High Temperature Superconductivity
A Roadmap for the Electric Power Sector

2015-2030

iea Energy Technology Network

SUPERCONDUCTIVITY

This work was done for and sponsored by the signatories of the International Energy Agency (IEA)

Implementing Agreement for a Cooperative Programme for Assessing the Impacts of High Temperature Superconductivity for the Electric Power Sector

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The Cover

The world's cities have a high concentration of energy demands and complex electrical networks. This photo of the Milan, Italy region at night shows the interconnectedness of their electric grid. Superconductivity for the electric power sector can help with grid modernization efforts. RSE and A2A Reti Elettriche collaborated to design, develop, test, and install Italy's first superconducting fault current limiter (12 kV/4.6 MVA). The device is located in Milan and provides single feeder protection for an in-grid distribution-voltage application.

Photo courtesy of the National Aeronautics and Space Administration in the United States.

International Energy Agency Mission

The IEA is an autonomous organization which works to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA has four main areas of focus: energy security, economic development, environmental awareness and engagement worldwide.

Founded in 1974, the IEA was initially designed to help countries co-ordinate a collective response to major disruptions in the supply of oil such as the crisis of 1973-1974. While this remains a key aspect of its work, the IEA has evolved and expanded. It is at the heart of global dialogue on energy, providing authoritative statistics and analysis.

As an autonomous organization, the IEA examines the full spectrum of energy issues and advocates policies that will enhance the reliability, affordability and sustainability of energy in its 29 members countries and beyond.

The four main areas of IEA focus are:

- **Energy security**: Promoting diversity, efficiency and flexibility within all energy sectors;
- **Economic development**: Ensuring the stable supply of energy to IEA member countries and promoting free markets to foster economic growth and eliminate energy poverty;
- **Environmental awareness**: Enhancing international knowledge of options for tackling climate change; and
- **Engagement worldwide**: Working closely with non-member countries, especially major producers and consumers, to find solutions to shared energy and environmental concerns.

FOREWORD

The energy systems of most countries worldwide are undergoing a very rapid evolution. The reasons for these changes are found in several trends, and in particular to:

- The increasing consciousness of the importance of reducing greenhouse gas emissions and mitigating the effects of climate change
- The necessity of adopting all means of increasing energy efficiency and reducing energy consumption
- The geopolitical events affecting countries mutual relationships
- The progressive aging of the electricity infrastructures that need to be modernized by deploying new technologies to enable upgraded capabilities, advanced real time monitoring, better failure detection, and improved cyber-security.

These trends reverberate across the energy system and have triggered important opportunities as the rapid deployment of renewable energy sources, the increasing need to empower local resources and responsibilities, and the use of advanced technologies to help modernize the electric power grids across the world.

Consequently, the design, management and control of the electricity networks are rapidly evolving, requiring more flexible and reliable networks to maintain the continuous, delicate equilibrium between generation and load that prevents instability and blackouts.

The aim of the *International Energy Agency Implementing Agreement for a Co-operative Programme for Assessing the Impacts of High Temperature Superconductivity on the Electric Power Sector* (HTS-IA) is to identify and evaluate the potential applications and benefits of superconductivity and the technical, economical and regulatory barriers to be overcome for achieving these benefits.

There are nine Contracting Parties and two Sponsors in the HTS-IA Executive Committee that are kept abreast of the state-of-the-art developments and standards regarding HTS component by manufacturers, cryogenics research, laboratories and trade organizations.

This document reports on the state-of-the-art of where the HTS industry is at now and what steps it should take to realize widespread adoption of superconducting based devices. It outlines research & development (R&D) challenges and needs in the short, mid and long term that can be tracked using metrics. It is intended also to serve as a roadmap for managers in the power sector and their technical advisors and to facilitate their efforts to guide and support future work toward commercial use of HTS-based technology. While the roadmap serves as a useful document to help inform the industry, it is a living document that will be regularly updated. In fact, due to the continuous HTS technology progress / development this roadmap is intended to be updated on a 2-year basis to capture recent advancements in the technology and relevant results from in field validation of HTS components demonstration as well as pre-commercial projects.

We would like to express our sincere thanks to the coordination team of the HTS-IA Executive Committee, with special thanks to the operating agents who collected the data for this Roadmap. Thanks to their efforts, this Roadmap represents a valuable reference for the deployment of HTS based devices on the electric power grid.

Chair and vice-Chair

Luciano Martini and Hiroyuki Ohsaki

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ACKNOWLEDGEMENTS

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GLOSSARY

1G	First generation HTS wires, formed by extrusion of BSCCO with a metal sheath.
2G	Second generation HTS wires, formed by depositing YBCO onto a metal substrate.
A/cm	Unit of critical current, I_c, for superconducting wire per 1 cm width. Used especially for YBCO because it is a tape form and the I_c depends on its width.
$/kAm	Unit of price in $ of superconducting wire per 1000 A of critical current, I_c, and per 1meter length of the wire. Common measure for comparison of the price, especially of YBCO wire.
$/m	Unit of price in $ of superconducting wire per 1m length of the wire.
AC	Alternating current.
AC loss	Thermal heat loss by AC current transporting in superconductor.
Artificial pinning center	Oxide fine particle or columnar structure to pin flux lines in the superconductor. Only used in 2G HTS wire. See Pinning Center.
Bi2223	Its molecular formula is $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ also known as BSCCO, which is used in 1G HTS wire.
Biaxially textured	Textured along two axes of the crystal lattice directions. Used in 2G HTS wire.
BSCCO	HTS compound composed of Bi, Sr, Ca, Cu, O, and sometimes Pb. Used in 1G HTS wire. See Bi2223.
Buffer layer	Material put in place between metal substrate and superconductor material to prevent contamination and provide texturing. Used in 2G HTS wire.
Closed system	Cooling system in which the cooling substance is recycled through the system and re-used.
Coated conductor	Also known as2G, YBCO HTS wire. The name is derived from the form of the YBCO wire where a superconducting YBCO film layer is deposited on a substrate.
COP	Co-efficient of performance used for cryogenic system efficiency. The ratio of the cooling power and the input power. The value varies from 0 to 1.0.
Critical current (I_c)	Maximum current through a material that allows it to remain in the superconducting state. See I_c.
Cryogenics	A branch of physics and engineering that studies and produces very low temperatures and the behavior of materials at those temperatures.
Cu stabilizer	Cu layer or matrix in the superconducting wire to absorb the heat generated in the wire during the transition to a normal state, which protects the wire from burning. It stabilizes the superconducting current transport.
Current density	Electrical current per cross-sectional area. Measured in A/cm^2 ($Amps/cm^2$) or A/m^2, A/mm^2. See J_c.
DC	Direct current.
Distribution voltage	Electric power grid classification for voltage, 10-66 kV.
Epitaxial	A thin film with the same crystal structure as the substrate it was grown on. The property of superconductor materials to grow this way is used to get films with good grain alignment. Used in in 2G wire.

