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# Technical Analysis and Assessment of Resilient Technologies for the Electric Grid

## *Task 2—Cost and Commercialization Assessment and Market Analysis*

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08-25-2018 Comments:
Added by PM Grant on 08-25-2018
FYI: To the best of my knowledge, the final version of this report, funded by DOE, has not been published or approved for distribution as of this date. Before referencing or "passing on", please check in with EPRI and DOE. Again, the complete and final report of this study has not been released by DOE as of this date. I've heard, anecdotally, several HTSC wire manufacturers have objected to its publication.
-PM Grant

# Technical Analysis and Assessment of Resilient Technologies for the Electric Grid

*Task 2—Cost and Commercialization Assessment and Market Analysis*

Technical Update, February 2016

EPRI Project Manager

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# ABSTRACT

This report is the second of a set of three reports on the application of an inherently fault current limiting (IFCL) high-temperature superconducting (HTS) cable technology to enhance the reliability and resiliency of the nation's electric grid. The three reports constitute the results of an independent, third-party assessment undertaken by the Electric Power Research Institute (EPRI) under contract to the U.S. Department of Homeland Security. The assessment will be carried out in three tasks, which address the underlying technology and its state of maturity (Task 1), the costs and commercialization potential of the technology (Task 2), and a comparison of the HTS technology with other technologies having potentially similar application (Task 3). This report documents the results of Task 2 and focuses on assessing the potential costs, commercialization strategies, and marketing prospects of this technology to meet specific utility needs.

This task assessed the various factors that impact the successful commercialization of the IFCL HTS cable. Subtasks in this effort include identification of base cases for the IFCL HTS cable, cost assessment, market analysis, and assessment of factors affecting commercialization.

Until now, costs have been a major unknown and have not been subjected to a rigorous, independent, and technology-based analysis. Utility acceptance of this new technology will be driven not only by cost but also by other factors such as the availability of alternative solutions; the demonstrated performance and reliability of HTS power technologies in utility systems; the ability of utilities to successfully operate, maintain, and repair HTS equipment; public policies that impact electric utility planning and operations; and actual and perceived institutional barriers or incentives. The success and proliferation of other products using the same or similar components as the IFCL cable will have a strong impact on both cost and acceptance. Market success will be highly sensitive to individual and site-specific factors, as well as to competition from alternatives. Particular markets may prove more accessible than others.

## Keywords

Applications for high-temperature superconducting (HTS) cable systems
Commercialization of high-temperature superconductor (HTS) technology
High-temperature superconducting (HTS) cables
High-temperature superconducting (HTS) cable system costs and value proposition
Resilient electric grid
Superconductivity

# EXECUTIVE SUMMARY

This report is the second of a set of three reports on the application of an inherently fault current limiting (IFCL) high-temperature superconducting (HTS) cable technology to enhance the reliability and resiliency of the nation's electric grid.[1] Details of the three-phase, triaxial power cable technology are discussed in the first of three reports. When completed, the three reports will constitute the results of an independent, third-party assessment undertaken by the Electric Power Research Institute (EPRI) under contract to the U.S. Department of Homeland Security. The three tasks to be accomplished in this assessment address the underlying technology and its state of maturity (Task 1), the costs and commercialization potential of the technology (Task 2), and a comparison of the HTS technology with other technologies having potentially similar application (Task 3). The first report (on Task 1) focused on the technology itself and provided a detailed assessment of it capabilities, developed a manufacturing and scalability baseline, and included an assessment of the risks associated with achieving its full potential as a viable and successful commercial product. This Task 2 report focuses on assessing the potential costs, commercialization strategies, and marketing prospects of this technology to meet specific utility needs. The third report (on Task 3) will compare this technology with alternative technologies in its ability to meet the needs of urban utilities and their customers, with a particular emphasis on the achievement of grid resiliency to allow power systems to maintain the availability demanded by their increasing importance to daily urban life.

Task 2, the present work, assesses the potential costs, commercialization strategies, and marketing prospects for IFCL HTS cable. Until now, costs have been a major unknown and have not been subjected to a rigorous, independent, and technology-based analysis. Utility acceptance of this new technology will be driven not only by cost but also by other factors such as the availability of alternative solutions; the demonstrated performance and reliability of HTS power technologies in utility systems; the ability of utilities to successfully operate, maintain, and repair HTS equipment; public policies that impact electric utility planning and operations; and actual and perceived institutional barriers or incentives. The success and proliferation of other products using the same or similar components as the IFCL cable will have a strong impact on both cost and acceptance. Market success will be highly sensitive to individual and site-specific factors, as well as to competition from alternatives. Particular markets may prove more accessible than others. This task assesses the various factors that impact the successful commercialization of the IFCL HTS cable. Subtasks in this effort include identification of base cases for the IFCL HTS cable, cost assessment, market analysis, and assessment of factors affecting commercialization.

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[1] The majority of the analysis in this report is not dependent on the IFCL capabilities of an HTS cable. Thus, the IFCL HTS cable is considered a subclass of the larger class of all HTS cables that are in view in the cost and commercialization aspects of this report.

## Assessment Methodology

To better understand site impacts, this study selects and defines three common urban network designs to serve as generic base cases for subsequent efforts in developing costs for the IFCL HTS cable and in understanding the prospects for marketing and commercializing the new technology. Although the details of these base cases draw on input that the team received from meetings, responses to questions, and information obtained with regard to five separate utilities, these base cases are reasonably generic. They do not reflect a specific application or the situation at any one of these utilities.

The three generic base cases, with some details, are listed below. Additional information is provided in the main report.

### *Base Case 1—Critical Infrastructure Support*

Base case 1 has the following attributes:

- *Critical infrastructure* is defined as an airport, hospital, stock exchange, or national or regional communication facility, the loss of which has major economic, life and safety, and national security implications.
- Support is assumed to improve both the *reliability* and the *resiliency* of the critical infrastructure (see definitions of reliability and resiliency in Section 3.2).
- It was assumed that conventional solutions have insufficient necessary space (for example, physical congestion above or below ground), unacceptable costs, unacceptable outage times, or other characteristics that make them undesirable or infeasible.
- The HTS solution is a fault current tolerant (as compared to an inherently fault current limiting) HTS cable system supplying at distribution voltage the critical infrastructure load from one or more existing substations that are not currently used to supply the critical load. The critical infrastructure may be 1 to 2 miles (1.6 to 3.2 km) from the substation.

### *Base Case 2—Urban Utility Asset Utilization Improvement*

Base case 2 has the following attributes:

- *Urban assets* for this case are defined as existing substations in nearby physical or electrical proximity that have varying degrees of age and utilization (for example, one substation may have a transformer at virtual end of life or a high-maintenance transformer that should be replaced, whereas another nearby substation may have excess capacity and newer or higher reliability equipment).
- Asset utilization improvement is assumed to be achieved through the sharing of assets across multiple substations, leading to improved *reliability* and *resiliency* (see definitions of reliability and resiliency in Section 3.2).
- This case may involve improving the reliability of a given substation from N-$x$ to N-($x$+1), where $x$ may typically be 1 or 2.
- It was assumed that conventional solutions have insufficient necessary space (for example, physical congestion above or below ground), unacceptable costs, unacceptable outage times, or other characteristics that make them undesirable or infeasible.
- The HTS solution is interconnection of two or more substations at their distribution buses, sharing unused assets across the network.

### *Base Case 3—Load Growth Support*

Base case 3 has the following attributes:

- There is urban or suburban load growth in a new load pocket that is or will be unserved by existing distribution networks or substations.
- The base case includes considerations of planning for the future (that is, plan for growth ahead of time rather than changing infrastructure as load changes).
- The conventional solution would require new transmission feeders and one or more substations with costs that may increase as a result of delaying implementation (due to continued load growth).
- The HTS solution is to extend the distribution feeder from one or more existing substations with an HTS cable system together with minimal switchgear at a *virtual* (no transformer) substation.

## High-Temperature Superconducting System Costs

A cost model was developed to support the determination of costs of HTS cable systems for use in quantifying commercial value propositions. Costs for complete HTS cable systems were developed for a range of project sizes, using a range of likely HTS wire price scenarios. Costs for cable and refrigeration components were based on interaction with current vendors of this equipment as well as EPRI-developed projections regarding future costs in a mature market. Construction costs were estimated using established underground transmission cable industry methods and practices, adapted for unique aspects associated with HTS cables. Cost estimation took into account regional variations in material and labor costs, as well. A typical output of the cost model for a one-mile, 13-kV, 3-kA HTS cable installation, with wire cost at US$50/kA-m, is shown in Table ES-1. Figure ES-1 presents the cost information in a pie chart to better illustrate the percentage contribution for each major component.

**Table ES-1**
**Typical high-temperature superconducting system cost model output**

| **Category*** | **Cost (US$)** |
|---|---:|
| Wire | 2,098,000 |
| Cable and cryostat material | 4,481,000 |
| Cable and cryostat installation | 1,755,000 |
| Civil works (except refrigeration) | 3,714,000 |
| Refrigeration (installed) | 3,753,000 |
| Engineering and management | 1,422,000 |
| Total (average U.S.) | 17,222,000 |
| Total (low region multiplier) | 16,332,000 |
| Total (high region multiplier) | 24,497,000 |

*Cable length, 1610 m; wire cost US$50/k A-m (DC); cable shipped separately

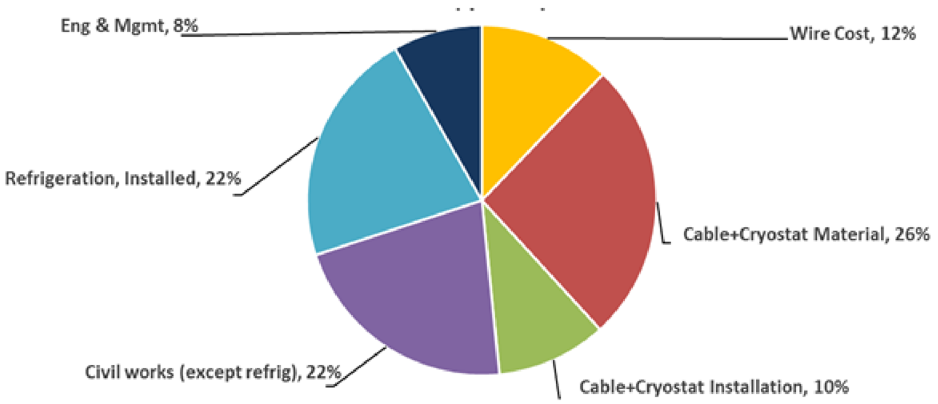

**Figure ES-1**
**Cost model output: one-mile, 13-kV, 3-kA high-temperature superconducting cable project, US$50/kA-m wire cost**

Using the EPRI cost model, various parametric cost studies were performed to show, for example, the impact of wire cost and project size. Figure ES-2 shows one of the results obtained.

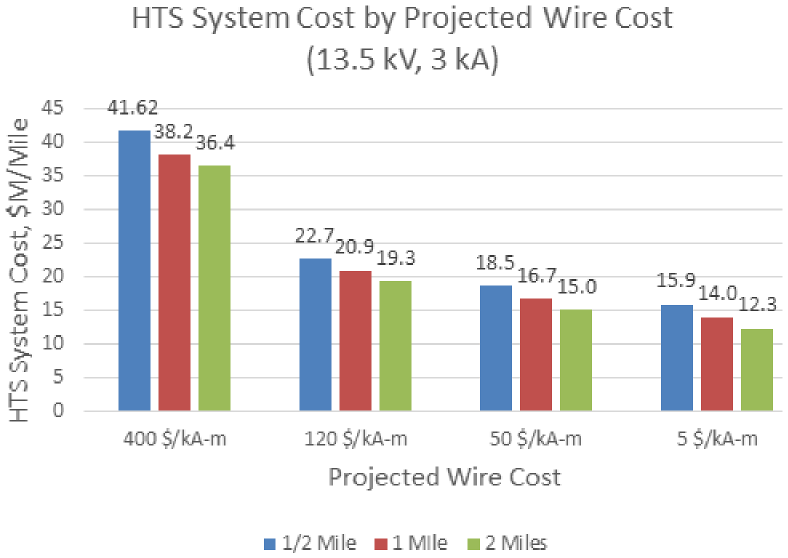

**Figure ES-2**
**High-temperature superconducting system cost per mile by projected wire cost for different project lengths**

## High-Temperature Superconducting System Value Propositions

The term *value proposition* means the sum of market and technical factors (including cost) in the mind of the customer that would add up to making the HTS cable system competitive with conventional technology. The establishment of a long-term, viable market for HTS cable systems would require the following:

- An HTS cable system that is price competitive with conventional system solutions
- Sufficient market demand for HTS power technologies to support product development
- Demonstrated reliability in utility systems sufficient to obtain widespread utility acceptance

HTS cable systems, like any technology for use in an electric utility network, must meet a stringent set of requirements that enable utilities to meet reliability standards required by regulatory agencies and their customers. Accordingly, the equipment that utilities use is subjected to extensive tests and trials before it is accepted for use on their systems.

Although several HTS power technologies have been installed and operated in electricity grids, they are currently still at the demonstration stage. For example, the total length of HTS cable systems that have been installed worldwide is several kilometers, using only a small fraction of the 30,000 km of wire per year that was estimated in Task 1 to be necessary to sustain a commercial business. Each of the generic base cases defined for this study might require hundreds of kilometers of wire. Thus, in evaluating the value proposition, one must also keep the following in mind: 1) more wire and cable will need to be produced on a more rapid schedule than for past demonstration projects, and 2) the HTS cable installations will have to be demonstrated to meet the same reliability requirements as the tried and tested conventional alternatives. Both of these factors will add time requirements and costs to those firms interested in developing and marketing HTS systems.

In light of these facts, this assessment adopted the following three-step method for determining the value proposition for HTS cable systems:

1. **Quantitative cost-benefit determination.** Establish a price point for a mature HTS cable system to be cost competitive with conventional solutions for each base case. (*Mature* means that a number of installations have previously occurred and that the revenues from these previous installations have been sufficient to allow the system vendors to recover the engineering costs that are typically associated with developing and bring to market a new technology. This would correspond to the technology at technology readiness level 9 and manufacturing readiness level 10; the presence of multiple vendors competing in the marketplace; and a sustainable demand, which was estimated in Task 1 to require sales of 30,000 km/year of HTS wire.)
2. **Potential markets analysis.** Analyze the existing and potential future markets for HTS power technologies to determine what would be required to generate enough demand for HTS wire to drive the development to maturity of HTS cable systems. (The cost of the wire is currently a substantial fraction of the cost of the HTS cable system and, thus, can drive decisions concerning investment in technology development and maturity.)
3. **Barriers identification.** Describe the barriers that are likely to affect the decision of utility companies to install HTS cable systems in their networks and, thereby, the decision of manufacturers to develop and to offer commercially such systems. Describe potential actions to reduce those barriers.

Direct cost comparison (Step 1, quantitative cost-benefit determination) may not be the deciding factor in the decision for which solution to use. The conventional solution might involve difficult siting issues associated with underground transmission lines and the amount of land and construction involved, and obstructions or underground congestion may preclude some conventional solutions because of their much larger cross-sectional space needs. The HTS solution would involve the same issues, but these may be easier to resolve because of the lower voltage and the smaller size of the required corridor. Most importantly in the current market, however, the HTS solution would involve installing in a utility system a new technology that would be required to have demonstrated reliability and capability for operation and maintenance over its lifetime. For a utility to decide to implement this solution, it would either have to represent a large cost advantage or enable something that cannot be done with the conventional solution.

Thus, the results from this aspect of the work may be viewed in two lights. In an undeveloped market, as today, the lessons obtained from all three of the above steps for value proposition determination should be applied. On the other hand, in a fully developed marketplace for HTS technology, HTS will be viewed by utilities equally alongside all other candidates. Cost will be primary. Nevertheless, even for mature and accepted technologies, other factors such as reliability, performance, and operability always come into play.

### *Quantitative Value Proposition Determination*

Three value proposition case studies were performed, using system configurations derived from the three generic utility base case applications. The price point at which a mature HTS cable system would be cost competitive with conventional solutions was determined by estimating the cost today of the conventional solution. In determining conventional solution costs, EPRI relied on input from utility company advisors as to costs they face today in similar situations. It is understood that these costs may change by the time that an HTS solution is fully commercial. Because those variations are indeterminate at this time, they were not accounted for in the present assessment. The cost of the HTS solution was, as described earlier, determined by exercising the EPRI cost model for the specific configuration of each base case. Those costs assumed a mature market, and thus used projected costs for HTS wire (a range of US$50/kA-m to US$5/kA-m) rather than current costs (a range of US$400/kA-m to US$120/kA-m). Hence, the cost-benefit determination must be viewed from the perspective that costs for the conventional solution will remain relatively unchanged. The quantitative cost-benefit aspect for the three base case value propositions is shown in Tables ES-2 through ES-4.

**Table ES-2**
**Base case 1: supplemental power for critical infrastructure**

| | **Conventional Solution** | **High-Temperature Superconducting Solution** |
|---|---|---|
| Power requirement | 120 MVA | 120 MVA |
| Distance | 2 km | 2 km |
| Voltage | 35 kV | 35 kV |
| Number of feeders | 7 | 1 |
| Cost | US$22 million | US$17 million to US$27 million (1)<br>US$15 million to US$24 million (2) |

**Notes:**

1. HTS wire cost, US$50/kA-m
2. HTS wire cost, US$5/kA-m

### Table ES-3
### Base case 2: utility asset load management

| | **Conventional Solution** | **High-Temperature Superconducting Solution, Both Options** |
|---|---|---|
| Number of transformers | 2 | N/A |
| Power requirement | 60 MVA | 60 MVA |
| Distance between substations | 1 km | 1 km |
| Voltage | 13.5 kV | 13.5 kV |
| Number of cables | 0 | 1 |
| Cost | Option A: US$2 million<br>Option B: US$42 million | US$9 million to US$14.3 million (1)<br>US$7.7 million to US$11 million (2)<br>(HTS solution costs apply for both conventional solution options shown.) |

**Notes:**

1. HTS wire cost, US$50/kA-m
2. HTS wire cost, US$5/kA-m

### Table ES-4
### Base case 3: planning for new load

| | **Scenario 1** | | **Scenario 2** | |
|---|---|---|---|---|
| | **Conventional Solution** | **High-Temperature Superconducting Solution** | **Conventional Solution** | **High-Temperature Superconducting Solution** |
| Power requirement | 60 MVA | 40 MVA | 240 MVA | 240 MVA |
| Distance | 8 km | 6 km | 0.5 km | 0.5 km |
| Voltage | 35 kV | 5 kV | 35 kV | 35 kV |
| Number of feeders/cables | 6 | 2 | 13 | 2 |
| Additional requirement | New substation | Compact substation | New substation (not included in cost) | New substation (not included in cost) |
| Cost | US$93 million | US$109 million to US$158 million (1)<br>US$80 million to US$124 million (2) | US$12 million | US$14 million to US$22 million (1)<br>US$12 million to US$19 million (2) |

**Notes:**

1. HTS wire cost, US$50/kA-m
2. HTS wire cost, US$5/kA-m

In base case 2, the two conventional solution options were to install a new transformer in one of the two interconnected substations (option A) and to construct a new substation in the city center area (option B). This accounts for the large differential in conventional solution cost. The HTS solution costs apply for either option because the HTS solution needs neither a new transformer nor a substation.

In base case 3, two scenarios were envisioned, reflecting suburban (scenario 1) and urban (scenario 2) load growth. In scenario 2, both the conventional solution and the HTS solution require a new substation, the costs for which were assumed to be the same and were therefore not included in the analysis.

The cost ranges shown in these tables represent the low and high regional cost estimates. The average U.S. cost will be found near the low end of these ranges in all cases, because the high region multiplier introduced a much greater percentage change in cost than did the low region multiplier.

From the foregoing analysis, it is clear that, on the assumption that wire cost will decrease (that is, from current costs to a range of US$50/kA-m to US$5/KA-m), HTS cable systems are economically viable against conventional solutions for each of the base cases. Both of the assumptions of this study regarding future wire cost (the more extreme US$5/kA-m and the moderate US$50/kA-m) produce costs lower than value in at least some situations for base cases 1 and 2. In base case 3, however, only the US$5/kA-m wire cost produces a viable result, and even then, the results are positive only for lower-cost regions. Moreover, the results for base case 1 show that the HTS value may be marginal in the highest-cost urban areas.

As a general statement, these results would seem to indicate that the shorter-length systems that are providing critical infrastructure or increased asset utilization in constrained urban settings (or both) are likely to be more economical (that is, base cases 1 and 2 are possibly more economical that base case 3). That said, a shorter project length for base case 3 would possibly be economical. As with all the base cases, the assumptions for this base case could significantly affect the outcome.

### Market Assessment

A market assessment was carried out, and was principally an analysis and update of two detailed HTS power technology market assessments: one performed in 2000 by Oak Ridge National Laboratory (ORNL)[2] and one performed in 2006 by Navigant Consulting, Inc. (NCI).[3] The EPRI team also used reviews of literature and specifications for HTS and conventional power equipment, and discussions with government, utility, and manufacturing industry representatives.

The ORNL and NCI market assessments clearly state the uncertainties associated with a market projection for new technology. Both use S-curve models of HTS power technology adoption (market penetration) that assume that the initial exponential growth of the S-curve is driven by a combination of reduction in HTS wire cost and utility acceptance of the technology, with the size

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[2] Joseph Mulholland, Thomas P. Sheahen, and Ben McConnell, “Analysis of Future Prices and Markets for High Temperature Superconductors,” U.S. Department of Energy, 2001.

[3] Navigant Consulting, Inc., “High Temperature Superconductivity Market Readiness Review,” Office of Electricity Delivery and Reliability Briefing, August 2006.

of the market determined by scaling new and replacement equipment needs according to electricity growth estimates in the Energy Information Administration (EIA) *Annual Energy Outlook*.[4] Both assessments projected market penetration that has not happened. Moreover, in many respects, the current situation with respect to the two key uncertainties (wire cost and utility acceptance) is similar to that which existed when the 2006 NCI assessment was performed. That assessment projected that "HTS cables are likely to enter the market on a commercial basis around 2014, after additional demonstration stages."

However, it is vital to note that the "additional demonstration stages" that were in the planning stages in 2006 did not occur, and existing demonstrations were, in fact, terminated prematurely from a utility acceptance perspective. Coincident with the cessation of HTS cable demonstrations in the United States were two events: the 2008 recession that resulted in the interruption of expected urban load growth in some areas, and the termination in 2010 of the U.S. Department of Energy (DOE) funding for HTS technology research, development, and demonstration, including cancellation of the Superconducting Partnership Initiative (SPI). The SPI provided a 50% government cost share for utility-hosted demonstrations of HTS technology. That event is deemed significant in light of a joint DOE/EPRI-sponsored survey of utility underground transmission engineers in the mid-1990s. The unpublished report on this survey showed that, for utility planners to consider acceptance of HTS cable technology, multiple in-grid demonstration projects having an average duration of 10 years each would have to occur. While illustrating the conservatism of the industry, this survey also underlines the importance of government-supported demonstration projects, lasting many years.

In this regard, it is noteworthy that in the same 10-year period after the NCI assessment, several other nations (Japan, Korea, China, Germany, and Russia) have stepped up the planning for and installation of in-grid HTS cable and fault current limiting projects. Most or all of these projects have significant levels of either state or national government funding support. For more information, refer to the EPRI report *Strategic Intelligence Update: Superconductivity for Power Delivery Applications, December 2015* (3002007192).[5]

Although there have been a series of demonstrations in power grids worldwide, no HTS cable project without government support has yet happened. Where and when can the demand for HTS power equipment begin and grow? Absent a groundswell among grid operators and utility companies, which both market assessment reports[1,2] argue will not come without resolution of the uncertainties in wire cost and system reliability, the major manufacturers who provide grid equipment to utilities seem to be the firms that are best able to nurture such a demand. They know how to demonstrate reliability in a way that the utilities will understand and accept, and they have the financial wherewithal to underwrite the development of such a first-of-a-kind technology, which one manufacturer estimated at US$100 million.

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[4] Energy Information Administration, *Annual Energy Outlook 2015 with Projections to 2040,* U. S. Government Printing Office, 2015.

[5] *Strategic Intelligence Update: Superconductivity for Power Delivery Applications, December 2015*. EPRI, Palo Alto, CA: 2015. 3002007192.

