High-temperature superconductors and their large-scale applications

Tim A. Coombs[1†], Qi Wang[1], A. Shah[1], J. Hu[1], L. Hao[1], I. Patel[1], H. Wei[1], Y. Wu [1], Thomas Coombs[1], Wei Wang[2]

[1] Department of Engineering, University of Cambridge, Cambridge, United Kingdom
[2] College of Electrical Engineering, Sichuan University, Chengdu, China

[†]e-mail: tac1000@cam.ac.uk

Abstract

For decades superconductor materials have promised high power, high efficiency, and compact machines. However, as of 2024, commercial applications are limited. One of the few successful examples is represented by low temperature superconductor (LTS) materials that are used for magnetic resonance imaging (MRI) in hospitals worldwide. High temperature superconductors (HTS) can support currents and magnetic fields at least order of magnitude higher than those available from LTS and non-superconducting conventional materials, such as copper. However, HTS are seldom used, even if there are important areas where these materials could perform better than conventional ones or LTS. For example, HTS can replace conventional materials in wind turbines and aeroplane motor-engines to improve power to weight ratios. In tokamak fusion reactors, HTS might enable sustainable positive power outputs. Additionally, in medicine, HTS might replace LTS for smaller MRI machines, producing high-resolution images, without the need to use a scarce resource like Helium (fundamental for LTS). The primary barriers to deployment are alternating current loss, quench, heat losses, and costs. Developments in HTS manufacture have the potential to overcome these barriers. Here we set out the problems, describe the potential of the technology and offer (some) solutions.

[H1] Introduction

A superconductor is a material that, when its temperature drops below a certain point, known as the critical temperature (T_c), shows a direct current (DC) electrical resistance of 0 Ω. Superconductors are classified according to their T_c. When a specific current density magnitude is reached (the critical current density, J_c), superconductivity is lost. J_c depends on the material, the temperature, the ambient pressure and the local magnetic flux density (B) [1 2 3].

Superconductivity was discovered in 1911, while investigating how electrical resistance of mercury varied with temperature [4]. At the time there were three different high-profile theories describing the behaviour of electrical resistance at low temperature: the first one stated that it should rise to infinity [5], the second one that it should drop steadily and gradually to zero [5] , and the third one that it should level off to a finite value [5]. The fact that, for certain materials, there was a temperature at which resistance disappeared altogether was a surprise. Various superconducting materials were discovered in the following decades, all of them either metals or alloys [6 7 8 9 10].

Prior to 1986, all superconductors operated at less than 35K and were described as low temperature superconductors (LTS). In 1986, superconductivity was discovered in Ba-La-Cu-O [11] and, soon after, in yttrium barium copper oxide (YBCO) at 93K [12]. This temperature is above the boiling point of Nitrogen (77 K). Liquid Nitrogen is cheap, non-toxic, easy to handle and readily available. Since Yttrium can be substituted by a range of rare earths, a whole family of superconductors was

identified, commonly known as rare earth barium cuprates (REBCO). A revolution in superconductivity had begun and the attention shifted to the new high temperature superconductor (HTS) materials [13 14 15 16 17 18 19]. HTS can have over 200 times higher current carrying capability than LTS at 4.2 K in self-field [20 21] and over 60 times higher than copper at 77 K in self-field [22 23]. This discovery opened the way to a greater range of materials and applications than was previously thought possible. 40 years later, large scale applications encompass superconducting generators for wind turbines [24 25], superconducting aeroplane motors [26], small and light magnetic resonance imaging systems (MRI) [27], and compact tokamak fusion reactors [28 29] .

However, there are challenges, or barriers, for HTS, that need to be overcome before they can see widespread use in large scale applications. The first is losses, most notably alternating current (AC) losses [30]. Second generation REBCO tapes commonly known as coated conductors are tapes and consequently have much higher losses than LTS which are typically wires when conducting AC [31]. Losses reduce efficiency and can, causing local heating, lead to quench. Quench is the sudden and violent termination of superconductivity. The sudden release of energy can cause substantial damage that can destroy the entire or large parts of a machine. Traditional means such as current leads can be responsible for some heat losses [32]. Providing the necessary amperage to fully use the superconductor's capabilities is not trivial. The final barrier is cost, this is due to a mixture of factors, such as raw material cost and manufacturing, currently HTS are more expensive than LTS and conventional materials [33].

Revolutions can sometimes be slow and may take an unexpected course. Usually, the original invention or discovery is only part of the story, and it takes further development for the item to really take off. Back in the 19th century some of the earliest cars were electric but it has taken more than a century for electric cars to be widely adopted. Similarly, superconducting materials have fantastic properties, but, since their inception, we have been working out ways to use those properties. This review looks at some available materials and assesses the barriers to their use. Also, it highlights successful applications and looks at the near and far future for superconductors.

[H1] Materials

There are a very large number of metals and compounds, which can be made to display superconductivity [34]. Superconductors can be classified according to the critical temperature: LTS and HTS. LTS normally refers to the most widely used LTS for engineering applications: Nb-based alloys (most commonly Nb-47wt.%Ti) and A15 (Nb_3Sn and Nb_3Al) superconductors. The critical temperature below which these materials display superconductivity is usually below 20 K. HTS includes REBCO (for example, YBCO, GdBCO), other cuprates (such as bismuth strontium calcium copper oxide, BSCCO, $Bi_2Sr_2CaCu_2O_x$ or $Bi_2Sr_2Ca_2Cu_3Ox$ and those based on Mercury and Thallium) and MgB_2. There are also other superconductors such as Pnictides which have T_cs up to 56 K [35].

From a large-scale applications point of view, the most interesting materials are LTS, the cuprates, and MgB_2. In addition, there are various exotic materials which have high critical temperatures, but which require high pressure in the range of GPa. For example, superhydrides have been often reported as having "room temperature" critical temperatures [36]. However, these claims are open to challenge [36] Starting in 1911, maximum T_c increased only slightly from 10K to around 25K in the 1970s, it was from 1986 to 1988 where the Cuprates took Tc from 30K to nearly 140K. At ambient pressure HgBaCaCuO at 133K in 1993 has not been surpassed to this day [37].

[H2] Relevance to large scale applications

Of the myriad number of HTS materials, there are, as of 2024, only three materials which are relevant to large scale engineering applications: REBCO, BSCCO, MgB_2 (Fig. 1). REBCO offers several advantages, including a high critical temperature of 93K, high critical current >10^9 A/m^2 at

77 K, and a high irreversibility line compared to the other two materials. However, REBCO also has drawbacks such as a high aspect ratio and vulnerability to AC losses. Additionally, REBCO bulks can be challenging to magnetise due to their high current density. In contrast, BSCCO exhibits lower AC losses than REBCO in wire form, but it has a lower critical current and its price is influenced by the use of silver in the matrix [38]. MgB_2 stands out for its lower cost compared to REBCO and BSCCO, but it has a lower critical temperature and critical current, making it more suited as a replacement for Nb-Ti [39]. Unlike REBCO, BSCCO and MgB_2 do not contain rare earth elements, giving them a material cost advantage.

REBCO materials are available in bulk and tape conductor forms. REBCO tapes are commonly manufactured with a multilayer structure, known as coated conductors, consisting of various layers. REBCO coated conductors can be sliced and stacked to create artificial bulks, which can be magnetised and used in the same way as bulk samples. Both REBCO bulks and tape stacks can serve as trapped field magnets after magnetization, finding possible applications in motors, generators, levitation systems, and more. REBCO tape stacks are transformed into trapped field stacks after magnetisation. The highest trapped fields achieved by trapped field magnets are 17.6 T for REBCO bulks at 26 K [40], and 17.89 T for REBCO trapped field stacks at 6.5 K [41]. Both BSCCO and MgB_2 are available in bulk, tape, and wire forms. While BSCCO bulks have been discussed in many studies [42] [43] [44], they have seen limited real-world applications due to their lower current density compared to REBCO. A fundamental parameter for applications is, in fact, the critical current density, defined as the amount of current per unit area which can be carried before superconductivity is lost. This parameter is related both to temperature and to the local magnetic field strength. The typical engineering current densities J_e[21], which is the current density across the entire tape cross section, of the three materials in tape (for REBCO and BSCCO) or wire (for MgB_2) forms are in the order of $2\sim9\cdot10^9$ A m^{-2} for REBCO, approximately $7\sim8\cdot10^8$ A m^{-2} for Bi-2223 and $2\sim3\cdot10^8$ A m^{-2} for Bi-2212 in terms of BSCCO, and $3\sim4\cdot10^9$ A m^{-2} for MgB_2 at 4K and self field[45] (Fig. 1j).

[H1] Barriers to application

There are four main aspect that prevent HTS from being widely adopted for practical applications: AC losses, quench, heat losses, and costs. AC losses means that some applications such as motors (for aircraft) cannot be fully developed at present. Quench can cause catastrophic damage to a machine. Heat losses arising from conventional power supplies, based on power electronics connected by accompanying current leads, need to be minimised or ideally eliminated altogether. Lastly, as of 2024, we are limited to high value applications, or applications where budget is less of a concern.

[H2] AC Loss and low loss cables

AC losses occur when a conductor is subject to an alternating field or current. Considering that the loss is incurred at low temperatures (typically < 77K), the equivalent loss — had it been incurred at room temperature — must be multiplied by a large factor. The maximum efficiency is given by the Carnot Cooler efficiency:

$$\frac{T_C}{T_H - T_C} * 100\% \quad (1)$$

Where T_C and T_H are the temperatures of the cold and hot reservoirs.

However, the full Carnot Cooler efficiency can never be achieved in a cryocooler. A typical maximum percentage of full Carnot would be 30%. For example, the cooling power of the Sumitomo CH110 single stage cooler, when the temperature is as low as 20 K, falls off rapidly to effectively zero (capacity chart). The F-70 compressor when driven at 60 Hz consumes 8 kW of power. Thus, when operating temperature of 40 K, each 1 W of heat needs 80 W to remove it.

