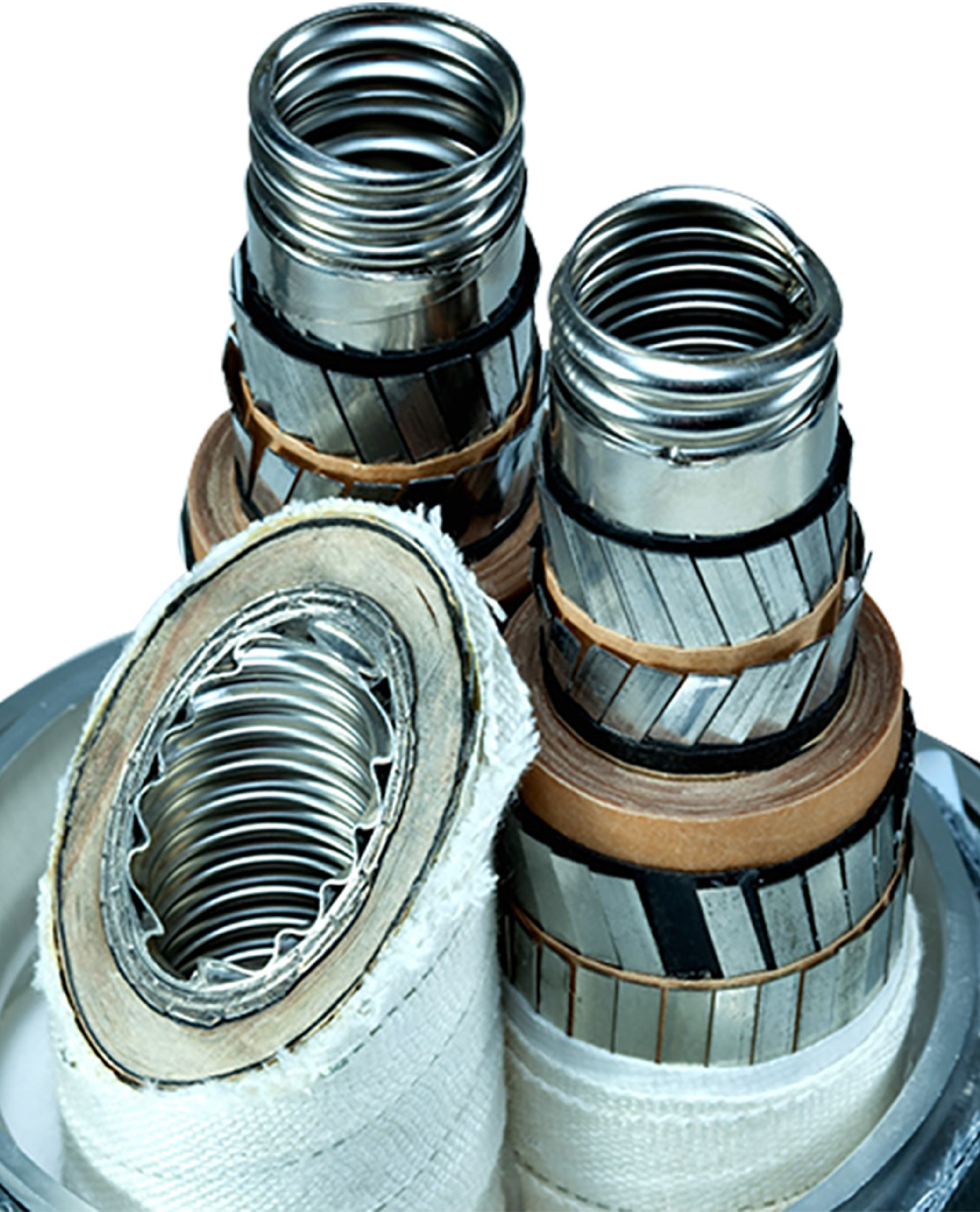
IEA Technology Collaboration Program on High Temperature Superconductivity

ANNUAL REPORT 2019

Superconductivity
INTERNATIONAL ENERGY AGENCY



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MESSAGE FROM THE CHAIR

The State of HTS in 2019 and Beyond

There has been a transition in the last several years such that high temperature superconductivity (HTS) projects are being considered as permanent infrastructure options to solve real-world electric grid problems. Moreover, in the long-term HTS has the potential to be considered for advanced transportation applications such as electric ships, aircraft, and rail. Almost thirty years of research and development has brought new equipment incorporating HTS to the threshold of greatly improving key sectors of the world's economy. However, there is still significant effort needed.