The development and demonstration of an HTS fault current limiter in the power grid in Augsburg, Germany, by the end of 2015 by Siemens[6] and the presence of other large utility vendors in demonstration products worldwide—ABB in a superconducting magnetic energy storage (SMES) project at Brookhaven National Laboratory,[7] Nexans in the AmpaCity project in Essen, Germany[8] (an example of base case 2), LS Cable in projects in Korea,[9] and Sumitomo[10] and Furukawa[11] in projects in Japan and the U.S.—provide encouraging signs of the interest of companies who could lead the market entry of HTS power technologies. So far, however, none has stepped up to make the necessary investment. (A commercial investment of about US$100 million in nonrecoverable engineering costs may be necessary for development and commercialization of a first-of-a-kind system. Beyond demonstration projects, what is needed is a corporate decision to build its own infrastructure for product development.)

Although the projected S-curve of market penetration of HTS power technologies has not yet occurred, there have been S-curve emergences in patent application filings in the United States Patent and Trademark Office in Classification 505 (Superconductor Technology: Apparatus, Material, Process) in the subclassifications for HTS wire, tape, cable, or fiber (230) and process of making HTS wire, tape, cable, coil, or fiber with coating (434), as well as process for producing HTS material (300). *S-curve emergence* means exponential growth in the cumulative sum of patent filings as a function of time.

The initial rise of these S-curves in patent application filings occurred between 2005 and 2010. The assignees include ABB, GE, Siemens, and Sumitomo, as well as major cable manufacturers, which is an indication that large utility vendors have invested in research and development and have made the decision to expend the financial resources necessary to pursue patents to protect their intellectual property. Patent applications can be thought of as "bets" that the technology will eventually have market value, so the fact that the large utility vendors are filing patent applications in HTS wire and related areas suggests that they believe HTS power technologies may have market potential.

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[6] Siemens and Stadtwerke Augsurg joint press release, "Siemens to use superconductors in building the power grid of the future in Augsburg," December 18, 2014, available online as of November 23, 2015 http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2014/corporate/pr2014120086coen.htm&content[]=Corp.

[7] Brookhaven National Laboratory, "Grant Funds Superconducting Magnet Energy Storage Research at Brookhaven Lab," August 31, 2010, available online as of November 23, 2015, https://www.bnl.gov/newsroom/news.php?a=11174.

[8] "Advanced Superconducting 10 kV System in the City Center of Essen, Germany," *IEEE/CSC & ESAS Superconductivity News Forum (SNF)*, Global Edition, October 2015. http://snf.ieeecsc.org/file/6006/download?token=milHtnQz

[9] LS Cable & Systems, "LS Cable & Systems to start demonstration of superconducting power transmission DC cable 10X Capacity," November 19, 2014, available online as of November 23, 2015, http://www.lscns.com/pr/news_read.asp?idx=2953&pageno=1&kType=&kWord.

[10] Sumitomo Electric, "High Tc Superconducting Cable Project," available online as of November 23, 2015, http://global-sei.com/super/cable_e/ingridj.html.

[11] Furukawa Electric, "Demonstration of 500m HTS Power Cable," available online as of November 23, 2015, http://www.furukawa.co.jp/kenkai/eng/superconduct/demonst.htm.

### Barriers

Power outages are costly. In 2012, the Congressional Research Service estimated the cost of weather-related outages at US$25 billion to US$35 billion annually.[12] A 2013 White House report[13] provides estimates of yearly costs of weather-related outages from 2003 to 2012 that range from a low of US$5 billion to US$10 billion in 2007 to a high of US$40 billion to US$75 billion in 2008. Although these estimates of costs related to outage impacts may be legitimate, they do not in any way create a retrievable cash flow benefit that could be used by utilities to fund reliability or resiliency improvements. In addition, utilities face many other cash flow and cost recovery challenges that limit their ability to proactively and aggressively fund new technologies, including the following:

- Utilities have the “obligation to serve,” which means that they must accept responsibility to provide capacity to meet any new load growth arising from any source.
- Utility funding is typically provided on a multi-year basis by rate case approval processes that in some cases can be adversarial.
- Failure to meet increasing reliability requirements can result in sometimes severe cost penalties for conditions that may be in some cases beyond the direct control of the utility.
- New issues (such as cybersecurity) or unpredicted major events (such as major storms or catastrophes such as 9/11) may occur following rate case approvals that make further diversion of funds needed for operation and maintenance necessary.

Faced with combinations of challenges that can include aging infrastructure, an increase in severe weather events, growth of distributed generation, load growth in urban areas, and the greater usage of electronic devices that are sensitive to power surges, utility regulatory agencies are placing increasing emphasis on improving the resilience of the power grid. The low impedance, high current-carrying capability, and fault current limiting properties of some HTS cables could be desirable to utilities as they address the resiliency challenge. However, the utility’s incentive is for reliability and resiliency, not specifically for HTS systems, and they must compete with conventional technologies and, even more importantly, the temptation to address emerging trends only incrementally to minimize near-term annual capital costs.

There are several important barriers to HTS cable system adoption by utilities. Other than cost, the most important is the need for demonstration of feasible and reliable operation in a utility system over an extended period. Conventional power cables have decades of operating experience and are tested extensively before being put into service. Although there have been several demonstration projects, including the AmpaCity substation interconnect in Essen, Germany, that has been live for more than year, utilities will be hesitant to connect a new technology into their system until that specific technology (the HTS cable system) has been tested and has demonstrated its reliability under the exact conditions under which it will be used.

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[12] Richard J. Campbell, *Weather-Related Power Outages and Electric System Resiliency*, Congressional Research Service: 2012. 7-5700, E42696. available online as of October 30, 2015, https://www.fas.org/sgp/crs/misc/R42696.pdf.

[13] *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages*, Executive Office of the President, August 2013. http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf.

Continued field demonstrations of both HTS and cryogenic systems are deemed essential to validate long-term reliability.

A second barrier is the question of maintenance of HTS cable systems after they are installed in a utility grid. Will the utility need to hire new staff—that is, develop an HTS team—to maintain the system and make repairs if and when problems arise? Will the HTS cable system vendor provide 24/7 maintenance and repair service in the event of a power outage that affects the HTS cable? Who will certify the HTS cable system and/or provide warranty? An EPRI-sponsored workshop and subsequent tutorial on cryogenics for utility personnel addressed some of these questions.[14,15] Continued educational approaches such as this may help to overcome this barrier.

A third barrier is related to the manner in which utilities make improvements to their transmission and distribution systems. Utility staff in transmission and distribution typically design and provide the specifications for such improvements, review competing bids, select vendors, and manage the projects. To date, only a handful of utilities that have been involved in HTS cable demonstrations have any experience with HTS cable systems, and all of these have been government-funded projects with much support from outside technical experts. For example, the Essen project was supported by a consortium of academic technologists. Dissemination of lessons learned from these projects to a larger utility audience would help to overcome this barrier.

Finally, there is the problem of inertia that accompanies any effort to bring a new technology or technical approach to a long-standing problem or institution. Utilities are extremely conservative organizations, because of both the well-established nature of the technologies that they use and their mission to provide continuous electric power to their customers despite variations in demand, performance of equipment, weather, and other contingencies. They will adopt a new technology only after its benefits have been demonstrated and its reliable operation and maintainability on their system has been proven.

It remains to be seen whether these still-significant barriers will be offset or revised in whole, or at least in part, by new potentially emerging utility drivers, including the following:

- Continuing load growth, particularly within urban centers
- Additional transmission, energy storage, and renewable capacity needs to offset renewable intermittency
- New demands for resiliency to cope with weather-related events, targeted attacks, and/or fuel disruptions, still meeting increasingly stringent reliability requirements
- The possibility that, if the reliability of cryogenic cooling can be fully achieved and demonstrated, superconducting cables may be significantly more reliable and exhibit less aging than conventional cables due to their inherent immunity to temperature changes stemming from daily and seasonal load cycling
- The continuing and accelerating issue of both above- and below-ground congestion due to vertical growth within urban centers

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[14] *EPRI Cryogenic O&M Workshop: Proceedings*. EPRI, Palo Alto, CA: 2004. 1008699.

[15] *Cryogenics*. EPRI, Palo Alto, CA: 2006. 1010897.

## Conclusions

Three major cost drivers for HTS cable systems were identified in the cost analysis—HTS wire, cryostats, and refrigerators. Of these, the cost of HTS wire is currently the largest significant fraction of the cost of the HTS cable system and thus is the principal driver for cost reduction. It is also the driver that is, conceptually, the easiest to project into the future due to its almost sole dependence on volume sales (discounting the possible emergence of a breakthrough technology development that could also lower costs). Reduction in cryostat costs, on the other hand, would likely require the introduction of additional competitors in the marketplace to eliminate the present sole-source situation. This is difficult to predict. Reduction of refrigerator costs will likely require significant research and development. However, for all three of these developments to occur, there would need to be a substantial increase in deployed HTS equipment.

In some cases, however, the analysis has shown that, even with HTS wire cost at its lowest projected value (US$5/kA-m), commercial viability is not achieved. In some of those cases, refrigeration and cryostat costs now represent significant cost drivers. Reduction of those costs could make those cases economically viable.

Analysis of the base cases provides estimates of how much cost reduction in HTS wire will be required for a mature HTS cable system to be cost competitive with conventional solutions. Considering that these base cases were chosen specifically because they involve conventional solutions that are both difficult to implement and expensive, broader use of HTS cable systems is likely to require further cost reduction.

Another important factor in the lack of growth of market demand in accordance with past projections is the difficulty of demonstrating the reliability of HTS power technologies in utility systems.

Demonstrating reliability at a level that could obtain widespread utility acceptance will require commercial products from a major vendor of utility equipment that can provide product warranties and support for operations and maintenance over the lifetime of the products in a utility system. A limited number of such vendors exist, and none has yet made the business decision that HTS power technologies are worth the major investment in a first-of-a-kind product. These companies are active in research, development, and government-supported demonstrations, and they have pursued related intellectual property, thus establishing a position for investment should a business case evolve. The barriers to the establishment of such a business case—including wire cost and availability in “practical length for large-scale applications” and number and quality of joints—were spelled out in a recent briefing.[16]

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[16] “Applied Superconductivity at General Atomics Company,” presented at the Advanced Superconductor Manufacturing Institute (ASMI) Workshop on Overcoming Manufacturing Challenges for Advanced Superconductors, November 11–12, 2015, Houston, TX.

Thus, cost reduction and proven performance in the field represent two major challenges for commercialization of HTS cable system technology. Costs of superconducting wire have shown a steady decline over past years and are projected to continue at a substantially similar rate over the foreseeable future through production improvements and volume benefits. New production techniques are currently in development by other entrants to this technology that could further ensure or exceed projected cost reductions. In-grid demonstrations of HTS technologies require a significant financial outlay, which will not be entirely borne by the utility industry. Solution of this problem will, therefore, require major investments, from either a large vendor of utility systems or government agencies, or both. However, in the absence of some level of private or public investment to achieve the projected cost and performance needed to demonstrate full commercial viability and long-term reliability, one cannot predict the success path of this technology with full confidence in the near term.

Nevertheless, a variety of situations exist today in which an IFCL HTS solution may provide substantial advantages over other solutions in desired performance, particularly with regard to achieving increased resiliency. In some current situations, other conventional solutions cannot be deployed due to underground obstructions or underground space constraints, and in others, even at current superconducting wire costs, the IFCL HTS solution may provide an additional cost advantage.

One of the advantages of superconducting designs is that they can be customized to meet specific needs related to resiliency, reconfigurability, and the ability to transfer large blocks of power at lower voltages and small underground cross-sectional footprints. These advantageous characteristics can be applied as follows:

- Continuously in service with limited fault current transfers
- Fault tolerant ride-through, remaining available quickly after a nearby fault
- Not normally connected, but immediately available after protection clears a nearby fault

Superconducting designs also offer the following potential long-term, unquantifiable benefits:

- Manage fault currents to enable increased access for distributed resources
- Potential for improved life and reduced failure rates of downstream distribution system components that would alternatively see higher fault currents
- After any infant mortality issues (installation problems) are avoided or corrected, and if an equally reliable design configuration is chosen for the cryogenic cooling and/or replenishment system, potentially quite high superconductor reliability due to inherent immunity to normal seasonal and daily load cycles because of near-constant cryogenic temperatures and inherent protection for some external events due to pipe-type construction of a cryostat

In addition, they offer future potential for even longer-term operational benefits, as follows:

- Ongoing migration of superconducting technology to even higher voltages can provide small-footprint, underground access to city centers with increasing load demands, through dense suburban areas (bridge between rural overhead transmission city centers that could also include inherent fault current mitigation)
- Coping with potential for major unplanned load increases (for example, due to climate change impacts on air conditioning loads, substitution of electricity as fuel for furnaces and water heating in city centers, or other unforeseen impacts)

Higher-voltage superconductors could also mitigate the rapidly increasing fuel-based regionalization of the U.S. grid in the event of fuel contingencies and also enable region-to-region transfers of electrical capacity to offset longer-term interruptions of intermittent renewable assets (such as six-day heat storms or polar vortexes).

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# 1

# INTRODUCTION

This report is the second of a set of three reports on inherently fault current limiting (IFCL) high-temperature superconducting (HTS) cable. It focuses on assessing the potential costs, commercialization strategies, and marketing prospects of this technology to meet specific utility needs. The first report focused on this technology itself and provided a detailed assessment of its capabilities, manufacturing and scalability baseline, and an assessment of the risks associated with achieving its full potential as a viable and successful commercial product. The third report will compare this technology with other alternative technologies in its ability to meet the needs of urban utilities and their customers, with a particular emphasis on the achievement of grid resiliency to allow power systems to maintain the availability demanded by their increasing importance to daily urban life.

Market success will be highly sensitive to individual and site-specific factors, competition from alternatives, and other factors that impact successful commercialization. This report uses three common urban network base cases to develop costs for the IFCL HTS cable to aid in understanding its prospects. The challenges faced by urban utilities as they grow vertically are also described. The cities on which the review was based either are, or are evolving into, dense urban locations. They already have mature design standards and a high degree of urban constraints against future design alternatives. Smaller cities that anticipate developing into urban centers will offer somewhat more freedom of design (less existing infrastructure, power density, and congestion restrictions) and, therefore, will be able to more easily make effective, unrestrained use of the IFCL HTS cable, as well as the available alternative technologies.

This report also points out the types of constraints created by existing design topographies and infrastructures of already dense urban centers and potential concerns that can be faced by urban networks as they grow. This will allow consideration of ways to anticipate and mitigate these concerns and limit at least some of the resulting constraints in advance of their appearance as the city increases in power density and congestion over time. For this reason, the Electric Power Research Institute (EPRI) team believes that this report will also provide valuable insights to smaller cities that anticipate population increases, increases in business development, and vertical growth in their future. Our goal is that the results of this report could also be used as a template and model for dialog and collaboration among utilities, regulators, and municipal city planners as major towns urbanize further and migrate toward becoming dense urban load centers. Because of the funding limitations that utilities typically face, the analysis also tried to focus these base cases on composite examples of typical, real-world needs faced by utilities over extended periods as their power systems evolve.

The report is organized as follows:

- Section 1, this section, provides the objective and overview of the study and the organization of the rest of the report.
- Section 2 describes the methodology used including the rationale for the study's base cases.
- Section 3 defines the three base cases chosen for specific evaluations of costs and benefits achieved.
- Section 4 provides the methodology and results for costs of HTS solutions, with explanations and representations of the costs to facilitate understanding of key drivers.
- Section 5 describes and quantifies the value propositions built around the base cases, followed by a broad discussion of the overall marketing assessment of superconducting power technologies, including the existing barriers and the conditions and strategic incentives that could mitigate them.
- Section 6 presents the conclusions that were reached based on this study.
- Section 7 presents a list of references.
- Four appendices provide additional explanatory information and details.

# 2

# COMMERCIALIZATION OF HIGH-TEMPERATURE SUPERCONDUCTING CABLES

## 2.1 Introduction

Task 2 assesses the potential costs, commercialization strategies, and marketing prospects for IFCL HTS cable. Until now, costs have been a major unknown and have not been subjected to a rigorous, independent, and technology-based analysis. Utility acceptance of this new technology will be driven not only by cost but also by other factors such as the availability of alternative solutions, the demonstrated performance and reliability of HTS power technologies in utility systems, the ability of utilities to successfully operate, maintain and repair HTS equipment, public policies that impact electric utility planning and operations, and actual and perceived institutional barriers or incentives. The success and proliferation of other products using the same or similar components as the IFCL cable will have a strong impact on both cost and acceptance. Market success will be highly sensitive to individual and site-specific factors as well as to the competition from alternatives. Particular markets may prove more accessible than others. This task assesses the various factors that impact the successful commercialization of the IFCL HTS cable. Subtasks in this effort include identification of base cases for the IFCL HTS cable, cost assessment, market analysis, and assessment of factors affecting commercialization.

## 2.2 Methodology

To better understand site impacts, this report selects and defines three common urban network designs to serve as generic base cases for subsequent efforts in developing costs for the IFCL HTS cable and in understanding the prospects for marketing and commercializing the new technology. Although the details of these base cases draw on input received from meetings, responses to questions, and information obtained with regard to five separate utilities, these base cases are reasonably generic. They do not reflect a specific application or the situation at any one of these utilities. These specific base cases and the related information instead attempt to provide the fullest possible picture of the following:

- The challenges faced by urban utilities as they grow vertically, as described in Appendix A. *Vertical growth*, as used in this report, is the increase in the number and proximity of high-rise building structures that geometrically increases the per square mile demand for electrical and other services. A typical value for a dense urban city center is 100 MW per square mile, but much higher power densities can be seen in localized concentrations of skyscrapers.
- How IFCL HTS or alternative technologies (described in Section 3) can potentially help in coping with these challenges.
- The challenges and risks that these technologies face in their deployments.
- The specific benefits that these IFCL HTS cable systems can provide, particularly with regard to improving resiliency.

In the course of developing this report, the EPRI conducted direct meetings and question-and-answer sessions with Southern Company in Atlanta; CenterPoint Energy in Houston; Los Angeles Department of Water and Power; American Electric Power in Columbus, Ohio; and Commonwealth Edison in Chicago. EPRI researchers also reviewed the historical information that was available from the initial Hydra project at Consolidated Edison in New York City and solicited utility participation on an advisory board to provide additional input on our efforts. EPRI also reviewed prior market assessment studies, sponsored by the Department of Energy (DOE) and others, which were based in some cases on input from U.S. utility companies.

The intent of choosing urban centers to develop these base cases is to study specific applications that are already heavily developed with their own, existing standard transmission and distribution interface and network designs, topologies, and practices. The plan is to first broadly identify the strengths, weaknesses, constraints, and challenges to an IFCL HTS cable system in meeting the future needs of an urban center. These include enhancements and additions to resiliency for recovery from power outages caused by severe weather, flooding, fuel disruptions, and other catastrophic events or scenarios. Relevant resiliency scenarios were based on discussions with the U.S. Department of Homeland Security, participants in the Resilient Electric Grid (REG) Program, their host utilities, and utilities that EPRI met with in developing this report. Although the cities reviewed present complex urban network situations, their individual design, topology, and operation are quite different.

These cities either are, or are evolving into, dense urban locations. They already have mature design standards and a high degree of urban constraints against future design alternatives. Urban centers typically have the following characteristics:

- Very high reliability and customer service expectations
- High load densities
- High fault currents
- Potential for future high load growth
- Urban area and community issues, including the following:
  - Traffic restrictions
  - Noise restrictions
  - Sensitivity to environmental impacts
  - Significant impacts of outages
  - Importance of public perceptions
  - High real estate prices and limited space availability
  - High costs of doing business

It is recognized that smaller cities that anticipate developing into urban centers will offer somewhat more freedom of design (less existing infrastructure, power density, and congestion restrictions) and, therefore, will be able to more easily make effective, unrestrained use of the IFCL HTS cable, as well as the available alternative technologies.

The descriptions of constraints created by the existing dense and mature design topographies and infrastructures of already dense urban centers attempt to point out the types of potential constraints and concerns that can be faced by urban networks as they grow. This will allow consideration of ways to anticipate and mitigate these concerns and limit at least some of the resulting constraints in advance of their appearance as the city increases in power density and congestion over time. For this reason, the EPRI team believes that this report will also provide valuable insights to smaller cities that anticipate population increases, increases in business development, and vertical growth in their future (see Appendix A). Our goal is that the results of this report could also be used as a template and model for dialog and collaboration among utilities, regulators, and municipal city planners as major towns urbanize further and migrate toward becoming dense urban load centers.

With respect to defining and describing each of the base cases, EPRI has taken into account other factors that must be considered when planning for deployment of the IFCL HTS cable solution to achieve improved resiliency. These include necessary utility plans for meeting capacity needs, improving asset utilization, increasing or maintaining reliability, as well as other planning and operations considerations.

Specific base cases are needed to enable comparative cost and performance evaluations of IFCL HTS versus alternative technologies. These base cases must meet current, real-world utility distribution operational needs. Examples of these types of needs include the following:

- Providing cost-effective reliability of electrical service
- Minimizing outage frequencies and durations caused by internal, random failures within their own design configuration and equipment population
- Providing sufficient robustness, protective barriers, practices (such as “no dig” contractor restrictions) and monitoring, maintenance and asset management (for non-electric utility assets) to cope with and minimize any added frequency of externally initiated failures from other infrastructures that are in proximity to underground electrical equipment (such as water mains, gas or steam lines, sewer lines, subways, and so on)
- Improving resiliency for the following:
    - More severe weather-related events and their likely geographical and topographical consequences (flooding, storm surges, and so on)
    - Extended-duration outages
    - Targeted attacks

Because of the funding limitations that utilities typically face (periodic regulatory approvals of budget funding and revenue retrieval via specific rate mechanisms), the EPRI team also tried to focus these base cases on composite examples of typical, real-world needs faced by utilities over extended periods as their power systems evolve.

# 3

# BASE CASE DEFINITIONS AND RATIONALE

## 3.1 Introduction and Background

Specific base cases have been chosen for detailed evaluation and comparisons in this report. These base cases were used for defining value proposition cases (described in Section 5) and for determining HTS cable system costs for different scenarios.

## 3.2 Base Case Definitions

There may be some variation of understanding with respect to certain terms used in describing HTS cable systems. For this study, EPRI developed the following definitions to facilitate a common understanding of the specific base cases:

- **Dense urban, urban, and suburban:**
  - Dense urban is downtown such as Chicago or Manhattan
  - Urban is downtown such as Houston or Atlanta
  - Suburban is outside but within a few miles of dense urban or urban
- **Fault current limiting:** A cable or cable system that is able to limit fault current to a nominal fraction of the prospective peak so that fault current duty capabilities of downstream equipment are not exceeded by the contribution of fault current from equipment interconnected by the HTS cable system. The cable or cable system may or may not remain in the circuit after limiting the fault; that is, it may or may not be “fault current tolerant” (defined below).
  - A cable or cable system that is fault current limiting by this definition and also remains in the circuit after the fault is cleared would be both “fault current limiting” and “fault current tolerant.” An example would be an HTS cable system in which a fast circuit breaker was able to switch in a reactor that is electrically in parallel with the fault current limiting portion of the system (that is, the reactor is in parallel with either a stand-alone fault current limiter [FCL] or the fault current limiting cable). In this case, fault current would be carried by the superconducting components only until the fast breaker operates and the limiting function of the system would allow the breaker to open. The system would continue to conduct nominal load current through the reactor until the superconducting component was restored to its superconducting state.
- **Fault current tolerant:** A cable or cable system that is able to carry design fault current from any source for the length of time required by protective devices to clear the fault, while remaining in the superconducting state and able to continually conduct nominal load current (that is, remain electrically connected).
  - A “fault current tolerant HTS cable system” may be implemented by either a fault current tolerant HTS cable alone or an HTS cable in electrical series with an FCL. If an FCL is present, the requirement for fault current tolerance of the cable alone would be either reduced or eliminated altogether. Moreover, the FCL would have to remain in service throughout and after the fault.

  - All HTS cables must be able to carry any anticipated fault current without being damaged until protective devices open (usually 50–150 msec). “Tolerance” in this context is the added capability of “remaining in the superconducting state throughout the fault event and remaining in service when the current has returned to normal values.”

- **HTS cable:** Just the cable (including the cryostat).
- **HTS cable system:** A complete system consisting of the cable together with any ancillary electrical equipment—such as a series FCL, circuit breakers, parallel (shunt connected) reactors, and so on—that may or may not be included for the purpose of accommodating fault currents. (It is assumed that refrigeration is part of any system.)
- **Reliability:** The ability to maintain service to customers in the face of the normal, though infrequent, system equipment failures (or contingencies). Examples include a failed circuit breaker, a transformer failure, or an interrupted transmission feeder due to an external event or equipment failure. This is generally a singular event affecting only a relatively small portion of the system at any one time. However, because these events can occur anywhere in the system, reliability against outages is a system-wide issue.
  - The potential impact is loss of service to a segment of customers. This may be and economic impact.
  - However, when a critical load is being served (such as a hospital, an airport, a manufacturing process, or life support facilities), system failures can have a societal impact in addition to an economic one.
- **Resiliency:** The ability to harden the system against high impact, low frequency events; and the ability to expediently recover from such events. Such events include severe weather, geomagnetic disturbances, and physical attacks. In contrast to outages, disasters cause loss of electric service for large areas and for long periods of time. They also impact the operation of other infrastructure besides power—communications, transportation, medical services, and so on. A *resilient electric grid* is one in which the impact of these events is limited and the restoration of critical services is improved.
  - There may be economic benefits to a more resilient grid.
  - Resiliency can have other, perhaps more societal benefits (such as national security, safety, and so on).

