APPENDIX 1

ENERGY SAVINGS IN HTS DEVICES

This Appendix collects and explains several of the key assumptions that are embedded within the calculations of this model. The interested reader will find that quite modest changes in certain of the numerical values here will dramatically shift the outcome of the study, often via a sequence of changes to the economic analysis of the individual HTS devices.

Table 1-1 displays certain important input assumptions pertaining to each type of HTS device. These numbers were derived mostly from reports given at the *1998 Peer Review and Cryogenics Workshop* by engineers who are currently engaged in developing prototypes of these devices made of HTS components.

Table 1-1 Energy Parameters of HTS Devices

Category	HTS tape required (km)*	Energy Saved, % of total energy entering device	Cryogenic capital cost required per unit stated ($)
Motors	134 per 20 MVA	1.246	4,427 per MW
Transformers	130 per 65 MVA	0.39	415,900 per 65 MVA
Generators	134 per 20 MVA	0.973	3,365 per MW
Cables #	14 per 100 m	1.470	368,170 per mile

* based on 1998 current-carrying capacity of tapes

\# assumes cable carries 2,000 Amps

The “energy saved” column of Table 1-1 contains numbers that at first may appear small. However, these are the *net* savings, after deducting the energy-equivalent of the *operating* cost of the refrigeration system—which acts as a parasitic charge against the total energy saved.

The cryogenic *capital* cost was estimated based on engineering judgment and extrapolation from existing 1997 figures (supplied by vendors) to an expected state around 2010. In this model, typical refrigeration systems have a *specific power* (SP) of 11 when the cold end is at 77 K, and 12 when it is at 70 K. Those optimistic estimated Specific Powers reflect the anticipation that by 2010, refrigerator manufacturers will routinely achieve 30 percent of Carnot efficiency. Today, for typical sizes (drawing a few kW power) and prices, the capital cost is roughly $60 per watt removed from the cold end. Hopefully, that capital cost will decline as modeled in Appendix 15.

It must be kept in mind that if electric motors (or generators) were operated at much lower temperatures (perhaps $T = 20$ K), the cost per watt of heat removal would rise by at least the ratio of Carnot efficiencies, or roughly a factor of four. This would be a very severe cost penalty (a big parasitic subtraction), which would badly hurt the economics of devices running at such temperatures.

The current-carrying capacity of second-generation HTS conductors was 100 Amps per tape in 1999. We anticipate that this figure will rise to 1,000 Amps by 2015. Such an improvement will have a dramatic (downward) effect on the cost of wire for each category of device, as discussed in Appendix 13. At present, the requirements are too high for economic viability. For example, the estimate of 14 km of tape to make 100 m of cable (3-phase cable carrying 2,000 A) derives from both the helicity of the windings and the low (100 A) current capacity J_c. Anticipated future improvements in J_c will reduce the requirement for tape per unit length of cable, thus driving the cost down.

Table 1-2 contains data pertinent to evaluating the life-cycle cost of each device. The incremental capital cost is the cost over and above that of cryogenics and HTS wire. In this table, the columns for capital cost and lifetime reflect the experience and considered judgment of utility engineers interviewed during this study.

Table 1-2 Life-Cycle Cost Parameters

Category	Incremental Capital ($) cost per unit	Lifetime of HTS unit	Discount Rate (%)
Motors	100/kW	31	10.0
Transformers	12/kW	40	7.0
Generators	40/kW	35	7.0
Cables	170,000/mile	40	7.0

Whenever a decision maker weighs the lower first-cost of conventional equipment against the lower life-cycle cost of HTS devices, the entire future savings stream must be brought back to its *Net Present Value*. That involves choosing a suitable discount rate. In Table 1-2, the choice of 7 percent as the discount rate for the “utility” cases may at first appear low, but remember that inflation has been omitted from this entire study. After inflation, 7 percent is reasonable; also, it is the percentage customarily used throughout the public sector for evaluating investments. By using it here, we gain a degree of uniformity with other investment- and market-studies, thus making comparisons slightly easier. Meanwhile, industrial buyers of motors would typically use a discount rate of 10 percent after inflation.

The costs associated with transmission cables deserve special comment. First of all, conventional transmission-line cable is very expensive. For major high-voltage towers marching across the land, the cost of acquiring right-of-way is typically \$200,000 per mile, owing to the need for a 125-foot wide swath. Moreover, the towers, insulators and wire for 3-phase electricity at 115 kV costs roughly \$250,000 per mile. The much smaller "footprint" (required right-of-way) of underground cables give HTS cables a substantial monetary advantage. However, that advantage is squandered by the very high cost of cryogenic refrigeration units. As discussed in Appendix 9, a mile of HTS cable would dissipate 7.8 kW in the cold zone, and that would require 85 kW of power to run the refrigerator—resulting in an estimated cryogenic *capital* cost of \$368,000 per mile, which appears in Table 1-1. That very high penalty is subsequently offset by the large Net Present Value of the electricity saved over its 40-year lifetime.

APPENDIX 2 (REVISED)

MARKET PENETRATION MODEL

A very fundamental question underlying any application of new technology is how fast it will be implemented in the marketplace. Accordingly, any estimate of the impact of new technology must have built into it a *market penetration model*.

There is a standard S-shaped curve that is often used [Andy S. Kydes, *Literature Survey of New Technology Market Penetration*, 1983] to represent the way in which a new product takes its place in the market over a period of years. This curve is represented analytically, which simplifies computation considerably. In this study, we have used this general S-shaped function to model the expected market penetration by HTS motors, transformers, generators and cables. Each of these devices has its own distinct curve, owing to the choice of parameters in each case.

Mathematical Formula

Figure 2-1 shows a pair of typical market-penetration curves; the dashed line lies generally left of the solid line. The time variable is denoted by u, customarily measured in years. The formula generating these curves is:

$$F(u) = b \frac{\exp[(u - c) / a]}{\exp[-(u - c) / a] + \exp[(u - c) / a]}$$

This is also equivalent to:

$$F(u) = b / \{1 + \exp[-2(u - c) / a]\}$$

This can easily be seen to have the solutions;

$$F(u) = b \text{ as } u \text{ goes to } + \text{infinity}$$

$$F(u) = 0 \text{ as } u \text{ goes to } - \text{infinity}$$

$$F(u) = b/2 \text{ when } u = c$$

The parameters are as follows:

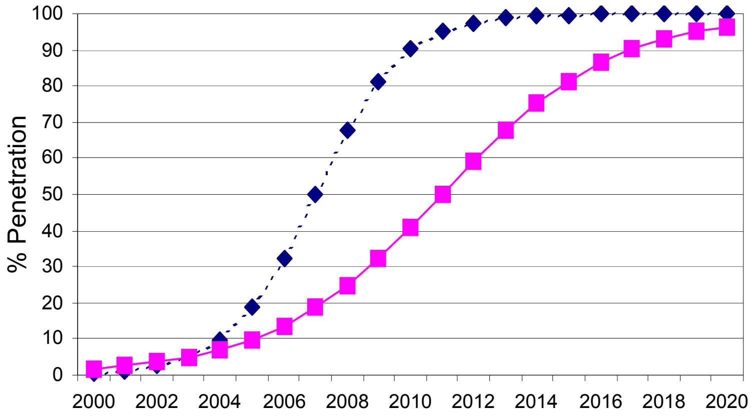
b is the asymptotic maximum value; typically less than 100 percent for plausible market-penetration scenarios.

c is the “halfway point” in time; when u = c, half the market is captured and F = b/2.

a is a parameter of width, determining the speed with which market share is captured.
76 percent of the final market share is gained between the years $u_1 = c - a$ and $u_2 = c + a$.

The two curves in Figure 2-1 differ only in the choice of the parameter c. The solid curve has c = 12 while the dashed curve has c = 8, which sets the midpoints of each at 12 years and 8 years, respectively.

Figure 2-1 Typical Market Penetration Curves



The width parameter, *a*, basically tells how fast market penetration takes place once it gets started. Further, 2*a* is the number of years between having 12 percent of the final market share and 88 percent. Several alternative ways to express the width are also available. If, for example, one were to say that after five years there will be 10 percent market penetration, then the market penetration function is constrained as follows:

$$F\,(u = 5) \;=\; b\;\frac{1}{\{1 + \exp\,[\,-\,2\,(5 - c)\,/\,a\,]\}} \;=\; 0.10$$

This expression can be inverted to present (***a***) as a function of (**b**) and (**c**), with the numbers 5 and 0.1 built in. Here {n = 5} and {F(n) = 10 percent}. Another method often found in textbooks is to postulate a "first-year market penetration" typically about 1 percent, denoted by {x = F(1)}, and then *a* becomes expressible as a function of {ln(**b**/**x**), etc.}. A very similar method is used here.

In Particular, the model begins with any wild guess about the "starting year," calculates some results, and then searches and finds the year in which the profitability of each device changes from negative to positive. That becomes the "first profitable year", or year "n" of market penetration, for which the amount of market penetration F(n) is a number well below 1%. All previous years are years of putting a "toe in the water," during which a few small test projects are tried, and for which profitability is not an issue. This "first profitable year" marks the real beginning of serious market penetration.

In this way, the entire market penetration curve is determined by specifying the four parameters {n, F(n), c, b}. The key position on the time scale is set by the choice of *when* that "first profitable year" (with small market penetration) occurs. It will correspond to a point in time, for example, 2011. A few years of negative profits down to u = 0 are included; for the same example, that might be 2008. Finite but tiny values of the S-shaped function F(u) for years less than u = 0 are truncated away by the computer program.

APPLICATION TO HTS ELECTRICAL DEVICES

A typical set of particular choices of {n, F(n), c, b}, used for the several devices of interest to this study are listed in Table 2-1. The "first profitable year" year for each device is determined by other economic factors external to this appendix.

Figure 1 of the main text displays the market penetration curves for the four HTS devices under certain specific economic circumstances, using parameters similar to those in Table 2-1.

Table 2-1 Parameters of the Market Penetration Model

HTS Device Category	First profitable year in market	previous unprofitable years at outset	F(n) % of market captured in first profitable year	c** years until 50% market penetration	b asymptotic market share (%)
Motors	2011	2	0.10	10	75
Transformers	2015	3	0.25	7	80
Generators	2010	2	0.20	9	50
Cables	2010	4	0.30	9	45

** To avoid awkward zeroes in computation, we move each calculation to "mid-year" by changing c to $c^* = c + ½$.

Some comments are in order here:

First, the fraction of the market captured in the very long run (b) is based on the expectations of knowledgeable utility staff who are familiar with the very broad range of applications in their industry. The relatively low asymptotic values for generators and for cables reflect the judgment that a big fraction of these applications will *never* find HTS technology attractive.

Second, the first year of profitability is a source of great uncertainty. If R&D directed toward reducing the manufacturing cost of HTS wire is not successful in the near future, all of the dates for market entry will slide into the future. If utilities are much more cautious than industry about accepting new equipment, the starting dates for components other than motors will slide further into the future.

Third, the market penetration in the early years cannot be taken with great seriousness; these numbers merely express the "width parameter" (*a*), which tells how spread-out the actual penetration of the market will be.

Fourth, the elapsed time to penetrate half the market (c) reflects engineering judgment about the rate of *acceptance* of new HTS technology. The *market* is the combination of replacements plus new growth. The *total inventory* of the national electrical system must never be confused with that (far smaller) subset about which purchasing decisions are being made.

Sensitivity to Parameters

The particular choices stated in Table 2-1 are open to criticism. The computer model used to carry out this study is readily adaptable to alternate choices for any parameters. Only by changing the asymptotic values (b) can the very long-run outcome be affected; but for years between 2010–2020, the economic outcome of the entire study is definitely sensitive to the starting time and shape of the market penetration curve.

The numbers we have chosen (especially the values for c, the 50 percent-year) for each HTS device are based on the belief that once utility managers see that commercial HTS devices are operating profitably elsewhere, they will gradually be willing to accept the new technology into their systems. That change in attitude awaits a *convincing* demonstration, as contrasted to the first tentative market entry by someone willing to experiment. The natural caution of utility managers suggests that even after the great majority are convinced of the merits of HTS devices, there will still be some applications (and some decision-makers) who will remain with conventional technology well into the future. Therefore, the S-shaped curve governs the later phase of market penetration as well as the early phase.

The width-parameter (a) is numerically determined by our choices of the percent of penetration F(n) in the n-th year. In most cases, we have simulated great caution here, with only 1 percent or so penetration occurring several years after first introduction. In other words, we predict it will be a *hard sell* to gain a foothold in the utility marketplace. The fact that factory managers are less risk-averse than utility managers suggests that electric motors will penetrate their rather limited market slightly quicker than other devices.

The model is easily adaptable to alternate hypotheses about preferences. We ran one special numerical example to simulate extreme reticence to the introduction of both HTS generators and cables, but an optimistic scenario for transformers -- market entry beginning around 2013, followed by spreading throughout the utility system, so that by 2020 nearly 80 percent of expansion or replacement transformers would be HTS devices. Figure 2-2 may be contrasted with Figure 1 of the main text. The point of this comparison is that the *perception* of what is reliable and risk-free is a dominant factor affecting utility choices, and how rapidly that perception *changes* affects market share. In the case of Figure 2-2, the perception about transformers begins to change around 2013, but for generators and cables it will have changed little by 2017.

Figure 2-3 illustrates the interplay among the parameters. Again focusing on transformers for the same initial conditions as Figure 2-2, the 50 percent-year (c) was set to only three years instead of seven; after a slow introduction lasting from 2009 to 2012, this choice forced the market penetration curve to rise to near saturation much too quickly to be realistic.

Needless to say, the actual revenue associated with this entire HTS industry will be strongly affected by what actually takes place in future years -- especially how soon true reliability is convincingly demonstrated. Our mathematical estimates certainly have very wide error brackets associated with them.

Figure 2-2 Penetration Curves

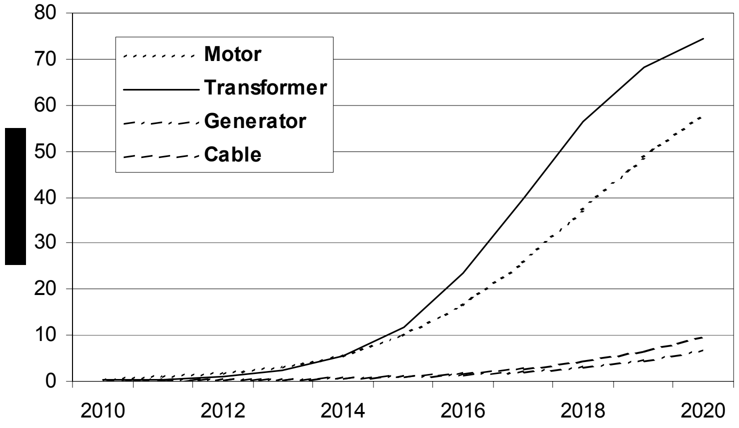
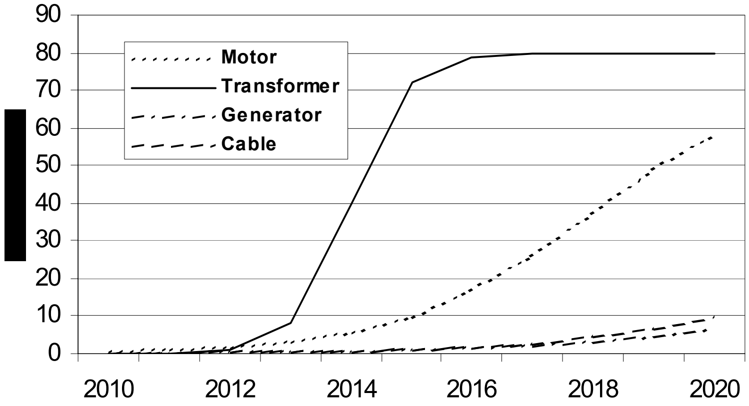


Figure 2-3 Penetration Curves



Appendix 3

U.S. ELECTRICAL SYSTEM LOSS ANALYSIS

In this Appendix, we review how spreadsheet analysis was used to segregate the losses at each stage of transformation, transmission and distribution, and to calculate the portion of such losses that are within the reach of HTS technology. Since our goal is to estimate HTS market impact, the remaining fraction of the national losses that cannot be changed via HTS are set aside from further analysis. By following this procedure of excluding unaffected power losses, we ensure that the market-impact of HTS is not overestimated. This conservative practice leads to a substantially lower estimate than has been reported elsewhere [Bob Lawrence, *High Temperature Superconductivity: The Products and Their Benefits,* July 1998].

Table 3-1 presents the data on electricity generation for the years 1996, 1998 and 1999, obtained from EIA data. In the middle of the table, the rows for *Total Energy to Grid*, minus *Total Sales* yields *Losses*. The units are TeraWattHours (Billion kWh). The total losses (255.9 TWh in 1996) correspond to $18 billion of lost revenue from end users. This gives an idea of the value associated with this topic. The only point to be made by displaying three consecutive years is that there is a small steady upward trend line in these figures. Near the bottom of Table 3-1, the year-to-year comparison shows that electricity prices have been declining slightly.

Although this appendix deals with numbers taken from 1996, the reader should understand that the same procedure applies to any other year for which EIA data is available.

Overview

This input data from EIA is used in the construction of Table 3-2, which traces the path of electricity through multiple stages of generation, transmission and distribution. Column L of Table 3-2 (*Annual energy*) begins with data taken from Table 3-1 and then follows the accumulation of losses (in TWh) en route to the end-user. The starting number for all of Table 3-2 is taken from Table 3-1 and appears in cell 1-L: that is the number of TWh entering the transmission system of the United States in 1996; that is, the sum of utility generators (3,175 TWh) plus cogeneration sold to utilities (154 TWh) = 3,329 TWh. Other fixed numbers taken from the EIA data in Table 3-1 include *imports* (37.5 TWh), *total sales* (3,110.1 TWh, cell 14-L), and *total losses* (255.9 TWh, cell 15-L).

To achieve a full understanding of the calculations in this study requires a thorough examination of Table 3-2, and that is the subject of the rest of this appendix.

Table 3-1 Electricity Supply, Disposition and Prices (Billions of kWh, unless otherwise noted)

Generation by Fuel Type	1996	1998	1999
Electric Generators			

Generation by Fuel Type	**1996**	**1998**	**1999**
Coal	1,745	1,826	1,833
Petroleum	72	115	100
Natural Gas	300	346	371
Nuclear Power	700	674	730
Pumped Storage	(2)	(2)	(1)
Renewable Sources	365	359	353
Total	*3,175*	*3,317*	*3,386*
Non-Utility Generation for Own Use	16	16	16
Cogenerators			
Coal	60	52	47
Petroleum	10	15	9
Natural Gas	200	197	206
Other Gaseous Fuels	3	8	5
Renewable	30	31	31
Other	4	7	5
Total	*307*	*310*	*302*
Sales to Utilities	154	158	151
Generation for Own Use	152	152	151
Net Imports	37.5	27	32
Total Energy to Grid	3,366	3,502	3,569

Generation by Fuel Type	1996	1998	1999
Electricity Sales by Sector			
Residential	1,080	1,128	1,146
Commercial	980	1,060	1,083
Industrial	1,030	1,040	1,063
Transportation	17	17.5	18
Total Sales	*3,110*	*3,253*	*3,309*
Losses	256	249	260
End-Use Prices (1997 cents/kWh)			
Residential	8.5	8.3	8.1
Commercial	7.7	7.6	7.3
Industrial	4.6	4.6	4.5
Transportation	5.5	5.4	5.3
All Sectors Average	*6.9*	*6.8*	*6.7*
Emissions (million short tons)			
Sulfur Dioxide	13.10	13.13	12.46
Nitrogen Oxide	5.80	5.83	5.45

Table 3-2 U.S. Electric System Loss Distribution Analysis

	A	B	C	D	E	F	G	H	I	J
		Marginal (Demand) Losses								
		Average Size MW	Power %	Power GW	Xfmr Noload Losses %	Xfmr Noload Losses (GW)	I2R Losses %	I2R Losses GW	Total Losses GW	Losses as % of Total
1	Generation		98.89%	691.0						
2	Step-up Transformer T1	425	98.89%	691.0	0.08%	0.6	0.24%	1.7	2.2	0.32%
3	Imports		1.11%	7.8						
4	500 kV, 345 kV & 230 kV Transmission		99.68%	696.5			0.54%	3.7	3.7	0.53%
5	Step-down Transformer T2	300	99.15%	692.8	0.12%	0.8	0.25%	1.7	2.6	0.37%
6	161 kV, 138 kV, 115 kV & 69 kV Transmission		98.78%	690.2			2.97%	20.5	20.5	2.94%
7	Step-down Transformer T3	30	95.84%	669.7	0.22%	1.5	0.47%	3.1	4.6	0.66%
8	Meter	60.0%	45.41%	317.3	0.80%	2.5			2.5	0.36%
9	Sales		45.05%	314.8						
10	25 kV & 12 kV Distribution		49.76%	347.7			6.00%	20.9	20.9	2.99%
11	Distribution Transformer T4	0.05	46.78%	326.9	1.08%	3.5	2.70%	8.8	12.4	1.77%
12	Meter		45.01%	314.5	2.00%	6.3			6.3	0.90%
13	Sales		44.11%	308.2						
14	Total Sales		89.16%	623.0						
15	Total Losses		10.84%	75.7					75.7	10.84%
16	Total Sales & Losses		100.00%	698.8						
17	Total Generation + Imports		100.00%	698.8						
18	Total Transmission Losses		4.00%				4.00%			
19	Superconductivity Eligible Losses						4.47%			
20	Volt 1			230.0						
21	Volt 2			138.0						
22	Average Load Factor			55.0%						
23	Transmission Sales Load Factor			70.0%						
24	Distribution Sales Load Factor			43.7%						
25	Demand To Energy Factor @ LF=55			0.36						
26	Demand To Energy Factor @ LF=43			0.24						
27	Transmission Losses - HTS Eligible									
28	Transformer Losses - HTS Eligible									

Table 3-2 U.S. Electric System Loss Distribution Analysis (Cont.)

