Subsea superconductors: the future of offshore renewable energy transmission?

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Abstract

The European Union has set the ambitious target of becoming climate-neutral by 2050 and reducing greenhouse gas emissions by at least 55 percent before 2030, compared to 1990. Greater energy generation can be achieved by increased reliance on renewable energy, but the transmission of this energy to match supply with demand is a likely bottleneck in maximising renewable energy use. In this paper, we examine medium-voltage DC superconductors as a potential solution for low-loss, high-power transmission of offshore renewables. We look at what has been achieved to date in onshore superconducting cable deployment and what needs to be done for such superconductors to be deployed subsea, with the goals of exporting electricity from offshore wind farms and acting as grid interconnectors. The offshore oil and gas industry represents state of the art in terms of subsea pipe design. This paper explores how the experience of the offshore oil and gas industry can be applied to subsea superconductor cable design and identifies aspects of superconductor design likely to present a challenge to subsea deployment. The key areas identified as requiring research are the development of flexible pipes suitable for cryogenic usage that can withstand the dynamic loading encountered in the marine environment; robust and low-maintenance insulation systems suitable for subsea deployment; and cooling systems to enable pipelines greater than 100 km in length. Although the primary focus of this research is on superconductor cables, the information is also applicable to other subsea conduits requiring cryogenic cooling such as 'green' hydrogen.

Highlights

- Superconductors can facilitate low-loss long-distance offshore energy transmission
- Offshore oil and gas experience provides insight into the challenges of deployment
- Dynamic loading and accessibility issues complicate use for offshore wind farms
- Low-maintenance subsea insulation and cooling systems must be developed
- Materials must be suitable for cryogenic usage and withstand high-frequency loading

Keywords

Subsea superconducting cable, High-temperature superconductors, Cryogenic cooling, Thermal Insulation system, Vacuum-Insulated Pipe, SuperGrid, MVDC Transmission, Floating Wind energy, Flexible Pipe

Word Count

9,939

List of Abbreviations

BSCCO Bismuth strontium calcium copper oxide

HTS High-temperature superconductor

HVAC High-voltage alternating current

HVDC High-voltage direct current

LN_2 Liquid nitrogen

LNG Liquefied natural gas

MgB_2 Magnesium diboride

PEEK Polyether ether ketone

TRL Technology Readiness Level

VIV Vortex-Induced Vibrations

XLPE Cross-linked polyethylene

YBCO Yttrium barium copper oxide

1 Introduction

In April 2021 the European Parliament and the Council agreed the binding objective of climate neutrality in the European Union by 2050 and a domestic reduction of net greenhouse gas emissions by at least 55% compared to 1990, by 2030 [1]. The European Commission published its Offshore Renewable Strategy in November 2020 [2], which includes the goal of expanding offshore wind energy installed capacity from 12 GW in 2020 to 300 GW in 2050. At present, bottom-fixed offshore wind turbines account for most offshore capacity (95% in 2019). Technology advancements (i.e. larger turbines and floating platforms) and increasing demand for renewable electricity lead to the development of sites further from shore and in deeper waters. While the development of floating wind and other ocean energy technology is continuing apace, Europe will shortly be in a situation where bottlenecks in the electricity grid will be the most significant barrier to achieving the 2050 targets. The Commission has stated that a new approach to grid infrastructure will be necessary. Transmission System Operators must cooperate to move to a meshed grid (with offshore elements), allowing electricity to flow in multiple directions from a single connection point. Hybrid projects with a direct connection between an offshore energy development and an interconnector between two EU member states are stepping stones to a fully meshed offshore grid. Such projects would require significant cross-border cooperation to achieve interoperability between national grid systems.