## 3.3 Specific Base Cases Selected for Evaluation and Comparison

The base cases chosen for this study attempt to provide a representative sample over a cross section of the wide and varying spectrum of situations and needs. The situational scenarios (specific, typical utility problems) do not represent any one utility or the specific constraints or challenges it may face; instead, they represent attempts to provide an array of different situations that real-world utilities face. They were developed from a combination of identifiable building-block ratings, distances, and installation cost factors (urban, suburban and rural) that may more easily allow re-combinations to represent other specific needs and service areas.

### 3.3.1 Base Case 1—Critical Infrastructure Support

Base case 1 has the following properties:

- Critical infrastructure is airport, hospital, stock exchange, or national or regional communication facility, the loss of which has major economic, life and safety, and national security implications.
- Support is assumed to improve both the reliability and the resiliency of the critical infrastructure (see definitions of *reliability* and *resiliency* in Section 3.2).
- It was assumed that conventional solutions have insufficient necessary space (for example, physical congestion above or below ground), unacceptable costs, unacceptable outage times, or other characteristics that make them undesirable or infeasible.[17]
- The value proposition is driven by resiliency of critical infrastructure considerations, as well as reliability.
- The HTS solution is a fault current tolerant HTS cable system supplying at distribution voltage the critical infrastructure load from one or more existing substations that are not currently used to supply the critical load. Distances may be 1 to 2 miles (1.6 to 3.2 km) from substation to critical infrastructure grid.
- Conventional solutions would require many new sub-transmission or distribution feeders from one or more substations nearby and/or a new transmission substation.
- It is assumed that the HTS cable is not fault current limiting (because it is fed by transformers that naturally limit fault).
- Installation may be urban or dense urban.
- Service to a hospital and service to an airport are two examples.

### 3.3.2 Base Case 2—Urban Utility Asset Utilization Improvement

Base case 2 has the following properties:

- Urban assets for this case are defined as existing substations in nearby physical or electrical proximity that have varying degrees of age and utilization (for example, one substation may have a transformer at virtual end of life or a high-maintenance transformer that should be replaced, whereas another nearby substation may have excess capacity and newer or higher reliability equipment).
- Asset utilization improvement is assumed to be achieved through the sharing of assets across multiple substations, leading to improved reliability and resiliency (see definitions of *reliability* and *resiliency* in Section 3.2).
- This case may involve improving reliability of a given substation from N-$x$ to N-($x$+1), where $x$ may typically be 1 or 2.

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[17] If conventional solutions were truly infeasible, there would be no easy means for making an economic comparison with the HTS solution. Rather, this assessment took the position that conventional solutions exist but may be too expensive and/or physically constrained, and/or that they require unacceptable extended outages, so that the problem continues to exist and grow in difficulty.

- It was assumed that conventional solutions have insufficient necessary space, unacceptable costs, or unacceptable outage times (for example, physical congestion above or below ground) or other characteristics that make them undesirable or infeasible. See base case 1 for a similar assumption.
- The HTS solution is interconnection of two or more substations at their distribution buses, sharing unused assets across the network.
- There are at least two potential scenarios for this case, as follows:
  - The HTS cable system is fault current tolerant and is ready for service but disconnected electrically until after the first or second contingency; it is not fault current limiting. (This scenario is used in the value proposition effort described in Section 5.)
  - The HTS cable system is fault current tolerant and fault current limiting so that it is always connected and energized between the interconnected substations. Because of the fault current limiting action, the host substation does not have to accommodate additional fault current contribution beyond original design levels.
- Any two interconnected substations are within 0.5 to 1.5 mi (0.8 to 2.4 km) of each other
- Construction may be urban or dense urban
- Proposed interconnection of three substations to solve replacement of aging auto transformer problem in one of them is an example of this base case (proposed by one of our utility advisors)

### *3.3.3 Base Case 3—Load Growth Support*

Base case 3 has the following properties:

- There is urban or suburban load growth in new load pocket that is or will be unserved by existing distribution networks or substations.
- The case includes considerations of planning for the future (that is, plan for growth ahead of time rather than changing infrastructure as load changes).
- The conventional solution would require new transmission feeders and one or more substations, with costs that may increase as a result of delaying implementation (due to continued load growth).
- The HTS solution is to extend the distribution feeder from one (or more) existing substations with an HTS cable system together with minimal switchgear at a *virtual* (no transformer) substation.
- The HTS cable system must carry current due to a fault in the virtual substation until the fault is cleared, but it is not required to remain in the circuit after the fault (that is, it is not fault current tolerant); it may remain out of service for up to one day.
- The HTS cable system is not fault current limiting (because it is fed by transformers that naturally limit faults).
- The HTS cable length is 1 to 3 mi (1.6 to 4.8 km).
- Assume two HTS cables from two independent substations (because many utilities require N-1 reliability).
- Construction is urban or suburban.

# 4

# HIGH-TEMPERATURE SUPERCONDUCTING CABLE SYSTEM COSTS

## 4.1 Methodology

### *4.1.1 Introduction*

To understand the commercialization potential for HTS cable systems, it is necessary to develop a detailed understanding of the costs and cost drivers in a fully mature commercial environment. However, it must be acknowledged at the start that costs of such cable systems are highly site specific. They are also not entirely predictable because, for the most part, there are no commercial components that have been designed and manufactured specifically for application in HTS cable systems. Thus, there is a further requirement to develop and present system and subcomponent costs in such a manner that they can be used as guidelines for application to a wide variety of situations. Finally, it is important not only to understand the installed costs in a given scenario but also to estimate the utility costs in deploying and operating the cable systems.

### *4.1.2 Approach*

EPRI developed a spreadsheet-based model for assessing the costs of advanced technologies in a mature or semi-mature commercial environment. Inputs to the cost model were developed for all the major subcomponents, using a variety of approaches, depending on the particular component. These are described in more detail later in this section. In general, the team used items such as historical data for capital equipment purchases, yield figures, learning curve factors, material costs, labor rates, and profit. The team also used price versus production volume figures, particularly for wire and cable. In addition, cost data for system components that are similar to those used in standard underground transmission cable projects (such as cable installation, operation, and maintenance) were derived from past EPRI research in those areas, as well as from discussions with current EPRI-member utilities. Costs were developed per unit when practical (such as cost per meter of superconducting wire and cable, cost per cold kilowatt for refrigeration, and cost per mile for cable construction and installation).

A building-block approach was used to determine smallest- unit costs. Building-block component costs were incorporated into the spreadsheet model. The model was then exercised to calculate costs at the major component level and rolled up to the installed system level for three different common urban network designs (the value proposition cases described in Section 5). Standard contingency factors were applied to all significant cost components, using accepted industry methods such as those documented in the EPRI report *Technical Assessment Guide (TAG)—Power Generation and Storage Technology Options: 2013 Topics* (3002001434) [1].

### *4.1.3 Discussion*

HTS superconductors that are now under development and in pre-commercial manufacturing status have prospects of being used on a large scale by the electric utility industry for power delivery applications. Transmission cables and FCLs are two of several applications being considered. Although wire (or tape) architecture may differ somewhat, other utility and nonutility applications will also see increased use of HTS superconductors. All of this portends an increasing manufacturing base involving significant scale-up of fabrication capabilities in the case of wire, in particular, and of design, performance, and cost improvements in the case of all major hardware components (wire, cable, cryostats, and refrigeration). However, commercial acceptance of HTS superconducting power delivery technology, such as the IFCL HTS cable proposed by American Superconductor, will depend on a number of factors yet to be validated in actual utility deployments. These include performance improvements for both the wire and the refrigeration systems, proven reliability in the field, and economic viability. Moreover, within the subject of economic viability, the initial capital cost of the fully installed cable system is the most important economic factor.

At present, estimates of the mature market capital costs of superconducting cable systems are based in part on either manufacturing operations on a scale that has not been previously attempted or operations that are essentially only scale models of a fully commercial, high-volume fabrication facility. Further, the estimates are often based on an extrapolation of manufacturing yields and component or material supply quantities that are substantially less than those required for commercial viability.

In carrying out the mature market cost estimating activities of this task, EPRI relied in part on the results of the in-depth critique of the technical capability, manufacturing, and scalability aspects of each major component that was completed in Task 1. Thus, the resulting cost estimate is based on an independent and never-before-achieved level of understanding of the key manufacturing issues associated with full-scale product fabrication. Nevertheless, known or projected costs of existing or proposed production equipment, materials, and so on were also used as a benchmark or starting point in developing costs for the full-scale production environment.

The analysis identifies key cost drivers (specifically wire, cable, refrigeration, and construction) and shows how variations in those cost drivers may affect total component or system cost. In some cases, areas for potential cost reduction are identified and incorporated.

The following cost estimating effort concerns costs, not prices. Prices will be determined by the marketplace, subject to the usual rules of supply and demand. This study does not attempt to address that dimension.

## 4.2 Component Costs

The following subsections provide additional information on how costs were obtained for this effort.

### *4.2.1 Wire*

With respect to the superconducting wire, which is a major cost component in the IFCL HTS cable system, a different approach was taken than that for the other major components. Rather than estimate wire costs on a bottoms-up basis (that is, building up a cost estimate by considering fabrication processes, materials, equipment, labor requirements, and corporate investment and profit requirements) the EPRI team simply assumed a range of potential wire cost.

For "current" wire cost, the team chose two values: US$400/kA-m and US$120/kA-m. The latter value is the approximate market price (based on anecdotal information) from Sumitomo for Gen 1, bismuth strontium calcium copper oxide (BSSCO) wire. It is relevant as "today's price" because any suppliers of Gen 2, yttrium barium copper oxide (YBCO) wire for a proposed project today would have to compete with this price (assuming that Gen 1 wire could meet the project needs). The US$400/kA-m value is something of a guess as to the true cost of American Superconductor Corporation (AMSC) IFCL wire today, against which the price reduction to "commercially viable" levels is to take place as a result of large volume production.

For projected high-volume production, mature market costs, the analysis used two values: US$5/kA-m and US$50/kA-m. The former has been estimated by knowledgeable researchers as the lowest achievable in the longer term for YBCO coated conductor, using some variation of the ion-beam-assisted deposition (IBAD) process [2]. Although AMSC does not use IBAD, it is reasoned that if vendors of IBAD process coated conductor were to offer wire at this price, any other wire manufacture would have to meet that price, all other things (such as performance) being equal. The US$50/kA-m cost is considered a more moderate goal for HTS wire costs resulting from high-volume wire manufacturing. It is based on information shared with EPRI by AMSC during a jointly funded project to estimate the costs of long distance, superconducting DC transmission lines. Those lines would be 1000 to 2000 miles in length, so they would represent a significant scale-up of current HTS wire production capability. (See the EPRI report *Program on Technology Innovation: A Superconducting DC Cable* [3] for cost information on those cables. The report is available to the public at no cost.)

Notwithstanding the above, to prepare the value propositions in this study, all projects were assumed to require Gen 2, YBCO HTS wire. This provides a common base for comparison purposes, and the sharp knee of Gen 2 wire's superconductivity/non-superconductivity transition curve and its higher physical ruggedness will provide better survival, endurance, and performance for power cable applications under fault conditions.

### 4.2.2 Cable

The costs for HTS cable include the manufacture, testing, shipment, and installation of the cable. EPRI visited two major triaxial cable manufacturers to understand both the manufacturing processes and the cost drivers. EPRI also obtained, under confidentiality agreements, budgetary cost estimates from manufacturers for cable systems in a mature, high-volume market scenario. Despite EPRI's request for uniformity of assumption, the estimates returned by the vendors used widely different assumptions and provided significantly different values for apparently similar products. As a result, EPRI developed its own estimate of cable costs for various scenarios. Table 4-1 shows the basic cost components that were used in this study. The table does not show certain ancillary costs, which were in any event included in the final cost estimate roll up (see Appendix C). These included costs for the vendor's field engineer, commissioning, various hardware items such as ground connections, contingency applied (25% on material), and taxes (5% on material). Some costs were increased by 5% to account for wastage during field installation.

**Table 4-1**
**Cost components for high-temperature superconducting cable manufacturing and installation**

| Cable Component | Cost (US$/m) | Cost (US$) |
|---|---|---|
| Triaxial cable | 450 | Length dependent |
| Cable cryostat (see note 1) | 850 | Length dependent |
| Return cryostat | 350 | Length dependent |
| Splice, installed | NA | 113,000 (each, as needed) |
| Terminations | NA | 444,000 (for both ends) |
| Cable installation (see note 1) | NA | 90,000 to 96,000 per pull |
| Cryostat installation (see note 2) | NA | 0 to 96,000 per pull |
| Return cryostat installation (see note 3) | NA | 60,000 per pull |

**Notes:**

1. Cryostat costs shown are considered to be artificially high due to the existence of only one manufacturer in the world, and these costs should decline with the emergence of more suppliers. Costs shown were based on information received during the development of the EPRI report *Program on Technology Innovation: A Superconducting DC Cable* [3].
2. For cable that is shipped separately from the cryostat, the maximum pull length is 1 km. For cable shipped inside the cryostat, the maximum pull length is 500 meters.
3. No separate cryostat installation cost for cable that is shipped from the factory already installed in the cryostat.
4. Return cryostat required for all installations > 1 km and optional for 1 km. Maximum pull length is 1 km.

For installation of HTS cable systems, two components must be installed: the cryostat and the cable within the cryostat. Currently, the HTS cable manufacturing industry promotes two methods for achieving this. One method is to install the cable into the cryostat at the factory, and then install both at the same time at the project site with one pull. This method has the potential to reduce the costs for installation (fewer pulls), but it is limited in pull length by the amount of cryostat plus cable that can be shipped (nominally 500 m). The other method ships and installs the cryostat and cable separately. The cryostat is pulled first, and then the cable is pulled into the cryostat. The amount of cable that can be shipped with this method is greater (nominally 1000 m), but the length of cryostat shipped is the same (500 m). Accordingly, our approaches to estimation of installation costs for these two methods were different and based on advice from the respective vendors. Although there was the potential for quite different installation costs, the opposite was found to be true. In all cases, particularly for longer systems, there was little difference. That said, in most cases, the separate ship and install method proved to be slightly less expensive than the cable plus cryostat method.

Longer cable systems will require a return cryostat. This is more fully described in the EPRI report *Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: Task 1—Technical Capability, Manufacturing, and Scalability Baseline and Assessment*. The exact length at which a return cryostat will be required must be determined in a detailed engineering optimization that takes into account the refrigeration system design and type, the cable and cryostat design, and the expected operations, among other factors. This optimization was beyond the scope of this study. As a result, the team used anecdotal information from previous planned or installed HTS cable projects (such as the New Orleans project and the Essen project) and decided that systems up to 1 km in length could be installed without a return cryostat. However, in the interest of completeness, costs for 1-km systems were developed for both situations: with and without a return cryostat.

An open trench and conduit/manhole method was assumed for cable and cryostat installation. Costs for trenching and for duct and manhole installation were estimated in considerable detail, based on a large body of construction experience for underground cable systems. When necessary, conventional cable installation labor hours and costs were adjusted for unique aspects associated with HTS cable systems. Site construction activities took into account the two different methods of shipping and installing HTS cable (cryostat and cable together or separate).

Substation interconnection costs were also estimated based on conventional underground transmission cable termination practices and, as with cable installation, were modified appropriately for unique aspects associated with HTS cable termination (such as high currents and vacuum/refrigeration connections). These costs are not shown in Table 4-1.

### *4.2.3 Refrigeration*

Estimates of refrigeration system costs were based on prior cryogenic refrigeration experience, with particular emphasis on the approaches used for HTS cables in the past. Three technologically different approaches are possible for this aspect of HTS cable design—the open bath, the reverse Brayton refrigerator, and the Stirling refrigerator. (These are described in the EPRI report *Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: Task 1—Technical Capability, Manufacturing, and Scalability Baseline and Assessment*, so the details of the technologies are not included here.) Because it proved difficult to obtain costs of some items—in particular, the reverse Brayton refrigerator—the cost estimates used in this study are based principally on the Stirling refrigerator, with some reference to the open bath system.

A detailed description of the methodology and results for refrigeration costs used in this study are provided in Appendix B. Table 4-2 presents a summary of those costs, as a function of cable length. These costs are commercial costs today for a mature technology, but they may not represent the true potential for lower refrigeration costs in the future. EPRI was unable to quantify that potential.[18]

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[18] Although the costs shown are based on using multiple Stirling cycle refrigerators, the cost of larger reverse Brayton refrigerators may be similar. EPRI attempted without success to obtain cost estimates for reverse Brayton machines. The difficulty appears to be that there are essentially no commercial offerings for such refrigerators that have been designed for HTS cable systems. However, one vendor provided costs for a reverse Brayton machine designed for liquid helium cooling in an accelerator application (that is, ~4.2 K cooling). When those costs were adjusted to reflect the different power level and increased efficiency of such a machine at liquid nitrogen temperatures for an HTS cable, it was found that the costs (in dollars per cold watt) were essentially identical to the Stirling costs. On the other hand, whereas Stirling system costs are essentially mature market values, the costs for reverse Brayton machines may likely decrease if a strong market emerges.

**Table 4-2**
**Refrigeration system costs**

| Cable Length (km) | Capacity (kW at 72 K) | Number of Refrigerators (note 1) | Capital Cost (note 2) (US$) | Annual Maintenance (US$) | Liquid Nitrogen and Power (note 3) (US$) | Installation (US$) | Total Installed Cost (US$) |
|---|---|---|---|---|---|---|---|
| 1 | 3.5 | 2 | 1,100,000 | 100,000 | 40,000 | 150,000 | 1,250,000 |
| 2 | 7 | 3 | 1,600,000 | 200,000 | 75,000 | 200,000 | 1,800,000 |
| 3 | 10.5 | 4 | 2,110,000 | 300,000 | 107,000 | 250,000 | 2,360,000 |
| 4 | 14 | 5 | 2,575,000 | 400,000 | 133,000 | 275,000 | 2,850,000 |
| 5 | 17.5 | 6 | 3,040,000 | 500,000 | 159,000 | 300,000 | 3,340,000 |
| 6 | 21 | 7 | 3,500,000 | 600,000 | 189,000 | 315,000 | 3,815,000 |
| 7 | 24.5 | 8 | 3,960,000 | 700,000 | 220,000 | 330,000 | 4,290,000 |

**Notes:**

1. Stirling SPC-4 cryogenerator. Number required assumes N-1 redundancy.
2. Includes piping.
3. Liquid nitrogen requirement includes both initial and periodic replacement.

The following comments describe the application of the costs in Table 4-2 to the various cable systems that were studied:

- The refrigeration capacity and costs are based on the Stirling cycle refrigerator. See Appendix B for details.
- Refrigeration capacity for any particular cable system length includes an additional refrigerator for N-1 redundancy. This also permits maintenance and repair operations without taking the system off line.
- Cable systems less than 1 km in length were assumed to use the same number of refrigerators (two) as the 1 km system.
- The capacity of the refrigeration system must be increased when there is a return cryostat. Refrigeration capacity was increased by 33% for such cases.

### *4.2.4 Testing*

Costs for testing, both in the factory and in the field after installation, were included in the component costs for the cable, cryostat, and refrigeration.

### 4.2.5 Field Installation

As with testing, installation costs are included with the individual major component costs. However, additional costs are included in this category, beyond those for the three major components (wire, cable, and refrigeration), and these also were estimated. They include substation equipment installation (such as bracing for cable terminations and buswork) and engineering project management. The engineering project management costs include preconstruction survey and geotechnical engineering, engineering, utility project manager, and field superintendent. Permitting and construction performance bond are additional installation costs, but these were not included because they would be determined in accordance with individual utility practice.

### 4.2.6 Operations and Maintenance

Operations and maintenance costs for the HTS cable system were determined as follows:

- Annual maintenance costs for the cable and cryostat were estimated at US$58,000 per kilometer of installed cable. (Two workers for two days per month at US$1200 per person per day for a 1-km cable installation.)
- Annual operations and maintenance costs for refrigeration are as shown in columns 5 and 6 of Table 4-2.

### 4.2.7 Other Costs

A contingency was added to all major cost category components, as shown in Table 4-3. These contingency values are in accordance with standard engineering and construction practices for underground transmission cable systems (cable and cryostat) and with EPRI methods for advanced technology deployment (wire and refrigeration). *Contingency* is **not** an estimate of error suggesting a possible range of expense. Rather, contingency reflects the as yet incomplete design and, therefore, it represents costs that will be incurred by the time that the project is complete. In addition, a sales tax of 5% was added to all material purchases.

**Table 4-3**
**Cost estimate contingencies applied**

| Component | Material Contingency | Labor Contingency |
|---|---|---|
| Cable and cryostat | 25% | 25% |
| Trenching, duct, and manholes installation | 25% | 25% |
| Terminations, substation equipment, and transition structures | 25% | 15% |
| Refrigeration | 40% | 40% |

### 4.2.8 Region-Specific Costs

The baseline total system cost for each scenario was calculated as an average U.S. cost. However, it is recognized that some costs—particularly labor costs—are quite region specific. To that end, EPRI determined a cost multiplier to be applied to the average U.S. cost. These multipliers, shown in Table 4-4, reflect higher costs in dense urban areas and lower than average costs in smaller cities or lower cost regions of the country. The multipliers shown are averages taken over several locations.

**Table 4-4**
**Region-specific multipliers**

| Region | Material Cost Multiplier | Labor Cost Multiplier |
|---|---|---|
| Higher cost region (dense urban city) | 1.015 | 1.54 |
| Lower cost region (smaller city or suburban/rural) | 0.99 | 0.87 |

## 4.3 System Costs

Rolled up system costs were developed, using the EPRI spreadsheet model (see Appendix C), for a variety of cable system lengths, wire prices, and other assumptions. Costs for the three base cases described in Section 3 and applied to the value propositions described in Section 4 are shown in Section 4 under each base case subsection. Details are shown in Appendix D. Therefore, in the following subsections, costs for a representative system are shown. This accomplishes several objectives. First, it shows the level of detail in the EPRI cost estimating effort. Second, it provides an understanding of the major cost drivers, including the varying impact of different wire price assumptions. Third, a comparison of costs per mile and per kilometer as a function of circuit length shows the effect of project size. Fourth, a comparison of cost per mile for a range of wire price projections provides some insight into the capability of a large project to reduce system costs.

### *4.3.1 Typical Cost Estimates*

#### 4.3.1.1 Cost Model Result Details

Table 4-5 shows the input parameters that are varied in the EPRI cost model. The values shown are for a 1-mi (1.6-km) cable system. All cost estimates are based on (only) variations in these parameters. The last row is a calculated quantity, not an input. It is shown here for completeness. The number of splices (and therefore, manholes) is a function of the length of the circuit and the method of shipping the cable. A return cryostat is required, as described in Section 4.2.2.

**Table 4-5**
**EPRI cost model inputs**

| Cost Parameter | Value (Typical) |
|---|---|
| Circuit length, m | 1610 |
| Cable shipped in cryostat (=0) or separate (=1) | 1 |
| Cable system voltage, kV | 13.5 |
| Cable design rating, kA ac | 3 |
| Wire cost: US$/kA/m (DC rating) | US$50 |
| Return cryostat (yes = 1;no= 0) | 1 |
| Number of triaxial cable splices | 1 |

For the model inputs shown in Table 4-5, the model output is presented in Table 4 6. The table shows costs categorized by major system components and the percentage of total cost that each represents. It also shows the impact of the low and high region-specific cost multipliers.

**Table 4-6**
**Typical cost model output for the cable system described in Table 4-5, cable shipped separately**

| **Category*** | **Cost (US$)** | **Percentage of total cost** |
|---|---:|---:|
| Wire | 2,098,000 | 12% |
| Cable and cryostat material | 4,481,000 | 26% |
| Cable and cryostat installation | 1,755,000 | 10% |
| Civil works (except refrigeration) | 3,714,000 | 22% |
| Refrigeration (installed) | 3,753,000 | 22% |
| Engineering and management | 1,422,000 | 8% |
| Total (average U.S.) | 17,222,000 | 100% |
| Total (low region multiplier) | 16,332,000 | |
| Total (high region multiplier) | 24,497,000 | |

*Cable length, 1610 m; wire cost US$50/k A-m (DC); cable shipped separately

A pie chart of these costs is shown in Figure 4-1. The pie chart clearly shows the major cost drivers, which in this case are the cable/cryostat material, civil works, and refrigeration. Civil works do not include the costs for installing the cryostat and cable, as these are shown separately. In addition, the material costs for the cryostat and cable are shown separately. This is important because, in some scenarios, the cost of this component, and particularly the cryostat, becomes the major driver.

