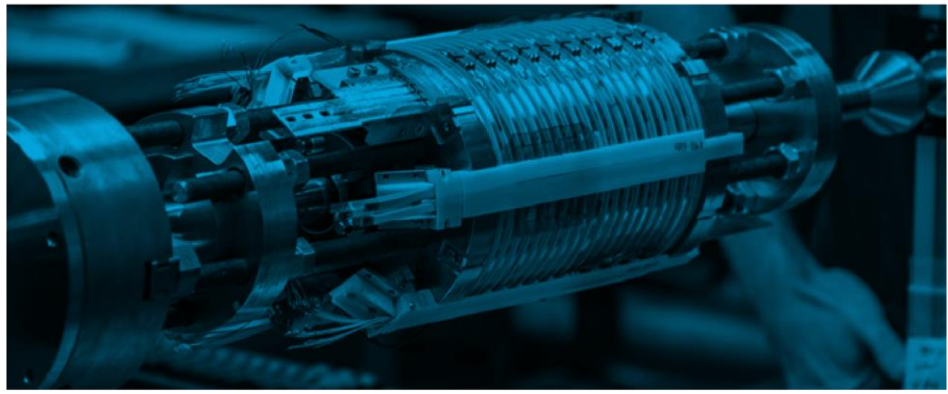
Energy Efficiency, Resilient Electric Systems, and Transportation Applications Using High-Temperature Superconductivity

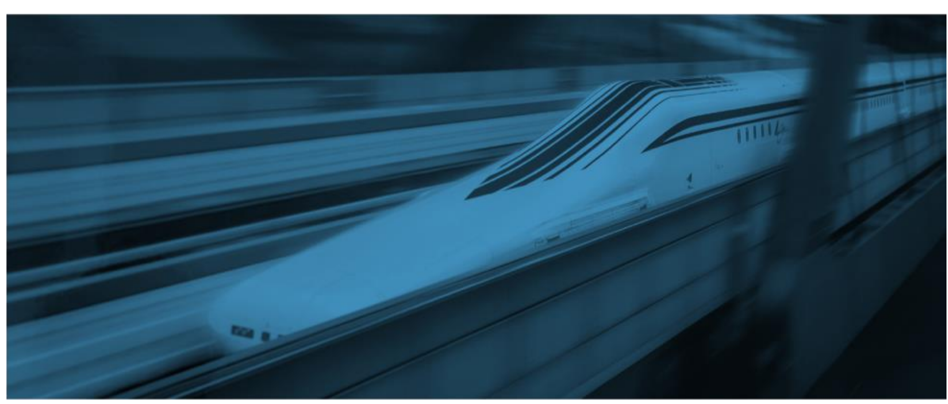
A Publication of the International Energy Agency's Technical Collaboration Programme on High-Temperature Superconductivity

July 2019



Superconductivity
INTERNATIONAL ENERGY AGENCY

iea
Energy Technology Network



Contents

1. Introduction

New technologies based on the use of high-temperature superconductivity (HTS) can lead to higher-efficiency and more resilient energy systems. HTS applications are creating unique opportunities for promising commercial components that can enable the needed evolution of the energy system; such components include high-capacity power cables, fault current limiters, high-efficiency generators for offshore wind turbines, energy storage, and innovative transformers. 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.

The International Energy Agency's (IEA's) Technology Collaborative Program on High-Temperature Superconductivity (HTS TCP) developed this paper. It will explore the potential capabilities of HTS-based devices to advance the transformation of today's electric power, industrial, and transportation systems.

1.1 About the International Energy Agency's Technology Collaboration Program on High-Temperature Superconductivity

The IEA actively promotes the dissemination and awareness of energy-related information, covering technical topics such as smart grids, demand-side management, renewable energy sources, and energy efficiency. HTSs for electric power system application is the focus of the IEA program for "Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector," the HTS TCP. Through its nine contracting parties and one sponsor, this international group fosters the penetration of HTS applications in electric power grids.

The HTS TCP mission is twofold: (1) to evaluate the status of and assess the prospects for the electric power sector's use of HTSs within the developed and developing world and (2) to disseminate the findings to decision makers in government, the private sector, and the research and development (R&D) community. The HTS TCP conducts outreach and directs it toward the following groups of stakeholders:

- *Electric utilities*, those who make decisions about technology adoption;
- *Governments*, those who make decisions about policies, subsidies, and funding for research, development, and demonstration (RD&D);
- *The professional engineering community*, those who implement and advise; and
- *The RD&D community*, those who invent, innovate, and solve complex problems.

These four groups are sources of expertise that can inform the evaluations and assessments undertaken by the TCP. HTS TCP participants also recognize the importance of educating the next generation of engineers and see this endeavor as a key outcome of their information sharing.

The HTS TCP's mission has attracted interest and action from collaborators across the globe. HTS demonstration projects have been successfully carried out in Asia, Europe, and North America, and new projects are underway. This work can produce better HTS materials, conductors, products, and devices at a time when public demands for energy efficiency and resilient systems are changing power sector requirements and increasing the need for impactful, cost-effective, government-sponsored RD&D.

The research conducted for this paper was sponsored by the HTS TCP. The paper is part of the TCP's ongoing efforts to provide information about the potential for superconducting applications to improve grid resilience, sustainability, and energy efficiency for industrial applications and transportation.