The International Energy Agency's Technology Collaborative Program on High Temperature Superconductivity (HTS TCP) is working to identify and evaluate the potential applications and benefits of superconductivity in the energy sector, as well as the current technical and also non-technical barriers that currently stand in the way. The Program is also considering ways to raise awareness of HTS's technology transfer possibilities outside the area of electric power applications. Through its nine contracting parties and one sponsor, the HTS TCP is developing technical communications documents, roadmaps, and analysis to provide information that will help a range of stakeholders.

The HTS TCP coordinated several information sharing and stakeholder engagement events, which were successful in developing public and private sector partnerships. We are actively approaching new members to join our TCP and add technical, market and policy experience to our executive committee. We are also looking forward to the future as the last several years have brought several commercial projects into the utility planning pipeline for permanent grid solutions.

HTS TCP Executive Committee Chairman

Luciano Martini

INTRODUCTION TO APPLIED RESEARCH

Electricity is the lifeblood of our economy. We depend on the electric power system more than ever to power our residential, commercial, and industrial sectors. But to meet our growing demand, new technologies and tools must be developed to enable smarter, more efficient, more reliable, more sustainable, and more resilient energy systems. High-temperature superconductivity (HTS) is one of the technologies that has the potential to do this.

Site installation of a KEPCO's 23 kV HTS cable system in Korea.

Image Courtesy of Dr. Chulhyu LEE, KEPCO.

Superconductivity is a phenomenon that enables the conduction of electric current with practically zero resistance at cryogenic temperatures. The values of these temperatures depend on the materials used, so each superconductor is characterized by a 'critical temperature' below which it offers no resistance to the passage of current. High-temperature superconductivity has progressed significantly since its discovery in 1986, moving from basic materials research to laboratory testing and, in the past decade, to demonstrations of full-size equipment.

Almost thirty years of research and development have brought new equipment enabled by high-temperature superconductivity to the threshold of electricity transmission and distribution applications. Not only do superconductor-based devices provide improvements over conventional electric grid technologies, but they also offer unique alternatives to system challenges that cannot be addressed otherwise. Laboratory-scale tests have transitioned to large-scale HTS-based projects that serve utility customers. HTS projects are now being considered for permanent infrastructure installations to solve real-world electric grid problems.

Devices based on superconductivity have been available in certain niche markets for decades. Superconducting magnets, in particular, are well-established in many applications that require powerful electromagnets like high-energy-physics particle accelerators and magnetic resonance and imaging (MRI) machines. Superconductivity has been employed or proposed for use in a variety of applications and sectors, including the energy,

A picture of Sieman's HTS-enabled Somatom X.cite CT scanner.

Image Courtesy of Siemens Healthineers.

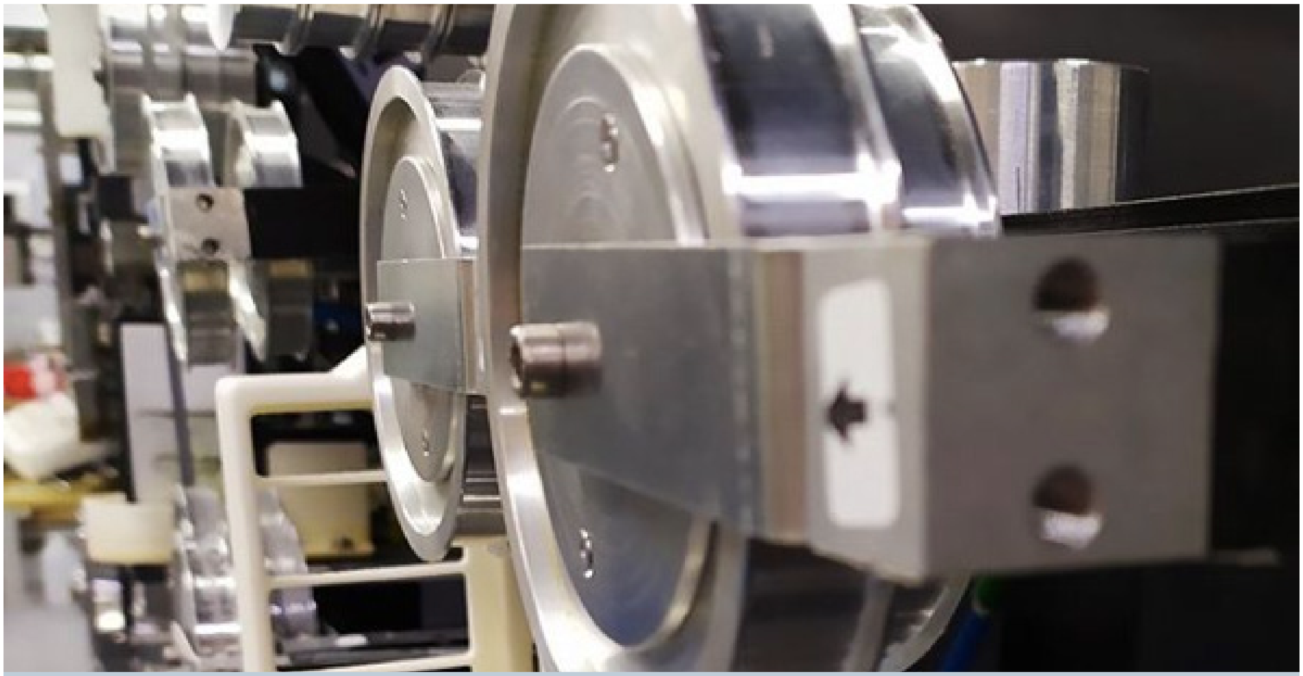
transportation, industrial, medical and defense sectors. High temperature superconducting (HTS) wire is the key enabler that makes devices for the electric power system more efficient and resilient than conventional solutions.