Ex-situ	In the wire fabrication process, first the superconducting material is formed, and then put into a metal tube to form a superconductor. Example: MgB_2 superconducting powders are prepared, put in to a metal tube, cold-worked and then heat-treated to form a wire. Compare In-situ.
Fault Current Limiter (FCL)	Device to reduce a fault current in an electrical power system.
Filament	In the wire, superconductor is sometimes divided into filament form of fine strips, which is continuous for whole length of the wire.
GM (Gifford McMahon)	One of the most widespread types of cryogenic systems used with superconducting devices such as MRI or Maglev. The cold head part of the system is cooled by the expansion of inert He gas to around 4 K.
Hastelloy	Trade name of commercial Ni-based high temperature alloys. A substrate metal used in 2G wire.
HTS	Ceramic materials that are superconducting with a T_c of 30 K or greater. Some examples are YBCO, BSCCO and MgB_2.
I_c	Critical current of a superconductor, the maximum amount of current that can flow below a fixed electric field or resistivity criterion.
I_c-B property	Critical current property against the applied magnetic field (B) to the wire.
In-situ	In the wire fabrication process, when the precursors are put into place before being reacted to form the superconducting compound. Example: Mg and B powders themselves are put in to a metal tube and then heat-treated to form MgB_2 superconductor. Also see Ex-Situ.
I-V	Current-voltage
J_c	Critical current density. Maximum current density (I_c per superconducting or total wire cross-sectional area) in a material that allows it to remain in the superconducting state.
Kelvin (K)	A scale of temperature measurement that starts at "absolute zero", the coldest theoretical temperature attainable. 0 K equals -273°C.
Liquid Helium, LHe	Coolant mainly used for especially LTS superconductor or its devices with the boiling point of 4.2 K.
Liquid Hydrogen, LH_2	Coolant with the boiling point of 20 K, considered to be possibly used in MgB_2 applications.
Liquid Nitrogen, LN_2	Coolant mainly used for especially HTS superconductor or its devices with the boiling point of 77 K.
LTS	Low Temperature Superconductor: Metallic materials with a T_c of less than 30 K. Typically, NbTi and Nb_3Sn.
Maglev	Magnetic levitation trains. Strong magnetic field generated by superconductor can levitate and propel the train at a high speed.
MgB_2	Magnesium diboride becomes superconducting at 39 K, which is a much higher T_c than other metallic superconductors. The materials of Mg and B are relatively inexpensive and lightweight.
MRI	Magnetic resonance imaging. In MRI, the human body is exposed to a strong, homogeneous and stable magnetic field by a superconducting coil. It displays the cross-sectional images of the human body and helps medical diagnosis.
Nb_3Sn	Typical metallic LTS superconductor made of Nb and Sn.
NbTi	Typical metallic LTS superconductor made of Nb and Ti.

NMR	Nuclear Magnetic Resonance. Its stable, homogeneous high filed by a superconducting magnet can precisely analyze medical, chemical or biochemical materials like proteins, which help advance medical science.
Off-shore wind turbine	Turbine used for a large windmill which is operated on the sea, where the wind is strong and stable. These turbines are expected to generate large amounts of power.
Pinning	Preventing the movement of flux lines within a superconductor. This suppresses destruction of superconductivity and increases a critical current.
Pinning center	A defect to pin the flux line movement.
Pinning property	The ability to pin the flux line movement. The higher pinning property, the larger I_c.
Pulse tube refrigerator	A kind of refrigerator developed in early 1980s based on thermo-acoustics. It is a closed system that uses an oscillating pressure at one end to generate an oscillating gas flow in the rest of the system. This gas flow can carry heat away from a low temperature point. The prime advantage is that they have no moving parts, resulting in high reliability for long time operation.
Quench	The phenomenon where superconductivity in a material is broken especially for a superconducting coil, usually by exceeding the maximum current the material can conduct (I_c or J_c) or exceeding the T_c.
RE	Rare earth element (such as La, Nd, Sm, Eu, Gd, etc.). Often used in YBCO replacing Y for RE element to improve the flux pinning ability.
REBCO	123 compounds formed with a rare earth instead of yttrium. See YBCO.
Roebel conductor	In this report, a transposed combined superconductor composed of a few bundles of YBCO wires to reduce AC loss.
SFCL	Superconducting Fault Current Limiter. See FCL.
SMES	An acronym for Superconducting Magnetic Energy Storage. Superconducting current circulates without any ohmic loss in the coil of SMES and then SMES can store the electric energy. The only method to store energy as in the form of electricity.
Stirling cryogenic system	A kind of system consisting of a piston, compression space, regenerator, heat exchanger, and expansion space. The working fluid is gaseous He, which is compressed and expanded. This cycle is used to reduce the temperature.
Striation	Making YBCO film of YBCO wire into divided thin parts by laser and so on. The dived parts are called filaments. See filament.
Substrate	The base (normally metal tape form) on which a superconducting HTS film layer is grown.
T_c	The critical transition temperature below which a material is superconducting.
Tesla (T)	Unit for magnetic flux density. Equal to one weber per square meter.
Texturing	Crystal grain alignment. A textured buffer layer is used to grow an aligned superconductor layer.
Three cores in one cable	A kind of structural configuration of the HTS power cable with each core transporting each phase of AC current.
Three phase coaxial type cable	A kind of structural configuration of the HTS power cable with a single core lapped with three layers of AC current phase.
Transmission voltage	Electric power grid classification for voltage, 66-275 kV.

