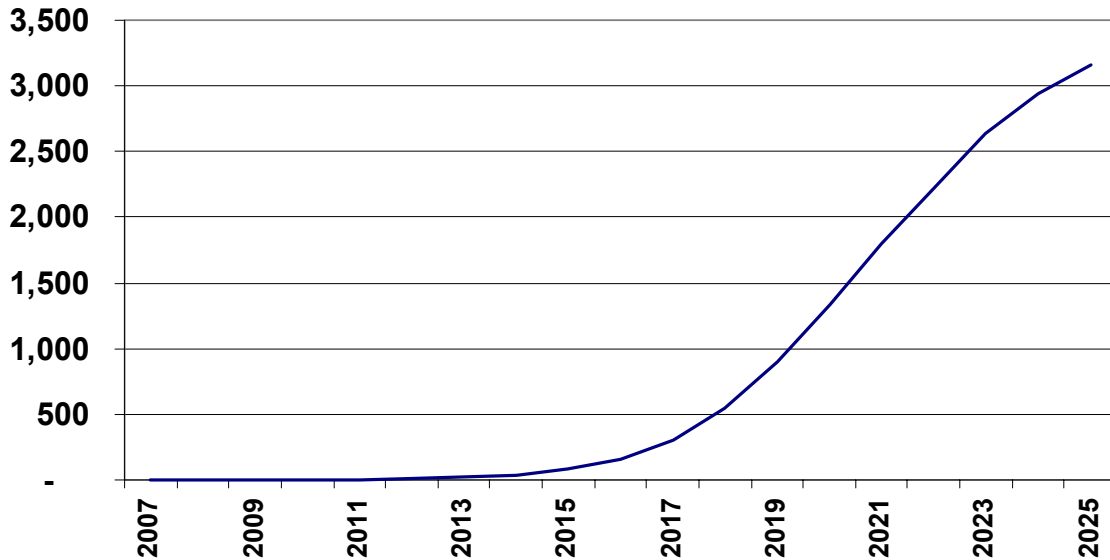**Figure 5 HTS Wire Cost ($/Kiloamp - Meter)**

Figure 6   Number of Cryogenic Units Required Each Year

If small cryocoolers do not become competitive, cryogenic temperatures will be produced using nitrogen made at high-efficiency remote refrigeration units. The liquid nitrogen will be trucked to local liquid nitrogen reservoirs to maintain cooling. With their strong concern for reliability, utilities may consider this condition an undesirable risk.

In this study, the benchmark of $60,000/kW_{cold}$ was only a starting point. Economies of scale typical of the cryogenic refrigeration industry were applied to represent the expected decline in refrigeration costs. This is discussed in more detail in Appendix 15. This declining cost model indicates that as large numbers of cryogenic refrigeration units are manufactured, the cost will drop to less than $20,000/kW_{cold}$.

The projected sales market for cryogenic refrigeration units is given in Table 2. The reason that cables remain the dominant user of refrigeration units over time is that cables require more "repeater" stations (roughly one per mile) as their cumulative length increases. By comparing Tables 2 and 1, we see that in the final year of this study, the cryogenics constitute over 13 percent of the cost associated with cables, but somewhat smaller fractions of the other three HTS devices. The steadily declining fraction attributed to cryogenic costs is shown by the data for transformers, where cryogenics are over 20 percent of the total cost in 2015, but under 10% percent in 2025.

Table 2   Projected Market for Cryogenic Refrigerators (Thousands of Dollars)

Year	Motors	Transformers	Generators	Cables	Total
2007	0	-	-	58	58
2009	2	-	83	249	333
2011	7	-	294	849	1,151
2013	32	-	1,081	3,319	4,432
2015	142	49	3,331	11,320	14,842
2019	1868	1,231	10,861	54,100	68,060
2021	4012	6,187	11,953	72,149	94,301
2023	5533	22,114	11,902	77,709	117,258
2025	6125	37,128	11,729	77,546	132,529

D. Energy Savings

The route to estimating energy savings contains many uncertainties, most prominently the degree of market penetration that will be attained in any given year. That is certainly affected by the cost of manufacturing HTS wire and the cost of cryogenics. Market penetration gains momentum as component prices decline with increasing amounts of production. This kind of positive feedback loop is a familiar characteristic of newly-opening markets.