The Benefits of High-Temperature Superconductivity

Examples of some applications that the International Energy Agency's Technology Collaborative Program on High Temperature Superconductivity (HTS TCP) monitors includes electric transmission and distribution, energy storage, wind energy, all electric aircraft and motors:

Electric Transmission and Distribution

Superconducting cables transport electricity with little to no losses. They can also transmit up to ten times more power than conventional copper cables or carry equivalent power at much lower voltages, alleviating constraints with limited rights-of-way. In addition, many of the world's utilities are coping with increasing fault (short-circuit) currents, possibly requiring new substation circuit breakers. An HTS fault current limiter (FCL) can help manage increasing fault currents more cost-effectively and reduce losses by at least 50% in solid-state FCLs and at least 90% in fault-current-limiting reactors.



A picture of SuperOx's patented superconducting tape that was deployed in Russia's first SFCL at United Energy Company's JSC Mnevniki Substation.

Image Courtesy of SuperOx.

A picture of Russia's first commercially operational SFCL at United Energy Company's JSC Mnevniki Substation in Russia.

Image Courtesy of SuperOx.

Energy Storage

Energy storage can increase the penetration of renewable resources and improve power quality. Superconducting Magnetic Energy Storage (SMES) has several advantages over other storage technologies, including rapid response times, nearly infinite charge/discharge cycles without degradation, and very high round trip efficiency.

Wind energy

HTS-based wind turbines have the potential to generate the same amount of power with roughly half the size and weight of conventional designs, needing less rare earth metals and making installation easier.

Beyond electric systems, HTS can improve ship degaussing, the process of decreasing or eliminating a remnant magnetic field to obscure ship radar signatures and avoid enemy detection. AMSC will deliver HTS degaussing systems for future U.S. Navy San Antonio class amphibious transport dock ships, beginning with LPD 30.

Image Courtesy of HII/Ingalls Shipbuilding

Motors

Electric motors account for almost two-thirds of all electric energy consumption in the United States and other developed countries. Superconducting motors have the potential to reduce losses by 50% and can be less than half the size and weight of conventional designs, which can improve the propulsion and maneuverability of transportation vehicles.

All-Electric Aircraft

The use of lightweight HTS could lead to eco-friendly, exceptionally quiet, and highly energy-efficient electric planes. Beneficial application of HTS technology is expected in the fields of power generation, power distribution and forming, and propulsion. In addition, auxiliary devices might be replaced by electric HTS-based solutions.

Remaining Challenges

Over the past few decades, significant efforts have been made worldwide on research, development, and field demonstration of applied HTS devices for the power sector. As a result of these activities, several HTS-based devices, specifically HTS cables and FCLs, are being energized in utility grids as permanent solutions to electricity delivery challenges. However, other applications are still lagging in deployment into commercial installations. The transition of HTS applications to widespread market maturity faces several challenges. Examples include:

- Manufacturing. There are still manufacturing problems regarding the optimal architecture and production processes for specific applications. For example, it is still difficult to grow the HTS to achieve higher critical current values, as well as choosing the correct buffer layers, without introducing excessive residual or thermal stresses for long lengths.
- Reliability. End users are generally unfamiliar with the materials used in HTS devices and cryogenic systems. Data that prove undiminished product performance of HTS components over 30 to 40 years are not available yet.
- Market. Uncertainty exists for total cost of ownership, maintenance, cost and availability of spare parts from suppliers in a relatively nascent market.
- Economics. The cost of HTS-enabled devices are still significantly higher than conventional, copper-based counterparts because the sophisticated production processes, current low yields, and limited throughput of HTS tape manufacturing processes have kept costs high – there are still no observed effects from economies of scale.

