Materials UK Preliminary Review
Superconducting Materials and Applications
A UK Challenge and an Opportunity

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IN THE FUTURE OF ENERGY, SUPERCONDUCTING MATERIALS MATTER AND WILL MAKE A MATERIAL DIFFERENCE.

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EXECUTIVE SUMMARY

Superconducting materials will have a significant role in advancing industrial and scientific applications with major benefits in various sectors including energy, environment, and healthcare. The UK has world-recognised strength in superconductivity research, innovative magnet design and manufacture, mainly in low temperature superconducting (LTS) applications. This is contrasted by limited presence in high temperature superconducting (HTS) conductor manufacture and limited investment in engineering and manufacturing of HTS applications.

Reliable power delivery will require effective electric storage solutions. Nowadays, renewable energy sources, such as wind and solar, are important sources of power but have variable and uncertain output. The variability of these sources has led to challenges regarding the reliability of an electric grid. Superconducting magnetic energy storage (SMES) can offer improved performance and efficiency compared with other utility devices. High capacity superconducting cables, for example, with their inherent high efficiencies, will enable a new generation of transmission and distribution electric grid that can meet the steady increase in demand on electric power and reduce the footprint of installations.

Superconducting magnetic energy storage (SMES) can offer improved performance and efficiency compared with other utility devices.

A clean, stable, and secure supply of electric power is essential for societies and is critical for national security, public health, and economic prosperity. Electricity is critical in keeping homes lit, businesses functioning and essential services like schools and hospitals operating. It is an integral part of daily life that people often take for granted. Innovation in superconducting power applications has the potential to become a leading 21st Century technology for enhancing the capacity of power equipment and improving efficiency and reliability.
There is a need for a strategic approach to UK R&D capacity and priorities for superconducting materials and applications. Superconducting application's in particular, those working at high operating temperatures around 77 Kelvin have a role in developing leading edge technologies and in addressing future needs of our society in relation to energy, economy and environment.

This Materials UK report reviews the role of superconductivity in enabling a range of innovative technology applications, which will form the basis for new commercial products that have the potential to transform our economies and daily life.

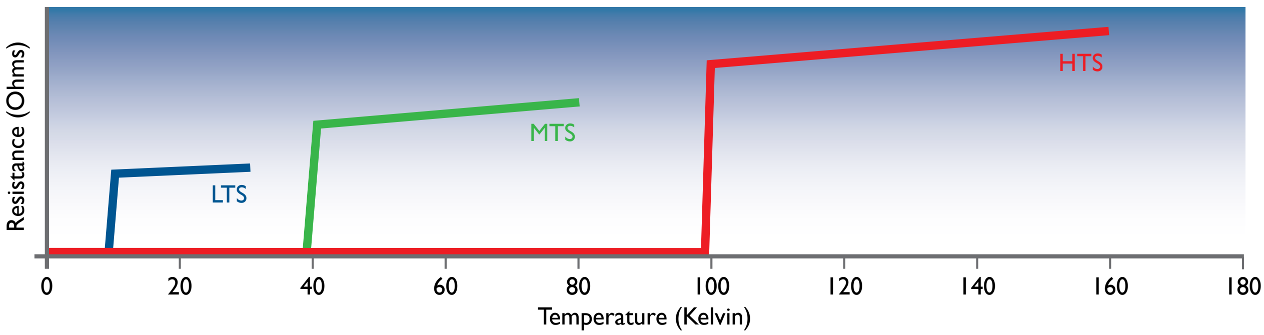
This report recommends a policy and investment support for the UK's role in leading the development of superconducting materials and applications through an integrated programme of R&D and prototyping to improve the delivery of innovative solutions for thre UK.

INTRODUCTION

Superconductivity is a phenomenon observed in certain metals and ceramic materials that, when cooled to very low temperatures, e.g. few degree Kelvin, they have no electrical resistance. It has the potential to bring a step change to electric power technologies that has not occurred since electricity was introduced a century ago.

This year, the world will celebrate 100 years of superconductivity [1]. However, it is only in the last 50 years that these novel materials have been used in industrial applications, dominated by superconducting magnets that could achieve much higher magnetic fields using copper wire. These copper coils were expensive to run and consumed high amounts of electric power and associated high heat losses. Almost all superconducting products today use low temperature superconductor (LTS) materials in applications of magnet systems. Examples range from compact magnets, used in research laboratories to large scale systems in particle physics and fusion experiments and including superconducting magnets for scientific, pharmaceutical and materials research. Magnetic resonance imaging (MRI) for medical diagnosis dominates the sector. Next, in terms of revenue, are applications in research and technological development (RTD) such as nuclear magnetic resonance spectroscopy (NMR). Together MRI and NMR account for over 90% of a market estimated at 4B€ worldwide [2]. The majority of these applications are using LTS conductors operating at liquid helium temperatures.

Figure 1: Electrical resistance of Low, medium and High Temperature Superconductors function of temperature in degree Kelvin, showing the sudden drop of electric resistance at certain operating temperatures



High temperature superconducting (HTS) materials have the potential to facilitate a more fundamental change to electric power technologies. There are four challenges that HTS materials have to overcome to be widely used: cost, refrigeration, reliability, and acceptance. Modest growth rates are expected for the well-established businesses of superconductivity, which may reach about 5 B€ in 2014 [2]. The contribution from HTS applications is anticipated to be in niche areas. This will continue till HTS see improved performance at about 65-75K operating temperature, at which the use of the Liquid Nitrogen cryogen will lead to neutralizing the impact of the cooling cost barrier.

First generation (1G) HTS wires are now being produced in industrial lengths, for example the IMPDAHMA project [3], has seen the first application of Bi-2212 wires (produced by Oxford Instruments). Last year Oxford Instruments demonstrated the first fully superconducting high field magnet using LTS and HTS materials, achieving a world record of 22.5T. This will provide the basis for development of ultra high field magnets of >25T and reduce the need for high field magnets using resistive coils.

"Materials and processes have influenced and guided technological progress for centuries. Superconducting materials and in particular HTS conductors are expected to play an important role in the advancement of scientific and industrial applications with significant benefits in health-care, energy and the environment."