Turbo Brayton system	A kind of cryogenic system comprising a turbo pump compressor, expansion turbine and heat-exchanger especially for large power applications of more than 1 kW.
Winding	Superconducting wire used in part of a coil for generating a magnetic field.
Wire	"Wire" is used, in a broad sense, for "round wire" (Bi2223, MgB_2 wires) and "flat tape" (YBCO wires).
YBCO	A well-known HTS superconductor composed of Yttrium, Barium, Copper and Oxygen. Its actual molecular formula is $YBa_2Cu_3O_7$-x also known as 123 compounds. Used in 2G wires.

EXECUTIVE SUMMARY

This document is a roadmap for high temperature superconducting (HTS) based devices for power system applications. The document paints a picture of where the HTS industry is at present and what steps it should take to promote widespread adoption of superconducting based devices. It outlines research & development (R&D) challenges and needs in the short, mid and long term that can be tracked using metrics. The intent of the document is not to make predictions about the future nor identify specific organizations to tackle certain problems. The analysis conducted was based on the best data available at the time and this is intended to be updated in approximately two years.

Key Drivers of Change

- Changing mix of electricity supply to low carbon solutions
- Customer participation in electricity markets
- Expectations for greater reliability and resilience
- Integration of digital devices for managing power systems

The International Energy Agency's (IEA) World Energy Outlook 2014 states the energy system is under stress now and there is a continued rise in global greenhouse-gas emissions in many of the world's fast-growing economies.[1] They reported that global energy demand is set to grow by 37% by 2040 and energy-related carbon dioxide (CO_2) emissions grow by 20%. Electricity is the fastest-growing final form of energy, yet the power sector contributes more than any other to the reduction in the share of fossil fuels in the global energy mix. IEA forecasted that approximately 7200 GW of capacity is needed for increasing electricity demand. The IEA projects global electricity generation from renewables to increase by 30% from 2015 to 2020, largely driven by policy support and their improving competitiveness. This increase will require large-scale integration into power systems. These factors contribute in IEA scenarios to a doubling of the annual investment in power grid infrastructure, from approximately 20 billion US$/year today to 40 billion US$/year in 2035.

Currently in the United States, 70% of large power transformers and transmission lines are twenty-five years or older, and 60% of circuit breakers are thirty years or older.[2] A catastrophic failure of a transmission asset threatens system reliability, and changing system dynamics may increase the likelihood that this can happen. As assets are replaced, there is an opportunity to install next-generation, higher-performance components, such as high temperature superconductivity based devices, but overall cost needs to be managed and optimized.

The changes affecting the electric power sector offer an unprecedented opportunity to transform the future grid. Increasing needs for flexibility, reliability, and resilience in the transmission and distribution (T&D) system require technologies and techniques not conceived of when much of the current infrastructure was deployed. During this period of transition, the deployment of new technologies will play a critical role in shaping the future grid. High temperature superconductors are potentially key in the suite of technologies that can help facilitate grid modernization, reduce losses and hence CO_2 emissions and increase energy security.

Superconducting based devices do not simply provide improvements over conventional electric grid technologies; they provide unique solutions to challenges that cannot be achieved otherwise. Examples of technologies that provide these unique solutions include superconducting fault current limiters, generators for off shore wind turbines, superconducting magnetic energy storage, and high-capacity power cables.

While the transition of HTS conductors (this document focuses on three types of wire: YBCO, Bi2223, MgB_2) from lab-scale to grid scale demonstrations has been accomplished, the transition to widespread market maturity faces several challenges. Examples include:

- **Economics.** The cost associated with manufacturing HTS wire due to sophisticated processes, low yields and limited throughput of the manufacturing processes makes it several times more expensive than copper wire. However, it is not reasonable to simply compare the cost of an HTS based device to a conventional one. Because of the unique attributes of HTS devices, a *system* cost analysis should be conducted.
- **Process control**. There is a general lack of manufacturing knowledge in producing HTS wires with nanometer-sized precipitates or phases uniformly distributed over kilometer lengths.
- **Long term reliability.** End users are generally unfamiliar with the materials used in HTS devices and cryogenic systems. Data are not available that proves undiminished product-performance HTS components life time over 30 to 40 years.
- **Business risk.** Uncertainty for total cost of ownership and cost and availability of parts from suppliers in a relatively nascent market.

The following section is a technology assessment summary and Table A.1 shows a general trend analysis of HTS based applications of past, present and future based on the data collected for this roadmap. It is important to note that the auspices of the IEA implementing agreement is on High Temperature Superconductivity and this roadmap will focus on this category of wire. However, there are still important partners and product development underway in the Low Temperature Superconductivity arena (LTS). LTS applications are described later in the document.

Technology Assessment

This section describes the present status and future perspectives for HTS technology and power applications from data gathered from HTS experts around the world. The section first describes the current status of the two core components of HTS systems, wires and cryogenic systems. It then provides an assessment of the state-of-the-art in the deployment of HTS systems in its four main applications: Cables, Fault Current Limiters, Generators, Superconducting Magnetic Energy Storage Systems, and Transformers.