PURPOSE AND SCOPE

The International Energy Agency's Technology Collaborative Program on High Temperature Superconductivity (HTS TCP) brings together key stakeholders to address the challenges of promoting the development and use of HTS technology in view of common interests. Particularly, the HTS TCP:

- Collaborates with electric utilities, governments, professional engineering organization and the RD&D community to confirm and communicate the potential benefits of HTS technology.
- Sponsors workshops, co-authors books and journal articles, exchanges information, introduces Executive Committee (ExCo) members' research facilities to other participants and guides the assessments.
- Develops position papers and strategic documents such as roadmaps and technical reports. Participants also ask experts from their countries to provide for input and to peer review draft reports. These activities help ensure consistency in the reporting and evaluate progress in the different considered fields.
- Provides expertise that can inform the evaluations and assessments performed by ExCo members.
- Interacts with other related IEA TCPs to leverage synergies and opportunities.
- Disseminates work at international meetings and workshops, and supports students, young

engineers, and scientists who are learning about HTS applications in the power sector.

- Addresses and clarifies perceived risks and hurdles to introduce a disruptive technology into the conservative electric power industry.

SUMMARY OF 2019 ACTIVITIES

ExCo activities included planning and convening technical meetings, developing technical documents and producing other forms of communication and outreach to stakeholders. Some of the examples include:

Lausanne, Switzerland ExCo Meeting

In April 2019, the IEA HTS TCP gathered in Lausanne, Switzerland at the Ecole Polytechnique Federale de Lausanne for an Executive Committee Meeting. The meeting also featured a workshop that gave member countries an opportunity share updates about superconducting projects in their region. The TCP was pleased to welcome new delegates from Korea, a new Operating Agent from Japan, and acknowledge the retirement of longtime TCP delegates from the United States and Israel. A delegate from every member country was in attendance, and the membership exchanged findings from new research developments in the United States, Korea, Italy, Japan, Israel, and Canada.

IEA HTS TCP Executive Committee members are greeted by the Swiss Delegate at the Lausanne ExCo Meeting in April 2019.

The table below highlights the 2019 and future ExCo meetings.

Summary of 2019 and Future ExCo meetings	
Lausanne, Switzerland	April 2019
Web Meeting	September 2019
Web Meeting Replacement for Pandemic	March 2020
Milan, Italy	June 2020
TBD	Spring 2021
Seoul, Korea	September 2021

International Symposium on Superconductivity (ISS 2019)

The TCP organized a special session at the 32nd International Symposium on Superconductivity (ISS 2019) this past November in Kyoto, Japan. ISS covers the latest findings and related topics in several research fields of superconductivity science and technology, including physics and chemistry, wires and bulk, electronic devices, and large-scale system applications. This session featured invited speakers from the United States and Korea to discuss their decisions to install HTS applications as permanent fixtures of their electric grids. There were invited presentations and a panel discussion with more than 100 attendees.

An international panel of utility representatives and academics discuss why HTS technologies were selected for power grids in their countries at ISS 2019.