Both BSCCO and MgB_2 can be made in the form of wires that can be twisted. Consequently, the loss can be reduced (but not eliminated altogether). REBCO HTS is the most promising material, having the best properties at the highest temperatures[21] . However, REBCO can be only made in the form of tape (and the AC loss is proportional to the x-sectional area of the tape). Hence there is a large driver to mitigate, or even solve, the AC loss problem. AC losses can also lead to quench which could damage the device. Unless AC losses are reduced to manageable levels (in the order of 10 mJ/cycle/m), large-scale applications that include AC conditions will not be economic. The operating and maintenance cost will increase by 20 % - 30 %. In a motor, for example, an induction machine has very high losses. A possibility is to consider a synchronous machine, in which only the rotor is superconducting and which sees a static field. In this case, however, the machine will only be half-superconducting and much of the advantage of using superconductors lost. Consequently, weight-sensitive applications such as aeroplane engines are difficult to optimise to the extent required for, for example, a wide-bodied jet.

There are several sources of AC losses, but the most important ones are coupling loss and hysteresis loss. Hysteresis loss is a function of the width of the conductor and can be reduced by filamenting the conductor. For example, cutting it into thin strips, or, as with BSCCO and MgB_2, drawing it down to a fine wire. This approach, however, leads to another source of loss, the coupling loss. Coupling loss occurs because the interaction between the magnetic fields of adjacent conductors leads to an electric field between them. Consequently, a current flow between the conductors which is flowing through the matrix which is non-superconducting. Twisting the conductors leads to magnetic field cancellation, hence reducing the electric field and, consequently, the coupling loss.

There are many different designs of cables all of which satisfy at least in part the need for twisting or filamenting (Fig. 2). Rutherford cables — named after the Oxford laboratory where they were developed — are the most popular and have been used since the early 1970s for LTS cables [46]. Other examples include the Roebel assembled coated conductor (RACC)[47], the patterned superconductors for AC Loss minimisation and current maximisation (PSALM, previously referred to "Roebel tapes")[48], the twisted stacked tape cable (TSTC)[49], and the cable on round core (CORC)[50].

These cables are all designed based on different application scenarios and have their own advantages and disadvantages. The Rutherford, the RACC, and the PSALM cables are designed to provide the minimum loss for the maximum current density, the TSTC maximises the current density and the CORC minimises the loss. The Rutherford cable has been around a long time, originally designed to prevent quench in LTS magnets, it is very successful, and its design is largely optimised. The Rutherford cable inspired both RACC and the PSALM. In both, an essentially flat HTS tape is interleaved with other tapes to create an effective twist and thereby reduction of loss. The difference between the Rutherford cable and the RACC cable is that a RACC cable is created by cutting multiple tapes in a zig-zag pattern and physically interleaving the multiple pieces of tape. The PSALM cable seeks to create the same effect by taking a single section of tape, patterning it into a zig-zag pattern, depositing another layer of superconductor on top and patterning it. The process is repeated as required. It is designed to use very large-scale integration techniques to achieve a continuous production process where the patterns are produced as the tape moves along the production line. The resulting tape is expected to have very high current per unit volume. The PSALM cable includes multiple REBCO layers with buffer layers in between, making the current density of such tape or cable higher than any other existing HTS cables. Each buffer layer is patterned into filamentary meander shapes which is mirrored by the REBCO layer. Adjacent REBCO layers have patterns in different directions so that the magnetic field generated by them can cancel each other. This field cancelling effect can not only mitigate the critical current degradation caused by the field generated by nearby layers, but also can reduce the AC losses when the

tape is carrying AC transport currents [51]. As of August 2024, demo samples of the cable containing a single layer REBCO patterned have been manufactured, and tested in liquid nitrogen [52]. Compared with normal HTS tapes, single-layer cables can reduce the transport AC loss by 60% due to patterning and double-layer cables can reduce the loss by a further 20% due to the field cancelling effect. The magnetisation loss reduction is proportional to the filament numbers: a 70% reduction can be obtained using 4 filaments [53]. These results have verified the high-current and low-loss features of the PSALM and indicate that it might be promising for compact and efficient magnets for fusion coils.

The CORC cable, firstly proposed in 2009 [50], contains several HTS tapes wound on a round core, also known as the former. The tapes are interlaced to make the current distribution more uniform. The former is usually made of metal, such as copper or aluminium alloy, to conduct heat and enhance mechanical strength. The CORC cable is considered one of the most promising cable structures for high-current (kA level) applications. In CORC, multiple layers of HTS tapes are included to increase the current capacity. It can contain up to 13 layers with 40 tapes in each layer [54], which means an extremely high current capacity can be realized. However, the engineering current density of a CORC cable ($6.78 \cdot 10^8$ A·m^{-2} at 12T, 4.2K [50]) is still lower than original HTS tapes because the round former does not carry any current. When the cable is carrying an AC or exposed to an alternating field, the former also generates eddy current losses, which make up the largest part of the total losses of the CORC cable [55]. Therefore, it is recommended to make the former hollow or insulating to reduce losses and allow coolant to flow inside. To further reduce the magnetization losses, filamentary HTS tapes can be used to make CORC cables [56]. Compared with simply stacking HTS tapes in parallel, this structure makes all the tapes experience the same electromagnetic environment by transposition and thus remarkably reduces the coupling losses. The isotropy also allows the cable to be wound into any shape within the bending allowance of the tape and the former. Fusion magnets using CORC cables are being tested around the world while the performance and the feasibility are still be to verified [57] [58] [59].The simplest way to assemble HTS tapes and increase the current capacity is stacking. However, due to the anisotropy of the REBCO tapes, stacked tape cables can only bend in-plane, and each tape experiences different magnetic environments. By twisting, the bending direction of the TSTC is no longer limited, and the magnetization performances to the magnetic fields in different directions are identical. TSTC cables have been proposed and fabricated for high-current magnets in fusion [60] [61]. Compared with CORC cables, the engineering current density of the TSTC is higher because of the absence of the former. However, the twisting process makes the cross-sectional area no longer rectangular but circular, which introduces current-free helix space. Besides, limited by the mechanical strength of HTS tapes, the twisting angle cannot be large, which means the twisting pitch is long and the reduction in the magnetization losses is limited. A similar cable structure is the twisted soldered-stacked-square wire [62] [63]. The basic structure of the twisted soldered-stacked-square wire is the same as the TSTC, but the tapes are only 1 mm wide and are soldered together to enhance the mechanical strength. The wire product is much thinner (normally several mm) and can be wound into almost any shape as normal copper wires do. The AC losses of the twisted soldered-stacked-square wire are also markedly reduced because of the small width of the tapes and the twisting treatment. However, the manufacturing process requires highly delicate techniques to cut wide tapes into 1 mm wide ones and solder them together orderly.

[H2] Quench and quench protection

Whilst it is well-known that employing superconductors on the stator of a rotating machine result in an AC loss — which must be considered when evaluating the machines efficiency — less obvious is that, in an application such as fusion where the current in the coils is ramped up and

down, AC loss incurs [64]. The main concern in this regard is quench, not efficiency. Quench is a lasting problem with superconducting magnets that can be mitigated by using protection circuits to minimise the damage. However, a better solution is to reduce the probability of quench happening by reducing the loss (such as AC loss) that occurs during ramping events and causes localised heating.

Quench is relatively common in LTS magnets. Famously in 2008, a quench occurred in the Large Hadron Collider affecting 100 magnets and requiring the replacement of 53 of them[65]. The quench was rapid enough to cause an electric arc (or discharge) which damaged the integrity of the supercooled helium's enclosure and vacuum insulation, causing the coolant's temperature and pressure to rapidly rise beyond the ability of the safety systems to contain it.

It is quite common for LTS magnets to quench and they are often deliberately quenched in a process known as training [66]. Quench is often caused by friction when adjacent conductors move relative to each other, causing local heating. Training processes enable the conductors to move into their final positions minimising further motions. An LTS wire is relatively robust and has a low minimum quench energy **[G]** (in the order of μJ) and a high normal zone propagation velocity **[G]** (typically in the order of m s^{-1}), so the problem is not acute because the energy associated with the quench is not too localised and can be dissipated rapidly.

HTS tapes are fragile and have a high minimum quench energy **[G]** (typically 2 or 3 orders of magnitude higher than for LTS) and low normal zone propagation velocity **[G]** (typically 2 or 3 orders of magnitude lower than LTS). The combination of these two factors means that there can be a rapid evolution in temperature in a relatively small part of the magnet. Thus, quench in an HTS magnet can be catastrophic. The onset of quench is difficult to predict and typically, once started, does not stop until there is no more energy left to dissipate. Because of the low normal zone propagation velocity **[G]** in HTS, localised hot spots can lead to rapid rise in temperature of 100's of degrees, damaging to the coil. Hence, training is not an option in HTS coils.

Reliably detecting rises in temperature or coil voltage prior to the quench is difficult. However, there are various techniques that could be employed. An active quench protection system involves heaters which drive large parts of the coil normal out of the superconducting state (rather than a small hot spot) so that the energy is dissipated over larger volumes, limiting the temperature rise[67]. Passive techniques involve a system of diodes that divert the current to external dump resistors [68]. Ultimately, in an HTS magnet, the best solution is trying to avoid quench running at current densities lower than J_c and reducing the AC loss to diminish the local heating.

[H2] Heat losses and thermal isolation

The third problem is providing the necessary amperage whilst minimising heat losses. Most applications of superconducting magnets are to generate very strong magnetic fields by transporting very large currents, ranging from hundreds of amperes (for example, in MRI) to tens of thousands of amperes (for example, in fusion). To reach such high DC output, conventional power supplies based on power electronics are expensive, bulky and energy consuming [69]. Current leads are also bulky and are required to be connected to external power supplies, forming a bridge between the room temperature and cryogenic environments that causes heat loss. The supply can be thermally isolated from the machine using a flux pump. Based on power consumption, that is a function of the squared current, the non-superconducting power electronics, and copper current leads ($R \neq 0$) can easily cause very large power dissipations.

LTS magnets have superconducting joints with zero resistance thus, the current can flow in the magnet without decaying. This process is known as persistent current mode (PCM). In PCM, an LTS MRI runs without a power supply, indefinitely, saving energy and enabling the power supply and the current leads to be removed and used elsewhere. The thermal bridge to the outside world

is also removed. For HTS, especially the crystalline compound REBCO, PCM remains a challenge as the perfect HTS joint is too difficult to manufacture and joint resistance is almost unavoidable [70]. A large HTS magnet can contain dozens of such joint resistances, causing current decay in the HTS magnet. Moreover, at higher operating temperatures, a phenomenon known as flux creep can also cause the decay of current [71]. These two factors prohibit the HTS from working in PCM. Power supply and current leads cannot be removed as for LTS.