Wire

Superconducting wire is the fundamental technology enabling an array of innovative devices. More than 15 companies are working actively to increase the total production capacity of HTS wire. Some companies can manufacture 1000 km/year of wire from the three most widespread materials, Bi2223, YBCO and MgB_2. Cost of the wire is recognized as a key factor for more widespread use in electric power applications; the current cost is around a few hundred $/kilo-amp-meter (kAm) (using critical current (I_c) at 77 K and self-field) for YBCO and should be reduced to around $10/kAm in 2030 for market maturity based on data collected from this roadmap effort. The $10/kAm level is competitive and has the potential for yielding positive returns for project developers under current market conditions. MgB_2 is now below $10-25/kAm (using I_c at 20 K and around 1 Tesla), but producers are aiming at further cost reductions to <$5/kAm by 2020 to enhance the market competiveness. While YBCO is more expensive than Bi2223 and MgB2 it has a higher I_c at high fields and temperatures. Bi2223 costs less than YBCO and has the potential to reduce thie cost by half in 2020 and still lower in 2030. Many companies are conducting research and development to increase over long lengths I_c, which results in lower cost per kAm unit.

Cryogenic Systems

One of the critical components of HTS applications is the cryogenic system. These systems operate at the temperature of liquid nitrogen (77 K or -196°C) and, in some cases, at a lower temperature (below 30 K or -243°C) for applications that involve high magnetic fields. There are several types of cryogenic systems available including:

- The **Gifford McMahon** (GM) system, which is most widely used for LTS commercial products such as Magnetic Resonance Imaging (MRI) machines because it has a relatively long maintenance free period of about 10,000 hours.
- **Pulse-tube** systems operate in a closed cycle, using helium as a working fluid and have no moving parts. The cold is generated by the use of acoustic waves that substitute for the typical pistons or rotating equipment found in other cryocoolers.
- **Stirling cycle** cryocoolers have been available in commercial volumes for HTS electrical devices since 2000. The Stirling cryocooler uses gas bearings, a single piston and displacer, a combination of gas and mechanical springs, efficient heat exchangers and a passive balancer used to minimize casing vibration. Stirling cryogenic system are being developed for high cooling power (>1 kW at 77 K) and reliability using a closed cooling system with a compact design.
- **Turbo Brayton** systems are being developed for power applications and discussed later in this chapter. Most of the data collected for this roadmap was for Turbo-Brayton cryogenic systems. These systems are expected to reach the stage of mass production by 2025 and market maturity by 2030. R&D is still needed to enhance performance, improve the interval time between maintenance operations, and reduce system cost.

Other cryogenic systems are being applied such as an open liquid nitrogen tank and circulation system for a cable and fault current limiter project in Essen Germany. An open system features lower complexity and potentially high reliability, but requires re-filling of a nitrogen storage tank in regular intervals. A closed system only needs electrical power supply after initial filling, but requires higher capital investment and specific methods to ensure availability and reliability.

Cables

> There is more than 20 years of operating hour experience with cable projects worldwide.

Among all HTS applications, including non-power devices, the most operational experience has been accumulated in cables. When combining the operating experience of all the cables in the world, there are more than 20 years of operating hours.[3] HTS cable projects have been energized in large scale grid demonstrations around the world ranging from approximately 10 kV—275 kV. Nearly ten cable demonstration projects are under development and are classified into distribution voltage (10 kV—66 kV) and transmission voltage (66 kV—275 kV). Although DC cables are gaining more interest due to their lower losses over hundreds of kilometers, this document focuses on AC cables because of the data available. One of the benefits of HTS cables is that they carry more power at lower voltages compared to conventional cable technologies. HTS cables are being targeted for technical solutions that conventional cables cannot provide. For instance, in dense urban areas with limited underground cable duct space, HTS cables can provide the same amount of power as conventional cables, but in a fraction of the space.

Data collected showed that cables were anticipated to reach market maturity in 2025 to 2030. To reach this stage, R&D is needed to 1) reduce the cost of wire, cryogenic system and cable fabrication, 2) improve safety and reliability of the system and 3) reduce system losses.

Fault Current Limiters

A fault current limiter (FCL) immediately limits the amount of short circuit current flowing through the electric grid and allows for the continual, uninterrupted operation of the electrical system, similar to the way surge protectors limit damaging currents to factories and household devices. The need for FCLs is driven by rising system fault current levels as increasing energy demand and feed-in from distributed generation and clean energy sources like wind and solar, requires further meshing of the grid in order to improve power quality and increase hosting capacity in already overburdened systems.

High-temperature superconducting fault current limiters (SFCLs) use superconducting-based material and reduce fault currents by introducing a larger-than-normal impedance into the path of the fault current. There are several types of SFCLs including resistive, inductive, and shielded core. This document focuses on the resistive type SFCL because many of the past or ongoing projects use this type. Superconducting fault current limiters do not use as much wire when compared relatively to other superconducting applications; each device only uses a few kilometers at most. Therefore, SFCLs could have market maturity around 2025, which together with HTS cables, is earlier than any other HTS application.

Generators

Because superconductivity offers the possibility of smaller and lighter generators than is possible with conventional materials, there is substantial interest for conducting R&D on HTS based machines. One of the key application areas are HTS generators in wind turbines. Demand for wind turbines is increasing because many country's goals are to increase the percentage of electricity being produced by renewables. There is exceedingly high interest in wind power—particularly off-shore wind turbines because there is a plentiful and reliable wind resource. There is also a current trend for turbines with larger rotor swept areas, as these can afford higher annual capacity factors and increase generation in areas with poorer wind source. Large offshore wind turbines of 10 MW or greater require a huge support structure, larger turbine blades and larger generators compared to conventional based devices. HTS based generators have the potential to reduce the weight of these large offshore wind turbines.

Generator projects are being designed using YBCO and MgB_2 wire especially for large off-shore wind turbine generators over 10 MW. At present, they are not in the stage of system demonstration, but simulations and basic studies are being conducted for coils and cryogenic systems. HTS based generators are anticipated to have market maturity in 2030.

