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PERSPECTIVE

A strategic roadmap for implementing superconductivity towards zero-emission transport

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Abstract
Superconductivity is an essential technology for reducing carbon emissions and electrifying the transportation sector. Its unique ability to provide higher power density and greater efficiency sets it apart from other technologies. This document outlines a plan for integrating superconducting technology into the transportation sector, identifying major challenges and interim steps to be taken to overcome them. Implementing this plan and securing public and private funds will help transition the transportation sector towards zero-emission aircraft, high-capacity efficient shipping, and widespread use of a superconductivity-liquid hydrogen energy platform for transportation.

1. Impact statement

Blueprints for the decarbonization of transport across the G20 nations identify several common actions [1]:

1. Electrification of transport must increase.
2. Hydrogen must become a primary transportation fuel.
3. Sustainable liquid fuels must be developed for heavy and long-range transport.

These blue prints have missed the impact capability of the superconducting materials, which have been too often regarded as a scientific curiosity rather than an important and mature technology. Superconducting technology has reached in several fields a high technology readiness level (TRL, see [2]) and has more potential applications under development. It can provide higher power density and greater efficiency in ways that no other technology can. Therefore, it can play a fundamental role in the path to decarbonization.

This document presents a roadmap for applying superconducting technology to the electrification of transport systems. Financing and executing these roadmaps will facilitate the transformation of the transport sector towards zero-emission solutions.

Since the discovery of superconductivity in 1911, the development of practical low-temperature superconductors in the 1960s, and the discovery of high-temperature superconductivity in the 1980s, mature practical superconductors have found their way into many commercialized applications, with magnetic resonance imaging (MRI) for hospitals and nuclear magnetic resonance (NMR) for chemical, biological, and materials research, as classic examples. Superconducting technologies have now advanced to a level such that superconducting transport applications have become feasible, opening the path to zero-emission aviation, shipping, and train transport. In taking these applications from laboratory demonstrations into commercial products, a huge environmental advantage will be gained, thereby addressing a key contributor to climate change and thus serving humanity as a whole.

2. Market opportunities

The estimates of the global airline industry's market size range from approximately USD 300 bn to 800 bn. At the same time, around 80% of the aircraft in operation are short-range (up to 5500 km), single aisle, commercial passenger aircraft with up to 230 passengers [3]. The current consensus is that it is technologically feasible for this large group of aircraft to be made emission-free using cryogenically-cooled superconducting technologies. Assuming that 50% of the fleet will use superconducting technologies in the future, and assuming an average reported market size of around USD 500 bn, this can represent a market opportunity of more than USD 250 bn globally.

Estimates of the cargo shipping market size vary wildly from around USD 2 bn to more than 2 tn, also depending on the exact definition of the market itself. Reasonable estimates could be around USD 50 bn for container and bulk cargo shipping, with trends towards ever-increasing cargo ship sizes [4–6]. Assuming that it is economically feasible to equip the largest 25% of these with superconducting technologies, this leads to a USD 12.5 bn market opportunity.

The estimated market size for railway transportation ranges from about USD 300 bn to 550 bn. Railway electrification has been a pioneering technology in the transport sector since the 1880s due to its lower emissions and operating costs. Currently, a significant fraction of trains worldwide run on electricity, with a smaller fraction still using other energy sources. However, superconducting technologies offer unique advantages that can promote conventional trains with higher efficiency, lighter weight, minimized volume, and reduced running costs [7]. These advancements also enable the Mag-Lev Train and potentially future Hyperloop trains. If it is deemed economical to invest in high-speed Mag-Lev technology for 10% of the connections, this could lead to a market value of around 40 bn USD.

