Method for Estimating Future Markets for High Temperature Superconducting Power Devices

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Abstract—**This paper describes a spreadsheet model for estimating the impact of High Temperature Superconducting (HTS) power devices on the national electric grid. The distribution of losses in the national grid is carefully traced and those losses that HTS can eliminate are identified. The energy savings achievable by the many sizes of HTS generators, transformers, cables and motors are then computed and totaled using a spreadsheet analysis. The economic savings are very sensitive to the price (and J_e) of HTS wire, and to the cost of cooling the devices to operating temperature. A market-penetration model is used to estimate how fast HTS devices become commercially successful. The emphasis of the paper is the analytic tool, not the numerical results of one specific case. This entire model is explicitly designed to allow others to enter their own estimated parameters and arrive at their own conclusions.**

Index Terms—**Analysis tool, projections of market for HTS power devices, impact of cooling, and conductor cost**

I. INTRODUCTION

For over a decade, high temperature superconductor (HTS) technology has been described in very general terms [1] as "promising". Possible applications [2] to the utility industry [3] have been widely discussed in various magazines [4]. However, *quantitative* estimates of how well (and how quickly) real HTS devices will serve their markets have been lacking. We describe one *Excel* spreadsheet analysis model that offers a means of estimating the future impact and market size for large-scale HTS power devices such as generators, motors, transformers and cables.

The **primary purpose** of this study has been to create a method of analysis that allows others to conduct quantitative modeling about the future HTS marketplace. Rather than seek "high priest" status, we have deliberately made the model transparent to allow changes in the input assumptions. A detailed report [5] including 16 appendices strives to enhance such flexibility.

The **secondary purpose** of this effort is to illustrate how to use the model. To do so, we proceed in four stages: The first step is to calculate the electric power and energy losses in the existing national electric grid, to define the "target" market for HTS devices. Second, we project the savings in electric energy losses that can be expected by using HTS technology. The third step is to compare the monetary *savings* attributable to HTS with estimated *costs* of HTS devices. Fourth, we model the *market penetration* of HTS devices into the grid. The output results are explicit numbers of kWh and dollars; however, the real intent is to illustrate how analysts might refine their judgments and estimates regarding future HTS markets.

The **scope** of this study is deliberately limited. Our model addresses HTS technology only for the following:

- Motors greater than 500 horsepower
- Generators greater than 500 MVA
- Transformers greater than 30 MVA
- Cables at transmission voltage levels

More specifically, this effort develops the savings parameters (described in the purpose) based on the assumption that HTS will be used in the electrical devices listed above. The time-span of the study covers the years 2000 to 2020. All calculations are in "real" dollars with no inflation correction. Finally, only the United States is addressed

The **approach** of this study is to use spreadsheet analysis to project the following for the years 2000 to 2020:

- Amount of HTS wire required,
- Cost of HTS wire,
- Cost of cryogenic devices, and
- The time rate of change of these variables.

Combining this data with engineering and business judgment about utility market penetration, projections are made for:

- Sales market for cryogenic devices,
- Sales market for HTS power devices,
- Energy savings, and
- The time rate of change of these variables.

Hopefully this type of analysis will allow the HTS industry to study the sensitivity of the HTS device markets to changes in the two critical factors defining HTS competitiveness – the cost of HTS wire and cryogenic cooling units.

II. DESCRIPTION OF THE ANALYSIS

The steps in preparing this analysis are enumerated below. The report is benchmarked on the 1999 National Energy Modeling System (NEMS) developed by the Energy Information Agency (EIA) [6]. The basic premise is that, on average, over the next 20 years the increase in electricity consumed throughout the United States will be generated by new generators, transformed by new transformers, transmitted by new transmission lines and cables, and partially consumed by new electric motors. Some of these new devices will be made with HTS materials [7]. The amount of energy generated, transformed, transmitted and consumed by these HTS devices will be a percentage (% market penetration) of the total *increase*