	(A)	K	L	M	N	O	P	Q	R
		Average (Energy) Losses							
		Energy %	Energy TWh	Xfmr Noload Losses %	Xfmr Noload Losses TWh	I2R Losses %	I2R Losses TWh	Total Losses TWh	Losses as % of Total
1	Generation	98.89	3329.1						
2	Step-up Transformer T1	98.89	3329.1	0.15%	4.9	0.16%	5.3	10.2	0.30%
3	Imports	1.11	37.5						
4	500 kV, 345 kV & 230 kV Transmission	99.70	3356.4			0.35%	11.9	11.9	0.35%
5	Step-down Transformer T2	99.34	3344.5	0.22%	7.2	0.16%	5.5	12.7	0.38%
6	161 kV, 138 kV, 115 kV & 69 kV Transmission	98.97	3331.8			1.96%	65.4	65.4	1.94%
7	Step-down Transformer T3	97.02	3266.4	0.40%	13.1	0.31%	10.0	23.1	0.69%
8	Meter	57.80	1945.9	0.80%	15.6			15.6	0.46%
9	Sales	57.34	1930.4						
10	25 kV & 12 kV Distribution	38.53	1297.3			3.39%	43.9	43.9	1.30%
11	Distribution Transformer T4	37.23	1253.4	2.47%	30.9	1.48%	18.6	49.5	1.47%
12	Meter	35.76	1203.9	2.00%	24.1			24.1	0.72%
13	Sales	35.04	1179.8						
14	Total Sales	92.38	3110.1						
15	Total Losses	7.60	255.9					256.5	7.62%
16	Total Sales & Losses	99.98	3366.0						
17	Total Generation + Imports	100.00	3366.6						
18	Total Transmission Losses					2.64%			
19	Superconductivity Eligible Losses					2.95%	42.4		
20	Volt 1		230						
21	Volt 2		138						
22	Average Load Factor								
23	Transmission Sales Load Factor								
24	Distribution Sales Load Factor								
25	Demand To Energy Factor @ LF=55								
26	Demand To Energy Factor @ LF=43								
27	Transmission Losses - HTS Eligible								1.94%
28	Transformer Losses - HTS Eligible								0.62%

Looking first at column A, the consecutive rows represent each step along the path from generation to end-user sale. All electricity generated in the U.S.A.—the overwhelming majority—is stepped up in a transformer to begin the first stage of high-voltage transmission. *Imported* electricity (1 percent) consists only of high-voltage DC power purchased at the Canadian border, which therefore enters after the first step-up transformer. Moving down column A, the stages of transmission and distribution are enumerated. Some electricity is sold after high-voltage transmission to major direct-service customers (60 percent), and the remainder goes through an additional *distribution* stage before reaching end-users in the commercial and residential sectors. This 60/40 split is a rough number, because the exact amount of high-voltage compared to low-voltage sales cannot be reconstructed from the data in Table 3-1 on sales to transportation, residential, commercial and industrial customers.

It is noteworthy that just ahead of two points-of-sale there are meters; and since meters run notoriously slow, a loss of 0.8 percent is assigned to post-transmission meters and 2 percent is assigned to post-distribution meters. These are not real losses of electricity, but the calibration error changes the amount of electricity that is *reported* as being sold. In order to balance reported generation and reported sales, the metering errors must be included, or else the losses would artificially appear to be much higher.

Listed at the bottom of column A is a variety of factors that bear upon the derivation of total losses.

Column B of Table 3-2 simply states an average MVA rating of each of the several transformers in the system.

The *Demand Losses* columns refer to the peak generation and transmission conditions; columns C through J pertain to the instantaneous *power* transmitted. The *Energy Losses* columns (K through R) pertain to the total annual electric *energy*. It is important to keep these two categories distinct in order to be able to identify the fraction of losses eligible for HTS technology.

DETAILS

A. Generation

The progression of electricity through Table 3-2 begins in row 1, where cell 1-L states the total American electric *energy* generated (TWh) in a year, brought over from Table 3-1. The first step must be to derive a *peak power* generation figure from this. Since different parts of the country peak in both generation and demand at different times of the day, it is not feasible to account for each region separately. Therefore, to construct a representative generation figure, we first divide the total TWh by 8,760 hours, and then also divide by a suitable *load factor* (from Appendix 4, we choose 0.55 for this number). The result is to infer a peak generation rate of 691.0 GW (cell 1-D) from a total energy of 3,329.1 TWh (cell 1-L).

In the same way, the known imports of electricity from Canada were 37.5 TWh in 1996 (from Table 3-1); when divided by 8,760 and 0.55, cell 3-D yields 7.8 GW, a valid means of estimating peak GW associated with imported power.

B. Transmission

Having established the starting point for analyzing transmitted power, it is instructive to march down the rows considering columns C through J together.

Beginning in row 1, we see that 98.89 percent (1-C) of electricity (= 691 GW, 1-D) is generated domestically, and (row 13) all of that is stepped up in a transformer (T1) prior to transmission. There is a slight loss in such transformers. The transformer size used here is a very large transformer, typically 425 MVA. Details appear in Appendix 8. The overall efficiency = 99.68 percent in such transformers, which is reflected by the choice of 0.32 percent loss in cell 2-J.

Dividing up this loss appropriately creates another point where engineering judgment is required: following *Load Flow Analysis* [Olle Elgerd*, Electric Energy Systems Theory: An Introduction*, 1971], we estimate that in a large transformer the *no-load loss* is about equal to the *i^2R loss* during average conditions, but at peak conditions the *i^2R loss* will be about triple the *no-load loss*.

Consequently, for transformer T1 the *no-load loss* is set at 0.08 percent (cell 2-E) and the *i^2R loss* is 0.24 percent (2-G); cells 2-F and 2-H show the actual GW losses. The total GW loss and percent loss appear in 2-I and 2-J.

After the imports (row 3) enter the transmission stream, the sum is now only 696.5 GW (= 99.68 percent of original generation), and that enters the transmission stage (row 4). During long-distance high voltages transmission, 3.73 GW is lost (4-H and 4-I), or 0.54 percent (4-G and 4-J).

The next stage is to step-down the voltage in transformer T2 (row 5) prior to further transmission at intermediate voltages. Whereas the step-up transformer following a generator is sized exactly and runs very near the maximum transformer rating, at the first step-down stage the transformer is commonly run at only 70 percent of its rating. Consequently, although the *no-load loss* would again be 0.08 percent for a comparable size of transformer, now that must be divided by 0.7, giving 0.12 percent as the entry in cell 5-E. The *i^2R loss* is 0.25 percent (5-G). The total loss at this stage is 0.37 percent (5-J).

Further transmission at voltages near 10^5 volts (row 6) takes a toll of 2.97 percent (6-G), simply because the voltage is lower and the current is higher, increasing the *i^2R loss* in the transmission lines. 20.53 GW are lost in this stage (6-H and 6-I), which is 2.94 percent of the total national power (6-J). That brings the total "surviving" electricity down into the 96 percent range.

As the power branches out through the transmission system, there is another step-down transformer T3 (row 7); its size is typically 30 MVA, much smaller than the step up transformer following the generator. Because the average size of these transformers is smaller, the losses increase. With the peak *i^2R loss* at 0.47 percent (7-G), the *no-load loss* is about one-third of that, divided by 70 percent, or 0.22 percent (7-E). This is consistent with a 30 MVA transformer operating near 100 kV. The total loss at this stage (7-I) constitutes 0.66 percent (7-J) of the original power generated.

The description of the entries in columns K through R are quite similar, but here the numbers are annual total *energy* figures (TWh) instead of *power* generation figures (GW). Accordingly, some of the percentages change.

The percentages in column K start off equal to column C at the generation stage. This is because, as stated above, peak GW (column D) is derived from annual TWh (column L) by dividing first by the average load factor (55 percent) and then by 8,760 hours/year. However, once transmission begins, the numbers start to drift apart, because the *actual* losses at peak are greater than their *average* values: *no-load losses* are nearly constant, but the *i^2R loss* is substantially lower on average than at peak. Expressed in percentages, this causes the no-load losses to increase in significance.

As explained in Appendix 4, each load factor L is accompanied by another factor G, an integral over variations in *i^2*. Under typical conditions in the American national grid, L=0.55 and G=0.36. Utility experience shows that residential distribution lines have a smaller load factor L=0.437, with G=0.24. To convert from *power* *i^2R loss* to *energy* *i^2R loss* requires multiplying the loss in GW by 8,760 hours/year and then by the factor G (usually 0.36) to reach TWh.

The first step-up transformer T1 shows these effect: Cells 2-M and 2-O show 0.15 percent and 0.16 percent respectively, for *no-load* and *i^2R losses*; this compares with the values of 0.08 percent and 0.24 percent in cells 2-E and 2-G. These percent changes are a direct consequence of the *load factor* being only 55 percent of peak generation.

Continuing down columns K-R, the high-voltage transmission stage eats up 11.79 TWh (4-P and 4-Q) over the course of a year, which amounts to 0.35 percent of the annual national electricity supply (4-R). This average figure is lower than the 0.5 percent lost at peak conditions (4-J), because the loss is all *i^2R loss*, which falls off as *i^2* with declining current.

The first step-down transformer T2 (row 5 again shows a reversal of the importance of *no-load loss* compared to *i^2R loss* (examine 5-E, 5-G, 5-M, 5-O), for the same *load factor* reason.

The second intermediate-voltage transmission stage (row 6) again shows a much smaller percentage loss than at peak (6-O or 6-R compared to 6-G or 6-J).

By now it is no surprise that in transformer T3 the loss percentages are again reversed, and the total annual energy loss at this stage, 23.08 TWh (7-Q) amounts to 0.69 percent of all electric energy (7-R). That compares with 0.66 percent (7-J) associated with the losses in T3 at peak. Because the transmission lines are less lossy on average, the transformer stages account for a greater *percent* of the total loss.

After the power has been stepped down into the 10-20 kV range, some is sold to major users at this point. Based on EIA data, we estimate that 60 percent of America's energy is sold this way. After the attenuation in stage T3 (7-Q), there remains 3,243.9 TWh, and 60 percent of that *energy* leaves the transmission stream and enters the meter (8-L). The equivalent *power* (8-D) is calculated by dividing 8-L by 8,760 hours and then by a load factor of 70 percent. This is higher than the *average* load factor (55 percent) but more appropriate for high-voltage sales. This equals 58 percent of the national *energy* (8-K), but that is only 45.4 percent of the *power* (8-C), due to the higher load factor.

The metering error (taken to be 0.8 percent) appears in row 8, column E; but since it only applies to the portion sold here, it shows up as a reduction of 0.36 percent of the national power budget (8-J). Again, this "loss" is purely fictional, an accounting necessity. The amount of electricity purchased (slightly reduced) appears in row 9. Cell 9-L contains 1,930.4 TWh, which equals 57.34 percent (9-K) of national electric energy.

C. Distribution

Meanwhile, the rest of the power must proceed through distribution lines (row 10) at substantially lower voltages and higher currents, where the *i^2R loss* is much higher. In Table 3-2, 669.7 GW entered transformer T3 (7-D), where 4.65 GW was lost (7-I); then 317.3 GW went to the high-voltage meter (8-D). All the rest (347.7 GW, cell 10-D) goes on to a further stage of distribution and voltage reduction. That equals 49.76 percent of peak power (10-C), but only 38.53 percent of energy (10-K), because the distribution network sees a substantially lower load factor, about 43 percent.

There follows many different pathways through lines carrying different loads. The distribution system is so complicated that we really cannot possibly calculate how much power is lost there. Using engineering judgment, we select the approximate value of 6 percent for the *i^2R loss* (10-G). Converting from power to energy involves multiplying that value by 8,760 hours and a suitable average value of $<i^2>$, which is 0.24 for the lower load factor typical of distribution lines.

Next, electricity undergoes yet another step-down transformer stage (T4) prior to distribution to residential and commercial customers, and this is shown in row 11. In contrast to prior transformer stages, the *no-load loss* here is only one-fifth the *i^2R loss*, but the transformers on average are loaded only 50 percent, so we obtain an estimate for the *no-load loss* of 1.08 percent (11-E) and an *i^2R loss* of 2.70 percent (11-G). Adding the two corresponding GW losses (11-F and 11-H) yields 12.4 GW (11-I), which is 1.77 percent of the national power budget (11-J). To get from the power *i^2R loss* (11-H) to the energy *i^2R loss* (11-P), it is necessary to multiply by 8,760 hours and then by a weighting factor G = 0.24, which corresponds to the lower load factor associated with the distribution stage.

The fraction of total annual energy entering the distribution stage to residential and commercial customers is lower (compare 10-C with 10-K), which reflects the lower load factor for these customers. The energy lost in the distribution lines and transformers is 2.77 percent {(10-R) + (11-R)}. The difference between this figure and the 4.76 percent at peak {(10-J) + (11-J)} shows how significant it is to utilities to minimize the afternoon peaking effects of air conditioners and/or electric appliances at the user-end of distribution lines.

Homes and businesses have meters (row 12), assumed to have a 2 percent calibration error (12-E), and this shifts the *purchased* electricity downward, reducing the national total by another 0.9 percent (12-J). No one is getting 2 percent of their electricity for free; the local utilities merely charge 2 percent more for the lower *apparent* sales.

Finally, the sales shown in rows 9 and 13 combine to form the total sales of row 14. Total sales of electric *energy* equals 92.4 percent of that produced (14-K), with losses of 7.6 percent (15-K). This contrasts with the sales of *peak power* generation = 89.16 percent (14-C) and peak losses of 10.84 percent (15-C). The 7.6 percent figure is more accurate than the rough rule-of-thumb "8 percent loss in transmission and distribution" which has long been cited.

Rows 16 and 17 must total 100 percent. The slight mismatch on the energy side shows the impossibility of knowing the load-factors perfectly.

In Appendix 5, we will examine the implications of all these numbers for the role of HTS in electric transmission and distribution.

APPENDIX 4

LOAD DURATION CALCULATIONS

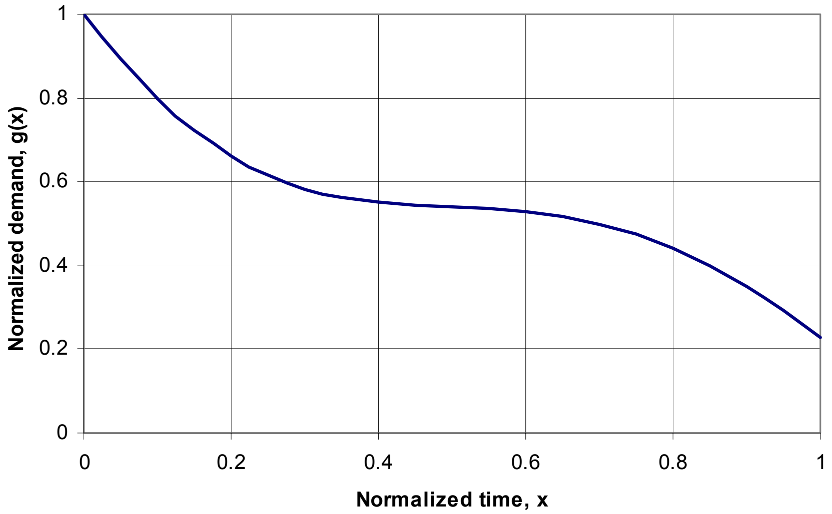
In a transmission line, there are both demand and energy losses, corresponding to *peak* and *average* losses. To ensure correct analysis in later appendices, it is necessary to establish the relation between these two.

As is well known, the use of electricity varies from hour to hour during the day, and therefore there is a varying *load duration* on any transmission line. There is adequate experience from many transmission lines to enable us to say how many hours of the day the line will carry 25 percent of capacity, 40 percent, 50 percent, and so forth up to 100 percent of rated capacity. A *Load Duration Curve* is an analytic function g(x)—typically a low-order polynomial—constructed by curve fitting the pairs of data points {x = fraction of day when current exceeds a certain load, y = fraction of full load}. The independent variable x {0<x<1} is related to time—a rearrangement of the hours in a day; g(x) represents the current flowing in the transmission line, but normalized to the interval 0<g(x)<1.

The average *load factor* L is the integral of g(x) over 0<x<1, $L = \int_0^1 g(x)\,dx$; that is, covering a full 24-hour day.

Figure 4-1 illustrates typical data from transmission lines; for this case, we find L = 0.55. The power factor p(x) is another important variable, representing the phase relationship between current and voltage at any portion of the day (it varies between 0.9 and 1.0).

Figure 4-1 Load Duration Curve



In order to calculate the i^2R *loss* in the line, a second useful integral is G, the integral over time of $[g(x)/p(x)]^2$, G = $\int_0^1 [g(x) / p(x)]^2 dx$. Again using typical data to construct g(x) and p(x), we find G = 0.3636. This means that the average i^2R *losses* over a long time will be 36.36 percent of the *peak* losses on the transmission line.

One other integral is H, the time-average of $[g(x)/p(x)]^3$, H = $\int_0^1 [g(x) / p(x)]^3 dx$. This is useful in analyzing AC losses, which vary as i^3. For the data of Figure 4-1, H = 0.248.

For a different *Load Duration Curve* g(x), these average integrals will change. *Distribution* lines to specific customers have different g(x) from the *transmission* lines serving their area. For example, with a typical distribution g(x), we find L = 0.437, G = 0.240.

When a superconducting cable displaces a conventional transmission line, the i^2R *loss* vanishes, but other contributions to the total loss remain, and the superconductor adds some losses of its own (notably the cryogenic cooling penalty). The separate computation of these various losses helps to maintain the validity of the economic comparison between conventional transmission lines and HTS cables.

APPENDIX 5

LOSSES RELEVANT TO HTS

High Temperature Superconductivity may be useful in several stages of the electrical transmission and distribution system, but not in all stages. In this appendix, we consider which of the many stages described in Appendix 3 can benefit from HTS wire, and then calculate the projected energy savings associated with introducing HTS. In order to get to this stage, we carefully separated *no-load losses* from i^2R *losses* in the calculations of Appendix 3. Moreover, we used engineering judgment about actual hardware to estimate whether HTS devices might actually be used in certain segments of the path from generation to end-user.

For example, it is our considered judgment that comparatively small transformers (< 1 MW) will not be built from HTS materials for economic reasons rooted in both manufacturing cost and operating (cryogenics) cost. Thus, the *Distribution* sector will not be modified by introduction of HTS technology elsewhere. Concomitantly, attending to Table 3-2, the losses associated with distribution lines and transformers are **not** considered eligible for HTS-related savings.

Beginning with Table 3-2, we compute the “HTS eligible losses” as follows:

Since superconductors have zero resistance, we can assert that the i^2R *loss* will drop to zero wherever HTS is introduced. That change will affect transmission cables as well as transformers [T1, T2, T3] throughout the transmission stages. In Table 3-2, this means locating and adding up the elements that will change with HTS wire. At first it seems that the total transmission losses are 3.5 percent (peak generation, 4-G + 6-G) or 2.3 percent (annual energy, 4-O + 6-O). Also, the total i^2R *losses* from all three eligible transformer stages amount to 0.96 percent (peak generation, 2-G + 5-G + 7-G) or 0.62 percent (annual energy, 2-O + 5-O + 7-O). There are entries in certain columns of rows 2, 4, 5, 6 and 7 that pertain to i^2R *loss*. In column G, these five add up to 4.47 percent of peak generation losses, and in column O the five add up to 2.9 percent of annual energy losses. In column P, the five i^2R *losses* sum to 98.1 TWh, and that electricity is worth nearly $4 billion annually.

However, not all transmission lines can be realistically considered eligible for HTS because of both technical and economic obstacles. Neither high-voltage cross-country transmission lines nor distribution lines is a plausible candidate for HTS; we have left out their i^2R *losses* from our accounting of “HTS eligible losses.” Consequently we considered only intermediate transmission. The topic of intermediate transmission voltage is developed in Appendix 9.

Alternative analyses are possible. Someone with a different opinion on what is plausible would reach different numbers for the total “HTS eligible losses,” in column G (peak generation), column O (annual energy percent) and column P (annual i^2R *loss*). We consider it essential to the validity of this study to allow for such alternate choices, and we strive to make our judgments eminently clear.

In this analysis, transmission lines are the larger part of the potential gain. Note that if *all* high-voltage transformers became HTS transformers, the maximum annual savings would be 0.6 percent of the nation’s electricity, about 20 TWh, worth only $1 billion. Meanwhile, the conventional intermediate transmission lines dissipate almost 2 percent of America’s electric energy which is worth $2.6 billion.

HTS is not a free ride. It must be remembered that HTS components carry an energy penalty due to necessary cryogenics as well as AC losses. These factors should be incorporated into the category of *no-load losses*.

APPENDIX 6

ENERGY LOSS SAVINGS IN ELECTRIC MOTORS

For each of the four major device applications, we have prepared a chart that tracks both the flow of energy and dollars, to reach a meaningful cost-comparison between the HTS device and the equivalent conventional technology. This appendix presents that analysis for the case of electric motors.

When a conventional motor is supplanted by a HTS motor, what savings will there be? That answer would depend on the value of the electricity saved, minus the cost of cooling the HTS motor. This appendix traces the analysis path by which the comparison is calculated.

Conventional motors suffer losses in five categories: stator loss, rotor loss, friction and windage, core loss, and stray loss. By substituting a superconducting rotor for a copper-wound rotor, all the i^2R loss in the rotor is eliminated. There is also some decrease in other categories, simply because an HTS motor is *smaller* than a conventional motor (less iron, lighter bearings, etc.)[1]. Accordingly, the advantage of an HTS motor is not limited to the rotor i^2R loss. Roughly *half* the loss in very large motors can be saved, so a hypothetical 98 percent efficient HTS motor can replace a 96 percent efficient conventional motor.

However, the refrigeration penalty for HTS motors eats into the savings. This penalty is comprised of both the *capital* cost of a refrigeration unit and the *operating* cost of running it. Because the type of motors being pursued within the SPI program use BSCCO wire and require operation below 30 K, this penalty is very severe. A future HTS motor design that would use YBCO and run at 70 K would have a considerably smaller penalty. That is the case we analyze here.

Table 6-1 presents the sequence of steps in the analysis. In the following text, the notation {*j*} refers to row number *j* in the chart. Column C of Table 6-1 states how the various factors were calculated.

