Summary Report: Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: High-Temperature Superconductivity

3002011527

Summary Report: Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: High-Temperature Superconductivity

3002011527

Technical Update, December 2017

EPRI Project Manager

R. Lordan

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATIONS PREPARED THIS REPORT:

Electric Power Research Institute (EPRI)

Power Delivery Consultants

Jonathan Demko, Consultant

Patrick M. Duggan Enterprises, Ltd.

RAND Corporation

W2AGZ

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

ACKNOWLEDGMENTS

The following organizations prepared this report:

Electric Power Research Institute (EPRI)
1300 West W. T. Harris Blvd.
Charlotte, NC 28262

Principal Investigators
R. Adapa
S. Eckroad
R. Lordan

Power Delivery Consultants
28 Lundy Lane, Suite 102
Ballston Lake, NY 12019

Principal Investigators
J. Williams
W. Hassenzahl (Advanced Energy Analysis)
T. Aabo (Power Cable Consulting)

Jonathan A. Demko, Consultant
118 Woodbridge
Longview, TX 75602

Principal Investigator
J. Demko

Patrick M. Duggan Enterprises, Inc.
9 DeForest Court
Valley Cottage, NY 10989

Principal Investigator
P. Duggan

W2AGZ
1147 Mockingbird Hill Lane
San Jose, CA 95120

Principal Investigator
P. Grant

RAND Corporation
1200 South Hayes Street
Arlington, VA 22202-5050

Principal Investigator
R. Silberglitt

This report describes research sponsored by the United States Department of Homeland Security, Science & Technology Directorate (DHS S&T). EPRI expresses special thanks to DHS S&T Project Manager Sarah Mahmood.

This project is the result of funding provided by the Science and Technology Directorate of the United States Department of Homeland Security under contract number D15PC00014.

This publication is a corporate document that should be cited in the literature in the following manner:

Summary Report: Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: High-Temperature Superconductivity. EPRI, Palo Alto, CA: 2017. 3002011527.

ABSTRACT

The U.S. Department of Homeland Security (DHS) Science & Technology (S&T) Directorate is involved in a multi-year, multi-partner research, development, and demonstration program, Resilient Electric Grid (REG), to facilitate the research, development, demonstration and commercialization of a high-temperature superconductivity (HTS) technology that has the potential to revolutionize the nation's electric grid, making it more resilient to natural and man-made threats. Through the proposed manufacture, installation, and operation of a long-length (3 or more miles; 4.8 or more km) HTS cable in a dense urban utility grid, DHS and its partners in the project believe that the costs of this technology can be reduced, while demonstrating the capability to meet the reliability needs of the electric utility industry. In conjunction with the proposed in-grid deployment of a long-length HTS cable in an urban network, DHS S&T contracted with the Electric Power Research Institute (EPRI) to conduct an independent, third-party evaluation and critical expert assessment of an inherently fault current limiting (IFCL) high-temperature superconducting cable technology.

EPRI carried out a comprehensive assessment, including technology issues, manufacturing readiness, costs and commercialization potential, and comparisons with technologies offering similar capabilities. The technology assessment addressed three critical hardware components as well as three major post-manufacturing steps in deployment, yielding a total of six focused research areas: the HTS wire, the HTS cable, and the cryogenic refrigeration system (components); and testing, installation, and operation and maintenance (deployment). Considering both component costs and commercialization status, EPRI analyzed the factors impacting the successful commercialization of IFCL HTS cable. Subtasks in this effort included defining a set of base cases, analyzing costs and the market, and assessing factors affecting commercialization. For example, the proliferation of other products using the same or similar components as IFCL cable will have a strong impact on both cost and acceptance. In the final stage of this assessment process, EPRI identified, characterized, and compared grid resiliency alternatives with respect to the three base cases that were identified for HTS cost analyses. The result is a comparison of the IFCL HTS technology with alternative technologies with respect to the capability to meet the needs of urban utilities and their customers. The comparison emphasizes the achievement of grid resiliency.

Keywords

Cryogenic refrigeration
Fault current management
High-temperature superconducting (HTS) cable
Resilient electric grid
Superconductivity
Superconducting wire manufacture

Deliverable Number: 3002011527

Product Type: Technical Update

Product Title: Summary Report: Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: High-Temperature Superconductivity: Product Subtitle

PRIMARY AUDIENCE: Utilities and regulators involved in planning for resilient electric power infrastructure.

SECONDARY AUDIENCE: City managers and emergency planners collaborating with utilities in preparing for the deployment of resilient systems; researchers and manufacturers in high-temperature superconductivity.

KEY RESEARCH QUESTION

High-temperature superconductivity (HTS) technology has the potential to increase the resiliency of the electric grid against both natural and man-made threats. Utility acceptance of this new technology will rely on a comprehensive understanding of both the commercial status of the technology and its projected costs, which until recently have lacked precision. EPRI assessed an inherently fault current limiting (IFCL) high-temperature superconducting (HTS) cable technology to identify technology issues, estimate costs and commercialization potential, and provide comparisons with technologies offering similar capabilities.

RESEARCH OVERVIEW

The U.S. Department of Homeland Security (DHS) Science & Technology (S&T) Directorate's Resilient Electric Grid (REG) program is a multi-year, multi-partner program to facilitate the research, development, demonstration, and commercialization of a high-temperature superconductivity (HTS) technology that has the potential to revolutionize the nation's electric grid, making it more resilient to natural and man-made threats. EPRI's independent, comprehensive assessment addressed critical hardware components (HTS wire, cable, and refrigeration) as well as key deployment factors such as testing, installation, and operation. Costs were analyzed in the context of other factors impacting successful commercialization. Alternative technologies for grid resiliency were compared with the HTS technology to establish the extent to which HTS is a viable choice and under what circumstances HTS may be preferred, even under current costs.

KEY FINDINGS

- The principal driver in the ultimate commercialization of HTS cable systems is superconducting wire manufacturing. Current best estimates suggest that the wire will be commercially available around the year 2025.
- As this technology matures, continued development of cable and cryostat testing protocols and quantification of standards for satisfactory results is needed, as well as training courses and materials for utility personnel to gain the needed skills to manage this equipment.
- HTS cables can provide dramatic power transfer within limited rights-of-way, facilitates increased reliability and resiliency, and enhances asset utilization.
- With continued urban load growth, HTS cables can be an effective alternative to new transmission using conventional distribution cable systems and the requisite substation systems.
- Though still an emerging technology, HTS cables compare favorably with alternatives to providing the reliability and resiliency that utilities seek to secure systems against high-risk events.

WHY THIS MATTERS

HTS technology has great potential for improving grid resiliency, a heightened utility concern in the wake of recent natural events such as Superstorm Sandy. Utility adoption requires clear understanding of the technology and its performance potential and costs, particularly in comparison to other technologies offering similar capabilities. This research provides a comprehensive picture of the current status of IFCL HTS technology, addressing components, manufacturing, deployment, performance, operations, and costs.

HOW TO APPLY RESULTS

This report provides a broad introduction to IFCL HTS technology to inform utility decision-makers concerned about grid resiliency. Utility managers can use this information to support planning for grid resiliency or to initiate discussion on comparative technologies in the context of long-term planning. The in-depth reports are also available to those seeking more detailed information on one or more topics in this study.

EPRI CONTACTS: Richard Lordan, Senior Technical Executive, rilordan@epri.com

PROGRAM: Underground Transmission, P36; Substations, P37

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

ACRONYMS

1G	first generation
2G	second generation
ac	alternating current
AEP	American Electric Power
AMSC	American Superconductor
BSCCO	bismuth-strontium-calcium-copper-oxygen (first-generation superconductor)
CIGRE	International Council on Large Electric Systems
ComEd	Commonwealth Edison
ConEd	Con Edison
dc	direct current
DHS	Department of Homeland Security
DOE	Department of Energy
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
FACTS	flexible alternating current transmission system
FCL	fault-current limiting
HTS	high-temperature semiconductor
IEC	International Electrotechnical Commission
IFCL	inherently fault-current limiting
IP	intellectual property
LIPA	Long Island Power Authority
LTS	low-temperature semiconductor
MRI	magnetic resonance imaging
MRL	manufacturing readiness level
NCI	Navigant Consulting, Inc.
O&M	operations and maintenance
OE	Electricity Delivery and Energy Reliability (DOE office)
R&D	research and development

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Background

Resiliency of the electrical grid and its interdependencies with the nation's other critical infrastructures have become increasingly essential. Technology-driven improvements in productivity are essential to the United States' competitiveness in the world economy, but improvements also increase the criticality of the need for reliable electric service on demand. The ubiquitous internet and increasingly geographically dispersed and continuous communication and computer-dependent business processes have further increased these interdependencies and extended the impacts of even local outages, in many cases, well beyond their immediate physical vicinity. Recent weather-related events such as Superstorm Sandy and the ozone depletion associated with the southern polar vortex have underscored the potentially wide regional direct impacts and longer durations that could be involved. They have also shown how these same interdependencies can impact the speed and completeness of recovery of the system. Such occurrences testify to the special challenges that loss of electric service can create in urban centers. Emergency planners need to take into account the number of people impacted; the logistics required to provide for their temporary, immediate needs; and the resources and coordination needed for recovery. Infrastructure improvements are needed to minimize the impacts of catastrophic events.

Third-Party Independent Assessment

In response to these needs, the U.S. Department of Homeland Security (DHS) has embarked on a multi-year, multi-partner research, development, and demonstration program to facilitate the commercialization of a high-temperature superconductivity (HTS) technology that has the potential to revolutionize the nation's electric grid. In the form of an inherently fault-current-limiting (IFCL) HTS cable system, superconductors may be used effectively to meet some of the challenges posed by an increasingly electrified economy and by the present vulnerabilities of the infrastructure that serves that economy.

There have been many successful demonstrations of HTS cable technology, and previous publicly-available EPRI reports have provided detailed descriptions, including operational data, for such projects [1,2]. While these demonstrations have included several deployments in electric grids around the world, HTS technology is still considered pre-commercial. For example, scale-up of the present capability to manufacture HTS wire to the production volume levels required for a mature market has not been achieved and may entail unexplored risks. (For the purposes of this research, a wire production volume of at least 98 million ft (30 million m), per year was assumed to characterize a mature market.)

Outstanding issues in such a scale-up, including yield and quality control, will impact the cost, availability, and performance of the material that would be used in commercial products such as an IFCL HTS cable system. In addition to the wire used for the cable, the cable itself and the refrigeration system for achieving superconducting temperatures are also subject to design optimization for utility practice and commercial scale-up. Testing, installation, and operation and maintenance are key aspects of a successful deployment that have yet to achieve the level of experience and standardization that utility companies expect for their conventional transmission facilities. As a result of uncertainties regarding cost, maintenance requirements, and operations reliability, there is reluctance on the part of most U.S. utility companies to seriously consider deployment of HTS cable for enhancing grid reliability and resiliency.

The DHS Resilient Electric Grid (REG) project is being undertaken in three phases. The objectives of Phase 1 and 2, collectively known as "Project HYDRA," are to design, develop, and qualify according to industry standards the IFCL cable (Phase 1); and then to install and demonstrate the IFCL cable in a utility grid environment (Phase 2). Phase 1 was completed at Oak Ridge National Laboratory (ORNL) in 2010 with the successful test of an 82 ft (25 m) IFCL cable manufactured by Southwire using AMSC IFCL superconductor. Phase 2 of the project is currently underway with the interconnection of two Con Edison substations in New York City. A 656 ft (200 m) cable will be installed to demonstrate the IFCL capabilities. The major components have all been manufactured and are awaiting installation at the chosen substation site.

A planned Phase 3 of the DHS Resilient Electric Grid (REG) project seeks to address and mitigate the scale-up issues and concerns mentioned above. In particular, it is hoped that by cosponsoring the manufacture, installation, and operation of a long-length (3 or more miles; 4.8 or more km) HTS cable in a dense urban utility grid, DHS and its partners in the project may be able to realize reduced costs, further demonstrate proven reliability, and demonstrate the inherent immunity of HTS cable to load cycling (due to near-constant cryogenic temperatures). Success in these areas could form a bridgehead to the next steps—commercially viable deployments by other utility companies in similar urban environments. Also, the increased production capability for the superconductor and the experience gained by the host utility may facilitate greater deployments of other HTS products, leading to a further reduction in technology cost and an improved confidence in the technology on the part of utility managers.

In order to provide a third-party, unbiased perspective on the long-term potential for HTS to feasibly improve resiliency in urban electric grids, DHS contracted with EPRI to conduct an independent evaluation and critical expert assessment of the technology. The need for such an assessment is clear—although current REG participants have done their best to evaluate the technical feasibility and the commercial prospects for the HTS cable, they are unavoidably constrained by a nearness to the technology itself and a distance from the engineering needs and operating environment of the electric power delivery industry they intend to serve (i.e., the ultimate end user). EPRI provides an impartial, distanced viewpoint with no vested interest in the commercial success of the wire manufacturing business. EPRI furthermore understands the electric utility industry drivers through independent, coordinated research and development R&D), including R&D for HTS cable technology since its discovery.

Approach

EPRI assembled a multi-disciplinary team of experts from widely varying disciplines to carry out this independent, third-party assessment for DHS. Team members came both from within EPRI's own technical staff and from external consultants. EPRI staff included experts in grid resiliency, fault current management, technical evaluation of conventional and advanced power delivery technologies, and cost estimating. The external consultants were technical experts who are well known in their respective fields, and most also have proven track records of successful work for EPRI on other, similar projects.