This problem has been mitigated with the invention of superconducting wireless DC power supplies, named HTS flux pumps [72 73]. Flux pumps enable an HTS magnet to operate in a regime similar to PCM without the current leads, substantially reducing the power consumption and heat loss. Moreover, any HTS magnet system equipped with a flux pump is more likely to become portable due to less auxiliary equipment such as a cryocooler, bulky power supplies, and current leads. Two categories of flux pumps, based on different mechanisms [74 75], travelling wave [76 77 78 79 80 81] and transformer rectifier [82 83 84 85] have been shown to reach more than kilo-ampere output [86 87 88]. Additionally, current leads and flux pump can be simultaneously removed from the cryostat [89]. Fast current regulation and accurate bipolar current control were also demonstrated [90 91]. With these developments and further advance in HTS flux pumps, addressing the barrier of heat loss, the inability for HTS magnets to operate in PCM is expected to be fully overcome in the next 5-10 years.

[H2] Cost of superconductors and their trend

The barrier of high cost of superconductors arises partly because there has never been, as of the middle of 2024, a true enabling application. Except for research magnets and large capital projects such as the Large Hadron Collider and the ITER, the only obvious large-scale market is given by MRI systems. These applications are all based on LTS systems

With respect to HTS, a surge in demand for superconducting cables and tapes has been registered, fuelled by advancements in fusion reactors and electrical machines. A compact tokamak fusion reactor such as the Commonwealth fusion SPARC reactor requires 10,000 km of 4mm wide REBCO superconducting cable [92]. EcoSwing — an European commission funded project — developed a 3.6 MW superconducting generator with 40 poles of 500m of superconducting tape on the rotor [93]. Airbus UpNext have launched the 'advanced superconducting and cryogenic experimental powertrain demonstrator' project to develop a superconducting electrical aircraft to meet their net zero target [94]. Thousands of kilometres of superconducting materials are used for each project, constituting a significant portion of their overall costs. Wind turbines will be the biggest beneficiaries from the potential price drop of HTS materials, because of the original intention of maximizing power generated at low-cost. This project has established a greatly increased demand for HTS, and cost reductions will surely follow.

When considering conductor pricing, it is important to differentiate between the manufacturing cost and the purchasing price. The manufacturing cost of a conductor is markedly influenced by the volume and the continuity of the production process. The purchasing price is determined by various factors that include manufacturing cost, profit margin, competition, market conditions, overhead expenses, taxes, etc., and it is ultimately set by the manufacturer. In general, the 2024 indicative purchase-prices of Ø 0.8 mm Bi-2223 and Bi-2212 are around 20 US$ m^{-1} and 75 US$ m^{-1}, respectively. The typical purchase-price for a 4 mm REBCO is around 40 US$ m^{-1} [42] but this value depends on the quality of the tape in terms of critical current and tends to be fixed at the point of sale. A substantial surge in demand for 2nd generation HTS tapes, attributed to fusion development, that will reduce the overall manufacturing cost thanks to a larger volume of production is expected [95]. Since the 2010s , the price of REBCO has dropped to about one-tenth of its previous

level, with a projected linear reduction over the next 5-10 years (2030-2035). Additionally, advancements in manufacturing technology have substantially enhanced the critical current density of REBCO tapes, offering greater flexibility with tape width during the design phase. Manufacturers can now produce wide tapes and then slit them into narrower ones or filaments according to specific requirements, thereby expediting the overall manufacturing process [96].

Conversely, projections cannot be relied upon solely for all materials. For instance, the price of Nb_3Sn has been increasing over since 2010, while the price of BSCCO remains stable. This difference is likely to be driven by mineral costs: BSCCO requires a silver matrix, and this tends to dominate the price. Although for REBCO the material cost is insignificant, accounting for only 1% of the current cost, meaning that reductions in price through increased production volume or improved manufacturing methods are not negatively offset by material costs.

The levelized cost of energy (LCOE) is one of the most important factors to determine whether a power generating system can break-even over its life cycle. LCOE values, expressed in US$ MWh^{-1}, can be estimated using the standard given by the United Kingdom Department for Energy Security & Net Zero:

$$LCOE = \frac{\sum_n \frac{CAPEX_n + OPEX_n}{(1+r)^n}}{\sum \frac{AEP_{net,n}}{(1+r)^n}} \quad (2)$$

where $CAPEX_n$, $OPEX_n$, and $AEP_{net,n}$ are the capital expenditures, operational expenditures, and net average annual energy production in year *n* respectively, and r represents the discounted rate [97]. Fundamentally, LCOE is the minimum cost of energy that must be sold at for a project to break even by the end of its lifetime.

A conventional fixed-bottom offshore 10 MW level wind turbine has a standard LCOE of 95 US$ MWh^{-1}, and the generator itself takes 36.6% of overall component cost (CAPEX) [98]. This means if electricity is sold at this price, the project will break even over the course of its lifecycle of 25 years. This gives 21 million US$ as the total sum cost across those 25 years. Increasing the electricity price higher than the estimated LCOE or reducing the overall expenditures will accelerate the project break-even point and lead to earlier profitability (Equation 2). If electricity is sold at a price 50% higher than the estimated LCOE, the project is likely to break even in year 15.

The LCOE of a 11 MW permanent magnet superconducting generator using about 300 km of MgB_2 on its rotor and 246.64 km on its stator, assuming 3 USD m^{-1}, consists of about 18.2% of total generator cost [99]. A 10 MW generator made with HTS materials with similar conditions as EcoSwing, has an estimated LCOE of 212.88 US$ MWh^{-1}, which is 6.1 US$ MWh^{-1} higher than the one of the permanent magnet at 206.78 US$ MWh^{-1} [100] . With a projected cost reduction of 40%, the LCOE of the super conducting turbine drops to 205.56 US$ MWh^{-1}. The calculations that produced these numbers assumed 25 years as the lifecycle of as turbine, the cost of the conductor to be 76 USD m^{-1} (price of 2021). Without that 40% reduction in conductor cost, the permanent magnet turbine is still more cost-effective with approximately 13 million US$ saved over the 25-year lifetime. Considering the reduction in conductor cost, the superconducting turbine comes out to be 2.6 million US$ cheaper over that lifetime. It should be noted that there is no data for either a permanent magnet- or a superconducting- turbine operating for 25 years. This is important because if the lifetime of the turbine is shorter than the capital expenditure is more important. The permanent magnet turbine costs around 7 million US$ and the superconducting turbine costs around 14.2 million US$[100]. Thus, the cost of superconductors is incredibly important. An in-depth analysis of cost evaluation presented for a magnet that constructed using Nb–Ti, Nb_3Sn, Bi-2223, or REBCO, in terms of capital-cost and operating-cost[101], showed that the total cost for REBCO is more than double that of Bi-2223, and more than four times the one for Nb-Ti

and Nb_3Sn[42] . Additionally, MRI is a very mature market and is largely satisfied by LTS. Consequently, historically, the MRI manufacturers have shown little interest in HTS solutions.

[H1] Applications

Superconductors would be ubiquitous, but for the fact that they require certain conditions to work such as low temperature or extremely high pressures, their practical applications are limited in the real world. As of 2024, HTS materials are always accompanied by cooling systems which make the whole device less compact and efficient. Despite this drawback, some applications, such as MRI, rotating machines, and nuclear fusion, are promising financially and efficiently.

[H2] MRI

The first MRI was proposed in 1969 by Damadian [102], who filed a patent in 1972 [103]. The first commercial MRI, a whole-body scanner, was built by FONAR in 1980 [104]. Following a rapid progress, the first mobile MRI system was produced in 1985 and, in the same year, a surgical procedure was performed inside an MRI at University of California Los Angeles[105].

An MRI scanner presents three main components (Fig. 3a): the main magnet, which generates the high magnetic field; the gradient coils, which can produce a varying magnetic field for the spatial encoding of signals; and the radio frequency (RF) coils, that are used to transmit a RF field that excites protons in the body and caused them to emit a signal that is detected by the scanner.

Typically, an MRI system uses a magnetic field of 1.5 T or 3 T (the higher the field the better the resolution of the images). Nevertheless, there are low-field examples based on permanent magnets and variations include open MRI and sit or stand-up MRI. As of 2024, most of the developments are concentrated on “low-cost” permanent magnet MRI’s and ultra-high field systems (> 10 T) [106]. Because the majority of MRIs are based on LTS, interest has been expressed in using MgB_2 [107] [108]. As for NbTi, MgB_2 is available as a wire and could potentially provide a direct replacement. The cost of the material (MgB_2) is comparable to that of Nb_3Sn and NbTi. However, MgB_2 magnets can be run at a higher temperature with respect to Nb_3Sn and NbTi ones. Thus, the primary driver behind the potential move to MgB_2 is the cost of power to keep the material cold .

REBCO, specifically YBCO, is also under consideration [109] [110] [111]. The price of the material is still prohibitive, with $70-100/m for 12mm wide tapes, but the running costs will be lower and, thanks to its much higher current density, the opportunity to build lighter, higher field, truly portable MRIs is a potential driver [110]. When comparing MgB_2, REBCO and BSCCO as potential alternatives to NbTi, the cost of the materials and other technical shortcoming, e.g. AC losses and quench of HTS conductors are still major barriers [112]. Quite a few HTS MRI magnets have been built and tested since the beginning of the 2010s. For example, a 1.5 T MRI scanner magnet was developed and tested in 2013 using YBCO tape [113]. A 3 T Bi-2223 HTS magnet was developed and tested in 2013 in Japan [114]. A 3 T HTS magnet was successfully used for imaging in 2016 [115]. In addition, the recent interest in Compact tokamaks using YBCO, is driving the cost of YBCO down[116].

[H2] Rotating machines

Superconductors can be used to construct rotating machines, either motors or generators. The rated power of a rotating machine depends on factors such as size, rotation speed, armature loading (stator current), and magnetic field strength. Superconducting machines have the potential for higher armature loading and magnetic field strength than those present in conventional machines. In the case of wind turbines, these characteristics can compensate for the relatively low rotation speed without the need for a gearbox; in weight-sensitive applications like airplane and ship engines, superconductors can reduce the size and weight of the motor.