OPERATING SAVINGS AND COSTS

The range of large electric motors deployed in America has been tabulated by the Department of Energy (DOE)[2]. Drawing from tables there, we consider only large motors above 500 hp. As listed in rows 3 to 8, we select as an average motor size 1,160 hp, or 865 kW. The population of interest is approximately 39,000 motors; the total energy used by them is 167,545 GWh/yr. The average motor runs 7,256 hours per year, or about 83 percent of the time.

Table 6-1 HTS versus Conventional Motors Loss Analysis
Motors 501 HP and Larger

	A	B	C Source
1	Average Size (HP)	1,160	*1*
2	Average Size (kW)	865	
3	Number of Motors	39,005	*1*
4	Energy Used (GWh/Year)	167,545	*1*
5	Operating Hours per Year per Motor	7,256	*1*
6	Average MWh/Motor/Year	4,295	B(4)/B(3)
7	Average Use per Motor (kW)	592	B(6)/B(5)
8	Capacity Factor	68%	B(7)/B(2)
	Conventional Motor		
9	Magnetic and Iron Loss Penalty Saved by HTS	0.51%	*2*
10	Windage and Friction Penalty Saved by HTS	0.28%	*2*
11	Average Field Winding Losses	0.61%	*2*
12	Average Loss Savings	1.40%	
13	Average Loss Savings (MWh/Motor/Year)	60	B(6)*(B(12))
	HTS Motor Losses		
14	Average No-Load Loss (W/Motor)	48	*3*
15	Average Losses Use Related (W Loss/kW Used)	0.03	*3*
16	Coolant Operating Temperature (Degrees Kelvin)	70	
17	SP	12.0	
18	Efficiency % Carnot	30%	
19	Average Cryo Energy Losses Hot Side (MWh/Motor/Year)	6.6	(B(14)*8.76+B(15)*B(6))*B(17)/1,000
20	Peak Power Losses Hot Side (kW/Motor)	0.889	(B(14)+B(15)*B(2))*B(17)/1,000
	Average Net Energy Loss Savings (HTS vs. Conventional)		
21	(MWh/Motor/Year)	53.5	B(13)-B(19)
22	(%)	1.25%	B(21)/B(6)
23	Average Cost of Energy in 2020 ($/MWh)	$40	*EIA*

	A	B	C Source
24	Average Savings ($/Motor/Year)	2,140	B(23)*B(21)
25	Average Life (Years)	31	*1*
26	Total Savings ($)	66,340	B(24)*B(25)
27	Discount Rate	10%	Industry Estimate
28	Net Present Value of Savings ($)	21,250	
29	Cost of HTS Wire in 2020 ($/Meter)	19.50	*5*
30	Meters of HTS Wire/Motor	580	*5*
31	HTS Wire Cost ($)	11,300	B(29)*B(30)
32	Cryogenic Capital Cost/Motor ($)	3,830	B(20)*4,306
33	Net Savings ($/Motor)	6,110	B(28)-B(31)-B(32)
34	Net Savings ($/kW)	7	B(33)/B(2)
35	Conventional High Efficiency Motor Cost ($)	97,750	113*B(2)

Sources, column C:

1. Xenergy, Inc., *U.S. Industrial Electric Motor Systems Market Opportunities Assessment*, Burlington, MA, Dec. 1998. Tables 1-15 and 1-24.

2. Zhang, Burt, Rockwell Automation Corp., Private communication, June 1999.

3. U.S. DOE, *Cryogenic Needs of Future HTS Electrical Power Equipment*, Workshop Proceedings, July 1998.

4. EIA, *Annual Energy Outlook 2001* Washington, DC, Dec. 2000.

5. This report, pp.10-12.

From these numbers, it is easy to calculate that the average motor consumes 4,300 MWh in a year {6}, which (spread over 7,256 hours) implies an average power of 592 kW {7}. Comparing that to the average motor *size* of 865 kW means the capacity factor is 68 percent {8}.

The energy savings achievable appear in rows 9-13. For a conventional motor[3] it is reasonable to estimate the rotor i^2R loss at 0.61 percent of the energy going through the motor. Some of the friction and windage loss will also be saved by a HTS motor; we estimate that portion at 0.28 percent. Reduced iron-core losses save another 0.51 percent. By combining these contributions, we arrive at a total amount of 1.4 percent that is *saved* by an HTS motor compared to a conventional motor {12}.

With an average use of 4,300 MWh/motor/year, the average savings to be gained is 60 MWh/motor/year {13}. This is the advantage of superconductivity, which will be partially offset by a cryogenic penalty.

Good engineering design ensures that, as much as possible, unavoidable losses occur at room temperature; thus, all bearings are placed outside the cold region, and need not be cooled. The same is true for the stator and the core. If some portion of those losses appeared as heat to be removed, that portion would have to be included under the category of cryogenic-penalized losses.

The calculation of the cryogenic losses proceeds as follows:

Starting with existing electric motor test data[3], we scale up by 16 percent (865/746) to estimate a *transfer loss* of 23.2 W and a *background loss* of 25 W, giving a total no-load loss of 48.2 W {14}. To this must be added certain "use-dependent" losses: the *i^2R loss* and the *AC loss* in the field coil. With adequate precision (over the range of currents expected), these two have been lumped together, giving a "use-related" loss of 0.03 W for every kW used by the motor {15}. In a year, for the average motor[4], these total:

48 W x 8,760 hr/(1,000 kW/MW) + 0.03 W/kW x 4,295 MWh = 551 MWh/kW = 0.55 MWh

The severest penalty enters the calculation at this point—all of this energy must be removed as heat from the cold part of the motor. The operating temperature of the motor is taken to be 70 K {16}.

For any cryogenic system operating between 70 K and 300 K, the *Carnot efficiency*[5] is $T_c / (T_h - T_c) = \eta_c = 0.304$. Using engineering judgment, we estimate how well a practical device can perform, and choose a number η_p between 20 and 30 percent of Carnot efficiency {18}. Multiplying these together and taking their inverse, we define the *Specific Power* = $1.0 / \eta_c\eta_p$ or SP. This number determines the severity of the cryogenic penalty. If SP = 12 {17}, this means that 12 W must be drawn from the power supply to remove 1 W from the 70 K part of the apparatus. Expressed another way, if electricity normally sells for 4 cents/kWh, then every kWh of heat generated at low temperature is worth 48 cents. Evidently it is a goal of cryogenic manufacturers to push their efficiency η_p as high as possible to reduce the cost of running the refrigerator.

There is a further point about operation temperature. Earlier in this study, we ran this motor example with a supposed operating temperature of 30 K, which is typical of the SPI motor now being built. Our calculations showed that the cryogenic penalty associated with such a motor would be so severe as to prevent it from *ever* being commercially feasible. In revising the operating temperature upward, we have presumed that a second-generation conductor will be developed that is suitable for use in electric motors. Whether that outcome is a result of another subsequent SPI program or from an industry initiative is not relevant here; the point is that a major improvement beyond today's technology is necessary for HTS motors to be commercially successful.

To remove 0.55 MWh, the input energy needed is 6.6 MWh {19}. The annual energy loss savings attributable to superconductivity (in this average motor) is thereby reduced to [60 - 6.6] = 53.5 MWh/motor/year {21}, or 1.25 percent of the motor's annual energy budget {22}. This is down somewhat from the 1.4 percent targeted above {12}. With large industrial users of electricity paying about \$0.04/kWh, the savings amount to \$2,140/yr {24}. For a motor whose electrical throughput is worth over $100,000 annually, this is hardly a sufficient incentive to purchase a superconducting motor. The advantage to industry must be in the smaller "footprint" of the HTS motor.

Note that if this motor had to run at 30 K, the *Carnot Efficiency* would be 1/9, and (all other things being unchanged) the cost penalty would be a factor of 30. In that case, the refrigeration penalty would be much worse, and the net savings insufficient to persuade buyers to leave conventional motor technology. This fact provides a major incentive to develop second-generation conductors.

CAPITAL COSTS

There are additional *capital costs* associated with a superconducting motor. First, HTS wire has a cost substantially higher than copper wire, and this will increase the selling price of the motor. Running at 70 K, a motor this size will require 580 meters {30} of wire[6]. By estimating a manufacturing cost[7] of $19.50/meter {29} for HTS wire[8] in 2020, we calculate a cost premium of $11,300 {31} for the motor. Even this assumes no additional price premium for the cryogenics or other design aspects of the motor itself.

Moreover, the refrigerator must be sized to deliver a peak cooling capacity corresponding to running the motor at full rating, not just at the *average* power during the year. For this 865 kW motor, that peak is 0.89 kW {20} of input power. A typical refrigeration price today is $4,300 per kW-input-power for a Gifford-McMahon system[4]. We estimate that will decline slowly in future years; thus we calculate $3,829 {32} for a hypothetical refrigerator drawing about 0.9 kW. This is a front-end cost that effectively increases the price of the motor.

Consequently, whatever money accrues over consecutive years from electricity savings must be offset by front end costs exceeding $15,000.

COMBINING SAVINGS WITH COSTS

The annual saving in operating costs represents an annuity that will continue for the lifetime of the motor (typically 31 years for very large motors). The *Net Present Value* (NPV)[9] of such an annuity depends on the discount rate, which is often set at 10 percent (after inflation) for industrial investment calculations. The *NPV multiplier* of an annuity that runs for n year is:

$$\mathrm{NPV} = 1/d - 1/[d(1+d)^n]$$

when the annuity is received at year end. For a continuous stream of revenue throughout the year, this formula needs to be adapted slightly by a "six-month" correction:

$$\mathrm{NPV}^+ = \mathrm{NPV}\,[(1+d)^{1/2}].$$

For the case of $n = 31$ years and $d = 0.10$, we find NPV = 9.48 and $\mathrm{NPV}^+ = 9.92$. Therefore, \$2,140 annual savings are worth \$21,250 today {28}. This is the figure that must be compared with the up-front higher cost of the motor and the refrigerator.

Following all the arithmetic above, the net gain for a motor of this size comes out to \$6,110 {33}, or about \$7/kW {34}. Clearly, there needs to be additional criteria to attract buyers to HTS motors. The smaller footprint continues to be a leading attraction.

The message of this analysis is clear—profitability is by no means assured. Among other things, if a factory uses a higher discount rate, the NPV of the cash flow stream would drop. If the cryogenics do not reach the efficiency anticipated here, the HTS motor would be more expensive. Moreover, there is still a great deal of research and development needed in order to reduce the cost of manufacturing wire below \$20/m, used in the example of Table 6-1.

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1. T.P. Sheahen, *Introduction to High Temperature Superconductivity* (Plenum Press: 1994). Chapter 22 (on Electric Motors) was written by Jordan, Schiferl and Sheahen, and represents the general design features favored by Reliance Electric Corporation.

2. *United States Industrial Electric Motor Systems Market Opportunities Assessment*, report by Xenergy, Inc. to DOE (December 1998).

3. B. Zhang, Rockwell Automation, private communication.

4. U.S. Dept. of Energy, Workshop Proceedings, *Cryogenic Needs of Future HTS Electrical Power Equipment,* July 22, 1998.

5. For a definition, see any text on the subject, e.g., R.F. Barron, *Cryogenic Systems* (London: Oxford Univ. Press, 1985).

6. Intermagnetics General Corp. presentation at *1997 Wire Development Workshop*.

7. American Superconductor Co, private communication.

8. This figure is controversial and optimistic. For an opposing view, see P. Grant & T. Sheahen, *Cost Projections for High Temperature Superconductors,* Applied Superconductivity Conference, September 1998.

9. Franklin Stermole, Economic Evaluations and Investment Decision Methods (Investment Evaluations Corp., 1974).

APPENDIX 7

GENERATORS

For generators, just as for motors, we strive to reach a meaningful cost-comparison between the HTS device and the equivalent conventional technology. Generators have similarities to motors—both their savings and economics derive from common characteristics of their operation. The numbers are quite different, of course, because generators are nearly 1,000 times bigger than motors. Accordingly, MW replaces kW, and GW replaces MW in the sequence of steps, but the tables used in the analysis have virtually identical formats.

Table 7-1 presents the analysis for one size of generator, which serves as a surrogate for all large generators. Rows 1 to 5 set the basic parameters—this unit is a 300 MW generator. We no longer need to cluster a collection of units together to get an average; we can analyze one unit at a time. It generates 1,840 GWh/year by operating constantly (8,760 hrs/yr). The energy generated in one year is 1,839,600 MWh (row 6); given the number of hours in a year, the average generation rate is 210 MW (row 7); which means that for a 300 MW unit, the average capacity factor is 70 percent (row 8). Column C of Table 7-1 states how the various factors were calculated.

We then compare conventional compared to HTS technology for this hypothetical average generator in order to establish the appropriate cost trade-offs. At this point, however, a crucial difference with the motor analysis occurs—because an SPI project is building an electric motor, there are actual measured losses that can be extrapolated to provide input for determining the losses eligible for recovery in a HTS motor [2]. There is no comparable basis for comparison when dealing with generators. A typical large generator of the type considered here costs about $13,500,000, and no R&D project has yet built a HTS generator. Thus, we are limited to using engineering judgment to estimate the extent of the superconductivity-eligible losses in a hypothetical generator.

Accordingly, the losses in a conventional generator were segregated according to categories: iron loss, friction and windage, field coil loss, etc. Rows 9-11 of Table 7-1 list our estimates of the losses that can be saved via HTS. It is a useful exercise to compare these losses in Table 7-1 with the corresponding losses for components within an electric motor. Other losses are simply left out of the discussion, because HTS will not change those losses. The average eligible loss savings accumulate to 1.08 percent (row 12), which amounts to 19.9 GWh per generator per year.

Table 7-1 HTS versus Conventional Generators Loss Analysis

Generators 300 MW

	A	B	C Source
1	Average Size (HP)	402,307	*1*
2	Average Size (MVA)	300	
3	Number of Generators	1	*1*
4	Energy Generated (Gwh/Year)	1,840	*1*
5	Operating Hours per Year per Generator	8,760	*1*
6	Average Mwh/Generator/Year	1,839,600	B(4)/B(3)*1000
7	Average Use per Generator (MW)	210	B(6)/B(5)
8	Capacity Factor	70%	B(7)/B(2)
	Conventional Generator		
9	Magnetic and Iron Loss Penalty Saved by HTS	0.40%	*2*
10	Windage and Friction Penalty Saved by HTS	0.17%	*2*
11	Average Field Winding Losses	0.51%	*2*
12	Average Loss Savings	1.08%	
13	Average Loss Savings (Mwh/Generator/Year)	19,868	B(6)*(B(12))
	HTS Generator Losses		
14	Average No-Load Loss (W/Generator)	16,729	*3*
15	Average Losses Use Related (W Loss/kW Used)	0.009	*3*
16	Coolant Operating Temperature (Degrees Kelvin)	70	
17	SP	12.0	
18	Efficiency % Carnot	30%	
19	Average Cryo Energy Losses Hot Side (Mwh/Generator/Year)	1,965	(B(14)*8.76+B(15)*B(6)) *B(17)/1,000
20	Peak Power Losses Hot Side (kW/Generator)	234.4	(B(14)+B(15)*B(2)) *B(17)/1,000
	Average Net Energy Loss Savings (HTS vs. Conventional)		
21	(Mwh/Generator/Year)	17,902	B(13)-B(19)
22	(%)	0.9732%	B(21)/B(6)

	A	B	C Source
23	Average Cost of Energy in 2020 ($/Mwh)	40	*4*
24	Average Savings ($/Generator/Year)	716,100	B(23)*B(21)
25	Average Life (Years)	35	*1*
26	Total Savings ($)	25,063,500	B(24)*B(25)
27	Discount Rate	7%	OMB
28	Net Present Value of Savings ($)	9,300,000	
29	Cost of HTS Wire in 2020 ($/Meter)	20	*5*
30	Kilometers of HTS Wire/Generator	200	*5*
31	HTS Wire Cost ($)	4,000,000	B(29)*B(30)
32	Cryogenic Capital Cost/Generator ($)	937,600	B(20)*4,000
33	Net Savings ($/Generator)	4,360,000	B(28)-B(31)-B(32)
34	Net Savings ($/kW)	14.50	B(33)/B(2)
35	Conventional High Efficiency Generator Cost ($)	13,500,000	45k*B(2)

Sources, column C:

1. Xenergy, Inc., *U.S. Industrial Electric Motor Systems Market Opportunities Assessment*, Burlington, MA, Dec. 1998. Tables 1-15 and 1-24.

2. Zhang, Burt, Rockwell Automation Corp., Private communications, June 1999.

3. U.S. DOE, *Cryogenic Needs of Future HTS Electrical Power Equipment*, Workshop Proceedings, July 1998.

4. EIA, *Annual Energy Outlook 2001*, Washington, DC, Dec. 2000.

5. This report, pp.10-12.

In a HTS generator, there are other types of losses that must be taken into consideration; chief among these is the *cryogenic penalty* associated with removing heat from a cold region [3]. Based on extrapolating from a 1,000 hp motor to a 300 MW generator (admittedly tenuous), we estimate the no-load loss as follows: the size ratio (300 MW compared to 746 kW) is 402.14; this scale factor is used to increase the background losses from 21.6 W to 8,686 W. The transfer losses are similarly scaled up from 20 W to 8,043 W. The sum of these two give a no-load loss of 16.7 kW per generator (row 14). This almost certainly overestimates the no-load losses for a generator, because a well-designed generator would have much smaller losses, but this way we are confident that the eventual cost estimate will err on the conservative side.

In the same way, we extrapolate from known motor data about *i^2R loss* and the AC loss induced by the stator current in the (cold) rotor. For a large generator, the current goes up from about 130 Amps to 1,000 Amps, so i^2 goes up by a factor of 60, and i^3 by a factor of 450. Over the typical range of currents in the generator, these can be fairly approximated by setting the "use-related" loss = 0.009 W for every kW flowing through the generator (row 15).

Furthermore, the operating temperature of the generator is taken to be 70 K (row 16).

For any cryogenic system operating between 70 K and 325 K, the Carnot efficiency is $T_c/(T_h-T_c) = \eta_c = 0.28$. Using engineering judgment, we estimate how well a practical device [3] can perforrn, and choose a number η_p near 30 percent of Carnot efficiency (row 18). Multiplying these together and taking their inverse, we define the *Specific Power* = $1.0/\eta_c\ \eta_p$ or SP (row 17). This number determines the severity of the cryogenic penalty. If SP = 12, this means that 12 W must be drawn from the power supply to remove 1 W from the 70 K part of the apparatus. Expressed another way, if electricity normally sells for 4 cents /kWh, then every kWh of heat generated at low temperature is worth 48 cents. Evidently it is a major goal of cryogenic manufacturers to push their efficiency η_p as high as possible, to reduce the cost of running the refrigerator.

Once these efficiency numbers are chosen, it is possible to combine the no-load losses (of which there are 8,760 hours/year) with the use-related losses (proportional to the *average* energy drawn in a year). Their sum must then be escalated by the SP to give the average total "hot side" *energy* losses (in annual MWh per motor, row 19) as well as the peak *power* "hot side" losses (in kW, row 20). Despite an average load factor well below 100 percent, it is the peak power loss that the cryogenic system must be sized to handle, which increases the cryogenic penalty about 9 percent.

For the case illustrated in Table 7-1, the cryogenic penalty amounts to almost 2 GWh per motor per year (row 19). This eats into the savings attributable to HTS of 19.9 GWh (row 13), leaving a net gain of 17.9 GWh/motor/year (row 21), which equates to a percentage gain of 0.97 percent (row 22) of the average energy used per year (1,840 GWh) by a generator of this size. Here the *operating* cost of the refrigerator has been merged in to reduce the apparent gain of the HTS generator when *operating*. The *capital* cost of the refrigerator will be discussed subsequently, as part of the *capital* cost of the generator.

Using a standard estimate [4] for the cost of electricity in year 2020 (row 23), the average annual savings is easy to calculate (row 24). Taking an average life expectancy of 35 years [1], the total savings over that lifetime are stated (row 26). However, the value of a future stream of savings must be discounted back to its *Net Present Value* (NPV). With a typical utility discount rate of 7 percent above inflation (row 27), the NPV in row 28 is far below the simple sum of the cash flow.

Moving further down Table 7-1, the next charge that must be placed against the HTS generator derives from the fact that HTS wire is much more expensive than copper wire. Going out to the year 2020, we estimate [5] the HTS wire cost at $20/meter (row 29), and with the expected improvement in current carrying capacity by then, 200 km will be required (row 30) to build a 300 MW generator. That much wire is expected to have a capital cost of $4,000,000 (row 31), which must be paid at the front end.

Next, the capital cost of the cryogenic refrigerator must be added in—a cost of roughly $4,000 per kW is anticipated. Since the refrigerator must be able to handle *peak power* dissipated within the cold part of the generator (a number which appears in row 20), the cryogenic capital cost (nearly $1 million, row 32) is much higher than it would be if only the *average* wattage needed to be removed. The cost comparison here is an argument in favor of a *hybrid* cryogenic system, one in which a liquid nitrogen reservoir is used in conjunction with a cryocooler.

Finally, the net savings for this generator (row 33) becomes the NPV of the savings (row 28) minus both the extra capital cost of HTS wire (row 31) and the cryogenic capital cost (row 32). The dollar value of the savings can alternately be expresses with reference to the size of the generator. Dividing by the size of the generator (row 2) yields a figure of $14.50/kW (row 34). For comparison, a conventional high-η generator tends to cost about $45/kW, so a 3,000 MW generator would cost about $13.5 million (row 35). The power provider contemplating buying new technology has to pay an extra $4.9 million for a HTS unit, but will realize a return of $25 million (row 26) over 35 years, which is worth $9.3 million today (row 28). Thus, this numerical example is profitable.

In the years ahead, as both HTS wire costs and cryogenic costs decline, it is reasonable to surmise that manufacturers of conventional equipment will likewise cut costs. Thus the HTS gain is at risk of being diminished by other improvements in conventional technology. Both HTS wire manufacturers and cryogenic manufacturers must never become complacent with modest gains over time.

APPENDIX 8

TRANSFORMER PARAMETERS

This appendix presents the input data used in subsequent computations pertaining to the efficiency of transformers, and in comparisons between conventional and high-temperature superconducting transformers. The data came from the database compiled by Federal Energy Regulatory Commission—the "FERC 715" filings by major electricity users.