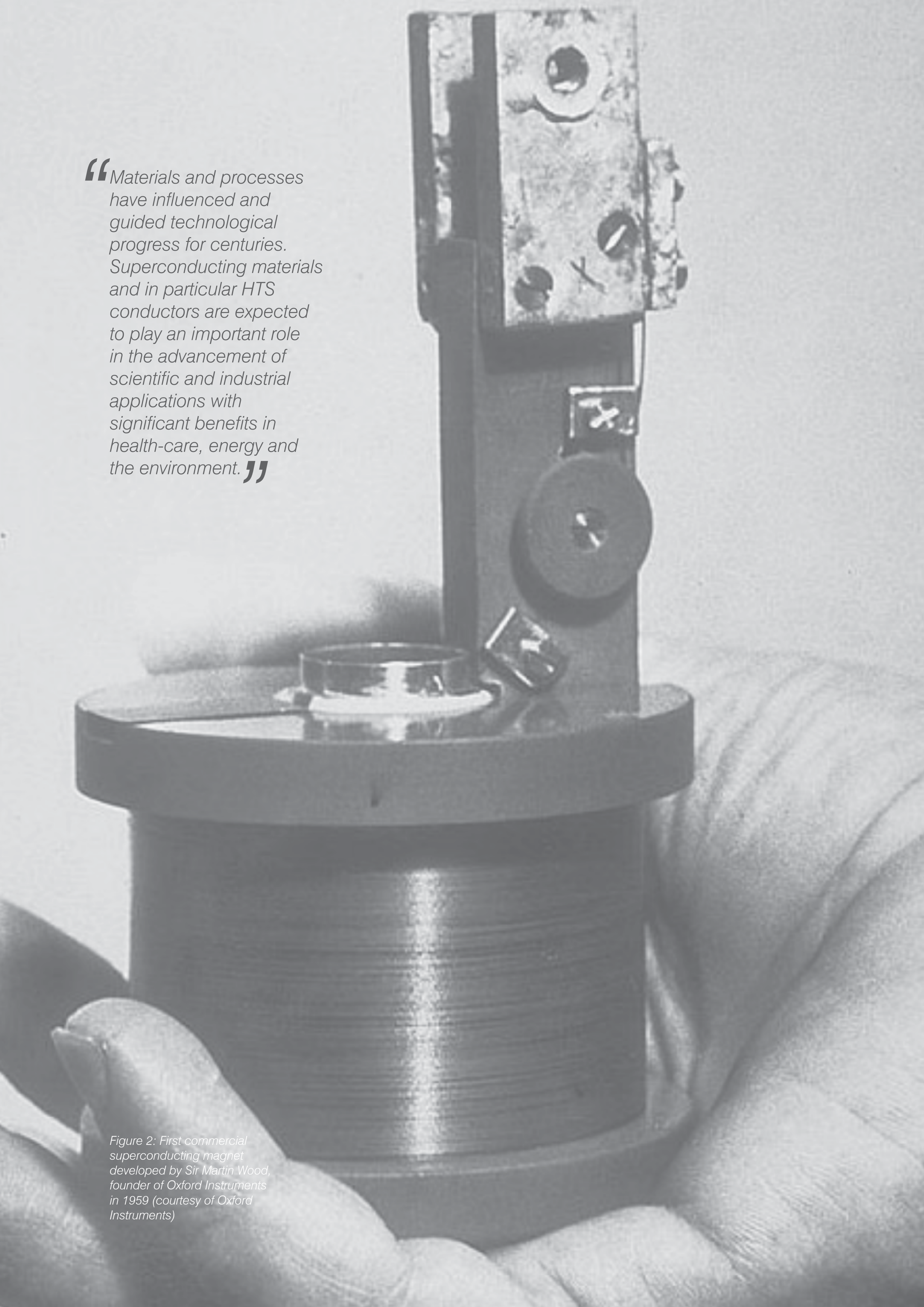
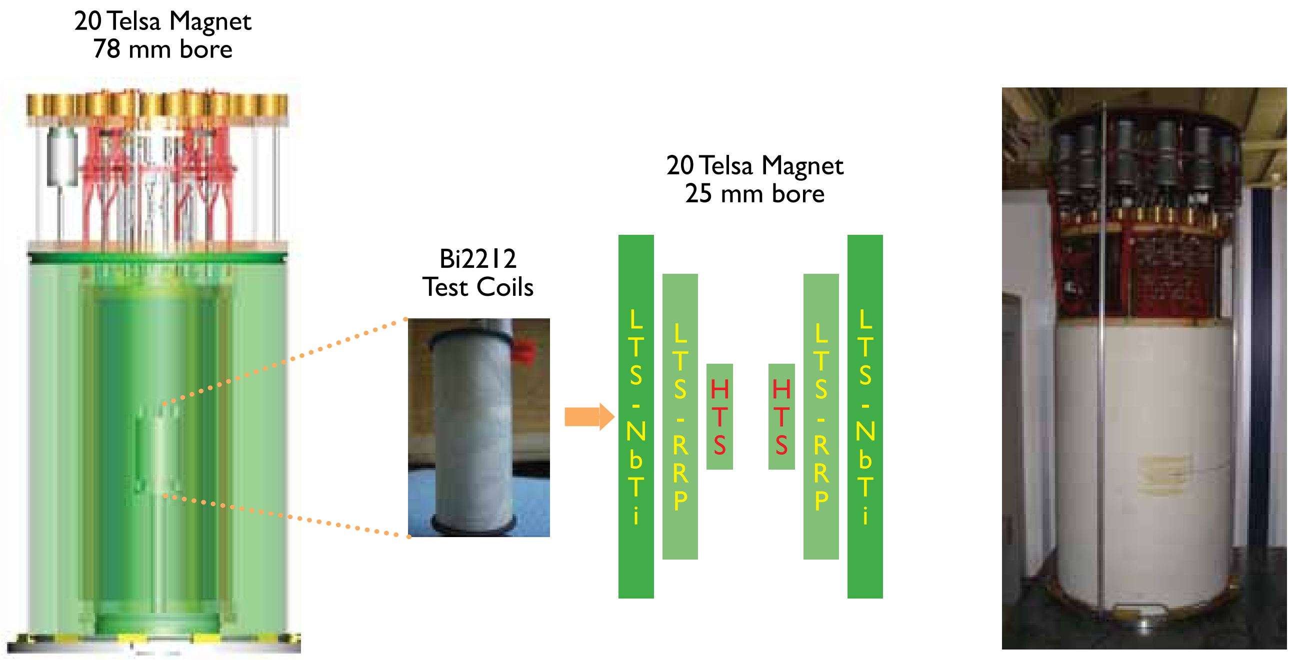


Figure 2: First commercial superconducting magnet developed by Sir Martin Wood, founder of Oxford Instruments in 1959 (courtesy of Oxford Instruments)

Production of second-generation (2G) materials such as YBCO tape and M_gB_2 wires has also increased during the last few years. A significant improvement in long length performance and price is still required to meet application and commercial requirements.