[H3] Generator

Numerous projects have focused on wind turbines, which are one of the most suitable and developed applications for superconducting generators. Both LTS and HTS wind turbines have been researched and developed thus far [117] [118]. LTS generators have historically lower costs due to the price of MgB_2; however, the development of REBCO material with increased critical current and gradually lower price have made HTS generator promising. The latest development of EcoSwing [93,96] is a direct drive HTS synchronous generator used on an existing permanent magnet one, with its corresponding power converter being replaced (Fig.3b). This project was tested on a commercial wind turbine and can operate under stable conditions at 2 MW level, as well as achieving the targeted 3.6 MW level [118].

[H3] Motors

In addition to wind turbines, the category of rotating machines includes motors, which present similar economic considerations. In this case, with a growing market demand for airplane motors, weight sensitivity is paramount. In a 2nd generation HTS motor used for electric propulsion, the permanent magnets on the rotor are replaced with HTS coils to produce magnetic fields (Fig. 3c) [119]. For a fully superconducting design, HTS coils can also be used in the stator windings. The targeted power-to-weight ratio is 20 kW kg^{-1} for wide-bodied long-range jets. Achieving this target is exceptionally ambitious, given that conventional electrical machines currently claim a maximum of approximately 10 kW kg^{-1} ref.[120]. Building a superconducting machine to meet this demand involves integrating a cryocooling system, which adds weight (typically 10-30 kg kW^{-1}, ref.[121]). To double the electric or magnetic loading necessary for such a machine poses challenges, especially considering that most electric motors are limited to a maximum flux density of 2 T due to the saturation flux density of iron. While air-cored machines are conceivable, they still face obstacles. Thus, practically, an all-superconducting machine is required, where both the magnetic and electric loading are increased by the presence of superconductors. However, this approach introduces the challenge of AC losses, which could reduce the efficiency of the machine to less than the >99% efficiency required. There are examples of superconducting electric motors for aeroplanes, such as ASCEND and the 'advanced superconducting motor experimental demonstrator (ASuMED)' project; however, the targets are still a long way away.

Hydrogen fuel-cell powered electric aircrafts have the potential to reduce climate impact by 75-90% and hydrogen turbine based electric aircrafts could reduce climate impact by 50-75% [122]. Large-scale hydrogen-powered electric aircrafts at a multi-MW level have highly demanding requirements regarding the power density and efficiency of the superconducting machines. The use of liquid hydrogen as the fuel source offers a cryogenic environment for the superconducting machines. For an aircraft like a Boeing 777, with two GE 90-115B engines, each engine produces roughly 23 MW or a total of 46 MW. A typical latent heat for hydrogen is 447 kJ kg^{-1}. At 1 % inefficiency, 460 kW of cooling would be needed meaning to boil off 1 kg s^{-1} of hydrogen. For a 12-hour flight, around 40000 kg of hydrogen would be needed. This value is lower than the capacity of a Boeing 777-200 (around 85200 kg) [123]. The numbers seem to work. However, this evaluation does not consider the mass (or indeed the volume) of the storage. "Whereas aviation fuel constitutes about 78 % of the combined weight of tank and fuel, liquid hydrogen accounts for just 18 % of the total in current storage designs. To compete with fossil fuels, the fuel weight fraction has to reach at least 28 %" [124], it is hard to see how this can be reached.

[H2] Fusion

To tackle the energy shortage and net-zero challenges, commercialized nuclear fusion is regarded as a necessary part of the solution. Fusion reactors are being developed in a type of magnetic

confinement device, named Tokamak. An HTS tokamak 3D model provided by SPARC is shown in Fig. 3d. The toroidal field coils generate a strong magnetic field that encircles the torus-shaped vacuum vessel, shielding the plasma from the wall and divertor. The poloidal field coils shape the plasma by adjusting the current, preventing instabilities using prepared models. The central solenoid coils and ion cyclotron heating can rapidly charge and heat plasma for operation. In a Tokamak, the energy gain and the power density are proportional to the third and fourth power of magnetic field strength respectively [125]. Developments in HTS magnets have demonstrated their potential of providing an over 20 T peak magnetic field in large magnet. In comparison, for LTS magnets, the largest existing tokamak ITER only achieves 8 T [126]. The net power production of tokamaks is expected to increase employing HTS over LTS. This change could not only reduce the size and cost of tokamak research facilities, but it also lead to the design of a potential new tokamak, called spherical Tokamaks [127]. Spherical Tokamaks have an aspect ratio of 2, between the major radius and the minor radius. Spherical Tokamaks have better confinement ability than a normal tokamak [128]. Better confinement leads to higher power output, which makes spherical Tokamaks a potential choice for future commercialised fusion reactors [28]. However, one necessary part of a spherical Tokamak, to produce a net positive power output, is a high magnetic field (> 15 T) which can only be provided by a HTS magnet.

Billions of US$ have been spent on tokamak prototypes [129], such as ST-series tokamak by Tokamak Energy, SPARC tokamak by Commonwealth Fusion System, STEP tokamak by Culham Centre for Fusion Energy. To sufficiently use HTS, data and experience from LTS tokamak prototypes are a good reference in tackling engineering issues such as quench and AC losses. Examples include ITER tokamak in France, EAST tokamak in China, KSTAR tokamak in Korea [130]. Among these proposals, SPARC tokamak and ST-series are the only two so far focusing on testing hybrid LTS-HTS and full HTS for large scale 20 T magnets. The structure of a typical spherical HTS tokamak magnet presents three formations of coils, including the toroidal field coils, the poloidal field coils and central solenoid field coils. SPARC tokamak is focusing on the construction of toroidal field coils and Tokamak Energy is assembling poloidal field coils. Most of other projects aim to test first wall, blanket, divertor, spherical structure, plasma confinement, etc [130]. Central solenoid field, poloidal field, and toroidal field coils magnet are proposed to be the most expensive parts in a tokamak among all the subsystems, according to the experience from ITER [131]. SPARC ST suggested that a total of 10000 km HTS tape will be needed for the construction of just the toroidal field coils, which is approximately the total amount of HTS tape manufactured globally in a year [132]. Therefore, for future commercialised nuclear fusion research and construction, cost reduction and simplified processes for manufacture are priorities to satisfy the incoming demand. According to trends and predictions we are moving towards this [133].

Nevertheless, assembling HTS in the toroidal field, poloidal filed and central solenoid field coils in SPARC tokamaks extremely challenging. The in-vessel components in SPARC are designed to a high standard against the extreme environment, as must the HTS coils be. Central solenoid field coils are settled in the centre, and typical HTS central solenoid field coils are proposed to continuously operate at high-field (> 15 T) and high current (25 kA), as well as relatively low AC loss during the ramp process for charging the tokamak. Furthermore, the HTS tape for the coils needs to have strong stability against material degradation under mechanical stress, thermal cycling and radiation damage. Additionally, reliable quench detection is necessary. Finally, all these parts need to be cheaper in price for future commercialisation [134].

To help construct these systems, different HTS cables have been developed and tested in different facilities. Popular ones on research include CORC, VIPER, ROEBEL, etc. Most of them are developed for REBCO, because Bi-2212 suffers under radiation damage. CORC is an appropriate option for ST because of its high current density and small bending radius. A 14 T background field magnet at 4 kA current for future ST central solenoid field coils was presented in July 2021 ref.[135]. VIPER cable was developed for toroidal field coils in SPARC, tested in 13 T field and achieved a less than 5% current degradation, which also shows potential to handle the magnetic flux swing during the ramp in poloidal field and central solenoid field coils [136]. Other than cables, methods that develop low-resistance joints, cooling systems, magnet design, quench protection, AC loss analysis, radiation shield are also popular research topics. Both government and private company funded tokamak have set the target of connecting HTS ST to grid by 2030 (Fig. 4). Overall, fusion technology is likely to dominate the superconducting world for decades to come [137].

[H1] Outlook

The superconductivity market is dominated by Asia Pacific Countries and North America. An Technavio analysis done in 2023 shows that the market for 2nd generation HTS wire has surpassed that of LTS wire [138]. The price of LTS is not dropping and the market which is dominated by MRI and nuclear magnetic resonance is largely mature. Factors affecting the price of 2nd generation wire include methods of production, volumes of production and the opening of new markets as it supplants LTS. “New” markets such as transmission and generation and data centres as well as the worldwide demand for power increases might be the drivers in the future [139] .

Even though the cost problem might be solved soon (by the end of the 2020s), the perennial problem of AC losses, which currently restrict the use of superconductors to DC applications, will still be there. Applications such as wind turbines or superconducting machines could be competitive if the cost is reduced. Trying to make a higher power density rotating machine requires the use of superconductors on both the stator and the rotor. This approach runs into the problem of AC losses: the machine might not have an efficiency high enough to be applied, for example, in aeroplanes. Even nuclear fusion, the current driver for HTS, would require a low loss AC cable to avoid the problem of catastrophic failure of our magnet through quench.

Notwithstanding the inherent problems, some interesting developments have been demonstrated in improvements in tape materials, such as PSALM, the building of new magnets, and the prevention of quench. For instance, a collaboration between the Lawrence Berkeley National Laboratory and the National High Magnetic Field Laboratory in 2021 yielded the world’s first HTS BSCCO ($Bi_2Sr_2CaCu_2Ox$) accelerator dipole magnet [140]. In this context, HTS enable more powerful magnets than LTS (such as Nb-Ti) due to the higher upper critical field (BC_2 above 100 T at 4.2 K). The final magnet was based on a canted cosine-theta design using Bi-2212 Rutherford cables that were made from 0.8 mm wires, with a dipole field of 1.64 T in a 31 mm bore at 4.2 K. In addition, the magnet showed excellent operating properties, with a quench current of 3600 A and a field hysteresis below 0.1 %. This example serves as a promising initial benchmark for HTS dipole magnets. In addition, a new YBCO HTS tape for tokamaks was fabricated using Y_2O_3 nanoparticles that can be easily produced over a long distance [133]. This tape showed excellent engineering current density, with reported values of 1000 A m^{-2} at 20 K per 20 T, and over 2000 A m^{-2} at 4.2 K per 20 T with a 40 μm substrate. The tape formulation involved adding Y_2O_3 nanoparticles that are native to YBCO as the vortex pinning centres. This approach contrasts with the commonly adopted method of introducing extrinsic nano-columns aligned about the c-axis as pinning centres. Consequently, the simplified approach resulted in over 300 km of YBCO wire manufactured in 9 months for a commercial fusion power customer. This simplicity is a key step in achieving the economies

of scale needed to lower the price of HTS wires to an acceptable price for fusion and widespread adoption.