Table 8-1 presents characteristics of a very wide range of transformers. The size of the transformer is commonly denoted by its MVA rating (= MegaVolt - Amps), and that appears in the first column. The next three columns present relevant numbers for conventional transformers of each size. Attending to column B, it is clear that the resistance drops as the size increases. The numbers in column C are the corresponding i^2R loss at *peak* power. Column D is the annual energy losses, in MWh, constructed by first finding the *average* i^2R loss. That average depends on the *load duration curve* and as discussed in Appendix 4, the average of i^2 is proportional to G, the integral over time of $[g(x)/p(x)]^2 = 0.3636$ of the peak value. Multiplying by 8,760 hrs/yr yields the entries in column D.

In general, the efficiency of transformers is initially good, and gets better as the size increases. For example, at the bottom left of Table 8-1, the entry for a 500 MVA transformer indicates that the losses are 1,005.13 kW, or roughly 1 MW, which means the losses are one part in 500, and so the efficiency is about 99.8 percent. (This is quite consistent with the standard loss and efficiency expected of very large transformers.) Column D of the 500 MVA row indicates annual losses of 3,201.57 MWh. This equals 3,201,570 kWh, and if each kWh costs about 4 cents, the cost of these losses would be over $125,000 annually. Similar computations can be done for each row in the table.

Columns E through H of Table 8-1 present hypothetical data expected for HTS transformers. The voltages in column E are the voltage on the *secondary* side of the transformer, and the amount of wire in the transformer (column F) is determined by the desired MVA rating (column A). The simple proportionality used is arbitrary and reflects the difficulty of choosing a value of *critical current density* (J_c) that will be associated with HTS wire. Appendix 13 presents our conjecture as to how the current-carrying capacity may improve over time. The particular numerical choice used here (30 km wire needed for a 30 MVA transformer, etc.) is traced to manufacturer's data [Intermagnetics General presentation at the 1997 *Wire Development Workshop*]. Refinement of this number is needed before any realistic statement can possibly be made about the true AC losses in HTS transformers.

At the present stage of research and development on HTS wire, the conversion from wire length to losses (column G) is conjectural, of course, but expectations here have been kept realistic. The unknown value of AC loss is estimated as 0.4 W/kA-m in constructing Table 8-1.

Table 8-1 Large Power Transformer Characteristic

A	B	C	D	E	F	G	H
	Conventional Transformers			**HTS Transformer**			
Capacity MVA	R-pu Xfmr Base	Losses kW	Losses MWH	Voltage kV	Wire km	Losses kW	Losses MWH
20	0.00515	103.02	328.16	12.47	20	12.57	25.68
30	0.00472	141.57	450.93	12.47	30	36.53	74.64
40	0.00442	176.88	563.40	12.47	40	82.57	168.69
50	0.00420	209.81	668.28	12.47	50	157.96	322.72
60	0.00401	240.86	767.18	24.94	60	37.51	76.64
70	0.00386	270.35	861.13	24.94	70	57.48	117.43
80	0.00373	298.52	950.86	24.94	80	83.87	171.36
90	0.00362	325.54	1036.92	24.94	90	117.61	240.28
100	0.00352	351.54	1119.72	24.94	100	159.59	326.05
110	0.00342	376.61	1199.60	24.94	110	210.73	430.54
120	0.00334	400.86	1276.82	24.94	120	271.94	555.59
130	0.00326	424.34	1351.62	24.94	130	344.13	703.07
140	0.00319	447.12	1424.19	24.94	140	428.20	874.85
150	0.00313	469.26	1494.68	24.94	150	525.07	1072.77
160	0.00307	490.78	1563.25	69	160	37.28	76.16
170	0.00301	511.74	1630.00	69	170	43.58	89.04
180	0.00296	532.16	1695.05	69	180	50.62	103.42
190	0.00291	552.08	1758.50	69	190	58.44	119.41
200	0.00286	571.52	1820.42	69	200	67.09	137.07
210	0.00281	590.51	1880.91	69	210	76.61	156.51
220	0.00277	609.07	1940.02	69	220	87.03	177.81
230	0.00273	627.21	1997.82	69	230	98.41	201.05
240	0.00269	644.97	2054.37	69	240	110.78	226.33
250	0.00265	662.34	2109.72	69	250	124.19	253.73
260	0.00261	679.36	2163.91	69	260	138.68	283.34
270	0.00258	696.03	2217.01	69	270	154.30	315.25
280	0.00254	712.36	2269.03	69	280	171.09	349.55
290	0.00251	728.37	2320.03	69	290	189.09	386.32
300	0.00248	744.07	2370.04	69	300	208.34	425.65
310	0.00245	759.47	2419.09	69	310	228.89	467.63
320	0.00242	774.58	2467.22	69	320	250.77	512.35
330	0.00239	789.41	2514.44	69	330	274.04	559.89
340	0.00236	803.96	2560.80	69	340	298.74	610.35
350	0.00234	818.25	2606.31	69	350	324.91	663.81
360	0.00231	832.28	2651.01	69	360	352.58	720.35
370	0.00229	846.06	2694.90	69	370	381.81	780.07
380	0.00226	859.60	2738.03	69	380	412.64	843.06
390	0.00224	872.90	2780.39	69	390	445.11	909.39
400	0.00221	885.97	2822.02	69	400	479.26	979.17
410	0.00219	898.82	2862.94	69	410	515.14	1052.47
420	0.00217	911.44	2903.15	69	420	552.79	1129.39
430	0.00215	923.86	2942.69	69	430	592.25	1210.01
440	0.00213	936.06	2981.56	69	440	633.57	1294.43
450	0.00211	948.06	3019.77	69	450	676.78	1382.72
460	0.00209	959.85	3057.35	69	460	721.94	1474.98
470	0.00207	971.46	3094.31	69	470	769.08	1571.29
480	0.00205	982.87	3130.65	69	480	818.25	1671.74
490	0.00203	994.09	3166.41	69	490	869.48	1776.42
500	0.00201	1005.13	3201.57	69	500	922.84	1885.42

Source: FERC 715 Filings by NERC, Summer 1998 and ECAR, Summer, 1998.

A	I	J	K	L	M	N	O
	Conventional vs. HTS						
Capacity MVA	Energy Loss Sav Ratio	Dist. of Units	Wtd. Loss Ratio	Wtd. Xfmr Size MVA	Wtd. Cryo Req'd. W/m	Wtd. Avg. Voltage kV	Wtd. Avg.Losses MW/A-m
20	0.08	0.2921	0.0229	5.84	0.1835	3.642	0.198200708
30	0.17	0.1560	0.0258	4.68	0.1899	1.945	0.136722241
40	0.30	0.1044	0.0312	4.17	0.2154	1.301	0.116324875
50	0.48	0.0762	0.0368	3.81	0.2407	0.950	0.103974955
60	0.10	0.0587	0.0059	3.52	0.0367	1.465	0.026434456
70	0.14	0.0468	0.0064	3.28	0.0385	1.168	0.023727093
80	0.18	0.0381	0.0069	3.05	0.0399	0.950	0.021566226
90	0.23	0.0314	0.0073	2.82	0.0410	0.782	0.019662338
100	0.29	0.0262	0.0076	2.62	0.0418	0.653	0.018055403
110	0.36	0.0222	0.0080	2.44	0.0426	0.554	0.016718143
120	0.44	0.0187	0.0081	2.24	0.0423	0.465	0.015214778
130	0.52	0.0163	0.0085	2.12	0.0431	0.406	0.01431112
140	0.61	0.0139	0.0085	1.94	0.0425	0.346	0.013107476
150	0.72	0.0119	0.0085	1.79	0.0417	0.297	0.012001049
160	0.05	0.0103	0.0005	1.65	0.0024	0.712	0.001795481
170	0.05	0.0091	0.0005	1.55	0.0023	0.630	0.001644865
180	0.06	0.0079	0.0005	1.43	0.0022	0.548	0.001481953
190	0.07	0.0067	0.0005	1.28	0.0021	0.465	0.001305264
200	0.08	0.0060	0.0004	1.19	0.0020	0.411	0.001193193
210	0.08	0.0056	0.0005	1.17	0.0020	0.383	0.00115335
220	0.09	0.0048	0.0004	1.05	0.0019	0.329	0.001023326
230	0.10	0.0044	0.0004	1.00	0.0019	0.301	0.000970448
240	0.11	0.0036	0.0004	0.87	0.0017	0.250	0.000832485
250	0.12	0.0033	0.0004	0.82	0.0016	0.226	0.000778966
260	0.13	0.0029	0.0004	0.76	0.0016	0.201	0.000713763
270	0.14	0.0026	0.0004	0.70	0.0015	0.179	0.000654398
280	0.15	0.0023	0.0004	0.64	0.0014	0.159	0.000600274
290	0.17	0.0020	0.0003	0.59	0.0013	0.141	0.000550744
300	0.18	0.0018	0.0003	0.55	0.0013	0.126	0.000505556
310	0.19	0.0016	0.0003	0.51	0.0012	0.113	0.000464136
320	0.21	0.0015	0.0003	0.47	0.0011	0.100	0.000426131
330	0.22	0.0013	0.0003	0.43	0.0011	0.090	0.000391453
340	0.24	0.0012	0.0003	0.40	0.0010	0.080	0.000359591
350	0.25	0.0010	0.0003	0.36	0.0010	0.072	0.000330315
360	0.27	0.0009	0.0003	0.34	0.0009	0.064	0.000303462
370	0.29	0.0008	0.0002	0.31	0.0009	0.058	0.000278824
380	0.31	0.0008	0.0002	0.29	0.0008	0.052	0.000256277
390	0.33	0.0007	0.0002	0.26	0.0008	0.046	0.000235522
400	0.35	0.0006	0.0002	0.24	0.0007	0.042	0.000216354
410	0.37	0.0005	0.0002	0.22	0.0007	0.037	0.000198819
420	0.39	0.0005	0.0002	0.21	0.0006	0.034	0.000182801
430	0.41	0.0004	0.0002	0.19	0.0006	0.030	0.000168011
440	0.43	0.0004	0.0002	0.17	0.0006	0.027	0.00015438
450	0.46	0.0004	0.0002	0.16	0.0005	0.025	0.000141891
460	0.48	0.0003	0.0002	0.15	0.0005	0.022	0.0001304
470	0.51	0.0003	0.0001	0.14	0.0005	0.020	0.000119857
480	0.53	0.0003	0.0001	0.12	0.0004	0.018	0.000110152
490	0.56	0.0002	0.0001	0.11	0.0004	0.016	0.000101226
500	0.59	0.0002	0.0001	0.11	0.0004	0.015	9.30289E-05
	Totals:	1.0000	0.2029	64.75036	1.2814	20.94646	0.756
	Average Loss Savings Ratio			0.2028500			
	Losses/meter of tape			1.2815	W/m		
	Average Transformer Size MVA			64.7504	MVA		
	Voltage			21	kV		
	Current			1784.78	Amps		
	Losses/Amp-meter of tape			0.756	mW/A-m		
	SP=	10.88400					

Therefore, AC losses grow linearly with transformer size. In addition to AC loss, there is a small i^2R loss in the lead-in wires, and a background loss (for cooling) that is independent of whether the transformer is operating or not. The AC losses are the dominant contribution. These are all multiplied by the *Specific Power* of the refrigerator—roughly 11 when operating at 77 K (see Appendix 14) to provide the total losses shown in column G.

Column H is the annualization of column G, as with columns C and D; but the load-duration averaging factor is $<g^3(x)> = 0.233$ when calculating AC losses, and the load duration factor for cooling is 1.0.

Column I shows the improvement that comes from HTS—the energy loss savings ratio. It is the ratio of annual losses in an HTS transformer to those in a conventional transformer: {H} / {D}. This means, that the loss savings will be {the % losses of transformers} times (1 - the loss ratio) = {B} x (1 - {I}). Scanning down the column, the percent savings diminish with increasing size, simply because very large transformers are inherently quite efficient. For example, if the ratio of losses of the HTS transformer to the conventional transformer is 0.59 as in the bottom row, then the percent savings for this extremely large transformer is 0.082%.

Column J gives the relative population of each transformer size in the national inventory. The smallest sizes (20 MVA) are the most common type, comprising 29 percent of all major transformers. Very large transformers are very few in number. This column is used as a weighting factor in what follows.

The right-hand columns present numbers pertaining to the *difference* between conventional and HTS transformers. The individual energy loss-savings ratios appear in column I, but the more important *weighted* loss ratio is in column K. The population distribution of column J is the weighting factor. Thus {K} = {I} x {J}. Similarly, the *weighted* MVA rating appears in column L, and the *weighted* cryogenic requirements are expressed in Watts/meter in column M. Finally, column N is the weighted average of the voltages [{N} = {E} x {J}].

To obtain "national" figures, it is necessary to sum all sizes of transformers, *weighted* for the fraction of each size in actual use. At the lower right of Table 8-1, some average numbers are presented: the average transformer size is 65 MVA, and the average voltage is 20.9 kV. In a three-phase system, MVA = V x I x $(3)^{1/2}$, the average current is 1,785 Amps. One very important output is the *Average Loss Savings Ratio* = 0.2029. Briefly, this means that the prototypical HTS transformer would have one-fifth the losses of a conventional transformer.

Transformers are treated by the model in a slightly different way from the other devices. All electricity is generated once and transmitted once, but it is transformed three times: first to step up the voltage from the generated to high-voltage long distance overhead wires; second to step it down to intermediate voltages, and third to step it down to distribution voltages. There are more step down stages during distribution, but these are not considered eligible for HTS. Thus the potential market for HTS transformers is based on three times the amount of electricity generated.

As mentioned in Appendix 3, step up transformers are quite large, typically 425 MVA. The first step-down transformer is likewise very large, typically 300 MVA. By contrast, the second step-down stage is often near to 30 MVA. These very different sizes of transformers have dramatically different values in columns {B} and {I} of Table 8.1, and therefore the percentage loss saving are also very different. A single number (displayed in Appendix 1) for % loss saving by transformers is inadequate to calculate the energy savings and economics associated with the way transformers are actually used.

The transformer data in Table 8-1 has been used in calculating the numerical values that appear in certain subsequent appendices, notably the % savings figure of Appendix 1. That number in turn strongly influences the conclusions stated in the main text.

APPENDIX 9

RATIO OF TRANSMISSION LOSSES

This appendix compares the losses associated with conventional overhead transmission cables against the losses associated with a hypothetical HTS underground transmission line (for the HTS cable, there is a cryogenic penalty for removing heat). The comparison is by no means perfect, because the HTS line does not yet exist, while the conventional lines are known in substantial detail. For HTS, we have only estimates, but for existing technology, we can calculate the losses (which are all i^2R losses) for various cable sizes used in utility transmission lines.

A superconducting cable has no i^2R losses, but must pay a price in refrigeration. HTS cable suffers from AC losses (which are current dependent) as well as some no-load losses, due to both termination losses and especially heat leaking through the insulation. At this early stage of development of HTS cables, only rough estimates have been made [Jonathan Demko, Oak Ridge National Laboratory, private communication]. With the HTS cable assumed to be carrying 2,000 Amps, we took the rough figure of 1 Watt/meter (W/m) for each phase for the AC losses, and we also used 1 W/m per phase for the heat leak. The termination loss (every mile) was estimated to be 2/3 kW per phase. Fortunately, the outcome of this study is not terribly sensitive to the wide error brackets on these estimates. In a numerical experiment, we found that increasing the AC loss by 50 percent only varied the calculated savings by 3.6 percent; and when AC losses were made five times as great, the savings changed by only 37 percent.

All losses within a superconductor appear as heat and have to be removed by the refrigeration system. For every Watt of heat to be removed, much greater power must be input. For refrigerators transporting heat between 300 K and 77 K, the Carnot efficiency is about 1/3, and real refrigerators typically operate around 20 percent of Carnot efficiency. On that basis, one would expect to input 15 Watts to remove 1 Watt. In this appendix, we exhibit optimism about future cryogenic technology (see Appendix 14) by choosing a factor of 11 as the *Specific Power* for heat removal. Therefore, the losses in the HTS cable are multiplied by a factor of 11 before comparing them to the i^2R losses of conventional cables.

Conventional Transmission-Line Losses

Intermediate voltage (stepped-down once) transmission lines are the “target population” for eventual replacement by superconducting transmission lines. Table 9-1 shows the losses occurring in each of eight specific types of wire used by utilities for such lines. The unweighted average properties of the whole group appear in the bottom row; that is, the row 8 entries are summed and divided by 8. For each wire size, the resistance and current capacity is taken from tabulated information [General Electric Wire Tables, 1990], and those numbers appear in columns A-C. It is then easy to calculate the i^2R loss when each of those wires is running at its peak capacity, and that occupies column D expressed as kW/mile.

- Columns C and D pertain to peak-current conditions. To compute the average power loss over a long time, it is necessary to correct for the *Load Duration Curve*. As calculated in Appendix 4, this means multiplying by 0.36361, the weighted average value of $[g(x)]^2$. That average power loss appears in column E.

- Column F is the voltage of each size of overhead transmission wire, and column G is its power factor (typically 0.9).

- Column H is the system’s peak *power*: $H = C \times F \times G \times (3)^{1/2}$.

- Column I is the total *energy* (GWh) transmitted in a year: $I = [H / G] \times 0.55 \times 8760$, where $L = \int_0^1 g(x)\,dx$ is the average value of the load duration curve (= 0.55), and there are 8760 hours in a year.

- By comparing column H with the peak power losses in column D, we obtain the percent losses shown in column J: $J = 0.001 \times D / H$. Similarly, comparing the annual losses in column E to the total energy transmitted in column I yields column K, the percent energy losses per mile: $K = (8{,}760/1{,}000{,}000) \times E / I$.

- Inspecting the algebra involved here reveals that $K / J = (0.36361 \times 0.9)/(0.55) = 0.59$.

Table 9-1 Cable to Wire Loss Ratio 3 Phase per Mile

	A	B	C	D	E	F	G	H	I	J	K	L
	Wire Size ACSR	Resistance OHMS/Mi	Capacity Amps	Demand I2R Losses kW/Mile	Avg. Power I2R Losses kW/Mile	Voltage kV	Power Factor	Total Power MW	Total Energy GWh	Demand % Losses per mile	Energy % Losses per mile	Energy Cable/Wire Loss Ratio
1	1192.5	0.0788	1160	318.1	115.7	161	0.9	291	1558	0.109	0.065	0.425
2	954	0.0982	1010	300.5	109.3	161	0.9	253	1357	0.119	0.071	0.392
3	795	0.117	900	284.3	103.4	138	0.9	194	1036	0.147	0.087	0.316
4	636	0.147	780	268.3	97.6	115	0.9	140	749	0.192	0.114	0.242
5	556.5	0.168	730	268.6	97.7	115	0.9	131	701	0.205	0.122	0.226
6	477	0.196	670	264.0	96.0	69	0.9	72	386	0.366	0.218	0.127
7	336.4	0.278	530	234.3	85.2	69	0.9	57	305	0.411	0.245	0.113
8	266.8	0.35	460	222.2	80.8	69	0.9	49	265	0.449	0.267	0.103
9	Average 161 kV and Below		780	270.0	98.2	112		148	795	0.250	0.1486	0.243
10	HTS Cable		2000			161	0.9	502	2687	0.0254	0.0276	
11		AC Losses	2000	4.8	2.4	1.2	0.6					
12		Termination Losses	2000	2.0	1.0	1.8	0.9					
13		Background Losses	2000	4.8	2.4	4.8	2.4					
14		Total	2000	11.7	5.9	7.8	3.9					
15		Cryo SP		10.884	10.884	10.884	10.884					
16		Total Power Req'd.	2000	127.4	21.2	84.7901	14.1					
17	From the U.S. Electric System Loss Distribution Analysis spreadsheet, the transmission losses are 1.94257.											
18	The ratio of HTS cable loss to conventional wire is 0.243151.					Therefore the loss savings will be % Loss Transmission* (1-cable/conventional loss ratio) which is 1.4702%.						
19	The number of miles /GWH transmitted over HTS cable is 0.022585.					That is the number of miles of HTS cable installed per GWh transmitted over them.						

HTS Cable Losses

An equivalent calculation of losses/mile can be carried out for the HTS cable, which is assumed here to carry 2,000 A. If a hypothetical voltage of 161 kV is selected (as in column F), and the power factor still is 0.9 (as in column G), then the peak power transmitted in such a system would be 2 kA x 161 kV x 0.9 x 1.732 = 502 MW [the same as H = C x F x G x $(3)^{1/2}$]. In exactly the same way as for conventional transmission lines, the total annual energy is 2,687 GWh.

To analyze the cryogenic penalty of HTS cables, it is necessary to attend carefully to the distinction between *peak* values of losses and *average* values. In a HTS cable, the AC losses are expected to vary as i^3, which means that the conversion from a peak value to an average value involves the integral over $[g(x)/p(x)]^3$, following the same notation as in Appendix 4. For the same Load Duration Curve as in appendix 4, that weighting factor is 0.25. Consequently, the rough AC loss estimate of 1 W/m (= 4.8 kW/mile, for all 3 phases) at *peak* current reduces to 1.2 kW/mile on *average*. The heat leak (1 W/m) likewise converts to 4.8 kW/mile, but that does not vary over time. The termination loss becomes 2 kW/mile at peak; it is very weakly current dependent, averaging to 1.8 kW/mile. The sum of these is 7.8 kW/mile = heat to be removed. When multiplied by SP = 10.9, we find an average cryogenic power requirement of 85.5 kW/mile to sustain the HTS cable at 77 K.

At the *peak* current, the *peak* heat dissipation is 11.7 kW (instead of 7.8 kW), which likewise must be scaled up by the SP. The peak-power requirement of HTS cable is 127.4 kW/mile; dividing by the 502 MW transmitted gives a *peak-demand* percent loss of 0.025 percent /mile. Comparing the *average* refrigeration power requirement of 85.5 kW (sustained for an 8,760-hour year) to 2,687 GWh gives an energy loss of 0.0276 percent/mile. These percentages are the HTS entries (row 10) for columns J and K of Table 9-1.