In many ways, the transmission and distribution of electricity is poised for advancement via HTS materials the way that the Internet was poised for its takeoff in the 1990s. Just as fibre optics enabled the "information superhighway" by supplanting lower-capacity copper, superconductivity is enabling an "energy superhighway" by supplanting copper electrical conductors with a ceramic superconducting alternative that has higher capacity while eliminating resistive losses.

Figure 3: The first fully superconducting magnet using LTS and HTS materials 22.5T @4.2K on Apr 2009 at Oxford Instruments during the work on the IMPDAHMA project, a partially funded project by the TSB [2].



SUPERCONDUCTING MATERIALS

Materials and processes have influenced and guided technological progress for centuries. Superconducting materials and in particular HTS conductors are expected to play an important role in the advancement of scientific and industrial applications with significant benefits in health-care, energy and the environment. UK industry has little presence in HTS conductor manufacture and only a limited investment in the engineering/manufacturing sector. This is despite the fact that Oxford Instruments, a UK company, pioneered and led the commercial use and development of superconductivity applications at low temperatures.

It took almost fifty years from the discovery of superconductors to find materials that were suitable for various applications i.e. can carry high current in a high magnetic field. Two main low temperature superconducting materials are widely used in LTS applications. These are NbTi and Nb_3Sn. They enabled the construction of magnets that can produce much higher magnetic fields than conventional copper-wire electromagnets. This is because the cooling of copper conductors becomes impractical after current densities exceed a value which is well below the current-carrying capacity of the high-field superconductors. The field levels produced by superconductors can exceed the magnetic saturation of iron, which is usually used to boost and focus the fields of copper/iron electromagnets, thereby eliminating the necessity for iron-core electromagnets.

Commercial superconducting materials currently include:

1. Low temperature Niobium Titanium (NbTi), the work horse of superconducting applications
2. Low temperature Niobium Tin (Nb_3Sn), critical material to enable high field magnets
3. (1G) BSCCO 2223 [Bismuth-Strontium-Calcium-Copper-Oxide]
4. (1G) (BSCCO 2212) [Bi-Sr-Ca-Cu-O – with number of compounds]
5. (2G) YBCO [Yttrium-Barium-Copper-Oxide]
6. M_gB_2 [Magnesium diboride]

The HTS materials are anisotropic which lead to difficulties in producing high performance with long lengths of HTS tapes. Other recent examples of new superconducting materials include the finding [4] that well-known material, magnesium diboride (M_gB_2), is a superconductor with a critical temperature Tc of 39K, certainly the highest for materials that look like traditional Bardeen-Cooper-Schrieffer (BCS) superconductors. Another example [5] is the fulleride compound, CsC60, with a Tc of 38 K. While the nature of the CsC60 compound makes it seem an unlikely candidate for applications, M_gB_2 may have a different fate. It appears to be more easily formed into wire-like shapes than the (1G) and (2G) wires/tapes, may carry significant currents in high magnetic fields, and has relatively low-cost constituents. Therefore, there is a strong effort to develop this material into wires

Figure 4: Superconducting billet before processing to long thin wires.

NbTi LTS	Nb_3Sn LTS	M_gB_2 MTS*	Bi-2212/Bi-2223 HTS	YBCO HTS
Tc = 9.8 K Maximum Field (4.2K) 9.5T (2.2K) 11.5T Tc = 18.1 K	Maximum Field (4.2K) 20T (2.2K) 23.5T Tc=39K	Maximum Field (4k) 10T-20T Tc = 90-110K	Maximum Field > 40 T @4.2K; 8 T @20K 4 T @65K Tc = 90-135K	Maximum Field > 40 T @4.2K 12 T @20K 8 T @65K

*Medium Temperature Superconductors (MTS) operating between LTS and HTS materials

Table 1: Main superconductors used in commercial and prototype applications

for applications, perhaps as a replacement for the workhorse NbTi. Most recently, an iron-based series of compounds [6], LaO1-xFxFeAs, have been discovered whose Tc has already risen to 52 K. These materials have not yet been produced in single crystal form but appear to be somewhat analogous to the cuprate HTS materials and may also have magnetically mediated pairing [7]. Their discovery suggests that the family of HTS materials and superconducting materials in general may supply still more surprises and expand further in the future.

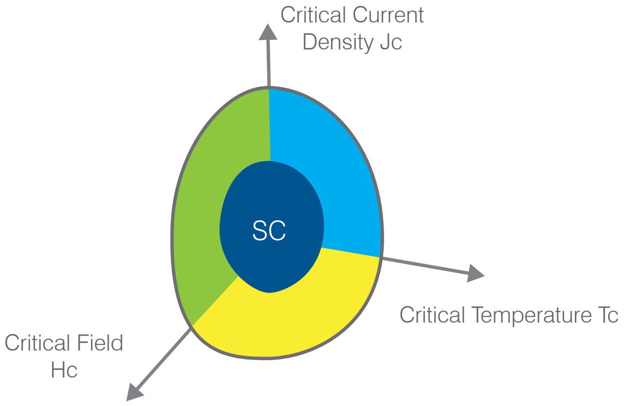
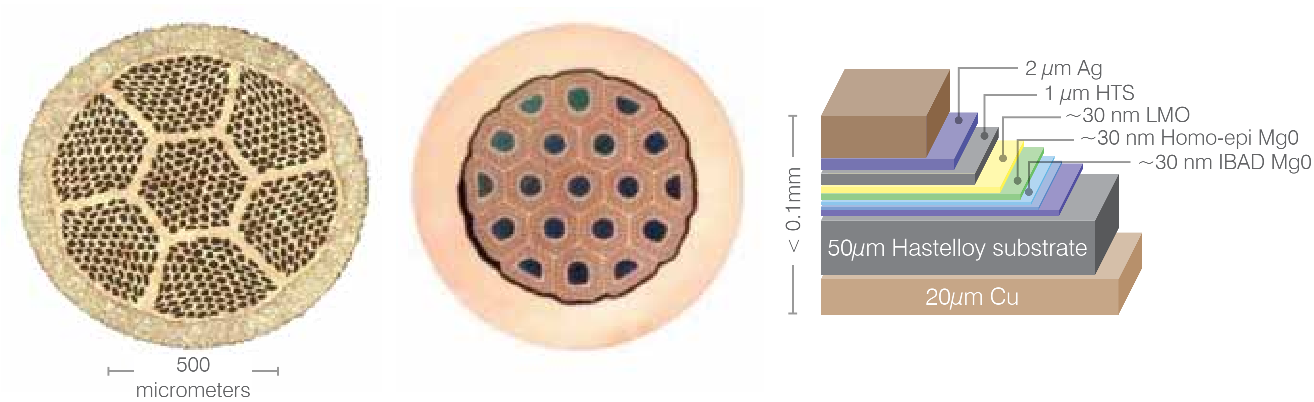