It is evident from the above numbers that the electrification of aviation has the largest potential in terms of market size. Thus it has the most significant ability to attract investors but also remains the most challenging sector to electrify. Although the exact number is debated, it is evident from multiple publications [8, 9] that some low-tens of the world's largest cargo ships pollute as much as all of the world's cars combined. Addressing shipping will have a significant impact on pollution. However, its overall market value is small compared to aviation, reducing incentives for investors. The economic argument to invest in superconducting technology for trains is hindered by the fact that a large fraction is already electric and thus could run on renewable electricity. In contrast, Mag-Lev requires significant investment in a dedicated infrastructure. The economic argument for superconducting trains is therefore less evident than for aviation and shipping.

3. Introduction

Climate-driven incentives to reduce greenhouse gas emissions yield increased focus on international transport, which accounts for 16.2% of emissions [9]. While electrification of the world's automobile industry is commencing, driven by government policies and industry, large-scale polluters that enable the transportation of large amounts of people or cargo are not sufficiently addressed. Trains, airplanes, and ships come to mind, all of which are of sufficient scale to accommodate superconducting technologies.

Although trains with superconducting levitation technologies (Mag-Lev) are being pursued around the globe, chiefly in Japan and China, the infrastructure for electric train transportation is already mostly present. This makes addressing train transportation less urgent, provided that these trains are mostly powered by green electricity from renewable energy. This leaves us with airplanes and ships.

Nevertheless, it is worth mentioning advances are demonstrated by superconducting traction transformers [7, 10], superconducting cables [11], and superconducting fault current limiters [12, 13] to realize an extra efficient, reliable, and safe high-speed train. In addition, ultrahigh-speed trains (such as the Hyperloop) have been proposed as an alternative to airborne transportation for short and medium hauls. In such cases, these trains will likely need to use superconducting technology for the levitation system and the electric network, which will play an important role in transport decarbonization.

Superconducting devices are known for their higher power density, efficiency, and compactness compared to conventional ones. As a result, they can be effectively utilized in aviation and maritime transportation to implement zero-emission transport. Several superconducting materials can be utilized. The most commonly used are:

- *High-temperature superconductors* (HTS), such as ReBCO, BSCCO 2212, and BSCCO 2223, are characterized by critical temperatures between about 90–110 K in self-field, at atmosphere pressure.
- *Medium-temperature superconductors* (MTS), such as MgB_2, with a critical temperature of about 39 K.
- *Low temperature superconductors* (LTS), including NbTi and Nb_3Sn, with critical temperatures below 20 K.

The need to maintain these materials at cryogenic temperatures necessitates in some cases the use of cryogenic fluids, such as liquid helium for LTS, gaseous helium or liquid hydrogen for MTS, and liquid hydrogen or liquid nitrogen for HTS. It should be emphasized that HTS materials can operate in a conduction-cooled and cryogenic-free environment, but the feasibility of this technique needs to be analyzed on a case-to-case basis.

In the following sections, the state-of-the-art in superconductivity for aviation and maritime transportation is detailed and discussed.

4. State-of-the-art

4.1. State-of-the-art in superconductivity for aviation

Many organizations are conducting R&D in electric power systems to support electric aircraft, with strong support from both the public and private sectors.

NASA Glenn Research Center in the US is undertaking multiple efforts within its Electrified Aircraft Propulsion program [14]. A compelling example is the NASA N3X Hybrid Wing Body aircraft with a turboelectric distributed propulsion [15, 16]. It has two HTS generators and 10–20 HTS motors to meet the required power load of about 40 MW and realize the benefits of distributed propulsion.

Boeing in the US has been investing in startups focusing on electric aviation, such as previously Zunum Aero and, more recently, Wisk Aero. It has also been running a partnership program with NASA (Subsonic Ultra Green Aircraft Research (SUGAR) [17]), and recently announced a partnership with GE Aviation and NASA to develop a hybrid-electric aircraft [18, 19].

In Europe, Airbus together with partners such as Rolls Royce, Siemens, Safran, and universities and laboratories, have invested in electrifying aviation. This gave ground to large partnership initiatives like the IMOTHEP collaboration [20]. Recently, Airbus UpNext has completed the ASCEND project and is is underway with their second phase of R&D with the CRYOPROP program [21]. A key difference here, with respect to NASA's distributed propulsion approach [17], is the attempt to retrofit a conventional aircraft layout with liquid hydrogen fuel and two superconducting propulsion motors [21].