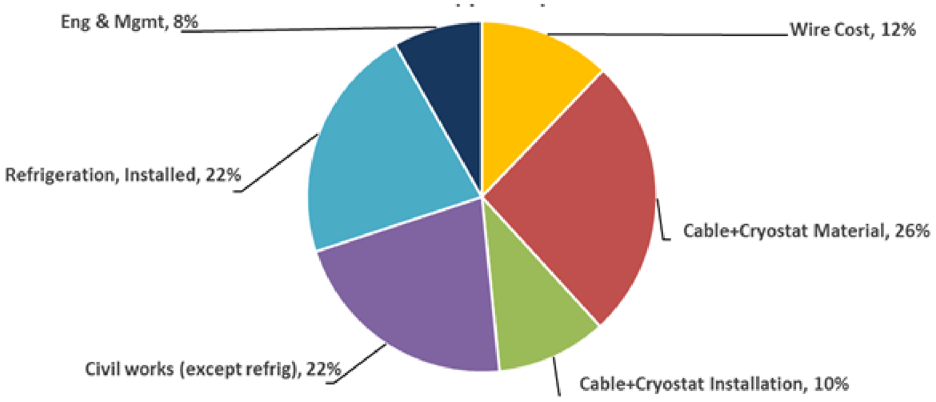

**Figure 4-1**
**Typical cost model output for the cable system described in Table 4-5, US$50/kA-m wire cost**

To see the impact on costs of the alternative method of shipping and installing the cable plus cryostat (that is, for the case in which the cable and cryostat are shipped and installed together), see Table 4-7. This method increases the cost by less than US$400K, or about 1.5%. Considering the accuracy of the inputs to the cost model, this is considered insignificant. Moreover, the same relative result was found in all simulations performed, and the difference became more significant only for a 500-m system. In that case, the cable plus cryostat installation was 2% less costly than the separate method, which is attributed to the fact that the cable plus cryostat approach is distinctly amenable to 500-m system lengths. Unless otherwise noted, all subsequent cost results in this report use the separate cable installation method.

**Table 4-7**
**Typical cost model output for the cable system described in Table 4-5, cable and cryostat shipped together**

| Category* | Cost (US$) | Percentage of total cost |
|---|---:|---:|
| Wire | 2,098,000 | 12% |
| Cable and cryostat material | 4,609,000 | 26% |
| Cable and cryostat installation | 1,770,000 | 10% |
| Civil works (except refrigeration) | 3,844,000 | 22% |
| Refrigeration (installed) | 3,753,000 | 21% |
| Engineering and management | 1,447,000 | 8% |
| Total (average U.S.) | 17,2520,000 | 100% |
| Total (low region multiplier) | 16,619,000 | |
| Total (high region multiplier) | 24,875,000 | |

*Cable length, 1610 m; wire cost US$50/k A-m (DC); cable shipped in cryostat

#### 4.3.1.2 Impact of Varying Wire Cost and Cost Drivers

Figures 4-2 through 4-4 show how the major cost drivers change as a function of varying the wire cost.

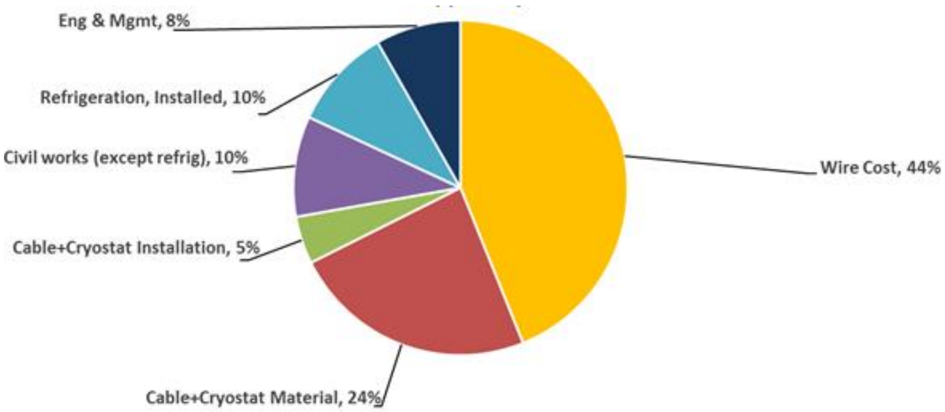

**Figure 4-2**
**Cost model output for the cable system described in Table 4-5, US$400/kA-m wire cost**

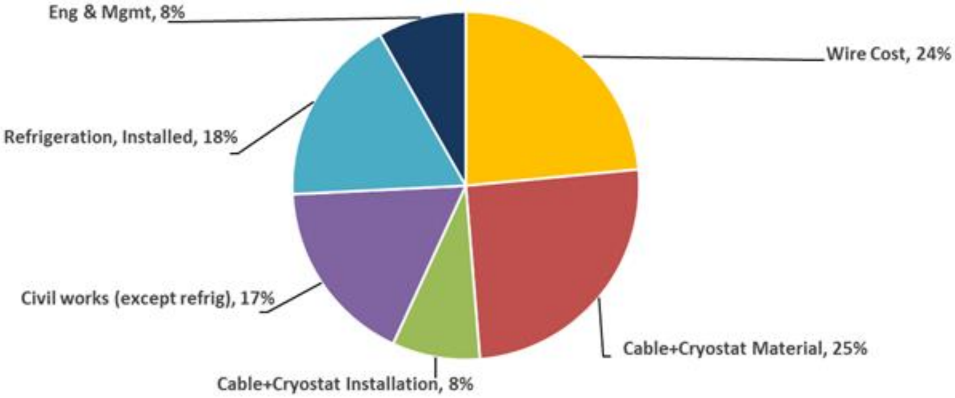

**Figure 4-3**
**Cost model output for the cable system described in Table 4-5, US$120/kA-m wire cost**

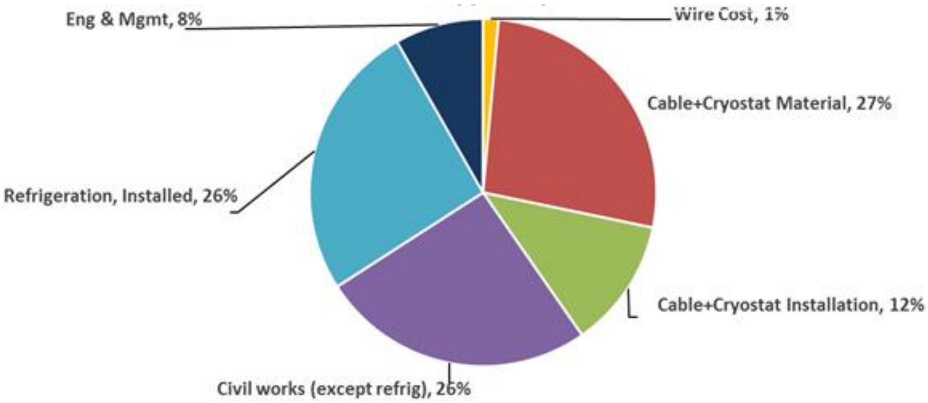

**Figure 4-4**
**Cost model output for the cable system described in Table 4-5, US$5/kA-m wire cost**

Although the wire cost is varied by two orders of magnitude in these charts, the cable and cryostat material represent a significant cost driver in all cases. For all but the highest cost wire (that is, wire cost < US$400/kA-m) the refrigeration and installation costs also appear as major drivers. For the case of US$5/kA-m wire, which is the assumed end-point of wire development expected over the next 15 years, wire cost is no longer a significant factor. That is, it has become a commodity at this cost level. This is not the case for conventional copper conductor cable, for which the cost of the copper conductor can represent 25% or more of the cable cost. However, unlike HTS cable, conventional cables do not have the added burden of a cryostat and refrigeration system. If, for the US$5/kA-m case, one adds together the costs for wire, refrigeration, and cryostat, it is found that these three components represent about 48% of the system cost. Therefore, although it may seem that a goal of US$5/kA-m for wire cost is unrealistic when compared to the relative cost of copper in conventional cables, the fact that HTS cables must be cooled and kept cool changes the economics considerably.

The cryostat costs used in the EPRI model are considered to be artificially high because they are based on assumed prices influenced by a market in which there is only one supplier of the large-diameter cryostats used by these HTS cable systems. The team estimated that cryostat costs could decrease by a factor of two or more if there were a competitive market. This could be a motivation for institutionally sponsored efforts to incentivize development of at least one other (U.S.-based) large-diameter cryostat manufacturer.

#### 4.3.1.3 Cost Reduction Potential by Reducing Wire Cost

One of the questions that this study was intended to help answer was what impact the deployment of a single, large-scale urban project would have on HTS system cost. Such a project, with an HTS cable length of three to five miles, was projected to bring total system costs down to within reach of utility companies without government subsidies. EPRI attempted to answer that question but was unable to do so without specific information from AMSC with regard to current wire cost and expected reductions in wire cost as a result of volume wire manufacturing for the proposed project. Instead, the team estimated the cost per mile as a function of wire cost for different project lengths. The graphs in this section show different ways of understanding the impact of both project length and wire cost.

Figures 4-5 and 4-6 show costs per unit distance of a 13.5-kV, 3-kA HTS cable system as a function of distance, for three projected wire cost scenarios. From these graphs, it is apparent that a project size effect favors longer systems.

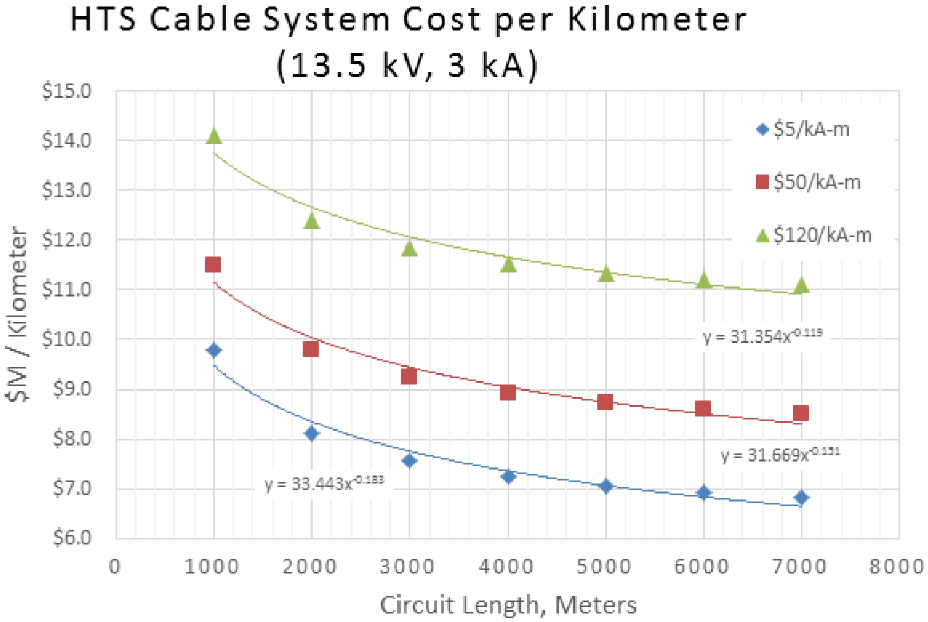

**Figure 4-5**
**High-temperature superconducting cable system costs per kilometer**

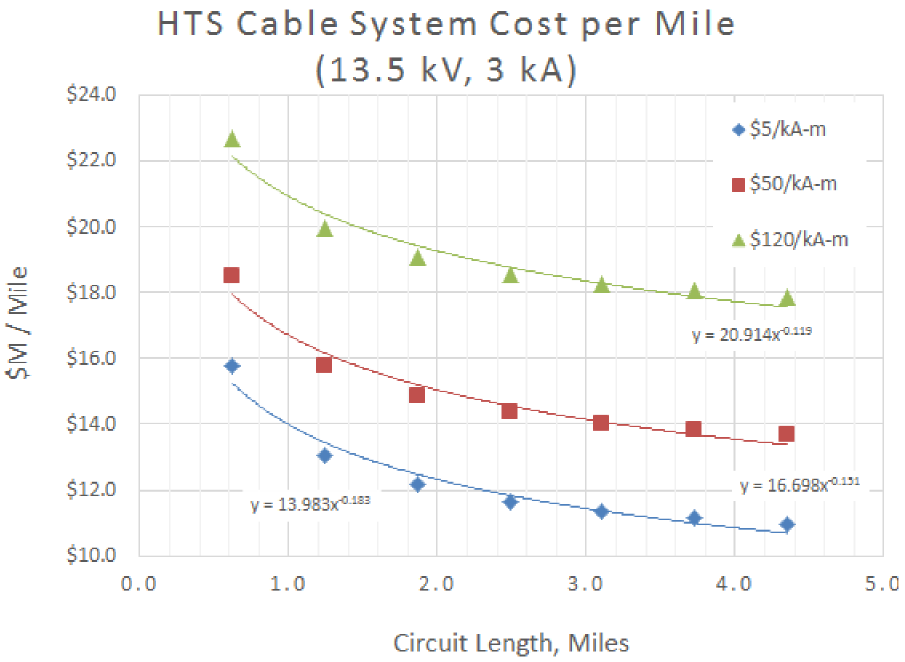

**Figure 4-6**
**High-temperature superconducting cable system costs per mile**

Figures 4-7 and 4-8 show comparisons of cost per mile for a range of wire price projections to provide some insight into the capability of a large project to reduce system costs. Nevertheless, it is still not possible to estimate how much a single, large (three- to five-mile) HTS cable project can lower wire cost. The figures simply show what will happen if wire costs are reduced.

Figure 4-7 shows system costs per mile for a full range of wire costs and for three different project lengths. It is clear that project length has a beneficial impact on cost per mile, but this is expected. However, the difference between the highest cost (assumed to be the current cost) and the AMSC-estimated, high-volume manufactured wire costs of US$50/kA-m (see Section 4.2.1) is more than a factor of two.

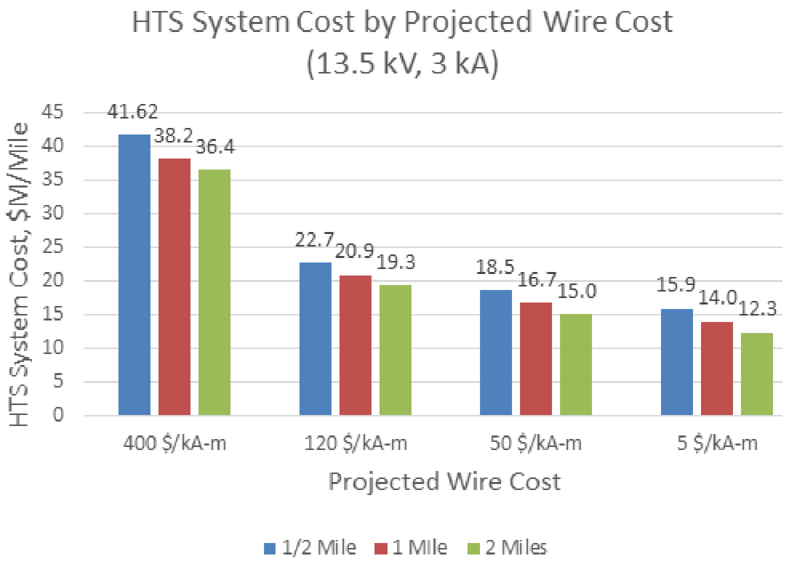

**Figure 4-7**
**System cost by projected wire cost**

Figure 4-8 provides a different view of the same information, but for only one project length, a one-mile project. In addition, it shows costs with construction costs removed, because these are site specific and may make it more difficult to assess vendor projections.

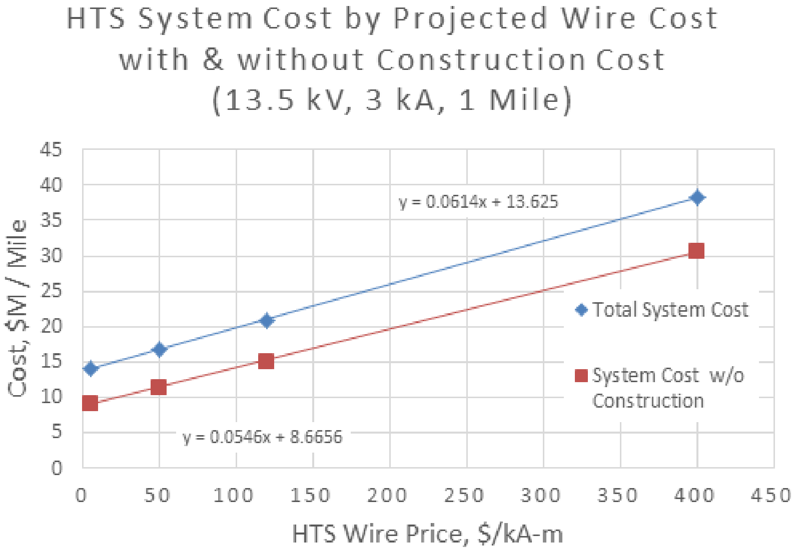

**Figure 4-8**
**System cost by projected wire cost, with and without construction costs**

# 5

# VALUE PROPOSITION FOR HIGH-TEMPERATURE SUPERCONDUCTING CABLE SYSTEMS

## 5.1 Introduction

This section presents an assessment of the value proposition for HTS cable systems. It also presents an assessment of the market conditions for HTS technologies and the current barriers to utility adoption of HTS technologies.

## 5.2 Value Proposition

The term *value proposition* means the sum of market and technical factors in the mind of the customer (including cost) that would add up to making the HTS cable system competitive with conventional technology. The establishment of a long-term, viable market for HTS cable systems would require the following:

- An HTS cable system that is price competitive with conventional system solutions
- Sufficient market demand for HTS power technologies to support product development
- Demonstrated reliability in utility systems sufficient to obtain widespread utility acceptance

HTS cable systems, like any technology for use in an electric utility network, must meet a stringent set of requirements that enable utilities to meet reliability standards required by regulatory agencies and their customers. Accordingly, the equipment that utilities use is subjected to extensive tests and trials before it is accepted for use on their systems. Demonstrating the reliability of new technology for electricity transmission or distribution is a difficult and time-consuming task. In their 2000 market assessment of HTS power technologies, Mulholland et al. [4] recognized this fact with the following statement:

> We predict it will be a hard sell to gain a foothold in the utility market place…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.

Their prediction was that this perception for generators and cables “will have changed little by 2018.”

Although several HTS power technologies have been installed and operated in electricity grids, they are currently still at the demonstration stage. For example, the total length of HTS cable systems that have been installed worldwide is several kilometers [5], using only a small fraction of the 30,000 kilometers of wire per year that was estimated in Task 1 to be necessary to sustain a commercial business. Each of the base cases described in Section 5.3 might require hundreds of kilometers of wire. Thus, in evaluating the value proposition, one must also keep the following in mind: 1) more wire and cable will need to be produced on a more rapid schedule than for past demonstration projects, and 2) the HTS cable installations will have to be demonstrated to meet the same reliability requirements as the tried and tested conventional alternatives. Both of these factors will add time requirements and costs to those firms interested in developing and marketing HTS systems. In light of these facts, this report adopted the following three-step method for assessing the value proposition for HTS cable systems:

1. It establishes a price point for a mature HTS cable system to be cost competitive with conventional solutions for each base case. (*Mature* means that a number of installations have previously occurred and that the revenues from these previous installations have been sufficient to allow the system vendors to recover the engineering costs that are typically associated with developing and maturing a new technology. This would correspond to the technology at technology readiness level 9 and manufacturing readiness level 10, the presence of multiple vendors competing in the marketplace, and a sustainable demand, which was estimated in Task 1 to require sales of 30,000 km/year of HTS wire.)
2. It analyzes the existing and potential future markets for HTS power technologies to determine what would be required to generate enough demand for HTS wire to drive the development to maturity of HTS cable systems. (The cost of the wire is currently a substantial fraction of the cost of the HTS cable system and, thus, can drive decisions concerning investment in technology development and maturity.)
3. It describes the barriers that are likely to affect the decision of utility companies to install HTS cable systems in their networks and, thereby, the decision of manufacturers to develop and to offer commercially such systems. It presents potential actions to reduce those barriers.

## 5.3 Analysis of the Base Cases

This section considers the three base cases defined in Section 3. For each base case, it describes a potential conventional solution and develops a cost point at which the purchase and installation costs for a mature HTS cable system would be cost competitive with this conventional solution. Because a mature HTS cable system is assumed, this cost point does not include any premium for the scale-up of wire and cable production or the utilities' costs of training, operation, and maintenance of this new technology requiring cryogenic cooling. Utilities typically maintain staff for planning, designing, and managing projects that install new capabilities. Thus, in addition to the issue of demonstrated reliability, a value proposition for HTS cable systems must take into account not only the cost of the systems but also the fact that the utility is unlikely to have the in-house technical capability to evaluate the project and then operate and maintain the system. It must somehow train existing employees, hire new staff, or execute contracts that will ensure safe and reliable operation and maintenance for the life of the system. It is, however, recognized that the cryogenic and compressed gases industry is a utility in itself, similar in age to the utility industry and both willing and anxious to meet this need in partnership with the utility industry. The value propositions developed here assume not only a mature technology but also a mature (or established) service and customer environment.

Direct cost comparison may not be the deciding factor in the decision for which solution to use. The conventional solution might involve difficult siting issues associated with underground transmission lines and the amount of land and construction involved, and obstructions or underground congestion may preclude some conventional solutions because of their much larger cross-sectional space needs. The HTS solution would involve the same issues, but these would likely be easier to resolve because of the lower voltage and the smaller size of the required corridor. Most importantly, however, the HTS solution would involve installing in a utility system a new technology that would have to have demonstrated reliability and capability for operation and maintenance over its lifetime. For a utility to decide to implement this solution, it would either have to represent a large cost advantage or enable something that cannot be done with the conventional solution. (Although true in the present marketplace, in a market environment having the assumed point of maturity for both technology and customer staff/process, HTS will be viewed by utilities equally alongside all other candidates. Cost will be primary. Nevertheless, even for mature and accepted technologies, other factors such as reliability and operability will come into play.) This is why each of the base cases involves a situation in which the conventional solutions involve difficult constraints such as lack of available space, siting issues, or load growth and management.

### *5.3.1 Base Case 1—Critical Infrastructure Support*

This base case involves bringing power to a facility such as an airport, hospital, or other critical infrastructure to supplement what is currently available and increase resiliency in the event of a large-scale outage, thus providing for increased activity, increasing the level of contingency that can be handled, and reducing the level of necessary backup power required. The team assumed that this facility already consumes all the power that is available from local distribution systems and any dedicated generation present, and that it is not possible to add additional dedicated generation. Table 5-1 summarizes the parameters and value proposition (cost point for a competitive HTS cable system) for this case. Details are provided in the following text. HTS solution cost ranges are described in Section 5.4

**Table 5-1**
**Base case 1: supplemental power for critical infrastructure**

| | **Conventional Solution** | **High-Temperature Superconducting Solution** |
|---|---|---|
| Power requirement | 120 MVA | 120 MVA |
| Distance | 2 km | 2 km |
| Voltage | 35 kV | 35 kV |
| Number of feeders | 7 | 1 |
| Cost | US$22 million | US$17 million to US$27 million (1)<br>US$15 million to US$24 million (2) |

**Notes:**

1. HTS wire cost, US$50/kA-m
2. HTS wire cost, US$5/kA-m

The HTS cable solution is to provide the additional power to this facility using one 35-kV HTS cable from the nearest transmission substation having available capacity, assumed to be 2 km away. The cable would be rated 120 MVA. Two cables would ensure N-1 redundancy, but only one was used in this case study because it is essentially a redundant source for the existing supply.

The conventional solution for providing the additional power was assume to use conventional, 35-kV copper conductor underground distribution feeders, each rated at 20 MVA. The team assumed that the power requirement is 120 MVA. This requires six feeders, and the cost per feeder is estimated at US$1.8 million per kilometer. The cost of the feeders is thus US$21.6 million. A new substation will be required to receive this power and distribute it at the facility site, but that will be the case whether the power is brought in by conventional feeders or the HTS cable system. Therefore, the value proposition for a mature HTS cable system to be cost competitive in this case is US$22 million. (The base case definitions and the feeder and other equipment costs in this and the other base cases are based on discussions with utility staff during this project. Underground distribution is required because the facility is in an urban area.)