We have arrived at the point where the energy savings from all installed HTS devices can be summed, producing an annual total. Based on the "eligible" energy savings associated with HTS, as well as reasonable projections of implementation timetables and the fraction of the market captured by HTS (as in section A above) we can construct national estimates of the total energy saved through this technology. This has been carried out; the total projected annual energy savings attributable to HTS devices are presented in Table 3. The results are given in gigawatt-hours (GWh = millions of kWh).

Table 3   HTS Energy Savings (Gwh)

Year	Motors	Transformers	Generators	Cables	Total
2009	0	0	2	1	3
2011	0	0	11	3	14
2013	1	0	44	13	58
2015	4	0	171	55	231
2017	15	2	556	196	769
2019	57	15	1417	598	2086
2021	154	94	2699	1336	4283
2023	300	449	4196	2289	7235
2025	468	1194	5785	3326	10774

By 2025, generators will be the largest energy saver. The modest contribution from motors reflects the fact that only a fraction of American electricity flows through big motors > 500 hp.

An alternate way to express the magnitude of these savings appears in Figure 7. There the same savings are expressed in terms of the equivalent number of households that would consume that much energy. Figure 7 shows the number of households that could be supplied each year from the savings in energy derived by the use of HTS as calculated in this study. The American cities superimposed on the graph help put the energy savings in perspective. In 2013, the energy savings will be equivalent to the electricity used by a small American town the size of Westborough, Massachusetts. However, by 2025, the savings from HTS would supply all the households in metropolitan Denver, Colorado.

Figure 7   Electricity Savings Due to Superconductivity Efficiency Improvement
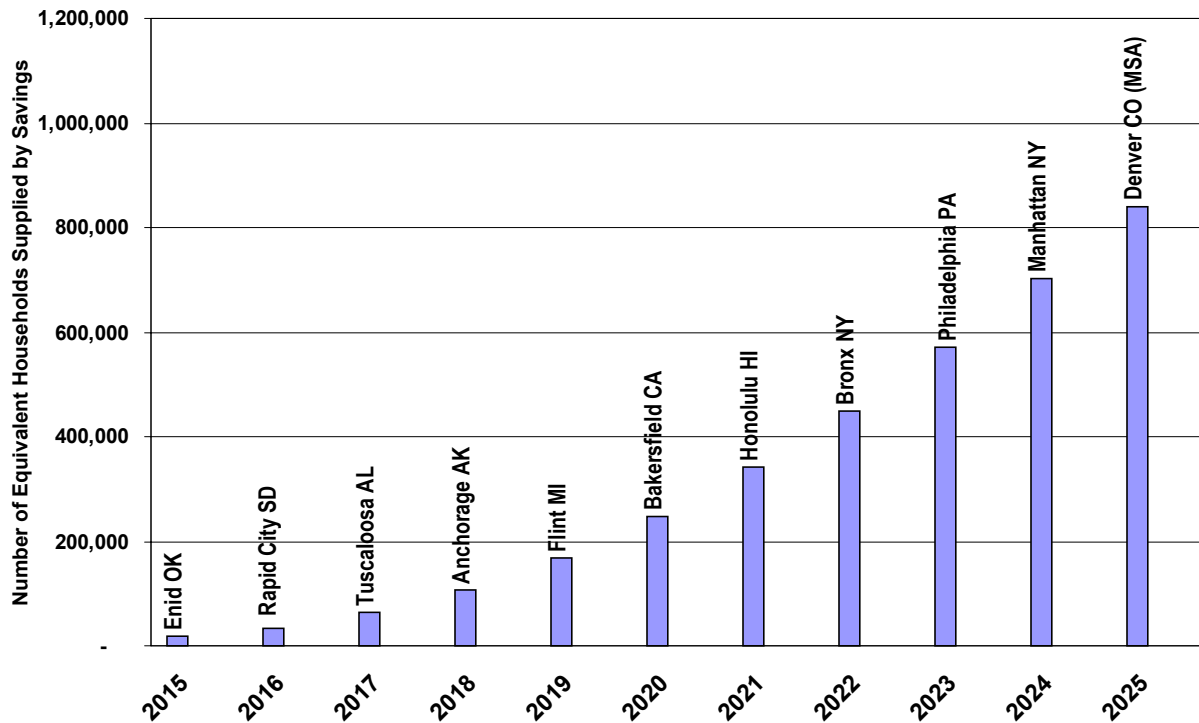
E. Emissions Saved