1.2 Industry Trends and Drivers

Industry trends in the electric power, industrial, and transportation sectors include decentralization, electrification, and digitization. Decentralization involves the changing mix and characteristics of electricity generation sources that are shifting electricity generation from relatively few large central station plants to many smaller and often variable generators. Decentralization also involves building inter-regional transmission infrastructure to offset temporary loss of regional generation capacity due to weather-related fuel disruptions or to compensate a mismatch of regional power generation and demand (e.g. coastline vs. mainland).

Another trend is the broader electrification of end-use technologies. This includes the changing demand loads in retail electricity markets resulting from demographic and economic shifts, growing consumer participation in electricity markets, and the proliferation of internet-enabled (e.g., Wi-Fi) and network (LAN) products for residential and commercial use. Wi-Fi, for instance, can account for a majority of a suburban home's electricity consumption. Electrification is rapidly adding new technologies and techniques to the grid as well, which enables its modernization but increases pressure on its already strained and aging electricity infrastructure.

The third trend, digitization, is the integration of smart grid technologies for managing complex power systems, driven by the availability of advanced technologies that can better manage progressively challenging loads. Digitization involves overlaying information technology (IT) infrastructure with the traditional electric grid. Expectations for a resilient and responsive power grid are growing in the face of more frequent and intense weather events, cyber and physical attacks, and interdependencies with natural gas and water systems. These trends are affecting how the electric grid is designed and operated, and they present opportunities for technology innovation in HTS.

The electricity sector has always been profoundly shaped by technological innovations that build on new discoveries to facilitate everyday life and provide access to new services, and significant improvements are not only possible, but required. However, annual global RD&D spending on efficiency, renewables, and carbon capture and storage has been relatively flat in the public sector (e.g., governments) in recent years, with a small uptick in 2017.[1] Some additional perspective on the amount of R&D investment in the private sector is shown in Figure 1 below. It includes the electricity sector but also other energy-related sectors such as transportation and renewables. Clean energy investment by companies could be as high as two-thirds of total corporate energy-related RD&D expenditure, up from one-half in 2012; the higher proportion is largely a result of declines in RD&D spending in the oil and gas sector since 2015, as well as growing "green" investments in the automotive sector.[2]

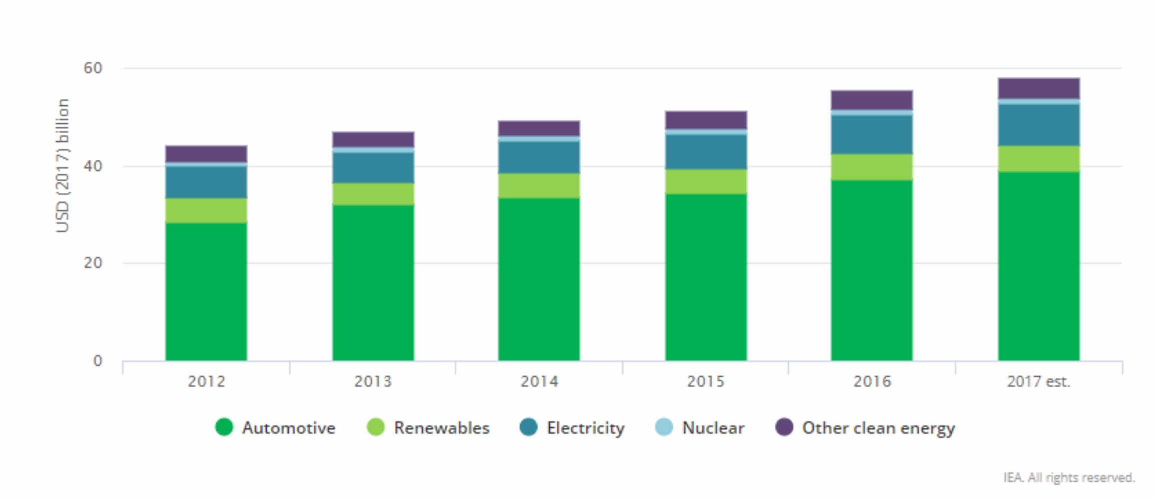


FIGURE 1. RESEARCH, DEVELOPMENT AND DEPLOYMENT SPENDING BY FIRMS IN CLEAN ENERGY RELATED SECTORS. GRAPHIC COURTESY IEA.

Additional public- and private-sector funding has the potential to move technologies and tools such as superconductivity further along the path of commercialization. Furthermore, education of governmental and electric industry regulators about the benefits of HTS and the need for increased RD&D efforts to realize its full potential may help to improve the funding outlook.

2. Resilient Electric Grids and HTS technology

There are a number of technologies, tools, and techniques used to improve grid resilience in the electric power sector. These solutions are at the substation, in the transmission and distribution lines, and with the end user. This section of the white paper will discuss some of the HTS-based technologies that can help provide grid reliability and resilience, with a focus on the later. Some of the technologies that can provide this service include superconducting fault current limiters (SFCLs), HTS cables, superconducting magnetic energy storage (SMES), and HTS transformers. However, this paper focuses on FCLs and cables, as these technologies are more mature and information is more readily available.

2.1 Grid Reliability and Resilience

A brief overview of the difference between reliability and resilience will help guide and inform the discussion of technologies that can improve resilience.

