Superconductivity
INTERNATIONAL ENERGY AGENCY

HIGH TEMPERATURE SUPERCONDUCTIVITY

Readiness Map for Industrial Applications

November 2023

Acknowledgements

This document was developed by the International Energy Agency's (IEA's) High Temperature Superconductivity Technology Collaborative Program (HTS TCP). The IEA HTS TCP works to identify and assess the potential applications and benefits of superconductivity, as well as what technical, economic, and regulatory barriers must be overcome to achieve those benefits. Through its contracting parties, the IEA HTS TCP develops technical communication documents that provide information for a range of stakeholders. More information is available at www.ieahts.org.

This document was produced using the guidance of IEA HTS TCP Executive Committee members and relevant international experts. The three tables below list all contributors to this readiness map.

Further updates will be made, including a synthesis of the possible technical achievements that could take place in the near future.

Members of the IEA HTS TCP

Country	Name	Organization
Canada	Prof. Frédéric Sirois	*Polytechnique Montréal*
Germany	Prof. Tabea Arndt Prof. Mathias Noe Prof. Bernhard Holzapfel	*Karlsruhe Institute of Technology* *Karlsruhe Institute of Technology* *Karlsruhe Institute of Technology*
Italy	Laura Serri (Chair) Giuliano Angeli	*Ricerca sul Sistema Energetico – RSE S.p.A.* *Ricerca sul Sistema Energetico – RSE S.p.A.*
Japan	Ms. Yurugi Yoshiko Dr. Hiroyuki Ohsaki (Vice-Chair) Mr. Susumu Kinoshita	*New Energy and Industrial Technology Development Organization (NEDO)* *The University of Tokyo* *NEDO*
Republic of Korea	Dr. Hyung Suk Yang Dr. Jeyull Lee	*Korea Electric Power Corporation (KEPCO)* *KEPCO*
Switzerland	Prof. Carmine Senatore Mr. Roland Brüniger Mr. Michael Moser	*University of Geneva* *Swiss Federal Office of Energy* *Swiss Federal Office of Energy*
United States	Merrill Smith	*U.S. Department of Energy*

Sponsors of the IEA HTS TCP

Country	Name	Organization
France	Jean Maxime Saugrain	Nexans
Italy	Christian-Eric Bruzek	ASG Superconductors

Additional Experts Consulted

Name	Organization	Topic Area
Uwe Pracht	Festo	Superconducting non-contact magnetic bearings
Keiichi Tanabe	Superconducting Sensor Technology Corporation	SQUIDS
Prof. Satoshi Fukui	Niigata University, Japan	Induction heating
Bai Song	Shanghai Superconductor	Induction heating
Oliver de Haas	EVICO	Cryostatic activities for HTS levitation
Andrej Kudymow	Vision Electric Super Conductors GmbH	Superconducting busbar
Joachim Bock	THEVA Dünnschichttechnik GmbH	Induction heating
Jongho Choi	Changwon National University	Induction heating

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Introduction

The International Energy Agency's (IEA's) High Temperature Superconductivity Technology Collaboration Program (HTS TCP) initiated a project to analyze the technology readiness levels (TRLs) of industrial applications that use high temperature superconductivity (HTS). This readiness map illustrates the TRLs of HTS industrial applications as they are today and as they are projected to be within the next ten years. Assessing the TRLs of superconducting applications for the industrial sector demonstrates to stakeholders that there may be viable alternatives to conventional technologies. Furthermore, if these technologies achieve high TRLs, they could affect the acceleration of superconducting equipment development for power grids and other applications.

To develop this readiness map, international experts assessed the present degree of technology readiness of superconducting non-contact magnetic bearings, superconducting busbars, superconducting induction heating processes, nuclear magnetic resonance (NMR), and superconducting quantum interference devices (SQUIDs). The applications with high TRLs are induction heating, NMRs, and SQUIDs. The applications with medium TRLs are contactless bearings and busbars.

The following are not within the scope of this industrial sector document: industrial applications, such as accelerator physics (e.g., the Large Hadron Collider) and superconducting direct current (DC) data centers; transportation (e.g., electric aircraft), including motors and generators; and space applications. The IEA HTS TCP developed a companion document that evaluated the TRLs of HTS for transmission, substation, and distribution applications.[1]

Importance of the Industrial Sector

The industrial sector plays a crucial role in the world economy.

- Production: The industrial sector is responsible for producing essential products and services, ranging from consumer goods (e.g., clothing, electronics, and automobiles) to capital goods (e.g., machinery and equipment).
- Employment: The industrial sector provides employment opportunities for millions of people around the world. The sector employs workers in a variety of roles, including production, research and development, engineering, and management.
- Innovation: The industrial sector is a key driver of innovation, as it invests heavily in research and development to create new products and processes that can increase efficiency, reduce costs, and improve quality.
- Trade: Industrial goods are a major component of international trade, accounting for a significant portion of global exports and imports. Countries with strong industrial sectors are often able to compete effectively in global markets, creating jobs and generating economic growth.
- Technology: The industrial sector is a major user of technology, which helps to increase productivity and efficiency. Many technological advances have been developed in the industrial sector, including automation, robotics, and artificial intelligence.

[1] High Temperature Superconductivity Application Readiness Map: Energy Delivery – Transmission, Substation and Distribution Applications, July 2021, https://ieahts.org/downloads/HTS-Readiness-Map-for-Energy-Delivery.pdf

Superconductivity Overview

Superconductivity is a phenomenon that causes certain materials, at low temperatures, to lose essentially all resistance to the flow of electricity. The lack of resistance enables a range of innovative technology applications. The temperature at which resistance ceases is referred to as the “transition temperature”, or critical temperature (Tc). Tc is usually measured in kelvin (K). HTS has a higher transition temperature (around 77 K, which can be achieved when using liquid nitrogen) than low temperature superconductivity (LTS) (around 4.2 K, which can be achieved using liquid helium).

Devices based on LTS have been available in certain specific markets for decades. Superconducting magnets, in particular, are well-established in many applications that require very high magnetic fields, such as high-energy physics particle accelerators and magnetic resonance and imaging (MRI) systems.