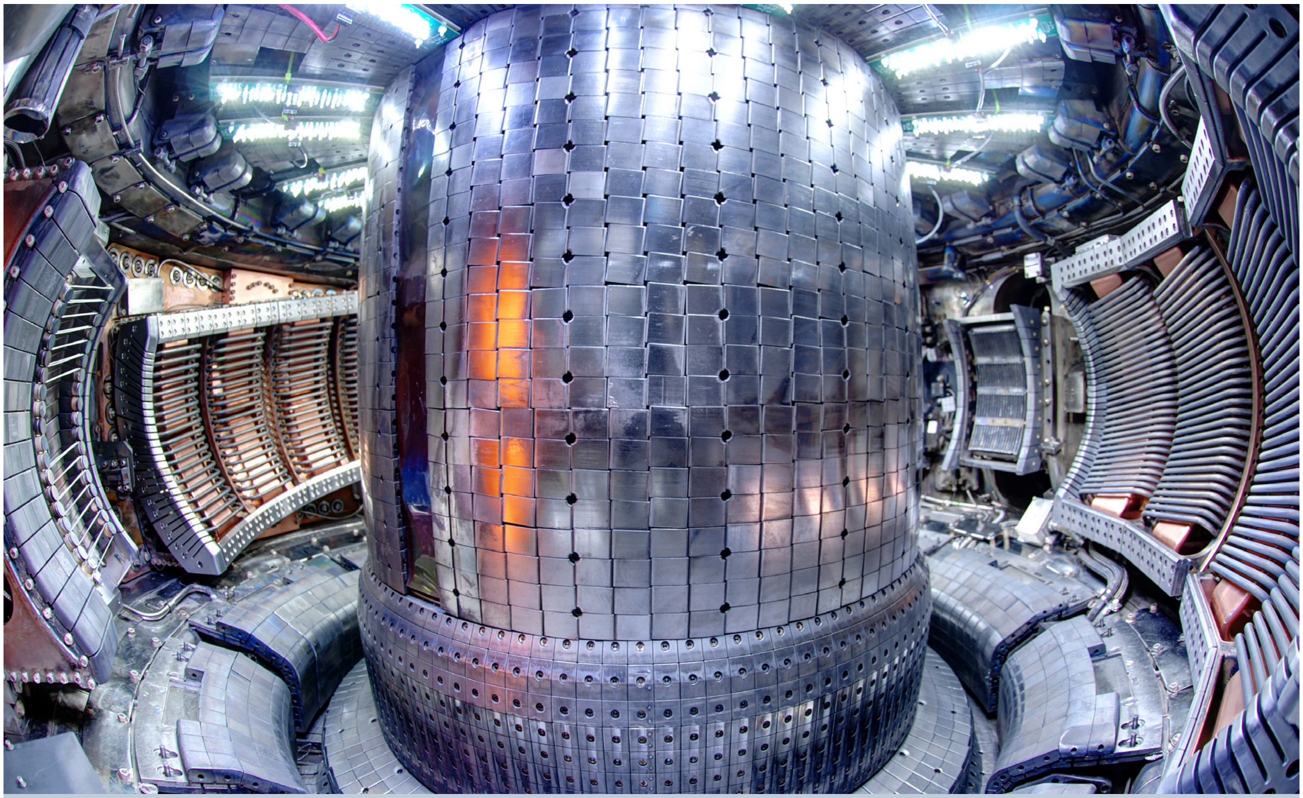
Image Courtesy of the ISS 2019 Secretariat.

Energy Efficiency, Resilient Electric Systems, and Transportation Systems Using HTS

The HTS TCP published a white paper on the use of Energy Efficiency, Electric Grid Resilience, and Transportation using HTS in July 2019. This white paper was also published with the title High Temperature Superconductor-Based Technologies as Enabler for Efficient and Resilient Energy Systems in IEEE Transactions in Applied Superconductivity, Vol. 29, Issue 5, Aug. 2019, which has received more than 90 Full text views.

HTS Tokamak Fusion Reactor White Paper

The TCP developed a white paper discussing the benefits of HTS versus low temperature superconductivity (LTS) tokamak fusion reactors. These benefits can include lower costs and a faster development schedule than large tokamaks like ITER. Among various approaches to achieving a practical fusion power reactor, the tokamak is generally acknowledged as the best approach with current technology and knowledge. In a tokamak fusion reactor, multiple "D-shaped" superconducting magnets arranged in a ring, produce a toroidal magnetic field that confines a hydrogen isotope plasma, which is then heated to ignition temperature. The heat from the fusion plasma is mechanically converted to electrical energy. Since tokamak size is inversely proportional to the fourth power of the magnetic field, a tokamak with HTS magnets would be 1/16 the size of one using LTS.



A picture of the Massachusetts Institute of Technology's Alcator C-Mod tokamak in the United States.
Image by Robert Mumgaard and courtesy of the Creative Commons Attribution-Share Alike 3.0 Unported License.

HTS-TCP Newsletter

The TCP published several newsletters on HTS news on an as-needed basis to give stakeholders insights on markets and technical developments. These newsletters were intended to disseminate HTS activities and news around the world in a timely fashion.

Superconductivity

HTS Application Projects

HTS applications like these are creating unique opportunities for commercial components that can enable the needed evolution of the energy system

High-Current Superconducting DC Busbar

A German research team has developed a superconducting high current DC-busbar. The demonstration project has a length of 25 m and a nominal current of 20 kA in a real-life industrial application: a chlorine electrolysis plant. The busbar is a modular system with rigid superconducting elements that were easily transported and installed at the industrial site. To manufacture such elements, several issues had to be addressed. The arrangement of the superconducting tapes was optimized with respect to the minimization of the magnetic self-field effects. The thermal contraction of the busbar had to be balanced, and the low-resistance joints between the superconducting elements had to be developed. The system operates at 70 K with liquid nitrogen using D-Nano and Theva superconducting wires with an energy efficient pulse-tube cryocooler and cryopump.