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in energy each year. In addition, HTS devices replace some retired conventional devices. Implementation requires:

1. The projected electric energy sales in the United States for 2000 to 2020 were taken from the EIA *Annual Energy Outlook 1999.* The EIA forecast ends in 2020.
2. The *Annual Energy Outlook 1999* uses a growth rate of 1.4 % annually. Available HTS power devices will supply or use a portion of this new energy growth.
3. Estimates of the replacement-rate for each device were made and combined with the growth in energy to establish the total energy market for which HTS devices might be considered.
4. To determine quantitatively the losses at each stage of national electric grid, the flow of electricity through the grid was examined [8]. Those losses were further segregated into *no-load losses* and *i^2R losses* to identify the "target" of HTS devices.
5. Estimates of energy-loss savings associated with HTS motors, generators, transformers and transmission cables were made. Using available literature, engineering judgment was used about the expected performance of new HTS devices. A *cryogenic penalty* was imposed here; to reflect realistic electric energy saved by HTS power devices in comparison to conventional technology.
6. Utilizing the declining cost projection for HTS wire and cryogenics, a market-penetration model for each HTS device was introduced. A standard [9] "S-curve" characterized the rate at which each new HTS device is expected to enter the marketplace.
7. For each device, the HTS-related energy saved was calculated by multiplying the loss-savings factors derived in step 5 by the market-penetration fraction.
8. The energy-saving factors from step 7 were multiplied by the energy generated, transformed, transmitted or used by electric motors. The contributions of many different sizes of each device were calculated and totaled.
9. The energy amounts calculated in step 8 were multiplied by the wholesale cost of electricity to obtain the market value of the HTS savings.
10. The projected higher capital costs associated with HTS conductor and cooling equipment were deducted from the monetary savings to yield the *net* financial benefit of HTS technology.
11. Finally, the contributions from all four of the device categories were summed to obtain the estimated total national energy savings attributable to HTS in each year. In keeping with the EIA NEMS, if we assume that an equivalent of 2/3 of all electricity comes from burning coal, a simple calculation estimates the reduction in CO_2, NO_x and SO_2.

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

a) HTS wire cost projections were obtained by extrapolating from today's R&D environment to a future commercial market. This is the most uncertain aspect of this study. We optimistically assumed that R&D would succeed in improving current-carrying capacity (J_e) of HTS conductor. Historical data derived from the fiber optics industry were used to estimate the decline of HTS wire cost to a future asymptotic production level costs.

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

It should be noted that there is a feedback loop embedded in the above process. Steps 10 and 6 are intertwined, because if either wire costs or cryogenic costs are very high and the net financial gain is small, there will be very few buyers of HTS equipment, and hence the market penetration time will stretch out longer. Conversely, a sharp drop in wire or cryogenic costs would make HTS devices more attractive, and that would accelerate market penetration.

It is for this express reason that this entire methodology is designed to enable others to carry out their own calculations based on their chosen input assumptions.

III. TYPICAL CALCULATIONS AND RESULTS

A concrete example is needed to enhance understanding and clarify the analysis methods. We present here one such calculation, using entirely plausible input data that seems to model the progress of HTS electric power devices. We again state that this is an example calculation and is not to be treated as "cast in stone." The careful reader will note that any model contains important elements of engineering judgment, subject to controversy and debate by other engineers.

A. *The National Power Grid*

This example was carried out using 1996 actual data from EIA. Tentative 1999 data is available; but the difference is well captured by the 1.4% annual increase predicted by the EIA [7]. For total 1996 annual electricity sales of 3367 TWh, the total losses are 7.6 %, or 256 TWh, which has $13 billion wholesale value – the maximum monetary value for present losses.

But, we can't recover it all. Since HTS can only eliminate *i^2R losses,* it is necessary to separate *i^2R losses* from *no-load losses*. Accordingly, it is necessary to follow the electricity flow through the national grid carefully, taking note of this distinction at each stage of transformation and transmission. Reference [8] and the appendices in reference [5] present the details.