Starting from the discovery of HTS materials in late 1980s, more than 30 years of research and development have brought new equipment incorporating HTS to the threshold of greatly improving the electric infrastructure, industrial applications, transportation, high-energy physics, and other applications. Laboratory-scale tests have transitioned to large-scale HTS-based projects. HTS materials have been employed or proposed for use in a variety of applications and sectors, including the energy, transportation, industrial, medical, and defense sectors. HTS wire is the key enabler of making devices for the electric power system that are more efficient and compact, and offer greater resilience, than conventional solutions.

Examples of sectors in which HTS is, or can be, used include energy delivery, energy supply, transportation, medicine, and industrial processes. Examples of well-recognized types of superconducting materials include:

- BSCCO (bismuth – strontium – calcium – copper – oxide), known as HTS first generation (1G)
- REBCO (rare earth – barium – copper oxide), known as HTS second generation (2G). REBCO may also be referred to as YBCO or GdBCO, as yttrium and gadolinium are the most commonly used rare earths in the manufacturing process
- MgB_2 (magnesium diboride), with critical temperature around 39 K
- Nb_3Sn (niobium–tin) and Nb-Ti (niobium–titanium) used in LTS applications

One of the most critical components of a superconductive device is the cryogenic (refrigeration) system for achieving operating temperatures. Because liquid nitrogen (LN_2) is relatively ubiquitous and less expensive than liquid helium, HTS technologies offer greater potential for cost-effective solutions.

Technology Readiness Levels

TRLs are used to rank the maturity of a technology and its readiness for implementation. There are nine levels of TRLs, with each level representing a different stage of technology development and maturity. Definitions of the TRL levels are found in Figure 1.

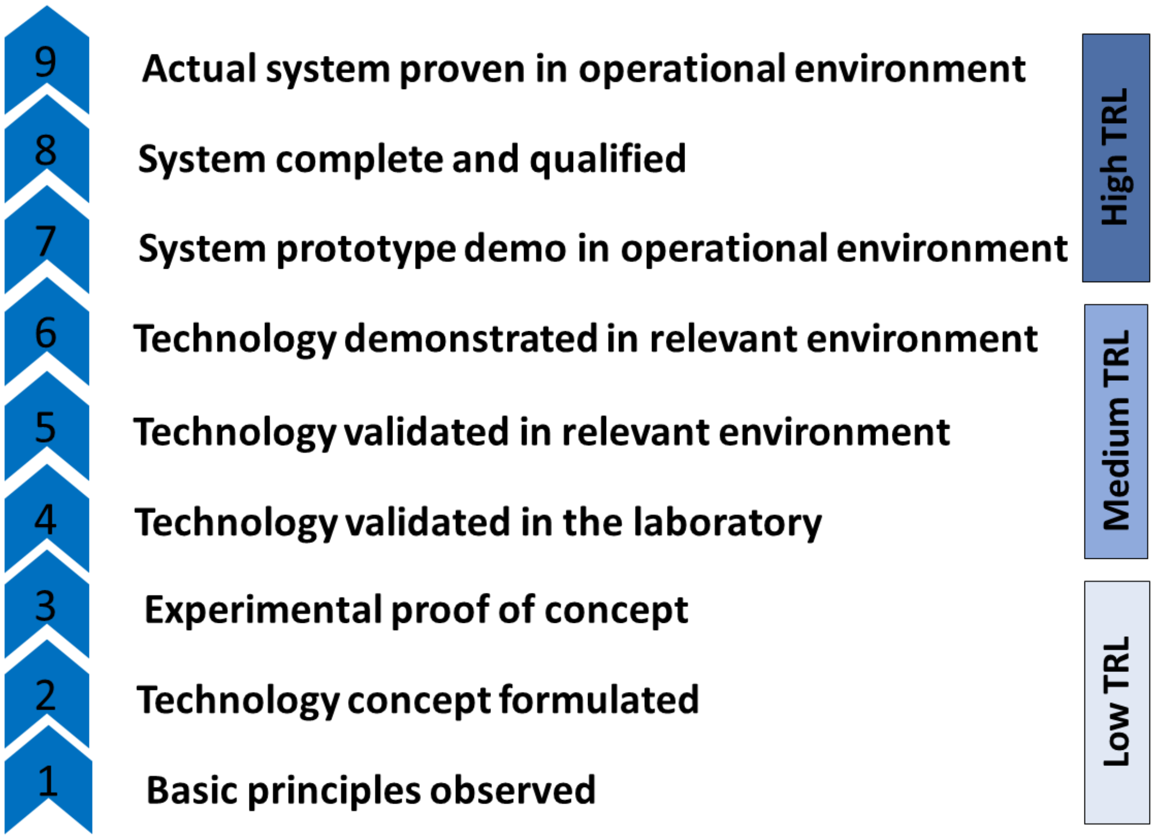

Figure 1. Technology readiness levels. Source: Based on TRLs from the United States Department of Defense

The TRL system was originally developed by the National Aeronautics and Space Administration (NASA, United States government) in the 1970s to assess the readiness of technologies for use in space missions, but it has since been adopted by many other organizations and industries as a standard way of understanding technology readiness. The European Commission has also adopted the TRL system.[2]

The TRL system provides a standardized way of assessing the maturity and readiness of a technology, which can be useful for funding decisions, project planning, and technology transfer. By providing a common language for describing technology readiness, the system can also facilitate communication and collaboration between different organizations and industries.

Technology Readiness Levels of Superconducting Industrial Applications

A readiness map is a way to illustrate the TRLs, over time, of HTS applications in various sectors. This document focuses on HTS industrial applications.