To conduct the assessment, the EPRI team members relied on their own background knowledge and extensive searches of publicly available information. EPRI believes that the results of its analysis are of significant authority and value but recognizes that some conclusions could possibly be fine-tuned by access to more accurate information. For example, EPRI's analysis would have been further enhanced by access to past studies, current information, and future projections that are related to equipment and product manufacturing, testing, and installation; material and labor costs; plans for capital equipment expansion; and other related project activities by all of the past and present participants in the REG project.

In approaching the cost and commercialization portion of the assessment, EPRI recognized that market success will be highly sensitive to individual and site-specific factors, competition from alternatives, and other factors that impact successful commercialization. EPRI established 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 addressed. 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.

The assessment team also looked into 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. Understanding such constraints 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 a 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. The 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.

Task Structure

EPRI's assessment was divided into the following three tasks:

- Task 1: Technical capability, manufacturing, and scalability baseline and assessment
- Task 2: Cost and commercialization assessment and market analysis
- Task 3: Analysis of alternatives

Task 1

The objective of Task 1 was to assess the risks, scalability, performance, and commercial potential of the components of an HTS cable system and the activities required to achieve successful deployment in an electric utility grid. The technology and current capabilities assessment was further subdivided into the three major subsystem components of an HTS cable system. The deployment assessment concentrated on three major spheres of activity. The three subsystem components are the following:

- HTS wire manufacture
- HTS cable design and manufacture
- Cryogenic refrigeration system design and operation

The three deployment activities are the following:

- Testing (components and completed system)
- Installation
- Operation and maintenance

Particular attention was given to the wire manufacturing process used by American Superconductor (AMSC) and to the triaxial cable as manufactured by Ultra Corporation, a joint venture of Southwire and NKT Cables, and Nexans. The production of HTS wire by other suppliers was also briefly surveyed.

In addition, based on its assessment efforts, the EPRI team of experts performed a technology and manufacturing readiness evaluation for the three major hardware system components. Using standard industry definitions, the EPRI team ranked the system components with respect to their technology readiness level (TRL) and manufacturing readiness level (MRL).

Task 2

Until recently, costs have not been well known, nor have they been subjected to rigorous, independent, and technology-based analysis. The costs of superconducting wire have shown a steady decline over past years and are projected to continue to decline 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, providing an additional cost advantage. Particular markets may prove more accessible than others, and market success will be highly sensitive to individual and site-specific factors, as well as to competition from alternatives. EPRI's assessment addressed the potential costs, contributors to cost changes over time, commercialization strategies, and marketing prospects for IFCL HTS cable.

Utility acceptance of this new technology will be driven not only by cost but also by other factors, including:

- The value proposition
- New capabilities provided by this technology
- 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
- Actual and perceived institutional barriers or incentives

One of the goals of DHS S&T in this study is to understand the viability of the IFCL HTS cable in urban networks across the U.S. However, there are many differences between specific urban network designs. To facilitate a meaningful comparison, three representative base cases were used in this effort. The assessment also generalized the key resiliency aspects of those base cases so that the evaluation result could be applied to other urban situations.

Within this cost and commercialization task, EPRI addressed these various factors that impact the successful commercialization of the IFCL HTS cable. Subtasks in this effort included:

- Identification of base cases for the IFCL HTS cable
- Development of a cost assessment
- Completion of a market analysis
- Assessment of factors affecting commercialization

A proven methodology was used to develop these comparisons, including both initial and lifecycle considerations. Implications for other transmission and distribution applications, configurations, technologies, and issues were also taken into account. Although the focus of this effort was on the distribution system (typically, voltages of 69 kV and below), implications for the power system and urban center as a whole are included, as appropriate.

Task 3

The objective of Task 3 was to place HTS technology prospects in the context of alternative grid resiliency technologies. 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. In other situations, even at current superconducting wire costs, the IFCL HTS solution, due to its reduced underground space needs, may provide an additional installed-cost advantage.

Subtasks for this effort consisted of:

- Characterizing a specific set of grid resiliency alternatives
- Developing an evaluation matrix to facilitate high-level understanding of commonalities and differences among alternatives
- Identifying underlying conditions, drivers, and constraints on feasibility, both technical and economic
- Accounting for impacts on other utility power system operation needs
- Considering the future impacts of load growth and other changes to the electrical grid and the urban centers they serve
- Assessing each technology's performance in meeting resiliency requirements established for Task 2 base cases, as well as meeting generic resiliency needs

Some alternative resiliency technologies are relatively mature products, while others have yet to fully achieve their promises for the future grid. More research, beyond the scope of this report, is required both to accelerate key technologies and to deal with major unknowns such as the following:

- Successful mitigation of intermittency issues with renewables
- Success in addressing hardware development and system complexity changes that are occurring on the grid

Organization of this Report

Sections 2 through 4 of this report summarize the results of the technological assessments of Task 1. Sections 5 through 7 cover the cost and commercialization study conducted under Task 2. Sections 8 and 9 present the comparison of HST with alternative technologies, as developed in Task 3. Overall results and conclusions are provided in section 10. A list of references and acronyms is in section 11 and appendix A, respectively.

2
TECHNOLOGY AND MANUFACTURING

Superconducting Wire for High-Temperature Superconducting (HTS) Cable Systems

Introduction

Wires and tapes made from HTS materials have a high potential for use in a variety of power applications. An underlying assumption for the present assessment of wire technology is that the cost of these materials and the quantity of production is limiting the commercial deployment of the technology. This suggests that advancement in the manufacture of these materials requires additional technical and financial support.

An alternative view is that what is limiting deployment is the lack of a strong compelling need, from which follows cost reduction and increased supply. The semiconductor industry is replete with many examples of a single niche application supporting advancement of technologies that achieved much wider deployment as cost were reduced and products were proliferated. An electric power analogy would be the expansion of high-voltage direct current (dc) transmission following World War II (the Pacific Intertie is a specific example) driven by the need to exploit and deliver bulk power from remote resources (such as hydro and nuclear). The evaluation of whether IFCL HTS cables, with respect to alternatives such as solid-state technologies, present a viable value proposition for electric utility companies is the subject of Tasks 2 and 3 of the EPRI assessment, and is discussed in Sections 5 through 9 below.

This report addresses issues associated with the manufacture of a particular HTS conductor, the second-generation (2G) material based on the perovskite yttrium, barium, copper, and oxygen (YBCO) material. (It should be noted that alternative formulations of the 2G material are possible in which the yttrium is replaced with another rare-earth material. The term rare-earth-barium-copper oxide (ReBCO) in place of YBCO is used to refer to all rare-earth perovskites, including those using yttrium.) To avoid confusion, for the purposes of this report the YBCO material deposited on a substrate will be referred to as 2G "wire" (i.e., 2G wire is an HTS conductor). The term "tape" will refer to the paper- or polymer-based electrical insulation that is applied in a fully manufactured cable. Several processes can be used to produce 2G wire, but for the main portion of this section, we address the manufacturing approach used by American Superconductor Corporation (AMSC). Alternative approaches are described in the body of the report.

The term IFCL is a term that AMSC applies to one of its several varieties of 2G wire. The IFCL property is achieved by the addition of certain, specific material layers to the underlying HTS wire during its production, augmented by specific cable design and operating scenarios, as needed to limit fault currents. In general, the information in this report applies to all varieties of 2G HTS wire, whether or not they are IFCL. If the text applies only to IFCL wire, the term "IFCL" is used.

Technology Status

Many types of superconductor are fabricated today for a variety of applications, including medicine (e.g., MRI), high energy physics (e.g., the Large Hadron Collider), and industry (e.g., for kaolin clay processing). Superconducting devices are also used in wireless communications and for precision measurements in a number of research fields [3]. The greatest quantity of superconducting wire is made of an alloy of niobium and titanium (NbTi), which is made into filaments and embedded in a copper matrix. This material is restricted to operation at temperatures around 4 K (the temperature range of liquid helium). Extrusion and drawing constitute a major portion of the fabrication sequence for this material. The equipment used is the same as that used in the production of copper wire. The copper wire manufacturing process is commercially mature, with a competitive market and many producers around the world.

Another superconducting material fabricated today is crystalline Nb_3Sn, which is a fragile, glass-like material. It also operates at low temperatures similarly to NbTi. The production of Nb_3Sn also uses the same extrusion and drawing equipment as copper. Because of the ability of NbTi and Nb_3Sn to use existing technology for a major portion of their fabrication, they can benefit from the economies of scale associated with large-scale production. These superconductors not only require the same type of fabrication equipment but also use the same pieces of equipment on a scheduling basis, so the depreciation of the capital cost and the maintenance and labor costs are assigned to the superconductors on the basis of the fraction of their use of the equipment. Table 2-1 summarizes fabrication features for along with those of other superconducting wire technologies discussed below.

The designation low-temperature superconductor (LTS) is applied to both NbTi and Nb_3Sn because their operating temperature is significantly lower than that of the HTS conductors. In significant contrast with LTS superconductors, the production of 2G HTS wires involves multiple steps, each with a set of sometimes unique equipment and rather complicated requirements. Although the equipment used in each of these steps is well understood, and in some cases is based on large-scale, mature technologies (such as the rolling of the substrate used by AMSC), that cannot be said for all steps. There is no existing large-scale production process using exactly the same procedures that are needed for the 2G wires. A much greater total volume of 2G wire must be fabricated to approach commercial viability. In essence, in a mature commercial environment, since the equipment is capital intensive it must be used a significant fraction of the available time to achieve a reasonable payback on the investment.

Two other superconductors—bismuth-strontium-calcium-copper-oxygen (BSCCO), also known as first-generation (1G) wire, and magnesium boride (MgB_2)—are also being considered for some power applications. Both use the extrusion and drawing procedures for copper and can be made in significant lengths.

Table 2–1
Superconductor classifications

Material	Designation (in this Report)	Critical Temperature	Fabrication System
NbTi	LTS	10 K	Same extrusion and drawing equipment as copper wire. Made in significant lengths. Annual production: many tons.
Nb_3Sn	LTS	18 K	Same extrusion and drawing equipment as copper wire. Made in significant lengths.
ReBCO (YBCO)	2G	92 K	No existing large-scale production process using exactly the same procedures that are needed for the 2G wires. Some steps require unique equipment and complicated process calibration requirements.
BSCCO	1G	110 K	Uses the extrusion and drawing procedures for copper and can be made in significant lengths.
MgB_2	None	39 K	Uses the extrusion and drawing procedures for copper and can be made in significant lengths.

The focus of this assessment is on 2G wire and systems that use this wire, particularly IFCL wire. Nevertheless, 1G wire HTS cable systems are given some coverage. The high critical field properties of 2G wires are not required for fault-current-limiting applications (such as the Essen, Germany, project that uses a 1G wire in a cable in series with a stand-alone fault current limiter). In addition, 1G wire production may be considered mature, albeit costlier to produce than what is believed eventually possible for 2G wire. Currently 1G wire is marketed at prices less than those for 2G wire, making it preferable for projects which have benefits that justify the relatively high cost and do not require an inherently fault current limiting capability.

Although MgB_2-based systems are beyond the scope of this study, we believe that they should be considered in the future. The wire is inexpensive, and the materials are non-exotic. It would be useful to assess the cost tradeoffs related to higher cost of the required cryogenic systems against the lower cost of the wire. This has not been done in a thorough manner and published to our knowledge.

In summary, the production (manufacturing) technology for 2G HTS wire is not mature compared to that of 1G wire and LTS superconductors. However, it is a viable technology that is being pursued by multiple developers worldwide. There is significant promise for commercial viability on the assumptions that production (and sales) volumes increase and wire performance (cost) improves. In spite of this situation, the history of 2G wire development over the past two decades suggests continuing, significant improvements in cost and production capability.

Wire Production Risks and Mitigation

Note: The use of the word “risk” in this and subsequent sections of this report should be understood in its common usage as referring to designs or processes where there is uncertainty related to the desired outcome (probability times impact) and thus potentially requiring additional foresight in planning or attention to detail in execution. It is not intended to convey the idea that the design or process is doomed to failure. It is also noted that this report uses the term “risk” in a qualitative way, and that no attempt has been made to quantify risk.

The production assessment addresses risks in two different areas. The first risk group consists of global issues associated with the production of 2G wire by the AMSC process, and the second risk group addresses risks associated with steps of the process itself. This report does not address risks and mitigation for other 2G wire production processes (i.e., by other manufacturers), although the global risks identified below may apply in a general way to a number of the other processes being developed.

Global Risks

Global risks to achieve full industry maturity include the following:

- Unforeseen issues may arise associated with the scale-up of production volume because the quantity of material required for a project is significantly greater than previous AMSC production.
- Intellectual property (IP) issues, particularly as the business becomes profitable, may arise. While potential threats relating to this area are now known, the risk remains.
- Other production processes for HTS 2G superconducting wire that are more desirable, less expensive, and have higher yield than the AMSC approach may emerge.

Regarding scale-up issues, we must consider two scenarios: one in which DHS Proposed Phase 3 project is successfully consummated and that characterized by full-scale commercial orders. In the first case, it was assumed that AMSC's current staff and facility at Devens, Massachusetts, is adequate for the production of the 2G YBCO wire in the lengths and in the time frame required for the installation of long-length (3 or more miles; 4.8 or more km) power cables in Proposed Phase 3 of the DHS REG program. This is based on the understanding that the Proposed Phase 3 project will not exercise AMSC manufacturing facilities at any greater degree than has been achieved in earlier projects.