In general, the *total energy* (kWh) must not be confused with the *instantaneous power or demand* (kW) flowing through any component. Because of diurnal variations in power demand, most utilities experience a 4x variation in demand between their peak load and base periods. By reordering the demand from peak to base and normalizing both variables, the actual demand maps into the function, g(x), with both $0 < x < 1$ and $0 < g(x) < 1$. This function is called the *Load Duration Curve*. Fig. 1 is an example. The average load is, the integral over g(x), $\langle g\rangle = L = 0.55$ being typical for many utilities. However, the *i^2R loss* is related to the integral over $g^2(x)$, $\langle g^2\rangle = G = 0.36$ for typical utility experience. The AC losses (pertinent to superconductors) depends upon $\langle g^3\rangle = H = 0.24$. During periods of sustained high demand, of course L rises, but G rises faster and H faster still. It is important to realize that the *i^2R loss* is much greater when the system is carrying the most power; this fact causes the instantaneous power demand to differ appreciably from the average energy losses.

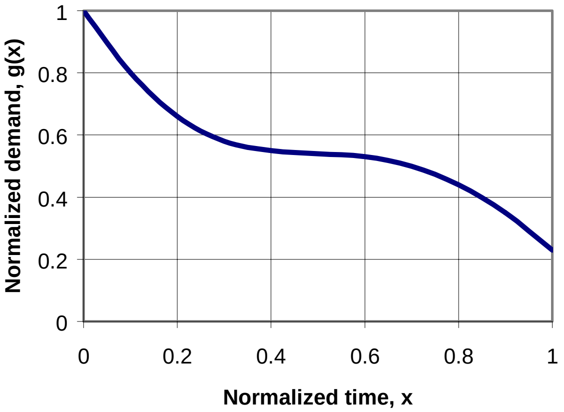

Fig. 1. Load duration curve for a typical utility. The average value of this data is 55% of the maximum.

In our model, we tracked energy flow carefully through the consecutive components of the national electric grid, and calculated the amounts of energy lost at each stage of transformation or transmission [5], [8]. In Table I we show the percentage lost at each stage (combining both *no-load* and *i^2R losses*), for both instantaneous power and total energy. This data can be further segregated into *no-load* and *i^2R* components; thereby, we obtain the "HTS eligible" loss at each stage. Reference [8] spells all this out in great detail.

After setting aside the *no-load* losses, we further limit our attention within the "HTS eligible" category. In our engineering judgment, normal feeder distribution circuits and distribution transformers are unlikely candidates for HTS application, owing to the large cryogenic penalty associated with components carrying only modest amounts of electricity. Therefore, we ask how much can be saved, by converting to HTS, only transformers and intermediate-level transmission cables. With that restriction, it turns out that 4.47 % of the power demand, but only 2.95 % of the total energy passing through the grid, is "HTS eligible." That much energy is worth about \$5 billion annually – an upper limit based on 100% conversion to HTS devices: a very unlikely scenario. In 20 years, if an electricity growth rate of 1.4% continues [6], the market will be 32% larger, and the upper limit becomes \$6.6 billion.

TABLE I
LOSSES ALONG THE ELECTRIC GRID

Stage	% Instantaneous Power	% Energy
Generation	0 (start)	0
Step-up transformer	0.32	0.30
Transmission 230-500 kV	0.53	0.35
Step-down transformer	0.37	0.38
Transmission 69 – 161 kV	2.94	1.94
Step-down transformer	0.66	0.69
Metering	0.36	0.46
Distribution 12 – 25 kV	3.00	1.30
Distribution Transformer	1.77	1.47
Metering	0.90	0.72

B. HTS Utilization

Having established the national opportunity, it became possible to examine the way in which various HTS devices (generators, transformers, cables and motors) can capture energy savings. In this analysis, considerable attention was given to collecting performance data on many different sizes of power devices. The size of the unit had a finite, nearly linear, effect on its cost. Certain commonalities were observed, and hence it is entirely permissible to select one intermediate size as the *representative* (or *surrogate)* for the entire set of that device. Thus, the "standard unit" of transformers = 65 MVA; the "standard unit" of generators = 300 MVA, and so forth. The numerical error introduced by this approximation was much smaller than the errors associated with several very uncertain parameters of *any* specific HTS device.