Also, in Europe, some smaller companies such as Mako Aerospace (UK), MAEVE (Netherlands) [22], and Aura-Aero (France) [23] are also pursuing electric aviation. GKN Aerospace is leading the £50 mn+ project H2GEAR in the UK, developing a liquid hydrogen-based sub-regional aircraft with a cryogenic powertrain [24]. In Spain, three companies are working together in the HIVOMOT EU-funded project framework for developing an HTS aircraft motor.

In multiple efforts, superconducting power distribution cables are being developed for electric aviation [25, 26]. The idea of producing liquid hydrogen using renewable energy sources, such as solar and wind energies, located in remote areas and transporting the liquid to places of demand, is generating additional interest in superconducting electric aircraft development [27, 28].

4.2. State-of-the-art in superconductivity for maritime transportation

During the past two decades, the US Navy has developed notional designs and technologies for electric ships, including superconducting motors, generators, and power cables. The US Navy's interest in superconducting power system components was strengthened by the successful demonstration of superconducting degaussing systems. HTS degaussing systems demonstrated an 80% weight reduction compared to their copper counterparts [29, 30].

HTS motors are the most advanced among the superconducting technologies for ships. The US Navy funded the development of a 5 MW HTS ship-propulsion motor. It was built and tested under dynamic load conditions in 2005 at the Center for Advanced Power Systems, Tallahassee, Florida [31]. Encouraged by this success, a full-size 36.5 MW HTS motor was developed and successfully tested under full power at the Land Based Test Facility in the Naval Surface Warfare Center, Philadelphia, in 2011 [32]. The motors were partially superconducting with a conventional (resistive) stator and a superconducting rotor. Even with the partially superconducting design, the 36.5 MW motor achieved a 70% weight and 50% size reduction [33]. The two motors used cryogenic gaseous helium circulation at around 30 K as the cooling method. The cold gas was produced by multiple Gifford-McMahon cryocoolers and circulated by a turbine fan.

Alternatively, less conventional solutions have been proposed, such as MagnetoHydroDynamic (MHD) propulsion using superconducting magnets [34–36]. This point highlights an interesting case of synergy: MHD propulsion can benefit from the advancements in high-field magnets used in other activities, such as the development of dipole and quadrupole magnets for high-energy physics accelerators.

5. Comparative and competitive advantages of superconductivity in transport

All transport applications require high efficiency, high power density, resilience, and robustness. However, the design features of the superconducting conversion chain are unique to each application.

The extraordinarily high current density of superconducting materials (about two orders of magnitude larger than copper, about 5 A mm^{-2} in copper at room temperature versus 500 A mm^{-2} in any superconducting material at cryogenic temperature) offers a potential solution to the challenges of electrifying multi-megawatt conversion chains for aviation and maritime transportation.

Several competing technologies in aviation and maritime transportation aim to address similar challenges or provide alternative solutions to those offered by superconductivity. Some notable examples are:

- *Synthetic alternative fuels:* for the near term in aviation, there is a drive to develop carbon-neutral synthetic alternative fuels. The challenge is getting the sell price close to conventional jet fuel. It might be an interim solution until efficient all-electric drivetrains are developed, and liquid hydrogen has a low enough cost and can be harvested 'green' in sufficient quantities.
- *Conventional components:* while they do not offer the same efficiency as superconductors, resistive components are well-established, cost-effective, and reliable. Conventional systems will continue to be utilized when the benefits of superconductivity may not outweigh the associated costs and complexities.
- *High-purity resistive conductors:* high-purity aluminum has an extremely low resistivity below 30 K with respect to room temperature. In the context of liquid-hydrogen aircraft, such high-purity conductors could operate at the liquid hydrogen temperature of 20 K.
- *Advanced power electronics:* power electronics technologies, such as silicon carbide (SiC) and gallium nitride (GaN) semiconductors, offer higher energy efficiency and faster switching speeds compared to conventional silicon-based semiconductors allowing for higher power density. Advanced power electronics can enhance the performance and efficiency of electrical systems.
- *Energy storage systems:* lithium-ion batteries are currently the dominant energy storage solution, providing high energy density and efficiency. However, other emerging technologies, such as solid-state batteries and supercapacitor systems, are being developed to overcome limitations.
- *Advanced propulsion systems:* in aviation, technologies like turbofans, geared turbofans, and electric propulsion systems are being developed to improve fuel efficiency and reduce emissions. Similarly, maritime transportation explores various propulsion options, such as advanced diesel engines, gas turbines, and electric propulsion systems, to enhance efficiency and maneuverability.