Moreover, an interesting project currently underway is the EU funded Super EMFL that aims to produce 32+ and 40+ T all-superconducting magnets. Magnets at this scale are typically hybrid, comprising of a superconducting coil with an internal copper coil. A pitfall of this hybrid construction is the excessive power consumption (several tens of MW) and the limited time of magnet operation. The Super EMFL explores the use of an HTS insert coil, which set the record for the field generated by an HTS insert with a bore diameter of 38 mm [140]. The insert was able to operate in a central field of 32.5 T, of which 14.5 T was generated by the insert itself. Cuprates HTS were used for the insert as they remain superconducting in much higher background fields than conventional LTS such as Nb-Ti. The insert used metal-as-insulation windings [141] to ensure stable operation and reduce the risk of irreversible damage from local HTS failure. The two main factors that hinder the development of an HTS superconductivity market are: cost which acts as a barrier to entry; and AC losses which acts as a block on certain utilizations. Different applications would be enabled if 1) the cost is reduced; 2) the AC loss problem is solved; and 3) nothing happens but market drivers become the dominant force (Table 1). Great effort is being spent on both of these factors: the magnet costs for LTS reactors rose from 37 % of the total reactor cost in 2018 to 45.9 % in 2020 [142], so the goal may still be receding for LTS, even as we are learning. It remains to be seen whether the same is true for HTS reactors.

[H1] Glossary terms

Minimum quench energy – This is the energy required to initiate quench. If the energy available is less than this then quench does not occur

Normal zone propagation velocity – Once quench has been initiated this is the rate at which quench will spread to other parts of the superconductor. A low velocity leads to problems because the quench energy is then concentrated in a small volume and this can lead to burn out.

[H1] References

1. Combescot, R. *Superconductivity: An Introduction*. (Cambridge university press, 2022).
2. Fossheim, K. & Sudbø, A. Superconductivity: Physics and Applications. *Supercond. Phys. Appl.* 1–427 (2005) doi:10.1002/0470020784.
3. Bardeen, J., Cooper, L. N. & Schrieffer, J. R. Theory of superconductivity. *Phys. Rev.* **108**, 1175–1204 (1957).
4. Van Delft, D. & Kes, P. The discovery of superconductivity. *Europhys. News* **42**, 21–25 (2011).
5. Goodstein, D. & Goodstein, J. Richard Feynman and the History of Superconductivity. *Phys. Perspect.* **2**, 30–47 (2000).
6. Kunzler, J. E., Buehler, E., Hsu, F. S. L. & Wernick, J. H. Superconductivity in Nb3Sn at high current density in a magnetic field of 88 kgauss. *Phys. Rev. Lett.* **6**, 89–91 (1961).
7. Matthias, B. T., Geballe, T. H., Geller, S. & Corenzwit, E. Superconductivity of Nb3Sn. *Phys. Rev.* **95**, 1435 (1954).
8. Hardy, G. F. & Hulm, J. K. The superconductivity of some transition metal compounds. *Phys. Rev.* **93**, 1004–1016 (1954).
9. Hardy, G. F. & Hulm, J. K. Superconducting silicides and germanides [11]. *Phys. Rev.* **89**, 884 (1953).

10. Banno, N. Low-temperature superconductors: Nb3Sn, Nb3Al, and NbTi. *Superconductivity* **6**, (2023).
11. Bednorz, J. G. & Müller, K. A. Possible high Tc superconductivity in the Ba-La-Cu-O system. *Zeitschrift für Phys. B Condens. Matter* **64**, 189–193 (1986).
12. Wu, M. K. *et al.* Superconductivity at 93 K in a new mixed-phase Yb-Ba-Cu-O compound system at ambient pressure. *Phys. Rev. Lett.* **58**, 908–910 (1987).
13. Schilling, A., Cantoni, M., Guo, J. D. & Ott, H. R. Superconductivity above 130 k in the hg–ba–ca–cu–o system. *Nature* (1993).
14. Schilling, A., Cantoni, M., Guo, J. D. & Ott, H. R. Superconductivity above 130 K in the Hg-Ba-Ca-Cu-O system. *Nature* **363**, 56–58 (1993).
15. Putilin, S. N., Antipov, E. V., Chmaissem, O. & Marezio, M. Superconductivity at 94 K in HgBa2Cu04+δ. *Nature* **362**, 226–228 (1993).
16. Kaneko, T., Yamauchi, H. & Tanaka, S. Zero-resistance temperature of Tl-based '2223' superconductor increased to 127 K. *Phys. C Supercond. its Appl.* **178**, 377–382 (1991).
17. Parkin, S. S. P. *et al.* Bulk superconductivity at 125 K in Tl2Ca2Ba2Cu3Ox. *Phys. Rev. Lett.* **60**, 2539–2542 (1988).
18. Gopalakrishnan, I. K., Yakhmi, J. V. & Iyer, R. M. Stabilization of superconductivity in TlBa2CuO5-δ at 9.5 K and its enhancement to 43 K in TlBaSrCuO5-δ. *Phys. C Supercond. its Appl.* **175**, 183–186 (1991).
19. Putilin, S. N., Bryntse, I. & Antipov, E. V. New complex copper oxides: HgBa2RCu2O7 (R = La, Nd, Eu, Gd, Dy, Y). *Mater. Res. Bull.* **26**, 1299–1307 (1991).
20. Choi, C. Q. Superconducting Wire Sets New Current Capacity Record. *IEEE Spectrum* https://spectrum.ieee.org/high-temperature-superconductor-current-capacity (2024).
21. Nationalmaglab. Engineering Critical Current Density vs. Applied Field for Superconductors Available in Long Lengths. https://nationalmaglab.org/media/4v0fnuzu/je_vs_b-041118a.pdf (2018).
22. eCAPITICAL. Record performance for HTS Wires: current carrying capacity of 1350 Amperes reached. https://ecapital.vc/news/record-performance-for-hts-wires-current-carrying-capacity-of-1350-amperes-reached/?cookie-state-change=1727188011213 (2020).
23. Sumption, M. D., Murphy, J., Susner, M. & Haugan, T. Performance metrics of electrical conductors for aerospace cryogenic motors, generators, and transmission cables. *Cryogenics (Guildf).* **111**, 103171 (2020).
24. Song, X. *et al.* Designing and Basic Experimental Validation of the World's First MW-Class Direct-Drive Superconducting Wind Turbine Generator. *IEEE Trans. Energy Convers.* **34**, 2218–2225 (2019).
25. Abrahamsen, A. B. *et al.* Superconducting wind turbine generators. *Supercond. Sci. Technol.* **23**, (2010).
26. Masson, P. J., Breschi, M., Tixador, P. & Luongo, C. A. Design of HTS axial flux motor for aircraft propulsion. *IEEE Trans. Appl. Supercond.* **17**, 1533–1536 (2007).
27. Cosmus, T. C. & Parizh, M. Advances in whole-body MRI magnets. *IEEE Trans. Appl. Supercond.* **21**, 2104–2109 (2011).
28. Sykes, A. *et al.* Compact fusion energy based on the spherical tokamak. *Nucl. Fusion* **58**, (2018).
29. Larbalestier, D., Gurevich, A., Feldmann, D. M. & Polyanskii, A. High-Tc superconducting materials for electric power applications. *Nature* **414**, 368–377 (2001).
30. Tsukamoto, O. *et al.* AC transport current loss of assembled conductor of HTS tapes. *Phys. C Supercond. its Appl.* **310**, 197–201 (1998).

31. Bucho, L. F. D., Fernandes, J. F. P., Biasion, M., Vaschetto, S. & Cavagnino, A. Experimental Assessment of Cryogenic Cooling Impact on Induction Motors. *IEEE Trans. Energy Convers.* **37**, 2629–2636 (2022).
32. Geng, J. *et al.* A kilo-ampere level HTS flux pump. *Supercond. Sci. Technol.* **32**, 74004 (2019).
33. Sung, H. J., Park, M., Go, B. S. & Yu, I. K. A study on the required performance of a 2G HTS wire for HTS wind power generators. *Supercond. Sci. Technol.* **29**, (2016).
34. P, D. *CRC Handbook of Chemistry and Physics*. *Journal of Molecular Structure* vol. 268 (CRC Press, 1992).
35. Chen, X. H. *et al.* Superconductivity at 56K in samarium-doped SrFeAsF. *J. Phys. Condens. Matter* **21**, 142203 (2009).
36. Boeri, L. *et al.* The 2021 room-temperature superconductivity roadmap. *J. Phys. Condens. Matter* **34**, 183002 (2022).
37. Yao, C. & Ma, Y. Superconducting materials: Challenges and opportunities for large-scale applications. *iScience* **24**, 102541 (2021).
38. Shipulin, I. A. *et al.* Effect of Silver Doping on the Superconducting and Structural Properties of YBCO Films Grown by PLD on Different Templates. *Materials* vol. 15 at https://doi.org/10.3390/ma15155354 (2022).
39. Muralidhar, M., Shadab, M., Sai Srikanth, A., Jirsa, M. & Jacques, N. Review on high-performance bulk MgB2 superconductors. *J. Phys. D. Appl. Phys.* **57**, 053001 (2024).
40. Durrell, J. H. *et al.* A trapped field of 17.6 T in melt-processed, bulk Gd-Ba-Cu-O reinforced with shrink-fit steel. *Supercond. Sci. Technol.* **27**, (2014).
41. Suyama, M., Pyon, S., Iijima, Y., Awaji, S. & Tamegai, T. Trapping a magnetic field of 17.89 T in stacked coated conductors by suppression of flux jumps. *Supercond. Sci. Technol.* **35**, (2022).
42. Godeke, A. High temperature superconductors for commercial magnets. *Supercond. Sci. Technol.* **36**, (2023).
43. Superconductivity, H. *Handbook of Superconductivity,Volume I*. (CRC Press, 2023).
44. Silver, T. M., Dou, S. X. & Jin, J. X. Applications of high temperature superconductors. *Europhys. News* **32**, 82–86 (2001).
45. Wulff, A. C., Abrahamsen, A. B. & Insinga, A. R. Multifilamentary coated conductors for ultra-high magnetic field applications. *Supercond. Sci. Technol.* **34**, (2021).
46. Gallagher-Daggitt, G. E. Superconductor Cables for Pulsed Dipole Magnets. *Techinical Rep. Rutherford Lab. Memo.* (1973).
47. Goldacker, W. *et al.* High current DyBCO-ROEBEL Assembled Coated Conductor (RACC). *J. Phys. Conf. Ser.* **43**, 901–904 (2006).
48. Hao, L. *et al.* Conceptual Design and Optimisation of HTS Roebel Tapes. *IEEE Trans. Appl. Supercond.* **32**, (2022).
49. Takayasu, M., Chiesa, L., Bromberg, L. & Minervini, J. V. HTS twisted stacked-tape cable conductor. *Supercond. Sci. Technol.* **25**, 014011 (2012).
50. Weiss, J. D., Mulder, T., Ten Kate, H. J. & Van Der Laan, D. C. Introduction of CORC® wires: Highly flexible, round high-temperature superconducting wires for magnet and power transmission applications. *Supercond. Sci. Technol.* **30**, 14002 (2017).
51. Hao, L. *et al.* Field Canceling Effect in Double-Layer Roebel Tapes. *IEEE Trans. Appl. Supercond.* **32**, (2022).
52. Hao, L. *et al.* AC Loss Measuring and Modeling of Single-Layer Roebel Tapes. *IEEE Trans. Appl. Supercond.* **34**, 1–5 (2024).