There are four primary input variables, which are embedded in many places throughout the model. The analyst must choose these based on sound engineering judgment. Clearly, such choices may be subjective and we encourage others to step forward with their own notions. The four variables are: (1) the current carrying capacity of HTS wire (related to J_e), (2) the manufacturing cost of HTS conductor, (3) the efficiency of cryogenics (% of Carnot), and (4) the capital cost of cryogenics (\$/kW of cooling capacity).

In our illustrative calculation, we took an extremely simple time-line for (1): For a typical HTS conductor, current will increase linearly with time from today's 100 Amps to 1000 Amps in 2015, and remain flat thereafter. For the manufacturing cost (2), we rejected the allure of *Moore's Law*; instead, we examined the experience of the fiber optics industry, which saw costs drop from \$1.80/m in 1977 to \$0.04/m in 1997. Looking ahead 20 years, we imagined a similar declining cost shape leading from \$100/m in 1997 to \$23/m in 2017. We put these judgments together to derive the trajectory of \$/kA-m shown in Fig. 2.

Clearly, any new breakthrough in HTS conductor technology, perhaps [10], will change (1), and that is the purpose of research. Dramatic improvements in wire performance would accelerate the market entry of all four HTS devices.

For cryogenic efficiency (3), we assumed that by 2010 (when HTS devices begin to appear in significant numbers) the performance would reach 30% of Carnot. Again, we have no secret knowledge that makes this official truth; we used our own engineering judgment here to steer a course between optimism and pessimism.

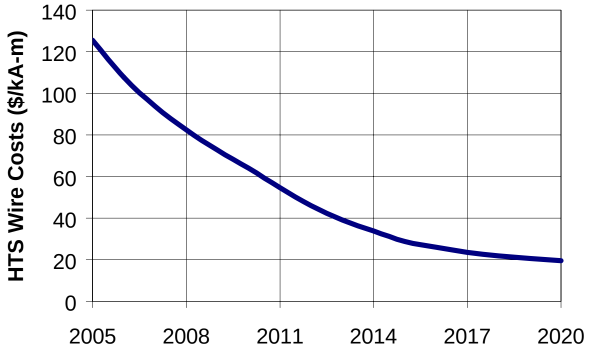

Fig. 2. Cost trajectory over time for HTS wire ($/kA-m), based on the projected current capacity discussed in the text and similarities expected with the experience of the fiber optics industry.

The likely decline of cryogenic capital cost (4) was modeled by observing the historically recurring similar behavior of many products as their markets expanded [11], [12]. That decline is linear on log-log paper with a slope of about –1/3. The number of refrigerators needed to service these HTS devices is anticipated to grow by a factor of 30 between 2007 and 2020, and hence their unit cost is estimated to decline by a factor of 3, due simply to increased production volume.

Again for cryogenics, should there occur an R&D achievement that improves either (3) or (4), costs will decline and market entry will be enhanced. Conversely, if performance improvements in wire never occur, demand for HTS devices will be small, and cryogenic unit costs will stay high, further eroding demand.

Once the performance and price behavior of wire and cryogenics are in place, the penetration of HTS devices into the notoriously conservative utility market can be modeled with good credibility. As stated in section II, the "market" comprises {all new expansion capacity} plus {replacement of a few % per year}. Because established reliability is a dominant factor in utility planning, there is no way that HTS devices could ever capture a market instantly. For a typical "S-curve" model of market penetration, the *width* parameter will be about 10 years, even for HTS devices that are proven and trusted. Moreover, experience has taught that many other factors are involved in purchase decisions, so that a product *never* captures an *entire* market. Also, a capital investment will not be made unless its *Return on Investment* is sufficiently attractive to exceed the *hurdle rate* for new investments; if not, the *lowest first cost* product will be purchased [13].