While electric utilities have improved grid reliability overall, extreme weather events, including storm surges, floods, heat storms, and droughts, continue to increase in intensity and frequency. Utilities, governments, and other stakeholders need to make concerted efforts at building resilience to limit and mitigate the risks to customers. There are technologies, tools, and techniques that utilities are using to improve resilience. Utilities will share information with each other about best practices and lessons learned. This white paper helps to facilitate this information exchange.

Reliability is generally referred to as the power system's ability to deliver electricity in the quantity and with the quality demanded by users. One measure of grid reliability concerns itself with frequency and duration of outages during otherwise normal, day-to-day operational circumstances. Grid resilience differs from reliability, so defined, in that it is the ability to withstand relatively infrequent or abnormal grid stress events without suffering operational compromise and/or, in the failure to remain 100% operational in the immediate aftermath of a stress event, the ability to restore power after that event quickly and safely. It is important for utilities to set expectations with customers regarding resilience. Grid hardening efforts by utilities may not prevent all outages but may help to restore power more quickly. The amount of resilience needed on the electric grid depends on the locations and costs of the solutions being integrated.

2.2 Fault Current Limiters based on HTS

Short-circuit currents are a well-known and unavoidable issue in electric grids. As electric loads increase on transmission and distribution circuits, those circuits are necessarily exposed to larger short-circuit currents, which need to be cleared (i.e., extinguished in time to prevent damage to circuit components). SFCLs today offer a robust approach to controlling fault-current levels on utility distribution and transmission networks. In fact, SFCLs provide a unique solution—one that conventional technologies cannot provide—to limiting faults on the transmission system. SFCLs operate with low impedance, and some are essentially invisible electrically. However, in the event of a fault, an SFCL can rapidly (nearly instantaneously) add impedance to the circuit, limiting the fault current and simultaneously providing the utility with a low-impedance, "stiff" system during normal operations and a reduced fault-current level. Figure 2 shows the reduction in fault current in a circuit achievable by an FCL.

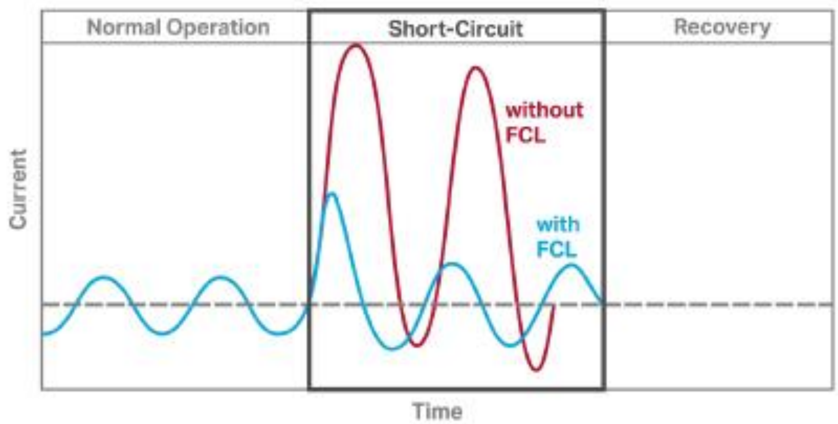


FIGURE 2. WHEN A SHORT CIRCUIT (OR FAULT) OCCURS, A TRANSMISSION OR DISTRIBUTION LINE'S CURRENT CAN SPIKE AND CAUSE DAMAGE TO DOWNSTREAM EQUIPMENT. AN FCL WOULD LIMIT THE CURRENT TO NORMAL LEVELS

An SFCL system was installed in-grid at the Knapps Corners substation, owned and operated by Central Hudson Gas and Electric Corporation in New York. The new system has limited more than 20 potentially disruptive faults on the AC power grid over a two-year span, successfully avoiding infrastructure damage and loss of power. Figure 3 shows the range of places on the electric grid where FCLs can be used.

Short-circuit current interruption in multi-terminal, high-voltage direct current (HVDC) grids is a challenge. The development of HVDC grids appears to be very promising for improving grid efficiency and incorporating more renewable energy sources. These sources are intermittent by nature, and the best areas to install them are not usually found within reasonable geographical proximity to cities or other large centers of electricity consumption. This separation of source from high demand increases the need for electricity distribution over longer distances, which creates a great advantage for DC connections.

Faults in a DC grid can have more severe consequences, potentially leading to blackouts. The protection scheme must handle the fault currents but also bring a supply quality through the service continuity of the healthy zones. In addition, these currents must be cleared or limited as fast as possible.

SFCLs enable the reduction of current intensity, which allows for the use of a "lower-current" conventional breaker in combination with the SFCL. This is advantageous for new installations, as it facilitates the utilization of existing breaker designs when upgrading the grid. An upgrade would normally result in higher fault currents; adding an SFCL allows the utility to keep the same breaker.