For each application, current and future TRLs were determined by using the input of industry experts. Factors influencing technology readiness include:

[2] https://euraxess.ec.europa.eu/career-development/researchers/manual-scientific-entrepreneurship/major-steps/trl

- Underlying scientific/engineering maturity (e.g., HTS wire design)
- Potential for ongoing research and development of component technologies (existing or planned research activities, institutional support, etc.)
- Maturity of component subsystems common to other applications (e.g., cryogenic systems)
- Specific application readiness (e.g., user need for nonconventional solutions)
- Education of developers as to customer needs

Figure 2 shows the results of this evaluation, in the form of TRLs for the five industrial applications listed in the introduction to this document. Instead of using a specific TRL number 1–9, this document categorizes the applications into low, medium, and high TRLs, as specific TRLs are less meaningful when looking at future years.

The rationale for the TRL for each application is described in the following sections.

LOW TRL | MED. TRL | HIGH TRL

Industrial Systems	Today	2025	2030	2035
Non-contact magnetic bearings	MED. TRL	- - - - - → HIGH TRL		
Busbar	MED. TRL	- - - - - → HIGH TRL		
Induction heating	HIGH TRL			
Nuclear Magnetic Resonance	HIGH TRL			
Superconducting Quantum Interference Device	HIGH TRL			

Figure 2. TRLs for HTS industrial applications

Superconducting Non-Contact Magnetic Bearings

The basic principle behind superconducting non-contact magnetic bearings is the use of superconducting materials that can generate strong magnetic fields when cooled to cryogenic temperatures. These magnetic fields interact with a set of permanent magnets, creating a repulsive force that lifts and supports the shaft without any physical contact.

The advantages of superconducting non-contact magnetic bearings include:

- Ultra clean: Dust-free operation makes them ideal for the protected conveyance of levitating objects in very clean environments.
- Low maintenance: Without physical contact, there is no need for lubrication or replacement of bearings, reducing maintenance requirements and costs.

- High precision: The non-contact design provides accurate and stable positioning of the shaft, which is important in applications where precise control is required.
- Low vibration and noise: These bearings are typically quieter and less prone to vibration than traditional bearing systems.

Two specific superconducting applications—contactless weight measurement and contactless motion of goods—are discussed below.

Contactless Weight Measurement

The pharmaceutical industry provides an example of a specific use of these bearings. A common procedure is weighing toxic and costly reactants in clean-room environments (e.g., isolators). Laboratory balances inside the isolators are prone to contamination and pose safety problems. Superconducting levitation allows for decoupling: the balance can be placed outside of the isolator, and the weighing plate remains inside.

TRL Analysis

Festo, an automation company, has demonstrated contactless weight measurement in a laboratory environment and is looking for partners to demonstrate and prove the technology in an operational environment.[3] As of this analysis, there are no other examples of this application. The TRL for contactless measuring of weight is medium.[4] Once proven in an operational environment at a commercial facility, the TRL would be considered high. Figure 3 is an actual assembly in the Festo facility.

Figure 3. Actual assembly of contactless measuring of weight. Photo courtesy of Festo.

[3] Presentation by Dr. Uwe Pracht, Festo, delivered to the IEA HTS Executive Committee on December 1, 2022.
[4] Personal communication with Dr. Oliver de Haas, evico GmbH, on June 27, 2023.

Contactless Motion of Goods

Biotechnology processing requires fully automated contact-free transport and handling of vials inside a clean or sterile environment. The field has the highest demands for cleanliness, so transport procedures should involve no abrasion or lubricant. Motion is realized by mounting the cryostats on a linear axis or at the end of a robotic arm.

There are challenges associated with the use of superconducting non-contact magnetic bearings, such as the need for cryogenic cooling systems to maintain the low temperatures required for superconductivity. Additional technical challenges will likely be revealed when the technology is demonstrated in an operational environment. Nonetheless, the technology has significant advantages over traditional bearing systems, and the number of industrial and scientific application projects using this technology is likely to increase.

TRL Analysis

Festo has developed a device that combines superconducting technology with permanent magnets and has demonstrated the device in a laboratory environment. A permanent magnet keeps a carrier hovering above a magnetic rail, with a large gap between the two. Another magnet, coupled with a superconductor, is attached at an angle of 90°, fixing the position of the work piece carrier above the magnetic coil. Covers are used to separate the working space from the surroundings and keep it clean. Using electrical axes, both the cryostat (with the superconductor) and the carrier coupled to it can be moved along the magnetic rail, as shown in Figure 4 below.

Figure 4. Actual assembly of contactless movement of goods. Photo courtesy of Festo.

Festo is currently looking for partners to demonstrate and prove this technology in an operational environment.[5] As of this analysis, there were no other examples of this application. There are older experimental examples of magnetic levitation using a superconducting coil.[6] The TRL for contactless measuring of weight is medium to high.[7] Once proven in an operational environment at a commercial facility, the TRL would be considered high.

Superconducting Busbar

A superconducting busbar is a type of electrical conductor that transmits electrical power with very low resistance and high efficiency. Many industrial processes such as the production of aluminum or steel rely on tens or hundreds of kiloamps of high direct electrical current. Currently, massive and rigid busbar systems supply the process plants with electricity. However, these systems produce waste heat, experience energy losses due to electrical resistance, and require a good deal of space. High-temperature superconductors can offer a solution because they transmit high direct currents with no loss.

The advantages of superconducting busbars include:

- High efficiency: They have zero electrical resistance, so electrical power can be transmitted through the busbar with minimal loss or waste.
- High power density: They can carry much higher amounts of electrical power than traditional copper or aluminum conductors of the same size.
- Compact design: They can be designed to be much smaller and more compact than traditional conductors, making them ideal for applications where space is limited.
- Low operating costs: Because they are highly efficient, superconducting busbars can reduce operating costs associated with electrical power transmission.

However, there are challenges associated with the use of superconducting busbars, such as the need for cryogenic cooling systems to maintain the low temperatures required for superconductivity. Despite these challenges, this technology has numerous advantages over traditional conductor materials, and the number of industrial and scientific application projects using this technology is likely to increase. Two project examples are highlighted below.