### *5.3.2 Base Case 2—Urban Utility Asset Utilization Improvement*

This base case involves the sharing of assets by urban substations that will increase the reliability of the system and allow loads in dense urban areas to be served using available power transfer capacity beyond that of the nearest substation(s). Sharing of assets will be accomplished in the HTS case by interconnecting nearby substations with a suitably rated and designed HTS cable. Interconnecting substations in a dense urban area with conventional underground cables is deemed to be not feasible because it would require many cables and conduits, with significant spacing between them, as well as probably extensive departure from the most direct routes between substations. In dense urban locations, the streets and otherwise available corridors for underground cable are already significantly congested. Instead, for the conventional solution (from which the value proposition is determined), an additional 60 MVA transformer was added to each substation to increase reliability. Table 5-2 summarizes the parameters and value proposition (cost point for a competitive HTS cable system) for this case. Details are provided in the following text.

**Table 5-2**
**Base case 2: utility asset load management**

| | **Conventional Solution** | **High-Temperature Superconducting Solution, Both Options** |
|---|---|---|
| Number of transformers | 2 | 0 |
| Power requirement | 60 MVA | 60 MVA |
| Distance between substations | 1 km | 1 km |
| Voltage | 13.5 kV | 13.5 kV |
| Number of cables | 0 | 1 |
| Value proposition for a mature HTS cable system | Option A: US$2 million<br>Option B: US$42 million | US$9 million to US$14.3 million (1)<br>US$7.7 million to US$11 million (2)<br>(HTS solution costs apply for both conventional solution options shown.) |

**Notes:**

1. HTS wire cost, US$50/kA-m
2. HTS wire cost, US$5/kA-m

For the HTS solution, the analysis assumed the distance between substations to be 1 km. However, although the distance between substations will affect the value comparison between HTS and conventional solutions, because cable length will affect the cost of the HTS cable system, it does not affect our estimation of the value proposition, which involves adding equipment to an existing substation. For this case, it was assumed that each substation has two 60-MVA transformers and serves a 60-MVA load, which provides for N-1 contingency.

#### 5.3.2.1 Option A

For option A, reliability is increased by adding an additional 60-MVA transformer—with the associated switchgear, buswork, protection, and so on—at each of the substations. For an urban substation location with existing space constraints, the cost is estimated to be US$2 million. This is the option A value proposition for a mature HTS cable system interconnecting these substations.

#### 5.3.2.2 Option B

For option B, the team considered the following. In a dense urban utility environment, there may be situations in which a substation will have insufficient available space to add transformers. Were that the case, the alternative would be to build a new urban substation, which is typically located inside a building in an area with high real estate values and high construction costs. The estimated cost for construction and electrical equipment of a substation outside a dense urban area is US$32 million. For this dense urban case, unless leased space is available, the land and construction costs would likely add at least another US$10 million, giving a total of US$42 million for option B.

For dense urban areas, even these costs may be on the low side in the future. Real estate availability at any price becomes more and more problematic as urban centers grow. Community board approvals are extremely difficult to obtain, and, as underground congestion increases, additional costs may be incurred to relocate existing utility-owned and/or city-owned underground infrastructures to create space needed to route new services in and out of new substations. In some cases, municipalities or communities may require utility funding of other neighborhood improvements as part of the price of approval for new facilities. Cooperative joint planning of long-term urban development needs with city planners is the best way to anticipate, mitigate, manage, and when possible, avoid some of these increasing costs over time.

### *5.3.3 Base Case 3—Load Growth Support with a Virtual Substation*

This base case involves planning for load growth in a previously underserved area by extending the reach of the existing distribution system using existing substation capacity through new distribution lines. The team considered two scenarios with different load demands and reflecting suburban (scenario 1) and urban (scenario 2) load growth. Scenario 1 involves extending the distribution bus beyond the 3.2-km limit of conventional 5-kV feeders. Scenario 2 involves planning for much higher load by extending higher-capacity 35-kV feeders. Table 5-3 summarizes the parameters and value proposition (cost point for a competitive HTS cable system) for each of these scenarios. Details are provided in the following subsections.

**Table 5-3**
**Base case 3: planning for new load—conventional solutions**

| | **Scenario 1** | | **Scenario 2** | |
|---|---|---|---|---|
| | **Conventional Solution** | **High-Temperature Superconducting Solution** | **Conventional Solution** | **High-Temperature Superconducting Solution** |
| Power requirement | 60 MVA | 40 MVA | 240 MVA | 240 MVA |
| Distance | 8 km | 6 km | 0.5 km | 0.5 km |
| Voltage | 35 kV | 5 kV | 35 kV | 35 kV |
| Number of feeders/cables | 6 | 2 | 13 | 2 |
| Additional requirement | New substation | Compact substation | New substation (not included in cost) | New substation (not included in cost) |
| Value proposition for a mature HTS cable system | US$93 million | US$109 million to US$158 million (1)<br>US$80 million to US$124 million (2) | US$12 million | US$14 million to US$22 million (1)<br>US$12 million to US$19 million (2) |

**Notes:**

1. HTS wire cost, US$50/kA-m
2. HTS wire cost, US$5/kA-m

### 5.3.3.1 Scenario 1

For scenario 1, it was assumed that the new load to be served is 40 MVA and is centered about 6 km away from the nearest distribution substation. Serving new load growth from the distribution substation with conventional 5-kV cables is possible, but it is limited in distance to 3.2 km because of voltage drop and loss per length of cable. Extending the distribution bus further at this voltage is not feasible because it would add too much additional voltage drop and loss. However, with HTS cables, the extension is possible. Therefore, the HTS solution is to provide two (for N-1 redundancy), 5-kV HTS cables, each rated at 40 MVA. These will feed a compact substation that does not require extensive permitting and land area purchase. The cost for the compact substation, which would likely include the use of SF6 switchgear, was assumed to be half the cost of the new substation in the conventional solution described in the following paragraph.

The assumed conventional solution would be to install a new, fully constructed and permitted substation in the middle of the projected growing load area. The new substation would be fed from an existing transmission substation with 35-kV feeders. In such a situation, in anticipation of future load growth in the area, the utility would most likely build a new 60-MVA distribution substation, with an estimated cost for construction and electrical equipment of US$32 million. The analysis assumed that new 35kV/5kV distribution substations would be typically 8 km from the nearest 138kV/35kV or 230kV/35 kV transmission substation and be fed with six 35-kV feeders.

Using the same cost per feeder as in base case 1, these feeders would cost US$76.8 million, for a total cost of US$108.8 million. The value proposition for a mature HTS cable system to be cost competitive for this scenario would be US$108.8 million, less half the cost of the substation (US$16 million) to compensate for the cost of the compact substation in the HTS solution. Thus, the value proposition for scenario 1, rounded to the nearest million, is US$93 million.

Three comments are in order here. First, there may be another conventional alternative to building a new substation, which is to use compact, pole-top substations to transform the 35 kV feeders to 5 kV. Although this would be cheaper than building a new substation, it would require many 35-kV feeders and many compact substations; therefore, it would not represent a replicable solution to load growth, it is not practical for city centers, and in a retrofit application using existing overhead distribution infrastructure, it could likely require pole replacements to meet increased support demands for the added weight of the new pole-mounted equipment. Second, the comparison between the extension of the 5-kV distribution bus with an HTS cable and the construction of a new substation is somewhat an apples-to-oranges comparison. The value of the new substation is greater because it provides for up to 120 MVA of load growth with the addition of two or three transformers (depending upon their rating) to the new substation, whereas the HTS solution is providing only 40 MVA. The radius of the load region of the new substation is also greater. However, the benefit of the HTS solution is that it allows extension of the 5-kV distribution bus without as much new substation construction (eliminating high-voltage buses and transformers) and with greatly reduced land/real estate requirements, thus serving new load in a manner that is replicable, as well as reducing the siting problems of a new substation. Even if further load growth were to eventually demand expansion of the substation, the deferral of these costs over time would provide significant financial cost flow benefits to the utility.

Third, the base cases chosen for this assessment are more representative of emerging and younger city centers. The assessment would be remiss, however, if it did not recognize that some mature city centers require much larger substations in their standard design and still face continued business and residential development, additional vertical growth within existing dense urban areas, and urban expansion into outlying areas of the city.

#### 5.3.3.2 Scenario 2

For scenario 2, the new load to be served is projected to be 240 MVA, which has occurred (or is planned to occur), for example, from vertical load growth (high-rise developments) within 0.5 km of an existing substation. For this scenario, a nearby existing substation will be expanded, and the new load will be served at 35 kV from the expanded, existing substation (that is, by extending the 35-kV bus of the substation). The cost of expanding the substation will be the same for the conventional and HTS solutions, so it is required to compare just the cost of the feeders—HTS or conventional. For the HTS cable solution, the new load would require two (for N-1 redundancy) 35-kV cables, each rated at 240 MVA. The conventional solution serves the 240-MVA load using 13 conventional 35-kV feeders (each rated at 20 MVA) for N-1 contingency. Using the same cost per feeder as in base case 1 (US$1.8 million/km), the estimated feeder cost is US$12 million, which is the value proposition for a mature HTS cable system to be cost competitive for this scenario.

## 5.4 Cost-Benefit Analysis Discussion

The cost ranges shown in the base case value propositions in Section 5.3 represent the low and high regional cost estimates (see Section 4.2.8). The average U.S. cost will be found near the low end of these ranges in all cases, because the high region multiplier introduced a much greater percentage change in cost than did the low region multiplier (see Table 4-4).

From the foregoing value proposition analysis, it is clear that, on the assumption that wire cost will decrease (that is, from current costs to a range of US$50/kA-m to US$5/kA-m), HTS cable systems are economically viable against conventional solutions in each of the base cases studied. Both of the assumptions of this study as to future wire cost (the more extreme US$5/kA-m or the moderate US$50/kA-m) produce costs lower than value in at least certain situations for base cases 1 and 2. In base case 3, however, only the US$5/kA-m wire cost produces a viable result, and even then, the results are positive only for lower-cost regions. Moreover, the results for base case 1 show that the HTS value may be marginal in the highest-cost urban areas.

As a general statement, these results would seem to indicate that the shorter-length systems that are providing critical infrastructure or increased asset utilization in constrained urban settings (or both) are likely to be more economical (that is, base cases 1 and 2 are possibly more economical than base case 3). That said, a shorter project length for base case 3 would possibly be economical. As with all the base cases, the assumptions for this base case could significantly affect the outcome.

Finally, cost is not the only (or even the major) factor in utility decision to deploy an HTS cable system. The various other market factors affecting the commercialization of HTS cable systems are described in Section 5.5.

## 5.5 Market Assessment of High-Temperature Superconducting Power Technologies

This section is based on an analysis of detailed HTS power technology market assessments performed in 2000 by Oak Ridge National Laboratory (ORNL) [4] and in 2006 by Navigant Consulting, Inc. (NCI) [6], reviews of literature and specifications for HTS and conventional power equipment, and discussions with government, utility, and manufacturing industry representatives.

The ORNL and NCI market assessments clearly state the uncertainties associated with a market projection for new technology. Both use S-curve models of HTS power technology adoption (market penetration) that assume that the initial exponential growth of the S-curve is driven by a combination of reduction in HTS wire cost and utility acceptance of the technology, with the size of the market determined by scaling new and replacement equipment needs according to electricity growth estimates in the Energy Information Administration (EIA) *Annual Energy Outlook* [7]. Both assessments projected market penetration that has not happened. Moreover, in many respects, the current situation with respect to the two key uncertainties (wire cost and utility acceptance) is similar to that which existed when the 2006 NCI assessment was performed. That assessment projected that “HTS cables are likely to enter the market on a commercial basis around 2014, after additional demonstration stages.”

However, the “additional demonstration stages” that were in the planning stages in 2006 did not occur, and existing demonstrations were, in fact, terminated prematurely from a utility acceptance perspective. Coincident with the cessation of HTS cable demonstrations in the United States were two events: the 2008 recession that resulted in the interruption of expected urban load growth in some areas, and the termination in 2010 of the U.S. DOE funding for HTS technology research, development, and demonstration, including cancellation of the Superconducting Partnership Initiative (SPI). The SPI provided a 50% government cost share for utility-hosted demonstrations of HTS technology. That event is deemed significant in light of a joint DOE/EPRI-sponsored survey of utility underground transmission engineers in the mid-1990s. The unpublished report on this survey showed that, for utility planners to consider acceptance of HTS cable technology, multiple in-grid demonstration projects having an average duration of 10 years each would have to occur. While illustrating the conservatism of the industry, this survey also underlines the importance of government-supported demonstration projects, lasting many years. In this regard, it is noteworthy that in the same 10-year period after the NCI assessment, several other nations (Japan, Korea, China, Germany, and Russia) have stepped up the planning for and installation of in-grid HTS cable and FCL projects. Most or all of these projects have significant levels of either state or national government funding support. For more information, refer to the EPRI report *Strategic Intelligence Update: Superconductivity for Power Delivery Applications, December 2015* (3002007192) [8].

The NCI assessment defined *market entry* as a “situation dominated by customer-driven cable projects without government support.” This definition is consistent with the *commercial* criterion in the Task 1 report, which estimates an earliest possible commercial date of 2025, 10 years from today as compared to the 8 years in the 2006 market assessment.

One of the “key takeaways” of the 2006 market assessment was that “the most important near-term energy and utility markets appear to be for fault current limiters and synchronous condensers,” with HTS cable systems projected to emerge years later. It is instructive, therefore, to examine what has occurred in the marketplace since 2006 with respect to HTS synchronous condensers and HTS FCLs. According to the NCI conclusions, market entry of those two HTS technologies would presage a market for HTS cables.

The synchronous condenser was projected by NCI for a 2011 market entry, which has not yet happened. The HTS synchronous condenser was modeled as a substitute (in some applications) for existing flexible ac transmission systems (FACTS) devices. The FACTS market was estimated based on 40,000 MVAR (the reactive component of the ac power transmitted) of FACTS devices installed worldwide as of January 2000, an annual growth rate tied to the EIA’s forecasted electricity growth rate, and the assumption that the HTS synchronous condenser would eventually capture 50% of this market. The basis for this projection might have been a Tennessee Valley Authority project that installed an HTS synchronous condenser at a substation serving a large industrial customer in 2004 and operated it successfully for about a year [9]. However, although the market for FACTS devices is still projected for rapid growth [10], currently some projects in North America are considering synchronous condensers for reactive support instead of FACTS. That is because synchronous condensers provide not only reactive power but also physical inertia, which is needed in power systems with increased penetration of renewables. Thus, the outlook for HTS synchronous condensers may still be positive, albeit delayed beyond the time frame shown in the earlier market assessment [9].

More recently, the desire to prevent power grid outages has led to the development and implementation of synchronous phasor measurement units (PMUs) that use global positioning satellite timing to simultaneously measure the real and reactive power and enable corrective action to damp out oscillations and prevent voltage collapse. Investments funded through the American Recovery and Reinvestment Act have supported the installation of more than 1000 PMUs across North America, as well as high-speed communications networks and advanced analytical applications to use the data [11]. PMUs can provide voltage and current phasor values with time stamps, so that accurate estimation of real and reactive power can be done in real time. PMUs will probably provide more accurate estimation of reactive power requirements but the reactive power support itself must be provided by other devices, such as shunt capacitors/reactors, FACTS, and synchronous condensers. Thus, the growth of PMU deployment to address potential problems with balancing real and reactive power in power grids also augers well for increased market penetration of synchronous condensers, including HTS devices. (NCI projected that HTS synchronous condensers “can effectively address 50% of the FACTS market” [12].)

The market for HTS FCLs has not grown as projected in 2014. A couple of factors may help to explain why. First, the interruption of anticipated load increases due to the economic downturn has suppressed load growth until quite recently, except for selected regions of the country. Second, other options have satisfied current needs, including conventional alternatives such as the simple insertion of a series reactor, with its penalty of continuous energy use. The recent development of a novel, transformer-based conventional FCL [13] that was tested and certified in Australia and installed at a UK Power Networks substation has demonstrated a non-HTS solution [14].

Therefore, it is still anticipated that the needs for fault current mitigation will increase in dense urban load centers. This will be primarily driven by capacity additions to serve new load growth, an increase in contribution due to the close proximity of distributed generation, and interconnections of additional assets to mitigate periodic unavailability of intermittent renewable assets. These drivers will be described more fully in the Task 3 report.

A new market assessment projects FCL market growth to US$5.2 billion by 2020, with a compound annual growth rate of 9.2% from 2015 to 2020, with the superconducting FCL “considered to be the best alternative when compared to conventional protection equipment” [15]. Although most FCLs currently in service operate at distribution voltages, U.S. utilities have been seeking transmission voltage FCLs for almost a decade. This need has gone unmet. For example, the termination of DOE’s SPI program caused the cancellation of a 138-kV HTS FCL demonstration project that involved Siemens, American Superconductor, and Southern California.

Some current development and demonstration work on HTS FCL systems is under way. For example, Applied Materials offers solid-state and superconducting FCLs [16]. Siemens has developed a distribution-voltage HTS FCL that eliminates the energy use penalty of the series reactor by bypassing a parallel-connected conventional reactor with the HTS FCL element. Thus, the reactor is used only under fault conditions, and the energy loss of the HTS FCL from the use of its cooling system is estimated to be only 50% of that of a series reactor. Siemens estimates that there are 44,000 series reactors installed worldwide, consuming more than a megawatt of electricity [17]. A Siemens HTS FCL is planned for installation in the power grid in Augsburg, Germany, by the end of 2015 [18]. If that project is successful, it should provide an experience base for market assessments of HTS FCLs in the future.

If either the HTS synchronous condenser market or the FCL market or both were to grow, it may provide an opportunity for utilities to become familiar with using equipment that requires cryogenic technology, paving the way for HTS cable systems to be accepted.

The current market situation is that the S-curve emergence (that is, the exponential growth of installed systems) of HTS power technologies projected by the 2000 and 2006 market assessments has not occurred. Moreover, the key uncertainties—cost of HTS wire and demonstrated reliability of the technologies to the level that could garner utility acceptance—exist as they did in 2000 and 2006, although second-generation (2G) wire is now available and its cost has the potential for reduction [2]. The two technologies that were projected to form the leading edge of HTS power technology emergence—synchronous condensers and FCLs—have not yet made their market entry. Moreover, there have been no U.S. demonstrations of HTS power technologies of sufficient duration and scope for utilities to consider acceptance of HTS cable systems. Although there have been a series of demonstrations in power grids worldwide, no HTS cable project without government support has yet happened.

Where and when can the demand for HTS power equipment begin and grow? Absent a groundswell among grid operators and utility companies, which both market assessment reports argue will not come without resolution of the uncertainties in wire cost and system reliability, the major manufacturers who provide grid equipment to utilities seem to be the firms that are best able to nurture such a demand. They know how to demonstrate reliability in a way that the utilities will understand and accept, and they have the financial wherewithal to underwrite the development of such a first-of-a-kind technology, which one manufacturer estimated at US$100 million.

The development and demonstration of the HTS FCL by Siemens and the presence of other large utility vendors in demonstration products worldwide—ABB in an SMES project at Brookhaven National Laboratory [19], Nexans in the AmpaCity project in Essen, Germany [20] (an example of base case 2), LS Cable in projects in Korea [21], and Sumitomo [22] and Furukawa [23] in projects in Japan and the U.S.—provide encouraging signs of the interest of companies who could lead the market entry of HTS power technologies. So far, however, none has stepped up to make the necessary investment. (A commercial investment of about US$100 million in nonrecoverable engineering costs may be necessary for development and commercialization of a first-of-a-kind system. Beyond demonstration projects, what is needed is a corporate decision to build its own infrastructure for product development.)

Although the projected S-curve of market penetration of HTS power technologies has not yet occurred, there have been S-curve emergences in patent application filings in the United States Patent and Trademark Office in Classification 505 (Superconductor Technology: Apparatus, Material, Process) in the subclassifications for HTS wire, tape, cable, or fiber (230) and process of making HTS wire, tape, cable, coil, or fiber with coating (434), as well as process for producing HTS material (300). *S-curve emergence* means exponential growth in the cumulative sum of patent filings as a function of time. For a description of our method for detecting such emergence, see Eusebi and Silberglitt [24].

The initial rise of these S-curves in patent application filings occurred between 2005 and 2010. The assignees include ABB, GE, Siemens, and Sumitomo, as well as major cable manufacturers, which is an indication that large utility vendors have invested in research and development and have made the decision to expend the financial resources necessary to pursue patents to protect their intellectual property. Patent applications can be thought of as "bets" that the technology will eventually have market value, so the fact that the large utility vendors are filing patent applications in HTS wire and related areas suggests that they believe HTS power technologies may have market potential.

## 5.6 Barriers to Utility Adoption

Power outages are costly. In 2012, the Congressional Research Service estimated the cost of weather-related outages at US$25 billion to US$35 billion annually [25]. A 2013 White House report [26] provides estimates of yearly costs of weather-related outages from 2003 to 2012 that range from a low of US$5 billion to US$10 billion in 2007 to a high of US$40 billion to US$75 billion in 2008. Although these estimates of costs related to outage impacts may be legitimate, they do not in any way create a retrievable cash flow benefit that could be used by utilities to fund reliability or resiliency improvements. In addition, utilities face many other cash flow and cost recovery challenges that limit their ability to proactively and aggressively fund new technologies, including the following:

- Utilities are the only entities that have the "obligation to serve," which means that they must accept responsibility to provide capacity to meet any new load growth arising from any source.
- Utility funding is typically provided on a multi-year basis by rate case approval processes that in some cases can be adversarial, including objections by interveners and financial "punishment" for past performance issues, both real and perceived.
- Not all maintenance or operational expenses predicted by the utility are accepted and funded by the regulators responsible for rate case approvals.
- Failure to meet increasing reliability requirements can result in sometimes severe cost penalties for conditions that may be in some cases beyond the direct control of the utility.
- Such cost penalties further reduce available budgetary funding available to the utility and force the utility to decide which required maintenance or operations will be deferred to future years to stay within annual budget limits.

- New issues (such as cybersecurity) or unpredicted major events (such as major storms or catastrophes such as 9/11) may occur following rate case approvals that make further diversion of funds needed for operation and maintenance necessary.
- Utilities face both customer privacy restrictions and uncertainties in new load types, electrical demand, load penetration rates, locations, and daily and seasonal load cycle impacts that make accurate prediction of load growth difficult.
- In the future, independent developer bankruptcies or equipment failures (such as distributed generators, demand-side management aggregators, microgrids, or independent power producers) could add to unpredicted new capacity demands. Another more incremental variation of this issue can occur if internal load increases exceed the available internal capacity of a distributed generation or microgrid facility and the developer has insufficient space or financial resources, or cannot obtain any required local approvals to perform the upgrades and/or replacements necessary to deal with the anticipated load growth. Even if the upgrade or replacement is funded and approved, the local utility may still have to deal with capacity shortfalls during any required repair or replacement outage durations. In addition, the utility may have to provide capacity beyond that which is available from any energy storage that has been installed to handle the intermittency of the renewable resources.

Faced with combinations of challenges that can include aging infrastructure, an increase in severe weather events, growth of distributed generation, load growth in urban areas, and the greater usage of electronic devices that are sensitive to power surges, utility regulatory agencies are placing increasing emphasis on improving the resilience of the power grid [27]. The low impedance, high current-carrying capability, and fault current limiting properties of some HTS cables could be desirable to utilities as they address the resiliency challenge. However, the utility's incentive is for reliability and resiliency, not specifically for HTS systems, and they must compete with conventional technologies and, even more importantly, the temptation to address emerging trends only incrementally to minimize near-term annual capital costs.

There are several important barriers to HTS cable system adoption by utilities. Other than cost, the most important is the need for demonstration of feasible and reliable operation in a utility system over an extended period. Conventional power cables have decades of operating experience and are tested extensively before being put into service. Although there have been several demonstration projects, including the AmpaCity substation interconnect in Essen, Germany, that has been live for more than year, utilities will be hesitant to connect a new technology into their system until that specific technology (the HTS cable system) has been tested and has demonstrated its reliability under the exact conditions under which it will be used. This would require utilities to install cryogenic cooling systems with the capability for splices and returns to allow testing of HTS cable system. Continued field demonstrations of both HTS and cryogenic systems are deemed essential to validate long-term reliability.

A second barrier is the question of maintenance of HTS cable systems once installed in a utility grid. Will the utility need to hire new staff—that is, develop an HTS team—to maintain the system and make repairs if and when problems arise? Will the HTS cable system vendor provide 24/7 maintenance and repair service in the event of a power outage that affects the HTS cable? Who will certify the HTS cable system and/or provide warranty? An EPRI-sponsored workshop and subsequent tutorial on cryogenics for utility personnel addressed some of these questions [28, 29]. Continued educational approaches such as this may help to overcome this barrier.