53. Hao, L. *et al.* Transport AC Losses in Multiple-Layer Roebel Tapes. *IEEE Trans. Appl. Supercond.* **33**, (2023).
54. Majoros, M., Sumption, M. D., Collings, E. W. & Van Der Laan, D. C. Magnetization losses in superconducting YBCO conductor-on-round-core (CORC) cables. *Superconductor Science and Technology* vol. 27 125008 (2014).
55. Terzioğlu, R. *et al.* AC loss characteristics of CORC® cable with a Cu former. *Supercond. Sci. Technol.* **30**, (2017).
56. Vojenčiak, M. *et al.* Magnetization ac loss reduction in HTS CORC® cables made of striated coated conductors. *Supercond. Sci. Technol.* **28**, (2015).
57. Jin, H. *et al.* The performance of first CORC cable solenoid insert for development of CFETR high-field magnet. *Nucl. Fusion* **60**, 096028 (2020).
58. Wu, Y. *et al.* Mechanical Analysis of CORC CICC for Future Fusion CS Magnet. *IEEE Trans. Appl. Supercond.* **34**, 1–5 (2024).
59. Mulder, T. *et al.* Design and Preparation of Two ReBCO-CORC® Cable-In-Conduit Conductors for Fusion and Detector Magnets. *IOP Conf. Ser. Mater. Sci. Eng.* **279**, 012033 (2017).
60. Takayasu, M., Mangiarotti, F. J., Chiesa, L., Bromberg, L. & Minervini, J. V. Conductor characterization of YBCO twisted stacked-tape cables. *IEEE Trans. Appl. Supercond.* **23**, (2013).
61. Takayasu, M., Minervini, J. V. & Bromberg, L. *HTS Twisted Stacked-Tape Cable Development*. *Report PSFC/JA-11-10* http://psfc.mit.edu/library1/catalog/reports/2010/%5Cn11ja/11ja010/11ja010_full.pdf (2011).
62. Wang, M. *et al.* Three-dimensional numerical study on transport ac loss of soldered-stacked-square-twisted (3S-T) wire. *IEEE Trans. Appl. Supercond.* **29**, (2019).
63. Wang, M. *et al.* Fabrication and Critical Current Evaluation for HTS Twisted Cables Consisting of Soldered-Stacked-Square (3S) Wires. *IEEE Trans. Appl. Supercond.* **31**, (2021).
64. Lei, Z. *et al.* AC loss study of high-temperature superconducting stacked conductors based on parameter identification method. *Phys. C Supercond. its Appl.* **619**, 1354451 (2024).
65. Wenninger, J. The LHC collider. *Comptes Rendus Phys.* **16**, 347–355 (2015).
66. Seo, K. & Morita, M. Guidelines for LTS magnet design based on transient stability. *Cryogenics (Guildf).* **46**, 354–361 (2006).
67. Huang, X. *et al.* An active quench protection system for MRI magnets. *IEEE Trans. Appl. Supercond.* **20**, 2091–2094 (2010).
68. Green, M. A. Various Quench Protection Methods for HTS Magnets. *IOP Conf. Ser. Mater. Sci. Eng.* **755**, 012134 (2020).
69. Neumeyer, C. *et al.* ITER power supply innovations and advances. *2013 IEEE 25th Symp. Fusion Eng. SOFE 2013* (2013) doi:10.1109/SOFE.2013.6635287.
70. Lu, J. *et al.* Lap joint resistance of YBCO coated conductors. *IEEE Trans. Appl. Supercond.* **21**, 3009–3012 (2011).
71. Feigelman, M. V., Geshkenbein, V. B. & Vinokur, V. M. Flux creep and current relaxation in high-Tc superconductors. *Phys. Rev. B* **43**, 6263–6265 (1991).
72. Coombs, T. A. Superconducting flux pumps. *J. Appl. Phys.* **125**, (2019).
73. Wang, W., Wei, J., Yang, C., Wu, C. & Li, H. Review of high temperature superconducting flux pumps. *Superconductivity* **3**, 100022 (2022).

74. Wang, W. & Coombs, T. Macroscopic Magnetic Coupling Effect: The Physical Origination of a High-Temperature Superconducting Flux Pump. *Phys. Rev. Appl.* **9**, 44022 (2018).
75. Geng, J. & Coombs, T. A. Mechanism of a high- Tc superconducting flux pump: Using alternating magnetic field to trigger flux flow. *Appl. Phys. Lett.* **107**, (2015).
76. Hoffmann, C., Pooke, D. & Caplin, A. D. Flux pump for HTS magnets. *IEEE Trans. Appl. Supercond.* **21**, 1628–1631 (2011).
77. Hamilton, K. *et al.* Design and Performance of a 'squirrel-Cage' Dynamo-Type HTS Flux Pump. *IEEE Trans. Appl. Supercond.* **28**, (2018).
78. Bai, Z., Yan, G., Wu, C., Ding, S. & Chen, C. A novel high temperature superconducting magnetic flux pump for MRI magnets. *Cryogenics (Guildf).* **50**, 688–692 (2010).
79. Fu, L., Matsuda, K., Shen, B. & Coombs, T. HTS Flux Pump Charging an HTS Coil: Experiment and Modeling. *IEEE Trans. Appl. Supercond.* **31**, (2021).
80. Wang, W. *et al.* Charging 2G HTS Double Pancake Coils with a Wireless Superconducting DC P ower Supply for Persistent Current Operation. *IEEE Trans. Appl. Supercond.* **28**, (2018).
81. Zhang, Y. *et al.* Compact Linear-Motor Type Flux Pumps with Different Wavelengths for High-Temperature Superconducting Magnets. *IEEE Trans. Appl. Supercond.* **30**, (2020).
82. Ma, J., Geng, J. & Coombs, T. A. Flux pumping for non-insulated and metal-insulated HTS coils. *Supercond. Sci. Technol.* **31**, 015018 (2018).
83. Leuw, B., Geng, J., Rice, J. H. P., Moseley, D. A. & Badcock, R. A. A half-wave superconducting transformer-rectifier flux pump using J c(B) switches. *Supercond. Sci. Technol.* **35**, 035009 (2022).
84. Geng, J., Brooks, J. M., Bumby, C. W. & Badcock, R. A. Time-varying magnetic field induced electric field across a current-transporting type-II superconducting loop: Beyond dynamic resistance effect. *Supercond. Sci. Technol.* **35**, 025018 (2022).
85. Geng, J. & Coombs, T. A. An HTS flux pump operated by directly driving a superconductor into flux flow region in the E- J curve. *Supercond. Sci. Technol.* **29**, (2016).
86. Wang, W. *et al.* Test of Two Kilo-Amp Linear-Motor Type Flux Pumps With Converged Output Current Over 3.1 kA. *IEEE Trans. Appl. Supercond.* **34**, 1–5 (2024).
87. Geng, J., Bumby, C. W. & Badcock, R. A. Maximising the current output from a self-switching kA-class rectifier flux pump. *Supercond. Sci. Technol.* **33**, 045005 (2020).
88. Venuturumilli, S. *et al.* Temperature dependent behavior of a kA-class superconducting flux pump with a continuous cylindrical stator. *Appl. Phys. Lett.* **123**, 202601 (2023).
89. Lei, Y. *et al.* Through-Wall Excitation of a Conduction Cooling HTS Magnets by a Linear-Motor Type Flux Pump. *IEEE Trans. Appl. Supercond.* **33**, 1–4 (2023).
90. Wu, C. *et al.* Fast Current Regulation and Persistent Current Maintenance of High-Temperature Superconducting Magnets with Contact Power Supply and Flux Pump. *IEEE Trans. Power Electron.* 1–10 (2023) doi:10.1109/TPEL.2023.3342471.
91. Lei, Y. *et al.* Symmetrical Bipolar Current Control of HTS Dynamo Based on a DC Magnetic Field. *IEEE Trans. Appl. Supercond.* **34**, 1–5 (2024).
92. Creely, A. J. *et al.* Overview of the SPARC tokamak. *J. Plasma Phys.* **86**, 1–25 (2020).
93. Winkler, T. The ecoswing project. *IOP Conf. Ser. Mater. Sci. Eng.* **502**, (2019).
94. Ybanez, L. *et al.* ASCEND: The first step towards cryogenic electric propulsion. *IOP Conf. Ser. Mater. Sci. Eng.* **1241**, 012034 (2022).
95. Molodyk, A. Faraday Factory: GA-m/year of 2G HTS in prospect synergies for accelerator magnets. (2023).
96. Werner Prusseit. *HTS-Wire for High Field Magnet Applications Future REBCO Capability in Industry*. *THEVA*