As a result of the energy savings associated with superconductor technology, there will be a significant reduction of emissions from electric generation. Specifically, it is known that approximately 60 percent of American electricity is generated by burning fossil fuels at the average rate of 10,000 btu/kWh. Thus, when electrical energy is saved using HTS, it is reasonable to assume 60 percent of that saved electricity need not be produced by burning fossil fuels. The concomitant savings of CO_2, SO_2 and NO_x is well-documented by the EIA, and consequently, it is a straightforward calculation to find the reduction in those gases associated with the electricity saved through HTS.

Table 4 below gives the savings in selected gases if the energy savings from HTS devices shown in Table 3 are realized.

Table 4   Emissions Savings Attributable to HTS Devices

Year	Energy Savings (GWH)	Carbon Savings (Metric Tons)	SOX Savings (Metric Tons)	NOX Savings (Metric Tons)
2009	3	489	6	3
2011	14	2,271	29	13
2013	58	9,183	113	52
2015	231	36,269	434	201
2017	769	120,716	1,384	657
2019	2086	324,801	3,594	1,749
2021	4283	662,176	7,099	3,510
2023	7235	1,109,613	11,662	5,765
2025	10774	1,638,940	16,891	8,351

V. <u>VARIABILITY</u>

Tables printed with several decimal places often convey authority, but it must be remembered that the accuracy of any model is fundamentally limited by the validity of its underlying assumptions. The output is sensitive to many different input variables, some of which seem entirely non-controversial. In this section we illustrate exactly that point by constructing a numerical experiment involving an seemingly innocuous assumption. The mechanics of the model in *Microsoft Excel* allows this to be done by any analyst.

In Appendix 11 there is discussion of the "replacement rate" of old equipment. It is well understood that not every device fails exactly at the mean lifetime of the device, but that is a close enough approximation to reality. Thus the maximum "theoretical" replacement rate is {1.0/*lifetime*}. The fact that fewer devices were installed 30 years earlier in a smaller electricity market is also recognized. Much more important is an intangible and subjective factor relating to the replacement decisions made by utility managers: for existing equipment that has worked fine for years, there is additional inertia to keep the replacement simple, and not to innovate when replacing.

If the full "theoretical" replacement market went to HTS devices, that replacement market would be almost double the "growth" market. The actual replacement market can plausibly be asserted to be anywhere from ½ to ¾ of the theoretical maximum. We could not find any good reason to choose any one particular value within that range. Therefore we decided to explore the importance of that replacement fraction.

The numerical experiment was carried out by writing a *macro* for *Excel*, in which the only assumption in the entire spread sheet that was varied was this fraction: it was varied from 0.5 to 0.9, and the grand total national energy saved (in GWh) was noted for the years 2020 and 2025. The result for 2020

appears in figure 8. It will immediately be seen that there is about a 30% variation in the total GWh saved, depending on this fraction.

Figure 8. Variability due to Replacement Rate
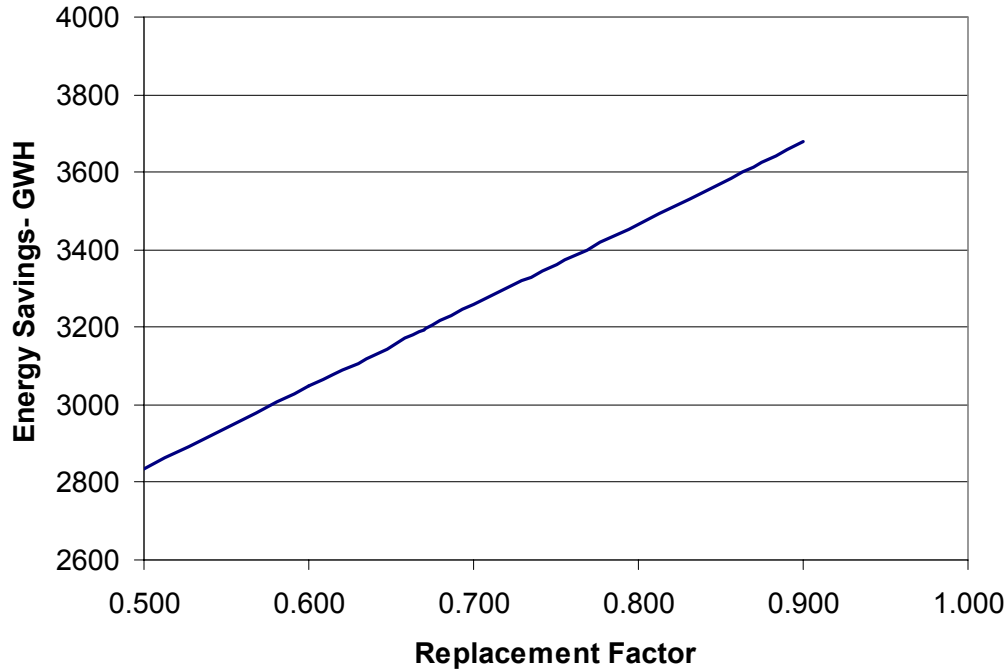
The message of this exercise is that there is considerable uncertainty embedded in the model. Unlike wire costs, the replacement rate is not a "hot button" issue in this study. Yet it makes a very large difference.