A third barrier is related to the manner in which utilities make improvements to their transmission and distribution systems. Utility staff in transmission and distribution typically design and provide the specifications for such improvements, review competing bids, select vendors, and manage the projects. To date, only a handful of utilities that have been involved in HTS cable demonstrations have any experience with HTS cable systems, and all of these have been government-funded projects with much support from outside technical experts. For example, the Essen project was supported by a consortium of academic technologists. Dissemination of lessons learned from these projects to a larger utility audience would help to overcome this barrier.

Finally, there is the problem of inertia that accompanies any effort to bring a new technology or technical approach to a long-standing problem or institution. Utilities are extremely conservative organizations, because of both the well-established nature of the technologies that they use and their mission to provide continuous electric power to their customers despite variations in demand, performance of equipment, weather, and other contingencies. They will adopt a new technology only after its benefits have been demonstrated and its reliable operation and maintainability on their system has been proven.

It remains to be seen whether these still-significant barriers will be offset or revised in whole, or at least in part, by new potentially emerging utility drivers, including the following:

- Continuing load growth, particularly within urban centers
- Additional transmission, energy storage, and renewable capacity needs to offset renewable intermittency
- New demands for resiliency to cope with weather-related events, targeted attacks, and/or fuel disruptions, still meeting increasingly stringent reliability requirements
- The possibility that, if the reliability of cryogenic cooling can be fully achieved and demonstrated, superconducting cables may be significantly more reliable and exhibit less aging than conventional cables due to their inherent immunity to temperature changes stemming from daily and seasonal load cycling
- The continuing and accelerating issue of both above- and below-ground congestion due to vertical growth within urban centers

# 6
# CONCLUSIONS

Three major cost drivers for HTS cable systems were identified in Section 4—HTS wire, cryostats, and refrigerators. Of these, the cost of HTS wire is currently the largest significant fraction of the cost of the HTS cable system and thus is the principal driver for cost reduction. It is also the driver that is, conceptually, the easiest to project into the future due to its almost sole dependence on volume sales (discounting the possible emergence of a breakthrough technology development that could also lower costs). Reduction in cryostat costs, on the other hand, would likely require the introduction of additional competitors in the marketplace to eliminate the present sole-source situation. This is difficult to predict. Reduction of refrigerator costs will likely require significant research and development. However, for all three of these developments to occur, there would need to be a substantial increase in deployed HTS equipment.

In some cases, however, this assessment has shown that, even with HTS wire cost at its lowest projected value (US$5/kA-m), commercial viability is not achieved. In some of those cases, refrigeration and cryostat costs now represent significant cost drivers. Reduction of those costs could make those cases economically viable.

Analysis of the base cases provides estimates of how much cost reduction in HTS wire will be required for a mature HTS cable system to be cost competitive with conventional solutions. Considering that these base cases were chosen specifically because they involve conventional solutions that are both difficult to implement and expensive, broader use of HTS cable systems is likely to require further cost reduction.

Another important factor in the lack of growth of market demand in accordance with past projections is the difficulty of demonstrating the reliability of HTS power technologies in utility systems.

Demonstrating reliability at a level that could obtain widespread utility acceptance will require commercial products from a major vendor of utility equipment that can provide product warranties and support for operations and maintenance over the lifetime of the products in a utility system. A limited number of such vendors exist, and none has yet made the business decision that HTS power technologies are worth the major investment in a first-of-a-kind product. These companies are active in research, development, and government-supported demonstrations, and they have pursued related intellectual property, thus establishing a position for investment should a business case evolve. The barriers to the establishment of such a business case, including wire cost and availability in “practical length for large-scale applications” and number and quality of joints, were spelled out in a recent briefing [30].

Thus, cost reduction and proven performance in the field represent two major challenges for commercialization of HTS cable system technology. Costs of superconducting wire have shown a steady decline over past years and are projected to continue at a substantially similar rate over the foreseeable future through production improvements and volume benefits. New production techniques are currently in development by other entrants to this technology that could further ensure or exceed projected cost reductions. In-grid demonstrations of HTS technologies require a significant financial outlay, which will not be entirely borne by the utility industry. Solution of this problem will therefore require major investments from either a large vendor of utility systems or government agencies, or both. However, in the absence of some level of private or public investment to achieve the projected cost and performance needed to demonstrate full commercial viability and long-term reliability, we cannot predict the success path of this technology with full confidence in the near term.

Nevertheless, a variety of situations exist today in which an IFCL HTS solution may provide substantial advantages over other solutions in desired performance, particularly with regard to achieving increased resiliency. In some current situations, other conventional solutions cannot be deployed due to underground obstructions or underground space constraints, and in others, even at current superconducting wire costs, the IFCL HTS solution may provide an additional cost advantage.

One of the advantages of superconducting designs is that they can be customized to meet specific needs related to resiliency, reconfigurability, and the ability to transfer large blocks of power at lower voltages and very small underground cross-sectional footprints. These advantageous characteristics can be applied as follows:

- Continuously in service with limited fault current transfers
- Fault tolerant ride-through remaining available quickly after a nearby fault
- Not normally connected, but immediately available after protection clears a nearby fault

Superconducting designs also offer the following, potential long-term unquantifiable benefits:

- Manage fault currents to enable increased access for distributed resources
- Potential for improved life and reduced failure rates of downstream distribution system components that would alternatively see higher fault currents
- After any infant mortality issues (installation problems) are avoided or corrected, and if an equally reliable design configuration is chosen for the cryogenic cooling and/or replenishment system, potentially quite high superconductor reliability due to inherent immunity to normal seasonal and daily load cycles because of near-constant cryogenic temperatures and inherent protection for some external events due to pipe-type construction of a cryostat

In addition, they offer future potential for even longer-term operational benefits, as follows:

- Ongoing migration of superconducting technology to even higher voltages can provide small-footprint, underground access to city centers with increasing load demands, through dense suburban areas (bridge between rural overhead transmission city centers that could also include inherent fault current mitigation)
- Coping with potential for major unplanned load increases (for example, due to climate change impacts on air conditioning loads and/or substitution of electricity as fuel for furnaces and water heating in city centers or other unforeseen impacts)
- Higher-voltage superconductors could also mitigate the rapidly increasing fuel-based regionalization of the U.S. grid in the event of fuel contingencies and also enable region-to-region transfers of electrical capacity to offset longer-term interruptions of intermittent renewable assets (such as six-day heat storms and or polar vortexes)

# 7
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# A

# BASE CASES—SUPPORTING INFORMATION

## A.1 Selection of Base Cases

Any attempt to identify universally applicable base cases faces a number of difficulties. The first of these is the fact that all utilities are different, and even the same individual utility faces different issues and design challenges over time. Differences can arise from the following:

- Characteristics of the service territory
- The design of the local and internal grid
- Operational conditions
- Economic conditions
- Customer characteristics
- Load characteristics
- Relationships with the regulator and the local governments

These differences can also be impacted by the sometimes quite different situations that neighboring utilities may face.

All of these variables can change significantly over time, particularly as the following events occur:

- Towns grow into cities
- Industries move in or out
- Populations grow
- Unanticipated new loads are added to existing facilities
- New residential and/or business development occurs
- Cities start to grow vertically, which causes the following:
    - Substantially increases load density
    - Precludes further use of overhead electrical services
    - Vastly increases above- and below-grade congestion
    - Decreases availability of real estate, sometimes at any price

Over time in a typical city, more locations and their loads become increasingly critical to maintaining the safety and health of the population. Large concentrations of populations require much more in services, whether it is to support delivery of supplies to sustain health and safety or to support even a partial evacuation of a small portion of a city.

Vertical growth has many benefits in the vastly increased day-to-day efficiencies it provides, such as better thermal insulation due to more typical brick-and-concrete construction and many more interior walls, but it also makes continued operation of elevators and closed ventilation systems essential to health and safety, particularly for older and physically challenged occupants of high-rise buildings. Some towns or cities require electrical power to pump water for drinking and fire protection. Food delivery and distribution, basic health services, command and control, and dissemination of information to inform and calm the public all require electric power.

### A.1.1 Types of Base Cases that Could be Proposed

The potential base cases that could be considered fall into different "benefits delivered" categories:

- **Improved reliability.** Service being provided to a critical load is one example. This could be a production line process facility that would suffer major financial impacts if an unplanned interruption of power were to occur or a vital service such as a hospital, airport, or major financial, communications, or emergency services center. The type of reliability improvement might be sharing capacity or assets between substations that would otherwise be precluded due to fault current or underground physical space constraints.
- **Improved resiliency**. This could include providing increased reconfigurability to help cope with major weather events, physical disasters, or targeted attacks on utility assets throughout the full recovery scenario, such as protective isolation of faulted assets, immediate restoration of power to the extent possible, maintenance of safety and essential services for extended outage durations, command, control, and situational awareness, and any necessary long-term recovery activities.
- **Improved asset utilization.** Sharing of excess capacity between substations, such as excess-capacity transformer banks or pairing large urban networks with differing (such as city center or residential) load cycles.
- **Physical congestion mitigation.** This might include the achievement of space savings and/or dealing with limited real estate or space availabilities at the planned substation site, such as routing high-capacity distribution directly into city centers (eliminating the need for the high-voltage portion of a new substation).
- **Direct economic benefits.** This may be a case in which the IFCL HTS is less costly than the available conventional alternatives, or the added capacity enables deferrals and delays of an otherwise required new substation, or it provides alternative reconfigurability to cope with unexpected load growth, or a staged installation of a virtual substation from solely distribution buses to successive transformer additions.

Other benefits or applications may be specific to the utility design challenges and limitations in providing increased reliability or significantly increased capacity in high power density and extremely physically congested city centers experiencing ongoing vertical growth, business development, and/or substantial load increases.

Superconducting designs can be customized to meet a utility's specific needs, as follows:

- Continuously in service with limited fault current transfers
- Fault tolerant ride-through remaining available very quickly after a nearby fault
- Not normally connected, but immediately available after protection clears nearby fault

Potential long-term unquantifiable benefits include the following:

- Manage fault currents to enable increased access for distributed resources
- Potential for improved life and reduced failure rates of downstream distribution system components that would alternatively see higher fault currents
- After any infant mortality issues (installation problems) are avoided or corrected (and if an equally reliable design configuration is chosen for the cryogenic cooling and/or replenishment system), potentially extremely high superconductor reliability due to the inherent immunity to normal seasonal and daily load cycles because of near-constant cryogenic temperatures and inherent protection for some external events due to the pipe-type construction of the cryostat.

Potential longer-term operational benefits in the future include the following:

- Ongoing migration of superconducting technology to even higher voltages can provide small-footprint underground access to city centers with increasing load demands through dense suburban areas (bridge between rural overhead transmission city centers that could also include inherent fault current mitigation)
- Coping with potential for major unplanned load increases (for example, due to climate change impacts on air conditioning loads and/or substitution of electricity as fuel for furnaces and water heating in city centers or other unforeseen impacts).

Higher-voltage superconductors could also mitigate the rapidly increasing fuel-based regionalization of the U.S. grid in the event of fuel contingencies and also enable region-to-region transfers of electrical capacity to offset longer-term interruptions of intermittent renewable assets (for example, six-day heat storms or polar vortexes).

## A.2 Impacts of Migration Toward Dense Urban Infrastructure

One universal issue as towns grow into cities and eventually migrate toward having vertically growing city centers is a relatively quickly worsening lack of space. Overhead transmission and distribution become effectively precluded. Underground space is also limited by other services such as sewers, water, gas, communications, and in some cases steam and/or transportation infrastructure such as subways. These same services that compete with utilities for underground space increase their own footprint to serve higher population densities and increased levels of business, residential, and service activities for both transient and residential populations. Increases in the height of structures can also create additional electrical demand to accommodate sealed heating, ventilation, and air conditioning systems, interior lighting, elevators, and increased needs for pumping effluents to higher building floor elevations.

This can be further aggravated by the fact that existing electrical loads can become more critical by virtue of the number of people being served, requiring additional redundancy of electrical services, which further increases space requirements. Emerging city centers also draw new business development, which in turn draws more service businesses and residential development that will likely spill over into immediately adjacent neighborhoods, further increasing the overall size of the high-population-density area. As a result, real estate becomes more costly and less available, sometimes at any price.

As cities grow, even heavier traffic congestion adds to this list of issues usually in two ways. First, a combination of noise and traffic restrictions makes getting permits for routine day-to-day operations, maintenance, and even emergency repairs more difficult. Second, as normal business commutation is further increased by holiday shoppers and sightseers, many larger cities have adopted bans on truck traffic—including utility vehicles—within city centers during holiday periods that, in the worst cases, extend from before Thanksgiving through the beginning of the new year.

As a result of these conditions, building a new substation in or near a city center becomes extremely problematic. Reinforcements to increase capacity or redundancies in many cases must shoehorn into any remaining available space within existing substations. Filing and approval processes for new and modified facilities vary widely. Permits for new facilities or even small extensions of existing facility boundaries are typically quite time-consuming, major unknowns for scheduling of critically needed upgrades or uprates and, in many cases, are denied. Even if sufficient space is available within the existing substation routing for cables to enter the substation, it may involve difficult routing with limited avenues of approach, multiple bends, and/or tunneling around or under obstructions to avoid impacts on normal traffic flow. In many cases, available routes may impact and need to be coordinated with other underground services. If these are municipal services, the utility may be required to incur additional “interference costs” and reroute their planned approach and/or pay for relocations of these other services, sometimes to accommodate future plans of the municipality.

Finally, as cities grow vertically, new and increased failure potentials are created beneath city streets. Higher densities and proximities of all (electric and non-electric) services interact with each other. Road salt increases the conductivity of ground water. Load cycling and freeze–thaw cycles may grow gaps in joints and tapped insulation. Water main breaks can flood underground electrical equipment or undermine structural supports of electrical manholes and ducts. In addition to the localized heating effects of steam lines, steam jet impingement can directly damage the neighboring infrastructures of other underground services. The much smaller underground footprint of superconducting technology makes it easier to use barriers and shielding to mitigate these potential jeopardies.

Younger cities have the benefit of well-supported, industry-standard voltages and current ratings. Those older cities that were the earliest to electrify and see the earliest population and vertical growth in some cases pioneered their own new distribution cable designs and contracted with equipment vendors to build equipment to their specific voltage and current ratings. This applied even more to fault current ratings (that is, physical bracing, short-term but very high thermal withstand capabilities, and arc interruption and quench capabilities) to ensure that all the power equipment that currents flow through can withstand the mechanical, thermal, and magnetic stresses caused by faults and can successfully open quite quickly to isolate the fault, so that the remaining (not isolated) portions of the power system can restore full power and voltage to the loads they serve.

Very high fault currents are a result of not only high power density but also the redundancy of parallel paths and the total number and capacity of power sources that are directly electrically connected to the location of the fault. A *fault* is a path either to ground or across phases of a three-phase power system that effectively bypasses the electrical load that would normally be served and becomes a much lower impedance path to ground. All power sources that are interconnected to the transmission and distribution grids that are ultimately electrically connected through any path to that fault will attempt to supply current to that easier (low impedance) path to ground. As the surrounding sources (such as transmission feeders, transformers, generators, and even other motor loads) try to supply current to that fault location, these currents collect and accumulate to much higher levels as they add together from all available sources.

Utilities more typically adopt standard designs that enable them to maintain more limited inventories of common spare parts and equipment. They are typically reluctant to change from these standards and use one-off solutions except when a particular utility feels that purposeful diversity provides a desirable advantage (for example, diversity of relay vendors to increase the likelihood that at least one redundant line of protection will isolate a fault). More typically, design standard changes involve adoption of a new standard intended for all future deployments and, in some cases, programmatic replacements of older types of equipment that require increased maintenance or are beginning to exhibit operational problems.

Distances between substations are dictated by load density and the capacity of the utility’s standard design substation. Whether the city center is concentrated geographically by natural barriers (bodies of water, steep hills, and so on) or more widely laid out in an “urban sprawl” has a major impact. Substations are typically closer together (ranging from one mile to several miles apart) in urban locations, but desired proximities can be difficult to maintain as vertical growth accelerates and real estate availabilities greatly decrease. Difficulties in obtaining real estate has become more problematic for utilities as a result of the increased attempts by municipalities to use eminent domain for economic development projects. In the past, communities were more receptive to needed utility distribution projects, but some now view these projects as “just another economic development project,” and others view them as unnecessary competition with renewables (despite their intermittency and need for backup).

## A.3 Networks

Many urban utilities have adopted mesh networks to serve high-rise load centers as they developed and expanded geographically. Most very dense urban utilities are now also breaking apart and migrating away from these same mesh networks as these urban centers mature. Does this mean that the original adoption of these mesh networks was a mistake? Absolutely not! Mesh networks allowed large blocks of power to serve emerging high-rise neighborhoods and business districts. This situated multiple connection points immediately adjacent to high-rise buildings and prevented the need to route separate feeders for the succession of major new “must have” loads all the way back to a source substation. This strategy minimized underground congestion and kept lead times for electrical service upgrades to reasonable durations.

Now that major blocks of load and load types have been deployed, breaking current mesh networks into smaller pieces (that is, spot networks) allows easier reconfiguration for segregation to accomplish the following:

- Provide additional redundancy of supply to only selected critical loads
- Focus resiliency efforts on those loads that are critical to emergency services, restoration efforts, public safety, command and control, and support of local area evacuations, if needed
- Reorganize connections as might be needed to facilitate operation and coordination of ancillary services, distributed generation, demand-side management, energy storage, microgrids, and so on while enhancing worker and public safety and maintenance accessibility
- Enable future differentiation in rates when justified by differences in service costs and ancillary services

# B
# REFRIGERATION SYSTEM COSTS

This portion of the U.S. Department of Homeland Security inherently fault current limiting (IFCL) cable study is based on prior cryogenic refrigeration experience, with particular emphasis on the approaches used for HTS cables in the past. Three technologically different approaches are possible for this aspect of HTS cable design—the open bath, the reverse Brayton refrigerator, and the Stirling refrigerator. (These are described in the EPRI report *Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: Task 1—Technical Capability, Manufacturing, and Scalability Baseline and Assessment*, so the details of the technologies are not included here.) The similarities and differences of the three approaches are described and are used to estimate system costs. Because it is difficult to obtain costs of some items, in particular the reverse Brayton refrigerator, the cost estimates are based principally on the Stirling refrigerator, with some reference to the open bath system. However, because the reverse Brayton requires less maintenance, maintenance and access issues for each of the three systems are described in Section B.2.

Past and existing cryogenic cooling systems for HTS cables have not been designed for the type of long-term service that is required for power system components. Here, it is assumed that a cable system is expected to operate for a period of 30 years, and life cycle costs for such operation are estimated. These life cycle costs include initial capital investment, operations and maintenance, electric power costs, and when appropriate, replacement costs at expected intervals.

Other options that have been used for various cryogenic components for HTS cables in the past are 1) rent and 2) a third party owns and operates. For example, RWE rents (or leases) the nitrogen tanks used for Essen cable. It is believed that the electric utilities would not consider this to be a viable long-term option for superconducting cables, at least not in the United States. However, for reference, some costs for short-term equipment rental are provided in Section B.3.

## B.1 Capital Cost

### *B.1.1 Refrigeration*

Because there was little reliable information on the reverse Brayton refrigerator cost, this cost exercise was carried out for a Stirling refrigerator-based cooling system. It was assumed that Gen 2 HTS material will be used for the cables of interest and that the operating temperature must be maintained between 67 K and 72 K.

#### B.1.1.1 Costs for the Stirling Refrigerator

Many Stirling Cryogenics SPC-4 cryogenerators are built and installed in a variety of applications each year. Today, these are supplied by DH Industries. The main product, the SPC-4, provides cooling from as low as 40 K to as high as 170 K. It provides a nominal 3.5 kW of cooling at temperatures from about 67 K to 72 K and requires 45 kW of electrical power in this range. Multiple SPC-4s can be combined to achieve almost any cooling power that might be required for an HTS power cable installation. Combined systems including up to eight SPC-4s have been installed. The number of units installed depends on the maximum cooling required and any redundancy requirements. In this case, N-1 redundancy was used for all installations; therefore, 10 kW of cooling would require four SPC-4s. The SPC-4, as delivered, is designed for water cooling. Each SPC-4 cooler requires ~4000 L/h of 15°C cooling water. If water cooling is not directly available, some form of radiator and air cooling is needed. The nominal cost of a single SPC-4, including air cooling and a liquid nitrogen pump, is US$440,000. The power required to operate the radiator is about 3 kW per refrigerator. The radiator may have adequate capacity for several refrigerators, or there may be one chiller for each refrigerator. See Table B-1.

**Table B-1**
**Stirling refrigerator costs**

| Capacity (kW at 72 K) | Number of Refrigerators (note 1) | Cost (US$) | Installation (US$) | Piping and Other Costs (US$) | Total Installed Cost (US$) |
|---|---|---|---|---|---|
| 3.5 | 2 | 880,000 | 150,000 | 220,000 | 1,250,000 |
| 7 | 3 | 1,320,000 | 200,000 | 280,000 | 1,800,000 |
| 10.5 | 4 | 1,760,000 | 250,000 | 350,000 | 2,360,000 |
| 17.5 | 6 | 2,640,000 | 300,000 | 400,000 | 3,340,000 |
| 24.5 | 8 | 3,520,000 | 330,000 | 440,000 | 4,290,000 |

**Notes:**

1. Stirling SPC-4 cryogenerator. Number required assumes N-1 redundancy.

### B.1.1.2 Costs for the Storage Cryostat

Some sort of storage cryostat will be required for any cable system. The volume of this cryostat will depend on the type of cooling technology. To limit frequency of access, the cryostat for the open bath cooling system is typically chosen to be quite large, on the order of 40,000 liters. The cost of a large cryostat of this size is about US$125,000. The storage cryostat for a refrigerator-based system is smaller; the analysis assumed 15,000 liters, which costs about US$75,000.

### B.1.1.3 Costs for the Temperature-Controlled Cryostat

Independent of the type of cooling system, a temperature-controlled cryostat is needed as an interface where liquid is prepared for entering the cable. This cryostat is maintained at a constant temperature either by the output of the refrigerator or by one or more vacuum pumps or both. The quantity of liquid in the cryostat liquid is maintained by makeup fluid from the main storage cryostat. Within this cryostat is a heat exchanger that receives return liquid from the cable system and possibly some makeup liquid from the supply cryostat. Typically, the incoming liquid is pressurized by a pump, which is designed to maintain the pressure in the cable, and a flow pump, for circulation of the fluid required by the cable system. Capital costs are provided for two temperature-controlled cryostats having different capacities: 5 to 10 kW at a nominal 70 K and 10 to 20 kW at a nominal 70 K. See Tables B-2 and B-3.

**Table B-2**
**Costs for temperature-controlled cryostat for a 5- to 10-kW system**

| Component | Characteristic | Cost (US$) |
|---|---|---:|
| Cryostat | 1500 L | 25,000 |
| Heat exchanger | 10 kW at 67 K | 15,000 |
| Liquid flow pump | 1.5 L/s at 30 bar | 7,000 |
| Pressurizing pump | Maintains 30 bar | 5,000 |
| Valves and connections | Various internal | 15,000 |
| Vacuum pump (note 1) | | 13,000 |
| Instrumentation | Data and control via Internet | 10,000 |
| Interconnections | | 25,000 |
| Installation | Mechanical and cryogenics | 40,000 |
| Total | | 150,000 |

**Notes:**

1. Under certain conditions, a vacuum pump may be required. It is included here.

**Table B-3**
**Costs for temperature-controlled cryostat for a 5- to 10-kW system**

| Component | Characteristic | Cost (US$) |
|---|---|---:|
| Cryostat | 3000 L | 40,000 |
| Heat exchanger | 20 kW at 67 K | 20,000 |
| Liquid flow pump | 3 L/s at 30 bar | 10,000 |
| Pressurizing pump | Maintains 30 bar | 5,000 |
| Valves and connections | Various internal | 20,000 |
| Vacuum pump (note 1) | | 25,000 |
| Instrumentation | Data and control via Internet | 10,000 |
| Interconnections | | 25,000 |
| Installation | Mechanical and cryogenics | 60,000 |
| Total | | 215,000 |

**Notes:**

1. Under certain conditions, a vacuum pump may be required. It is included here.

## B.2 Maintenance

### *B.2.1 Maintenance for the Refrigerator System*

Maintenance for various systems depends on the type of refrigerator and the operating mode. The Stirling refrigerators require maintenance every six months. This maintenance requires approximately one day, and repair and replacement costs are about US$50,000. If needed, this can be done with a minimum of interference with the operation and can be accomplished while the rest of the system is cold. The assessment assumed redundancy of refrigerators so that maintenance can be done on an out-of-service refrigerator. This maintenance can be scheduled so that there will be no interference with the operation of a cable system. In addition to the refrigerator, there is a helium pump that supplies compressed helium to operate the refrigeration part of the SPC-4. The maintenance frequency and cost provided here include this component.