Demo200 HTS Busbar

In the Demo200 research project, components for a high-current system based on high-temperature superconductors are being developed for the aluminum industry. The project has potential to significantly reduce power losses in industrial systems and make their operation more efficient. The functional efficiency of a modular current lead with a 200 kA direct current busbar system is being tested. Auxiliary equipment and the LN_2 cooling circuit have to be integrated into system design and construction, as well as sensor and control equipment and safety management. The projects tasks

[5] Presentation by Dr. Uwe Pracht, Festo, delivered to the IEA HTS TCP on December 1, 2022.
[6] Eijiro Maruo and Mochimitsu Komori, Basic Study on Superconducting Magnetic Bearing using Superconducting Bulk and Coil, The Twelfth International Symposium on Magnetic Bearings (ISMB 12), Wuhan, China, August 22–25, 2010, https://www.magneticbearings.org/wp-content/publications/ismb12/ismb12_submission_48.pdf.
[7] Personal communication with Dr. Oliver de Haas, evico GmbH, on June 27, 2023.

involve extensive calculations of magnetic fields and current forces arrangement of superconducting tapes and optimized layout evaluation of electrical, thermal, and construction data of all components.[8,9]

The project goal is to replace the return conductor with an HTS busbar that should reduce electrical losses by approximately 94%. Installation is underway at TRIMET Aluminum SE in Voerde, the project host. The project partners include Vision Electric Super Conductors GmbH for current leads, power supply, system design, and integration and operation; Karlsruhe Institute of Technology for superconducting module design; and Messer SE for cryogenic systems. The associated partners are Theva Dünnschichttechnik GmbH for the superconducting tapes and TRIMET Aluminum SE. The project is funded by the Federal Ministry for Economic Affairs and Energy of Germany.[10]

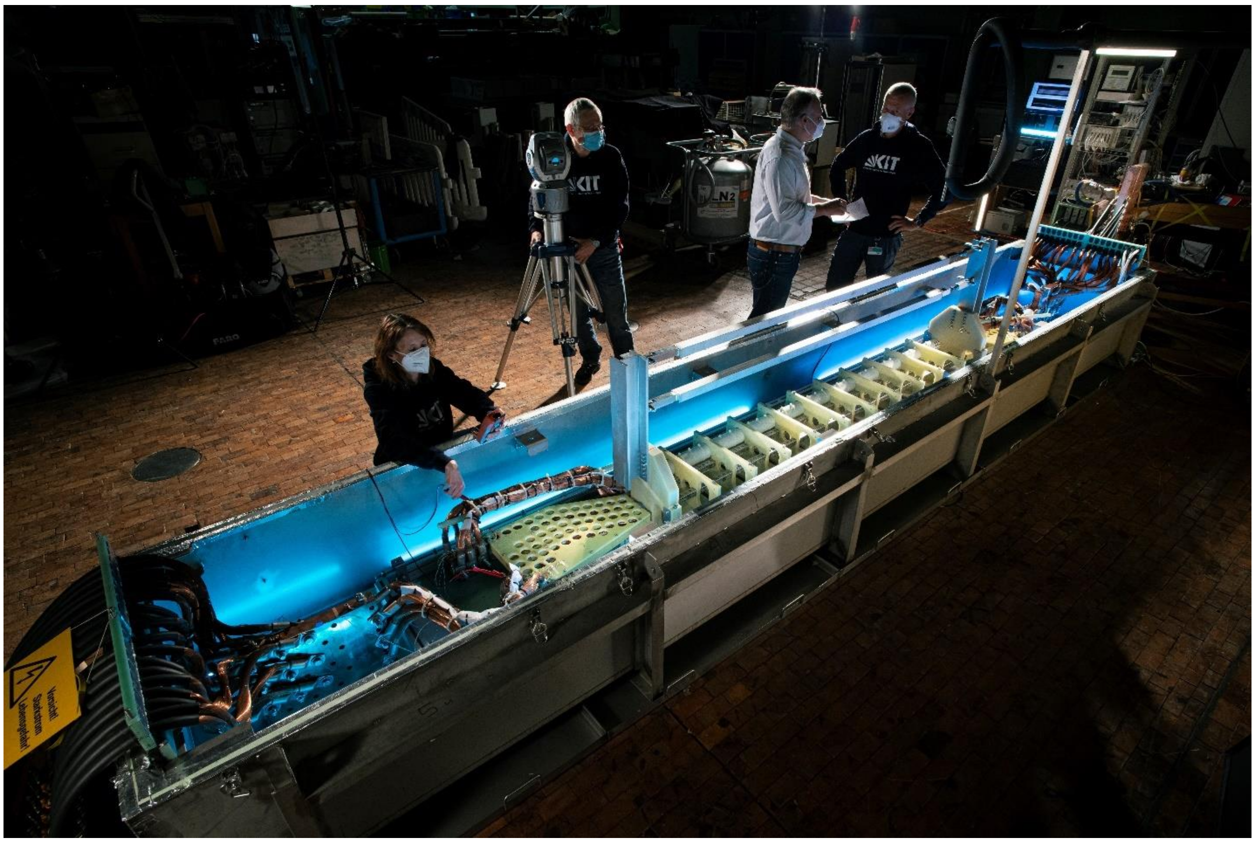

Figure 5. Testing of the Demo200 busbar. Photo courtesy of Karlsruher Institut für Technologie (KIT).

3S Busbar

3S was the first modular superconducting busbar and operated from 2016 to 2020 in a chlorine electrolysis plant at BASF Ludwigshafen, Germany. The purpose of the project was to demonstrate the

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[8] Mathias Noe and Wolfgang Reiser, Entwicklung einer supraleitenden 200.000 Ampere Industriestromschiene (Demo200), Braunschweiger Supraleiterseminar, June 23–24, 2021, https://demo200.de/wp-content/uploads/2021/06/DEMO200-Braunschweiger-SL-Seminar-2021-06-21.pdf.
[9] Demo200 website, https://demo200.de/.
[10] Wolfgang Reiser, Till Reek, and Viktor Stark, Building of a Superconductor Busbar at 200 kA for an Aluminum Plant, 2022, www.vesc-superbar.de/wp-content/uploads/2022/07/M163919_REVIEW1-2021-10-12.pdf.

technical feasibility of a superconducting system in a real production environment. The demonstration included the completion of stringent safety, environment, and health audit processes. 3S was funded by the German Federal Ministry for Economic Affairs and Energy. The system has a length of 25 meters, a nominal current of 20 kA, and an operating temperature of 70 K. The project demonstrated that superconducting busbars can be used in industry for production applications, with benefits including significantly reduced line losses, lower resource consumption, and reduced space requirements for installation room.