The wider issue is, what other similar things are tucked away within the model?

The foremost such item of great numerical uncertainty is the amount of AC losses. We took 1 watt/meter for numerical simplicity. That number has taken on a mystical importance that is not supported in any way by experimental measurements. If AC losses were 20% higher or lower, it would make a huge difference in the amount of energy saved by each HTS device (compared to conventional technology). Subsequently, that would lead to big differences in the monetary value of energy saved, which in turn would affect both the starting date of market entry and the market penetration rate.

Another example: The cost of alternative conventional technologies were based on sound engineering judgment in 1999, but were not permitted much variation over the lifetime of the study. Some innovative cost saving in conventional technology would disrupt the cost comparisons used in this study to determine profitability, with a concomitant adverse influence on market penetration.

The *Load Duration Curve* discussed in Appendix 4 has been taken to have one typical shape. The resulting average value is L = 0.55, and the relevant factor for i^2R losses is G = 0.36. Choosing a different shape for the curve would change those numbers, and hence the value of savings obtained by eliminating i^2R losses.

VI. CONCLUSIONS

This study has carefully traced the losses in the existing American electricity delivery system and estimated the possible savings associated with high temperature superconductivity. Of course, the degree of market penetration over the next two decades is sensitive to future reductions in the manufacturing cost of HTS conductors, and estimates of these parameters have been included as part of this analysis. The need for cryogenics associated with superconductors is recognized as a cost component that will affect market penetration; the anticipated declining cost to manufacture cryogenic coolers as volume increases has also been factored in here.

In this as in any model, the numerical results obtained depend heavily on the assumptions and engineering judgment that went into the calculations. There is no one "correct" way to make such choices, and it is very easy to criticize particular assumptions. Recognizing this reality, the authors have provided in the appendices that follow a careful presentation of the pathways they have followed, which led to the numbers presented in the main text. This was done explicitly to make it easy for others to vary the computational parameters using their own assumptions, and thus derive alternative results using the same general framework of this study.

Regardless of the results of particular calculations, we believe there will be widespread agreement on our central conclusion: HTS technology will have an important influence on America's energy future.

Deregulation of electricity is a key factor. HTS devices, such as transformers, cables, and current controllers, may prove to be vitally important in the new electrical energy markets as deregulation spreads across the nation. HTS devices will give efficiency advantages to small and large energy marketers alike, thus enabling more entities to compete in the open electric energy markets. For example, HTS cables will give marketers the ability to deliver large amounts of energy into congested locations with minimal right-of-way requirements. This will not only solve power transmission problems, but it will bring benefits to the general public by reducing the number of areas where the cost of electricity would rise to very high levels because of congested transmission conditions.

HTS technology still requires significant amounts of applied research in order to develop second generation wire to the point where it has the current carrying capacity to be competitive. Moreover, both HTS wire and components (especially cryogenics) will have to reach much higher levels of durability and reliability if they are to be incorporated into a utility system. However, at this point in its development, HTS appears likely to become a valuable resource in the nation's efforts to be more competitive, reduce energy consumption, and thereby reduce emissions.

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ACKNOWLEDGMENTS