In general, the increase in efficiency in comparison to conventional systems depends on the current and system length. The biggest component a superconducting system's losses occur at the current leads, and consequently, optimized designs are mandatory. Superconducting systems can be more energy efficient at currents above 10 kA and lengths beyond 20 m. As an example, with a current of 60 kA and a length of 60 m approximately a 50% higher efficiency can be achieved in a 2-pole system.

The figure shows the busbar inside the cryostat and the exposed area being soldered

iea Energy Technology Network

Wind Power Projects

A countryside windfarm

In July 2019, the U.S. Department of Energy (DOE) selected three projects totaling up to $8 million to develop next-generation wind turbine drivetrain technologies that will facilitate the continued growth of wind turbines for both land-based and offshore applications. These projects will develop more efficient, smaller, and lighter-weight generators that have the potential to lower costs.

Each of the selected projects will receive up to $500,000 to design a wind turbine generator that can be scaled up to at least 10 megawatts to capitalize on the trend of larger, more powerful wind turbines, especially for offshore applications.

One project is developing a "direct drive" permanent magnet generator design that is smaller, lighter, less expensive, more reliable, more efficient, and uses less rare earth content than conventional gearbox designs.

Two projects will develop superconducting generators, which make a much stronger magnetic field using superconducting windings. This results in a significant size and mass reduction over conventional generators and significantly reduces the need for rare earth materials. AMSC will develop a high-efficiency lightweight wind turbine generator that incorporates HTS materials to replace permanent magnets in the generator rotor, potentially reducing size and weight by 50%. General Electric will develop a high-efficiency ultra-light low temperature superconducting (LTS) generator, leveraging innovations from GE's magnetic resonance imaging (MRI) business. The generator will be tailored for offshore wind and scalable beyond 12 MW.

These research projects have the potential to develop machines up to 50% smaller and lighter while reducing the cost of wind generation by 10–25%. After these projects

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World Projects at a Glance

The ExCo maintains an interactive web-based map that catalogs HTS-based projects around the world. Data are collected by region: North America, the European Union, Japan, Korea, China and Russia. The map is updated as needed with data such as current and voltage ratings, current status, partners, budget and references. *www.ieahts.org*.

Around the worls, projects are demonstrating the technical feasibility of equipment incorporating HTS. The text below highlights several project examples that have made recent progress.

PROJECT UPDATES

Around the world, projects are demonstrating the technical feasibility of electric power equipment incorporating HTS tapes. The text below highlights several project examples.

KOREA

The KEPCO-sponsored Shingal-Heungdeok triple-core HTS power cable project is ready for commercial operation after passing its commissioning tests. The Onsu-YG Project is KEPCO's next step in advancing the deployment of HTS technology that interconnects two 345-154 kV substations.

A 23 kV triad-type HTS distribution cable applied in KEPCO's Shingal Project.

Image courtesy of LS Cable and System.

CHINA

While China has yet to join the IEA HTS TCP, it remains a critical partner in the technological and particularly commercial development of HTS technology. The Shanghai Economic Information Commission launched China's first kilometer-scale high-temperature superconducting power cable in the Shanghai Baoshan City Industrial Park, while another project experimented with different coolants. A direct current cable project in China is currently being cooled by LN2 and indirectly cooled with LNG as part of a project that combines LNG transmission and electric power transmission.

JAPAN

Japan maintained its strong global leadership on HTS technology developments in 2019, particularly in railway transportation applications. In July, its Railway Technical Research Institute (RTRI) has been developing and testing a 1200-m superconducting feeder system. In addition, RTRI successfully conducted a disconnection and power-on test in July 2019 of a superconducting power transmission system using actual vehicles on a railway that supplies power at 600 V DC. This had been the world's only demonstration of such a system until RTRI announced the following month they had completed the same test on a commercial high-speed rail system's power supply at 1500 V DC. These tests, in addition to others on superconducting joints for persistent current nuclear magnetic resonance devices, were critical milestones to commercializing a superconducting railway power transmission system.

Japan also made significant advancements in more traditional HTS power system applications. A NEDO project in Japan is working on a demonstration of a compact tri-axial HTS AC cable in a private factory, which will be installed in April 2020 and become fully operational in May 2020.