It is worth noting that these technologies are not necessarily direct substitutes for superconductivity but rather alternative approaches to improving efficiency, power delivery, or propulsion in aviation and maritime transportation. They could even be combined with superconductivity.

6. TRLs of superconducting components for transport

6.1. Superconductivity for aviation

In this section, we look at the opportunities superconductivity offers for aviation.

The Boeing 787 is the state-of-the-art starting point, as it is the most 'electric' aircraft today. With a total installed electrical power of 1 MW, this aircraft incorporates electrical generators with a power-to-weight (PTW) ratio of 2.2 kW kg^{-}.

The turbo-electric topology is the most interesting architecture for electrically propelled aircraft. However, an airliner with more than 200 passengers would require an electric power of 30 MW and electrical machines with a PTW ratio >10 kW kg^{-1}.

Besides, some aircraft manufacturers believe that electrifying the propulsion of an airliner is currently a utopia with today's electrical storage technology. Indeed, it would take >150 tons of batteries to get an 80 ton Airbus A320 off the ground! Nevertheless, an economical and feasible case can be made for combining hydrogen and superconductivity technologies for short-range, single-aisle airplanes ('Cityhoppers') that represent 80% of flights, and the aviation industry recognizes this.

6.1.1. Superconducting motors & generators

The challenging PTW ratio target can be achieved using superconductivity. Indeed, the PTW of any cylindrical electric machine is expressed as [37]:

$$PTW \propto I_s \cdot B_{\text{gap}} \cdot RPM \tag{1}$$

where I_s is the armature current, B_{gap} is the airgap magnetic field and RPM is the rotor speed. In conventional motors the current I_s is limited by the joule effect and related requirements of the thermal design while the magnetic field B_{gap} is limited by the saturation of the ferromagnetic material, so the required PTW ratio is far from attainable. With superconducting materials, which can carry much higher currents (orders of magnitude) and generate much larger magnetic fields (with the possibility of ironless air-cored machine designs), the required PTW ratio is within reach [38]. Using superconductors, it is also possible to design air-cored machines without the ferromagnet structure, which reduces the overall weight of the machine [39].

A liquid-hydrogen cooled, partially superconducting machine could achieve a PTW ratio of ∼10 kW kg^{-1} (including active parts, cryogenic and mechanical support structures, and housing), while a fully superconducting machine could achieve a PTW ratio of >30 kW kg^{-1} [40]. Note that the latter value is equivalent to the power of a small car engine with the mass of a one-liter bottle of water, illustrating the required power-densities. Hence, superconducting motors and generators would be significantly lighter and more compact than conventional ones [41]. Thus, superconducting rotating machines are key enablers of electric aviation.

There is also a geopolitical reason for using superconductors. Many conventional state-of-the-art electrical machines use rare earth permanent magnets (Re—PM). For just two applications—electric vehicles and wind turbines—over the next 20 years, the current production capacity for Re-PM would have to be increased fivefold. This is virtually impossible to achieve. With 85%–90% of the market being controlled by a single country by 2035, prices will rise and a shortage will occur. In the meantime, superconductor prices continue to decrease and the supply from many manufacturers will increase [42, 43]. Superconducting machines may become economically competitive while being also an excellent insurance policy against rising prices and shortages of Re-PM.