TRL Analysis

The TRL for the superconducting busbar is medium. A high TRL would require more operational experience in industrial applications, and the Demo200 demonstrator with a current lead has not yet been installed and tested in an aluminium plant. Additionally, the demonstration will not be connected inside the aluminium plant's power supply; the project is simply demonstrating the technology onsite to the potential customer. This is the only project underway using this application. The TRL could be considered high beyond 2025, if the Demo200 is successful and additional demonstrations are conducted in an operational environment.

Superconducting Induction Heating Processes

Superconducting induction heating is a process that generates high-frequency magnetic fields, which can induce electrical currents in a conductive material, causing it to heat up. This process is commonly used in various industrial applications, such as melting metals and annealing and heat treatment of materials.

High-frequency alternating current (AC) induction heating methods are commonly used for billet heating in aluminum hot extrusion processes. The aluminum industry would benefit from development of highly efficient and fast methods to heat aluminum billets, since conventional methods—high-frequency AC induction heating of aluminum billets using water-cooled copper coils—are generally low-efficiency. Induction heating by rotating the aluminum billet in a strong DC magnetic field has been demonstrated to show high efficiency. By applying HTS magnets for the DC induction heating, it is possible to significantly improve the process's heating capacity and energy efficiency.

Compared to conventional systems, HTS-based induction heaters have the following benefits:

- Reduced transformer size
- Reduced room temperature of the factory
- Smaller installation space
- Lower operational cost

However, there are challenges associated with the use of superconducting induction heating systems. One challenge is the need for cryogenic cooling systems to maintain the low temperatures required for superconductivity, which can add cost and complexity to the system. Another challenge is the design and construction of the superconducting coils, which must be carefully optimized to achieve the desired magnetic field strength and frequency.

Below are four examples of ongoing projects studying this technology.

Megawatt-Scale Induction Heater in China

The world's first megawatt-scale high-temperature superconducting induction heating device has been put into operation in the northeastern province of Heilongjiang, China, at the Northeast Light Alloy Co., LTD, Heilongjiang Aluminum Corporation of China. The project was developed by Jiangxi Lianchuang Optoelectronic Superconducting Application Co., LTD. The induction heater has one superconducting magnet supporting two heating units. Each unit operates at 500–600 kW. The magnet uses 10 km of HTS tape; however, the project started in 2013 and consumed approximately 100 km of HTS tape during the entire research and development phase.

Using conventional methods, heating an aluminum ingot weighing more than 500 kg from 20°C to 403°C takes at least nine hours, but with the new technology in place, the process takes only 10 minutes. According to the project team, the technology has doubled the energy efficiency conversion rate of induction heating devices and reduced carbon emissions by more than half.[11] With the use of HTS tape from Shanghai Superconductor, the device realized the characteristics of ultra-high fields of large-diameter magnets at approximately 0.4–0.5 T at 25 K.

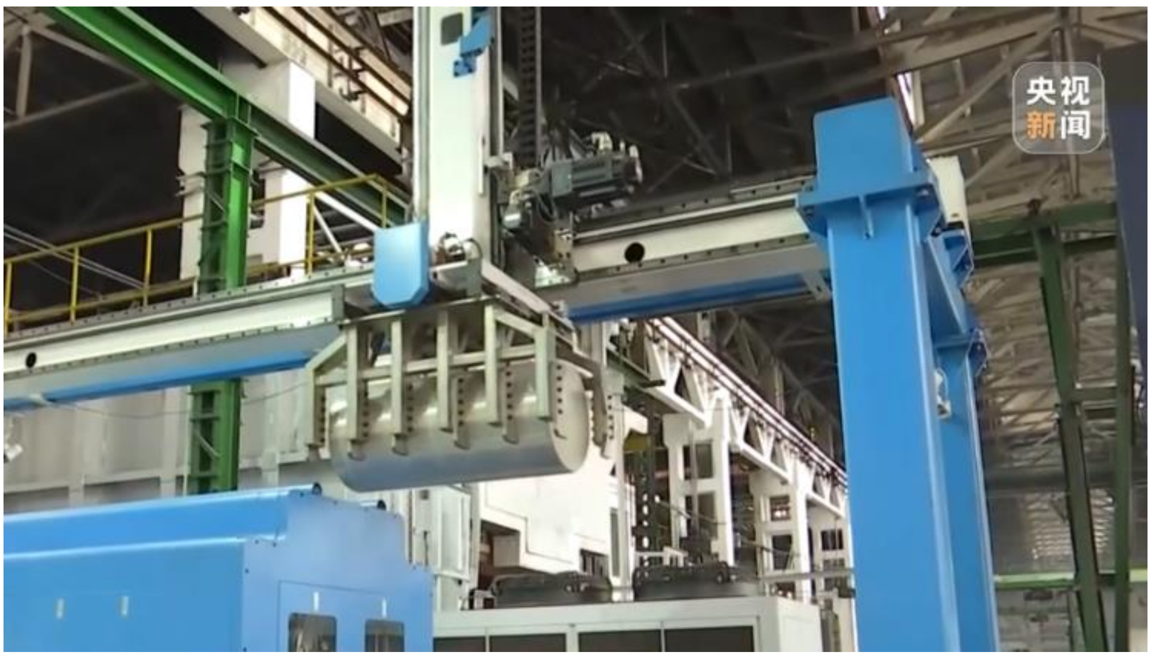

Figure 6. Megawatt-scale induction heating. Photo courtesy of Chinese Academy of Sciences.