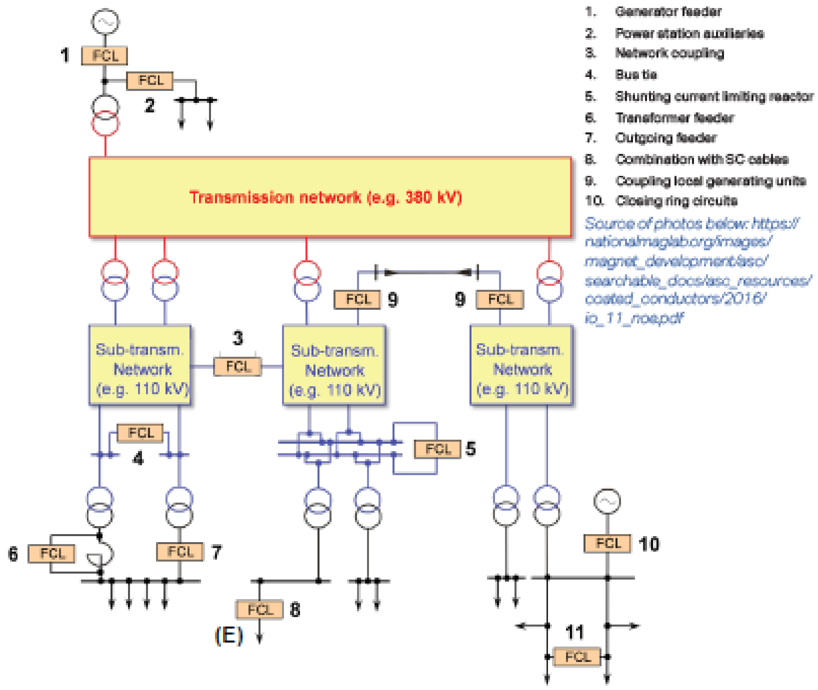


FIGURE 3. FCLS CAN BE INTEGRATED INTO VARIOUS LOCATIONS ON THE ELECTRIC GRID.

If a conventional breaker remains necessary, the SFCL will limit the current to levels consistent with the breaker's capability; this process occurs during the time it takes to clear the current (on the order of a few tens of milliseconds). This strongly reduces the risk of damage occurring before fault clearance and allows time for the breaker to operate—which may provide additional benefits, such as enabling the use of mechanical breakers.

2.3 Cables based on High-Temperature Superconducting technology

Electric transmission and distribution underground cables are critical for connecting generation to load when there are constraints to the use of ordinarily less-expensive overhead lines. In HTS cables, wires made from superconductors replace a manifold of the copper or aluminum wires in conventional underground cables and enable transportation of higher power in a smaller cross section. HTS cables may be used in utility power networks or in commercial and industrial applications such as data centers—in both DC and AC systems. An underground or conduit-installed power cable system requires significant engineering in design, fabrication, and installation. Unlike overhead lines, which rely on the large air space between the line and the ground for electrical insulation (except at towers), underground cables require a sophisticated electro-mechanical design. This design includes the electrical conductor in a mechanically protected insulating sheath, splices/joints installed in a system of conduits and underground vaults, and substation termi-

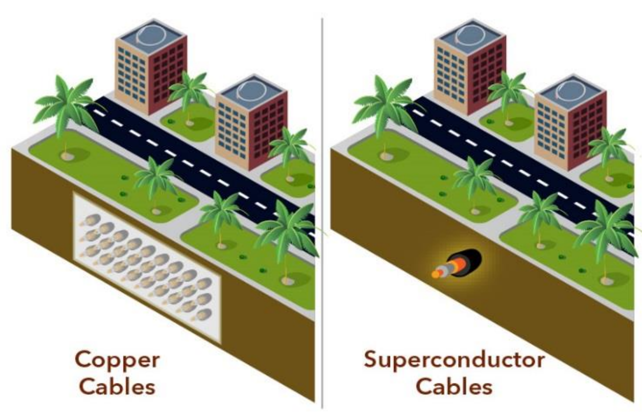


FIGURE 4. SUPERCONDUCTING CABLES CAN REPLACE MANY CONVENTIONAL COPPER CABLES AND TRANSFER TRANSMISSION-LEVEL POWER AT DISTRIBUTION VOLTAGES.

nations. In addition, HTS cables entail a cryogenic cooling system to maintain proper operating conditions.[3] Figure 4 shows a comparison of the power-carrying capacity of HTS cables versus conventional copper cables in an urban setting.

HTS cables are very cost-sensitive. Existing copper cables are approximately $60 kA-m (at a copper cost of ~$3/lb). While they may not need to be exactly on price parity with conventional cables, HTS cables do need to be cost-competitive with copper after accounting for cooling system costs. Second-generation HTS wire needs to be long, with consistently high critical current.[4] However, HTS cables can be installed using conventional cable pulling techniques, as shown in Figure 5.

Some cables have very high amperage targets—approximately 5000 A versus 1200 A in conventional cables. The high current strength allows for increased power without increased voltage, so utilities in cities could use medium-voltage cables, rather than high-voltage. For DC superconducting cables, the losses are independent of the power carried by the cable, making them more attractive than extra-high-voltage AC overhead lines for bulk power transmission.[5]

Figure 5. HTS cables can be installed using conventional cable pulling techniques. Photo courtesy of Nexans.