6.1.2. Superconducting cable systems

Aircraft operation at high altitudes limits operating voltages to ∼10 kV, due to the risk of partial discharge at low pressures. For a 30 MW DC aircraft power system, limiting the voltage to 10 kV requires a high current of ∼3 kA DC. The typical ampacity of a copper conductor is ∼5 A mm^{-2} making them large and heavy. Copper, with a density of 8900 kg m^{-3}, will be prohibitively heavy and large as an option. Superconductors, with a current-carrying capacity several orders of magnitude higher than copper, will allow high PTW ratios.

6.1.3. Cryogenic cooling

Although superconductors enable high PTW ratios required for electric aviation, they must operate at cryogenic conditions requiring mechanical cryocoolers or liquid cryogens serving as heat sinks.

While compact mechanical coolers are available, they add weight and require periodic maintenance. Possible cryogens for >20 K include liquefied natural gas, liquid nitrogen, liquid neon, liquid hydrogen, and helium gas. Liquid hydrogen is being explored because of the combined advantage of serving as a heat sink and an energy carrier (see section 6.4).

6.2. Superconductivity for maritime transportation

In this section, we examine the opportunities offered by superconductivity for maritime transportation. Many of the benefits discussed for aviation are also applicable to maritime transportation. We highlight only the specific differences in the following subsection.

Future all-electric ships are expected to have integrated medium voltage direct current (MVDC) power systems operating at 12–18 kV [44]. The total installed electrical power will be ∼100 MW, which poses a challenge for traditional copper-based systems to satisfy the power density and efficiency requirements [45]. A superconducting electric propulsion system (SPS) offers higher efficiency due to the absence of joule and iron losses.

Nearly 90% of new cruise ships built use integrated full electric propulsion (IFEP). Out of the 67 ships larger than 10 000 t, 42 were IFEP and only 8 were diesel ships. IFEP ships are inherently fast and easily maneuverable, requiring powerful, versatile, and numerous engines constituting a potential market for superconducting propulsion. Several market analysis studies have focused on the topic [46, 47]. Other ships as tug-boats or ice-breakers also require a large power in a limited space benefitting the SPS option.

6.2.1. Superconducting motors & generators for cruise ships

The use of a superconducting propulsion system can have positive benefits to other aspects of a cruise. Some of them are described below.

- Increasing the ship's hydrodynamic efficiency: this is one of the major indirect advantages of the SPS since its reduced volume allows installation inside orientable pods, which permits the elimination of shafts and rudders, allowing placement in optimum positions, and improving the hydrodynamic design of the ship's stern.
- Increasing the payload for the same overall dimensions: reducing the SPS volume and the possibility of placing the pods outside the hull allow for a smaller engine room and consequently more payload space.
- Reducing contaminants of the primary source of energy: new trends in green shipping aim at net-zero emissions, at least when the ship is maneuvering or staying at the harbor. Trends point to hydrogen and renewables to complement the ship's propulsion and to develop hybrids of full-electric propulsion systems. In any case, the use of electric motors is mandatory, and the advantages of being superconducting are significant, especially in terms of PTW.

Further arguments in favor of electric propulsion and, hence, of SPS is the change in shipping patterns brought about by shifting demographics, economic developments, and increased shipping levels. This leads to the requirement of operating in more extreme environments such as the Arctic (the Arctic Challenge), which requires vessels that can provide more efficient power [48, 49].

Conventional energy storage devices such as batteries cannot meet the multi-megawatt-level power demands and target power densities for these electric ships.

6.2.2. Superconducting cable systems

HTS power cables have been of interest for electric ship applications because of their weight reduction and additional capabilities, such as fault-current limiting [26]. The size of copper cables required to meet the power levels of 100 MW would be prohibitively large and heavy to meet the design criteria of electric ships. Compact HTS cables with ampacities of 3–5 kA have been designed and demonstrated [50] with innovative electrical and cryogenic design features.