Niigata University Aluminum Billet Heating

A 400 kW aluminum billet heater using an HTS magnet for the extrusion processes is being developed. The required performance of the aluminum billet heating device is to heat a 155 mm x 500 mm aluminum billet from 20°C to 500°C within 60 seconds, requiring a maximum heating capacity of 400 kW. Using finite element method (FEM) analysis, it was determined that 1 T is needed to obtain the heating capacity of 400 kW. The HTS coils require 2.3 km of REBCO tape, which is supplied by SuperOx. The rated current of the HTS coil is 200 A. In the magnet, the HTS coil is directly wound on the iron core, which was separated from the room-temperature yoke and installed in the cryostat. At this stage in the project, the aluminum billet heater was fabricated, and the heating tests at 400 kW were successfully

[11] Chinese Academy of Sciences, Press release. Accessed September 13, 2023

completed, demonstrating energy efficiency of 74.5%. The technology is expected to be operational in an aluminum factory by 2025. The project partners are Niigata University, TERAL Inc., National Institute of Advanced Industrial Science and Technology, Chubu Electric Power Co., Inc., and Hiroshima Prefectural Technology Research Institute.[12]

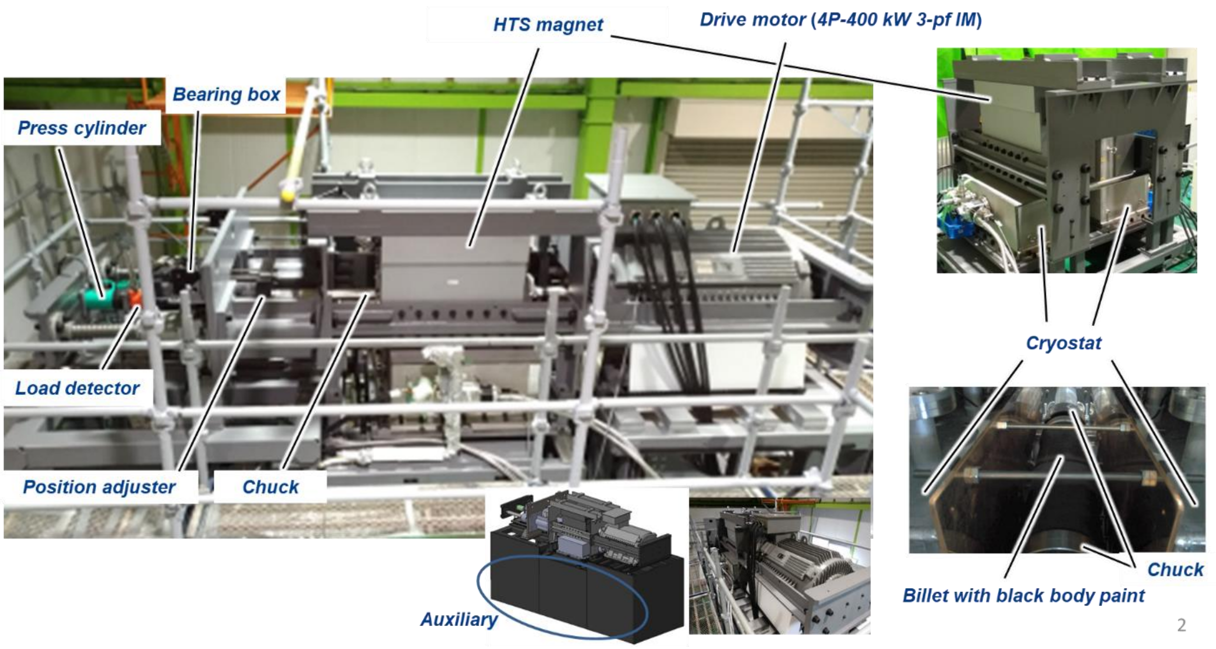

Figure 7. 400 kW class HTS induction heating assembly. Image courtesy of Teral Inc.

RoWaMag – German Robust and Low-Maintenance Magnetic Heating with HTS 2G Tape

In Germany, 800,000 tons of aluminum are processed every year. Heating the aluminum to 500°C requires 97 GWh annually. Using HTS induction heating can save 55 GWh annually, corresponding to 30,000 tons of CO_2.[13]

The first magnetic billet heater was installed at Weseralu GmbH & Co. KG in Minden, Germany, in July 2008. The technology—which was provided by the company Zenergy, in partnership with Bültmann GmbH—uses Bi2223 (a type of BSCCO) wire. The Weseralu project proved that using high-efficiency superconductor components to heat metal billets reduces electricity consumption by half while increasing productivity levels by 25%. A second system (also developed by Zenergy and Bültmann) is being operated by Wieland in Vöhringen, Germany, and that system has been operating reliably for more than 10 years. After the bankruptcy of Zenergy, no further systems were installed.

The two operational systems show that magnetic billet heaters can be operated very reliably in an industrial environment.

[12] Ito, T. et al, Fabrication and Test of HTS Magnet for Induction Heating Device in Aluminum Extrusion Processing IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 4, JUNE 2022
[13] Heinz Arnold, 30% less electricity in aluminum production, Elektroniknet.de, May 16, 2019

Figure 8. Bültmann magnetic billet induction heater installed at Weseralu in Minden, Germany. Photo courtesy of Bültmann.

THEVA, in collaboration with partners Bültmann GmbH, Beck Maschinenfabrik GmbH, and KIT, is developing a superconducting magnetic induction heater for two billets of nonferrous metals, primarily aluminum. The RoWaMag (Robuster Wartungsarmer Magnetheizer) induction heater is able to achieve 70% energy efficiency, which is a dramatic improvement over traditional induction heating systems.[14] The operating current is 505 A, and the technology uses 3,110 meters of HTS tape. The project started in May 2019 and, at the time of this publication, was scheduled to be completed in 2023.[15]