In the second case, scaling up to full commercial status could result in production issues that may significantly impact production schedules and product cost in the near term. It is EPRI's understanding that scale-up activities can potentially cause interruptions in manufacturing while equipment and process parameters are fine-tuned to enable the desired greater production volume. This view is that of one of the lead researchers at Oak Ridge National Laboratory (ORNL) during the initial wire manufacturing process development period, and was obtained by EPRI as part of its research for this project. While the view is likely supported by the many peer-reviewed papers and publications that came out of this effort, it was beyond the scope of the present effort to further document it. (Interested readers may also turn to the annual U.S. Department of Energy publications that resulted from DOE funding of wire development activities at ORNL from 1998 to 2008.)

Because the national laboratory expertise that assisted AMSC during that scale up process is no longer available, advance preparation may be important to maintain good chances on-time delivery of HTS material during production. A key element is recognizing that some outside expertise may be needed in the event of issues arising. One viable approach, suggested by EPRI during this assessment project, would be for AMSC to develop a team of experts that would cover the various steps of wire production. With such a team available for consultation in advance of a critical production run, one or more members of the team might be able to provide a rapid assessment of any production issues. AMSC responded to the suggestion by noting that it “already uses consultants with the appropriate expertise to assist when needed. Likewise, we have outside labs which are used to perform analysis when in-house capabilities do not exist.” EPRI is not in a position to judge the efficacy of any specific approach to arranging for expert support.

Regarding IP issues, many patents apply to the various steps in the production of YBCO. It is uncertain just how many there might be, but the experience with other technologies is that as they become profitable, patent holders will materialize to assert their claim. This occurs even in those cases in which due diligence has been carried out and the producer can see no potential infringement in their action. Intellectual property may be a risk in the process used by AMSC, and it is not possible to anticipate just what might occur in this case. Mitigation in advance of precise knowledge is not possible, but some anticipation on the part of AMSC and their clients may reduce the risk of any claims, at least during the course of Proposed Phase 3 of the DHS REG program. In the long term, such claims may or may not impact the ability of the technology to mature, and they may determine the beneficiaries of large-scale production.

Regarding emerging processes, as is the case with any technology maturation, the risk is either positive or negative, depending on how AMSC would adjust to the emergence of lower-cost or otherwise preferred manufacturing methods. At present, there appears to be no serious competition from any of the several alternatives, but this situation could change after a successful project in Chicago. Thus, mitigation may be a coalescence or a synthesis of different approaches to the manufacture of the wires and may include procedures that do not exist at present.

Specific Process Risks for HTS Wire

The AMSC HTS wire process apparently functions well for relatively small order levels (e.g., production of enough wire for the Phase 2 cable for Con Edison, which is about 656 ft or 200 m in length). However, with respect to scaling up the AMSC process to full commercial status (i.e., to supply a market for manufacture of tens of kilometers of superconducting cables), the major specific risks are described below. They are listed in order of sequence in the processing of the wire (i.e., the list is not prioritized).

The reader is reminded as to the meaning of “risk” as used in this report – described in the “Note” at the beginning of this section. The reader will also note that a common theme in the paragraphs to follow is to point out the obvious risk that if the particular step isn’t done right, wire properties will suffer. Likewise, the obvious mitigation of the risk is to control the process. While this type of analysis and response applies to any manufacturing process, it is important to understand just what aspects of the HTS wire fabrication process are of potential concern. That is, for any of the manufacturing steps listed below there are a number of process variables, the control of which may carry little risk. However, the point of the description below is to identify that aspect of each step which may be of most concern when carrying out a significant scale-up of manufacturing volume. Again, it is affirmed that just because an item is flagged as being a “risk” this does not imply ultimate failure – only the need for closer attention during scale-up activities.

The risks and suggested mitigations include the following:

- The first step is the AMSC process is rolling of the Ni/W tape. The process, referred to as rolling-assisted–biaxially textured substrates (RABiTS), uses a multipass rolling mill that begins with an 11 in. (30 cm) wide, ~0.1 in. (3 mm) thick sheet, and results in a ~50 µm thick tape of the same width. The risk associated with the process is that the orientation of the crystals is not uniform across the 11 in. (30 cm) width of the tape. One method of mitigation of this risk requires precise control of the annealing process (maintaining temperature below the secondary recrystallization temperature) and the roller tolerances (camber and pressure), along with monitoring of the tape characteristics during the various passes through the rolling mill. Another approach to mitigation is to select different portions of the original 11 in. (30 cm) wide tape for wires of different performance capability.
- Hydrogen sulfide (H_2S) gas is applied to the substrate surface at an elevated temperature to obtain a surface layer of sulfur atoms that rest in the interstices between the W/Ni atoms. The risk is that the gas concentration or temperature will vary across the width of the tape or along the tape. The result would be reduced critical current.
- Deposition of three seed/buffer layers—yttrium oxide (Y_2O_3), yttria-stabilized zirconia (YSZ), and cerium oxide (CeO_2)—is done by radio-frequency (RF) sputtering sequentially during a single pass of the tape through a special chamber. The risk in each of these processes is having variations in the texture, density, and thickness, which can lead to reduced critical current. Mitigations to these issues consist of ensuring tight control of the oxygen and water partial pressures, establishing backup power for the sputtering process, and ensuring that the targets are adequate for the run time.
- The YBCO chemical solution is applied by a slot-die process at ambient temperature, which is followed by low-temperature decomposition, establishing a precursor layer. Following this step, the tape is stored before high-temperature YBCO superconductor formation. The formation of the YBCO precursor layer is straightforward, but the storage of the tape is critical because the YBCO is in a state that is susceptible to environmental contaminants, including oxygen and water. Variation in the precursor along the length of the tape will affect the critical current in the final wire. Because the tape is on a reel and is still quite wide (i.e., 11 in. or 30cm), it is difficult to maintain consistent characteristics if any change is allowed. Thus, the container with the tape must have an atmosphere that leaves any exposed precursor unchanged. Mitigation is twofold—tape storage must be for as short a time as possible, and humidity and oxygen content should be controlled in the storage container for the precursor coated tape.
- YBCO superconductor is formed by high-temperature processing of the precursor coated tape. This step is straightforward, but there are potential risks, which depend on the final application of the tape. The YBCO forms heteroepitaxially on the CeO_2 layer. The annealing temperature, the annealing time, and the atmosphere affect the properties of the YBCO layer. Also, during this process, non-superconducting nanoparticles of rare-earth oxides form within the layer. These normal particles will remain intact in the following steps and will provide pinning points (or pinning centers) for magnetic fields, which they isolate from the majority of the superconducting layer. The major risk in this process is a lack of homogeneity along the length and width of the tape. Mitigation is the careful control of process variables and feedback from post-processing measurements of the YBCO layer.

- A thin layer of silver is sputtered onto the YBCO layer of the tape before final processing into the superconducting state. The silver provides a contact layer for current to enter the superconductor and for attachment of the final tape to other materials. Perhaps the most critical purpose of the silver is to allow passage of oxygen from the environment to the YBCO during the processing step in which the orthorhombic superconducting crystalline structure is formed. The risk is that the formation of this layer will not have a constant thickness along the length and width of the tape, thereby causing a variation in critical current in the finished wires. Mitigation is to establish the sputtering process so that power to the system does not vary during a run and that the sputtering target has sufficient material so that it will not degrade during a run.
- The final YBCO processing step is the conversion of the YBCO into a superconducting layer. This is done in a furnace at a precisely controlled, elevated temperature and in an atmosphere with a carefully controlled partial pressure of oxygen, the combination of which converts it into the superconducting orthorhombic crystalline structure. The risks are variations of temperature and oxygen partial pressure during the conversion process and the time that the tape is in the active region of the furnace. Mitigation is the precise control of the oxygen partial pressure, the temperature, and the speed of the tape in the furnace. Having an emergency power source for the reaction furnace can decrease this risk. Over the course of a large production, careful monitoring of the critical current of produced wires can provide feedback on this and other procedures in their production.
- After the conversion of the YBCO into a superconductor, the tape is laminated with a stabilizing material such as copper or, for some applications, a more resistive material. The tape is then slit to the appropriate width for the application, typically 0.17 in. (4.4 mm). These two processes may be in one step, or they may be separate. Both are generally straightforward. The risk is that the wire will be stressed in such a way that the integrity and interconnectivity of the superconductor will be lost, resulting in a reduced critical current. Mitigation is careful registry of the tape in the laminating and slitting machines and critical current testing of the wire in its final form. This test will provide feedback on the process for subsequent tapes in a production run.

Summary of High-Temperature Superconducting Wire Manufacturing Scale-Up

All the processes described for the production of 2G HTS wires remain in the developmental stage, although the one used by AMSC has been used for the production of more wire than any of the others. This applies to all types of 2G HTS wire, including the type that AMSC designates as IFCL wire. Nevertheless, AMSC's production process is judged to be still in the pre-commercial stage of development.

It is reasonable to expect that an increased production volume will inevitably improve the manufacturing process (such as improvements in yield, reduction in labor, and increases in wire performance). It also reasonable to expect that manufacturing scale-up, although it will be ultimately successful, will not be without issues and delays to solve problems associated with, for example, obtaining greater throughput with existing equipment or applying the risk mitigation measures described in this report. Manufacturing improvements, of course, lead also to lower cost for the HTS wire. However, with respect to the specific focus of this study (scale-up prospects for AMSC wire), the required scale of production increase to effect a commercial market and the timing for such could not be determined due to the lack of specific production information from AMSC.

The current Proposed Phase 3 of the DHS Resilient Electric Grid (REG) project proposed for Commonwealth Edison in Chicago will not use the IFCL wire that AMSC has used in earlier the earlier phases of the project. Moreover, the production schedule planned for the project will not exercise AMSC manufacturing facilities at any greater degree than has been achieved in earlier projects. Thus, the proposed Phase 3 of the project will not constitute a manufacturing scale-up and should, therefore, be achieved with minimal risk.

The superconductor produced by AMSC appears to perform satisfactorily for the various applications in which it has been used. The expectation is that, given an adequate market and a low enough cost of fabrication on the part of AMSC, 2G HTS wires can be competitive for use in a variety of electric grid applications.

High-Temperature Superconducting Cable Design and Manufacture

High-Temperature Superconducting Cable Design

There are three geometric schemes for cold dielectric HTS cable constructions manufactured today: three-phase coaxial, triad, and triaxial. In addition, three cable components are common to all three designs: the cable former, the stabilizer, and the cryostat. Each scheme has unique characteristics that make it useful for particular cable applications. Figure 2-1 illustrates the three schemes. (The term *coaxial* in the top left of the figure refers to the fact that each of the three phases is coaxial. The top right construction also has three coaxial phases. The difference is in the design of the cryogenic envelope, as described below.)

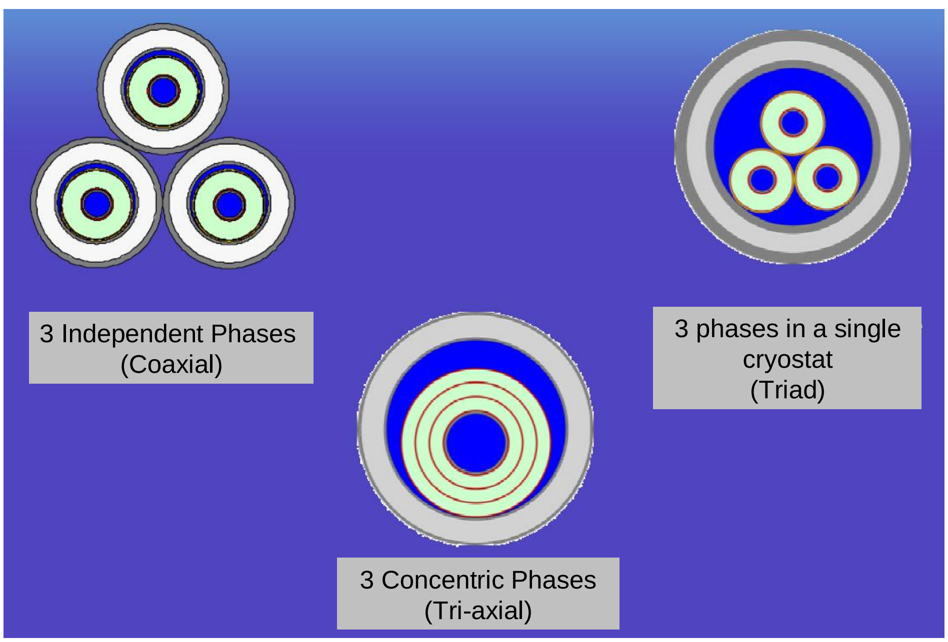

Figure 2–1
Three cold dielectric cable configurations
Source: Nexans Deutschland Industries GmbH & Co. KG

All HTS cables have a central member, called a former, whose primary role is to serve as a structural member onto which the HTS wires can be applied and to provide strength during pulling and mechanical stresses associated with cooldown. The former may also serve as a path for the liquid nitrogen (LN_2) flow required for the cooling requirements. The stabilizer is a non-superconducting material through which the excess current is shunted during a fault. The stabilizer can be an integral part of the HTS wire—such as a lamination of copper, brass, bronze, stainless steel, or other resistive material (for example, the AMSC IFCL wire)—or it can be a separate component of the cable, or both. A cryostat is used to achieve and preserve the cryogenic environment for the cable. The cryostat typically consists of two flexible stainless steel tubes, one within the other, with the annulus between them typically evacuated and fitted with thermal insulation. The HTS cable core (HTS conductors plus electrical insulation) is placed within the inner tube of the cryostat, which also provides a path for the flow of coolant. The outer tube of the cryostat is at ambient temperature and is jacketed for electrical and mechanical protection. Figure 2-2 shows a typical cryostat construction. In Figure 2-1 above, the cryostat is depicted as the lightly colored outermost shell in each of the cable design schemes. The light green components inside the cryostat represents the HTS cable core.