On the one hand, cryogenic helium-circulation systems were designed to achieve high mass-flowrates to support large HTS cable systems on electric ships [51]. The cables are cooled using cryogenic helium-gas circulation to meet the safety standards for ships. This process also allows for higher power densities by operating at temperatures lower than what is possible with liquid nitrogen. Liquid nitrogen systems cannot be used below 64 K because nitrogen solidifies at 63 K. Design features that enhance the resiliency and stability of HTS cable systems have been explored. One study used solid nitrogen buffer in the cable terminations to handle suggested heat surges in a fault or to provide time to respond in the event of a failure of a cryocooler [52].

6.2.3. Cryogenic cooling

Efficient cryocoolers were developed to suit the rugged operating environment of ships [53]. In this frame, it is also important to mention the possibility of combining the transportation of liquid natural gas (LNG) in specially designed ships with superconducting motors. The natural gas is cooled to −162 °C to transform it into a liquid state (LNG), reducing its volume by about 600 times. LNG is stored in cryogenic tanks and transported via specially designed ships or trucks. Both LNG and HTS motors require cryogenic temperatures to operate effectively. The cooling systems used for LNG can be adapted to also cool HTS motors, creating a synergistic relationship and reducing operational costs and environmental impact.

6.3. Cryogenic power electronics

The application of superconducting motors, generators, and cables in aviation and maritime transport requires operating them at cryogenic temperatures. Power-electronic converters are necessary between the AC components (motors and generators) and the DC bus, which requires specific interface components and significantly increases the heat transfer between cryogenic and room-temperature conductors.

Cryogenic power electronics have several benefits.

1. A reduction in heat flux at the ambient/cryogenic interface, and the possibility of using a single cooling loop.
2. The cryogenic fluid's high dielectric strength is anticipated to raise power density.
3. Some semiconductors' static and dynamic performance improves at cryogenic temperatures, which would boost converter efficiency.

Cryogenic power electronics do not necessarily operate at the same temperature as the superconducting components. One option is, for example, to cool the power electronics using the cryogen leaving the superconducting motor, which is hotter but still at cryogenic temperature (liquid or gas). Another option would be to mount the power electronics on the cryogenic stator (using the stator as a heat exchanger). This would further increase the machine's power density.

6.4. Hydrogen-superconductivity synergy

Liquid hydrogen (LH_2) can potentially serve both as a fuel and as a cryogenic coolant for superconducting systems.

Hydrogen has a gravimetric energy density of about 120 MJ·kg^{-1} [54], nearly three times greater than that of conventional jet fuel or kerosene (≈43 MJ·kg^{-1} [55]), making it a lightweight energy carrier. However, the volumetric energy density of hydrogen depends strongly on its physical state. In its gaseous form at ambient conditions (1 bar, 300 K), hydrogen contains only about 0.010 MJ l^{-1} [54], while compressed hydrogen at 700 bar reaches roughly 5.0 MJ l^{-1} [55]. In contrast, liquid hydrogen at 20 K attains a volumetric energy density of about 8.5 MJ·l^{-1} [54, 55], which is still only about one quarter that of kerosene (≈34 MJ l^{-1} [56]). This makes LH_2 the preferred option for fuel storage for long-range transportation but necessitates large storage volumes or innovative tank geometries.

With a boiling point 20.3 K [57], the cryogenic temperature of LH_2 enables direct use as a coolant for superconducting systems. Its temperature range aligns well with the operational requirements of MTS, and can also support the operation of HTS when operated in the subcooled regime. The latent heat of vaporization of LH_2 is approximately 446 kJ kg^{-1} [57], nearly five times greater than that of liquid nitrogen (199 kJ kg^{-1} at 77.3 K [57]), providing large thermal buffering capacity.

The ability to leverage a single cryogenic infrastructure for both fuel storage and superconductor cooling could offer significant system-level advantages. As hydrogen production and liquefaction scale to support carbon-neutral energy systems, the synergy of LH_2 cooling loops with superconducting power devices could enable high-efficiency, zero-emission transport.