Figure 5: Operating parameters of a superconductor wire, where the outer lines outline the limits of superconducting operation regime, and the middle volume represents a zone of engineering design, with safety margins.



Cross section of a B-2212 HTS filamentart wire (Courtesy of Oxford Instruments)

Cross section of a Nb_3Sn LTS wire filamentary wire (Courtesy of Oxford Instruments)

Layers of YBCO tape (Courtesy of SuperPower Inc)

Figure 6: Cross sectional layout of selected wires and tapes

SUPERCONDUCTING APPLICATIONS

The unique properties of superconductivity facilitated many great discoveries of the 20th century such as the magnetic resonance imaging (MRI) technique. Established commercial applications of superconductivity are dominated by the use of LTS materials and include:

- Magnets for Magnetic Resonance Imaging (MRI)
- Low and high field magnets for Nuclear Magnetic Resonance (NMR)
- Low and high field magnets for physical sciences and research
- Accelerators for high-energy physics
- Large scale magnet demonstrators for plasma fusion reactors
- Industrial magnets for materials magnetic separation

All these applications are only possible because of the significant improvement in production of LTS wires in long lengths with uniform performance.

Other small-scale commercial applications of superconductivity that use LTS materials include research magnets, Magneto Encephalography (MEG) based on Superconducting Quantum Interference Device (SQUID) technology used for measuring weak magnetic fields generated by the brain.

These superconducting magnets saw their first uses in laboratories as an enabling device for experimentation and developed into a market of 4B€ [2] dominated by the bioimaging Magnetic Resonance Imaging (MRI) scanning machines and the Nuclear Magnet Resonance (NMR) scientific instruments used widely by researchers

Figure 7 (upper right): 950 MHz NMR magnet developed by Oxford Instruments 2005

Figure 8 (right): The LHC ring using hundreds of superconducting coils at CERN (Courtesy of CERN)

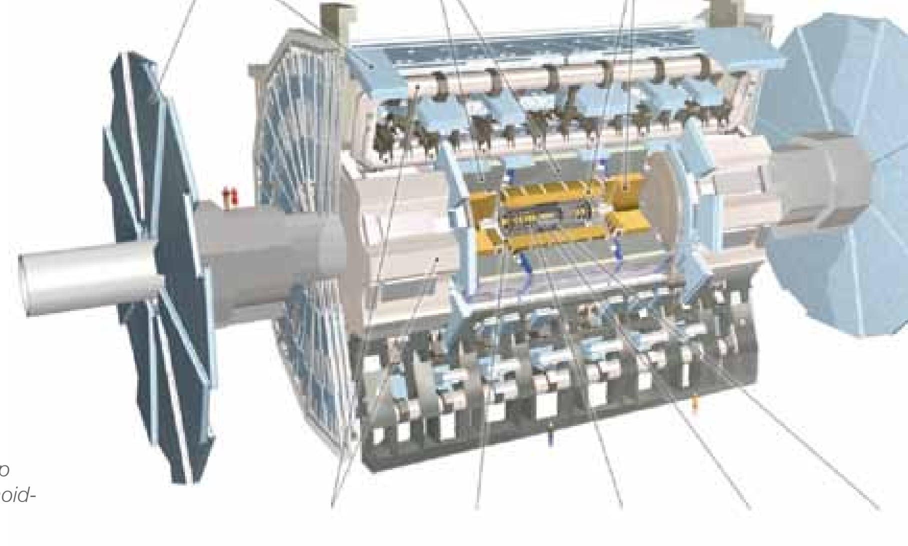


Figure 9: The ATLAS (A Steroidal LHC Apparatus) Detector is a general-purpose detector, which has been built, for probing p-p and A-A collisions at LHC employing a 2T very wide bore solenoid-superconducting magnet (Courtesy of CERN)

and pharmaceutical companies for drug research and development. Oxford Instruments, pioneered 50 years ago the commercialisation of LTS materials. MRI, together with NMR magnets are examples of successful exploitation of superconducting materials by a UK company. Figure 7 shows the 950MHz NMR magnet developed by the company. Another major LTS application is large-scale instruments for high-energy physics research, for example the Large Hadron Collider (LHC) at CERN. The LHC is the largest machine in the world with a circumference of 27 miles using over 5000 magnets.

In energy applications, LTS materials are playing a pivotal enabling role in developing the 15B€ Fusion energy project, the International Thermonuclear Experimental Reactor (ITER). This project will lead the way towards large scale and clean energy generation. It can only be made possible using superconducting materials because of the high field required and that could only be generated cost-effectively by using the low loss superconducting materials.

In 1986, Bednorz and Muller [8] discovered superconductivity in a class of copper oxides with Tc up to 138 K (164 K under pressure). This discovery produced great excitement and accelerated the race to develop applications at much higher operating temperatures, for example at the much easier to achieve boiling point of liquid nitrogen (77 K). For HTS materials to be adopted it is important that not only the critical temperature Tc, but also the wires, must carry large critical current (Ic) or current density (Jc) in significant magnetic fields, which also have an operating critical magnetic field (Hc) limit (see Fig. 1).