Superconducting Magnetic Energy Storage (SMES)

Superconducting Magnetic Energy Storage (SMES) technologies have the ability to store electricity in the magnetic field of direct current. SMES uses a superconducting magnet, which can generate a high magnetic field with negligible losses. This is possible because the current circulates in the resistance free superconducting coils rather than in the coils of copper or other metal conductors, which have resistance. HTS wire is favorable for use in SMES devices because of its high current carrying capacity even at a high magnetic field.

There are several key applications that SMES devices can provide. These include power, energy, and controlling phase of current. A Niobium Titanium based-SMES system (using "low" temperature superconducting materials) is running in a liquid crystal screen factory, but a fully integrated high temperature superconducting based SMES system has not yet been made. HTS coils, one of the critical components for SMES, have been developed using YBCO wire in US, Japan and Korea.

The market maturity stage was estimated to occur in 2025 to 2035 for 10—20 MJ SMES used in voltage dip compensation applications. To reach this stage, wire cost lower than $5/kAm will be needed according to the experts consulted for this roadmap effort; and approximately 250—300 km of wire will be needed for a 20 MJ device. For R&D, a large coil fabrication and testing at a high-field will be needed to verify its tolerance for a high hoop stress. MgB_2-SMES operating at 20K cooling could be expected sooner due to the lower cost of the wire.

Transformers

HTS Transformer R&D is arguably one of the most difficult of the superconductivity AC power applications because of the need for very low AC losses, adequate fault and surge performance and rigors of the application environment. Therefore, worldwide activity in HTS transformer R&D is farther behind the other applications. Projects were started in Japan and in the US, but those efforts have ramped down. There is currently very little R&D being conducted on HTS transformers. However, one example is a transformer project developed by the Robinson Research Institute in New Zealand that measured energy losses at half of a conventional transformer (please see section 8, page 50).

There was not much data collected for this application in this roadmap document. As a result, it was difficult to obtain when the market maturity and other development stages would occur. Research and development is still needed to reduce cryogenic losses and AC losses in the wire. Moreover, suitable technical solutions are also needed for the key components such as the cryostat, vacuum seal, and current leads.

Table A.1 Trend Analysis.

Area	Past (last ~5 years)	Today	Future (next 5 years)
Policy	National energy strategy documents do not highlight HTS as a potential solution for grid modernization.	HTS based devices rarely mentioned as part of the broader strategy for grid modernization.	HTS based devices are routinely mentioned as a potential solution for grid modernization efforts.
Technical	Successful large scale demonstrations conducted to prove technical feasibility in the electric grid.	Projects/demos being considered as permanent infrastructure to solve real world electric grid problems.	Devices installed to be permanent components in the electric grid; devices installed without government subsidies.
	Concerns that wire companies would not be able to provide enough product volume. Five companies at most could provide long length wire (>1 km).	Production from wire companies has increased; more than 15 companies are producing HTS wire (several that can produce long lengths of >1000 km/year.) YBCO wire remains several times more expensive than conventional copper.	Wire capacity and performance continues to improve, and is cost competitive compared to conventional technologies. Wire is tailored to suit different operating temperatures and magnetic fields.
	A range of superconducting based technologies show potential for modernizing the electric grid.	HTS cables and fault current limiters have the most operating experience in grid conditions.	Performance and reliability for cables and fault current limiters continue to improve and other applications are demonstrated in the grid.
Market	Decisions to install HTS system based almost exclusively on the device cost.	Evaluating HTS systems being looked at through a different lens; they can provide additional services that conventional technologies cannot.	Decision to install systems will continue to depend on cost, but grid functionality and system aspects play heavily into decision making.
	General conservative nature of utilities has made it difficult to get HTS devices into the electric grid. HTS is perceived as a complex technology still to be proven.	Targeted outreach to utilities backed by worldwide HTS project experience is slowly starting to change end-users perspectives about the potential benefits and risks with HTS devices.	Communications and outreach to utilities and the regulatory community continues to teach them about system benefits; regulatory structures change to better incentivize R&D in innovative technologies like HTS
	Unfamiliarity with cryogenics along with additional cost and maintenance intervals hinder HTS based technology adoption.	Cryogenics require additional power and maintenance cycles that conventional systems do not have.	Costs for cryogenic systems continue to decline and maintenance intervals increase.

1. INTRODUCTION

The International Energy Agency's (IEA) World Energy Outlook 2014 states the energy system is under stress now and there is a continued rise in global greenhouse-gas emissions in many of the world's fast-growing economies.[4] Global energy demand will increase by 37% by 2040 and carbon dioxide (CO_2) emissions grow by 20%. The power sector is leading the transformation of global energy and contributes more than any other to the reduction in the CO_2 emission. It is forecast that 7200 GW of capacity is needed to meet increasing global electricity demand. Many power plants are due to retire by 2040 (around 40% of the current fleet). Similarly, the strong growth of renewables such as wind power raises their share in global power generation to one-third by 2040 because of its low carbon emissions.

These profound changes affecting the electric power sector offer an unprecedented opportunity to transform the future grid. Increasing needs for flexibility, reliability, and resilience in the transmission and distribution (T&D) system require technologies and techniques not conceived of when much of the current infrastructure was deployed. During this period of transition, the deployment of new technologies will play a critical role in shaping the future grid.