1. Corrugated Inner Pipe
2. Spacer
3. Vacuum Space
4. Multi Layer Super Insulation
5. Corrugated outer pipe
6. PE jacketing

Figure 2–2
Cryostat constructed from concentric corrugated stainless-steel tubes
Source: DOE [4]

Three-Phase Coaxial Cable Scheme

The three-phase coaxial cable scheme consists of three independent coaxial cores, each operating as one of three electrical phases. Each phase has its own independent cryostat. The cable former may be either a central copper conductor (acting as a stabilizer) or a hollow, flexible tube. HTS wires, followed by taped electrical insulation, are wrapped over the former. If there is a hollow former, a stabilizing layer of copper can be applied over the superconductor, unless the wires themselves are self-stabilized. A shield, consisting of a second layer of HTS wires and a copper concentric neutral, is applied over the insulation. During normal operation, the HTS wires in the shield carry the same current as the inner HTS wires, but 180° out of phase. As a result, the external magnetic field is essentially zero.

Similar to conventional cables, the shield may also provide the return path for fault currents, through either the HTS wires or the copper concentric neutral (if the currents are greater than the critical current of the HTS layer). The HTS layers, the stabilizer, and the concentric neutral must all be designed for the specific electric network into which the cable is to be inserted, requiring complex calculations. Finally, a layer for mechanical protection is applied over the shield layer, and the completed core is factory installed in the inner chamber of the cryostat. The outer wall of the cryostat has an extruded polyethylene jacket for protection during the process of pulling the cryostat assembly into the duct.

Because there are three separate cryostats, a typical arrangement for the supply and return coolant paths is to supply LN_2 through one of the phase legs, with the return path through the second and third phase legs. In this approach, asymmetrical temperatures and cryogen flows will result in the phases, which must be accounted for in the design of the refrigeration system. In the case of a hollow former, the LN_2 path may be through both the cable former and the annular space between the cable and the inner cryostat wall.

The three-phase coaxial design permits installation of the HTS cable in three existing ducts that are smaller in diameter than would be required for the other two HTS cable designs. Three independent cores also allow for replacement or repair of one without replacing the other two. However, the use of three cryostats and three separate cable pulls increases both material and installation labor cost. Because the system operation at any voltage level for this design is the same, this design can be manufactured to operate at any standard underground transmission cable voltage level (e.g., up to 345 kV).

Triad Cable Scheme

The triad cable scheme contains three single-phase coaxial cores, as described above, but in a common cryostat and with a single LN_2 flow path between the inner cryostat wall and the three coaxial cores. The LN_2 return path is typically through a separate, smaller cryostat. The construction of each cable core is essentially identical to that of each of the three individual cable cores in the three-phase coaxial design, except that a hollow cable former is not used. The bundled and twisted cores are factory installed in the inner chamber of the cryostat, and the cryostat with the cables is then installed in the field. This design has the advantage of a reduced cold surface area compared to the three-phase coaxial design, reducing the cryogenic cooling load, but a larger duct is required for the cable and cryostat. The design is suitable for a wide range of distribution and transmission voltages.

Triaxial Cable Scheme

In the triaxial cable scheme (see Figure 2-3), all three electrical phases are arranged concentrically on a common axis (typically a hollow, corrugated cable former) in a single cryostat. As with the coaxial design, the triaxial design uses two possible LN_2 paths: 1) the supply path through the center of the cable (hollow cable former) and the return path in the annular space between the cable core and the inner cryostat wall, or 2) the supply path through both the center of the cable and in the annular space between the cable core and the inner cryostat wall, with the return path through a separate, smaller cryostat (for cable lengths greater than ~ 0.62 mi or 1 km).

The dielectric between phases is designed for the phase-to-phase voltage rather than phase-to-ground voltage. Because the net vector sum of the magnetic fields from the three concentric phases is essentially zero for this design, an HTS current return path is not required. Rather, there is an HTS and/or copper concentric neutral on the outside of the cable core to contain the small magnetic fields resulting from the asymmetry of the three concentric phases and to provide a fault current return path. The concentric arrangement of the phases allows for about a 50% reduction in HTS wire compared to the other two designs, significantly reducing overall system costs and allowing the use of a relatively small-diameter cryostat. However, the triaxial design is suitable for distribution voltages only up to 34 kV (or possibly 69 kV) because of difficulty in obtaining uniform cooling across the three phases due to thicker electrical insulation.

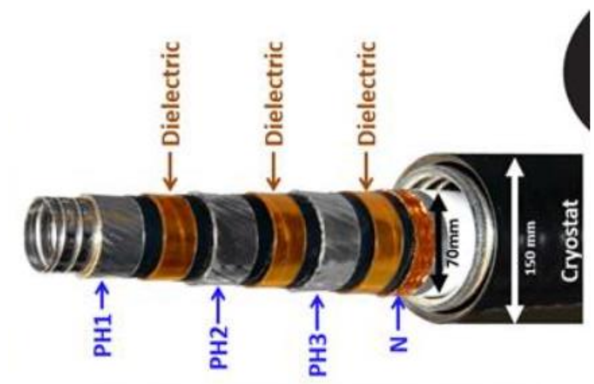

Figure 2–3
Triaxial cable configuration
Source: Southwire Corporation

High-Temperature Superconducting Cable Manufacture

The cable manufacturing process for HTS cables is similar to that used for more than 100 years to produce paper-insulated power cables. The paper-insulated cable method has seen continued improvements and is at a point at which only minor adjustments are made to accommodate different materials used in conventional cables. The use of the HTS conductor wires changes the machine setup, but it does not change the process. Because of the mechanical properties of the HTS wires, special attention is required during the setup to apply the HTS wires and the insulation tapes. Conventional copper wire stranding machines, if used for stranding the HTS wires, must be modified to accommodate the unique properties of superconducting wires compared to copper wires (lighter mass, greater sensitivity to bending and axial strain, and orientation limitations associated with the shape of the HTS wire as compared to a round wire). Alternatively, a specially designed HTS wire application head can be used. Both approaches are in use, but in either approach, there is elevated risk above that for conventional cable manufacturing. Many years of manufacturing experience have led to the highly reliable performance of copper wire stranding for conventional cables. Thus, it is reasonable to assume that additional experience (beyond the very few HTS cables that have been made to date) will be needed to arrive at a similar level of manufacturing reliability.

After the initial setup, the machine operates similarly to a standard paper-cable taping machine, with the exception that the HTS wires and insulating tapes are usually completed at the same time in a continuous run. (For conventional cables, the conductor is usually fabricated elsewhere and has been completed before it is run through the taping machine.) This process modification also introduces some risk beyond that of conventional cable taping because tensions and velocity of the cable core in the composite machine will need to be coordinated for the different requirements associated with stranding wire versus applying dielectric insulating tapes. Here again, experience gained over many production runs will be needed to reduce risk.

The HTS wires produced today have not resulted in significant changes in the cable manufacturing process. However, new developments and new mechanical properties in the HTS wires may result in minor changes in the way that the taping equipment is set up and operated. All other components incorporated in manufacturing the HTS cable are well known to the cable manufacturers that are producing paper cables.

The splicing and terminating of cables with HTS wires requires craftsmanship similar to that for splicing conventional transmission cables. The producers of the HTS wires have also developed the process for connecting two wires. Because of the low number of HTS cable splices installed and no known failures, there is no experience of failure modes.

The existing manufacturers of HTS cables use traditional taping equipment that is capable of producing cables up to a 5 in. (15 cm) diameter. This equipment can be used to manufacture triaxial cables up to 69 kV, the present maximum voltage level considered for this construction. The production time for .62 mi (1 km) of 12 kV triaxial cable is about 10 days (80 hours) on existing manufacturing equipment. If 3.1 mi (5 km) of triaxial cable were produced at one time, the manufacturing time would be 20 to 25 days because the machine setup time would be substantially reduced. Based on today’s manufacturing technology for triaxial cables, it is possible to produce 62 mi (100 km) of distribution-voltage class cable in one year. If additional shifts were added, the production could conceivably be tripled. For the single-conductor HTS cables of 69 kV and higher (three-phase coaxial and triad schemes), it could be possible to manufacture a substantial amount (perhaps 62 mi/100 km) of HTS cable per year.

In summary, the manufacturing of HTS cable is quite similar to manufacturing a paper-insulated power cable and is a well-established process. For experienced taped-cable manufacturers, the only difference is the handling and application of the HTS wires. The available experience indicates that the HTS wires applied to date behave similarly and have not created any manufacturing issues. Therefore, when HTS cable is manufactured by experienced taped-cable makers, there are no known manufacturing issues that would be different from those found in conventional cable manufacturing. With respect to terminations, which are custom designed, the transition from low to ambient temperature is well understood and established designs exist. The ambient temperature portion of the termination is similar in design to a standard cable termination which has an excellent operating record.

Scale-up to larger production runs from that of current or historical HTS cable manufacturing experience is also not expected to result in significant risks. Conventional transmission cable is custom-manufactured in a batch process, with specific lengths made according to customer specifications. An HTS cable would be made in the same manner. The only differences in this process between today's production of HTS cable and a mature market would be the length of each cable piece and the number of cable reels supplied to the field. The mature market may require cable spool lengths of 1968–2624 ft (600–800 m). The longest triaxial cable section produced to date is a 1640 ft (500 m), 10 kV section manufactured and installed by NEXANS in 2013 in the city of Essen, Germany, where two sections are joined to produce an overall .62 mi (1 km) cable installation. Scale-up would consist of simply repeating this process for multiple reels.

Refrigeration Systems for High-Temperature Superconducting Cable Systems

Reliable performance of HTS cables requires proper temperature control throughout the cable system. The operating temperature range of HTS cables is determined by two main factors. The first is that it must be low enough for the superconductor to carry sufficient current, and the second is the physical limitations of the fluid used for cooling. To maintain proper operating temperature, the superconducting cable must be thermally isolated from the outside environment heat loads by enclosing it in a cryostat that extends along its entire length. In addition to heat from the environment, internal heat is generated in an alternating current (ac) cable. Also, some heat flows along the power leads that connect the superconducting elements to the ambient temperature power grid. Coolant flow and the total cooling power of a cryogenic cooling system must be designed to maintain the desired operating temperature by removing the heat from these sources. These requirements are satisfied by the three main elements of an HTS cable's thermal management system: the refrigeration system, the cryogenic fluid flow, and the cryostat. The refrigeration system and cryogenic fluid flow are first jointly considered, after which the cryostat will be discussed.

Three types of refrigeration systems have been used successfully for HTS superconducting power applications: the open bath system, and two different types of refrigerator. These two refrigerators are based, respectively, on the Stirling and the Brayton thermodynamic cycles. In the open bath system, there is no refrigerator as such. Instead liquid nitrogen (LN_2) is periodically delivered to the project site and kept in large tank. Pumps are used to establish the desired coolant temperature (by reducing the pressure on the LN_2) and to produce the required coolant flow through the cable.

The Stirling and Brayton thermodynamic cycles, originally conceived, were devised to use a temperature difference to produce work. When these cycles are used in a refrigerator the cycle is reversed, and work (or energy) is used to produce a reduction of temperature. (Note: Because the thermodynamic cycle is reversed for a refrigerator the word "reverse" is sometimes added to the description of the refrigerator. This has become the custom for the Brayton cycle refrigerator. Moreover, all reverse Brayton cycle machines use a turbo-expander and in some descriptions the word "turbo" is also inserted [5].) This report will use the phraseology reverse turbo-Brayton to refer to this refrigerator, while also acknowledging that there are different configurations for the turbo-expander that have been deployed. In the LIPA I and II projects, the actual configuration and equipment used in the two LIPA refrigerators is different but, for the purposes of the current objective of addressing technology maturity and risk assessment, it was decided that these differences would not impact the study conclusions

The different types of refrigeration and the overall cryogenic system design entail different risks and consequent risk mitigation. The open bath technology has been proven as a rugged approach for the cooling of HTS cables. For example, it was determined to be the lowest cost approach for the Essen cable project and has operated without trouble for almost two years. It was also used by Southwire for both their onsite cable and for the AEP Bixby Substation project, both of which operated for many years. There are potentially two risks associated with this approach. The first is that the LN_2 supply must be highly reliable because interruptions in liquid nitrogen production or transportation to the cable site can affect cable availability. This risk can be accommodated, to a certain extent, by using a large enough storage tank to accommodate delivery delays that are significantly longer than normal. The second risk is associated with the need for frequent access to the LN_2 storage tank, which may require access to the electrical substation by non-power-company personnel. Substation access procedures for utility personnel are well established for reasons of both safety and security. Establishing access for the truck drivers of LN_2 trucks could be problematic. This issue can be accommodated by 1) having the delivery point for the LN_2 outside the fence of the utility substation, or 2) having a utility employee either drive the LN_2 to the point of delivery or accompany the delivery vehicle to the site.

There is a different set of risks and risk mitigation strategies for refrigerators. While refrigerators also require delivery of LN_2, the need is so infrequent that it can be addressed as a special circumstance requiring the attention of one or a few individuals with specific training. Rather, there are more important issues for refrigerators, which also differ depending upon the refrigerator type. Existing Stirling refrigerators provide only 3 to 4 kW of cooling at liquid nitrogen temperature, so several may be required for HTS power cable installations. Though this creates a potentially more complex installation, the fact that several identical units are in place provides some redundancy to the cryogenics. Stirling refrigerators have a reciprocating piston and require maintenance by certified personnel approximately every 8 months of full-time operation. The fact that there are several units installed means that there is little chance that maintenance will affect cable availability, but it does require access of non-utility personnel to the substation.