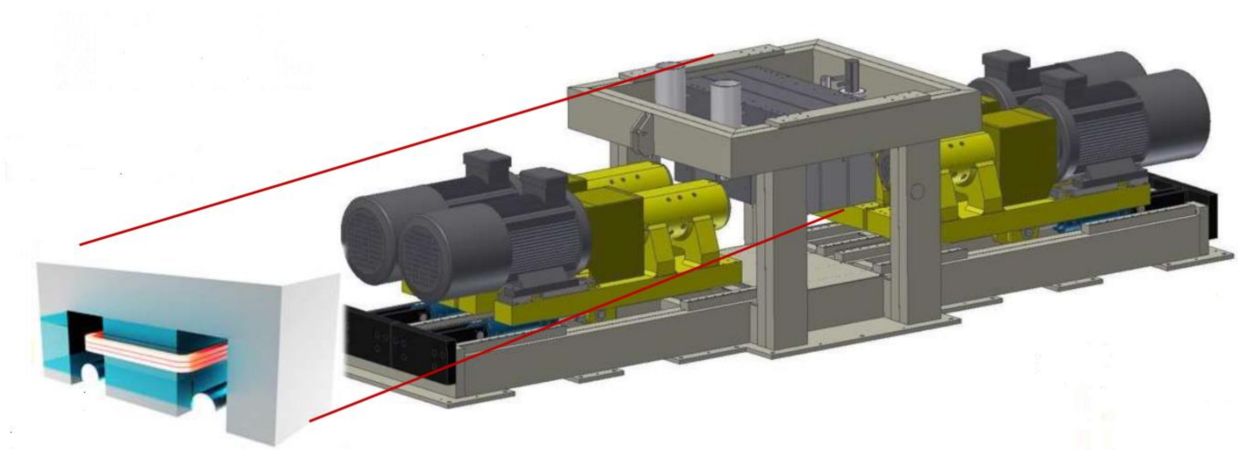

Figure 9. Schematic of HTS billet heating project. Image courtesy of THEVA.

Superconducting Induction Heater with HTS Magnets in Korea

[14] Superconductor Week, May 11, 2022.
[15] Presentation by Dr. Cornelia Hintze, Zeihl VIII conference, September 2022.

Supercoil Company Ltd. has developed a 300 kW induction heater with two high-temperature superconducting magnets. Supercoil also developed a 1.2 MW induction heater using MgB_2 magnets. The simulation results of the MgB_2 magnets were analyzed using FEM analysis models.[16]

TRL Analysis

Two long-standing induction heating projects have been operating successfully in Germany in commercial applications using first-generation HTS wire. Several promising new projects using second-generation wire have the potential to drive additional interest in new projects. Currently, this application's TRL is considered high, given the long-standing operation of the two projects in Germany.

Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) is a technique used to study the structure and properties of molecules by observing the behavior of their atomic nuclei in a strong magnetic field. NMR is a powerful tool using low temperature superconductivity for determining the structure of molecules, including proteins, nucleic acids, and other complex molecules.

The basic principle behind NMR is that atomic nuclei with an odd number of protons and/or neutrons have a magnetic moment, which causes them to behave like tiny magnets. When placed in a strong external magnetic field, the atomic nuclei will align with the field, either parallel or anti-parallel, depending on the number of protons and neutrons.

If a sample containing such atomic nuclei is subjected to a strong magnetic field, the nuclei will absorb and emit electromagnetic radiation at a specific frequency, which depends on the strength of the magnetic field and the chemical environment of the nucleus. This frequency can be detected and used to obtain information about the chemical structure and environment of the molecule.

NMR is commonly used in chemistry and biochemistry to determine the structure and dynamics of molecules in solution. It is also used in medicine for imaging and diagnosis, where it is known as magnetic resonance imaging (MRI). MRI uses strong magnetic fields and radio waves to generate detailed images of internal body structures, allowing doctors to diagnose and treat a wide range of medical conditions.

NMR is a versatile and powerful technique that has revolutionized the fields of chemistry, biochemistry, and medicine. It has many applications in both basic research and industrial settings, including drug discovery, materials science, and quality control.

At the core of the NMR spectrometer is a superconducting magnet. High field values and high homogeneity and stability of the magnetic field are essential to achieving the resolution and precision required for protein structure determination and other NMR analysis.

Below is a project example that falls within the scope of this analysis.

NMR Food Analysis

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[16] J. Choi and C.-K. Lee, "Development of a 1.2 MW Superconducting Induction Heater Using MgB2 NI Magnets," *IEEE Transactions on Applied Superconductivity*, Vol. 32, no. 6, pp. 1–5, Sept. 2022, Art no. 4603505, doi: 10.1109/TASC.2022.3167649.

NMR provides a characteristic peak for each compound in a mixture. It can provide simultaneous identification and absolute quantification of all components of a sample. Bruker has tailored this technology specifically for the analysis of food, including but not limited to honey, wine, olive oil, and juice profiling.

TRL Analysis

The NMR equipment available for food analysis is already in the marketplace and is therefore considered to be at a high TRL.

Superconducting Quantum Interference Device

Superconducting quantum interference devices (SQUIDs) are highly sensitive magnetometers that detect and measure extremely small magnetic fields.

SQUIDs are composed of two superconducting Josephson junctions connected by a small superconducting loop (typically several tens of micrometers). Applying a magnetic field to the loop causes a change in the magnetic flux, which in turn induces a change in the electrical properties of the device. By measuring the change in voltage, SQUIDs can detect magnetic fields as small as 10^{-15} T, making the SQUID one of the most sensitive magnetometers available.

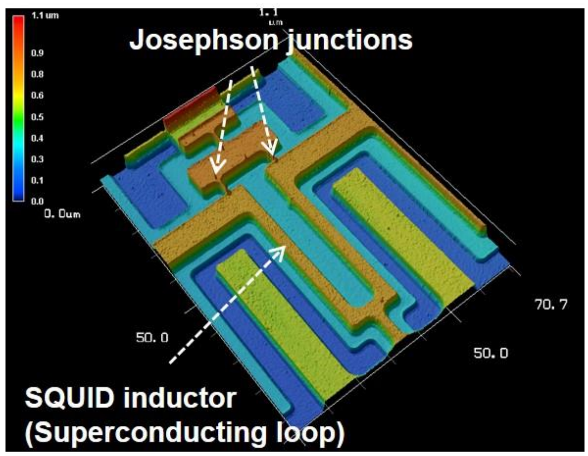

Figure 10. Magnified image of a main part of an HTS SQUID. Photo courtesy of Sustec.