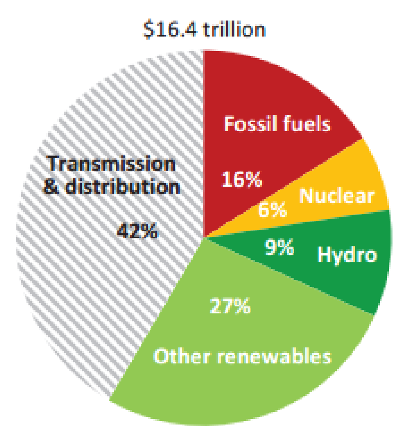
Key Drivers of Electric System Change

- Changing mix of electricity supply
- Customer participation in electricity markets
- Expectations for greater reliability and resilience
- Integration of digital devices for managing power systems
- More autonomous and self-organizing behavior on various grid levels

Flexible grid system operations and demand response can enable renewables and reduce the need for new bulk-power-level infrastructure. End-use efficiency, demand response, storage, distributed generation, and high capacity cables can reduce the expected costs of new transmission equipment investment. Investments in energy efficiency, smart grid technologies and more autonomous grid technology, storage, and distributed generation can contribute to enhanced resiliency and reduced pollution, as well as provide operational flexibility for grid operators. Innovative technologies have significant value for the electricity system. New technologies and data applications are enabling new services and customer choices. These hold the promise of improving consumer experience, promoting innovation, and increasing revenues beyond the sale of electric kilowatt-hours.

For the global power sector, the International Energy Agency estimates that $16.4 trillion of investment will be made; transmission and distribution is expected to account for $7 trillion under their New Policies Scenario from 2014-2035 (in 2012 US$).[5] See Figure 1.1. The Edison Electric Institute estimated that the total infrastructure investment in the United States will be between $1.5 trillion and $2.0 trillion; transmission and distribution is expected to account for about $900 billion by 2030.[6]

Figure 1.1 Global Power Sector Investment



High temperature superconductivity (HTS) based devices have the potential to play a critical role in helping to transform the global transmission and distribution grid.

1.1 Superconductivity as a Solution

Superconductivity is widely regarded as one of the greatest scientific discoveries of the 20th century. This property causes certain materials, at low temperatures, to lose all resistance to the flow of electricity. The lack of resistance enables a range of innovative technology applications. As we proceed in the 21st century, superconductivity is creating opportunities for new commercial products, such as ultra-high efficiency electricity cables and electric machinery that can transform our economy and daily life.

> "Ways to reduce additional issues with siting include the use of existing transmission line corridors…and even superconducting cables."
>
> *—U.S. Department of Energy, Quadrennial Energy Review, April 2015*

Superconducting technologies are already a proven job creator worldwide, contributing more than $5 billion per year to medical and high energy physics industries, but there is a potential for several times this amount for power applications in the clean energy field.[7,8] Currently, the major commercial applications of superconductivity involve low-temperature superconducting (LTS) materials and high field magnets, and are in the medical diagnostic, high energy physics, scientific and industrial processing fields. HTS greatly reduces the energy needed to keep the superconductor cool, making applications potentially more economical. HTS-based equipment can reduce energy losses, increase grid reliability, reduce right-of-way requirements, and alleviate grid congestion at a significantly lower cost than LTS-based applications. LTS devices are cooled using liquid helium to around 4 K and HTS can be cooled using a lower cost option—liquid nitrogen—to around 77 K.

In addition to its superior properties at relatively higher temperatures, HTS materials also come along with significantly expanded magnetic field capabilities. For several magnet applications such as analytical nuclear magnetic resonance (NMR) and high energy physics, these enabling properties are required for next generation equipment.

1.2 Value Added Over Conventional Grid Solutions

The electric grid has relied on traditional copper and aluminum conductors for more than a hundred years. These tried and true materials are well understood by the utility industry and are cost effective. HTS based cable and ancillary devices such as cryogenics are not well understood by the utility industry and generally cost more and will continue to cost more in the near future when compared to conventional solutions.

However, superconductor devices do not simply provide incremental improvements over conventional technologies; they provide unique solutions to challenges that cannot be achieved otherwise. Examples of electric power applications that provide these unique solutions include, superconducting fault current limiters (SFCLs), generators for off-shore wind turbines, and high-capacity power cables (See Table 1.1).

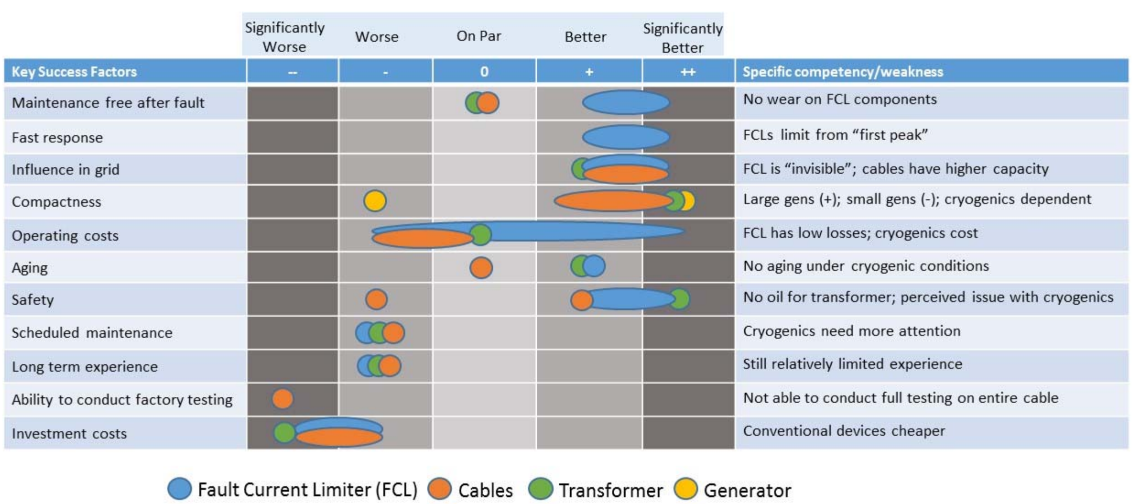
Table 1.1 Unique solutions from superconducting based devices.

Challenges	Existing Solution	Superconducting Based Solution
Reducing power electric system fault currents	Very limited	**Empowering renewables, distributed generation and clean energy sources.** These devices almost instantaneously "limit" fault current and then are ready for another surge.
Compact and light weight generators for >10 MW off-shore wind turbines	Very limited	**Energizing large-scale wind power with compact superconducting-based generators.** Superconducting rotor and stator coils provide compact and light weight generator and related nacelle design.
Transmitting high power through constrained rights-of-way	None available	**More power in smaller spaces – meeting high demand for electricity.** Retrofitting existing lines to carry 5 to 10x more power in a fraction of space compared to conventional technologies.