One caveat: ideally, the cryogenic system should be *sized* to run at 127.4 kW/mile, which is the worst-case condition. That constitutes an extremely severe penalty, which would run up the capital cost of refrigeration equipment to over $500,000 per mile. Because that far exceeds the cost of buying 120-foot wide right-of-way for conventional transmission lines, that price would “break the bank,” and would eliminate underground superconducting cable from all but the most stringent geographical conditions. Therefore, something else has to be done to break this impasse.

The cooling mechanism in HTS cables is very likely to be a tube of LN_2 or helium gas flowing down the core of each phase [T.P. Sheahen, *Introduction to High Temperature Superconductivity*, 1994]. Therefore, we assume the existence of a *hybrid* refrigeration system, in which a large enough reservoir of liquid nitrogen is available to absorb fluctuations in the heat load at different times of day. This circumvents the need to design for *peak* cooling, instead providing capacity to match only the *average* load. That still leaves a very large capital cost of cryogenics— $368,000/mile today— but we have built into the model a steady decline of cryogenic prices in future years (as discussed in Appendix 15).

Comparison

Finally, a fair comparison between HTS cable and each kind of conventional wire can be made. On a basis of percent-loss-per-mile, HTS cable is substantially better than any of the overhead cables.

Using annual energy losses, column L of Table 9-1 displays the ratio of cable losses to wire losses. Each entry in column L is $L_i = 0.0276 / K_i$. Should that ratio > 1, it would mean HTS cables are worse than conventional overhead lines; that is the case for high-voltage transmission lines (230 kV and above), which are therefore omitted from Table 9-1. By contrast, wherever the ratio < 1, there can be improvement by converting to HTS cables, and that is the case for intermediate-voltage lines. (Realistically, no high-voltage line would be a candidate for superconductivity anyway.)

Referring back to Appendices 3 and 5 and the *U.S. Electrical System Loss Distribution Analysis* (Table 3-2), this means setting aside the first transmission stage following generation and step-up transformation (i.e., the entire line 4 of Table 3-2). That leaves intermediate transmission lines (in the voltage range 69 kV-161 kV) as plausible candidates for substitution by HTS cables. From Table 3-2, we find that 1.94 percent of the nation's electricity remains eligible for savings via HTS cable [cell 6-R].

How much of that 1.94 percent can actually be captured? The ratios in column L of Table 9-1 enable us to calculate that. For the assortment of eight cables operating at voltages between 69 kV and 161 kV, we find that their average cable-to-wire loss ratio is 0.243 [cell 9-L]. The maximum fraction of savings that can be obtained is therefore [1 - 0.243], assuming all conventional intermediate-voltage lines were replaced by HTS cables. Thus the 1.94 percent available is trimmed to 1.47 percent (= 1.94 x 0.757). This number appears in Table 1.1 of Appendix 1, and becomes a central assumption of the spreadsheet calculations.

Recognizing the many uncertainties associated with the losses anticipated in future HTS cables, this figure should be taken as 1.5 percent +/- ½ percent. At stated above, the outcome is not terribly sensitive to the actual AC losses, and it is simply good engineering practice to minimize the heat leak wherever possible. The chief source of uncertainty is in choosing SP = 11, a rather optimistic value. Some experience with *real* HTS cables must be obtained before these estimates can be refined.

References:

[1] Jonathan Demko, Oak Ridge National Laboratory, private communication.
[2] GE Wire Tables, 1990.
[3] T.P. Sheahen, *Introduction to High Temperature Superconductivity*, p. 408.

APPENDIX 10

ELECTRICITY USED IN LARGE ELECTRIC MOTORS

This appendix computes the amount of electricity that is "eligible" for savings via HTS motors. It relies heavily on a previous study for DOE, *United States Industrial Electric Motor Systems Market Opportunities Assessment*—a report by Xenergy, Inc., to Oak Ridge National Laboratory (Burlington, MA: 1998). Their electric-motor data runs through 1996. For our study, we have taken 1996 as the base year, and used the EIA database annual escalation factor of approximately 1.8 percent to estimate electricity use in subsequent years.

Because the Xenergy report focuses only on the industrial sector (and not the commercial sector), there are discrepancies between the total national electricity in our Appendix 3 (derived from EIA national data) and their report. However, the motors of interest for high-temperature superconductivity applications are those over 500 hp, nearly all of which exist in the industrial sector. Therefore, the Xenergy data suffices for our purposes and the discrepancies easily fall within the error brackets of our study.

The first column of Table 1-24 on page 51 of the Xenergy report is of great importance. The collection of industrial motors is divided into size categories, and the number of motors and the energy used by each category is presented. For their two largest categories (i.e., motors over 500 hp), for 1996 Xenergy calculated 39,005 motors that used 167,545 GWh; that energy is 29.1 percent of the total annual energy of 575,428 GWh. Escalating 1.8 percent per year, these numbers will all be 53 percent larger by 2020, but we have assumed that the share of energy going into big motors—29 percent— will remain the same.

It bears mentioning that this total energy passing through big motors is a relatively small component of the national electricity budget. One hundred percent of electricity is generated, transformed and transmitted, but only about 5 percent goes through big motors. Consequently, the HTS savings associated with large electric motors is comparatively small, and motors contribute less to the economics of HTS devices.

In Appendix 6, where the energy flow through a "typical" electric motor is explained, we simplified the analysis by assuming that all 39,000 large motors were of one average size: 1,160 hp = 865 kW. If we further approximate their annual running time as 7,500 hours, operating at a load of 68 percent of rated power, this leads to an estimate of total energy used as follows:

$$865 \text{ kW} \times 0.68 \times 7{,}500 \text{ hrs} \times 39{,}005 \text{ motors} = 1.72 \times 10^{14} \text{ watt-hours/yr.}$$

This coincides with the Xenergy figure of 167.5 GWh/yr for motors above 500 hp. Another route to a similar estimate is as follows: page 9 of the Xenergy report states that 25 percent of U.S. electricity goes into motors. The total national electricity is 3,360,000 GWh/yr, and one-fourth of that is 840,000. It is plausible to say that about two-thirds of this motor energy goes to industrial motors, or 560,000. 29.1 percent of this is 162,000, again close to the Xenergy figure for big motors of 167.5 GWh/yr.

APPENDIX 11

REPLACEMENT RATE UNCERTAINTY

The market-penetration model is structured in terms of capturing a certain *percentage* of the possible sales at any given time, but to determine the number of units actually sold, it is necessary to know the size of the available market.

We have used very reliable estimates from EIA to project the future *growth* of markets for electrical equipment; 1.8 percent per year is typical. However, it is also necessary to add in an estimate of the *replacement rate* of old equipment being retired. This latter estimate is far less reliable than the EIA growth projections.

First of all, there are very few occasions where overhead transmission lines might be replaced with underground HTS cable. Once a right-of-way has been purchased, the remaining cost of overhead lines is much less than underground cable. As the market grows, new transmission may be via underground cables, but the only “replacements” of existing cables will come in exceptional circumstances where demolition and new construction is taking place.

Certain lifetimes have been assigned to certain types of equipment: 31 years for motors, 35 years for generators, and 40 years for transformers and cables. Naively, then, each year 1/31 of motors (3.2 percent) and 1/35 of generators (2.9 percent) would need to be replaced, which is about double the “growth” market. However, major electrical equipment does not break down like a *One-Hoss Shay*; actual experience shows a probability distribution about a mean, and the width of the Gaussian peak can only be guessed. Motors that are pushed too hard may break down much earlier; but when they do, the factory may choose to have a motor rewound instead of replacing it. The same is true of transformers.

Furthermore, the assumption is the equipment that will break down in 2015 was probably installed around 1980. The size of the market was significantly smaller then; when a market escalates at only 1.8 percent/year, it grows 43 percent in 20 years and 71 percent in 30 years. Therefore, the “pool” of eligible replacements in any year is certainly less than 3 percent of the contemporary market. In conclusion, there is great uncertainty in the size of the “replacement” market in the years ahead.

To test this, the model has been run in a number of simulations, with various fractions less than 100 percent of the theoretical replacement market actually being replaced. (This was carried out by writing a *macro* for the *Excel* program.) It is possible to construct plausible arguments for any fraction between 50 and 75 percent; that is, for replacement rates ranging from one-half to three-quarters of the “mean lifetime” replacement rate. Figure 11-1 shows that this is a very important source of uncertainty in the predicted economic impact of high temperature superconductivity—the vertical scale (in dollars) shows how the size of the *potential* market varies when the replacement rate varies. Since replacements, naively calculated, would be *double* the growth factor, it is very easy to forget that 30 years ago there was less equipment which would lead to an overestimation of market size.

Devoid of any reason to select a particular fraction between ½ and ¾, we settled on the *Golden Ratio* = 0.618, and carried out our calculations using the replacement rate {0.618/lifetime}. Our choices of replacement rates are as follows:

Motors	2.0 percent annually
Transformers	1.5 percent annually
Generators	1.8 percent annually
Cables	0.2 percent annually

As discussed above, the replacement rate for cables is very small. Clearly, the message of Figure 11-1 is that there is at least a 20 percent uncertainty in all economic projections associated with this study.

Figure 11-1 Energy Savings vs. Replacement Factor

APPENDIX 12

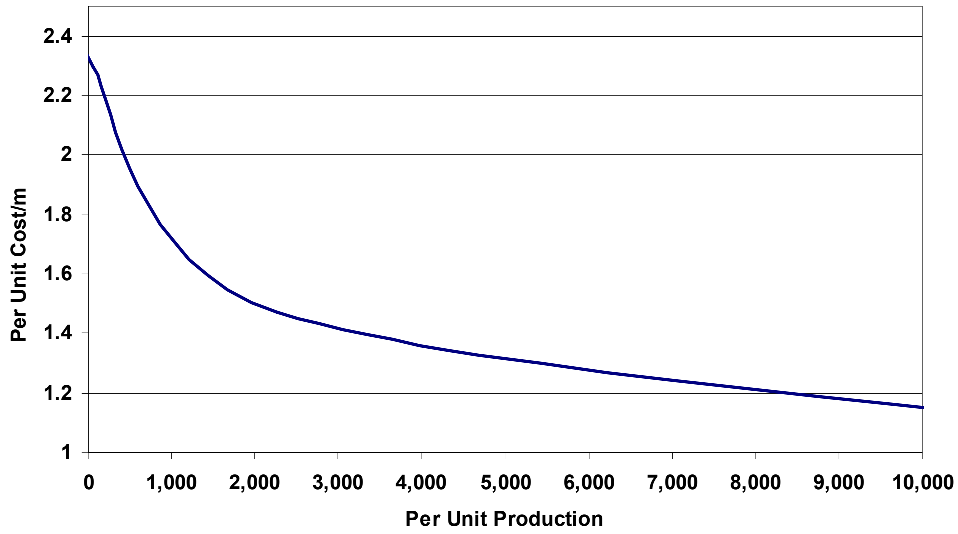
FIBER OPTICS COMPARISON

It is widely expected that as experience grows with YBCO-coated conductors, the cost of manufacturing will decline. It is risky to be too optimistic about the difficulties of making such a special material, but there is room for optimism based on previous history of declining manufacturing costs. The use of fiber optics provides a good example of a technology that went from laboratory discovery to mass production in about 25-30 years, with both performance (information transmission capacity) and cost-per-meter changing dramatically. A corresponding decline in YBCO manufacturing costs is by no means guaranteed, but the analogy is relevant.

Table 12-1 below tabulates the key events in the history of fiber optics, and alongside that is the 20-year projected history of YBCO conductors. In 20 years, the performance of fiber optics improved by a factor of 1,000, and the cost per meter dropped from \$1.80 to \$0.04, sufficiently low to be the basis today for a national telecommunications network.

Figure 12-1 has the proper shape of the "per unit cost" curve for the decline of HTS manufacturing cost as production increases. Effectively, both axes are in arbitrary units, but the shape of this curve is reminiscent of the historical curve for fiber optics.

Figure 12-1 HTS Per Unit Cost Curve



For HTS conductors, today's cost is far too high (by many hundred dollars) to support commercialization of HTS devices such as motors, transformers, etc. In Figure 12-1, we are off-scale at the upper left. Our fiber optics analogy will become applicable only when sufficient production has occurred to establish a fixed point along this production curve. There is a positive feedback mechanism at work here. The conversion of the horizontal axis to time depends on the production rate, which in turn is dependent on how rapidly HTS devices are introduced and on how quickly the cost of HTS conductors falls.

The least squares curve fit of the logistic curve to actual fiber optic sales penetration is presented in Figure 12-2. It is interesting to note how well the actual data is modeled by the penetration curve used for HTS in this paper.

Figure 12-2 Fiber Optics Sales in Millions of Meters

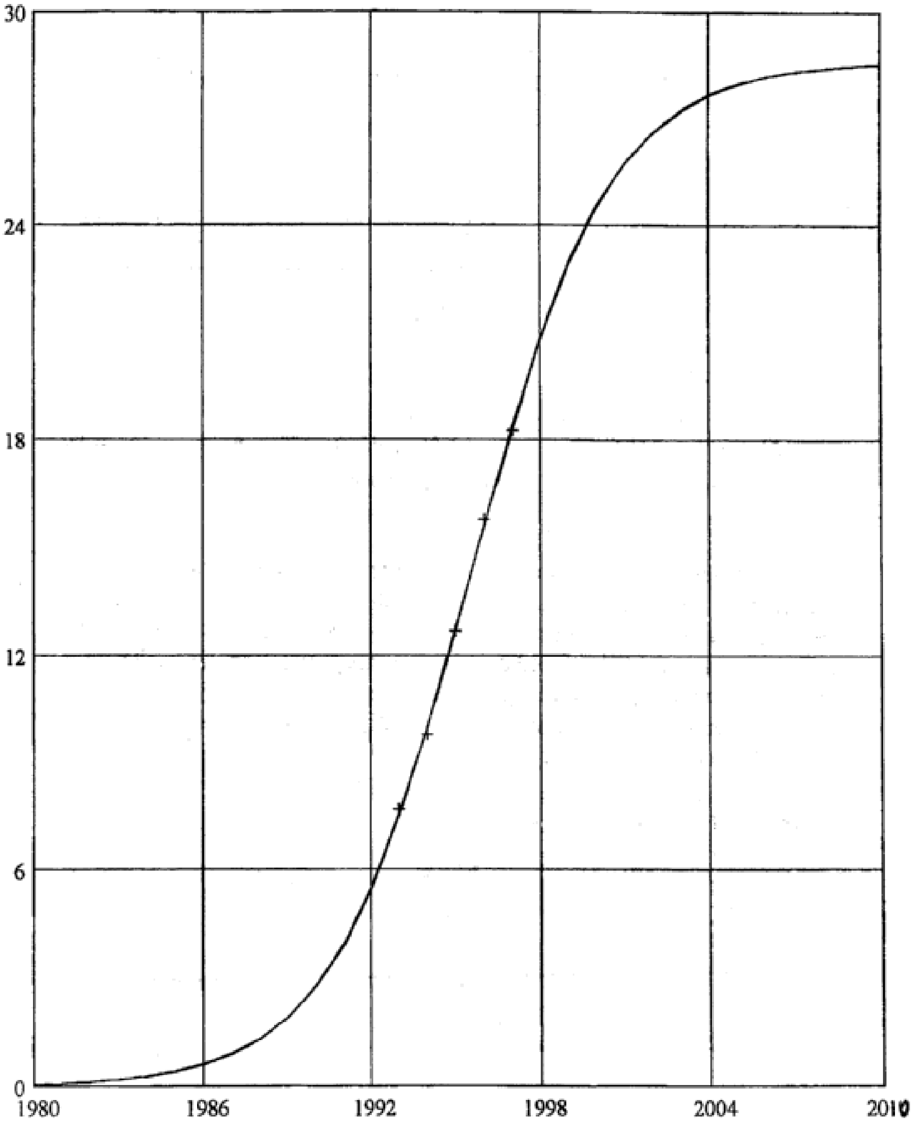


Table 12-1 Historic Comparison of HTS Development to Fiber Optics Development

FIBER OPTICS		HTS	
YEAR		YEAR	
1967	Discovered	1987	Discovered
1968		1988	
1969		1989	
1970		1990	
1971		1991	
1972		1992	
1973		1993	Ag-coated BSCCO 10 m length
1974		1994	
1975		1995	
1976	Installed at the Cape for NASA	1996	
1977	$1.80/m Performance = 1	1997	$100/m Peformance = 20 amps $5000/kA-m
1978		1998	
1979		1999	
1980		2000	
1981		2001	
1982		2002	
1983		2003	
1984	Commercial	2004	Commercial
1985		2005	
1986		2006	
1987		2007	
1988		2008	
1989		2009	
1990		2010	
1991		2011	
1992		2012	
1993		2013	
1994		2014	
1995		2015	
1996		2016	
1997	$.04/m Performance = 1000	2017	$23/m Performance = 1000 Amps $23/kA-m
1998		2018	
1999		2019	
2000		2020	

APPENDIX 13

HTS WIRE COST ESTIMATING PROCEDURE

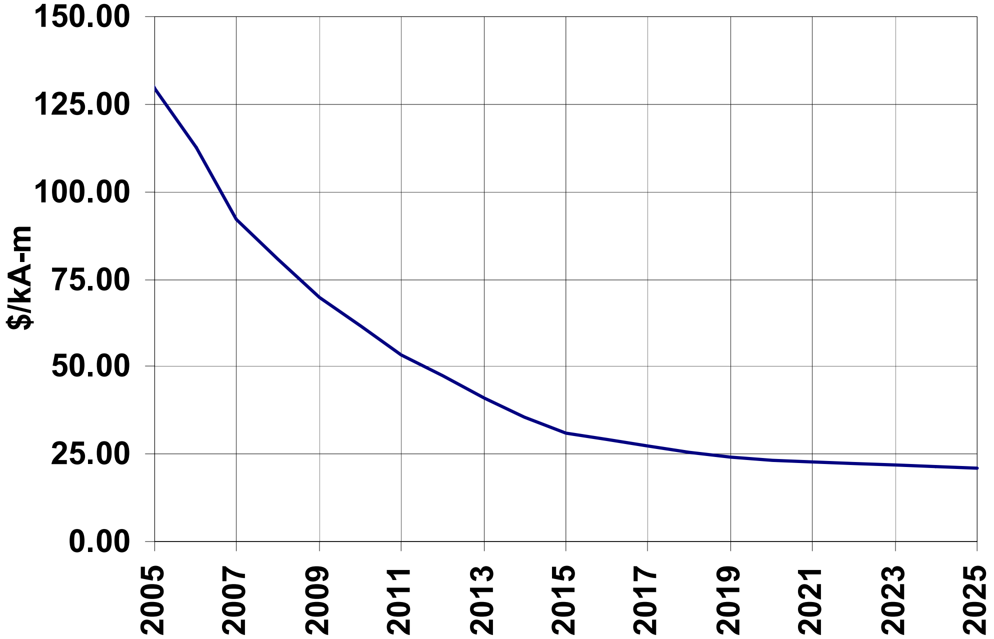
When dealing with HTS conductors, the figure of merit is not \$/m, but \$/kA-m. It is reasonable to assume that both performance (*engineering critical current density* J_e) will increase and manufacturing costs will decrease as experience is gained and the first steps are taken out of the laboratory. If the analogy with fiber optics holds true, then in about 20 years, we may expect to see the cost of YBCO-coated conductors drop to about \$20/kA-m. We have taken this similarity as the basis for estimating the future cost of HTS conductors, and therefore, have calculated a gradually declining cost of HTS devices during the time frame of this study.

Specifically, we postulate an improvement of one full order of magnitude in J_e over the next 15 years. Phrased differently, the second-generation conductor of today (with certain geometrical dimensions) carries 100A, but by 2015, it will carry 1,000 A. This obviously assumes considerable success in the research and development laboratory. In thin short samples, films of YBCO have already exceeded $J_c = 10^6$ A/cm^2 [A. Goyal, ORNL presentation at 1999 Wire Development Workshop, January 1999]. To date, no one has maintained such high J_c in long conductors having films thicker than one micron. There are very serious difficulties confronting the effort to grow thick films with excellent grain-boundary alignment sustained over kilometer distances [Steve Foltyn, Los Alamos National Laboratories, private communication].

Our conjecture in this appendix optimistically trusts that over the next 15 years, researchers and manufacturers will successfully collaborate to deliver long lengths of conductors with a performance factor of 10 better than today's conductor. Without reason to presume otherwise, our model assumes a *linear* improvement in current-carrying capacity over time, going from 100 A to 1,000 A in 15 years and leveling off after that.

Combining this with the fiber-optic analogy (see Appendix 12) for declining manufacturing cost over time, we obtain the curve shown in Figure 13-1 for the cost of conductors (in \$/kA-m) over the period of this study. The same figure appears as Figure 5 in the main text. The asymptotic value is about \$20/kA-m. It must be remembered that if this prediction does not come true, it will adversely affect the degree of market penetration (see Appendix 2) of all these HTS devices.

Figure 13-1 HTS Wire Cost ($/kA-m)



APPENDIX 14

CRYOGENIC EFFICIENCY AND COST

The cryogenic requirements for each HTS device constitute a severe cost penalty, which eats into the savings achieved when i^2R losses are eliminated. There is both a *capital cost* to purchase the refrigerator, and an *operating cost* of cooling the device. Throughout this study, we have converted the operating cost to an equivalent energy penalty, and reduced the gains achieved by each device accordingly. We have treated the capital cost as a front-end expense, just the same as the incremental cost to manufacture HTS wire. It is an obvious goal of cryogenic manufacturers to reduce these cost penalties by raising the efficiency of their refrigerators.

In the example of this appendix, we select (as representative of the entire range of possible refrigerators) a *Gifford McMahon Single Stage Cryocooler*. It draws 4,000 W input power. This is not a very restrictive or specialized choice; other cryocoolers have comparable performance curves. The price of such a unit is taken to be \$17,225 based on industry estimates [*Cryogenics Needs of Future HTS Electrical Power Equipment*, Workshop Proceedings, July 22, 1998]. That price implies that *cost per unit of capacity* on the hot side is \$4,300/kW; that is a *capital* cost.