For the reversed turbo-Brayton refrigerator there are different concerns. Positively, the turbines on reversed turbo-Brayton refrigerators are known to operate for as much as 100,000 or more hours without failure or maintenance. However, potential issues for the reversed turbo-Brayton type of refrigerator include freezing of nitrogen in a small part of the system, causing damage or flow blockage, and inadequate removal of lubricating oil used in the compressors, affecting refrigeration performance and possibly damaging the turbine [6]. More importantly, non-utility personnel require physical access to the refrigerator during this time.

For all three approaches described above, transient loss of refrigeration after a fault is a potential risk. This issue is mainly associated with systems with counterflow cooling, and is not so significant when there is a separate return cryostat, which tempers the timing for acute temperature changes in the return flow. Refrigeration systems may be designed to accommodate a fairly wide range of heat loads. However, there is an issue with dramatically changing loads over a short period of time—such as may occur as a result of a through-fault in the cable. Depending on the cryogenic circuit design, the effect of and recovery from such an event can take minutes to hours and may possibly require operator intervention. Mitigation for such a situation depends on the type of refrigeration and how much flexibility has been designed into the system. One method of mitigation is to have a separate return path for the cryogen, as is the case in the ComEd project [7]. An advantage of the open bath system in this regard is that, in such an event, it will simply raise the temperature and decrease the density of the return fluid. The situation is not so simple for a counterflow cable using a Stirling or reversed turbo-Brayton refrigerator. For these refrigerators, there are several approaches methods for mitigation. One is to operate the system at a pressure that is so high that the cryogen does not become gaseous at the maximum temperature during the fault. Another is to use a buffer tank that is cooled by the refrigerator with a heat exchanger in that tank. Yet another approach is to operate the refrigerator at a higher power level than is needed and provide a variable heat source in the system to maintain the temperature.

As stated above, the third element of the cryogenic cooling system is the cryostat. Cryostats for cable and commercial cryogen transfer lines are currently made in lengths of about 328 ft (100 m), although manufacturers such as Nexans have begun using longer lengths of about 1640 ft (500 m), for example for the Essen cable. (Note that cables of such long lengths are proposed for the ComEd installation [7].) These longer cryostat sections would be in one piece and may have multiple vacuum pump outs along the length or may have only pump locations at the terminations. In either case, the intent is to use only the pump outs near the terminations once the cable is installed. In the past, most cable cryostat were made of several 328 ft (100 m) sections welded together to produce the appropriate length of cryostat as required by the cable section. The most likely failure in a cryostat is degradation of the vacuum causing an increased heat leak that raises the temperature of the cable and coolant. In essence, the performance of the power cable is dependent on the level of the vacuum in each cryostat section. The longer a section is the greater will be the impact on cable performance and the more difficult it will be to restore proper vacuum. To date, the shorter length cryostats (i.e., those of 328 ft or 100 m or less) have maintained their integrity for existing HTS cables. Studies of the use of many 328 ft (100 m) sections indicated that the reliability of very long cables consisting of sections could be an issue [8]. At present, there are no analyses of reliability for the longer cable lengths now being used. At this time, a rigorous determination of cryostat reliability is not possible.

The mitigation of a cryostat failure (degraded vacuum) depends on the amount of heat that enters the cable during operation. If the increase in heat input is minimal, it may be accommodated by operating at a slightly higher temperature, by increasing the flow of coolant, or by reducing the allowable power flow in the cable. Either of the first two possibilities may be adequate for the entire life of the cable system but will require some initial margin in the capabilities of the refrigeration system or an upgrade to the refrigerator after the increased heat load appears. The effect of reduced power delivery must be weighed with the cost of repair or system modification. If the heat input is significant, the cable and cryostat must be taken out of service and a section may have to be replaced. To minimize downtime, this could be accomplished with some spare components, such as sections of cable that are the appropriate length to go between vaults or manholes. At this time, it is not possible to predict the time required to replace a cryostat section.

In addition to being a mature technology, there are multiple manufacturers of various components that meet the needs of the HTS cable. Cryostats of the type envisioned for the HTS cable have had many years of satisfactory commercial service for a variety of applications, most of which utilize short length (e.g., tens of miles/meters). For the longer length cryostat installations envisioned for HTS cable systems (e.g., kilometers in length) the long-term reliability is indeterminate at present. Moreover, there are few suppliers of this type of cryostat at present—really only one (Nexans). While there are no anticipated problems with initial quantities or quality of the cryostat itself for early demonstration projects, a greatly expanded market would require (and possibly motivate) the entrance of additional suppliers. The U.S. utility industry in general prefers and is sometimes required by state regulatory agencies to solicit competitive bids from multiple suppliers for the equipment it procures

With respect to technology status, the thermal management needs of an HTS power cable of the type under consideration for ComEd will not tax the capabilities of the industrial gas sector that makes and uses this technology. That is to say there is an existing, century-old industry that makes commercially available products using well-understood methods, upon the back of which a new application such as HTS power cables can establish itself. HTS cables will simply represent yet another, and new, market for this well-established industry's business. The cryogenic industry has as much experience as the electric power industry in manufacturing and delivering a similar commodity—one that is often required in large-scale quantities for mission-critical, "just-in-time" commercial, medical, and research endeavors. Each of the three major elements of the HTS cable—the refrigerator, the cryostats, and the fluid flow system—can use components that are produced in significant quantities for a variety of commercial applications today. On the other hand, a period of product optimization for this new market must take place. In the long run, optimization and customization of commercially available hardware and refrigeration methods to meet the specific needs of HTS cables will be required before this technology can be considered mature for electric utility system applications. Optimization can be addressed by means of standard engineering and production tasks, as well as by the lessons learned from continued demonstration projects such as that proposed for Com Ed.

In some cases, cryogenic system components are based on technically different concepts, such as the three different refrigerator technologies. All of the technologies are able to provide similar performance for an HTS cable, but because of the conceptual and practical differences, there are tradeoffs that will be appropriate for cables in different environments and different locations.

In summary, the advanced status of refrigeration technology should minimize any apprehension on the part of the electric power sector in terms of functionality and reliability. However, the various risks and risk mitigation approaches must be adequately considered during the planning and implementation of a superconducting cable project.

3
TESTING AND INSTALLATION

Testing of High-Temperature Superconducting Cable Systems

Testing of an HTS cable system must occur at various points of design, manufacturing, installation and commissioning. Components to be addressed are the cryostat, wire, cable, splices, terminations, refrigerators and other cryogenics, controls, and the completed system. Of critical importance regarding test procedures and test results is that both the user (utility) and the technology supplier (vendor of each component) agree to the details of the tests and interpretation of results before the final contract is issued.

The basis of analysis in this project was the conventional transmission-voltage cable, for which testing protocols have been established and refined over many decades. The more stringent testing procedures for transmission-voltage cables are more appropriate than the procedures for conventional distribution-voltage cables, which are essentially an off-the-shelf commodity.

High-Temperature Superconducting Cable Testing

With respect to the HTS cable itself, the international engineering organization CIGRE published a technical brochure “Recommendations for Testing of Superconducting Cables,” (TB-538) in 2013 [9]. That brochure provides many good recommendations, covering both factory testing and field acceptance testing. However, the present assessment concluded that several additional tests should be performed, most of them relating to cryostat and cable system installation. In many cases, procedures for conventional cable systems will be applicable. In some cases, testing protocols must be developed, and standards for satisfactory results must be quantified. These procedures will be expanded as experience is gained in cable system installation and operation.

There is a notable risk associated with the inability to perform factory high-voltage testing of HTS cables. Other than a continuity check, no electrical testing is performed on the complete cable before shipment, because the cable would have to be brought to the cryogenic operating temperature. This is in marked contrast with the practice for conventional transmission cables, which are 100% factory tested. Although uncommon, lengths of conventional cables have failed factory electrical tests; those lengths were not shipped to the field where the results of a failure would be far more serious. There is no fully acceptable mitigation of this risk at the present time, the consequences of which may only become apparent when long lengths of cable begin to be manufactured. After installation and cooldown, the cable system will be subjected to electrical tests similar to those performed on standard cable systems. Testing experience from projects worldwide is described in a more recent CIGRE document “Common Characteristics and Emerging Test Techniques for High Temperature Superconducting Power Equipment” [10].

There is also the possibility that successful completion of testing that is performed at room temperature may not adequately indicate performance at LN_2 temperatures for both factory and field tests. The time and cost are generally large for room-temperature tests and would be greater for LN_2-temperature tests that can be performed only after the entire line is installed and cooled down for the field tests. Problems found after cooldown will probably require warmup before repairing or replacing components, and then subsequent cooldown and retesting would be required. Careful correlation of test procedures and results at ambient and LN_2 temperatures is necessary to obtain the desired confidence in successful operation before undertaking the nitrogen filling and cooldown of the line.

Refrigeration System Testing

CIGRE's TB-538 has an annex that mentions refrigeration systems and tests, but it does not provide test requirements or expected results. Our assessment recommends a testing procedure for these systems that is based on or is an extension of practices that are commonly used for commercial systems or that have been used in HTS cable projects to date. The initial factory tests (electrical, mechanical, and pressure) of the cryogenic refrigerators must ensure proper performance, including measurements of actual cooling capacity. Details of this test, including reporting, should be included in the refrigerator specifications. In the case of an open bath cooling system, there may be no qualification test, but each component will be tested.

Cryogenic system acceptance testing in the field will reduce risk by providing verification that the system will meet the expected heat removal requirements of the cable. Test procedures will depend on which cooling method is being used. However, many tests are independent of refrigerator type, and the goals of the tests are similar—that is, to demonstrate that the refrigeration system meets the specified requirements and can perform the necessary automated operations under various operational scenarios. Refrigerator tests should provide a baseline measurement of cooling capacity and of the heat loads present in the refrigerator itself. This information will be useful throughout the life of the cable system to determine whether changes in operational heat loads are caused by the cable, the various connections, or the refrigeration system. Records should be kept of all data collected during testing.

Superconducting Wire Tests

A variety of tests have been conducted to verify the properties of superconducting wires. The breadth of these tests is too great to be described here, but a summary of the various tests is given in IEC-61788-21 [11]. A companion document, IEC-61788-20 [12], describes the general features of superconducting wires. A smaller list of tests that are particularly relevant to power cables is given in TB-538 [9]. Specific tests for superconducting wires are described in several IEC documents, IEC 61788-1, IEC 61788-2, IEC 61788-3, and IEC61788-4, which provide details of critical current measurement requirements for different types of superconducting materials [13, 14, 15, 16].

The exact tests to be carried out for materials being prepared for use in superconducting power cables will depend on a variety of factors. A major driver for the choice of tests is fact that HTS wires are in a pre-commercial stage of development. Various tests of each wire in an HTS cable are needed to verify that it meets the specifications agreed upon by the wire manufacturer and the cable manufacturer. These tests could be done by the wire manufacturer, by an independent testing agency, or by a laboratory. The most important wire parameter that must be determined is the critical current. This parameter can vary along the wire; therefore, it must be determined for every few meters of conductor in the cable. This has been done for other superconducting wires when there was uncertainty during the quality control in the manufacturing process, and yield was uncertain in the times of early production. Depending on details of the cable design, tables and graphs of critical-current test results are used by cable manufacturers to choose the optimal use of conductor in the cable.

As with many other technologies, when production volumes increase and production processes become better understood, the tests of a statistically representative sample of materials may prove to be adequate.

Installation of High-Temperature Superconducting Cable Systems

Installation of an HTS cable system on an electric power system embraces both similarities and differences when compared to electric utilities' longstanding experience with conventional underground cable systems. The assessment focused primarily on the risks involved in installing the HTS-related equipment, including the cryostat, cable, splices, terminations, refrigerators and other cryogenics, and substation components.

With respect to the cable core and the cryostat, which are separate components, there are two approaches for installation. One approach is to pre-install the cable into the cryostat in the factory. The cable and cryostat are then shipped to the job site and installed into a duct in a single operation. The other approach is to separately install the cryostat into the duct in the field, and then pull the cable core into the cryostat. Several prototype installations of short lengths of HTS cable using both approaches have been successful, and there have been no reports of cable damage during installation or failures during operation. There is no experience with installation of individual sections of HTS cables longer than 1000 m.

With respect to cable accessories (splices and terminations), factory type-testing has verified their integrity, but there have been few field installations, particularly of splices. Although there have been no reported problems with splices, the small number of installed units makes them much more in their infancy than the terminations. All prototype installations, of course, have had terminations installed. They are generally made to accommodate the current and voltage requirements of the cable and the substation where the cable is installed. There is no standard design for the terminations, but they use standard components where possible. Standard, off-the-shelf bushings that operate at ambient temperature may be specified and agreed on by the cable manufacturer and the host utility. Thermal conditions within the termination depend on the details of cable design and the type of cryogenic system used for cable cooling. There have been no installation issues associated with terminations for prototype HTS cable installations to date. In part, this is because the utilities make electrical connections to bushings with which they already have experience. Installation procedures for all of these components are similar to those successfully used for decades on underground power cable systems.

Many of the risks for HTS cable systems are common to conventional cable installation, but there are additional risks associated with the new technology and the lower ruggedness of the HTS cable system.