Table 1.2 is an adaptation of data collected from a 2014 International Superconductivity Industry Summit (ISIS) Technology Scorecards.[9] ISIS is a worldwide group of superconductivity practitioners. The table shows qualitatively the relative position of HTS based devices compared to the most advanced conventional technology that exist on the electric grid. HTS based cables, fault current limiters, generators and transformers were analyzed against a number of key success factors. However, there are some gaps in the data and, therefore, not all four of these HTS based technologies were compared against every key success factor. The elongated shapes represent a varied response regarding the relative position. For instance, some data collected shows that operating costs for SFCLs were worse than conventional technologies while other data shows significantly better costs depending on the application.

The rows near the top of Table 1.2 are key success factors where HTS performs better or even significantly better compared to conventional technologies. Examples include maintenance after faults, fast response to fault currents, benefits to the grid, and overall compactness of the system. Some of the factors that HTS devices lag when compared to conventional technologies are indicated in the rows near the bottom of the table and include the initial investment cost, ability to conduct factory testing, long term reliability and scheduled maintenance.

Table 1.2 Relative Position of HTS Devices Compared to Most Advanced Conventional Technology.



1.3 About the Roadmap

This Roadmap analyzes the current state of the superconductivity activities, lays out a vision for where superconductivity for electric power systems could be by 2030 and then identify the gaps for reaching this vision. Figure 1.2 is a summary of where the industry stands now and what some of the key challenges are that need to be overcome in order to reach the vision. These challenges are expanded on in Table 1.3.

There are several purposes and non-purposes of the roadmap document.

- Purposes of the roadmap
  - To describe the current state of the art and where the industry and other stakeholders are heading in the future;
  - To identify what the challenges and needs are for widespread integration superconducting based devices into electric grids across the world;
  - To educate decision makers about main benefits of HTS investments; and
  - To encourage adoption of HTS applications as part of both IEA and country energy strategy/initiatives to help modernize the energy sector.
- Non-purposes
  - To develop an exhaustive detailed list of projects around the world
  - To make predictions about future market characteristics

Figure 1.2 A Pathway to Reaching the Vision.

Current Situation

- HTS projects are exclusively funded using public/private cost share
- More than a dozen wire manufacturers exist today with capability of manufacturing a variety of wire configurations
- Utilities are not familiar with operations and maintenance of HTS based devices and are reluctant to install them without proven experience

Gaps/Challenges

- Raw materials cost-reduction for HTS Wire
- Quality control/in-line process control for wire manufacturing
- Lack of standard testing facilities that could allow accelerated testing
- Lack of utility acceptance with respect to reliability
- Development of compact efficient and cost effective cryogenic systems

Vision

- By 2030, high temperature superconductivity based applications will help to energize a competitive worldwide marketplace for electricity. It helps to connect customers to abundant, affordable, clean, efficient, and reliable electric power anytime, anywhere. It provides the best and most secure electric services available in the world.

Table 1.3 Gaps/Challenges and Needs.