To inquire about the *cost per unit of capacity* on the cold side, we need to know the operating temperature and the percentage of *Carnot efficiency* that the cryocooler can achieve. The *Carnot efficiency* η_c is defined as $[T_c / (T_h - T_c)]$. The cold temperature is often $T_c = 77$ K, and the best cryocoolers produced today run above 20 percent of *Carnot efficiency*. The true efficiency is η_c times the percentage efficiency. The *Specific Power* (SP) is the inverse of that number, and expresses how many Watts must be drawn from the power source to remove one Watt at low temperature. Researchers commonly take room temperature $T_h = 300$ K. Depending on what the percentage efficiency is, we find the values in the table below for the *Specific Power* of an idealized cryocooler at selected low temperatures. Two different percentage efficiencies are calculated here.

T_c	η_c	SP (20%)	SP (30%)
77	0.345	14.5	9.7
70	0.304	16.4	11.0
30	0.111	45.0	30.0

On the other hand, in the real world, actual cryocoolers have a performance curve where, as the temperature declines, the heat removed falls off faster than a linear slope. Moreover, if typical utility/factory conditions are assumed, then ambient temperature is about 120 F = 322 K = T_h, in which case, the *Carnot efficiency* drops and the Specific Powers increase. Here are more accurate values for the Specific Powers in the temperature and efficiency ranges of interest:

T_c	η_c	SP (24%)	SP (30%)
77	0.314	13.3	10.6
70	0.278	15.1	12.0
30	0.103	67.1	53.3

Note that the percent of Carnot efficiency declines from 24 percent to 15 percent and from 30 percent to 18 percent, respectively, in the above table as the temperature changes from 77 to 30 K.

In this study, we have optimistically assumed progress by manufacturers such that by 2010, cryocoolers will routinely achieve 30 percent of Carnot efficiency. Offsetting this advantage slightly, we have set the device operating temperature at $T_c = 70$ K. Also, the flow of coolant through rotating components cuts into efficiency somewhat. As a result, in most calculations we use SP = 11 for transformers and cables and SP = 12 for motors and generators.

Once the SP is known for any set of conditions, the *cost per unit of capacity* on the cold side is simply the product of the hot side cost multiplied by the SP. For the case of 30 percent of Carnot efficiency, the SP values are those in the right-hand column; so when the cold side is at 70 K, the *capital* cost is \$51.68/W and for a 30 K cold side, the cost is \$229.63/W. Should only 24 percent of Carnot percent efficiency be achieved, those two numbers will increase to \$65.05/W and \$289/W, respectively.

The *operating* cost is likewise inflated by the SP. For each Watt of heat dissipated in the cold region, the power supply must draw {SP} times as much. In a typical case, if electricity costs \$0.04/kWh, and SP = 12, the effective cost at the cold end is \$0.48/kWh.

APPENDIX 15

DECLINE IN CRYOGENIC COSTS

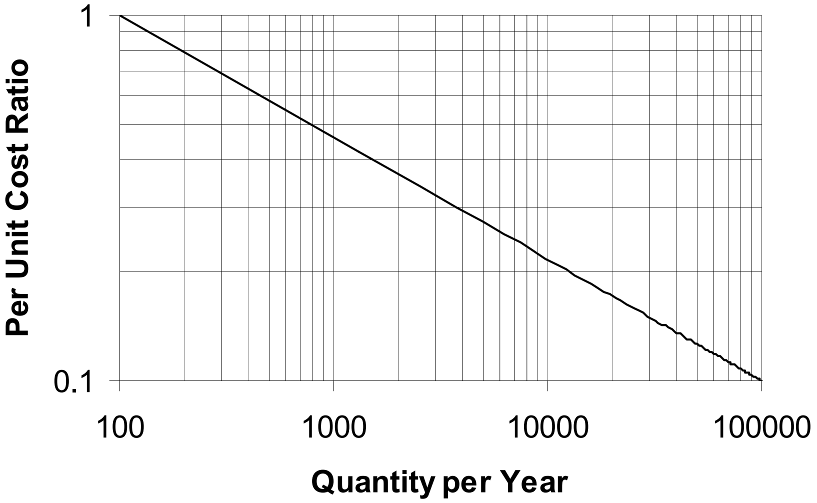
This appendix explains our model of how the costs of cryogenic refrigerators are expected to drop in the years ahead, as HTS devices become more plentiful and create a demand for even more refrigeration units.

Figure 15-1 is a graph on log-log paper of the decline in the per-unit cost of cryocoolers as the quantity produced rises. There is a considerable similarity between the cost/quantity relation for cryocoolers and that for many other products. Although we do not display all the data, the estimates by various cryocooler manufacturers (as well as manufacturers of other products) show one surprising commonality—the slope of all the curves tends to be the same, which demonstrates a remarkably general law about manufacturing costs. Explicitly, the slope = - 1/3. This means that the unit costs are related to the quantity produced by the relation:

$$\frac{\$ (N_1)}{\$ (N_2)} = (N_1 / N_2)^{-1/3}$$

where N_1 and N_2 are two different amounts of units produced. The universality of this relationship serves as the starting point for our analysis.

Figure 15-1 Estimated Cost of 60-80 Degrees K Cryocoolers vs. Quantity Per Year



We do not start with only *one* unit of production, because we know that would be so prohibitively priced as to destroy any hope of market penetration. Instead, we assume that for any standard type of cryocooler, there will be a "background level" of about 100 units sold annually to applications unrelated to HTS devices. That sets a "relative cost" level of 1.0 for cryocoolers sold in the early years of the HTS market.

As HTS devices begin to make inroads upon conventional technology, the number of cryocoolers will grow and manufacturing costs will begin to decline. The growing number of units produced allows a conversion to a time coordinate in years. Table 15-1 is a year-by-year tabulation of cryocooler costs. The second column shows the estimated number of new cryocoolers required to service the HTS devices deployed in that year, whether motors, transformers, generators or cables. The baseline of 100 is always part of the total number.

In Table 15-1, Column 3 shows the relative cost ratio from one year to the next, which declines from 1.0 to 0.85 and then rises again. Column 4 displays the cost ratio, which declines steadily from 1.0 at the outset to only 0.266 by 2025. Thus, the cryogenic cost in the foreseeable future is expected to be only about one-fourth of today's cost, simply due to increasing production volume.

Figure 15-2 is a graph of the cost ratio data in column 4. This was used to calculate the steadily declining costs of the HTS devices over the many years.

Figure 15-2 Cryorefrigeration Cost

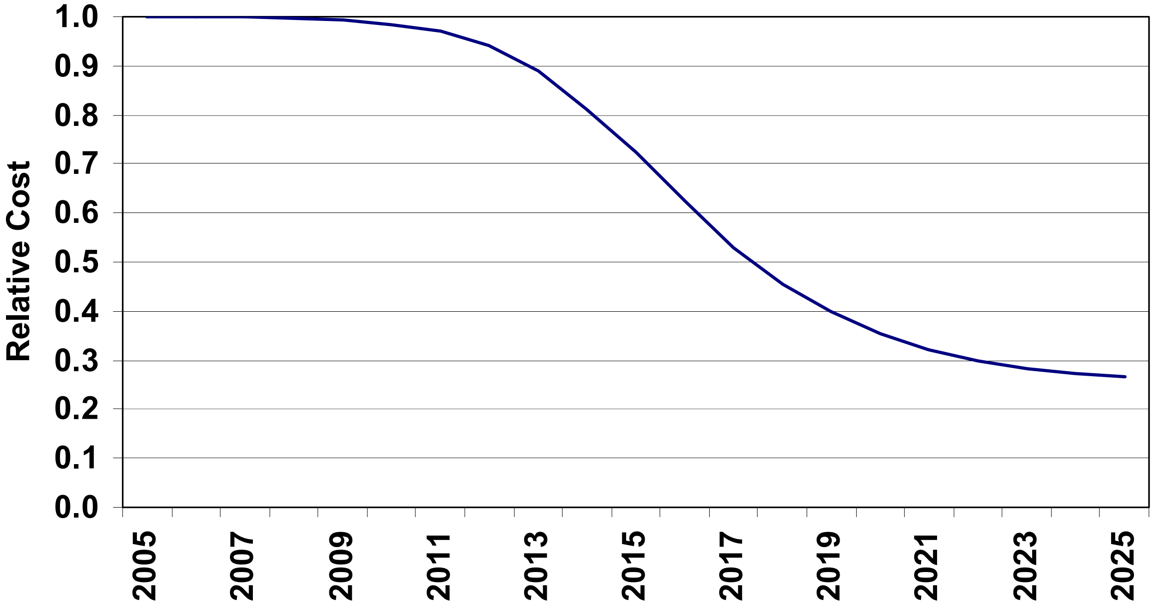


Table 15-1 Cryocooler Costs

Cryo Units Required		Rel. Cost Ratio	Cost Multiplier
2002	100	1.00	1.000
2003	100	1.00	1.000
2004	100	1.00	1.000
2005	100	1.00	1.000
2006	100	1.00	1.000
2007	100	1.00	0.999
2008	100	1.00	0.996
2009	010	1.00	0.992
2010	103	0.99	0.985
2011	105	0.98	0.970
2012	110	0.97	0.940
2013	120	0.95	0.889
2014	141	0.91	0.811
2015	184	0.90	0.726
2016	254	0.86	0.622
2017	398	0.85	0.528
2018	641	0.86	0.453
2019	998	0.88	0.400
2020	1,439	0.88	0.353
2021	1,896	0.91	0.321
2022	2,327	0.93	0.299
2023	2,742	0.95	0.282
2024	3,043	0.96	0.273
2025	3,262	0.98	0.266

APPENDIX 16 (REVISED)

BASIC ASSUMPTIONS

This appendix is a compendium of the major assumptions that underlie the model presented in this document. We distinguish these from the "assumptions" input data, which are numbers that can be changed by the user; those are described variously in the main text or some appendices, and the location of such data is presented in appendix 17. The emphasis in this appendix is upon those fundamental assumptions that are built into the very nature and structure of the model.

From the outset, it was recognized that any model is an imperfect representation. It was a major goal to keep this model simple enough to allow other interested parties to change assumptions and input parameters that are of specific concern to them. To make that possible, we deemed it necessary to lock certain other assumptions and principles into the basic structure of this model. Wherever specific "engineering judgment" has been built in, we always strive to call attention to it.

Fixed Numerical Constants

There are certain numbers that no one disagrees with. For example, there are 8760 hours in a year, and there are 3412 Btu in one kWh. Wherever such numbers are needed in the computations, they are simply typed into the individual Excel locations. A few other locations contain curve-fitting parameters as hard numbers.

American Electric Grid

This model makes certain approximations that are known to be imperfect, but which are necessary for keeping the analysis tractable.

Foremost among these is the assumption that the entire United States electrical grid is monolithic. It is presumed that there is one grid, one market, one load duration profile. We know that is not true, first because there are different time zones in the United States, second because there are only limited interconnects between the regional grids, third because different regions experience peak demand in different seasons of the year; and so on. In a more advanced future version of the model, it would be desirable to relax this restrictive assumption.

The Load Duration Profile is likewise given by a single curve, commonly written g(x). This is a rearrangement of the hours in a day to express the power used as a fraction of the maximum. The curve we used is shown in Appendix 4, fig. 4-1. By numerical integration, we found that for this curve the average value $\langle g(x)\rangle = L = 0.55$; the mean-square value $\langle g^2(x)\rangle = G = 0.36$; and the integral $\langle g^3(x)\rangle = H = 0.24$. If an analyst chooses to modify this curve, it has consequences for the average load, the i^2R losses, and AC losses. When L goes up, so do G and H.

In trying to optimally utilize power-generation resources, it is a goal to reduce the highest peak of the load duration curve (peak shaving), boost the low end of the curve (sell more power late at night), and generally increase the average (L) of the curve. Transmitting power across time zones and across different weather regions helps to achieve these goals. Again, in a future version of the model, it would be desirable to be able to deal with an assortment of simultaneous Load Duration Curves.

The way that electricity flows through the transmission / distribution system amounts to an assumption, within the structure of this Excel spreadsheet. In an ancillary study by Mulholland[1], both the i^2R and the no-load losses at each stage of transmission were carefully delineated. That paper is presented in this document as Appendix 3. With electricity flowing down the pathway so determined, the losses in transformers and transmission cables that are eligible for recovery by HTS devices are likewise bounded. In Appendix 5 we state the reasoning behind the engineering judgment about which elements of the system will or will not involve HTS devices. The analyst may easily vary the behavior of any individual device; and the total national power entering the grid may be varied away from the EIA input data in future years. However, the eligible electricity-savings percentages are constrained by the national grid model, as described in appendix 3, and modification of that takes much more care.

Cryogenics

The performance of a cryogenic refrigerator is characterized by the single parameter, *Specific Power*. As discussed in Appendix 14, that assumption can be readily changed. What is not so easy to change is the guiding principle that the cryogenics must be sized to deliver the peak power dissipated by the device, rather than the average power. If one sought to model cooling via a bath of LN_2, it would be necessary to revise the way cryogenic requirements for each device are calculated.

It is assumed that the cost of cryogenics declines with increasing numbers of units manufactured (see Appendix 15). A baseline annual production of "100 units" is presumed in the absence of any HTS devices in the market, and those sell for a certain fixed price. However, any declines below that price are associated with mass production. The model contains a feedback loop that observes the sales of cryogenics in one year to determine the manufacturing cost for the next year; that in turn affects the profitability of associated HTS devices, and hence affects the market penetration by the devices.

The model as it stands presumes a "one size fits all" market for cryogenic sales. As a result, early sales of cables increase the number of cryogenic units sold, and thus reduce the price for cryogenics serving transformers later on. If cryogenic sales prove to be device-specific, the model should be modified to carry four separate curves of cryogenic costs.

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[1] J. Mulholland, "Model of the Losses in the U. S. Electrical System," **Proc. Fourth Conference on Distributed Generation and On-Site Power**, San Antonio, TX (March 21, 2000)

Wire

The performance to be expected of HTS conductor in any future year is a huge wild card – it is the subject of intense R&D efforts at both national laboratories and private companies. BSCCO, YBCO and MgB_2 are candidate materials; there may be more downstream.

On the subject of declining wire cost over time, this model offers some modest flexibility. Appendices 12 and 13 discuss the declining-cost trajectory that we employed, which is a combination of optimism about future R&D accomplishments with a curve based on experience in the fiber-optics industry. As it stands now, the model assumes two different competing types of wire, and switches from one to the other to choose the lower number for cost (in $/kA-m). Our numerical entries are for BSCCO and for YBCO coated conductors; we found a cross-over around 2010.

It is not hard to change either of these inputs. We suspect that other analysts will simply replace one of these cost trajectories with a series of values for wire cost in each year, based on estimates from their own shop. The model will calculate a cross-over date for the introduction of that alternative conductor.

For wire, we do not include a feedback loop comparable to that for cryogenics, because the outcome of R&D is unpredictable. Either a breakthrough or a setback in wire performance would have much more profound effects on wire cost than would the "economy of scale" associated with increasing production volume. If wire production becomes predictable and routine sometime in the future, the model can be modified to include feedback for wire volume, comparable to the feedback loop for cryogenics.

Devices

A cornerstone of this model is that each of the four kinds of devices can be represented by a single size device, chosen to be the surrogate for a broad range of sizes of each device. For example, we took 1160 hp (= 865 kW) as the single motor size, "elected" to represent all large motors. The numerical value is easy to change; the principle of representation is not.

The number of devices is not necessarily an integer. Thus, in the first few years, the "number" of generators (of 300 MVA size) might be 1.4, which implies total generation of 420 MVA. This might actually be made up of a 250 MVA unit and a 170 MVA unit; but the model treats it as 1.4 units of 300 MVA size.

Some anomalies are created by this assumption. For HTS electric motors, the "representative size" notion hides the fact that economics of cooling changes as the size changes; for example, a 5000 hp motor can be operated profitably at 30 K, but a 1000 hp motor cannot. When one representative size is nailed down (e.g., 1160 hp operating at 70 K), constraints are placed on the entire class that may not be accurate and realistic across the full spectrum of actual devices.

One important type of constraint that is easily overlooked is the cost of alternative (conventional) technology. For example, the cost of right-of-way for overhead cables is a single number ($200,000 per mile in our version, for a 120-foot wide corridor); and this does not distinguish between regions of different population density.

Thinking about a future model, it would be possible to introduce new categories of devices, such as {"motors over 2000 hp" and "motors under 2000 hp"} or {"cables in dense urban locations" and "cables in suburbia"}. Each of these revised categories would be eligible for less electricity savings, but their economics would not be lumped into a single pathway, and so their profitability (and hence their rates of market penetration) could be set independently. The sum of all such contributions would be accumulated to obtain the final results. This proliferation of categories is limited by the analyst's endurance. Implementing such changes would require the analyst to construct new blocks of data on each of the associated spreadsheets (see Appendices 17, 18 & 19), which would have mostly similar inputs as the device-specific blocks in the current model. However, a few key parameters on the assumptions spreadsheet would differ among the subdivided categories.

Energy Savings by Devices

As stated above, each device category is represented by a single size of that device. Moreover, the amount of energy saved is also one fixed number for each representative device. The numerical values that appear in Appendix 1 strongly control the economics of these devices, and analysts need to be particularly attentive to the origin of those numbers. Appendices 6, 7, 8 and 9 contain all the details for the four devices.

Electric motors provide an instructive example: Appendix 6 explains that via engineering judgment, the fractional savings in several categories (due to HTS) can be estimated. These sum to 1.4%, which means an average of 60 MWh/motor/year. However, the cryogenic penalty eats into that slightly (about 6.6 MWh/motor/year), and so the net savings is only 1.25%. This number would become larger if the various contributions to savings were revised upward, and would become smaller if cryogenics took more parasitic energy. A change in the capacity factor of the representative motor, or the number of hours/year that it runs, would also modify the 1.25% number. By no means is this just a random number. However, other analysts will likely change it for good technical reasons.

The same procedure can be followed for the other three devices. The point to be understood is that any estimate of a percentage saving over an entire category (especially of things that have not yet been built for the marketplace) necessarily involves considerable engineering judgment, and therefore will remain a soft number until firm experimental data is in hand.

Market Penetration

The market penetration model is discussed in Appendix 2. There are four parameters that specify the market penetration curve for each device. What is fundamental is that all four devices have an S-shaped curve, in accord with standard textbooks[2] on the subject.

The time when serious market penetration starts for each device is also an important variable. The entire S-shaped curve must be slid back and forth to pick a realistic starting time. If there were very high costs for cryogenics or wire or some other factor, the model would calculate many years of negative economic savings, and that would be unrealistic, because no one would buy unprofitable HTS devices.

In an earlier version of the model, the analyst had to change the "starting year" by hand. Now the program invokes an iterative process, by which a guess is made at the "first year of profitability" and the model run. If the first several years of device sales give negative numbers for savings, that signals that the guess was "too soon." The guess is automatically revised (either delayed or advanced) until savings appear early in the market penetration trajectory. One or two unprofitable years at the outset are allowed on the assumption that a few early-adapters are motivated by other than financial considerations. The iterative process is described more fully in Appendix 20, which deals with Macros associated with the model.

Looking out toward the end of this study (the year 2025): when market penetration is virtually complete for all four devices, the only parameter of interest any more is (b), the asymptotic value for percent of market captured. Analysts are more likely to argue about this long-term asymptote than the other parameters. The ability to test the effect of variations in market-penetration scenarios is built into the model.

APPENDIX 17 (REVISED)

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[2] See, for example, Andy S. Kydes, *Literature Survey of New Technology Market Penetration,* 1983.

Location Guide to the *Assumptions* Spread Sheet

Preamble:

The entire "Mulholland" model is contained in a large *Microsoft Excel* file. There are four major spreadsheets linked together: *Assumptions, Database, Results and Graphs*. This appendix is devoted to the *Assumptions* spread-sheet; the following two appendices treat *Database* and *Results*. The *Graphs* spreadsheet is obvious and self-explanatory. **Appendix 20** contains descriptions of several Macros that run within the model and manipulate numbers on the various spreadsheets. In each appendix, the locations of the various inputs or blocks of data are presented. Some discussion of the links between these elements is also given.

When one sheet is displayed on a computer screen, then every cell has an associated formula, which is displayed atop the screen. Moreover, the "auditing" function within *Excel* can be used to trace links to/from any cell, both forward and backward. In this way, the analyst can pinpoint how each number fits into the entire spread-sheet.

It is wise not to expect too much symmetry among the locations of the various pieces of the puzzle. This model grew over a period of several years, and whenever new elements of study were added, previous blocks of data were not relocated elsewhere at those times. Consequently, the reader today may find some things in non-ideal positions. The intent of this appendix is to explain *where* everything is, not *why* it is there.

As a general rule, across all spread-sheets, whenever specific devices are considered, the sequence is {motors, transformers, generators, cables}.

No one should try to make changes in the model without having all the other appendices at hand. The explanations contained therein are crucial to understanding the model, which in turn is a prerequisite to modifying it correctly.

Device Parameters:

The most important variables of the model are entered on the Assumptions spread-sheet. The analyst wishing to change the model will find that nearly all the changes will occur on this sheet.

This *Assumptions* spread-sheet is at most 46 rows deep, but goes across to column CG. When printed, there are 7 pages to it. Figure 17-1 shows columns A through L, which contain the most important information. The labeling at the top includes the function "today", which gives the current date in cell I-2.

Cell D-6 contains the percentage rate at which the total electricity of the nation is expected to escalate in future years. Since this study runs out for several decades, even small changes in this percentage will have profound effects on the results (for both energy savings and sales of devices) in the out-years.

Therefore, we have added a *Macro* to the program that runs several different values of the escalation rate, ranging from about 1.7% to 2.7% annual growth, and captures the major results in years 2020 and 2025. This Macro is describe more fully in Appendix 20.

Stepping downward, each block of data follows the sequence: {motors, transformers, generators, cables}. Column C, rows 11 – 14, contain the estimates for the percent of electricity saved by each HTS device compared to conventional technology. **These are the four most important numbers in the entire model.** Appendix 1 explains these numerical choices. For each device, they depend on several variables, including engineering judgment about the way that device works. Appendices 6, 7, 8 and 9 show the calculations that led to them. For cables, this number is about 1 ½ %, but for transformers less than ½ %;. These numbers correspond to the "representative size" of each device for our version of the model. Later in the model, a great deal depends upon these numerical choices, so the analyst should attend carefully to these values.