7. Estimated TRLs

The TRLs of components required for superconducting transport applications differ substantially across application fields, as summarized in table 1. While superconductors have zero direct current (DC) resistance, a small but finite resistance appears when they experience any time-varying current and/or magnetic field, resulting in so-called alternating current (AC) loss. Regrettably, most currently available and popular REBCO conductors have significant AC losses, while low AC loss configurations are available for Bi-2212 and MgB_2 [58]. Using high AC loss conductors causes undesired heat loads on the cryogenic

Table 1. Estimated technology readiness levels (TRL) for the components of superconducting conversion chains for aviation and maritime transport.

Technology component	TRL
DC MTS and HTS conductors	8
AC MTS and HTS with low AC loss	6
Partially-superconducting generator	7
Fully-superconducting generator	2
Partially-superconducting motor	4
Fully-superconducting motor	2
DC HTS cable (5 kA for aviation and 10 kA for ship)	6
AC HTS cable (5 kA for aviation and 10 kA for ship)	6
Cryogenic power electronics	5
Liquid hydrogen storage and distribution	2
System level integration	2

system and the risk of thermal runaway. A low AC loss conductor is essential to enable a superconducting stator. Significant progress has been made in the development of low AC-loss MgB_2 and Bi-2212 materials by reducing the filament size and filament transposition [58–60], and low-loss winding configurations are currently emerging. Further R&D on their implementation is, however, needed.

LTS, MTS, and HTS generators have been studied and designed. Generators typically operate at a higher frequency compared to motors, which means AC losses are significantly higher since some components of AC losses vary with the square of the frequency. Although low AC loss MTS and HTS wires and coils are emerging, they have yet to be fully implemented in large-scale manufacturing. This explains why fully superconducting machines have a lower TRL than partially superconducting ones.

Most HTS generator studies and hardware demonstrations have been around wind power generators. In 2020, a 3.6 MW wind turbine generator demonstrator was installed and operated, successfully demonstrating the TRL of HTS generator technology up to 7 [61].

Although power cables are maturing for electric grid applications [11], they have not yet been optimized to meet the specifications of onboard networks in aircraft and ships. The lack of extensive testing justifies why their TRL seems relatively low, but a rapid improvement is projected.

Rapid advances are also being made in cryogenic power electronics [62, 63]. Still, current estimates suggest that the losses generated by the power electronics amount to more than half of the total cryogenic system losses, indicating the need for further research and development in this area.

8. Strategic roadmap (SR) for HTS components for transport

Superconducting technology could make it possible to achieve the high power densities and PTW ratios required for aviation and maritime transportation. Research is underway with encouraging results, as described in the previous sections. Significant investment from governments, industry, and private parties, as well as political support, are now needed to move from laboratory-scale prototyping to commercial applications. In table 2, an ambitious roadmap is proposed.

9. List of grand challenges

Two grand challenges are proposed here:

1. Design and realization of a cargo ship with 10 MW installed power, utilizing fully superconducting motors cooled by liquid hydrogen. In this design, liquid hydrogen is used as a coolant and fuel.
2. Realization of an airliner equipped with a liquid hydrogen tank and superconducting technology, providing 30 MW of power.

To achieve the goal of these two grand challenges, several activities have to be performed, which are listed as follows:

Table 2. Roadmap to development for the components of superconducting conversion chains for aviation and maritime transportation.

Ambition	4 years	7 years	10 years
Fully-superconducting motor	Basic technology elements available and demonstrated	Prototype demonstrated in a lab	Ready for commercial use in aviation
Fully-superconducting generator	Basic technology elements available and demonstrated	Prototype demonstrated in a lab	Ready for commercial use in aviation
DC HTS cable	Demonstrated in lab	Ready for commercial use in aviation	
AC HTS cable	Demonstrated in lab	Ready for commercial use in aviation	
Cryogenic power electronics	Optimized for cryogenic usage	Required components demonstrated in a lab	Ready for commercial use in aviation
Liquid hydrogen storage and distribution	Safety criteria established	Prototype demonstrated in a lab	Ready for commercial use in aviation
System level integration	Design refinements based on component performances	Selection of optimal configuration and design	Ready for commercial use in aviation