Superconducting applications in the long-term, especially those working at high temperatures will lead to a step

Figure 10: Typical LHC magnet (Courtesy of CERN)

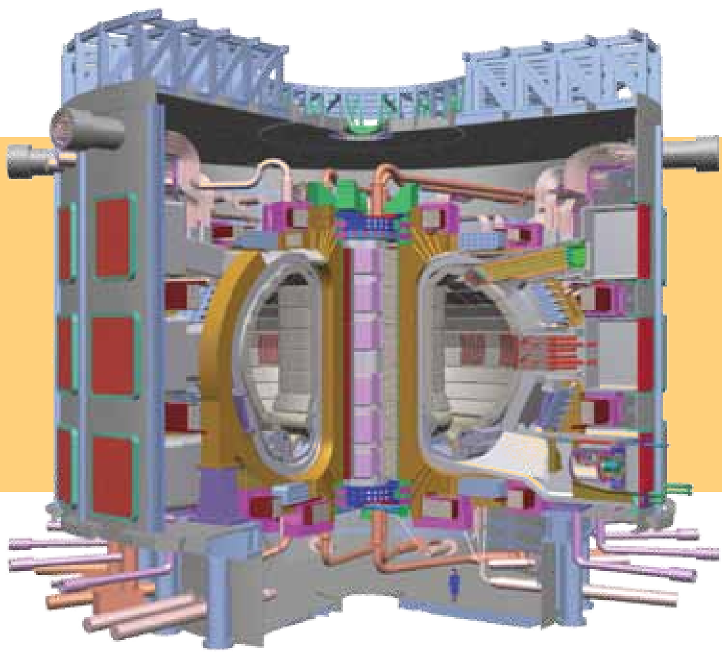


Figure 11: ITER machine mass: 23350 t (cryostat + V V + magnets) – Shielding, divertor and manifolds: 7945 t + 1060 port plugs – magnet systems: 10150 t; cryostat: 820 t.
Courtesy of ITER publications.

change and revolutionise our energy generation, delivery, and management. If we take, for example, copper materials, combined with the discoveries and inventions in the late 18th and early 19th Centuries by Ampere, Faraday and Ohm. They spearheaded copper into a new era of industrial applications and played a pivotal role in launching the Industrial Revolution. Recently, the fibre optic "information superhighway" was constructed by replacing copper wires with a higher-capacity alternative. Superconductivity can, and will, provide a comparable "energy superhighway" by replacing copper wires with a ceramic superconducting alternative that has higher capacity while eliminating resistive losses.

HTS energy applications have the potential to become a key twenty-first century technology and offer powerful new opportunities for improving the reliability of the electric power grid and increasing its capacity and efficiency. This will translate to a dramatic reduction in waste and offers a potential contribution to UK international obligations on CO_2 emissions. From the generation point to the consumption point of electricity, countries that advance superconducting technology will be impacted by the application of the technology to electric power equipment. Some examples of emerging power applications are already demonstrated in power cables, motors and generators, fault current limiters and large-scale storage, (superconducting magnetic energy storage, SMES).

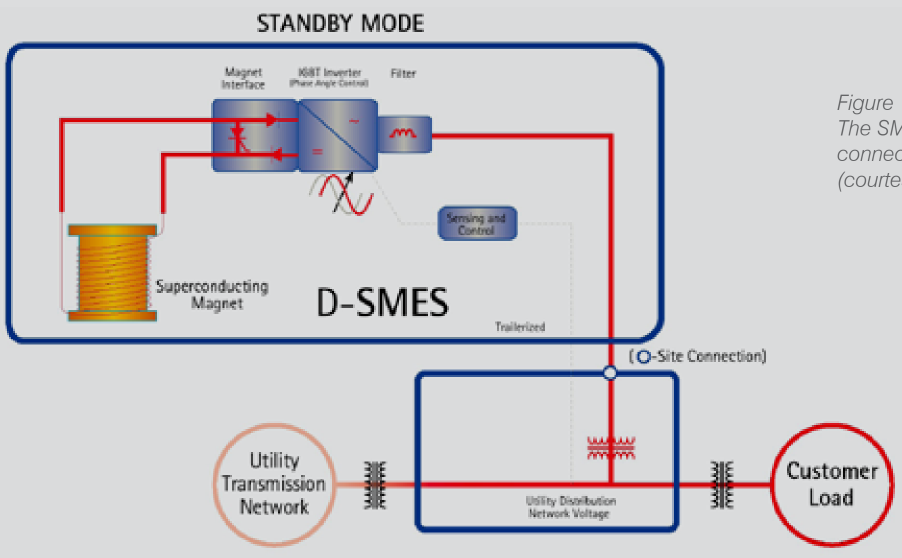


Figure 12a: Illustration of an application of SMES. The SMES unit supports the site to which it is connected in order to maintain system stability (courtesy of ClimateTechWiki) [15]

Superconducting Magnetic Energy Storage (SMES)

SMES offer improved performance and efficiency (98-99%) compared with the 90% of other utility devices, such as fuel cells. SMES store energy in the magnetic field of a DC current that flows in a superconductor wire / tape. Energy losses are negligible, making it possible to inject and extract current very quickly. Because the major parts in an SMES are static, wear is minimal and reliability is high. One major constraint is the need to operate at cryogenic temperatures. Power used in the refrigeration process must also be taken into account in any rigorous energy balance.

Figure 12a illustrates the use of SMES in power application. The SMES technology is based on three concepts unique to it. First, HTS materials carry current with no resistive losses. Second, electric currents produce magnetic fields. Third, magnetic fields are a form of pure energy which can be stored. SMES was originally proposed for large-scale, load levelling, but, because of its rapid discharge capabilities, it has been implemented on electric power systems for pulsed-power and system stability applications

SMES offer commercial and power management benefits that include:

- Maintaining quality power, stability, and reliability across the transmission and distribution networks
- Avoiding outages
- Use of environmentally-friendly materials
- Greater control, flexibility, response & convenience in energy storage and delivery
- Enhance and facilitate asset utilisation and defer upgrades by including storage capability at the substation level
- Facilitate continuous electricity supply by storing excess capacity from intermittent renewable energy generation sources.