In addition to the specific maintenance on the refrigerator, there is a need for regular inspection and observation. It was projected that this would require two person days per month and that the annual cost of this will be about US$20,000 per year, independent of refrigerator capacity.

### *B.2.2 Maintenance for the Temperature-Controlled Cryostat*

There will be little need for maintenance on most parts of this component. The two significant items that will require replacement after some period of operation are the vacuum and liquid pumps. Here, the analysis assumed that they will have a life expectancy of about 10,000 hours or three years. The cost for rebuilt Kinney vacuum pumps is about 70% of the cost of a new pump. The analysis assumed that the three-year maintenance will be this percentage of the original cost. Information on used liquid pumps is not certain, and they may have to be replaced completely. However, they are not that expensive.

Because the vacuum pumps are at ambient temperature, their replacement will be straightforward and can be accomplished in a day (probably a few hours). The liquid pumps will require some components to be warmed to ambient, and ideally would be scheduled when the cable will be offline.

In addition to this maintenance, the system will have to be inspected routinely. This should probably occur during normal substation inspection. If part of such a routine inspection, it will probably require only an extra hour be added.

### *B.2.3 Liquid Nitrogen Delivery*

Frequency of access to refill the supply cryostat depends on the type of cooling. In the case of the open bath cooling system, access will be necessary at least monthly, and perhaps weekly. The frequency of access does not affect the base cost of the nitrogen that is used in the cable. For cooling systems that use refrigerators, the frequency of access and refill will depend on nitrogen use rate and boil-off due to heat that enters the cryostat from ambient. Boil-off on typical storage cryostats ranges from 0.2 % to about 0.6% per day. The percentage is relative to the maximum capacity of the cryostat. Typical cryostats for open bath systems store in excess of 40,000 liters and have a boil-off of about 80 liters per day. Cryostats in the 15,000 liter range that might be used for refrigerator-based cooling systems have boil-off rates of around 0.4%, or 40 liters per day.

At present, the cost of liquid nitrogen delivered in bulk is around US$0.20 per liter. The initial cooldown and fill of a typical HTS cable may require up to 10 liters of liquid nitrogen per meter of length. In addition, there is the initial fill of the storage and temperature-controlled cryostat. Initial and refill costs for liquid nitrogen for various systems are presented in Table B-4.

**Table B-4**
**Liquid nitrogen costs for various systems**

| Cooling Capacity | Cable Length | Stirling | | Open Bath | |
|---|---|---|---|---|---|
| | | Initial | Annual | Initial | Annual |
| (kW at 72 K) | (km) | (US$) | (US$) | (US$) | (US$) |
| 3.5 | 1 | 5,000 | 7,000 | 8,000 | 40,000 |
| 7 | 2 | 7,000 | 9,000 | 9,000 | 73,000 |
| 10.5 | 3 | 9,000 | 11,000 | 10,000 | 110,000 |
| 17.5 | 5 | 12,000 | 14,000 | 12,000 | 165,000 |
| 24.5 | 7 | 14,000 | 20,000 | 14,000 | 220,000 |

## B.3 Power Costs

Annual power costs for the Stirling and open bath refrigerator systems for HTS power cables are given in Table B-5. Costs are based on base power costs of US$0.10/kWh.

**Table B-5**
**Power consumption costs for Stirling and open bath systems**

| Cooling Capacity (kW at 72 K) | Cable Length (km) | Stirling Annual (US$) | Open Bath Annual (US$) |
|---|---|---|---|
| 3.5 | 1 | 33,000 | 5,060 |
| 7 | 2 | 66,000 | 10,000 |
| 10.5 | 3 | 96,000 | 15,000 |
| 17.5 | 5 | 145,000 | 22,000 |
| 24.5 | 7 | 200,000 | 30,000 |

### *B.3.1 Costs to Rent Cryogenic Equipment for High-Temperature Superconducting Power Cables*

Several types of cryogenic equipment have been rented or leased for HTS power cables. This has not proved to be an effective long-term strategy because the owners of the cryogenic equipment have many demands for the equipment’s use, and when initial contracts have been satisfied, the cryogenic companies move the equipment to another location. Because many of the components of the HTS cables are not nearly as well developed as the cryogenics, various operations and tests did not occur on schedule. As a result, projects such as the program for the Albany cable were not completed as planned.

Nevertheless, some data is available on the Albany and Essen cable systems. In the case of the Albany cable system project, for which the U.S. DOE supported the installation, the refrigeration system was considered as a part of the manufacturers’ contribution to the project. In the case of the Essen cable, some of the components are rented by RWE—in particular, the liquid nitrogen storage tank, for which the rental fee is about US$1200 per month. Other information for the cryogenics for the Essen cable is that its overall cost was about US$550,000, and the annual nitrogen cost is about US$20,000. These costs are a bit less than was estimated for the smallest open bath system. However, the Essen cable is made of Gen 1 material and operates at a higher temperature than is possible with Gen 2 material. The total load of the Essen cable is only about 2 kW and occurs at a temperature greater than calculated for the refrigerator systems described in this report.

## B.4 Costs for Simplified Building Blocks

The values in Table B-6 are not for the specific building blocks, which may change, but for estimated total lengths of cable made of Gen 2 material in which the heat leak per kilometer, including ends and connections, is about 3.5 kW.

**Table B-6**
**Refrigeration system costs for simplified building blocks**

| Cooling Capacity (note 1) | Cable Length | Capital Cost | Annual Maintenance | Annual Liquid Nitrogen and Power |
|---|---|---|---|---|
| (kW at 72 K) | (km) | (US$) | (US$) | US$ |
| 3.5 | 1 | 1,250,000 | 100,000 | 40,000 |
| 7 | 2 | 1,800,000 | 200,000 | 75,000 |
| 10.5 | 3 | 2,360,000 | 300,000 | 107,000 |
| 17.5 | 5 | 3,340,000 | 500,000 | 159,000 |
| 24.5 | 7 | 4,290,000 | 700,000 | 220,000 |

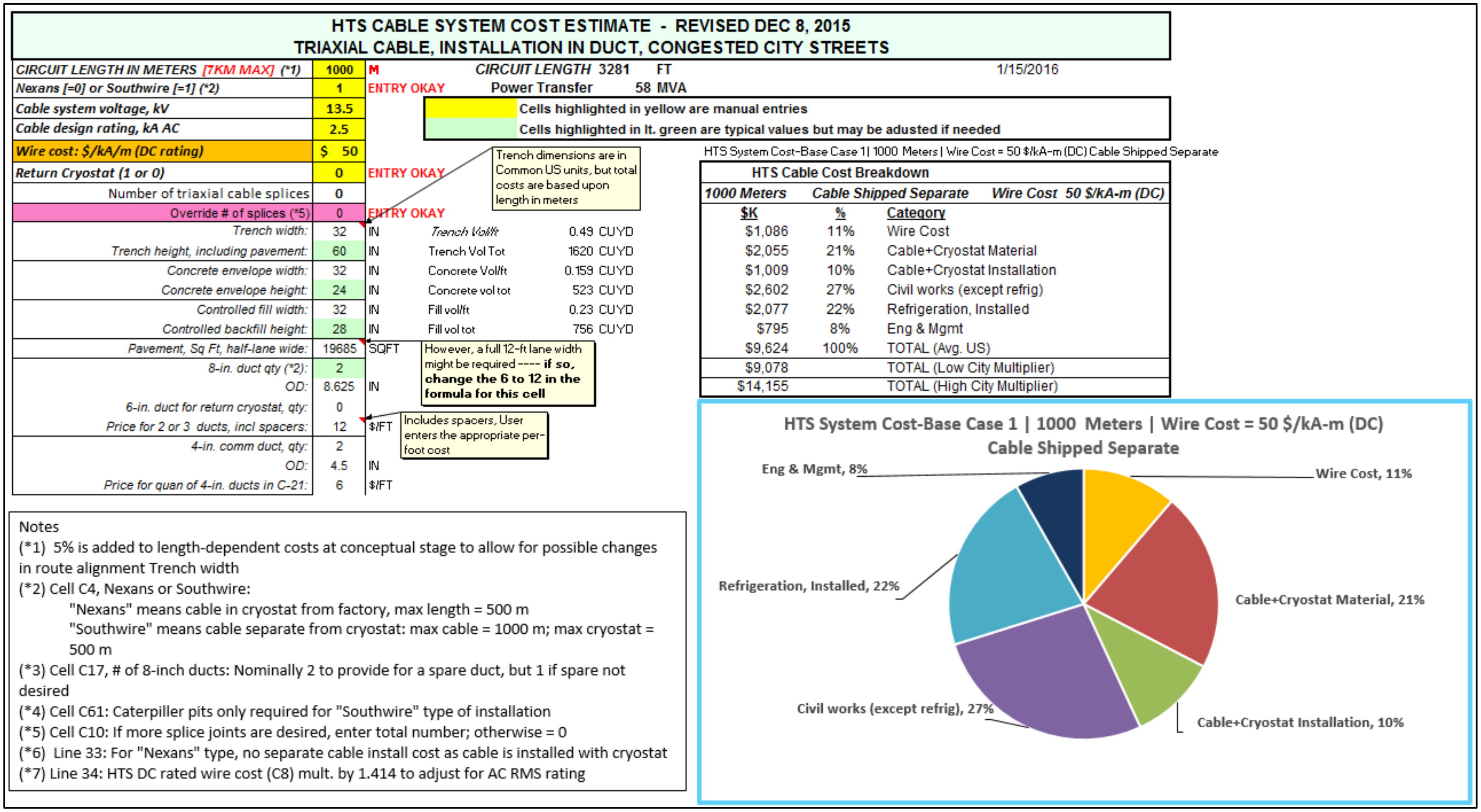
**Notes:**

1. Assumes N-1 redundancy.

# C

# HIGH-TEMPERATURE SUPERCONDUCTING CABLE SYSTEM COST MODEL SPREADSHEET

Figures C-1 through C-3 show sample screens from the EPRI HTS cable system cost model spreadsheet. Inputs and outputs for one of the scenarios from base case 1 are shown. Appendix D shows all the inputs and outputs for all the base case scenarios.



HTS CABLE SYSTEM COST ESTIMATE - REVISED DEC 8, 2015
TRIAXIAL CABLE, INSTALLATION IN DUCT, CONGESTED CITY STREETS

1/15/2016

| | | | | | |
|---|---|---|---|---|---|
| *CIRCUIT LENGTH IN METERS [7KM MAX] (*1)* | 1000 | M | *CIRCUIT LENGTH* | 3281 | FT |
| *Nexans [=0] or Southwire [=1] (*2)* | 1 | ENTRY OKAY | Power Transfer | 58 | MVA |
| *Cable system voltage, kV* | 13.5 | | | | |
| *Cable design rating, kA AC* | 2.5 | | | | |
| *Wire cost: $/kA/m (DC rating)* | $ 50 | | | | |
| *Return Cryostat (1 or 0)* | 0 | ENTRY OKAY | | | |
| Number of triaxial cable splices | 0 | | | | |
| Override # of splices (*5) | 0 | ENTRY OKAY | | | |
| *Trench width:* | 32 | IN | *Trench Vol/ft* | 0.49 | CUYD |
| *Trench height, including pavement:* | 60 | IN | Trench Vol Tot | 1620 | CUYD |
| *Concrete envelope width:* | 32 | IN | Concrete Vol/ft | 0.159 | CUYD |
| *Concrete envelope height:* | 24 | IN | Concrete vol tot | 523 | CUYD |
| *Controlled fill width:* | 32 | IN | Fill vol/ft | 0.23 | CUYD |
| *Controlled backfill height:* | 28 | IN | Fill vol tot | 756 | CUYD |
| *Pavement, Sq Ft, half-lane wide:* | 19685 | SQFT | | | |
| *8-in. duct qty (*2):* | 2 | | | | |
| *OD:* | 8.625 | IN | | | |
| *6-in. duct for return cryostat, qty:* | 0 | | | | |
| *Price for 2 or 3 ducts, incl spacers:* | 12 | $/FT | | | |
| *4-in. comm duct, qty:* | 2 | | | | |
| *OD:* | 4.5 | IN | | | |
| *Price for quan of 4-in. ducts in C-21:* | 6 | $/FT | | | |

**Cells highlighted in yellow are manual entries**

**Cells highlighted in lt. green are typical values but may be adusted if needed**

Trench dimensions are in Common US units, but total costs are based upon length in meters

However, a full 12-ft lane width might be required ---- **if so, change the 6 to 12 in the formula for this cell**

Includes spacers, User enters the appropriate per-foot cost

HTS System Cost-Base Case 1| 1000 Meters | Wire Cost = 50 $/kA-m (DC) Cable Shipped Separate

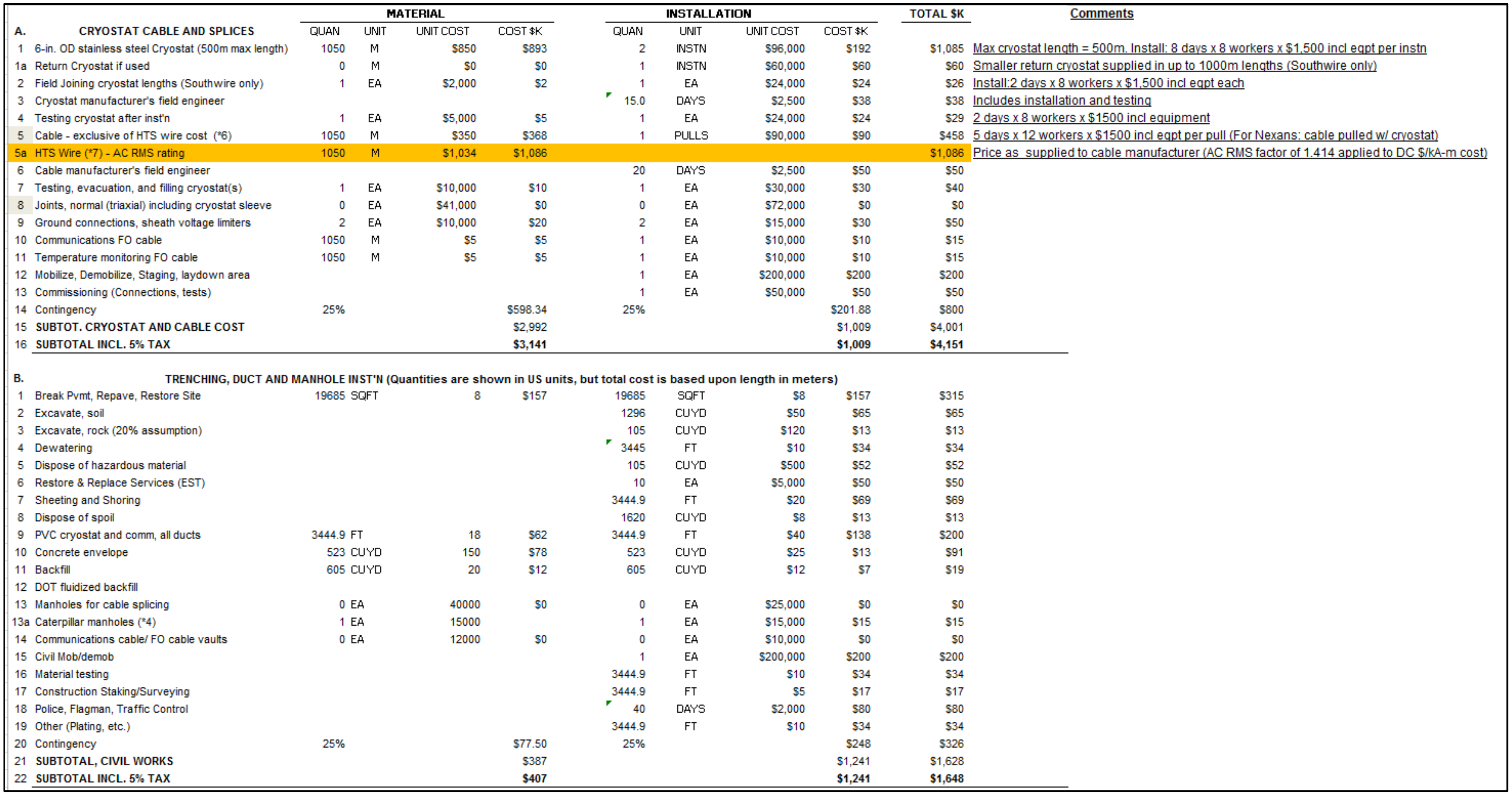
**HTS Cable Cost Breakdown**

***1000 Meters*** ***Cable Shipped Separate*** ***Wire Cost 50 $/kA-m (DC)***

| $K | % | Category |
|---|---|---|
| $1,086 | 11% | Wire Cost |
| $2,055 | 21% | Cable+Cryostat Material |
| $1,009 | 10% | Cable+Cryostat Installation |
| $2,602 | 27% | Civil works (except refrig) |
| $2,077 | 22% | Refrigeration, Installed |
| $795 | 8% | Eng & Mgmt |
| $9,624 | 100% | TOTAL (Avg. US) |
| $9,078 | | TOTAL (Low City Multiplier) |
| $14,155 | | TOTAL (High City Multiplier) |

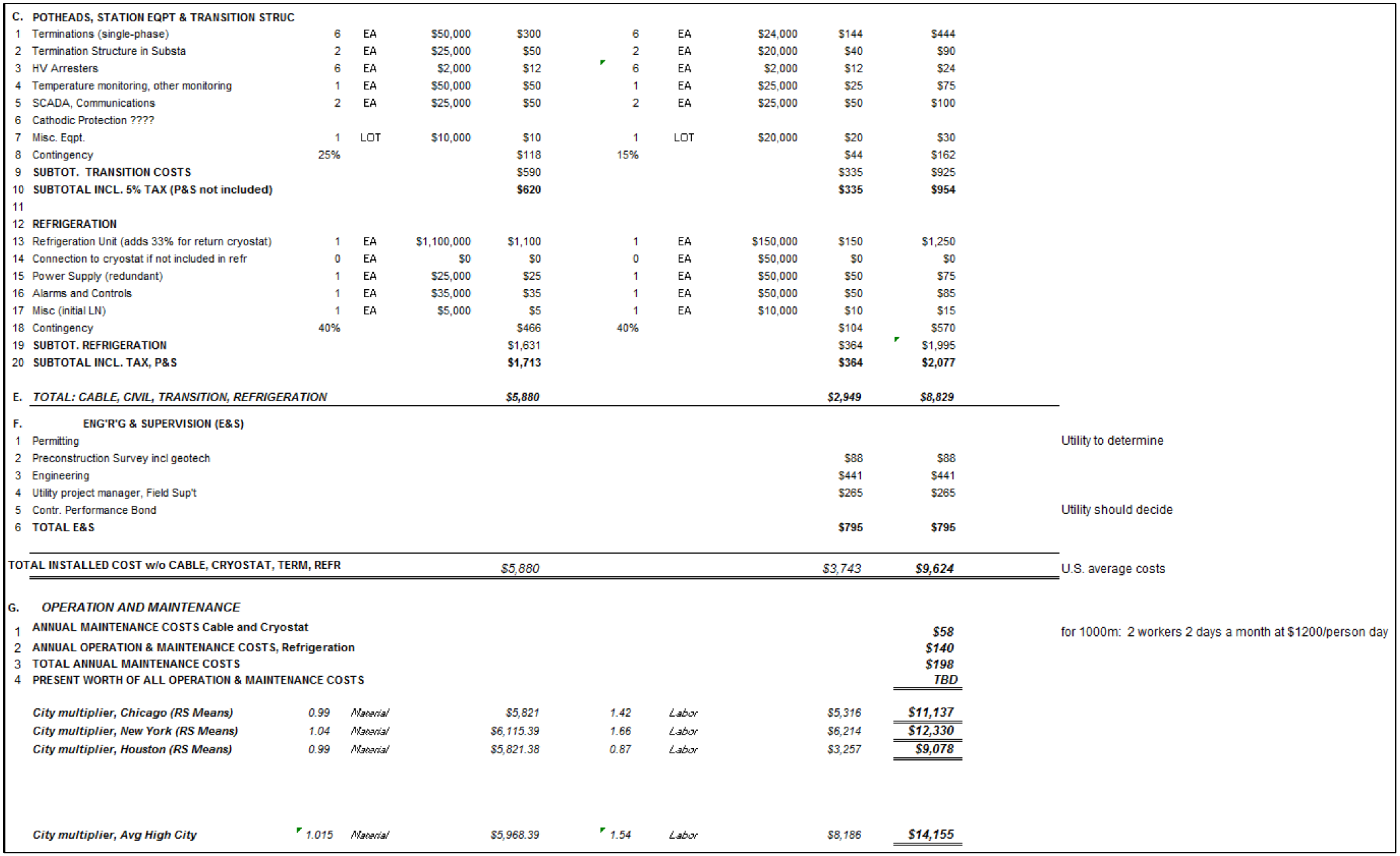
Notes
(*1) 5% is added to length-dependent costs at conceptual stage to allow for possible changes in route alignment Trench width
(*2) Cell C4, Nexans or Southwire:
"Nexans" means cable in cryostat from factory, max length = 500 m
"Southwire" means cable separate from cryostat: max cable = 1000 m; max cryostat = 500 m
(*3) Cell C17, # of 8-inch ducts: Nominally 2 to provide for a spare duct, but 1 if spare not desired
(*4) Cell C61: Caterpiller pits only required for "Southwire" type of installation
(*5) Cell C10: If more splice joints are desired, enter total number; otherwise = 0
(*6) Line 33: For "Nexans" type, no separate cable install cost as cable is installed with cryostat
(*7) Line 34: HTS DC rated wire cost (C8) mult. by 1.414 to adjust for AC RMS rating