SQUIDs have many practical applications, including in medical imaging, materials characterization, and geophysical exploration. They are used, for example, in the detection of brain activity through magnetoencephalography (MEG), as well as in the detection of tiny magnetic signals produced by the human heart (magnetocardiography, or MCG). SQUIDs also have applications in studying the magnetic properties of materials, such as superconductors and nanoparticles, and in detecting mineral deposits and oil reserves deep in the earth. This industrial application is the focus of this document.

The SQUID transient electromagnetic method (TEM) is one of the standard physical exploration methods for metal deposits and is typically used to narrow down the drilling point. The exploration depth for conventional TEM equipment using an induction coil as a magnetic sensor and a 100- to 200-meter square loop excitation coil is typically 500–600 meters. By employing SQUID sensors with ultra-high sensitivity that measure magnetic field B directly (instead of dB/dt for the induction coil case), very weak magnetic fields generated by underground current from deeper positions can be detected, and thus the exploration depth is extended to around 1000 meters.

The TEM equipment using HTS SQUIDs is very compact, and since LN_2 is cheap and available everywhere in the world, many systems have been used to explore metal deposits.[17] SQUID TEM systems have been demonstrated in the exploration of geothermal reservoirs located around 2000 meters in depth by employing a 2- to 5-km-long cable with both ends grounded as an excitation coil and measuring later-time B transient at many points several kilometers from the cable. However, such measurement configuration presents a problem: obtaining precise underground resistivity structure requires measurement of three (x, y, z) field transients and execution of 3D inversion analysis. Recently, 3D inversion analysis of three field transient data obtained by new SQUID TEM systems has been successfully demonstrated in an actual geothermal region. This combination is also expected to detect a slight resistivity change in carbon capture and storage where carbon dioxide is injected in an oil reservoir or a formation under the sea, for example.

Superconducting Sensor Technology Corporation (SUSTEC, formerly ISTEC) Project Examples

In or around 2003, the Japan Organization for Metals and Energy Security (JOGMEC) commissioned a SUSTEC SQUID TEM system to explore metal deposits. Mitsui Mineral Development Engineering Co. Ltd. (MINDECO) helped develop and test the systems. In 2012, a practical system had been completed. It had one HTS SQUID sensor and an exploration depth of about 1000 meters.

In 2014–2015, SUSTEC developed an advanced SQUID TEM system with three HTS SQUID sensors measuring x, y, z magnetic fields to explore metal deposits. Also in development in 2014 was a SQUID TEM system with one sensor to reach deeper targets, such as geothermal and oil reservoirs; this work ended in 2017.

JOGMEC also funded the first application of SUSTEC SQUID TEM systems to geothermal exploration in Indonesia, and 3D subsurface resistivity structure was successfully obtained by 3D inversion analysis. The work was also supported by the Ministry of Economy, Trade and Industry (METI) Asia Green Growth Promotion Program.

2018 saw the initial development of a SQUID TEM system for low-cost monitoring of carbon capture and storage (CCS) in shallow sea regions. This work, which is supported by Ministry of Environment, is ongoing.

Current SUSTEC partners are TechnoImaging LLC (United States), which is in charge of TEM data analysis and 3D imaging, and Sumitomo Corporation, which is in charge of marketing.

In 2020, a recently established company, SSTC, developed a new SQUID TEM system with three component sensors and an exploration depth over 3000 meters.[18]

[17] Four JOGMEC systems were produced, and more than 20 SQUID TEM systems from Supracon AG, a German company, have been used for exploration of metal deposits.
[18] Personal Communication with Keiichi Tanabe, Superconducting Sensor Technology Corporation

SUSTEC's most recent SQUID-TEM systems also have exploration depth of over 3000 meters. These systems were developed with internal funding, with support from the New Energy and Industrial Technology Development Organization (NEDO).

TRL Analysis

The applications of SQUID TEM systems to metal exploration have a high TRL. For geothermal exploration applications, demonstration is still required in already developed geothermal regions with production and return wells. Production and return wells with steel casings disturb magnetic field transient. High-voltage electricity lines near power plants also give rise to field noise (50, 60 Hz) substantially larger than TEM signals. Thus, proper analysis technology is required.

Application of SQUID-TEM systems to carbon capture and storage monitoring is at a medium TRL.

Acronyms

°C	Degrees Celsius
1G	First Generation
2G	Second Generation
A	Ampere(s)
AC	Alternating Current
BSCCO	Bismuth – Strontium – Calcium – Copper – Oxide
CCS	Carbon Capture and Storage
dB/dt	Ratio between change in amplitude of the magnetic field (dB) and time to make the change (dt)
DC	Direct Current
FEM	Finite Element Method
GdBCO	Gadolinium – Barium – Copper Oxide
HTS	High Temperature Superconductivity
IEA	International Energy Agency
JOGMEC	Japan Organization for Metals and Energy Security
K	Kelvin
KIT	Karlsruher Institut für Technologie
LTS	Low Temperature Superconductivity
LN_2	Liquid Nitrogen
MCG	Magnetocardiography
MEG	Magnetoencephalography
METI	Ministry of Economy, Trade and Industry (Japan)
MgB_2	Magnesium Diboride
MINDECO	Mitsui Mineral Development Engineering Co. Ltd.
MRI	Magnetic Resonance and Imaging
MT	Magnetotelluric
Nb_3Sn	Niobium–Tin
Nb-Ti	Niobium–Titanium
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NMR	Nuclear Magnetic Resonance
REBCO	Rare Earth – Barium – Copper Oxide
RoWaMag	Robuster Wartungsarmer Magnetheizer
SQUID	Superconducting Quantum Interference Device
SUSTEC	Superconducting Sensor Technology Corporation

T	Tesla(s) (a unit of measurement to define magnetic flux density)
Tc	Critical Temperature
TCP	Technology Collaborative Program
TEM	Transient Electromagnetic Method
TRL	Technology Readiness Level
YBCO	Yttrium Barium – Copper Oxide