The Republic of Korea is the first country in the world to deploy a commercial HTS AC cable.[6] The first commercial use of a DC superconducting cable was at an alumina electrolyzer plant in China. The 362-meter warm dielectric cable, installed in early 2011, is rated 10 kA at 1.3 kV.[7]

American Superconductor (AMSC) and Commonwealth Edison Company (ComEd), a utility in Chicago, Illinois, are collaborating on a new HTS cable project that will link existing electric power infrastructure within the City of Chicago. The system is expected to become a permanent part of Chicago's electric grid and to strengthen and enhance its load-serving capacity, resilience, and reliability. The project is funded in part by the U.S. Department of Homeland Security (DHS) as a component of the federal effort to secure the nation's electric grid against catastrophic events such as extreme weather.[8] According to ComEd leadership, this installation of AMSC's superconducting cable system is part of the utility's vision to deploy new technology that supports the evolution of a smarter and more resilient electric grid. AMSC leadership believes that some dozen opportunities exist in the United States for installations similar to that envisioned for Chicago.[9]

2.4 Transformers with HTS Technology

Though research is being pursued in a number of laboratories and universities around the world, HTS transformers are only at a developmental stage. For commercialization, significantly more research must be conducted, followed by successful demonstration. The HTS transformer must be competitive with conventional transformers, which are effective, highly developed, and continuously improving. The slight efficiency improvement offered by HTS transformers is not thought to provide a compelling incentive to their deployment. HTS transformers do have some special characteristics that could make them attractive in some niche applications. One feature is the relevant ease with which fault-current-limiting capability could be incorporated. Second, unlike conventional transformers, an HTS transformer is capable of operating under overload conditions with no consequent reduction in life.

A novel application of HTS technology is the rapid recovery transformer that DHS is developing. The project, called RecX, is a mobile spare extra-high-voltage (EHV) transformer designed for rapid deployment in the event of a transformer failure. Like the HTS cable being installed in Chicago, the RecX will improve grid resilience against catastrophic events that result in loss of multiple transformers in a region. The use of an HTS transformer would greatly mitigate the difficulties posed by conventional transformers' weight and size, which impede mobility and rapid deployment. To be effective, such an HTS transformer would require development of a suitable solid dielectric.[10]

3. Industrial Applications using High-Temperature Superconductivity

HTS can enable energy-efficient systems in several industrial applications. This paper highlights motors, busbars, induction heating, and magnetic separation.

3.1 Motors

The current market potential for HTS motors begins at a power of approximately 1 MW. Motors powered by electricity, as opposed to gas-powered turbines, are usually asynchronous. These asynchronous motors are usually very cheap but are not very efficient. Therefore, HTS technology has to compete with far less expensive conventional technologies. As long as industry sees little value in discernible advantages of HTS-based machines and a supportive policy framework remains absent, the replacement of large asynchronous motors with HTS-based machines is likely to be limited to niche opportunities.

Advanced motor prototypes employing HTS technology have been tested for industrial, naval, and aerospace applications. Most of these machines have been of synchronous type. Such machines can be broadly divided among the following categories:

- Synchronous machines with HTS excitation winding on the rotor
- Induction motors with superconducting rotor cage winding[11]
- AC homopolar machines with HTS excitation winding on the stator

The wound rotor synchronous machines are most attractive for delivering power-dense, compact, efficient motors. However, in these machines, the rotor carries a superconducting DC excitation winding that requires a steady coolant supply to maintain its superconducting state. This configuration presents challenges. The rotor speed of such machines is limited (<7000 RPM) by the need to support the field winding on the rotor. The induction motors with HTS cage winding do not require DC excitation, and the cage winding on the rotor might be simpler to support than the wound winding, so it may be possible to achieve slightly higher speeds. However, these motors still require coolant transfer to the rotor. The induction motors are less power-dense, less compact, and less efficient than the wound rotor machines.

Synchronous machines with permanent magnet rotors look attractive, as there is no need for supplying DC or coolant to the rotor. However, these machines are likely to be even less power-dense, compact, and efficient than the induction motors. The AC homopolar machines do not employ active windings on the rotor, for both excitation and armature windings reside in the stator. Such machines could be operated at very high speeds—speeds limited only by the rotor material's mechanical stress capacity. Since magnetic iron is employed to guide flux lines, and only half of axial length is active at any time, these machines tend to exhibit lower relative power densities and efficiencies, as well as a limited capacity for compactness. By contrast, a 5000 HP, 1800 RPM motor was built for industrial applications that utilize

HTS field winding on the rotor.[12] This motor is approximately half as large, in size and mass, as a conventional motor of identical rating.

3.2 Busbars

In electric power distribution, a busbar is a metallic strip or bar, typically housed inside switchgear, panel boards, and busway enclosures for local high current power distribution. Busbars are also used to connect high voltage equipment at electrical switchyards, and low voltage equipment in battery banks. Industrial applications like chlorine, zinc or copper electrolysis and aluminum plants will have very large busbars used to carry tens of thousands of amperes to the electrochemical cells that produce aluminum, for instance, from molten salts. Busbars are produced in a variety of shapes, such as flat strips, solid bars, or rods, and are typically composed of copper, brass, or aluminum as solid or hollow tubes.[13] Superconducting material can be used to replace these traditional metals and provide higher efficiency system with low losses.

A German research team has developed a superconducting high current DC-busbar.[14] The demonstration project has a length of 25 m and a nominal current of 20 kA in a real-life industrial application: a chlor 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, in particular, had to be developed.[15] Figure 6 shows the busbar inside the cryostat and the exposed area being soldered. 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.

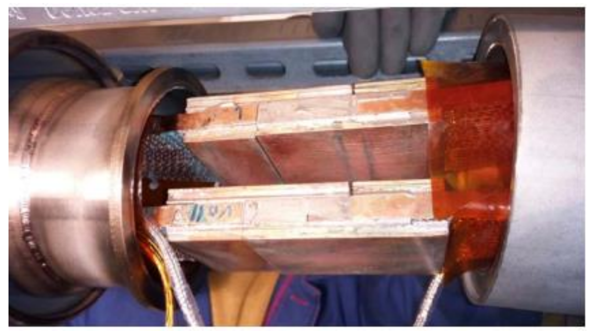


FIGURE 6. SOLDERING OF THE BUSBAR [14] IMAGE COURTESY OF VISION ELECTRIC SUPERCONDUCTORS

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.