With these constraints, we selected market penetration models for each of the four HTS devices of interest to utilities. In all four cases, by 2020 the model predicts that market penetration will be well along. The asymptotic values of expected market capture are:

- Transformers 80%
- Motors 75%
- Generators 40%
- Cables 35%

The fairly low numbers here for generators and cables represents our best engineering judgment about the real utility system within the United States. The choice of 35% for cables is actually generous, because it means that 1/3 of all new transmission in the intermediate range (60–200 KV) would be underground cable. That's fine for cities, but questionable for rural transmission. Fig. 3 presents the four market penetration curves calculated with these input parameters. Saturation is within sight for all four by 2020.

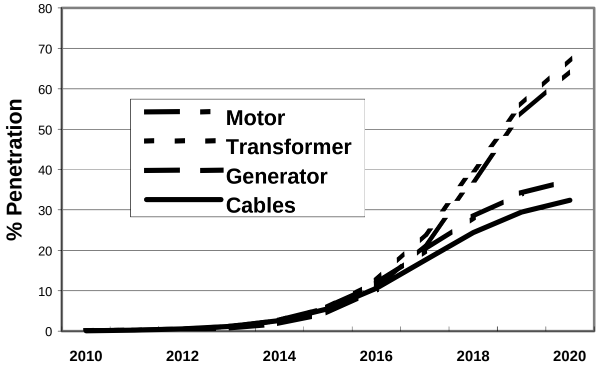

Fig. 3. Market penetration curves for HTS motors, transformers, generators and cables, using the numerical inputs discussed in the text.

From here it is a straightforward computation (just a summation over many contributions) to arrive at the total sales of HTS devices and the total energy saved by them. Fig. 4 indicates that total sales will reach about $1 billion in the year 2020. This follows a very slow start, in which sales in 2010 are still below $5 million. Fig. 4 rises more steeply than fig. 3, partly because the market enlarges each year, but mainly because it represents the sum over all four devices.

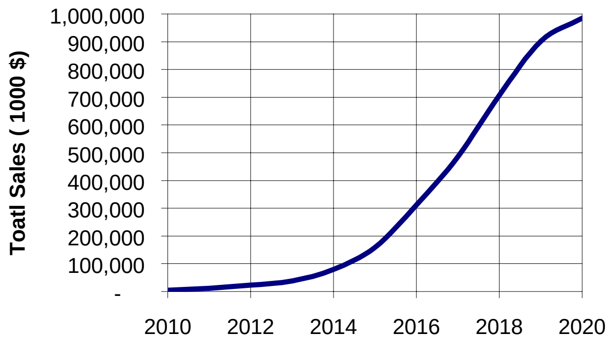

Fig. 4. Estimated total sales for all four categories of HTS devices over time that result from the combination of input values used for market penetration, wire, and cryogenic parameters.

As unit sales of HTS devices occur, energy savings slowly accumulate as well. Because by 2020 the national grid still