- *Superconducting materials:* enable the production of long-length conductors with homogeneous properties for practical implementation; develop conductors and cables specifically adapted to the operation of superconducting motors and generators; develop superconducting cables with reduced AC losses to improve overall system efficiency; advance manufacturing processes such as coil winding, superconducting joints, assembly techniques, and quality control.
- *Cryogenic cooling systems:* develop efficient, compact, and plug-and-play cryogenic cooling systems designed explicitly for superconducting conversion chains in the cold kilowatt (kW) range.
- *Electrical insulation*: develop better electrical insulation materials that can operate at cryogenic temperatures; study the effects of temperature cycling, mechanical stress, and electrical stresses on insulation performance; improve insulation reliability and longevity.
- *Cryogenic power electronics:* reduce the number of thermal links, by operating the power electronics at cryogenic temperature; investigate the feasibility of cryogenic/superconducting power electronics.
- *System integration*: develop the appropriate infrastructure to integrate superconducting conversion chains into aircraft or ships; develop systems that are customer-friendly (‘plug and play’) and reliable with low maintenance.
- *Quench detection and condition monitoring of superconducting applications*: develop an accurate, reliable, and extra-fast quench detection technique, as quench can cause irreversible damage to superconducting coils and devices. Quench detection and real-time condition monitoring, driven by advanced artificial intelligence and big data techniques are feasible and should be on board the aircraft and ships to safeguard their reliable operation, coordinated with other protective systems [64].

Addressing these technological needs and scientific questions is crucial for successfully developing and implementing superconducting conversion chains for aviation and maritime transportation.

10. Partnerships and consortia

Table 2 presents the main lists of ambitions in superconductivity and related technologies, as well as in conversion chains for aviation and maritime transportation. These companies, among others, could potentially serve as partners or collaborators (in alphabetical order).

Aviation transportation: Airbus, BAE Systems, Boeing, General Dynamics, General Electric (GE), GKN Aerospace, Honeywell, Lockheed Martin, Mitsubishi Electric, Northrop Grumman, Rolls-Royce, RTX

(Raytheon Technologies Corporation, Collins Aerospace, Pratt & Whitney), Safran, Siemens, Thales Group,

Maritime transportation: ABB, BAE Systems, General Dynamics, Mitsubishi Electric, Rolls-Royce, Safran, Siemens, Thales Group, Toshiba,

Superconducting cable manufacturers: Advanced Conductor Technologies, Furukawa Electric, Nexans, Prysmian Group, Solid Material Solutions, Sumitomo Electric Industries,

Cryogenic systems and technologies: Air Liquide, Air Products, Chart Industries, Cryofab, Cryomech, Cryostar, Linde (Praxair), Oxford Instruments, Sumitomo Heavy Industries,

Hydrogen technologies and infrastructure: Air Liquid, Air Products and Chemicals, Inc., Ballard Power Systems, Hydrogenics, ITM Power, Linde, McPhy Energy, Plug Power,

Superconductor wire and tape manufacturers: ASG Superconductors (Columbus Superconductors), Bruker, Hyper Tech, Luvata, Shanghai Superconductors, Solid Material Solutions, Sumitomo Electric Industries, Faraday Factory Japan, SuNAM, SuperPower Inc., Theva,

11. Call to action

As demonstrated in this strategic roadmap, superconducting technology has the potential to play a significant role in the decarbonization of the transport sector. The grand challenges identified require both technical development and the establishment of fruitful collaborations between government, industry, and academia. This ScGA initiative aims to create bonds between industries with expertise in superconducting technologies and those acting in the transport sector. Furthermore, this initiative aims to catalyze the efforts of industries and academia first to achieve the goals listed in the grand challenges of this strategic roadmap, and ultimately fully exploit the potential of superconductors to reduce greenhouse emissions in the transport sector.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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