3.3 Induction Heating

Superconductors are primarily suitable for DC coils and are therefore *not* suitable for coils that generate high-frequency fields for induction heating. MgB_2 conductors are under consideration for AC applications, but very high-frequency coils are a distant possibility. One of the best applications of HTS coils is to deploy them as a DC field source and rotate the load to be heated in this field, as was explained at a recent Institute of Electrical and Electronics Engineers (IEEE) conference.[16] Such induction heaters are much more efficient than gas furnaces and high-frequency AC induction heaters. All types of HTS conductors (DI-BSCCO, REBCO, and MgB_2) are suitable for manufacturing DC coils for such induction heaters.

A conventional copper-based induction heater is produced by winding an AC-driven copper wire around the (extrusion) billet. Because of the copper coil system's impedance (inductance plus ohmic resistance), the system's efficiency settles within the range of 35% to 45%. An HTS-based induction heater consists of an HTS DC coil generating an inhomogeneous field for the rotating billet. The DC operation causes the inductance problem to vanish, and the HTS eliminates the ohmic resistance. Together, these effects push the induction heater system efficiency over 80%. For example, one ton of aluminum (heating power 500 kW to reach a temperature of 520°C) in a conventional system would consume approximately 280 kWh, compared to approximately 160 kWh for an HTS-based system.[17]

Extrusion technology is still widespread and an important production step in semi-finished products and parts of metal, so HTS-designed induction heaters would dramatically increase the efficiency of these process steps and contribute considerably to energy savings in industry.

3.4 Magnetic Separation

High field gradient coils have been used to separate impurities in liquids and grounded ores of various kinds. The advent of superconducting magnet technology has greatly extended the range and potential of magnetic separation to include a myriad of exciting applications in many key sectors such as mining, manufacturing, medicine, and biochemical and environmental technology.[18] Today, the minerals industry remains the largest user of magnetic separation, employing it for material sorting, ore treatment, and mineral improvement.

Today's state-of-the-art superconducting magnet technology reliably provides magnetic separator systems that produce very high magnetic fields (> 5 Tesla), which increases the machine's processing capacity. Most separation systems could operate with minimal supervision, thanks to high levels of reliability and automation, so the technology's potential benefits extend well beyond technical performance improvements.

Some of the challenges include system integration—including coils and refrigerating machines—compatible with sediment decontamination equipment that can be carried by trucks and other equipment. Osaka University has teamed with a construction company to research the decontamination apparatus.

4. Transportation Applications Using High-Temperature Superconductivity

HTS can add value added to several transportation applications and improve efficiency over conventional systems. This white paper highlights all-electric aircraft, high-speed rail, and electric ships.

4.1 All-Electric Aircraft

All-electric aircraft are being developed worldwide to reduce pollution and improve the efficiency of planes.[19] Such aircraft are being considered for both civil and military applications. Smaller, battery-powered planes capable of carrying up to 20 passengers are being developed for short-haul (500- to

1,000-mile range) applications. Larger planes will need to employ generators for generating bulk power, which will be used to power smaller propulsion motors. Figure 7 shows an example of a turbo electric propulsion system.

A hybrid wing–body aircraft combined with a turboelectric distributed propulsion system, such as is shown in Figure 6, could reduce mission fuel burn by 70% to 72% from the baseline without compromising payload, range, or cruise speed. Aircraft applications require generator ratings of over 22 MW at 6500 RPM, weights of around 1000 kg, and efficiencies of >99.3%.[20] Likewise, aircraft propulsion motors are rated at 3 MW with 4500 RPM, weights of 236 kg, and efficiencies of 99%. These motors and generators are required to be compact, lightweight, and efficient. Conventional copper-based devices will not meet the required power-to-mass ratio of >30 kW/kg. This presents an opportunity for HTS devices, particularly in the plane's power train, as they enable higher efficiencies and higher power-to-mass ratios.

FIGURE 7. A TURBOELECTRIC PROPULSION SYSTEM REDUCES FUEL USAGE WITHOUT COMPROMISING PERFORMANCE. THE REQUIRED ELECTRICAL MACHINES ARE SHOWN IN THE SCHEMATIC ABOVE. IMAGE COURTESY OF THE UNITED STATES NATIONAL AERONAUTICS AND SPACE ADMINISTRATION.

An aircraft's transportation cost is proportional to the airframe's lift-to-drag value (L/D) and the power train efficiency. Today's fuselages are optimized in L/D to a very high degree, but actual trends in further optimization are mainly in "boundary layer ingestion" acceleration.[21] A higher L/D might be reached by switching to very different fuselages of aircrafts. The efficiency of the propulsion turbines scales with their size, so having few but large turbines is a cost-saving strategy.

Unfortunately, aircrafts suffer from oversizing needs similar to those of large ships. The reduction of a turbine's net power with increasing altitude is equal to decreasing density of air and the power need at the very last period of climbing, which defines the turbine's design power. This design power is much larger than the power needed to maintain cruising speeds, so for most of the flight's duration, its turbines are operating at only a small fraction of their capacity, which is quite inefficient.