EUROPE

Europe's 12-partner project, FASTGRID, developed a cost-effective fault current limiter using advanced superconducting tapes for future high voltage direct current grids. In Italy, the DRYSMES4GRID Project funded by the Italian Ministry of Economic Development (MISE) is developing a dry-cooled (cryogen-free) SMES using magnesium diboride (MgB_2) conductors.

Germany has made significant HTS advancements this year. For instance, a research team developed a superconducting high-current DC-busbar for use in a chlorine electrolysis plant. HTS material was used to replace traditional busbar metals and now delivers a higher efficiency system with lower losses. Furthermore, an HTS cable in Essen's distribution network was successful and now its operation has been prolonged for a longer period.

UNITED STATES

The Commonwealth Edison electric utility is constructing the first phase of an HTS cable in downtown Chicago, Illinois, USA after receiving approval in 2018. This project, which the Department of Homeland Security partially funds, will tie two substations together with an HTS cable to increase this grid's resilience during fault currents.

U.S. Federal Government support for HTS-enable research and development activities also continued through the U.S. Department of Energy (DOE), which selected two projects totaling up to $8 million to develop next-generation superconducting wind turbine drivetrain technologies that will facilitate the continued growth of wind turbines for land- and offshore-based applications.

WORKING ARRANGEMENT

There are currently two operating agents (OAs) supporting the HTS TCP, one based in the United States and one in Japan. They are managed by the ExCo, whose duties are specified in a contract with the OAs and include provision of technical and support services. The HTS TCP operation is supported by a combination of cost-, task-, and knowledge sharing. ExCo members cover their travel expenses to attend ExCo meetings and bear all the costs incurred in conducting task activities, such as report writing and travel to meetings and workshops.

The ExCo Chairman, vice-chairman and operating agents prepare an annual work plan and associated annual budget for the calendar year, which are submitted for approval by the ExCo. The expenses associated with the operation of the HTS IA ExCo and the annual work plan, including the operating agent's time and travel and other joint costs of the ExCo, are met from a Common Fund to which all HTS TCP members contribute. No changes to either the working arrangement or current structure fee are anticipated. In FY 2017 the fee structure had been modified based on the GDP of the member countries. The HTS TCP Common Fund is financially secure, and has had a surplus for the past several years.

Membership in the ExCo remained the same since the previous annual report, but the ExCo is making a concerted effort to increase membership.

The TCP has a strong policy relevance within each of its member countries. It provides unbiased technical expertise to policy makers and contributes to documents in the public domain by gathering data for publication. For instance, the HTS TCP maintains this relevance through various channels such as:

- Government officials from Japan and U.S. participate in the ExCo
- One of the German delegates advises the responsible persons in its government
- The Italian representative is supporting the Ministry of Economic Development
- Korea is represented by its electric power company which has a vigorous HTS RD&D program that is among the world's leaders

ALIGNMENT WITH IEA MISSION

The HTS TCP's strategy is aligned with key components of the IEA mission. These include energy efficiency, energy security, system integration of renewables and engaging stakeholders around the world.

Energy Efficiency

- Contributes to several applications with improved efficiency over conventional systems in electricity grids, industry and transportation. Examples include, components for AC and DC grids such as cables, transformers, energy storage systems, busbars, but also induction heaters and in future transportation applications for all-electric aircraft, high-speed train, and electric ships.

Energy Security

- Supports energy security focusing on HTS-based technologies - primarily fault current limiters and superconducting magnetic energy storage systems (SMES), that can help to enhance grid reliability and resilience.

System Integration of Renewables

- Provides research, analysis and information related to the use of HTS components - such as high-capacity power cables, fault current limiters, high-efficiency generators for offshore wind turbines, energy storage, and innovative transformers able to facilitate increased renewable generation integration in electric grids.

Engagement Worldwide

- Actively engages groups of stakeholders, such as electric utilities, governments, the professional engineering community and the RD&D community, worldwide.
- Connects with other IEA TCPs such as the International Smart Grid Action Network.

FUTURE ACTIVITIES

Several activities that could be undertaken in the next year include:

- Developing an updated roadmap that describes where the HTS industry is now and what steps it should take to realize widespread adoption of superconducting-based devices in the electric sector.
- Bridging the gap between technology developers and electric utility system planners by developing technical materials to explain how the systems work and provide best practices and lessons learned from other projects.
- Increase communication and active engagement with relevant industry sectors where appropriate, extending the distribution of policy recommendations to a wider industry audience.
- Continue to document environmental benefits from the future deployment of HTS power equipment.
- Collectively work to build new HTS application projects to help realize environmental benefits.
- Organizing workshops to help gain visibility with other TCPs.
- Organizing at least two executive committee meetings in 2020 and co-locating other industry meetings to leverage expertise from other experts.