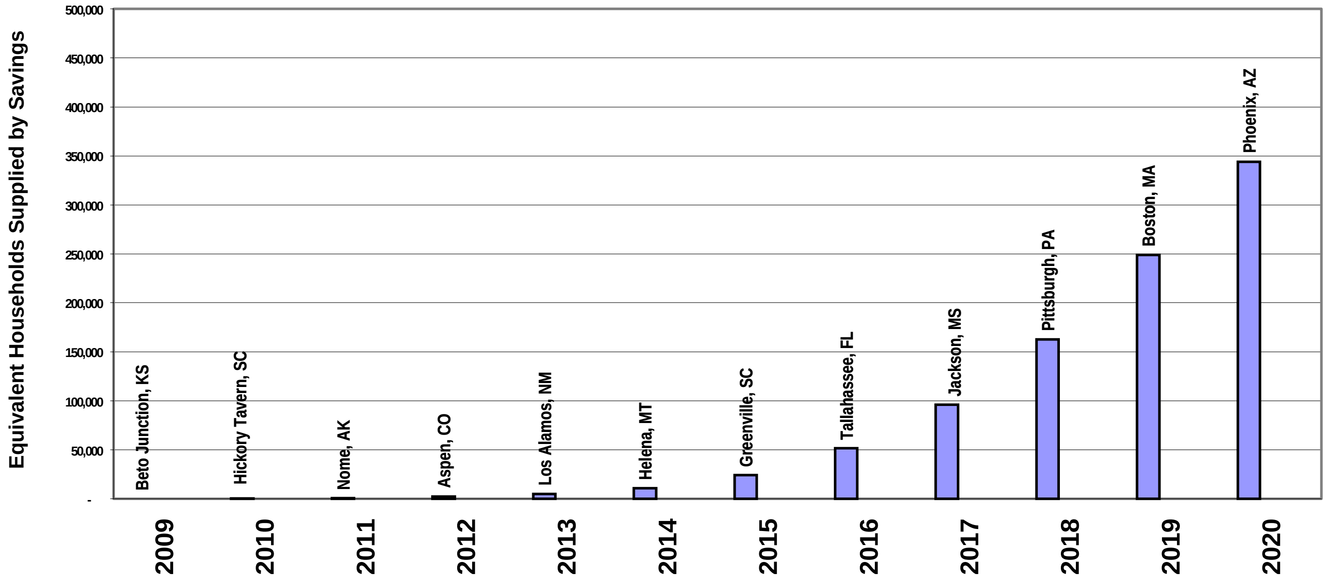

Fig. 5. Equivalent of energy saved via HTS devices, using various American cities to denote the magnitude of savings.

has a lot of perfectly working conventional equipment, we are still only partway to recovering the potential 2.95% of national electricity savings projected for HTS equipment. Annual replacement will require another 30 years to retire the stock of conventional equipment. By 2020, our model suggests that HTS generators will cumulatively save over 1,500 GWh (= 1.5 billion kWh) and the combination of all four HTS devices will cumulatively save about 3,600 GWh. To give perspective to the steady increases in annual electricity savings, we display in fig. 5 a bar chart of the number of typical homes that would be served by the corresponding savings for that year. For example, Pittsburgh, PA the site of the 1996 *Applied Superconductivity Conference*, would have its entire residential electricity demand offset by the HTS-related savings of 2018.

C. Trade-Offs

One of the most useful features of this model lies in its ability to provide answers to “What if…?” questions about various combinations of input assumptions. For a single change in one parameter, the “running time” of the computation is under a second, so user I/O dominates the interaction time. We have run many different scenarios to discern how sensitive the model is to small changes, and how robust it is against sources of uncertainty.

One of the peripheral studies that we carried out was to look at cases where the financial benefits came out zero – known as a “break even” case. For such cases, a small increase or decrease in either the cost of wire or the cost of cryogenics would move the outcome to a gain or a loss. Once again we selected a single size of a device as a surrogate for the entire class. We varied the cryogenic cost and the wire cost in opposite directions so as to stay right on the “break even” line, and thus establish a “Trade-Off” between those two cost components.