Engineers could potentially solve this dilemma by electrifying aircrafts with decentralized power generation and consumption/propulsion systems, perhaps by deploying large turbines in the fuselage with many electric motors along the wings. A variety of motor and generator concepts are being developed with HTS technologies, and attractive options are likely to emerge in the next few years. In addition, environmental policy regulations are strengthening; for example, the European Union's Advisory Council for Aeronautics Research in Europe (ACARE) has established that, in 2030, CO_2 should be reduced by 75%, noise by 65%, and nitrous oxide by 90%. Such rulings will drive the aviation industry to invent entirely new flight systems technologies and designs.

4.2 Maglev Trains

One of the earliest applications of superconductors was in very high-speed maglev (magnetic levitation) trains. Two possible maglev concepts are electromagnetic suspension (EMS) and electrodynamic suspension (EDS). Both Nagoya, Japan, and Shanghai, China, currently have an EMS system employing copper coils in commercial service. An HTS superconductor version of this design was proposed by Grumman, but it was never implemented.[22] An EDS system employing low-temperature superconductivity (LTS) has been developed successfully in Japan, and a commercial line between Tokyo and Nagoya (about 290 km) is now under construction and aims to enter commercial service in 2027. The commercial line will be extended to Osaka by 2045 or earlier, and the total length of the line will become about 440 km. The cost of the guideway will be much higher than conventional high-speed railways, and therefore, a superconducting maglev can be introduced in regions that have very large traffic demands. Maglev trains will essentially eliminate the emissions of CO_2, NOx, and noise, which are serious environmental pollutants. Other high-speed maglev trains projects have been proposed in the United States, China, and elsewhere.

In 2005, the Japanese superconducting maglev project fabricated and tested a Bi2223 superconducting magnet at the Yamanashi Test Line, with good results. There were no serious problems in the HTS magnet as the vehicle accelerated to 550 km/h during testing. HTS magnet development using Bi2223 and REBCO wires continues, but the reliability, safety, and economics of HTS magnets are key areas to consider in the development of practical applications.

4.3 Electric Ships

Large ships for cruises and cargo are another potential transportation application for electrification and HTS. These ships have a high power demand of several megawatts. They are also powered by heavy fuel oil, which is the most polluting diesel fuel in the world. Using larger generators for the bulk of the power has potential to decrease pollution and achieve more reliable systems.

Maximum power for cruise ships is determined not by power used for cruising but by the power needed for accelerating/decelerating the vessel to and from cruising speed in a reasonable time. As a consequence, the machines are rarely operated in the optimum nominal power range. Cargo ships have only small changes in velocity, and power is optimized for long-distance constant cruising; therefore, they tend to be more efficient than cruise ships.

HTS rotating machines are superior to the conventional ones in terms of efficiency, weight and volume, and operational stability. The smaller shaft height of the motors will reduce the volume consumed by the distance to the propeller. The HTS power train might result in a lower voltage level, reducing weight and volume of all components. The transformers are more efficient, compact, and lightweight. In general, the efficiency in part load operation will increase to levels higher than for conventional equipment. Having several HTS-based devices on a ship will leverage synergies from the cooling system, which will be much more compact than a conventional system, which has ancillary equipment routed throughout the ship.

One approach to improving the efficiency of the ships is to use decentralized power generation and consumption. By using suitable energy storage systems, decentralization can avoid mechanical coupling of generation and propulsion, allowing the power generation equipment to operate in the preferred regime of highest efficiency, while the propulsion is driven by demand. Switching from heavy fuel oil to liquefied natural gas will reduce the CO_2 footprint and other pollutants (e.g., NOx and SOx) considerably.

The cruise ship "AidaNova," which set out on its maiden voyage in December 2018, is demonstrating this electrification. By electrifying the power train, the efficiency from fuel to propulsion can be raised to >50% from 30% on a >50 MW level. HTS devices could replace several components in the power train: turbo generators, fault current limiters, transformers, cables, and motors.

A DC distribution bus, combined with power electronic converters, is proving to be the key enabling technology for electrification of large ships.[23] It enables the deployment of a variety of motors, generators, and other equipment that do not have to adhere to a fixed AC bus frequency. Figure 8 shows a 36.5 MW ship propulsion motor that was successfully tested with a power electronic converter.[24] The DC bus system also enables the integration of fuel cells, solar cells, batteries, and flywheel-type energy storage devices. Naval ships are also employing HTS DC loops for reducing the magnetic signature of ships and for powering electromagnetic guns and aircraft launching systems. The total electrification of ships will ease the implementation of individual sub-systems.

FIGURE 8. THIS 36.5 MW SHIP PROPULSION MOTOR EMPLOYS HTS FIELD WINDING. PHOTO COURTESY OF AMSC.

The adoption of HTS technology for ships is contingent upon resolving affordability and reliability issues. However, the key challenges for integration of HTS devices in large ships are not technical but are related to education and perception. The technology needs to be proven reliable even in harsh conditions at sea; the electrical engineers have to be informed and trained. Policy regulations such as the International Maritime Organization's (IMO's) 2020 sulfur cap will help drive the ship builders and operators toward a more sustainable future of mobility.