Figure 12b: SMES devices (Courtesy of Conectus)

Power Cables

Superconducting wires carry up to five times the current carried by copper wires with the same cross section, enabling higher capacity HTS power lines to provide transmission and distribution systems with smaller footprints. They allow additional capacity to be placed in service along existing rights-of-way. Superconducting cables are cooled cryogenically to remove the resistance to the flow of electricity, cutting down on the losses that typically occur during transmission. Their use will be especially attractive in urban areas where it will be very cost effective to replace existing copper cables with superconducting cables, avoiding expensive new underground constructions. The last ten years saw a rapid implantation of the use of superconducting cables in utilities with the shortest about 30 meters and the longest about 600m. Most of these are in the US and Japan and plans exist for two in Europe, but none in the UK. Fig.13 illustrates the relatively complex engineering required for future HTS cabling. Some of the benefits for high-temperature superconducting cables include:

- Delivering up to five times more current than conventional power lines of the same diameter;
- Alleviates congestion by transmitting more electricity with higher efficiency;
- Facilitating grid reconfiguration capabilities;
- Enable flexibility in substation/transformer placement and network connections;
- Reduction of right-of-way requirements since HTS cables have a smaller footprint compared to conventional cables while carrying more power;
- Carrying more current at lower voltages;
- Large power transformers can be located farther away from urban centres, allowing urban planners to free up valuable real estate for development or green space.

Below is a selected list of superconducting cable projects

1. Brookhaven Cable: LTS, 330 MVA,138 kV (80 kV), 1971-1986
2. Southwire Carrollton: HTS, 27 MVA, 12 kV, 30-m, 1998-2006
3. Detroit, Pirelli/AMSC: HTS WD, 100 MVA, 24 kV, never on grid
4. SEI/TEPC Japan: HTS CD, 114 MVA, 66 kV, 100-m, 2001-2002
5. NKT/Copenhagen: HTS WD, 100 MVA, 30 kV, 30-m, 2001-2003
6. CRIEPI/Furukawa Elec: CD, 77 kV, 1 kA, 500-m, 2004-2005
7. Albany, SuperPower/SEI: CD, 48 MVA, 34.5 kV, 350-m, 2006-2008 (30-m 2G section)
8. Columbus, Ultera: CD, 69 MVA, 13.2 kV, 3 kA, 200-m, 2006-
9. LIPA, AMSC/Nexans: CD, 215 MVA, 138 kV, 610-m, 2008-
10. New Orleans, Ultera: CD, 48 MVA, 13.8 kV, 1760-m (planned)
11. Korea, DAPAS: CD, 1000 MVA, 154 kV, YBCO, (planned)
12. Japan, M-PACC: CD, 66 kV@5 kA, 275 kV@3kA, YBCO (planned)

Figure 13: Concepts and installation of three-phase power cables based on BSCCO (Courtesy of Conectus)

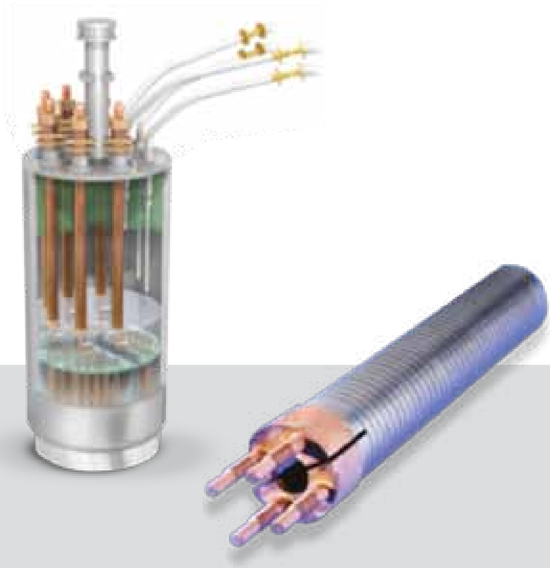


Figure 14: HTS fault current limiter based on melt-cast BSCCO: system design and HTS components for voltages up to 110 kV (Courtesy of Conectus)

Fault Current Management

Another potential application of HTS materials, are fault current conditioners, which, in the occurrence of a fault, limit the current in a crucial branch of the circuit so that no component in the system becomes overloaded. Superconducting fault current limiters (FCLs) will facilitate the expansion of present networks, avoiding costly new installations. FCLs work by inserting impedance in a conductor when there is a surge of current on utility distribution and transmission networks. Under normal circumstances, they are invisible to the system, having nearly zero resistance to the steady-state current. When there is an excess of electricity, otherwise known as a fault current, the FCL intervenes and dissipates the surge, thus protecting the other transmission equipment on the line.

Smart components like HTS fault current limiters have the potential, unlike traditional FCLs, to save utilities money and make the modern grid more efficient by protecting high voltage power lines and the electric grid equipment from damages, and by helping to avoid outages. Superconducting reactive power regulators further enhance reliability by instantaneously adjusting reactive power for maximum efficiency and stability in a compact and economic package that is easily sited in urban grids. HTS transformers will cut the size, volume, weight, and losses of conventional transformers by a factor of two and do not require the contaminating and flammable transformer oils that violate urban safety codes. Not only do superconducting motors and generators cut losses, weight, and volume by a factor of two, but they are also much more tolerant of voltage sag, frequency instabilities, and reactive power fluctuations than their conventional counterparts,while electrical storage exploits superconducting magnetic energy storage. Most of these recent developments are dependent on the latest innovations in materials and processes. Some of the benefits of FCL include:

- Enhanced stability, safety, reliability, and efficiency of power-delivery systems.
- Reduced wide-area blackouts, localized disruptions, and increased recovery time when disruptions do occur.
- Protected transmission and distribution (T&D) equipment and eliminated or reduced replacement of T&D equipment, such as circuit breakers.

Figure 15: Field test of a fault current limiter in the medium voltage (MV) power grid (Courtesy of Conectus)

Figure 16: Supersonic Aerospace International's Quiet SST may have solved the sonic boom problem through the shape of its fuselage. Futuristic superconductive energy storage and electrically driven turbofans based on a design first developed by Henri Coanda in 1910 could be the precursor of petroleum-free flight (Courtesy of EV world)

Motors and Generators

In the case of motors and generators, superconductivity will enable smaller, more efficient systems with significant performance enhancements. These efficiency advancements will lead to energy conservation and increased environmental protection through decreased emissions.