**Figure C-1**
**High-temperature superconducting cable cost model spreadsheet—input and output screens**



| | | MATERIAL | | | | INSTALLATION | | | | TOTAL $K | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **A.** | **CRYOSTAT CABLE AND SPLICES** | QUAN | UNIT | UNIT COST | COST $K | QUAN | UNIT | UNIT COST | COST $K | | |
| 1 | 6-in. OD stainless steel Cryostat (500m max length) | 1050 | M | $850 | $893 | 2 | INSTN | $96,000 | $192 | $1,085 | Max cryostat length = 500m. Install: 8 days x 8 workers x $1,500 incl eqpt per instn |
| 1a | Return Cryostat if used | 0 | M | $0 | $0 | 1 | INSTN | $60,000 | $60 | $60 | Smaller return cryostat supplied in up to 1000m lengths (Southwire only) |
| 2 | Field Joining cryostat lengths (Southwire only) | 1 | EA | $2,000 | $2 | 1 | EA | $24,000 | $24 | $26 | Install:2 days x 8 workers x $1,500 incl eqpt each |
| 3 | Cryostat manufacturer's field engineer | | | | | 15.0 | DAYS | $2,500 | $38 | $38 | Includes installation and testing |
| 4 | Testing cryostat after inst'n | 1 | EA | $5,000 | $5 | 1 | EA | $24,000 | $24 | $29 | 2 days x 8 workers x $1500 incl equipment |
| 5 | Cable - exclusive of HTS wire cost (*6) | 1050 | M | $350 | $368 | 1 | PULLS | $90,000 | $90 | $458 | 5 days x 12 workers x $1500 incl eqpt per pull (For Nexans: cable pulled w/ cryostat) |
| 5a | HTS Wire (*7) - AC RMS rating | 1050 | M | $1,034 | $1,086 | | | | | $1,086 | Price as supplied to cable manufacturer (AC RMS factor of 1.414 applied to DC $/kA-m cost) |
| 6 | Cable manufacturer's field engineer | | | | | 20 | DAYS | $2,500 | $50 | $50 | |
| 7 | Testing, evacuation, and filling cryostat(s) | 1 | EA | $10,000 | $10 | 1 | EA | $30,000 | $30 | $40 | |
| 8 | Joints, normal (triaxial) including cryostat sleeve | 0 | EA | $41,000 | $0 | 0 | EA | $72,000 | $0 | $0 | |
| 9 | Ground connections, sheath voltage limiters | 2 | EA | $10,000 | $20 | 2 | EA | $15,000 | $30 | $50 | |
| 10 | Communications FO cable | 1050 | M | $5 | $5 | 1 | EA | $10,000 | $10 | $15 | |
| 11 | Temperature monitoring FO cable | 1050 | M | $5 | $5 | 1 | EA | $10,000 | $10 | $15 | |
| 12 | Mobilize, Demobilize, Staging, laydown area | | | | | 1 | EA | $200,000 | $200 | $200 | |
| 13 | Commissioning (Connections, tests) | | | | | 1 | EA | $50,000 | $50 | $50 | |
| 14 | Contingency | 25% | | | $598.34 | 25% | | | $201.88 | $800 | |
| 15 | **SUBTOT. CRYOSTAT AND CABLE COST** | | | | $2,992 | | | | $1,009 | $4,001 | |
| 16 | **SUBTOTAL INCL. 5% TAX** | | | | **$3,141** | | | | **$1,009** | **$4,151** | |
| **B.** | **TRENCHING, DUCT AND MANHOLE INST'N (Quantities are shown in US units, but total cost is based upon length in meters)** | | | | | | | | | | |
| 1 | Break Pvmt, Repave, Restore Site | 19685 | SQFT | 8 | $157 | 19685 | SQFT | $8 | $157 | $315 | |
| 2 | Excavate, soil | | | | | 1296 | CUYD | $50 | $65 | $65 | |
| 3 | Excavate, rock (20% assumption) | | | | | 105 | CUYD | $120 | $13 | $13 | |
| 4 | Dewatering | | | | | 3445 | FT | $10 | $34 | $34 | |
| 5 | Dispose of hazardous material | | | | | 105 | CUYD | $500 | $52 | $52 | |
| 6 | Restore & Replace Services (EST) | | | | | 10 | EA | $5,000 | $50 | $50 | |
| 7 | Sheeting and Shoring | | | | | 3444.9 | FT | $20 | $69 | $69 | |
| 8 | Dispose of spoil | | | | | 1620 | CUYD | $8 | $13 | $13 | |
| 9 | PVC cryostat and comm, all ducts | 3444.9 | FT | 18 | $62 | 3444.9 | FT | $40 | $138 | $200 | |
| 10 | Concrete envelope | 523 | CUYD | 150 | $78 | 523 | CUYD | $25 | $13 | $91 | |
| 11 | Backfill | 605 | CUYD | 20 | $12 | 605 | CUYD | $12 | $7 | $19 | |
| 12 | DOT fluidized backfill | | | | | | | | | | |
| 13 | Manholes for cable splicing | 0 | EA | 40000 | $0 | 0 | EA | $25,000 | $0 | $0 | |
| 13a | Caterpillar manholes (*4) | 1 | EA | 15000 | | 1 | EA | $15,000 | $15 | $15 | |
| 14 | Communications cable/ FO cable vaults | 0 | EA | 12000 | $0 | 0 | EA | $10,000 | $0 | $0 | |
| 15 | Civil Mob/demob | | | | | 1 | EA | $200,000 | $200 | $200 | |
| 16 | Material testing | | | | | 3444.9 | FT | $10 | $34 | $34 | |
| 17 | Construction Staking/Surveying | | | | | 3444.9 | FT | $5 | $17 | $17 | |
| 18 | Police, Flagman, Traffic Control | | | | | 40 | DAYS | $2,000 | $80 | $80 | |
| 19 | Other (Plating, etc.) | | | | | 3444.9 | FT | $10 | $34 | $34 | |
| 20 | Contingency | 25% | | | $77.50 | 25% | | | $248 | $326 | |
| 21 | **SUBTOTAL, CIVIL WORKS** | | | | $387 | | | | $1,241 | $1,628 | |
| 22 | **SUBTOTAL INCL. 5% TAX** | | | | **$407** | | | | **$1,241** | **$1,648** | |

**Figure C-2**
**High-temperature superconducting cable cost model spreadsheet—calculation page, part 1**



| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **C.** | **POTHEADS, STATION EQPT & TRANSITION STRUC** | | | | | | | | | | |
| 1 | Terminations (single-phase) | 6 | EA | $50,000 | $300 | 6 | EA | $24,000 | $144 | $444 | |
| 2 | Termination Structure in Substa | 2 | EA | $25,000 | $50 | 2 | EA | $20,000 | $40 | $90 | |
| 3 | HV Arresters | 6 | EA | $2,000 | $12 | 6 | EA | $2,000 | $12 | $24 | |
| 4 | Temperature monitoring, other monitoring | 1 | EA | $50,000 | $50 | 1 | EA | $25,000 | $25 | $75 | |
| 5 | SCADA, Communications | 2 | EA | $25,000 | $50 | 2 | EA | $25,000 | $50 | $100 | |
| 6 | Cathodic Protection ???? | | | | | | | | | | |
| 7 | Misc. Eqpt. | 1 | LOT | $10,000 | $10 | 1 | LOT | $20,000 | $20 | $30 | |
| 8 | Contingency | 25% | | | $118 | 15% | | | $44 | $162 | |
| 9 | **SUBTOT. TRANSITION COSTS** | | | | $590 | | | | $335 | $925 | |
| 10 | **SUBTOTAL INCL. 5% TAX (P&S not included)** | | | | **$620** | | | | **$335** | **$954** | |
| 11 | | | | | | | | | | | |
| 12 | **REFRIGERATION** | | | | | | | | | | |
| 13 | Refrigeration Unit (adds 33% for return cryostat) | 1 | EA | $1,100,000 | $1,100 | 1 | EA | $150,000 | $150 | $1,250 | |
| 14 | Connection to cryostat if not included in refr | 0 | EA | $0 | $0 | 0 | EA | $50,000 | $0 | $0 | |
| 15 | Power Supply (redundant) | 1 | EA | $25,000 | $25 | 1 | EA | $50,000 | $50 | $75 | |
| 16 | Alarms and Controls | 1 | EA | $35,000 | $35 | 1 | EA | $50,000 | $50 | $85 | |
| 17 | Misc (initial LN) | 1 | EA | $5,000 | $5 | 1 | EA | $10,000 | $10 | $15 | |
| 18 | Contingency | 40% | | | $466 | 40% | | | $104 | $570 | |
| 19 | **SUBTOT. REFRIGERATION** | | | | $1,631 | | | | $364 | $1,995 | |
| 20 | **SUBTOTAL INCL. TAX, P&S** | | | | **$1,713** | | | | **$364** | **$2,077** | |
| **E.** | ***TOTAL: CABLE, CIVIL, TRANSITION, REFRIGERATION*** | | | | ***$5,880*** | | | | ***$2,949*** | ***$8,829*** | |
| **F.** | **ENG'R'G & SUPERVISION (E&S)** | | | | | | | | | | |
| 1 | Permitting | | | | | | | | | | Utility to determine |
| 2 | Preconstruction Survey incl geotech | | | | | | | | $88 | $88 | |
| 3 | Engineering | | | | | | | | $441 | $441 | |
| 4 | Utility project manager, Field Sup't | | | | | | | | $265 | $265 | |
| 5 | Contr. Performance Bond | | | | | | | | | | Utility should decide |
| 6 | **TOTAL E&S** | | | | | | | | **$795** | **$795** | |
| **TOTAL INSTALLED COST w/o CABLE, CRYOSTAT, TERM, REFR** | | | | | *$5,880* | | | | *$3,743* | ***$9,624*** | U.S. average costs |
| **G.** | ***OPERATION AND MAINTENANCE*** | | | | | | | | | | |
| 1 | **ANNUAL MAINTENANCE COSTS Cable and Cryostat** | | | | | | | | | ***$58*** | for 1000m: 2 workers 2 days a month at $1200/person day |
| 2 | **ANNUAL OPERATION & MAINTENANCE COSTS, Refrigeration** | | | | | | | | | ***$140*** | |
| 3 | **TOTAL ANNUAL MAINTENANCE COSTS** | | | | | | | | | ***$198*** | |
| 4 | **PRESENT WORTH OF ALL OPERATION & MAINTENANCE COSTS** | | | | | | | | | ***TBD*** | |
| | ***City multiplier, Chicago (RS Means)*** | *0.99* | *Material* | | *$5,821* | *1.42* | *Labor* | | *$5,316* | ***$11,137*** | |
| | ***City multiplier, New York (RS Means)*** | *1.04* | *Material* | | *$6,115.39* | *1.66* | *Labor* | | *$6,214* | ***$12,330*** | |
| | ***City multiplier, Houston (RS Means)*** | *0.99* | *Material* | | *$5,821.38* | *0.87* | *Labor* | | *$3,257* | ***$9,078*** | |
| | ***City multiplier, Avg High City*** | *1.015* | *Material* | | *$5,968.39* | *1.54* | *Labor* | | *$8,186* | ***$14,155*** | |

**Figure C-3**
**High-temperature superconducting cable cost model spreadsheet—calculation page, part 2**

# D

# INPUT AND OUTPUT DETAILS FOR ALL BASE CASES WITH DIFFERENT WIRE COSTS

Figures D-1 through D-4 show full details for inputs and outputs for all the base case scenarios that were carried out in support of the value proposition effort described in Section 5 of this report.

| BASE CASE | 1 | | 1 | | 1 | |
|---|---|---|---|---|---|---|
| File name suffix | BC1-5-1 | BC1-5-0 | BC1-50-1 | BC1-50-0 | BC1-120-1 | BC1-120-0 |
| ***CIRCUIT LENGTH IN METERS*** | 2000 | | 2000 | | 2000 | |
| ***Cable shipped inside cryostat*** | No | Yes | No | Yes | No | Yes |
| ***Cable system voltage, kV*** | 35 | | 35 | | 35 | |
| ***Cable design rating, kA*** | 2 | | 2 | | 2 | |
| ***Power transfer, MVA*** | 121 | | 121 | | 121 | |
| ***HTS wire rating, kA DC*** | 4.2 | | 4.2 | | 4.2 | |
| ***Wire cost: $/kA/m (DC rating)*** | 5 | | 50 | | 120 | |
| ***Return Cryostat (1 or 0)*** | Yes | Yes | Yes | Yes | Yes | Yes |
| | | | | | | |
| ***System Costs, 2015 $K*** | $K | | $K | | $K | |
| Wire Cost | $174 | $174 | $1,737 | $1,737 | $4,170 | $4,170 |
| Cable+Cryostat Material | $4,774 | $4,903 | $5,263 | $5,391 | $6,023 | $6,151 |
| Cable+Cryostat Installation | $1,800 | $1,815 | $1,800 | $1,815 | $1,800 | $1,815 |
| Civil works (except refrig) | $4,270 | $4,400 | $4,270 | $4,400 | $4,270 | $4,400 |
| Refrigeration, Installed | $3,753 | $3,753 | $3,753 | $3,753 | $3,753 | $3,753 |
| Eng & Mgmt | $1,329 | $1,354 | $1,514 | $1,539 | $1,801 | $1,826 |
| TOTAL (Avg. US) | $16,101 | $16,399 | $18,338 | $18,636 | $21,817 | $22,116 |
| TOTAL (Low City Multiplier) | $15,182 | $15,469 | $17,374 | $17,662 | $20,784 | $21,072 |
| TOTAL (High City Multiplier) | $23,744 | $24,123 | $26,231 | $26,610 | $30,100 | $30,478 |
| | | | | | | |
| COST RANGES - SINGLE CABLE | Low | High | Low | High | Low | High |
| Wire Cost, $kA/m | 5 | | 50 | | 120 | |
| Low to High City Range | $15,182 | $24,123 | $17,374 | $26,610 | $20,784 | $30,478 |
| Average U.S. | $16,101 | $16,399 | $18,338 | $18,636 | $21,817 | $22,116 |
| | | | | | | |
| X (TIMES) NUMBER OF CABLES | 1 | 1 | 1 | 1 | 1 | 1 |
| Low to High City Range | $15,182 | $24,123 | $17,374 | $26,610 | $20,784 | $30,478 |
| Average U.S. | $16,101 | $16,399 | $18,338 | $18,636 | $21,817 | $22,116 |
| | | | | | | |
| Value Proposition, $K | $25,200 | | | | | |

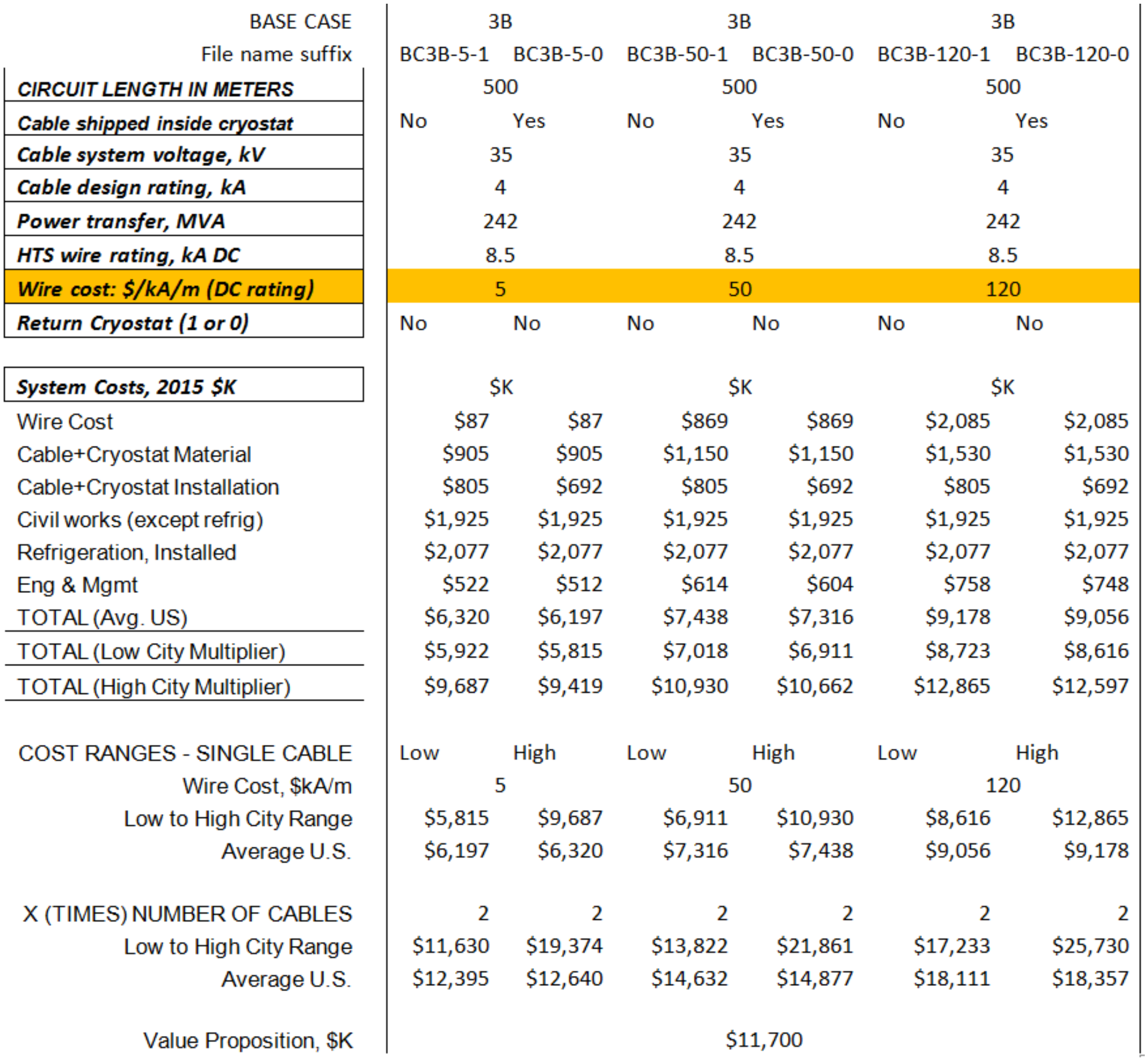
**Figure D-1**
**Base case 1 inputs and outputs for different wire costs**

| BASE CASE | 2 | | 2 | | 2 | |
|---|---|---|---|---|---|---|
| File name suffix | BC2-5-1 | BC2-5-0 | BC2-50-1 | BC2-50-0 | BC2-120-1 | BC2-120-0 |
| ***CIRCUIT LENGTH IN METERS*** | 1000 | | 1000 | | 1000 | |
| ***Cable shipped inside cryostat*** | No | Yes | No | Yes | No | Yes |
| ***Cable system voltage, kV*** | 13.5 | | 13.5 | | 13.5 | |
| ***Cable design rating, kA*** | 2.5 | | 2.5 | | 2.5 | |
| ***Power transfer, MVA*** | 58 | | 58 | | 58 | |
| ***HTS wire rating, kA DC*** | 5.3 | | 5.3 | | 5.3 | |
| ***Wire cost: $/kA/m (DC rating)*** | 5 | | 50 | | 120 | |
| ***Return Cryostat (1 or 0)*** | No | No | No | No | No | No |
| | | | | | | |
| ***System Costs, 2015 $K*** | $K | | $K | | $K | |
| Wire Cost | $109 | $109 | $1,086 | $1,086 | $2,606 | $2,606 |
| Cable+Cryostat Material | $1,750 | $1,808 | $2,055 | $2,113 | $2,530 | $2,588 |
| Cable+Cryostat Installation | $1,009 | $987 | $1,009 | $987 | $1,009 | $987 |
| Civil works (except refrig) | $2,602 | $2,667 | $2,602 | $2,667 | $2,602 | $2,667 |
| Refrigeration, Installed | $2,077 | $2,077 | $2,077 | $2,077 | $2,077 | $2,077 |
| Eng & Mgmt | $679 | $688 | $795 | $804 | $974 | $983 |
| TOTAL (Avg. US) | $8,226 | $8,335 | $9,624 | $9,733 | $11,798 | $11,908 |
| TOTAL (Low City Multiplier) | $7,708 | $7,816 | $9,078 | $9,186 | $11,210 | $11,318 |
| TOTAL (High City Multiplier) | $12,600 | $12,710 | $14,155 | $14,264 | $16,572 | $16,682 |
| | | | | | | |
| COST RANGES - SINGLE CABLE | Low | High | Low | High | Low | High |
| Wire Cost, $kA/m | 5 | | 50 | | 120 | |
| Low to High City Range | $7,708 | $12,710 | $9,078 | $14,264 | $11,210 | $16,682 |
| Average U.S. | $8,226 | $8,335 | $9,624 | $9,733 | $11,798 | $11,908 |
| | | | | | | |
| X (TIMES) NUMBER OF CABLES | 1 | 1 | 1 | 1 | 1 | 1 |
| Low to High City Range | $7,708 | $12,710 | $9,078 | $14,264 | $11,210 | $16,682 |
| Average U.S. | $8,226 | $8,335 | $9,624 | $9,733 | $11,798 | $11,908 |
| | | | | | | |
| Value Proposition, $K | $2,000 to $42,000 | | | | | |

**Figure D-2**
**Base case 2  inputs and outputs for different wire costs**

| BASE CASE | 3A | | 3A | | 3A | |
|---|---|---|---|---|---|---|
| File name suffix | BC3A-5-1 | BC3A-5-0 | BC3A-50-1 | BC3A-50-0 | BC3A-120-1 | BC3A-120-0 |
| ***CIRCUIT LENGTH IN METERS*** | 6000 | | 6000 | | 6000 | |
| ***Cable shipped inside cryostat*** | No | Yes | No | Yes | No | Yes |
| ***Cable system voltage, kV*** | 5 | | 5 | | 5 | |
| ***Cable design rating, kA*** | 4.5 | | 4.5 | | 4.5 | |
| ***Power transfer, MVA*** | 39 | | 39 | | 39 | |
| ***HTS wire rating, kA DC*** | 9.5 | | 9.5 | | 9.5 | |
| ***Wire cost: $/kA/m (DC rating)*** | 5 | | 50 | | 120 | |
| ***Return Cryostat (1 or 0)*** | Yes | Yes | Yes | Yes | Yes | Yes |
| | | | | | | |
| ***System Costs, 2015 $K*** | $K | | $K | | $K | |
| Wire Cost | $1,173 | $1,173 | $11,727 | $11,727 | $28,145 | $28,145 |
| Cable+Cryostat Material | $14,541 | $14,927 | $17,840 | $18,226 | $22,970 | $23,356 |
| Cable+Cryostat Installation | $4,693 | $4,738 | $4,693 | $4,738 | $4,693 | $4,738 |
| Civil works (except refrig) | $10,502 | $10,892 | $10,502 | $10,892 | $10,502 | $10,892 |
| Refrigeration, Installed | $7,689 | $7,689 | $7,689 | $7,689 | $7,689 | $7,689 |
| Eng & Mgmt | $3,474 | $3,548 | $4,721 | $4,794 | $6,660 | $6,734 |
| TOTAL (Avg. US) | $42,072 | $42,966 | $57,171 | $58,066 | $80,659 | $81,554 |
| TOTAL (Low City Multiplier) | $39,769 | $40,631 | $54,568 | $55,430 | $77,588 | $78,451 |
| TOTAL (High City Multiplier) | $61,080 | $62,215 | $77,867 | $79,002 | $103,980 | $105,115 |
| | | | | | | |
| COST RANGES - SINGLE CABLE | Low | High | Low | High | Low | High |
| Wire Cost, $kA/m | 5 | | 50 | | 120 | |
| Low to High City Range | $39,769 | $62,215 | $54,568 | $79,002 | $77,588 | $105,115 |
| Average U.S. | $42,072 | $42,966 | $57,171 | $58,066 | $80,659 | $81,554 |
| | | | | | | |
| X (TIMES) NUMBER OF CABLES | 2 | 2 | 2 | 2 | 2 | 2 |
| Low to High City Range | $79,538 | $124,431 | $109,136 | $158,005 | $155,177 | $210,231 |
| Average U.S. | $84,143 | $85,933 | $114,342 | $116,132 | $161,318 | $163,108 |
| | | | | | | |
| Value Proposition, $K | $93,000 | | | | | |

**Figure D-3**
**Base case 3, scenario 1 inputs and outputs for different wire costs**



| BASE CASE | 3B | | 3B | | 3B | |
|---|---|---|---|---|---|---|
| File name suffix | BC3B-5-1 | BC3B-5-0 | BC3B-50-1 | BC3B-50-0 | BC3B-120-1 | BC3B-120-0 |
| ***CIRCUIT LENGTH IN METERS*** | 500 | | 500 | | 500 | |
| ***Cable shipped inside cryostat*** | No | Yes | No | Yes | No | Yes |
| ***Cable system voltage, kV*** | 35 | | 35 | | 35 | |
| ***Cable design rating, kA*** | 4 | | 4 | | 4 | |
| ***Power transfer, MVA*** | 242 | | 242 | | 242 | |
| ***HTS wire rating, kA DC*** | 8.5 | | 8.5 | | 8.5 | |
| ***Wire cost: $/kA/m (DC rating)*** | 5 | | 50 | | 120 | |
| ***Return Cryostat (1 or 0)*** | No | No | No | No | No | No |
| | | | | | | |
| ***System Costs, 2015 $K*** | $K | | $K | | $K | |
| Wire Cost | $87 | $87 | $869 | $869 | $2,085 | $2,085 |
| Cable+Cryostat Material | $905 | $905 | $1,150 | $1,150 | $1,530 | $1,530 |
| Cable+Cryostat Installation | $805 | $692 | $805 | $692 | $805 | $692 |
| Civil works (except refrig) | $1,925 | $1,925 | $1,925 | $1,925 | $1,925 | $1,925 |
| Refrigeration, Installed | $2,077 | $2,077 | $2,077 | $2,077 | $2,077 | $2,077 |
| Eng & Mgmt | $522 | $512 | $614 | $604 | $758 | $748 |
| TOTAL (Avg. US) | $6,320 | $6,197 | $7,438 | $7,316 | $9,178 | $9,056 |
| TOTAL (Low City Multiplier) | $5,922 | $5,815 | $7,018 | $6,911 | $8,723 | $8,616 |
| TOTAL (High City Multiplier) | $9,687 | $9,419 | $10,930 | $10,662 | $12,865 | $12,597 |
| | | | | | | |
| COST RANGES - SINGLE CABLE | Low | High | Low | High | Low | High |
| Wire Cost, $kA/m | 5 | | 50 | | 120 | |
| Low to High City Range | $5,815 | $9,687 | $6,911 | $10,930 | $8,616 | $12,865 |
| Average U.S. | $6,197 | $6,320 | $7,316 | $7,438 | $9,056 | $9,178 |
| | | | | | | |
| X (TIMES) NUMBER OF CABLES | 2 | 2 | 2 | 2 | 2 | 2 |
| Low to High City Range | $11,630 | $19,374 | $13,822 | $21,861 | $17,233 | $25,730 |
| Average U.S. | $12,395 | $12,640 | $14,632 | $14,877 | $18,111 | $18,357 |
| | | | | | | |
| Value Proposition, $K | $11,700 | | | | | |

**Figure D-4**
**Base case 3, scenario 2 inputs and outputs for different wire costs**

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