https://indico.cern.ch/event/1032199/contributions/4359092/attachments/2255357/3826776/THEVA %40 CERN roadmap workshop 010621.pdf (2021).
97. BEIS. Electricity Generation Costs 2023. 1–35 (2023).
98. NREL. 2022 Cost of Wind Energy Review . 627281636 (2023).
99. Hoang, T. K., Queval, L., Vido, L. & Nguyen, D. Q. Levelized Cost of Energy Comparison Between Permanent Magnet and Superconducting Wind Generators for Various Nominal Power. *IEEE Trans. Appl. Supercond.* **32**, 1–6 (2022).
100. Jung, G. E., Sung, H. J., Dinh, M. C., Park, M. & Shin, H. A comparative analysis of economics of pmsg and scsg floating offshore wind farms. *Energies* **14**, 1386 (2021).
101. Teyber, R., Brouwer, L., Godeke, A. & Prestemon, S. Thermoeconomic cost optimization of superconducting magnets for proton therapy gantries. *Supercond. Sci. Technol.* **33**, 105005 (2020).
102. Damadian, R. Tumor detection by nuclear magnetic resonance. *Science (80-.).* **171**, 1151–1153 (1971).
103. Bottomley, P. A., Hardy, C. J., Argersinger, R. E. & Allen moore, G. A review of 1H nuclear magnetic resonance relaxation in pathology: Are T1 and T2 diagnostic? *Medical Physics* vol. 14 1–37 (1987).
104. Damadian, R. Field focusing n.m.r. (FONAR) and the formation of chemical images in man. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **289**, 489–500 (1980).
105. FONAR History. https://www.fonar.com/history.html.
106. Yanagisawa, Y., Hamada, M., Hashi, K. & Maeda, H. Review of recent developments in ultra-high field (UHF) NMR magnets in the Asia region. *Supercond. Sci. Technol.* **35**, 044006 (2022).
107. Choi, Y. *et al.* Persistent-mode operation and magnetization behavior of a solid-nitrogen-cooled MgB2small-scale test coil towards a tabletop 1.5-T osteoporosis MRI. *Supercond. Sci. Technol.* **33**, 125007 (2020).
108. Kodama, M. *et al.* Feasibility study of novel rapid ramp-down procedure in MgB2MRI magnet using persistent current switch with high off-resistivity. *Supercond. Sci. Technol.* **34**, 74003 (2021).
109. Yokoyama, S. *et al.* Design and cooling properties of high stable field REBCO superconducting magnet for MRI. *IEEE Trans. Appl. Supercond.* **30**, 1–4 (2020).
110. Ozturk, Y. *et al.* Current Status in Building a Compact and Mobile HTS MRI Instrument. *IEEE Trans. Appl. Supercond.* **31**, 1–5 (2021).
111. Wang, T. *et al.* Conceptual Design of 3-T All HTS MRI Using No-Insulation Winding Technology: Electromagnetic Stress Reinforced Structure. *IEEE Trans. Appl. Supercond.* **31**, 1–5 (2021).
112. Parizh, M., Lvovsky, Y. & Sumption, M. Conductors for commercial MRI magnets beyond NbTi: Requirements and challenges. *Supercond. Sci. Technol.* **30**, 014007 (2017).
113. Parkinson, B. J., Slade, R., Mallett, M. J. D. & Chamritski, V. Development of a cryogen free 1.5 T YBCO HTS magnet for MRI. *IEEE Trans. Appl. Supercond.* **23**, (2013).
114. Terao, Y. *et al.* Newly designed 3 T MRI magnet wound with Bi-2223 tape conductors. *IEEE Trans. Appl. Supercond.* **23**, (2013).
115. Corporation, M. E. *Mitsubishi Electric , Kyoto Univ . and Tohoku Univ . Succeed in World ' s First 3 Tesla MRI with High-Temperature Coils*. https://www.mitsubishielectric.com/news/2016/pdf/0524.pdf (2020).
116. Molodyk, A. & Larbalestier, D. C. The prospects of high-temperature superconductors. *Science (80-.).* **380**, 1220–1222 (2023).

117. Kalsi, S. S. Superconducting Wind Turbine Generator Employing MgB2 Windings Both on Rotor and Stator. *IEEE Trans. Appl. Supercond.* **24**, (2014).
118. Song, X. *et al.* Commissioning of the World's First Full-Scale MW-Class Superconducting Generator on a Direct Drive Wind Turbine. *IEEE Trans. Energy Convers.* **35**, 1697–1704 (2020).
119. Karmaker, H. *et al.* High-Power Dense Electric Propulsion Motor. *IEEE Trans. Ind. Appl.* **51**, 1341–1347 (2015).
120. H3X | Electric Aircraft Propulsion. https://www.h3x.tech/#hpdm-3000 (2023).
121. Haran, K. S. *et al.* High power density superconducting rotating machines - Development status and technology roadmap. *Supercond. Sci. Technol.* **30**, (2017).
122. Undertaking, F. C. & H. J. *Hydrogen-Powered Aviation | Www.Fch.Europa.Eu*. (2020). doi:10.2843/766989.
123. Ford, T. Boeing 777 fuel system. *Aircr. Eng. Aerosp. Technol.* **70**, 199–202 (1998).
124. Kramer, D. Hydrogen-powered aircraft may be getting a lift. *Physics Today* vol. 73 27–29 at https://doi.org/10.1063/PT.3.4632 (2020).
125. Wesson, J. *Tokamaks*. (Oxford University Press, 2011).
126. Bruzzone, P. *et al.* High temperature superconductors for fusion magnets. *Nucl. Fusion* **58**, 103001 (2018).
127. Peng, Y. K. M. & Strickler, D. J. Features of spherical torus plasmas. *Nucl. Fusion* **26**, 769–777 (1986).
128. Kaye, S. M., Connor, J. W. & Roach, C. M. Thermal confinement and transport in spherical tokamaks: A review. *Plasma Phys. Control. Fusion* **63**, 123001 (2021).
129. $6.2 Billion Fusion Energy Funding Race : Turning the Dream of Creating a Star on Earth into Reality — Nuclear Business Platform. https://www.nuclearbusiness-platform.com/media/insights/62-billion-fusion-energy-funding-race-turning-the-dream-of-creating-a-star-on-earth-into-reality.
130. Meschini, S. *et al.* Review of commercial nuclear fusion projects. *Front. Energy Res.* **11**, 1157394 (2023).
131. SEIFE, C. World's Largest Fusion Project Is in Big Trouble, New Documents Reveal | Scientific American. *Scientific america* https://www.scientificamerican.com/article/worlds-largest-fusion-project-is-in-big-trouble-new-documents-reveal/ (2023).
132. Zhai, Y., Otto, A. & Zarnstorff, M. Low cost, simpler HTS cable conductors for fusion energy systems. *IOP Conf. Ser. Mater. Sci. Eng.* **1241**, 012023 (2022).
133. Molodyk, A. *et al.* Development and large volume production of extremely high current density YBa2Cu3O7 superconducting wires for fusion. *Sci. Rep.* **11**, 1–11 (2021).
134. Hartwig, Z. S. *et al.* VIPER: An industrially scalable high-current high-temperature superconductor cable. *Supercond. Sci. Technol.* **33**, 11LT01 (2020).
135. Zhai, Y., van der Laan, D., Connolly, P. & Kessel, C. Conceptual design of HTS magnets for fusion nuclear science facility. *Fusion Eng. Des.* **168**, 112611 (2021).
136. Hartwig, Z. S. *et al.* The SPARC Toroidal Field Model Coil Program. *IEEE Trans. Appl. Supercond.* **34**, 1–16 (2023).
137. Zhai, Y. *et al.* R&D Needs for a U.S. Fusion Magnet Base Program. *IEEE Trans. Appl. Supercond.* **34**, 1–5 (2024).
138. Technavio. High Temperature Superconducting Wires Market Trends [2023 Report]. https://www.technavio.com/report/high-temperature-superconducting-wires-market-analysis.

139. Patel, I. *et al.* Stochastic optimisation and economic analysis of combined high temperature superconducting magnet and hydrogen energy storage system for smart grid applications. *Appl. Energy* **341**, (2023).
140. Fazilleau, P., Chaud, X., Debray, F., Lécrevisse, T. & Song, J. Bin. 38 mm diameter cold bore metal-as-insulation HTS insert reached 32.5 T in a background magnetic field generated by resistive magnet. *Cryogenics (Guildf).* **106**, 103053 (2020).
141. Song, J. Bin *et al.* Metal-as-Insulation HTS Insert for Very-High-Field Magnet: A Test Report after Repair. *IEEE Trans. Appl. Supercond.* **32**, (2022).
142. Lindley, B., Roulstone, T., Locatelli, G. & Rooney, M. Can fusion energy be cost-competitive and commercially viable? An analysis of magnetically confined reactors. *Energy Policy* **177**, 113511 (2023).
143. Namburi, D. K., Shi, Y. & Cardwell, D. A. The processing and properties of bulk (RE)BCO high temperature superconductors: Current status and future perspectives. *Supercond. Sci. Technol.* **34**, (2021).
144. Christen, D. Current limits to wire technology. *Nature* **392**, 862–863 (1998).
145. Chen, P. *et al.* Development of a persistent superconducting joint between Bi-2212/Ag-alloy multifilamentary round wires. *Supercond. Sci. Technol.* **30**, 025020 (2017).
146. Zhang, Z., MacManus-Driscoll, J., Suo, H. & Wang, Q. Review of synthesis of high volumetric density, low gravimetric density MgB2 bulk for potential magnetic field applications. *Superconductivity* **3**, 100015 (2022).
147. Braccini, V., Nardelli, D., Penco, R. & Grasso, G. Development of ex situ processed MgB2 wires and their applications to magnets. *Phys. C Supercond. its Appl.* **456**, 209–217 (2007).
148. Goldacker, W. *et al.* Roebel cables from REBCO coated conductors: A one-century-old concept for the superconductivity of the future. *Supercond. Sci. Technol.* **27**, (2014).
149. Van Der Laan, D. C., Weiss, J. D. & McRae, D. M. Status of CORC® cables and wires for use in high-field magnets and power systems a decade after their introduction. *Supercond. Sci. Technol.* **32**, 33001 (2019).
150. Takayasu, M., Chiesa, L., Allen, N. C. & Minervini, J. V. Present status and recent developments of the twisted stacked-tape cable conductor. *IEEE Trans. Appl. Supercond.* **26**, 25–34 (2016).
151. Takayasu, M. Width-bending characteristic of REBCO HTS tape and flat-tape Rutherford-type cabling. *Supercond. Sci. Technol.* **34**, 125020 (2021).
152. Bergen, A. *et al.* Design and in-field testing of the world's first ReBCO rotor for a 3.6 MW wind generator. *Supercond. Sci. Technol.* **32**, 125006 (2019).
153. This Fusion Reactor Is Held Together With Tape - IEEE Spectrum. https://spectrum.ieee.org/fusion-2662267312.
154. Davies, A. High-Temperature Superconducting Magnet Technology for Fusion Energy. *Tokamak Energy* https://www.energy.cam.ac.uk/files/tokamak_energy_ltd_-_10_nov_2023.pdf (2023).
155. Venuturumilli, S. Tokamak Energy HTS magnet technology. https://snf.ieeecsc.org/files/ieeecsc/slides/Venturumilli presentation final.pdf (2023).
156. McNamara, S. *et al.* Achievement of ion temperatures in excess of 100 million degrees Kelvin in the compact high-field spherical tokamak ST40. *Nucl. Fusion* **63**, (2023).
157. Philip Ball. The Race to Fusion Energy. *Nature* **599**, 362–366 (2021).
158. Rodriguez-Fernandez, P. *et al.* Overview of the SPARC physics basis towards the exploration of burning-plasma regimes in high-field, compact tokamaks. *Nuclear Fusion* vol. 62 (2022).