Other Emerging Technologies to Benefit from Superconductivity

Products and applications utilizing HTS materials are clean and environmentally very friendly compared to their conventional counterparts. Their use is associated with non-generation of greenhouse gases, and is cooled by liquid nitrogen, a non-flammable cryogen available in large quantities over 80% of our atmosphere. The expected reduction in overall size varies between 50% and 80%, and associated with equivalent reduction in weight. These benefits will lead to economic incentives and have already led to the developments of many new superconducting applications in the following sectors:

- **Medicine**
  Employing HTS materials will lead to cheap, portable, and compact MRI systems, as well as wider use of non-invasive diagnosis of human organs like heart and brain via magnetic source imaging (MSI) and magneto cardiology (MCG) systems

- **Transportation**
  HTS will enable new generation transport technologies, e.g. magnetically levitated trains, ship propulsion systems, electric cars, aeroplanes, and space ships.

  These emerging markets will become a reality when cost of materials goes down, supply of large quantities become available and associated cryogenic requirements are engineered cost effectively

- **Communications**
  HTS filters will enhance signal-to noise ratios in cellular communications systems leading to reliable communication services with fewer spaced cell towers.

Figure 17 (above): Illustration of conventional copper ship propulsion motor and right is a photo of the HTS 36.5 MW ship propulsion motor completed by AMSC and Northrop Grumman (Courtesy of AMSC)

Figure 18 (right): JR-Maglev at Yamanashi, Japan test track in November 2005. 581 km/h. (Courtesy of Wikipedia)

Market Potential and Challenges

It is anticipated that the potential of HTS markets may increase rapidly at 10-15% per year to an excess of 3 B€ by 2020 [2]. The dates for widespread market penetration are uncertain with significant developments necessary before the industry can fulfil its potential. Despite the uncertainties, it appears to be unanimously agreed that HTS applications will make it to market at some point in the future and that they will bring significant benefits to the end-users, as evidenced by the large sums of public and private money that are being invested in R&D projects in the US, Japan, Korea and some EC States.

HTS market penetration in energy sector is very sensitive to the level of development and adoption of power devices. If very few HTS devices are built, their cost will be very high, they will not be cost effective, and penetration will be slow. On the other hand, the cost will drop with increasing demand and more production. It is anticipated [12] that the sales of HTS devices (i.e., market penetration) will remain small until 2015. That is because the performance of wire changes only slowly with advances in R&D and manufacturing experience, and reaches an asymptotic value in 2015. Figure 19 [12] displays four distinct market penetration curves for selected HTS devices. Evidently, market penetration is very slow at first, (until wire costs and cryogenic costs come down), but eventually motors and transformers penetrate to nearly the same levels; cables and generators asymptotically reach a smaller fraction of their available markets.

Wide use and introduction of HTS materials in energy is faced with four challenges; these are cost, operating conditions, reliability, and acceptance. We have all witnessed in the last 24 months steep increases in cost of energy. This will address the cost and acceptance challenges and will accelerate of adoption of HTS materials for wide use in energy applications. The UK needs to enhance its readiness to be an active and a leading contributor to the potential fast adoption of HTS for commercial exploitation in the energy sector.

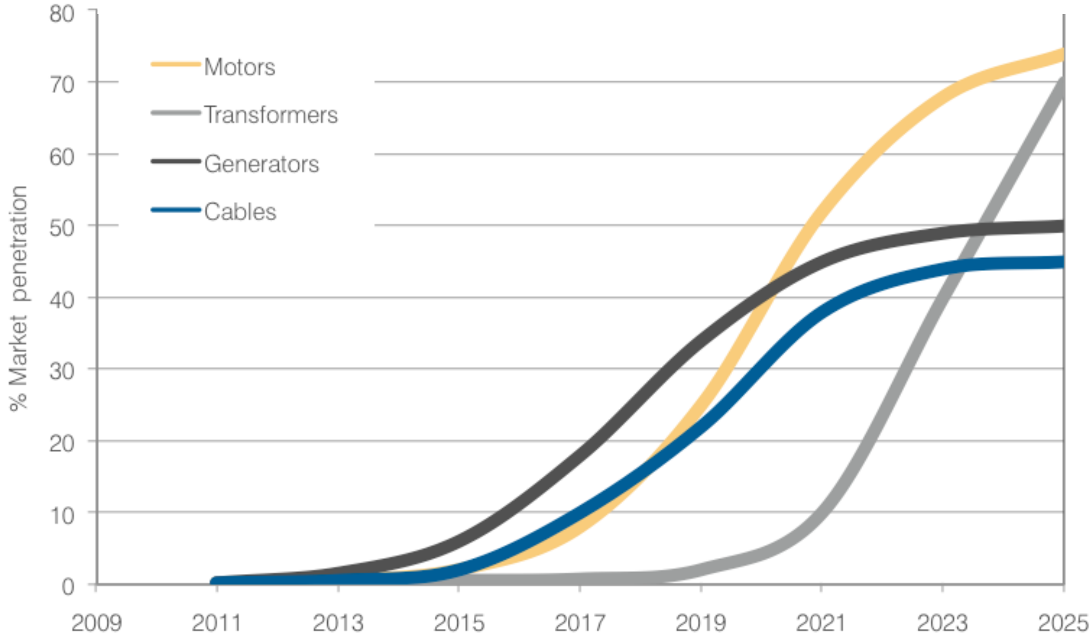


Figure 19: Predicted market penetration curves - HTS power devices

As indicated in Table 2 [2], LTS contributions are predicted to continue their steady growth with a total market share of about 4.6 B€ in 2013. Estimates for HTS are in the range of 0.4 B€ for 2013. They are based on the forecast that several new businesses will start during the next years. It is expected that in the long term they may well exceed the size of the established businesses. In well-established businesses, the EU market share is nearly half of the total world market today, whereas the future EU share of value chains in new fields is expected to be considerably smaller.

Market figures represent the annual sales of materials, components, and (sub-) systems, providing a specific technical function for which superconductivity is indispensable. All after sales services, warranties and related maintenance as well as commercial orders and pre-commercial orders related to RTD activities, prototype testing and field tests, are included.