Columns { D E F G H }, rows { 11 12 13 14 } contain the parameters of the market penetration model, described in Appendix 2. It is an S-shaped curve, whose shape is determined by several parameters: Column D is the year that a device first appears on the market, while E is the first year of profitability. This implies that a few buyers put a "toe in the water" before the market really gets under way. Such "early adapters" generally do so for non-economic reasons not modeled here, offsetting the negative profit. In year E, the device has captured the fraction of a percent of the available market given in F; columns E and F together combine to create "a" of Appendix 2, which is a measure of the "width" of the market penetration curve. G is the "halfway point", the number of years until 50% of the maximum market is reached, or "c" of Appendix 2. H is the maximum market share gained by the device, in the very long run; this is "b" in Appendix 2.

Continuing rightward, column I (rows 11-14) gives the number of kilometers of HTS wire required (in the fiducial year 1997) to build one unit of the "representative" device size (discussed below). For example, using our input data, it takes 134 km of HTS tape to wire 20 MVA worth of generator in 1997, because the Jc of tape is rather poor at this time. The idea of requiring 14 km of wire to make only 100 meters of cable (capable of carrying 2000 Amps) seems stunning, until one remembers that there are 3 phases, and each cable is helically wound in both directions, and each individual tape carries only 100 Amps. As mentioned in Appendix 1, the improvement expected over time in wire performance will lead to lower length requirements for all these devices.

Rows 5 & 6 of columns J and K contain our wire-improvement model: In year 2000, a tape carries only 100 Amps, but by 2015 it carries 1000 Amps; after which no further advance is assumed. This is an extremely simple model, discussed briefly in Appendix 1. As experience grows, surely a more sophisticated model than this can be formulated; but in 2002 there was no plausible reason to offer any more intricate forecast for the time-trajectory of wire improvement.

Column K, rows 11-14, contain the "tentative first profitable year" for each device. This is a step in an iterative calculation to decide where to position the market-penetration curve, so as to achieve a reasonable and credible pattern of profitability over the years. Prior to beginning this calculation, the analyst inserts a guess (a wild guess will do) for the first year of profitability into column E, rows 11-14;

the program remembers and stores these numbers in rows 2 – 5 of column E. The entire procedure for modifying the market penetration model is presented in Appendix 20. Cell E-15 contains either the word "converged" or the words "try again" to indicate whether that iterative calculation has reached a satisfactory solution. When convergence occurs, K{11-14} match E{11-14}.

Staying to the left of this spread-sheet, but moving downward, we find in rows 20-23 some data about each device that bears on its life-cycle cost and energy use. Column C is the "representative size" of each device, the single surrogate for all the various sizes made. (For cables, the "size" is always a mile, and the conversion factor to kilometers appears in D-23.) Since cryogenic costs are treated as parasitic costs (an economic penalty associated with these devices), column E contains the cryogenic capital cost required for each device, in the unit of size shown in column C. For example, using our data, the cryogenic capital cost (per mile) of a cable is several hundred thousand dollars; the rationale for that number is spelled out in Appendix 9.

Column F is the discount rate used to calculate the present value of future savings from these devices. Column G is the average expected lifetime. Appendix 1 discusses these parameters. Column H is the percent of such devices replaced each year. There is considerable uncertainty about the rate of replacement, as discussed in Appendix 11. Cell H-25 is the "replacement factor", and the *replacement rate* = {repl. factor/lifetime}. The uncertainty inherent in column H directly affects the size of the total market, since *replacement* of devices is of the same order of magnitude as new growth. Recognizing this, we have written a *Macro* that calculates the results for many different values of the "replacement factor." That *Macro* is described in Appendix 20, and a typical outcome is shown as a graph in Appendix 11.

Column I gives the average energy flowing through each device per year, in GWh. Cell I-23 is the average number of transmission miles needed to carry one GWh. These numbers play a role in calculating certain results later on; by having them on the *Assumptions* sheet, the independent analyst can find them and change them easily.

Column K is the fraction of national power going through each device. Thus, 100% of power is generated and transmitted, but only about 5% of national electricity goes through big electric motors. (Although power is transformed three times as it traverses the transmission grid, only one stage is a suitable candidate for HTS: the second step-down transformer. This is discussed in Appendix 8.)

At the lower left of this spread-sheet (rows 30 – 41), comparison is made between the cost of building HTS and conventional technology. For cables (rows 39 & 40, columns C & D) the cost difference is large (see Appendix 1). For the other devices (rows 30, 33, 36), the cost difference is small. Moreover, as indicated in row 41, HTS cable carries almost 2 ½ times as much current as conventional cable. (It bears mentioning that conventional technology does not stand still; in 2003, for example, 3M corp. announced a forthcoming new aluminum-alloy overhead cable that may triple the current-carrying capacity of conventional cable; if so, this would change cell C-41.)

In columns F, G and H we present the characteristics of the Load Duration Curve, described in Appendix 4. The three integrals over the distribution function {L, G, H} relate to the average current <i>, the resistive losses <i^2> and AC losses <i^3>. These values are used in Appendices 6 – 9 to model the behavior of the HTS devices, as well as calculating the load on the cryogenic system.

Columns I, J and K give parameters relevant to the cryogenic system. From I and J the *Carnot* efficiency is calculated, and when that is multiplied by the percentage of Carnot efficiency given in [K-31, K-34, K-37, or K-40], the result is equivalent to [1.0/(*specific power*)]. The *specific power* is the number of watts input required to remove one watt of heat from the cold end. J-43 contains the <u>cost</u> of removing a Watt of power from the hot end. *Specific Power* appears in [K-30, K-33, K-36 and K-39]. These values are the <u>minimum</u> Specific Power and the <u>maximum</u> percentage efficiency, corresponding to an improved future state of cryogenics after an R&D period (discussed below regarding column V). The original *Specific Power*, used in simplified calculations, is shown in K-43.

Annual Variable Computed Inputs:

Moving to the right of this spread-sheet, there are several large blocks of data that vary each year. In each block, year 2000 is in row 15 and year 2025 is in row 40.

The first block (columns N through S) show how the amount of conductor required (for the "representative size" of each device) falls off as wire performance improves over the years. Appendix 13 covers this topic. Wire performance (column O) improves according to a linear model established by rows 7 and 8, columns Q and R, and does not increase further after the year in Q-8.

The next block begins with the evolution of refrigerator efficiency: column V shows how the percent of Carnot efficiency changes over time, somewhat akin to the way wire gets better over a finite number of years. That percentage is taken to improve linearly according to a "Cryo Efficiency Ramp" given in rows 7 and 8, columns W – Z. It presumes that improvement will take place over a period of R&D on cryogenics. The values in Column V turn up in the *Results* spread-sheet, where the cryogenic penalty for each HTS device is calculated in Column E. Increasing cryogenic efficiency over several years lowers the size of refrigerator needed, and hence lowers the cryogenic cost.

After that comes the first example of a feedback loop between the *Assumptions* and the *Results*. Columns W to Z give the declining cost of cryogenics as more and more units are produced. Appendix 15 explains this behavior; on log-log paper the decline is a straight line with increasing production. The slope of that line is stated in cell Z-5. There is a minimum (cell X-5) of cryogenic units presumably sold elsewhere in the absence of <u>any</u> HTS activity. As a result, the cost only starts to decline when production substantially exceeds that minimum. But when does that occur? Column W imports from the *Results* spread-sheet the number of cryogenic units sold for all devices combined. Column X is a year-to-year decrease in cost, and column Y is the cumulative decline in manufacturing cost of cryogenic units. Y is what makes the price go down over time, and this affects the cryogenic penalty of *Results* column E.

HTS wire cost projections are calculated in the next several blocks. Column AC of *Assumptions* = AN of *Results* = the total wire. Column AD is the "labor factor" for either case, which depends upon the total wire needed each year. Columns AF to AM present factors leading to the cost of manufacturing BSCCO tape, and columns AO to AW are for YBCO coated conductor.

Raw materials, labor, overhead, etc. combine to give a total cost to manufacture a meter of conductor (column AK or AU). Next, depending on the improvement in the performance of the HTS material over years (column AL or AV), the figure-of-merit $/kA-m is calculated (column AM or AW). Depending on which of these is smaller (AM or AW), either BSCCO or YBCO is selected, and the appropriate cost per length (AK or AU) is chosen and placed in column AY. Likewise, AZ is the choice of wire amperage between AL and AV. It is those numbers that are used to determine the cost of conductor.

Thus, the model can switch over from BSCCO to YBCO (or conversely) depending upon the expected future trajectories of their costs. Another analyst with a different opinion about either type of conductor (or perhaps something entirely new, like MgB2) can insert their own forecast for one conductor and not bother changing the model for the other conductor.

Optional Model Elements:

Some other calculations are placed on the *Assumptions* spread-sheet. Farther to the right (columns BG to BO), there is presented a "wire reduction curve", which is a numerical functional fit to data about fiber optics (see Appendix 12). Experience with fiber optics shows that the cost of production drops by 30% for an increase of 100% (doubling) in production. This general idea can be used to predict the decline in per-length cost as the amount manufactured increases.

That fiber optics analogy is exploited in columns BB to BF. BC is the numerical function of (i.e., the same shape as) the fiber optics data, bent slightly to conform to HTS conditions. BD is the same as BC until cost drops below $21.40/meter; after that, BD drops further by only 1% per year. (That is done to prevent an excessive and unrealistic decline in projected cost.) BE is a repeat of column AZ, and the figure of merit $/kA-m finally appears in BF = BD/BE. Although BF is not used elsewhere in the model, the point of this exercise is to show that the way estimated costs decline for either BSCCO or YBCO resemble the historical experience of fiber optics manufacturing. That in turn reinforces the plausibility of the cost trajectory found by adding up various costs of material, labor, etc.

If one believed very strongly in the fiber optics analogy, then one would re-examine the choices for factors of labor, overhead, etc. (columns AR, AS, AT or AH, AI, AJ) and tweak those values until the final outcome (AY) resembled BD better. In principle, *Results* for the amount of wire sold could be fed back here to guide the tweaking. However, the uncertainties surrounding both performance (J_c and J_e) of wire and manufacturing processes are presently so great that the error brackets are huge. Accordingly, we have not chosen to include such feedback in the model at this time.

Macro Input Data:

Certain Macros have been written to scan across plausible values of particular assumed values, in order to see how the results change. The Macros are described in Appendix 20; the input values to run these Macros is stored in columns to the far right of the *Assumptions* spreadsheet.

Columns BQ – BW pertain to varying the maximum degree of market penetration achieved in the long run by each of the four devices. *Assumptions* parameters H11, H12, H13 and H14 are the "saturation" values of the market-penetration model (see Appendix 2). Columns BT, BU, BV and BW contain alternate values of these parameters. Beginning with row 12, various combinations of Low, Medium and High saturation by the various devices are enumerated. The macro runs all these cases, substituting a value from BT for H11, BU for H12, and so on.

Columns CA – CG pertain to varying the first profitable year in the market for each device. *Assumptions* parameters E11, E12, E13 and E14 are the "first profitable year" values, the important timing point for each S-shaped market-penetration curve (see Appendix 2). This year is the number that gets slid around by the Macro for market entry described in Appendix 20. Columns CD, CE, CF and CG contain alternate values of these parameters. Beginning with row 12, various combinations of Slow, Normal and Fast market penetration for the several devices are enumerated. See Appendix 20 for an explanation of how these are used.

APPENDIX 18 (REVISED)

Location Guide to the *Database* Spread Sheet

The statements in the Preamble to Appendix 17 apply here as well.

The *Database* spread-sheet is a collection of basic input data that changes from year to year. It barely needs mentioning that all future data is a forecast. We used data from the *Energy Information Administration* (EIA) wherever possible. Other analysts may choose a different source of data on such matters as the annual energy budget or the population of the USA.

Also present on this spread sheet are some calculated entities that depend on both the assumptions and basic input data. For example, the market penetration model is composed of assumptions (about the shape of the penetration curve) acting upon the projected amount of electricity used over the years by the various devices; accordingly, the calculated annual market penetration percentages are presented on this sheet.

Changing the basic input data about electricity use in the future will change quite a lot of the numbers on this entire spread-sheet, which will in turn affect the results produced by the model.

Layout:

This spread-sheet contains data across the top and down the left side. Most of the space is empty (in the middle and lower right). The sets of data across the top are year-by-year values for certain quantities; this is where the data input from EIA is found.

The sets of data downward are device-specific, again following the sequence {motors, transformers, generators, cables}; they too are year-by-year entries, giving the benefits associated with each device. These sets of numbers are not pure inputs; they are calculated quantities derived from the inputs combined with certain assumptions of the model. Because they constitute an intermediate step, they are presented on the *Database* spread sheet instead of the *Results* spread sheet.

EIA Data:

The *Energy Information Administration* (EIA) NEMS model has provided certain data about population, electricity produced and sold, and the emission of gases from burning fossil fuels. All that data appears across the top of the *Database* spread-sheet.

Column A is the year and column B is devoted to the total electricity of the United States for that year. For past years, B contains a number that represents the total electricity going into the national grid; it is an amalgam of {generation + imports - exports} with corrections for electricity not sold but used "on site" or nearby. (This is greater than "sales" by a percent or two.) For future years, each entry in B is the previous year escalated by a *growth factor* that is presented in cell B-8. Thus if future electricity is expected to grow 2.2% annually (from *Assumptions* cell D-6), the consecutive rows in B will each be 2.2% greater than the previous year's electricity. Those numbers are duplicated for each device lower down the left side of the spreadsheet, where they are used repeatedly en route to figuring the possible market size for the various HTS devices.

There are other EIA inputs going across to the right. Generally, the top rows are left blank, to position the years vertically in a symmetric way. Emissions data appears in columns AA through AL. AA and AB are duplicates of columns A and B. Based on this much electricity, and presuming a known fraction is produced by burning fossil fuels, the amount of carbon, SO_2 and NO_x is readily found, and presented in columns AC through AL. This information is used later to calculate an amount of emissions saved by implementing HTS devices.

The population of the USA is also provided by the NEMS model; it appears in column CL. Knowing how much electricity goes to the residential sector (column CM), it is easy to compute the electricity per person, or number of people per gigawatt, in column CN. Columns CP and CQ relate to the coal used to produce most electricity.

Market Penetration Factors:

The market penetration model, which is an S-shaped curve determined entirely by certain assumptions (see Appendix 2), has been calculated and displayed in columns AN through BG of the *Database* spreadsheet. The assumptions are device-specific, so there are four market penetration curves given here: motors in AO to AR, transformers in AT to AW, generators in AY to BB, and cables in BD to BG. Atop each block (in rows 14-17) are listed the key parameters of the corresponding market penetration curve: starting year, b,c and a. See Appendix 2 for definitions.

Each of these clusters is characterized as follows: the first column (e.g., AO) is the number of the year after penetration begins; the second and third columns (AP and AQ) are exponential factors used in the calculation; and the fourth column (AR) is the market penetration factor itself. A glance at the tabulated data will show that the halfway point clearly stands out in the final column, and the values near year 2025 are close to the asymptotic final value of market penetration. These yearly values of market penetration are used elsewhere in both *Database* and *Results* to determine sales of each of the HTS devices.

Present Value Calculations:

In columns BK through CG, the values of savings associated with each HTS device are tabulated. Each device has its own mean lifetime (row 20) as well as its own appropriate financial discount rate (row 21). Column BK is the year, and BL is the price of electricity. When that discount rate is applied to that electricity price, the savings through the year 2025 appear in columns {BM, BN, BO, BP}. Presuming that each device will last longer than that, the savings from 2025 through the expected lifetime of the device are shown in columns {BR, BS, BT, BU}. (For all years beyond 2025, the price of electricity is assumed constant.) For each device, the sum of those two terms appears in columns {BW, BX, BY, BZ}. In this way, the total lifetime discounted revenue stream associated with saving one kWh of electricity by that particular device is determined. Those latter four columns are carried to the *results* spread-sheet, where they are combined with the amount of Gwh saved nationally, to produce the present value of energy savings in dollars (*Results* columns BA - BD).

Columns {CC, CD, CE, CF} are again device-specific discount factors applied to the price of electricity in each year. Column CG is the sum of those four columns.

Device-Specific Data:

Now we return to the left-hand portion of the *Database* spread-sheet, to consider the benefits of the various HTS devices. It could be argued that all this data might have been spread out to the right, rather than downward, because each block contains year-by-year calculated data that depends on inputs from the sections that are spread out to the right. Nevertheless, these similar blocks of data are stacked vertically, to facilitate comparisons between devices within certain categories.

In the upper left is presented “HTS Motor Benefits”. The first block deals with new motors, and spans from column A to column S. The number of years calculated takes the table down to row 49 by year 2025. Right below that is equivalent data for replacement motors, spanning from column A to column W. The row numbers run from 59 to 97.

Moving downward, next is data for “HTS Transformer Benefits”, spanning columns A to M and rows 106 to 144. After that comes “HTS Generator Benefits” in the same columns but rows 153 to 191. Finally there is “HTS Cable Benefits” occupying rows 199 to 237.

In all these cases, column A is the year, and B is the national electricity budget – the total sales of all electricity in that year. After that, the various columns become more device-specific.

Motors

As noted above, there are two “motor” blocks: new and replacement motors.

For either block, column C gives the portion of national electricity that goes to industry, and D is the electricity going into motors (over all sectors, not just industry). Column E is vestigal: it was to be the electricity going into motors of size between 50 and 125 horsepower, but since motors of that size are not candidates for superconductivity, the entries have all been set to zero. Column F, on the other hand, shows the electricity into motors above 500 hp, which are eligible for superconductivity. Column G, like E, can be ignored as too small for superconductivity. Column H is the annual increment for large motors; note the shift in scale from TWh down to GWh. H is the first column in which there is a difference between new motors and replacement motors. Columns I and J are values calculated from the market-penetration model; because there are no energy consequences, column I can be ignored. The data in J shows how the available market is expected to gradually be captured by HTS motors. In a revised model, it would be possible to employ columns E, G, I, and K to represent other motor sizes, perhaps > 5000 hp.

Continuing across either block, column K (small motors) has been set to zero, and column L is the electricity going to large HTS motors. M = K + L. N is the cumulative electricity over years; N is the integral over M. Column O presents the electrical losses saved by HTS compared to conventional motors; O = N multiplied by the fraction of savings stated on the *Assumptions* spread sheet (cell C-11). Column P is the price of electricity, and so Q is the monetary value of the savings in O. Column O turns up in *Results* column M (rows 15-40), and Q turns up in *Results* column T (rows 15-40).

Column R is the time-integral over Q, the cumulative value of the savings. Note that R is a double-integral over time: the accumulation of savings which in each year were the cumulative results of all previously-installed motors.

For new motors, column S is simply the number of large motors sold each year.

For the replacement motors block, that equivalent number is pushed out to column W.

Within the replacement data block, however, column S is a duplicate of new column Q, and column T is a duplicate of new column R. What is going on here is that the *grand total* monetary benefits of *all* motors is about to be calculated: In the replacement data block, U = Q + S and V = R + T. Column U is the total annual benefits of all motors installed to date, and V is the accumulated benefits over all years.

Transformers:

"HTS Transformer Benefits" appear in rows 106 – 144. As in the case of motors, column A is the year and B is the total national electricity budget. Appendix 8 of the report presents fine details about different types of transformers, both conventional and HTS. Columns C and D are the estimated amounts of electricity that will appear in the replacement and new transformer markets, respectively. Column E is the market penetration curve. Column F is the number of GWh captured by all HTS transformers in that year; F = E * (C + D). Column G is the time-integral over F, the cumulative electricity flowing through all HTS transformers installed to date. Column H is a small fraction of G, the amount of the savings accruing from HTS vs. conventional technology. G is multiplied by the percentage of energy saved (cell C-12 of the *Assumptions* spread sheet) to produce the savings attributed to HTS transformers.

Column I is the price of electricity. Multiplying H times I gives the annual dollar savings due to HTS in column J. Similar to motors, columns H and J transfer to the *Results* spread sheet in columns N and W (rows 15-40).

Column K is the accumulation of all savings, the integral over J. As with motors column R, note that K here is a double-integral over time: the accumulation of savings which in each year were the cumulative results of all previously-installed units. Column L is the equivalent number of large transformers sold each year, and M is the total capacity (in MVA) of those HTS transformers.

Generators:

Continuing down the left-hand side of the *Database* spread-sheet, the data for "HTS Generator Benefits" is located in rows 153 – 191. Appendix 7 is where generators are covered in the report. As usual, A is the year and B is the total national electricity. Columns C through K are the exact counterparts of the columns pertaining to transformers, above. Column L is the equivalent number of 300 MVA generators that are installed each year. Columns H and J go to *Results* columns O and V (rows 15-40).

Cables:

Similarly, the data for "HTS Cable Benefits" appears in rows 199-237. Appendix 9 gives plenty of details. The columns are each comparable to those for both transformers and generators. Note, however, in column C that there is only a tiny fraction of electricity assigned to replacement cables. This is because no one tears down an overhead line, once installed. The market for HTS cables is almost entirely new installations. Even then, the asymptotic value of market penetration is smaller than for the other HTS devices. F is the number of GWh sent through cables installed in that year. The cumulative savings due to all HTS cables over all years are given in column K.

Column L is the number of miles of HTS cable installed each year, which depends only on column F, the GWh installed annually; L = 0.022585 F, where the numerical factor comes from table 9.1 of Appendix 9. Like its counterpart under transformers, Column M is a measure of the total carrying capacity of the mileage installed in L. Rolling several constants together, M = 0.129 F.

Columns H and J go to *Results* columns P and W (rows 15-40).

APPENDIX 19 (REVISED)

Location Guide to the *Results* Spread Sheet

As before, the statements in the Preamble to Appendix 17 apply here as well.

The *Results* spread-sheet is where the calculated outputs of the model are presented. This is what most people want to hear about. However, it cannot be emphasized too strongly that no modeling result is better than its input parameters! Despite the fact that this spread-sheet is big, imposing and looks authoritative, the numerical results depend intimately on numbers ***which each analyst is free to choose,*** and which appear on the preceding spread-sheets.

Layout:

Like the *Database* spread-sheet, the *Results* spread-sheet also goes down the left side and across the top. All graphs are in a separate spreadsheet. Device-specific results are found down the left side; at the bottom left are the maximum possible benefits that could accrue from these HTS devices, if they were fully implemented right now. At the upper right are cumulative savings, variously of tons of emissions, GWh, dollars, or power plants.