CONTACT INFORMATION FOR EXCO DELEGATES/ ALTERNATES, SPONSORS AND OPERATING AGENTS

Country	Nomination	Name and Organization	Contact Info
Executive Committee			
Canada	Delegate	**Dr. Julian Cave** *Hydro Quebec*	*Cave.Julian@IREQ.ca*
		Dr. Frédéric Sirois *Polytechnique Montréal*	*f.sirois@polymtl.ca*
Finland	Delegate	**Dr. Risto Mikkonen** *Tampere University of Technology*	*Risto.Mikkonen@tut.fi*
	Alternate	**Dr. Antti Stenvall** *Tampere University of Technology*	*Antti.Stenvall@tut.fi*
Germany	Alternate	**Dr. Tabea Arndt** *Karlsruhe Institute of Technology*	*tabea.arndt@kit.edu*
	Delegate	**Prof. Mathias Noe** *Karlsruhe Institute of Technology*	*mathias.noe@kit.edu*
	Alternate	**Prof. Bernhard Holzapfel** *Karlsruhe Institute of Technology*	*bernhard.holzapfel@kit.edu*
Israel	Delegate	**Prof. Guy Deutscher** *Tel-Aviv University*	*guyde@post.tau.ac.il*
Italy	Delegate	**Dr. Luciano Martini (Chairman)** *Ricerca sul Sistema Energetico – RSE S.p.A.*	*Luciano.Martini@rse-web.it*
	Alternate	**Dr. Michele de Nigris** *Ricerca sul Sistema Energetico – RSE S.p.A.*	*michele.deNigris@rse-web.it*
Japan	Delegate	**Mr. Yasunori Yajima** *NEDO*	*yajimaysn@nedo.go.jp*
	Alternate	**Prof. Hiroyuki Ohsaki (Vice-Chairman)** *The University of Tokyo*	*ohsaki@k.u-tokyo.ac.jp*
	Alternate	**Mr. Susumu Kinoshita** *NEDO*	*kinoshitassm@nedo.go.jp*
Republic of Korea	Delegate	**Dr. Sang Chul Han** *KEPCO*	*sangchulhan@kepco.co.kr*
	Alternate	**Dr. Gye-Won Hong** *Korea Polytechnic University*	*gwhong@kpu.ac.kr*

Country	Nomination	Name and Organization	Contact Info
Switzerland	Delegate	**Mr. Michael Moser** *Swiss Federal Office of Energy*	michael.moser@bfe.admin.ch
	Alternate	**Dr. Bertrand Dutoit** *Ecole Polytechnique Fédérale de Lausanne*	bertrand.dutoit@epfl.ch
	Alternate	**Mr. Roland Brüniger** *Swiss Federal Office of Energy*	roland.brueniger@r-brueniger-ag.ch
United States	Delegate	**Dr. Kerry Cheung** *U.S. Department of Energy*	kerry.cheung@hq.doe.gov
	Alternate	**Dr. Dominic Lee** *Oak Ridge National Laboratory*	leedf@ornl.gov
Sponsors			
Italy		**Dr. Giovanni Grasso** *ASG Superconductors SpA, Columbus MgB2 Wire Unit*	grasso.giovanni@as-g.it
		Mr. Matteo Tropeano *ASG Superconductors SpA, Columbus MgB2 Wire Unit*	tropeano.matteo@as-g.it
Operating Agents			
United States		**Brian Marchionini** *Energetics Incorporated*	bmarchionini@energetics.com
		Donald Mosteller *Energetics Incorporated*	dmosteller@energetics.com
Japan		**Ataru Ichinose** *CRIEPI*	ai@criepi.denken.or.jp

ABOUT THE INTERNATIONAL ENERGY AGENCY

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 coordinate 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 member 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.

ENERGY TECHNOLOGY INITIATIVES

The IEA energy technology network is an ever-expanding, co-operative group of more than 6,000 experts that support and encourage global technology collaboration. At the core of the IEA energy technology network are a number of independent, multilateral energy technology initiatives – the IEA Technology Collaboration Programmes (TCPs).

Through these TCPs, of which there are currently more than forty including 4E, experts from governments, industries, businesses, and international and non-governmental organizations from both IEA member and non-member countries unite to address common technology challenges and share the results of their work. Each TCP has a unique scope and range of activities.

Further information is available at: ***http://www.iea.org/tcp***

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