Global market for Superconductivity (in M€) Conectus, December 2009				
Business Feld	Year 2007	Year 2009	Year 2011	Year 2013
Research & Technological Development (RTD)	660	765	845	955
Magnetic Resonance Imaging (MRI)	3300	3355	3435	3525
TOTAL of RTD & MRI	3960	4120	4280	4480
New Large Scale Applications	65	100	155	325
New Electronics Applications	60	80	125	180
TOTAL of Emerging New Businesses	125	180	280	505
TOTAL MARKET	4085	4300	4560	4985
Market Shares for Low-Tc Superconductors	4025	4205	4385	4600
Market Shares for High-Tc Superconductors	60	95	175	385

Table 2: Superconductivity Market analysis (Courtesy of Conectus) [2]

UK CAPABILITIES ON SUPERCONDUCTING AND CRYOGENIC APPLICATIONS

Fifty years ago saw the first commercial spinout from Oxford University. Oxford Instruments started out in a garden shed, where the world's first superconducting magnet was invented. This, in turn, led to the development of the MRI machine, which changed the face of medical diagnostics. There are now over 30,000 MRI systems in the world [16] and Oxford Instruments was involved in supplying one third of them. The company is now a worldwide business, supplying commercially successful, high-tech tools and systems into diverse markets, which include industry, research, education, space, energy, defence, life science research, and health. Table 3, shows a summary of the current UK capabilities in superconducting applications.

Organization	Specialization
Oxford Instruments, Oxfordshire	• Superconducting magnets • Cryogenics • Ultra Low Temperature applications • Consultancy/superconducting applications and cryogenics • Superconducting Materials characterisations • Superconducting wires (LTS and HTS)
Converteam, Warwickshire	• Generators (conventional and HTS)
Siemens Magnet Technology, Oxfordshire	• MRI superconducting magnets (LTS)
Agilent, Oxfordshire	• NMR and MRI superconducting magnets (LTS)

Table 3: Examples on UK industrial capabilities in superconducting applications

ENVIRONMENTAL AND SOCIAL IMPACT

The design of new power applications using HTS materials (cables, motors, grid stability solutions) promises significant advances in energy efficiency. The use of HTS conductors instead of copper is forecast to cut losses and increase energy efficiency. This translates as a dramatic reduction in waste and offers a potential contribution to UK international obligations on CO2 emissions.

HTS products are anticipated to be more powerful and smaller than existing systems offering increased energy density where space is limited (e.g. underground cables) or when weight reduction is important (e.g. compact generators/transformers for remote areas such as wind farms and aerospace applications).

Operating at higher temperatures these materials will also dramatically reduce the reliance on liquid helium as a coolant, a rare and expensive commodity. For example, mechanically cryo-cooled HTS magnets, as well as being much more energy efficient could enable a new range of mobile, specialised, MRI magnets for medical imaging. HTS applications working in the temperature range 65-75K will enable the use of liquid nitrogen as a cryogen much cheaper than helium and available in abundance.

The advent of high field magnets using HTS insert coils has the potential to bring >25T magnetic fields to conventional physics laboratories. Currently, very high field magnet systems rely upon large water-cooled resistive magnets with huge power-operating costs and are only available at a select few large national facilities. Coupled with advances in cryo-free/re-condensing technology and HTS current leads, it represents a similar opportunity to the introduction of reliable low temperature superconductor (LTS) magnets 30 years ago. Consequently, it will not only enlarge the traditional user base of material scientists and condensed matter physicists, but also bring in frontier fields such as nano-sciences. This will be invaluable to the investigation of matter at high magnetic fields, such as in the use of NMR for development of advanced materials, complex molecules and new drugs.

SPECIFIC R&D NEEDED FOR INDUSTRY TO ADOPT HTS MATERIALS

Below are some of the research and development areas the UK can do to enable wide use of HTS devices and commercialisation of HTS applications.

HTS materials

- Uniform critical current along full length of wires and tapes
- Cheap and competitive conductor
  - 2G today, ~ 400 $/kAm for long lengths [9]
  - 1G today, ~ 180 $/kAm for long lengths [10]
  - Desirable target for future applications ~ 20 $/kAm
- Conductor must have low AC losses in applications

Superconducting coils

- Coils must be able to cope (mechanically & thermally)
  - With over–currents and fault–currents
  - Without excessive AC loss in routine operation
  - Without excessive AC during over–current operation
  - Without excessive AC loss during the fault

Dielectrics

- Suitable electrical insulation must be identified
- LN2 must be shown to be a good coolant and dielectric under operating conditions

Cryogenic system and heat loads refrigeration

- Cryo-coolers must be
  - Less expensive (Desired cost reduction from $100 to $25/W)
  - More reliable to allow continuous availability of 99.9%
  - High Carnot efficiency (25%-30%)
  - Remotely connectable and monitoring
  - Long lived in utility environment
  - Standards on loss measurements and performance during operation
- Cryostat must be less expensive (one piece would be helpful)

Device development and engineering

- Terminations (demonstrate & standardize)
- Robustness - duration of faults
- System Integration - in harmony with network
- Overload capacity / duration

CONCLUSIONS AND RECOMMENDATIONS

The deployment of more superconducting devices will increase the reliability, availabilty and quality of power for customers sensitive to these parameters and will provide size, capacity, environmental and efficiency benefits. The table below summarises some of the HTS contribution to key performance improvements required by the energy sector

In order for the benefits of HTS to be realized, the following activities need to be addressed:

1. Improving the performance of HTS wire over longer lengths while reducing manufacturing costs
2. Conducting fundamental studies necessary to support wire and systems development
3. Demonstrating the applicability and the potential benefits of superconductivity in electric power systems
4. Strategic research on supporting fundamental research activities to better understand relationships between the microstructure of HTS materials and their ability to carry large electric currents over long lengths
5. Support research and development activities to design superconducting materials
6. Increased funding should be available to train more engineers and scientists in superconducting applications
7. Funding for prototyping should be reviewed to ensure the UK has a leading position in superconducting applications
8. Demonstrate HTS superconducting applications to raise their impact on UK energy strategy.

Finally, the UK needs to review the role of superconducting materials and applications as a strategic sector and ensure adequate support and full inclusion in its plans for enhancing it as role leader in technical and engineering innovation and scientific research.

Reliability	Efficiency	Security	Environmental Impact
Larger capacity relieves congestion and helps prevent outage	High operation efficiency conserves energy and reduces supply-side pollutants	Fewer critical nodes to secure Ability to share power between assets ensures continuity in electricity delivery and shortens recovery time from incidents	Minimizes environmental impact through oil-free operation and decreased demand for new rights of way

Table 4: High Temperature Superconductivity Contributing to Key Performance Improvements in the Energy Sector

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