The initial stages of cable installation—routing, civil works, and duct installation—closely follow well-established practices and should not produce any more risk than a conventional installation.

Cryostats and cables are less rugged than the equivalent components on conventional systems, so they will require more careful installation procedures. The thermal and mechanical requirements associated with operating at LN_2 temperatures are unfamiliar to installers, so installers will require different equipment plus training and experience. Installing the cryostat is a much more delicate operation than installing the steel pipe used for paper-insulated conventional cables or for installing cross-linked polyethylene (XLPE) cable. Cryostat usage is mature in other industries, but we believe that additional attention is needed for several areas that are specific to long-distance power cable installation in a duct system. Procedures have been developed and successfully applied for prototype installations, but ruggedness of the cryostat, attachment methods, and test methods need further demonstration before cryostat installation in a duct and manhole system can be considered a low-risk operation.

Cable installation should be able to follow conventional practices, but attention must be paid to attachment of the pulling line to the cable and potential damage to the conductors and insulation layers during cable pulling, particularly for field-installed cable. Simple and rapid room-temperature tests should be developed to verify cable integrity before splicing and the installation of terminations.

Operation and Maintenance of High-Temperature Superconducting Cable Systems

An assessment of the various issues associated with operation, maintenance, and repair of an HTS cable system revealed that the well-established procedures for conventional cables and cryogenic systems are applicable to most aspects of HTS cable systems, including those with fault-current-limiting capability. Although they are different in many details, operation and maintenance issues with HTS cables have many parallels with conventional cables.

An HTS cable system can include one or more individual cable lines. If there are several lines, they may or may not be connected electrically, even if they work together to improve system performance. The design of a superconducting cable system depends on its planned functionality and how it is to be integrated into the grid. Similarly, details of HTS cable system operation will change from installation to installation, depending on the requirements of the host utility.

Operation of the HTS cable system can benefit the reliability of the utility system, but the operators must deal with the potential several-hour outage of an HTS line following a through-fault (that is, for those systems in which the outage is part of the through-fault design). The fact that an HTS line may be out of service for several hours following a through-fault will be unfamiliar to system operators, and the operators may not permit loading lines to their capability because of this potential condition. It is hoped that long-term experience in operating the HTS system will provide the required level of confidence.

Maintenance and repair procedures can be similar to established procedures for conventional cable systems. The need for specialized services and the time necessary for warmup and cooldown will likely extend the duration of an outage on an HTS line compared to an outage for repairs on a conventional cable system. Utilities should establish ongoing contracts with cable and refrigeration specialists for maintenance and rapid mobilization for possible repair.

Although most of the operation and maintenance procedures and the repair scenarios follow conventional practice, the fact that this is a system filled with LN_2 at temperatures near 77 K is likely to create concern among utility personnel about safety (both temperature and possible oxygen deficiency) and work procedures. Extensive training is recommended. This may achieved by designing and carrying out a training course for utility users of cryogenic equipment.

Unfamiliar spare parts and requirements for outside specialists to perform much of the work can create problems in operation, maintenance, and repair. The time needed to warm up for repairs and to cool down and test after repairs are complete can result in outage times that are longer than typical for cable systems. Maintaining adequate spare parts and establishing an ongoing contract with specialized repair firms can help mitigate this problem.

4
TECHNOLOGY AND MANUFACTURING READINESS

Approach

Detailed descriptions of current technology status, manufacturing processes, scale-up issues, risks and proposed mitigation steps are presented in the Task 1 HTS technology assessment report [17]. Based on the knowledge gained in carrying out those assessments, the EPRI team of experts developed a technology and manufacturing readiness summary for each of the three core HTS cable system components: HTS wire, HTS cable, and refrigeration systems. The readiness scores are provided for the technology and manufacturing as these stand today, also provide projections assuming a maturation process that includes successful completion of the DHS REG Proposed Phase 3 Project. The results of that summary are presented in Table 4-1.

Two scales were used, one for technology readiness and one for manufacturing readiness. The technology readiness scale was adapted from the Department of Energy Technology Readiness Levels (TRL) scale [18]. The manufacturing readiness scale was adapted from a scale developed by Advanced Product Transitions Corporation [19] for the Department of Defense. According to the APT web site, the Manufacturing Readiness Levels (MRLs) were designed to mirror the TRL structure and process. The ten levels of MRL range from basic manufacturing status to full production. Relevant portions of these scales are shown in the table.

EPRI's TRL/MRL assessments shown in Table 4-1 should not be taken as a "scientific" survey or exercise. Rather, it represents the consensus opinion of a group of subject matter experts. The EPRI team is as well qualified as any other group for such an ad hoc assessment. Nevertheless, one may wish to attach a plus or minus one (±1) to the numbers shown in the table.

In making the TRL/MRL assessment, the EPRI team used the following guidelines:

- **Superconducting wire.** Superconducting wire readiness was evaluated only from the perspective of its use in HTS cables. However, it was assumed that production for other applications (e.g., FCLs, generators, motors, transformers) would continue at similar or greater rates than at present. The TRL evaluation was from the point of view of a finished product delivered to a cable manufacturer. The MRL evaluation was from the point of view of capability to produce wire for a cable. Commercial maturity for superconducting wire was assumed to be equivalent with achieving a TRL and MRL that, combined, can deliver market quantities of wire. "Market quantity" of wire is assumed to be in the range of 3107 to 31,086 mi (5 million to 50 million m) of wire per year, following a DOE-sponsored study of the potential for coated conductor (Gen 2 HTS wire) to reach a price of US$5/kA-m or less [20]. However, this price may be too stringent, with full market acceptance occurring at a price as much as an order of magnitude higher. From the DOE study cited, the annual production required for a wire price of US$50/kA-m would be approximately an order of magnitude lower (i.e., 311 to 3107 mi or 0.5 to 5 million m of wire per year).

Table 4–1
HTS cable systems—technology and manufacturing readiness levels

	Current Status		Post-Chicago Status		Earliest Year Commercial§
	TRL	MRL	TRL	MRL	
Wire					
AMSC 2G wire (including IFCL)	6	7	7*	8*	2025
2G wire from all <u>other</u> manufacturers	6	6	NA	NA	2025
1G wire	9	9	NA	NA	§§
Cable					
Triaxial design cable from Southwire and Nexans	7	8	8	8*	2020
All HTS cable from all manufacturers (Southwire, Sumitomo, Nexans, LS Cable, Furukawa, Russia, China, etc.)	6	8	6	8	2020
Refrigeration Systems					
"Open" systems (such as Essen and AEP Bixby)	7	7	NA	NA	2020
"Closed" systems using refrigerators (such as LIPA, Albany, the two DHS REG projects (ConEd and ComEd)	7	7	8	8	2020
Complete HTS Cable System (2G Wire Only) §§§					
From knowledgeable utility customer perspective	7	7	8	8	2025

Headings should be interpreted as follows:

- Current Status: The situation as of 4th Quarter, 2015.
- Post-Chicago Status: Result of installing the Proposed Phase 3 Project in Chicago by the year 2018 with subsequent successful operation for a minimum of two years (to year 2020). Also assumes successful completion and operation of the DHS REG Phase 2 ("Project HYDRA") in New York City.
- Earliest Year Commercial: The earliest year that TRL/MRL could reach 9/10 for each system component, and for the system as a whole, assuming that 1) the Chicago and New York City projects are successful; 2) successful HTS cable system development/deployment in in other markets occurs at same or greater rate as present; and 3) market factors including price and value proposition produce significant incentives to install HTS cable systems. This is an estimate of what is **possible** within reasonable technical and manufacturing constraints, not a projection of what **will** occur.

***** The ratings would be one step higher if the wire and cable for the Chicago project were produced all in one run rather than multiple smaller runs over a several year period, and if the cable were IFCL.

§ "Commercial" means TRL/MRL = 9/10, respectively. There are multiple suppliers competing in the marketplace. Production assumptions are: wire – 18,641 mi (30 Mm) per year production at US$5/kA-m; cable and refrigeration – 31 mi (50 km) per year production. If these targets were not met, the commercial year would be later than shown.

§§ 1G wire is commercially available today, but from only one major supplier. Viable projects are in place today and may continue to be deployed. However, at approximately US$90 to US$100/kA-m, it does not meet the price point we have established for wire to be commercial (<US$5/kA-m); moreover, it is not ever expected to reach that goal.

§§§ Although 1G systems for high value proposition markets could reach TRL/MRL = 9/10 levels before 2025 those markets are not expected to meet our definition of "commercial" and thus we do not include 1G systems in this category.

- **HTS cable.** Evaluation of cable readiness was for HTS cable systems, and not in respect of the underlying underground transmission cable technology (which is considered to be mature) except where such technology is directly applicable (such as taping). The TRL evaluation was from the point of view of actual deployed cable to date, whether lab or field. The MRL evaluation was from the point of view of capability to produce the cable for those deployments. For full commercial status (TRL = 9 and MRL = 10) we assumed cable production to be 31 mi per year (50 km/year). For the sake of ranking the cable, an assumed market size was taken as given; however, we recognize that the actual cable market size will be driven in part by progress toward commercialization of the other components, among other factors.

  The amount of wire production annually for this amount of cable is calculated to be approximately 7767 mi (12.5 Mm) per year, which is more than twice the required annual wire production estimated to reach a wire price of US$50/kA-m (see above), or roughly one half of the production volume required to reach the price target of US$5/kA-m. (This calculation assumes the cables have a dc critical current capability of 8 kA for a nominal 4 kA ac delivery. For a superconductor having I_C = 130 amps/tape, about 820 ft/250 m of wire would be required for each meter of cable, allowing a factor of 1.3 for twist pitch and rounding up to 820.)
- **Refrigeration systems.** Evaluation of refrigeration readiness was for systems specifically designed and manufactured for HTS cable systems, and not in respect of the underlying refrigeration technology (which is considered to be mature), except where such technology is directly applicable. The TRL evaluation was from the point of view of technology that is fully optimized for utility-scale HTS cable systems and not for a modified version of a commercial unit designed and built for other applications. The MRL evaluation was from the point of view of manufacturing those systems. For full commercial status (TRL = 9 and MRL = 10) we assume refrigeration system production to be sufficient to meet the needs of the assumed annual cable production.
- **Complete HTS cable system.** Evaluation was from the point of view of systems actually deployed to date in utility projects or laboratory demonstrations, regardless of supplier or customer. The evaluation considered the system as a whole, as it would be seen by a potential, knowledgeable, utility customer.

Results

With respect to current status, the team rated technical readiness for 2G wire at TRL 6, whether AMSC wire or that of other manufacturers. However, for manufacturing readiness, AMSC wire was judged to more mature. Nevertheless, it is asserted that 2G wire in general will require significant advancement before becoming commercial.

Cable and refrigeration technology and manufacturing, based as they are on commercial products for other applications, fare much better. The technology of triaxial cable and refrigeration systems for HTS cable are considered to be still in prototype stage, but only because the underlying technology has not been fully optimized for utility application. Manufacturability is more advanced, at MRL 8, reflecting the fact that the equipment is produced in similar ways as commercial products. There are as many as six manufacturers of HTS cable worldwide with significantly different levels of product experience and cable design. Of these, only two manufacturers (Southwire and Nexans) have produced and installed a triaxial cable in utility grid environments. While the current TRL of triaxial cable was rated at 7, when considering all manufacturers together a TRL of only 6 was believed to be more appropriate, reflecting the wider variation in product experience. The Chicago project was not judged to have an impact on that rating since only one of that relatively large group of manufacturers will gain experience from the project.

Table 4-1 shows the impact of the DHS REG Proposed Phase 3 project in Chicago (with the assumption also of successful completion of the Phase 2 project in New York City). Because the Chicago project would require a significant increase in the amount of wire produced (about 932 mi or 1500 km) and the longest ever installed cable (about 3.7 mi or 6 km), a one-step improvement may be expected in technology readiness for all three components: wire, cable, and refrigeration. However, for manufacturing readiness of wire and cable, the improvement is judged less than it could be. That is because, based on current forecasts, the cable system will be manufactured and installed in as many as four separate steps, spread over a period of several years. Thus, the annual factory production for wire and for cable may not be greater than previous projects. On the other hand, if the project were to be accomplished all in one step, that could improve both the TRL and MRL for wire and cable by one additional step, as shown in the table notes.

With respect to the "earliest year commercial" assessment, one of the conclusions to be drawn is that, unsurprisingly, the major driver in the ultimate commercialization of HTS cable systems is the superconducting wire. The rating suggests that the wire will not be commercial before the year 2025, based on production volume and price, whereas the cable and refrigeration technology and manufacturing readiness could reach commercial status by about 2020, assuming a large enough market (in our exercise, assumed to be 31 mi/year or 50 km/year of cable). Because the size of the market will be driven by a number of factors, one of which is wire price, it was concluded that the maturity date for a complete system is more likely to be 2025 or later. In addition, the earliest year commercial assessment does not take into account a number of external factors, both positive and negative in their impact. The various factors that will influence commercialization, including price, value proposition, utility acceptance, regulatory environment, competing technologies, and so on will be assessed and reported in Task 2 of this project.

As a final point of discussion, it is noted that 1G wire is essentially commercial today, at least for one manufacturer. Moreover, several successful HTS cable projects have used 1G wire, including systems that have a fault-current-limiting capability. However, it is believed that the price of the wire will not achieve further reductions below its current value of about US$90 to US$100/kA-m. Because 2G wire is, at present, larger than that value, we expect that additional HTS cable projects using 1G wire may be deployed in the near term. Such projects could help commercialize HTS technology in some respects (cable manufacture, refrigeration, utility experience and acceptance, and so on). Nevertheless, the longer-term market is expected to belong to 2G wire. For this reason, 2G systems are the basis for the commercialization projections made in this assessment.