Maximum Possible Results

It is instructive to first see what the upper limit of the effect of High Temperature Superconducting devices could possibly be on the American utility grid. This calculation appears at the lower left, in columns A to W, rows 272 – 297. Column A is the year, and B is the national electricity data from the *Database* column B; B_j(Results) = B_{j-248}(Database). By simply multiplying this electricity by the assumed savings associated with replacing a conventional device by a HTS device (*Assumptions* cells C_{11}, C_{12}, C_{13}, C_{14}), we obtain columns C, D, E and F. The sum of these is in G. That energy is converted to equivalent power plants displaced in H and to number of people served in I.

Columns J, K and L are blank, but the same thinking continues in M, N, O, P, where the maximum dollars savable are listed for each device. Q is the sum of these 4 columns, and R is the cumulative savings that might have occurred between that year and 2025 if HTS had been fully implemented.

Columns U, V, W are the theoretical upper limits for savings of emissions of various gases, relying upon the slowly-declining EIA annual data for emission of CO_2, SO_2 and NO_x , which are stored in *Database* columns AC, AE and AG. For example, we have $U_j = G_j$ x (*Database* AC_{j-248}).

The point of this exercise is to place an upper limit on the importance of HTS to the utility sector. There are only three ways to change these numbers:

A) Revise the future estimates for the national electricity budget; or

B) Revise the *assumptions* (C_{11}, etc.) for savings attributable to HTS vs. conventional devices; or

C) Revise the yearly price of electricity.

No one pretends that any of these numbers could come true; they are simply a *what if* scenario associated with having HTS technology in place *today*.

Actual Sales

The upper left corner of the *Results* spread-sheet contains the projected annual sales of HTS devices. This is the “bottom line” that is so often wished for, but the reader absolutely must understand that it is a result of numerous assumptions and input data. Changing any one of them will change these numbers, and that is the whole point of this model – the user is free to revise it.

In rows 15 – 40, column A is the year, and columns B, C, D, E are the annual dollar sales of each type of device. Column F is the sum of all four devices. H = F/1000, expressed in million dollars.

Stepping downward one block, the projected sales of HTS wire appears in rows 45 – 70. As above, column A is the year; columns B, C, D, E are device-specific, and column F is the sum of the four devices. In every year, wire going for cables dominates this market.

The very next block is the projected sales of cryogenics, occupying rows 75 to 100, and following the same organization among columns. There is an important element of feedback in the model here: column F (the total sales for all four devices) is related to the total number of cryogenic units built; this goes back and affects column W of the *Assumptions* spread-sheet, which in turn leads to a prediction of a declining cost for cryogenics over the years.

Cost-Effectiveness

Continuing down the left side, the next four blocks evaluate how the cost-effectiveness of each device evolves over the years. Columns A through J present the elements of the calculation. The row numbers are: Motors 118 – 143, transformers 154 - 179; generators 191 – 216; cables 228-253.

For each block, column A is the year. Column B is the present value of the savings achieved by the HTS device. The number of kilometers of HTS wire is shown in C, and its cost is in D. The cost of cryogenics is in E, and the number of each device (always taken to be of one standard size) is in F. Column G contains the incremental cost of building one of that size device. Each of these columns is derived from pieces stored elsewhere on the *Results* sheet, usually derived from the *Assumptions* or *Database*. For example, the annual cryogenic cost in E changes with variations in cryogenic efficiency taken from Columns V and Y of *Assumptions*.

Column H is very significant: it is the total cost of building all units in that year, plus the cost of wire plus the cost of cryogenics, minus the present value of the savings from using HTS technology. That is:

$$H_j = F_j*G_j/1000 + D_j + E_j - B_j$$

Thus, column H presents the true cost of owning the HTS device. Column I gives the cost of the alternative, conventional technology. Finally, column J presents the savings of HTS compared to conventional devices; $J_j = I_j - H_j$. A glance at the data shows that in the early years, J is a negative number, which means that conventional technology is cheaper at that time than the corresponding HTS device. Later, as per-unit costs of both wire and cryogenics decline, HTS becomes cheaper.

A negative J in early years is an anomaly, and implies that HTS is "jumping the gun" to some extent. On grounds of dollars alone, it does not make sense to buy a HTS device in that year. The reason a buyer would choose HTS technology in the face of unfavorable economics must be found in other factors not modeled here. For example, a cable under a major city might be HTS because that is the only way to get enough power there. Whenever calculated results show several years of negative "savings" values (J), it suggests to the analyst that the starting date of the market-penetration model should be moved downstream. In that way, the "wait and see" attitude of most utility managers can be more faithfully reflected.

As part of the Macro that iterates to find proper timing for market entry, a function has been written that examines column J and identifies the year (A) in which profitability changes from negative to positive. That is used to slide the market penetration curve back and forth, as described in Appendix 20.

It bears mentioning that there is a "chicken & egg" effect at work here. Before about 2010, none of the HTS devices is cost effective, so market penetration will remain tiny under such circumstances. Unless the cost of wire and cryogenics decline over time, there is no reason for cost-effectiveness to improve, and further sales cannot be expected. However, the decline in manufacturing cost of anything is generally tied to its volume of production. In this study, we model that behavior for cryogenics, via a feedback loop. For HTS wire, we do not include a similar feedback loop, because at the present time so very little is known about the future cost of HTS conductor. We hypothesize that HTS wire cost will decline over years in a rough analogy with historic fiber optic costs (see Apps. 12 & 13), but we concede that there is great uncertainty in that analogy.

Savings of Energy and Dollars

Returning to the top rows of the *Results* spread-sheet, and moving rightward, we find several blocks of cumulative numbers for the savings achieved through HTS.

Columns L through Q deal with the GWh saved by each device class (M – P) and in total (Q). The data in M is taken from the *Database* spread-sheet, the sum of savings by new plus replacement motors in certain rows of column O. For the other three devices, columns N, O, P are merely copied from the appropriate rows in *Database* column H. The total energy in GWh saved by all four devices is summed in column Q. The numbers shown are all *cumulative*, presuming that devices installed in one year continue to save in subsequent years. Thus, column Q is as much a "bottom line" of this study as is column F for devices sold, discussed above.

Continuing rightward, columns S through Y deal with the dollar value of those energy savings. The dollar savings by both types of motors, appearing in column Q of the *Database* spread-sheet, are summed to form column T here. Columns U, V, W are copied from appropriate rows of *Database* column J. Again, all these numbers are *cumulative* savings. X is the sum of all four devices. Y is the time-integral over X, that is, the accumulated money saved over all the prior years up to the current year. Column Y is not used in further calculations, but appears on the graph of "Net Power Cost Savings in Millions of Dollars".

Column Z is the maximum possible savings, repeated from rows 272- 297 of column Q. Column AA is the ratio of X/Z, which gives the net effective saturation of HTS technology into the American electric grid. AA is displayed on the graph named "Net Effective Penetration - %" The numerical values show that, even by the end of this study, the impact is under 10%. That is because there is so much equipment already in place that has not worn out; it will be retired only very gradually over many future years.

Manufacturing

As discussed in the main report, each device category is represented by a single size of that device. Column AC through AG present the number of each such device built in each year. AC is the year. AD is the sum of new plus replacement motors from *Database* columns S (rows 24-49) and W (rows 72-97). For the other three devices, columns AE, AF, AG are copied from appropriate rows of *Database* column L. Subsequently, these are in turn copied into the proper rows of *Results* column F, where they participate in the calculations of cost effectiveness, discussed above.

For each standard-sized device, it is known how much HTS wire is required to build one. (Those numbers are variants upon *Assumptions* column I; see Appendix 17.) Therefore, given the numbers in columns AD … AG, it is easy to compute the length of wire needed each year for each device category. That has been done in columns AJ through AM. The sum of the four gives the total HTS wire requirement in column AN. If one assumes YBCO will be the conductor of choice, then it is an easy further calculation to obtain the Yttrium required, shown in column AO. If one were to build in a feedback loop relating a declining cost of wire to the total manufactured, column AN would be the pivotal set of numbers.

Emissions

Columns AQ through AX deal with the emissions saved as a result of saving electricity via HTS technology. The "bottom line" energy savings of column Q are repeated in column AR. This is multiplied by the tons of carbon per MWh (EIA data in *Database* column AD) to produce column AS, the annual savings of carbon. In the same way, AR (= Q) is used with comparable EIA data for SO_2 and NO_x (Database AF and AH) to determine the tonnages shown in columns AT and AU. Columns AV, AW and AX are the cumulative savings of emissions of carbon, SO_2 and NO_x.

Additional Calculations

In the discussion of cost-effectiveness above, the present value of the savings was given in column B (in appropriate rows for each device). Those numbers were obtained from the data appearing in columns BA through BE.

Remember that the present value depends on the discount rate being used (denoted by r). In this study we allowed the discount rate to be different for each device. Typically, industrial customers use a higher rate than utilities. Row 12 of columns BA, BB, BC, BD contains the factor $[1/(1 + r)]$ used in figuring present values.

Database columns BW, BX, BY and BZ contain the total lifetime value of a kWh saved by each device, using the proper discount rate. The total energy flowing in each year through each class of HTS device is given in appropriate rows of *Database* column F. The percent savings associated with this energy flow is given by *Assumptions* cells C_{11}, C_{12}, C_{13}, C_{14}. These three factors are multiplied together to produce the entries in *Results* columns BA, BB, BC, BD. BE is the sum of all four.

Column BH is a repeat of *Assumptions* column AY, placed here for calculational convenience; it is used to find column D of the cost-effectiveness blocks. Column BI is a repeat of column AS (annual carbon averted) and BJ is AV, the cumulative sum of AS.

Power Plants Offset

Concluding the *Results* spread-sheet, the equivalent number of power plants offset by HTS devices is given in column BK. (It is presumed that all power plants are 500 MW and all run at a capacity factor of 50%.) BK is the sum of column Q from the start to the current year. Finally, the number of households served by the savings appears in column BL. Here the "bottom line" energy savings (Q) are multiplied by the EIA estimate of people per GWh (column CL of *Database*), and then divided by 2.6 people per household. BL is the basis for the bar chart that is figure 7 of the main report.

Macros in the Mulholland Model

This appendix describes several *Macros* that have been written and incorporated into the Mulholland Model, in order to test the effect of certain variations in parameters. Several of the Macros vary a parameter over some pre-selected range of values. One Macro is invoked to achieve convergence of a feedback loop that modifies the market-penetration model according to a criterion of profitability. The variations so tested are the ones of greatest interest to most observers who have expressed interest in how the Mulholland Model can enhance their ability to estimate the future of HTS devices.

In general, each of these Macros involves "scanning" across a plausible range of the numerical entry in some cell on the *Assumptions* spread-sheet, and then selecting a certain few elements of data from the *Results* spread-sheet for reporting or graphing. Presumably the analyst can then look over the data generated by this scanning, choose one value from that range to run the model over again, and thus obtain a full set of results for detailed examination.

To exercise any of the Macros, one need only scroll down below "tools" to "Macro" and click on that to display the choices. It doesn't matter which spread-sheet is being displayed at the time. Any particular Macro can then be highlighted and run.

1. Electricity Growth Rate Variation: *ElectricityEscalation*

The rate at which electricity demand will grow in the future is speculative, but it strongly affects the predictions of the Mulholland Model. In an earlier version, the EIA projected values through 2025 were built in as numerical entries. Now the escalation rate appears in one single cell (D-6 of *Assumptions*), which the analyst can easily change.

Moreover, there is a macro that varies the escalation rate across the range from 1.7 % annually to 2.6 % annually, and tabulates certain selected *Results* that obtain for each of eight different escalation rates. The selected values span beyond the range between the EIA prediction of 1.8% (low) and more optimistic predictions derived from recent actual experience (2.4%, high). Furthermore, a graph is drawn showing the sales of HTS devices in 2020 and 2025 as a function of the escalation rate.

The particular years for which sales data is displayed come from *Results* column F, rows 35 and 40, and the energy savings come from Q35 and Q40 -- both corresponding to 2020 and 2025. The numbers are printed sequentially in *Results* columns AG to AK, rows 81 to 88. The graph of how sales varies with escalation rate comes from this data.

This Macro is very easy to change: With this Macro highlighted, one can open it in "edit" mode, and change any line of code within it. The numerical choices of escalation rate can be re-set to any values the analyst wishes. The choice of years reported can also be changed by editing this Macro. Thus if a future version of the Mulholland Model runs out to 2040, more rows or different rows from Column F or Q can be displayed and graphed.

2. Replacement Rate Variation: *EnSavVsReplace*

This is the earliest Macro written, and its motivation has already been described well in Appendix 11. The fact is that we don't know what the replacement rate (of old conventional equipment by HTS equipment) will be, because we cannot read the minds of factory and utility managers, and cannot predict how well they will accept new technology. This Macro runs the Mulholland Model for a series of different choices of the replacement rate. A graph of the output shows that total sales can easily swing around 20% just due to the replacement rate alone.

Cell H25 of the *Assumptions* spread-sheet contains the replacement ratio. As described in Appendix 11, we have no criterion by which to prefer any value between about 0.5 and 0.8 for this value. This Macro takes a series of 11 different values (from 0.4 to 0.9) which are tabulated in *Results* column AB, rows 81 to 91. Each such replacement rate is loaded into H25, the Mulholland Model runs, and then the energy savings in 2020 and in 2025 (= *Results* Q35 and Q40) are placed in AC76 and AD76. For each new replacement rate value, these results are transcribed into columns AC and AD, rows 81 to 91. Also, a graph is made of these two outputs as a function of the replacement rate.

It is well to remember that Macros are not automatically revised by the *Excel* language when blocks of text are moved. Therefore, the analyst must take care before relocating the entries in *Results* columns AB to AD, rows 76 to 91. Some editing of the Macro will be required.

3. Market Saturation Level Variation: *Saturation*

This Macro explores variations in how much market share each HTS device will ultimately capture. It amounts to varying the parameter "b" of the market penetration curve for each HTS device (see Appendix 2).

Each device is assigned a *saturation parameter* corresponding to low, medium or high market capture. Fifteen different scenarios have been constructed to emulate different combinations of low, medium or high saturation for each of the four devices. The numerical values for each of these scenarios appear in *Assumptions* Columns BT, BU, BV and BW.

The most pessimistic case is where all four devices have low saturation; the standard case, or "business as usual", is when all four have a medium saturation level; the most optimistic case is where all four have high saturation. Beyond these three cases, the Macro also examines:

1. Two cases where *motors* have low and high saturation, but the other three HTS devices have medium saturation;

2. Two cases where *transformers* have low and high saturation, but the other three HTS devices have medium saturation;

3. Two cases where *generators* have low and high saturation, but the other three HTS devices have medium saturation;

4. Two cases where *cables* have low and high saturation, but the other three HTS devices have medium saturation;

5. Two cases where *motors and generators* have low and high saturation, but *transformers* and *cables* remain at medium level;

6. Two cases where *transformers and cables* have low and high saturation, but *motors and generators* remain at medium level.

In all cases, what is printed out on the *Results* spreadsheet are the total energy saved and the total sales in the years 2020 and 2025. These numbers are drawn from columns F and Q, and are placed in columns AH to AK, rows 119 to 133. The way the Macro runs is this:

To begin one loop, the selected "saturation" values (stored in columns BT to BW of *Assumptions*), are copied and pasted into positions H11 to H14. That causes the *Results* to change, and selected entries from *Results* appear in row 113, columns AH to AK. Next, that data is copied to a row below (row 119 and beyond), and thus one loop is complete. The next case is run by going back to *Assumptions* BT to BW and looking at the next row. At the conclusion of running the macro, the collected output of all 15 cases thus appears in rows 119 to 133, where they can be inspected and compared.

The number of cases is open-ended, not limited to 15; other "saturation" values can be added at will, without modifying the code of the Macro. However, it should be noted that the rows and columns on both the *Assumptions* spread-sheet and the *Results* spread-sheet are entered as specific numbers, and therefore it is not trivial to move a block of this data around and expect *Excel* to keep track of the change and correct for that move. If a block of this data is relocated to a different location, some corresponding minor editing of the Macro code is required.

The intent is that the analyst would run the Macro, look at this very limited series of results, and select one particular case; then choose suitable values for the saturation parameters and insert those into Assumptions cells H11 to H14. The Mulholland Model would then produce all the results and graphs corresponding to that collection of market saturation values for the four devices.

4. Market Entry Variation: *YearProfitable*

This Macro behaves quite analogously to the preceding Macro. For whatever reason, a device can be hypothesized to enter the market early, normal or late. For example, a particular device might be granted a special tax credit, thus shifting entry to an earlier date. The reasons need not concern us here.

Exercising this Macro computes a series of scenarios in which various devices enter the market at different times. Fifteen different scenarios have been constructed to emulate different combinations of early, normal or late market entry for each of the four devices. The starting years for each of these scenarios appear in *Assumptions* Columns CD, CE, CF, and CG.

The most pessimistic case is where all four devices have late entry; the standard case, or "business as usual", is when all four enter the market at normal times; the most optimistic case is where all four enter early. Beyond these three cases, the Macro also examines:

1. Two cases where *motors* have early and late entry, but the other three HTS devices have normal entry;
2. Two cases where *transformers* have early and late entry, but the other three HTS devices have normal entry;

3. Two cases where *generators* have early and late entry, but the other three HTS devices have normal entry;

4. Two cases where *cables* have early and late entry, but the other three HTS devices have normal entry;

5. Two cases where *motors and generators* have early and late entry, but *transformers and cables* remain at normal entry;

6. Two cases where *transformers and cables* have early and late entry, but *motors and generators* remain at normal entry.

In all cases, what is printed out on the *Results* spreadsheet are the total energy saved and the total sales in the years 2020 and 2025. These numbers are placed in columns AH to AK, rows 160 to 174. The way it works is this:

To begin one loop, the selected "first profitable" years (stored in columns CD to CG of Assumptions), are copied and pasted into positions E11 to E14. That causes the *Results* to change, and selected results appear in row 154, columns AH to AK. Next, that data is copied to a row below (row 160 and beyond), and one loop is complete. The next case is run by going back to *Assumptions* CD to CG and looking at the next row. At the conclusion of running the macro, the collected output of all 15 cases thus appears in rows 160 to 174, where they can be inspected and compared. As with the *Saturation* Macro, repositioning data requires minor code editing.

Again, after running this Macro to get a rough idea, the analyst can make a particular choice of "first profitable" years, insert them into *Assumptions* E11 to E14, and obtain all the outputs and all the graphs of the Mulholland Model for that case.

5. Market Penetration Convergence Calculation: *FirstProfit*

This Macro is the heart of the feedback loop that shifts the position of the market penetration curves to produce a plausible scenario of profitability. Such a scenario we term "equilibrium."

Superficially, this Macro appears minor, because all it does is transfer values from *Assumptions* K11 to K14 into *Assumptions* E11 to E14, and repeats this four times. However, what is important are its links to other features in the *Excel* coding.

When an analyst changes some parameter of the Mulholland Model, it is reasonable to assume that the profitability of one or more HTS devices might change, in which case the year in which it first becomes profitable might change. This can indirectly affect the other 3 HTS devices as well. This macro is what enables the analyst to find that new "equilibrium" of the model, by shifting around the market-penetration curves until all four devices show reasonable market-entry behaviors.

It doesn't matter how wild a guess (for first profitable year) might have been used at the outset; this Macro iterates until a plausible outcome is obtained. This is quite different from # 4 above, which forces a certain choice of years for each particular case, regardless of profitability. Macro # 4 is intended to give a preliminary look, but Macro # 5 strives to reach a self-consistent solution for market penetration.

The position of the market-penetration curve (for each HTS device) is set by the entry in *Assumptions* E11, E12, E13 or E14. The initial year in market appears in D11 (etc.) and the mid-year of market penetration in G11 (etc.); those two entries are fixed with reference to E11. Depending on factors like the performance of wire, the cost of wire, the efficiency of cryogenics, the cost of cryogenics, and so on, the Mulholland Model will calculate sales of each device, energy saved, and profit for each year of market activity. In the first few years (termed "toe in the water" years) the profit is usually a negative number, but becomes positive after a few years. That is the *real* "first year of profitability." The objective of dynamically varying the entries in E11 to E14 is to discover what that year is.

5.1 The Function ***firstposyear***

Within the Mulholland Model is a function named "f*irstposyear*" . It is not listed among the Macros, but it does convey with the program when downloaded. The function examines column J of *Results* and finds (for each device) the row corresponding to the transition from negative to positive profitability. It then goes to column A – the year in which the transition happens -- and places that year atop the section of column J appropriate to each device: cells J113, J149, J186, J223. Next, the contents of those four cells is copied to *Assumptions* K11, K12, K13, K14.

5.2 Comparison and Convergence

The next step is that column K is compared with column E. On the *Assumptions* spread-sheet, the formula bar for cell E15 contains a very lengthy "if" statement that compares all four of the pairs {E11, K11}, {E12, K12}, etc. If they are all the same, the word "converged" is printed in E15. If any are not the same, it will print in E15 the phrase "try again, rerun". Meanwhile, E16 contains the phrase "first profit Macro". Note that sections 5.1 and 5.2 here always happen, and don't require running a Macro.

5.3 Running the Macro *FirstProfit*

This is where running the Macro ***FirstProfit*** comes in. This Macro transfers the values from K11 to E11 etc., at which point the Mulholland Model runs again and creates new profit values (*Results* J), new years (*Results* A), and new values for *Assumptions* K11, K12, K13, K14. This iteration is repeated 4 times. If the years converged to a reasonable profit pattern on the second iteration, then it performed two unnecessary additional cycles. If convergence was not achieved, the message conveyed to the analyst says to run it over again, thus invoking 4 more iterations.

The 4-at-a-time rule is completely arbitrary and may be edited in the Macro [Do While Index < 5]. Because the "toe in the water" first year is often only two years early, the market penetration curve will not slide more than two years per iteration, and thus for big changes or for a very bad initial guess it might take 5 or more iterations to locate the equilibrium locations of the market penetration curves.

This iterative loop has been tested for various conditions and performed well. It needs to be verified by other analysts who may invent conditions we haven't thought of.