159. Commonwealth Fusion Systems. Commonwealth Fusion Systems Signs $15 Million DOE Agreement To Advance Commercial Fusion Energy. https://www.prnewswire.com/news-releases/commonwealth-fusion-systems-signs-15-million-doe-agreement-to-advance-commercial-fusion-energy-302166614.html (2024).
160. Iter. WHAT IS ITER? *iter.org* https://www.iter.org/proj/inafewlines (2023).
161. Dittmar, M. *Status and Prospects of the ITER Plasma Physics Experiment: Is It Time to Terminate the Project?* http://ihp-lx2.ethz.ch/energy21/ITERreport1.pdf (2019).
162. ITER. Summary of Presentation by Pietro Barabaschi, ITER Director-General. https://www.iter.org/doc/www/content/com/Lists/Stories/Attachments/4056/Baseline_Press_Conference_Summary_July-2024_b.pdf (2024).

[H1] Acknowledgements

The authors thank xxxxx

[H1] Author contributions

T.A.C, L.H., A.S., J.H., Q.W., I.P., H.W., Y.W. researched data for the article. T.A.C., L.H., J.H., T.C. contributed substantially to discussion of the content. T.A.C, L.H., Q.W., W.W. wrote the article. T.A.C, L.H., A.S., J.H., Q.W., H.W., Y.W., T.C. reviewed and/or edited the manuscript before submission.

[H1] Competing interests

The authors declare the existence of a financial/non-financial competing interest. Professor Tim Coombs is the director of Magnifye a company which specialises in research and development of superconducting devices

[H1] Peer review information

Nature Reviews XXX thanks [Referee#1 name], [Referee#2 name] and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

[H1] Related links

- An HTS tokamak 3D model: https://spectrum.ieee.org/fusion-2662267312
- ASCEND: https://www.airbus.com/en/newsroom/stories/2023-12-ascending-to-new-heights-with-cryogenic-superconductivity
- ASuMED: http://www.asumed.oswald.de/index.php
- CORC: https://www.advancedconductor.com/corccable/
- EAST tokamak: http://east.ipp.ac.cn/
- European Magnetic Field Laboratory: https://emfl.eu/
- F-70 compressor: https://shicryogenics.com/product/f-70-indoor-water-cooled-compressor-series/
- ITER: https://www.iter.org/
- ITER tokamak: https://www.iter.org/mach
- KSTAR tokamak: https://www.kfe.re.kr/eng
- Large Hadron Collider: https://home.cern/science/accelerators/large-hadron-collider
- ROEBEL: https://iopscience.iop.org/article/10.1088/0953-2048/27/9/093001/meta
- SPARC tokamak: https://www.psfc.mit.edu/sparc
- ST-series: https://tokamakenergy.com/2022/10/26/tokamak-energy-announces-st80-hts-advanced-prototype-on-path-to-demonstrate-grid-ready-fusion-power-in-the-early-2030s/

- STEP tokamak: https://step.ukaea.uk/
- Sumitomo CH110: https://shicryogenics.com/product/ch-110-77k-cryocooler-series/
- Super EMFL: https://emfl.eu/superemfl/
- The capacity chart of Sumitomo CH110: https://shicryogenics.com/wp-content/uploads/2020/09/CH-110_Capacity_Map.pdf
- Tokamak Energy: https://tokamakenergy.com/
- United Kingdom Department for Energy Security & Net Zero: https://www.gov.uk/government/organisations/department-for-energy-security-and-net-zero
- VIPER: https://iopscience.iop.org/article/10.1088/1361-6668/abb8c0

[H1] Key Points

- Low temperature superconductors (LTS) require either cryocoolers or costly and increasingly rare liquid helium. Whereas high temperature superconductors (HTS), though still needing cryogenic conditions, can operate at more accessible temperatures using liquid nitrogen, and can support current at higher magnetic fields than LTS
- The primary factors that are impeding the adoption and development of large-scale applications of HTS are high manufacturing and cooling costs the latter of which is exacerbated by alternating current losses
- The price of LTS is stagnant, and the market, mostly magnetic resonance imaging, is fully developed. Many applications such as motors, and fusion coils require much higher fields than can currently be produced by LTS or conventional materials (where 2 T is the maximum practical value for iron).
- Increased demand and improved manufacturing techniques for HTS, is driving the price of HTS down.
- Developments to tackle AC losses are continuing and promising. With innovations such as PSALM, building on previous work such as Rutherford and Roebel, with other cables such as CORC also slowing being taken up. Compared with normal HTS tapes, single-layer PSALM cables can reduce the transport AC loss by 60% due to patterning and double-layer PSALM cables can reduce the loss by a further 20% due to the field cancelling effect. The magnetisation loss reduction is proportional to the filament numbers: a 70% reduction can be obtained using 4 filaments.

[H1] Display items

Table I | **The way ahead for high temperature superconductors (HTS).** For each application (rotating machines, nuclear fusion and HTS magnetic resonance imaging (MRI)), the role of the cost, AC loss and market forces is reported. The colour code describes the significance of the factors with respect to the application: high (dark blue), medium (blue), low (light blue). Alternating current (AC); magnetic resonance imaging (MRI); direct current (DC).

	Cost	AC Loss	Market Forces

Rotating Machines	The high HTS cost is not offset by benefits such as weight savings and simpler turbine construction.	AC losses are a crucial problem in superconducting machines. Unless AC losses are reduced to manageable levels, applications such as motors and generators will be problematic.	Climate change is a key market driver for the wider adoption of HTS machines as they offer emissions-free operation despite the high cost.
Nuclear Fusion	The current costs of superconductors are not a key hindrance. Most fusion projects are funded by governments. Breakthroughs in fusion prototypes will lead to inevitable cost reduction of HTS due to economies of scale.	Mitigating the AC loss problem improves the energy (and cost) efficiency of fusion magnets as they can operate closer to their critical current.	Interest in fusion is highly motivated by the possibility of a having clean, long-term energy source, driven by the need for addressing climate change and finding alternatives to fossil fuels.
HTS MRI	The high cost of HTS is a key barrier to the widespread adoption of HTS MRI coils.	AC losses are not a significant problem as coils are DC-operated.	Pressing market drivers include the need for light, compact, and portable MRI. With HTS magnets these targets can be achieved. Consistent increases in helium prices affect LTS MRI systems.

Figure 1 | **Characteristics of rare earth barium cuprates (REBCO), bismuth strontium calcium copper oxide (BSCCO) and MgB_2.** **a**, an REBCO (yttrium barium copper oxide, YBCO) single grain bulk [143]. **b**, the layer structure of a REBCO (YBCO) coated conductor [143]. **c**, REBCO stacked tapes. **d**, the general pellet form for BSCCO bulks. **e**, a standard industrial superconducting tape, with 'BSCCO' filaments embedded in a matrix of silver [144]. **f**, the cross section of a 1.3 mm diameter Bi-2212 round wire [145]. **g**, a MgB2 bulk sample fabricated by modified precursor infiltration and growth (MPIG) process [146]. **h**, the cross section of a mono-filamentary MgB_2/Fe tape [147]. **i**, a 78-filament low ac loss MgB_2 wire from Hyper Tech Research [121]. **j**, engineering current densities of the most common HTS materials as a function of applied magnetic field at 4.2 K [45].

Figure 2 | **Examples of rare earth barium cuprates (REBCO) cables.** High temperature superconductor (HTS) Roebel cable or Roebel assembled coated conductor (RACC) [148]; cable on round core (CORC) [149]; twisted stacked tape cable (TSTC) [150]; Flat-type HTS Rutherford cable [151]; Patterned superconductors for AC Loss minimisation and current maximisation (PSALM) [53]. Alternating current (AC).

Figure 3 |**Examples of high temperature superconductors (HTS) applications. a,** HTS magnetic resonance imaging (MRI) scanner. The main magnet is used to produce a high magnetic field; the gradient coils can produce a varying magnetic field for the spatial encoding of signals. Radio frequency (RF) coils are used to transmit RF fields that excites protons in the body and causes

them to emit a signal that is detected by the scanner. **b,** Schematic view for the EcoSwing HTS generator, with cooling system [152]. **c,** Basic schematic of a 2nd generation HTS motor used for electric propulsion., The permanent magnets (PMs) on the rotor are replaced with HTS coils to produce magnetic fields. HTS coils can also be used in the stator for a fully-superconducting design [119]. **d,** HTS Tokamak 3D model provided by SPARC. The toroidal field coils generate a strong magnetic field that encircles the torus-shaped vacuum vessel, shielding the plasma from the wall and divertor; the poloidal field coils shape the plasma by adjusting the current to prevent instabilities using prepared models; the central solenoid coils and the ion cyclotron heating can rapidly charge and heat plasma for operation [153].

Figure 4 | **Development timelines for different tokamak system founded by both government organizations and private companies.** Component level timeline for ST-series by Tokamak Energy (UK private company). System level timelines for ST-series by Tokamak Energy, smallest possible arc (SPARC) by commonwealth Fusion Systems (CFS) in collaboration with the Massachusetts Institute of Technology's (MIT) and international thermonuclear experimental reactor (ITER) developed by 7 different countries (China, the European Union, India, Japan, Russia, South Korea and the United States). References for Tokamak Energy: [28 154 155 156] ; References for SPARC [92 136 157 158 159]; References for ITER: [160 161 162]

[H1] Online TOC

High-temperature superconductors are now used mostly in large scale applications, such as magnets and scientific apparatus. Overcoming barriers such as alternating current losses, or high manufacturing costs, will enable many more applications such as motors, generators and fusion reactors.