Recommendations for Further Work

On the basis of the foregoing summary of the results of the Task 1 assessment, the following recommendations are made for further work to enhance the commercialization process for HTS cable systems:

- Ensure access to wire manufacturing experts to assist in resolving wire manufacturing scale up issues in a timely manner.
- Sponsor or facilitate the continued development of cable and cryostat testing protocols and quantification of standards for satisfactory results beyond the current industry status (which is considered to be deficient).
- Develop and implement courses and material for the training of utility users of cryogenic equipment.

5

COST AND COMMERCIALIZATION METHODOLOGY

To better understand site impacts, this study selected and defined 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 EPRI team received from meetings, responses to questions, and information obtained with regard to five separate utilities, these base cases are attempted to be reasonably representative of dense urban network systems. They do not necessarily 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 can be found in the second volume of the full report [21].

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, where:
  - Reliability is the ability to maintain service to customers in the face of the normal, though infrequent, system equipment failures (or contingencies).
  - Resiliency is the ability to harden the system against high impact, low frequency events; and the ability to expediently recover from such events.
- It is assumed that for the specific base cases, 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. Nevertheless, to make the analyses more widely applicable, conventional solutions are considered for comparison purposes.
- The HTS solution is a fault current tolerant (as compared to an inherently fault current limiting) HTS cable system supplying distribution voltage to the critical infrastructure load from one or more existing substations It is assumed that this case is not approaching fault current limitations. The critical infrastructure may be 1 to 2 mi (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 approaching its design end of life or a high-maintenance transformer that is scheduled for replacement, 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 above).
- 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 IFCL 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 and build for growth now, 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 IFCL 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.

6
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 (1.6 km), 13-kV, 3-kA HTS cable installation, with wire cost at US$50/kA-m, is shown in Table 6-1. Figure 6-1 presents the cost information in a pie chart to better illustrate the percentage contribution for each major component.

Table 6–1
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, 1 mi (1610 m); wire cost US$50/k A-m (dc); cable shipped separately

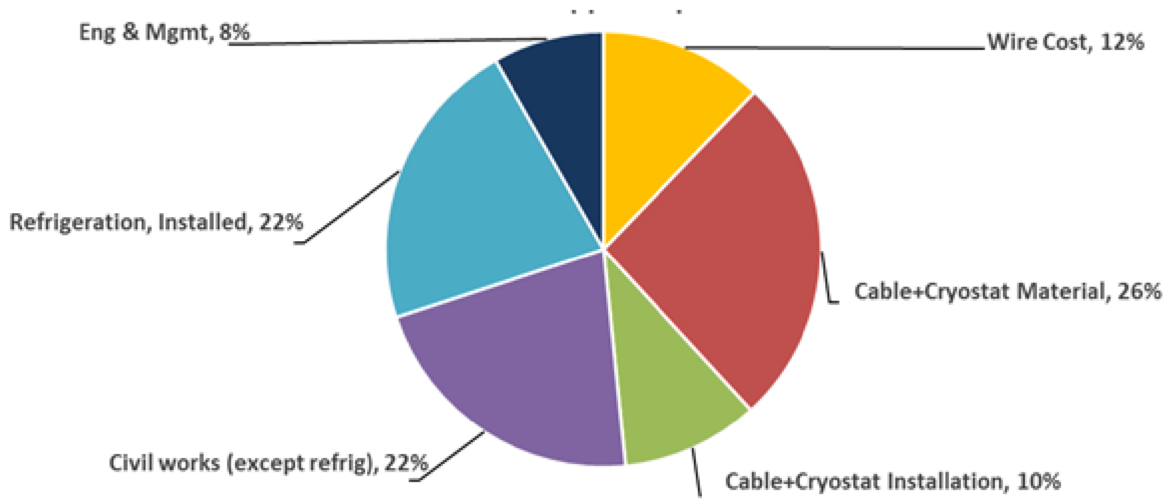

Figure 6–1
Cost model output: one-mile (1.6 km), 13-kV, 3-kA high-temperature superconducting cable project, US$50/kA-m wire cost

Using the EPRI cost model, various parametric cost studies were performed to show, for example, the impact of wire cost and project size. Figure 6-2 shows one of the results obtained.

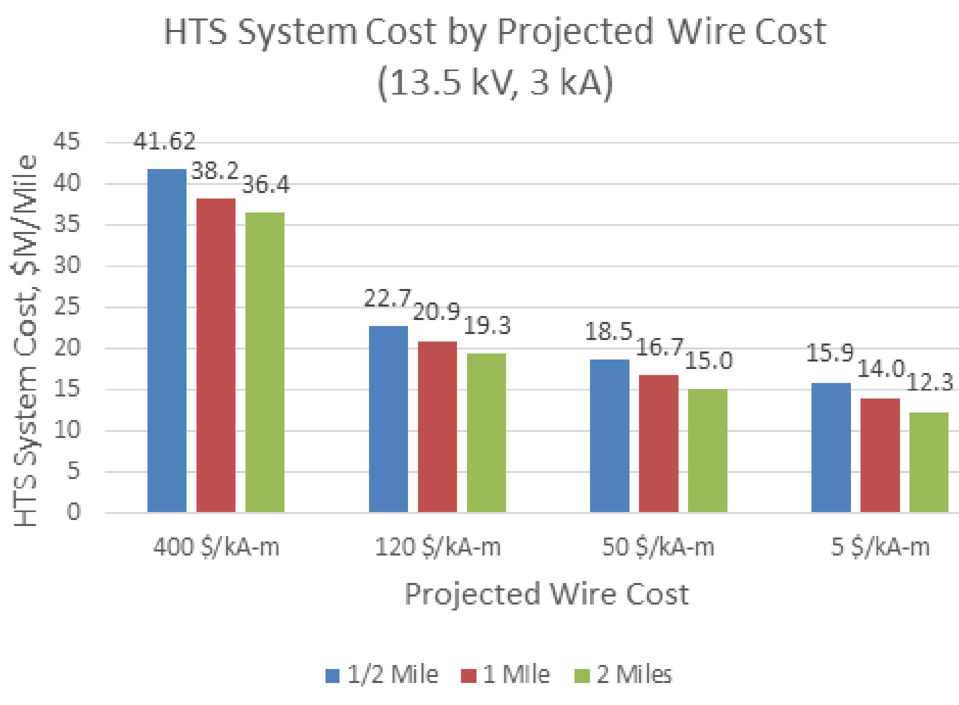

Figure 6–2
High-temperature superconducting system cost per mile by projected wire cost for different project lengths

7

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, many are at the demonstration stage. An exception is an Essen, Germany pilot superconducting cable project [22]. For example, the total length of HTS cable systems that have been installed worldwide is several kilometers. An analysis in Task 1 estimated the per annum output of wire required to sustain commercial viability at about 18641 mi (30,000 km) of wire per year. However, cable manufacturers have projected lower estimates of required output to sustain 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 18641 mi or 30,000 km 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. A conventional solution for a dense urban network system might involve difficult siting issues associated with underground transmission lines and the amount of land and construction involved, and/or obstructions or underground congestion may preclude some conventional distribution solutions because of their much larger cross-sectional space needs. The HTS solution could involve similar issues, but these may be easier to resolve in a dense urban setting because of the lower voltage and the smaller size of the required corridor. For a utility to commit to implement an HTS solution, conventional solutions would need to be impractical in a dense urban setting, or HTS would need to represent a large cost advantage and/or capability that cannot be met with a 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 and practicality will be primary. Nevertheless, even for mature and accepted technologies, other factors such as reliability, performance, operability, and maintenance 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 from the utility's perspective in a dense urban setting. 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 7-1 through 7-3.

The first 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 7–1
Base Case 1: Supplemental power for critical infrastructure

	Conventional Solution: Distribution Requiring 7 feeders	**High-Temperature Superconducting Solution**
Power requirement	120 MVA	120 MVA
Distance	1.2 mi/2 km	1.2 mi/2 km
Voltage	35 kV	35 kV
Number of feeders	7	1
Cost	US$22 million	US$17 million to US$27 million (1) 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

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 the conventional solution cost. The HTS solution costs apply for either option because the HTS solution needs neither a new transformer nor a substation. Although these cases are generic in nature, it is assumed that space could be acquired in the urban setting for a substation, which would drive up the cost for a substation alternative dramatically. Actual conditions will vary.

Table 7–2
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	.62 mi/1 km	.62 mi/1 km
Voltage	13.5 kV	13.5 kV
Number of cables	0	1
Cost	(not including any required new transmission) Option A (new transformer): US$2 million Option B (new substation): US$42 million (highly dependent on substation cost in dense urban setting)	US$9 million to US$14.3 million (1) US$7.7 million to US$11 million (2) (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 Base Case 2

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. Although these cases are generic in nature, it was assumed that space could be acquired in the urban setting for a substation. Actual conditions will vary.

Table 7–3
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	5 mi/8 km	3.7 mi/6 km	0.3 mi/0.5 km	0.3 mi/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) US$80 million to US$124 million (2)	US$12 million	US$14 million to US$22 million (1) 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

The cost ranges shown in these tables represent the low and high regional cost estimates based on a review by team members of historical project costs. 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, assuming that wire cost will decrease 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. A principal driver in dense urban settings is space for cable and substations. This will be an important driver in the value proposition. Because design challenges and land costs vary significantly for any situation, a cost comparison is impossible. It can be concluded, however, that land is both scarce and expensive in dense urban settings. For specific cases, a detailed analysis is encouraged.

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 actual conditions 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) [23] and one performed in 2006 by Navigant Consulting, Inc. (NCI)[24]. 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 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* [25].Both assessments projected market penetration that has not yet taken place. 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 discontinuation of funding in 2010 of the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) Program 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) [1].

Although there have been a series of demonstrations in power grids worldwide, no HTS cable project without government support has yet occurred.

The development and demonstration of an HTS fault current limiter in the power grid in Augsburg, Germany, by the end of 2015 by Siemens [26] 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 [27], Nexans in the AmpaCity project in Essen, Germany [28] (an example of Base Case 2), LS Cable in projects in Korea [29], and Sumitomo [30] and Furukawa [31] in projects in Japan and the U.S.—provide signs of the interest of companies who could lead the market entry of HTS power technologies.

Although the projected S-curve of market penetration of HTS power technologies has not yet occurred, there have been S-curve emergence in patent application filings in the United States Patent and Trademark Office in Classification 505 (Superconductor Technology: Apparatus, Material, Process) in the sub-classifications 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 R&D and have made the decision to expend the financial resources necessary to pursue patents to protect their intellectual property Patent applications can be considered as an indication that industry leaders believe 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.

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 [32]. A 2013 White House report [33] 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.
- 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 resiliency 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 HTS must compete with conventional technologies.

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. 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 [34,35]. 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 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 a tendency towards risk avoidance that accompanies any effort to bring a new technology or technical approach to a long-standing problem or institution. Utilities are conservative organizations, because of the well-established nature of the technologies that they use as well as 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.

8 IDENTIFICATION AND CHARACTERIZATION OF OPTIONAL TECHNOLOGIES TO ACHIEVE GRID RESILIENCY

EPRI identified and characterized a suite of potentially viable grid resiliency alternatives with IFCL HTS cable respect to both the commonalities and differences related to key attributes. The key attributes chosen were those deemed to determine the ultimate desirability, technical feasibility, and cost effectiveness in providing improvements to grid resiliency.

Technologies that are currently believed to have the potential to improve grid resiliency in urban networks, and thus would be considered to be competing with the IFCL HTS cable include the following:

1. HTS alternating current (ac) cable in series with or without a fault current limiting (FCL) device (either superconducting or non-superconducting). An FCL device or cable would be required if circuit breaker or other equipment fault ratings would otherwise be exceeded, if necessary to support a fault current tolerant superconducting cable design or in specific applications such as tying two substations together in a way that would exceed either substations fault ratings.
2. Conventional ac cable in series with an FCL (either superconducting or non-superconducting).
3. Adding renewable or nonrenewable generation into the existing grid to increase grid resiliency (identified in this report as distributed generation, under the assumption that such resources are deployed on or near the urban distribution system).
4. Microgrid concept applications to increase grid resiliency.
5. Construction of additional substations or new transmission feeders that are tied to transmission grid to increase grid resiliency.

Options 1 and 2 are considered as direct alternatives to IFCL HTS cable because these will be considered one-to-one replacing technologies with same rating as IFCL HTS cable. Options 3 through 5 are considered additions to the existing system that may require additional system studies (load flow and short-circuit studies) working closely with the utility staff. All of the above technologies can help to maintain capacity margins as loads increase, which is also essential to preserving reliability and acts as a necessary baseline upon which to build resiliency.

The key physical and performance attributes and features deemed to impact desirability and against which these technologies may be compared were selected by EPRI research team, as follows:

- Required space above ground
- Required space underground
- Cost (initial and O&M)
- Noise

- Fault current reduction
- Fault current margin for addition of distributed generation (DG)
- Mitigation of voltage support issues
- Additional complexity for transmission and distribution operations
- Meeting capacity needs
- Margins for future load growth
- Customer safety
- Operational safety
- Improving asset utilization
- Increasing asset sharing
- Increasing or maintaining reliability

Thus, a comparison was made of the above five technology options, one with another, according to their relative physical and performance attributes and features. The IFCL HTS cable was also evaluated alongside these. The results are shown in Table 8-1. The numbers in parentheses after certain of the attributes (column one of the table) refer the reader to respective sections in the Task 3 report for additional description and/or clarification of the attribute [36]. The results of this comparison could help guide decisions in the future as to which technology may be the most appropriate in each given situation.