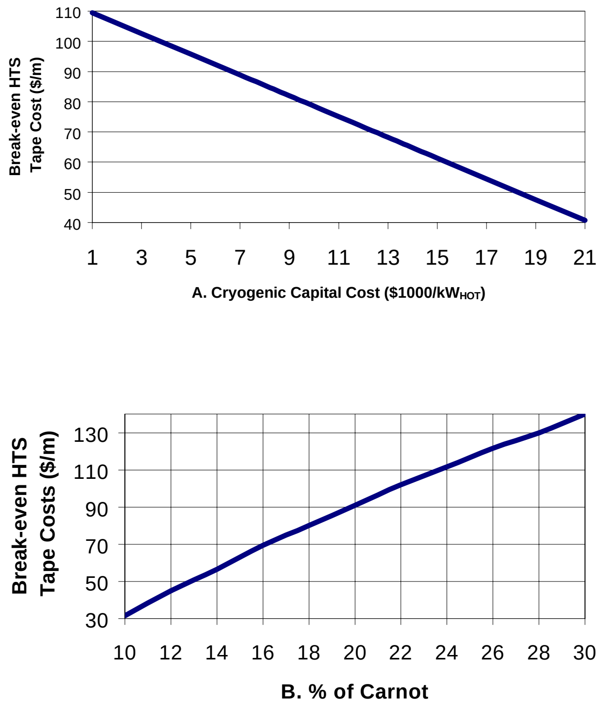

Fig. 6. Trade-off between wire cost and cryogenic parameters: A) As capital cost of cryogenics declines, the price of HTS wire at which a project “breaks even” is allowed to rise; it is financially neutral to install such a device. B) As cryogenic efficiency increases, the “break even” price of HTS wire can increase.

Fig. 6 shows the results. First, (6A) the *capital cost* of both the cryogenic system and the cost of HTS wire were varied showing that a decrease of $1/Watt {hot side} allows the cost of HTS wire to rise by $3.44/meter while maintaining break-even conditions. Next, (6B) the *cryogenic efficiency* {fraction of Carnot} was varied. Increasing efficiency by 1% allows the cost of HTS wire to rise by $5.45/meter. Hence, if 30% efficiency is reached (vs. today's 20%), wire can be over $50/meter more expensive, calling attention to the value of cryogenic R&D.

Many other trade-off studies and "What if?" questions are likewise easy to explore. For example, the *cost of capital* can be set to whatever rate the user wishes, and that too can be varied to see its effects. One very uncertain engineering parameter is the ac losses associated with HTS wire; inserting several different values would quickly show how sensitive the overall energy savings are to that parameter. Likewise, the load duration curve can be modified easily since a dense urban area will probably experience higher values for the load-duration factors L and G than the national average.

IV. CONCLUSIONS

We have constructed a model of the U.S. electric grid and considered how HTS devices would become part of it. Embedded in this national spreadsheet analysis are models of the behavior of the four main HTS devices (motors, generators, transformers and cables) that would be sold to utilities and industrial customers. For any particular choice of input conditions, the model calculates the expected future impact of HTS equipment, and the electricity savings that accrue.

This model is very flexible and input assumptions are easily changed, allowing others to obtain independent estimates. We have employed our engineering judgment to select certain inputs, and have produced a comprehensive output to illustrate how the model works. Our results include:

A) Of the total energy flowing through the U.S. national electric grid, slightly under 3% can be saved via HTS devices.
B) Full penetration of utility markets by HTS devices will be more than 20 years in coming.
C) Not surprisingly, R&D is still needed to:
    - Improve cryogenic efficiency;
    - Improve current carrying capacity of HTS wire;
    - Reduce HTS wire cost and cryogenic cost.

The preceding text has emphasized the dependence of this model upon input assumptions about wire and cryogenic costs, and noted a strong feedback loop with market penetration that makes it so important to reduce the costs of both. Utilities are businesses, and (now largely deregulated) will not buy experimental, unproven or expensive gadgets. Prices have got to come down dramatically!

We did ***not*** presume that today's status quo would continue, but optimistically assumed gains of over an order of magnitude in both wire performance (J_e) and wire manufacturing cost reduction. Better and much cheaper (factor of 3) cryogenic systems were also used in our inputs. It should be clearly understood that a failure to meet either of these goals would cripple the ability of HTS device manufacturers to sell their products to utilities. Only specialized (niche-market) applications could bear the resulting high cost of HTS technology.

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