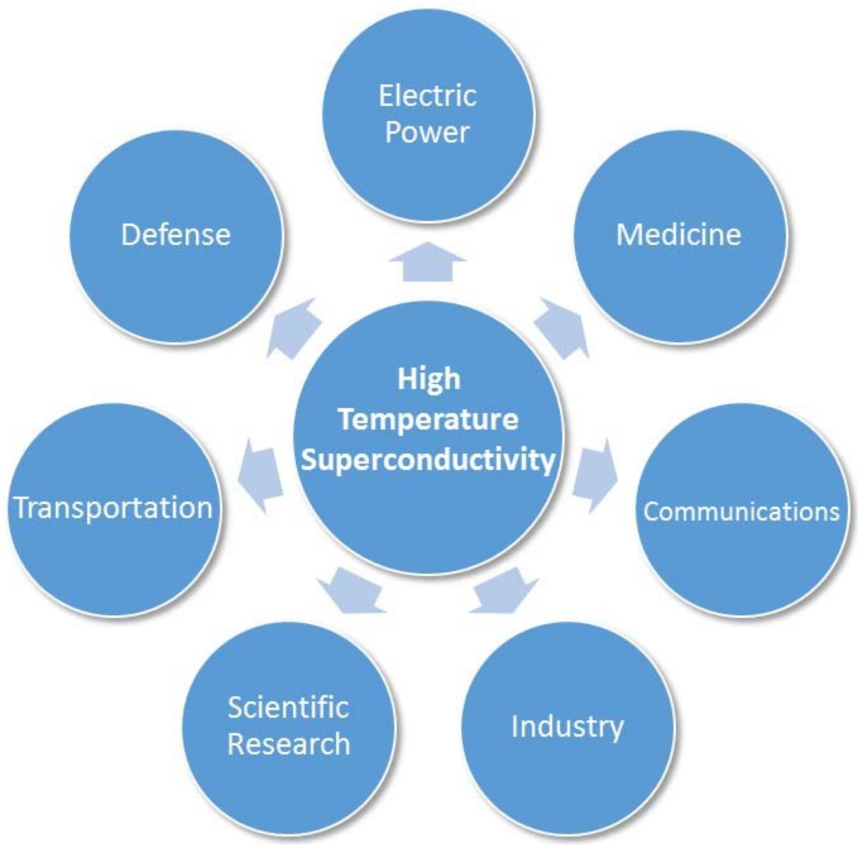
Gaps/Challenges	Core Issue	Needs to Overcome the Challenge
Technical/Manufacturing		
Raw materials cost-reduction	• Multi-filament wires often use HTS filaments embedded in a silver matrix while so-called coated conductors are manufactured by depositing certain material, including silver, on a tape.	• Reduction of the amount of silver used in manufacturing several classes of HTS wires is a primary lever to lower the materials cost. • Reduction in the amount of Hastelloy or Ni-based metals for YBCO wire substrates in the case of $10/kAm cost-level.
Quality control/in-line process control	• Scrap wire against the ordered specifications: wire residual means extra labor and thus cost, and turnover of the factory machines will be lowered. • HTS materials are advanced composite materials that contain either very fine filaments of micrometer-size within a metal-alloy or multiple layers of metals and oxides down to nanometer-scale in addition to the superconductor material. • The purity of complex starting chemicals or powders, and the depositing condition are paramount to producing uniform filaments and nanometer thick layers.	• Precise control of the wire dimensions in processing and homogeneity of I_c or other properties along the length or width. • Manufacturing yield would be significantly improved by the removal of small secondary particles or non-superconducting phases in the starting precursors that lead to either breaks or disruption in the current capacity in the final wires. • For fine filaments, evaluating filament uniformity is critical. High-throughput methods to control the quality of the precursors and deposited films will greatly enhance the manufacturing yield.
Lack of standard testing facilities	• Cooling to cryogenic temperatures accompanied by high current capacity at almost zero voltage is unique to superconductors and testing facilities and expertise are not readily available. • Thin film formed YBCO wire shows unique mechanical and electromagnetic behaviors of delamination and large screening current. • Variety of the test procedures in each HTS power device or in each developing institute. • Electric-grid applications require high reliability and undiminished product-performance over very long lifetime (30 to 40 years).	• Develop testing facilities with expert resource that can test mechanical stresses or high magnetic fields, in reel-to-reel systems over long lengths of wire. • Develop testing standard especially for film layered YBCO wire for delamination of the film and screening current effect. • Develop testing standards for HTS power devices. • The availability of facilities that can perform accelerated lifetime testing of wire, and components fabricated from wire, is essential to confirm reliability or guide product improvements.
Interconnections for users	• Superconductor wires used in large-scale devices must be joined to existing electrical connections, to each other (spliced), or to special terminations or current leads. • The joints and terminations must be robust at low temperature (i.e. withstand stresses due to cooling), have low electrical resistance and carry large currents.	• Manufacturing development of such joints, splices and terminations is important to facilitate adoption of superconductors into the marketplace as it will enable original equipment manufacturers to readily integrate superconductors into their systems and end-users install the overall device into its location.
Cost and reliability of cryogenic systems	• The ancillary cost for cryogenic cooling of the superconducting devices adds to the cost of the system. There is limited experience with operating HTS superconducting systems.	• Focus on cryogenic equipment, such as pulse tube and equivalent technologies, cryostat and insulation, to increase reliability and overall life cycle cost reduction. • Demonstration of complete, integrated cryogenic cooling systems that incorporate both the equipment and support infrastructure required for long-term, reliable operation.

1.4 Scope of the Roadmap

Superconducting applications span a broad range of sectors in the world's economy as shown in Figure 1.3. However, the scope of this roadmap will focus on applications for electric power systems. It is also important to note that the auspices of the IEA implementing agreement is on High Temperature Superconductivity and this roadmap will focus on this category of wire. However, there are still important partners and product development underway in the LTS arena. In addition to the core components of HTS conductor and cryogenic systems, electric power devices include:

- Cables
- Fault current limiters
- Generators
- SMES
- Transformers

Figure 1.3 Superconductivity has broad applications.



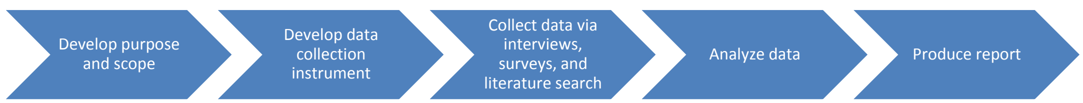
1.5 Sponsorship

The preparation of this report was sponsored by institutions in Canada, Finland, Germany, Israel, Italy, Japan, Korea, Switzerland and the United States. These institutions are signatories to an International Energy Agency (IEA) Implementing Agreement, entitled *Implementing Agreement for a Co-Operative Programme for Assessing the Impacts of High Temperature Superconductivity on the Electric Power Sector* henceforth referred to as IEA IA HTS.

1.6 Roadmap Methodology

Figure 1.4 below shows the methodology used to develop the roadmap. This process was adapted from the International Energy Agency roadmap process.[10] Work included developing purposes and non-purposes and adhering to a clearly defined scope of the technologies.

Figure 1.4 Roadmap Development Process.



Next, a standard data collection instrument, or survey, was developed in order to collect information from expert stakeholders. This survey was reviewed by IEA IA HTS executive committee to ensure that it contained the appropriate amount of detail and would yield the required information.

The next step was to collect information from expert stakeholders using several methods. The primary method was disseminating the survey to key stakeholders in the HTS community. Care was taken to get a cross section of respondents from across the world using several data collection methodologies. In some cases, in-person and telephone interviews were conducted to gather additional information from the respondents. The survey was sent directly to approximately 100 targeted experts in the field and also distributed through the Superconductivity News Forum (SNF) http://snf.ieeecsc.org, which reaches about eight thousand superconductivity specialists around the world. Data were also collected from various meetings across the globe including Applied Superconductivity Conference in Charlotte, NC, USA in August 2014; The IEA IA HTS Executive Committee meetings in Milan, Italy in June 2014 and Jeju Korea in December 2014; and the 27th International Symposium on Superconductivity (ISS) November 2014. Data were also collected from publically available websites and other published journals.

After collecting the data, it was analyzed and categorized into several key technology areas including wire, cryogenic systems, cables, superconducting fault current limiters, off-shore wind turbine generators, superconducting magnetic energy storage (SMES), and transformers. An analysis of each of these areas started with an assessment of the current state of the technology, technology targets to reach more widespread adoption, and R&D needed to reach these targets. The technology areas form the basis for the subsequent chapters in this document.