5. Conclusion

HTS technology has sufficiently matured for use in many areas, including electricity grids, industry, and transportation. However, major impediments to the technology's employment include the high cost of HTS conductors and the need for low-cost and reliable cooling systems. In addition, fully assembled systems must demonstrate reliable operation in post-laboratory development applications over long periods. To gain acceptance in the marketplace, it is essential to build and operate prototypes in environments like those of the final applications. Moreover, prototype systems must undergo much longer demonstrations than those to date. One study in the 1990s (unpublished) by the U.S. Department of Energy and the Electric Power Research Institute showed that electric utility planners and engineers wanted to see HTS cable system technology demonstrations lasting 10 years before considering the technology as a replacement for conventional cables.

More recent trends and drivers in the industry could help increase market pull for superconductivity. Resilient electric grids and energy efficiency are areas in which superconductivity can play a role and add value over conventional solutions.

6. Acknowledgements

The IEA HTS TCP would like to thank the following outside experts for their contributions to this paper: Steve Eckroad, Tabea Arndt, Tim Haugan, Mathias Noe, Swarn Kalsi, Piere Legendre, Michael Ross, Mike Tomsic, and Osami Tsukamoto.

7. Endnotes

[1] IEA, R&D investment in the public sector, 2017 preliminary estimate, https://www.iea.org/tcep/innovation/tracking-rdd (accessed March 31, 2019).

[2] Ibid.

[3] M. Stemmle, et al., "Ampacity Project – Update on World's First Superconducting Cable and Fault Current Limiter Installation in a German City Center," CIRED, 23rd International Conference on Electricity Distribution Lyon, June 15–18, 2015.

[4] IEA HTS TCP, High Temperature Superconductivity – A Roadmap for the Electric Power Sector, 2015–2030, 2015.

[5] J. McCall, M. Ross, B. Gamble, and S. Eckroad, "DC Supergrid Implementation Using Compact Very High Capacity Superconductors for Bulk Power Transport," in The Electric Power System of the Future: Integrating Supergrids and Microgrids, CIGRE Symposium, Bologna, Italy, September 13–15, 2011.

[6] S. J. Lee, M. Park, I. Yu, Y. Won, Y. Kwak, and C. Lee, "Recent Status and Progress on HTS Cables for AC and DC Power Transmission in Korea," in *IEEE Transactions on Applied Superconductivity* 28, No. 4 (June 2018): 1–5, Art no. 5401205, doi: 10.1109/TASC.2018.2820721,

http://ieeexplore.ieee.org/stamp/stamp.jsp?p=&arnumber=8327882&isnumber=8241050.

[7] EPRI, *Superconducting Power Equipment: Technology Watch 2012*, Palo Alto, CA (2012): 2-8-2-9, https://www.epri.com/#/pages/product/000000000001024190/?lang=en-US.

[8] *Superconductor Week* 32, No. 10 (November 23, 2018): 4.

[9] Ibid.

[10] D. Lindsay, et al., U.S. Patent 8,391,938 B2, March 5, 2013.

[11] T. Nakamura et al., "Development and fundamental study on a superconducting induction/synchronous motor incorporated with MgB_2 cage windings," *Superconductor Science and Technology* 25, No. 1 (December 2011): 014004.

[12] S. Kalsi, "Applications of High Temperature Superconductors to Electric Power Equipment," Wiley/IEEE Press, 2011 ISBN: 978-0-470-16768-7.

[13] A. Morandi, "HTS dc transmission and distribution: concepts, applications and benefits," Supercond. Sci. Technol., vol. 28, no. 12, 2015, p. 123001.

[14] Florian Schreiner, Bernd Gutheil, Mathias Noe, Wolfgang Reiser, Stefan Huwer, Claus Hanebeck, Carsten Räch, Marcus Röhrenbeck, and Fabian Schreiner, Design and Manufacturing of a Multistage Cooled Current Lead for Superconducting High Current DC Busbars in Industrial Applications, IEEE Transactions on Applied Superconductivity (Volume: 27, Issue: 4 , June 2017)

[15] Ibid.

[16] J. Choi, "Recent Progress of Superconducting Induction Heater with HTS Magnets in Korea," IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2017. Invited presentation Tu-Mo-Or11-01 given at MT25, August 27–September 1, 2017, Amsterdam, The Netherlands.

[17] M. Noe, ZIEHL 2008, "Energieeffizienz mit Supraleitung."

[18] P. A. Beharrell, "Applications of Superconducting Magnetic Separation," Quantum Design Inc., San Diego, CA.

[19] K. S. Haran, S. Kalsi, T. Arndt, et al. "High power density superconducting rotating machines—development status and technology roadmap," *Superconductor Science and Technology* 30, No. 12 (2017): 123002.

[20] Ibid.

[21] NASA, "Reduce Fuel Burn With a Dose of BLI," *Explore NASA's Moon to Mars Plans*, March 10, 2017, https://www.nasa.gov/aero/reduce-fuel-burn-with-a-dose-of-bli.

[22] S. Kalsi, "Applications of High Temperature Superconductors to Electric Power Equipment," Wiley/IEEE Press, 2011 ISBN: 978-0-470-16768-7.

[23] G. Sulligoi, A. Vicenzutti and R. Menis, "All-Electric Ship Design: From Electrical Propulsion to Integrated Electrical and Electronic Power Systems," *IEEE Transactions on Transportation Electrification* 2 , No. 4 (December 2016): 507–521.

[24] S. Kalsi, "Applications of High Temperature Superconductors to Electric Power Equipment," Wiley/IEEE Press, 2011 ISBN: 978-0-470-16768-7.