Table 8–1
Candidate technology comparisons according to relative physical and performance attributes and features

Technology **Attributes** (See numbered sections in Task 3 report for details [36])	**IFCL HTS**	**HTS + FCL**	**Conventional Cable + FCL**	**Distributed Generation**	**Microgrids**	**New Substation**
Above-grade space requirements (2.2.1)	Small	Small	Medium	Variable	Variable	Extremely large
Below-grade space requirements (2.2.1)	Medium	Medium	Medium	Variable	Variable	Small
Costs (2.2.2)	High	High	High	Low	Low	High to very high
Audible Noise (2.2.3)	Low	Low	Low	Low	Low	Medium
Fault current reductions	Substantial	Substantial	Substantial	Increases fault current	Segregates fault current	Segregates fault current
Fault current margin for addition of DG (2.2.4)	Increased	Increased	Increased	N/A	Increased	Increased
Mitigation of voltage support issues (2.2.12)	Potentially improves	Potentially improves	Potentially improves	N/A (potentially worsens)	Potentially improves	Improves
Additional complexity for transmission and distribution operations (2.2.11)	Minor	Minor	Minor	Much higher	Higher	None
Meeting increasing capacity needs (2.2.9)	Yes	Yes	Yes	Yes	Yes	Yes
Margins for future load growth (2.2.5)	Increased	Increased	Increased	May be increased	May be increased	Increased
Customer safety (2.2.10)	Preserved	Preserved	Preserved	May be affected	May be affected	Preserved
Operational safety (2.2.10)	Preserved	Preserved	Preserved	May be impacted	Study required	Preserved

NOTE: The ranking qualifiers in this table are subjective and based on the experience of the project team. They are also generic so that individual results will vary. Detailed, case-specific designs or specifications may give more definitive results. See indicated report sections for explanation of the ranking terms chosen.

9 ASSESSMENT OF THE ABILITY OF CANDIDATE TECHNOLOGIES TO MEET RESILIENCY REQUIREMENTS

The candidate technologies characterized in Table 9-1 with regard to key attributes were then evaluated with respect to their ability to achieve specifically desired resiliency benefits. To better understand site impacts, the Task 2 study had selected and defined 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. The details of these base cases draw on input received from meetings, responses to questions, and information obtained from EPRI member utilities, which was then recast into generic applications. In the Task 3 effort, the same base cases are used to compare the relative likelihood of each technology achieving the Task 2 projected reliability and resiliency benefits. The three base cases are the following:

- Base Case 1—critical infrastructure support
- Base Case 2—urban utility asset utilization improvement
- Base Case 3—load growth support

Because the base cases might not cover all distribution system resiliency issues, the research team defined additional “generic” resiliency applications—asset utilization, asset sharing, and reliability.

For each of the base cases the IFCL HTS cable and the candidate alternative technologies were evaluated with regard to their effectiveness in providing the expected resiliency enhancement benefits. In performing the evaluation, the research team reviewed and then applied the results of the technology comparisons described above.

Table 9-1 summarizes the results of this assessment. The table shows how well a given technology could meet the needs of a given base case or generic application, with a score of “Excellent,” “Good,” “Fair,” or “Poor.” Additional considerations or issues are noted in some cases, as well. These qualitative assessments express the technology’s capability for meeting reliability/resiliency requirement, and include annotations with respect to procurement, installation, and operation obstacles. They do not include comparisons regarding the cost, be it installation cost or lifetime cost.

Table 9–1
Comparison of alternative technologies for base cases and generic resiliency applications

Technology Base Case	IFCL HTS	HTS + FCL	Conventional Cable + FCL	Distributed Generation	Microgrids	New Substation
Base Case 1, critical infrastructure support	Excellent	Excellent	Good	Fair, but marginal if intermittent	Excellent for external faults when isolated	Excellent, but space may be an issue
Base Case 2, fault tolerant	Excellent in standby; moderate in service	Excellent	Fair; underground space may be an issue	Fair; may be subject to nearby faults	Poor, but excellent for external faults when isolated	Poor; space is an issue
Base Case 2, fault limiting	Excellent	Excellent	Fair; underground space may be an issue	Fair; may be subject to nearby faults	N/A but does not limit fault currents when grid connected	Poor; space is an issue
Base Case 3, load growth	Excellent	Excellent	Good	Good, but marginal if intermittent	Limited to existing in-house capacity	Fair; space may be an issue

10
CONCLUSIONS

The principal driver in the ultimate commercialization of HTS cable systems is the superconducting wire. Current estimates suggest that the wire will not be commercial before the year 2025, based on production volume and price, although the cable and refrigeration technology and manufacturing readiness could reach commercial status by about 2020. Considering all the other factors in commercial readiness, while noting that the wire is a limiting factor, the maturity date for a complete system is more likely to be 2025 or later. In addition, this earliest-year assessment does not take into account a number of external factors, both positive and negative in their impact, including—in addition to price and the value proposition—utility acceptance, the regulatory environment, and competing technologies.

Work that will enhance the commercialization process for HTS cable systems would begin with ensuring access to experts in wire manufacturing, so that scale-up of that process can proceed smoothly and quickly. A concerted effort to facilitate continued development of testing protocols and quantitative standards is needed, as testing and standards in the current industry are inadequate. Utility users of cryogenic equipment will also need to devote time to training in the use and maintenance of such equipment, so courses and training materials for that process will also be valuable.

With continued load growth (energy density) in dense urban settings, HTS will continue to be considered as an alternative to new transmission or conventional (multiple) distribution cable systems and the requisite substation systems. HTS offers additional benefits over conventional solutions such as providing dramatic power transfer within limited rights-of-way. HTS also facilitates increased reliability, resiliency, and asset utilization because it can connect multiple sources and loads. These characteristics need to be considered in addition to costs.

Results of Cost Analysis

Three major cost drivers for HTS cable systems were identified in the cost analysis—HTS wire, cryostats, and refrigeration systems. 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, which is difficult to predict. Reduction of refrigerator costs will likely require significant R&D. 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 were both difficult to implement and expensive, broader use of HTS cable systems is likely to require further cost reduction.

Costs of superconducting wire have shown a steady decline over time and are projected to continue at a 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 is unlikely to 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, the success path of this technology cannot be predicted with full confidence in the near term.

Demonstrating Reliability

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 can 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 worthy of 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 if a business case evolves. 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 described in a 2015 briefing [37].

Situations in Which HTS Provides Advantages Over Other Solutions

A variety of situations exist today in which an IFCL HTS cable solution may provide advantages over other solutions in desired performance, particularly with regard to achieving increased resiliency. These situations may occur because of some physical constraint (such as space) associated with deploying the conventional solution. Another determinant may be simply that the IFCL HTS cable solution is projected to be more cost effective either in the near future or when the technology reaches maturity.

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:

- The designs may be able to manage fault currents to enable increased access for distributed resources.
- The designs have the potential for improved life and reduced failure rates of downstream distribution system components that would alternatively see higher fault currents.
- After any early-deployment failure issues (installation problems) are avoided or corrected, and if an equally reliable design configuration is chosen for the cryogenic cooling and/or replenishment system, the designs have the potential for quite high superconductor reliability. This is due to their 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, HTS systems 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).
- The systems may be able to cope with the potential for major unplanned load increases (e.g., 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).

A number of factors provide a substantial advantage to the combination of superconducting and supporting FCL technologies, including continued vertical growth of urban centers, which increases load density, and the associated combination of long-term load and fault current growth, increased above- and below-grade congestion, and limited availability and high cost of real estate (in mature dense urban load centers). However, it is clear that there are alternative technologies to those superconducting technologies addressed in this study, which may be preferred in certain situations. These technologies may also experience further cost or performance improvements (for example, stand-alone FCLs, dc cables, and FACTS devices).

R&D Needs

Although some of the alternatives evaluated in this study may be considered commercial, others—including both superconducting and non-superconducting options—are still on a path to reach maturity. Thus, a continuing program of R&D is needed to achieve the projected cost and performance necessary to demonstrate full commercial viability and long-term reliability of these technologies. The evaluations and relative comparisons developed in this study may be used to identify areas in which continued R&D efforts may be warranted.

11
REFERENCES

1. *Strategic Intelligence Update: Superconductivity for Power Delivery Applications, December 2015*. EPRI, Palo Alto, CA: 2015. 3002007192 https://www.epri.com/#/pages/product/000000003002007192/.
2. *Superconducting Power Equipment: Technology Watch 2012*. EPRI, Palo Alto, CA: 2012. 1024190.
3. *Superconductivity: Present and Future Applications*. Coalition for the Commercial Application of Superconductors (CCAS). 2014. http://www.ccas-web.org/pdf/CCAS_Brochure.pdf
4. "Demonstration of a Pre-Commercial Long-Length HTS Cable Operation in the Power Transmission Network", DOE Peer Review Update, Washington, D.C. August 2–4, 2005. http://www.htspeerreview.com/2009/pdfs/presentations/day%203/applications/3-LIPA-Cable-Projects.pdf
5. "LIPA II Project", DOE Peer Review Update, Arlington, VA. July 29–31, 2008. http://www.htspeerreview.com/2008/pdfs/presentations/wednesday/applications/10_lipa_II.pdf
6. Demko and Duckworth, IEEE Transactions on Applied Superconductivity (particularly Figure 6), Vol. 19, No. 3, June 2009, pp. 1752–1755.
7. Communication from AMSC to EPRI, dated February 29, 2016, in conjunction with its review of this report.
8. Gouge et al, *Advances in Cryogenic Engineering*, Vol 53 Am. Inst. Phys., 2008, pp. 1343–1350.
9. *Recommendations for Testing of Superconducting Cables.* CIGRE Working Group B1.31, June 2013. CIGRE Technical Brochure 538.
10. *Common Characteristics and Emerging Test Techniques for High Temperature Superconducting Equipment*. CIGRE Working Group D1.38 CIGRE Technical Brochure 644. 2015.
11. *Superconductivity – Part 21: Superconducting Wires - Test Methods for Practical Superconducting Wires – General Characteristics and Guidance*, International Electrotechnical Commission (IEC). 1 May 2015. http://standards.globalspec.com/std/9918721/iec-61788-21.
12. *Superconductivity – Part 20: Superconducting Wires – Categories of Practical Superconducting Wires – General Characteristics and Guidance*, International Electrotechnical Commission (IEC). 28 July 2014. https://webstore.iec.ch/publication/5921.
13. *Superconductivity – Part 1: Critical current measurement – DC critical current of Nb-Ti composite superconductors*. International Electrotechnical Commission (IEC). 2006. https://webstore.iec.ch/publication/5909.
14. *Superconductivity – Part 2: Critical current measurement – DC critical current of Nb3Sn composite superconductors*. International Electrotechnical Commission (IEC). 2006. https://webstore.iec.ch/publication/5920

15. *Superconductivity – Part 3: Critical current measurement – DC critical current of Ag- and/or Ag alloy-sheathed Bi-2212 and Bi-2223 oxide superconductors.* International Electrotechnical Commission (IEC). 2006. https://webstore.iec.ch/publication/5922.

16. *Superconductivity – Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti and Nb3Sn composite superconductors*. International Electrotechnical Commission (IEC). 2016. https://webstore.iec.ch/publication/24054.

17. *Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: Task 1—Technical Capability, Manufacturing, and Scalability Baseline and Assessment*. EPRI, Palo Alto, CA: 2015.

18. *Technology Readiness Assessment Guide* (DOE G 413.3-4A, 9-15-2011). https://www.bnl.gov/techtransfer/docs/Technology-Readiness-Levels-Definitions-and-Descriptions.pdf.

19. Advanced Product Transitions Corp, McLean, VA. http://www.aptcorp-us.com/mrlintroduction.html.

20. V. Matias and R. H. Hammond, "HTS superconductor wire: $5/kA-m by 2030?" *International Workshop on Coated Conductor Applications 2014 (CCA2014),* Jeju Island, South Korea, December 2, 2014.

21. *Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: Task 2—Cost and Commercialization Assessment and Market Analysis*. EPRI, Palo Alto, CA: 2016.

22. "World premiere in Essen: RWE integrates superconductor cable for the first time into existing power grid," Press Releases, Nexans, 5 May 2014. http://www.nexans.de/eservice/Germany-en/navigatepub_148782_-33667/World_premiere_in_Essen_RWE_integrates_superconduc.html.

23. Joseph Mulholland, Thomas P. Sheahen, and Ben McConnell, "Analysis of Future Prices and Markets for High Temperature Superconductors," U.S. Department of Energy, 2001.

24. Navigant Consulting, Inc., "High Temperature Superconductivity Market Readiness Review," Office of Electricity Delivery and Reliability Briefing, August 2006.

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

26. 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.

27. 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.

28. "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.

29. 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.

30. Sumitomo Electric, "High Tc Superconducting Cable Project," available online as of November 23, 2015, http://global-sei.com/super/cable_e/ingridj.html.
31. 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.
32. 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.
33. *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.
34. *EPRI Cryogenic O&M Workshop: Proceedings.* EPRI, Palo Alto, CA: 2004. 1008699.
35. *Cryogenics*. EPRI, Palo Alto, CA: 2006. 1010897.
36. *Technical Analysis and Assessment of Resilient Technologies for the Electric Grid: Task 3—Analysis of Alternatives*. EPRI, Palo Alto, CA: 2016.
37. "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.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

3002011527

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com