The "SuperGrid" refers to the concept of an interconnected power transmission network overlaying the existing grid that spans the countries of Europe to facilitate renewable energy distribution. A SuperGrid allows efficient dispatch of renewable energy from Europe's peripheries, where the largest resources are (wind and solar), to inland load centres. Access to a diversified energy supply reduces reliance on a single source and enhances energy security. Figure 1 shows conceptual plans for a European SuperGrid. High Voltage Direct Current (HVDC) cables represent the current state of the art for bulk transmission of power and allow power transfer between grids operating at different frequencies. Losses from HVDC cables are voltage-dependent but estimated at 3% per 1000 km for a ±800 kV line compared to 7% for a similar High Voltage Alternating Current (HVAC) cable [3]. Both HVDC and HVAC utilise a copper core for transmission. Superconducting cables are an alternative technology for bulk power transmission. Implementation of superconducting cables on small scale pilot projects have resulted in reduced cable losses compared to HVDC and HVAC counterparts.

A superconductor is a material that, in the right conditions, can conduct electricity with no resistance, and, therefore, no losses. The current density is significantly higher than that achievable with copper-based technology, facilitating power transmission at lower voltages. The concept of using superconductors to achieve large scale power transmission over very long distances has been around for over fifty years [4]. In the last two decades, the concept has started to become a reality with the commissioning of several demonstration projects (see Section 3.3). Lower-voltage transmission with negligible losses using superconductor technology has the potential to be a gamechanger for interconnectors, for connecting far-from-shore wind farms to the grid, and ultimately developing a meshed SuperGrid that delivers Europe's 2050 targets.

This paper examines superconductors as a potential solution for low-loss high-power transmission of electricity generated offshore. Superconductor technology is described and case studies of onshore power transmission using superconductors are presented. The offshore oil and gas industry represents the state of the art in terms of subsea pipe design. This paper explores how offshore oil and gas industry experience can be applied to subsea superconductor cable design and identifies aspects of superconductor design likely to present challenges to subsea deployment.

The paper is organised as follows: Section 2 introduces basic principles of superconductors and superconductor conduits. Section 3 discusses state-of-the-art high power transmission systems and the advantages of superconductor cables. Section 4 presents the engineering challenges to be overcome in deploying superconductors subsea, with a particular reference to the experience of the offshore oil and gas industry with similar systems. Section 0 discusses areas of research and development to pave the way for superconductors to become an integral part of achieving the EU's goal of climate neutrality by 2050. Section 6 provides a summary and concluding comments.

Figure 1 Conceptual plans for a Europe-centred Super Grid (Source: SuperNode)

2 Superconductor technology

Superconductivity was first discovered in 1911 by Dr Kamerlingh Onnes. Early superconductors had very low critical temperatures (i.e. less than 20 K), and thus the cooling cost was extremely high, rendering them unsuitable for industrial application. In 1986, advances in ceramic materials led to the discovery of the first high-temperature superconductors (HTS) [5]. HTSs are materials that behave as superconductors above 77 K, which is the boiling point of liquid nitrogen at 1 bar pressure. This discovery enabled the cooling of superconductors using liquid nitrogen (LN_2) rather than helium or liquid hydrogen (the boiling points of helium and hydrogen at 1 bar are approximately 4 K and 20 K, respectively). Using liquid nitrogen vastly reduces the cost of the cooling process due to the more efficient thermodynamic cycle (Carnot cycle) and the lower cost of the LN_2 itself compared with other coolants. This cost saving increases the potential for the application of superconductor technologies to electricity distribution networks. Some studies, including [6] and [7], provide overviews of the evolution of superconductor technology, from AC low-temperature superconductors developed in the 1970s to present-day DC technology.

Superconducting materials used for AC or DC power cables fall into three categories: Yttrium barium copper oxide (YBCO), bismuth strontium calcium copper oxide (BSCCO), and magnesium diboride (MgB_2). YBCO was the first HTS discovered with a critical temperature above the boiling point of nitrogen. It can be readily synthesised in a small-scale laboratory setting and has been extensively studied. BSCCO, discovered in 1988, was the first HTS made from a compound free of rare-earth elements and has a critical temperature of -160°C (113 K). First-generation HTS wires for industrial applications were made from BSCCO. Second-generation wires have since largely moved to coated conductor based on YBCO compounds. Magnesium diboride (MgB_2) is a low-temperature superconductor with a critical temperature of -234°C (39 K) and requires cooling with liquid hydrogen or gaseous helium. The advantages of MgB_2 are its simple and low-cost manufacturing process compared to its high- temperature counterparts.

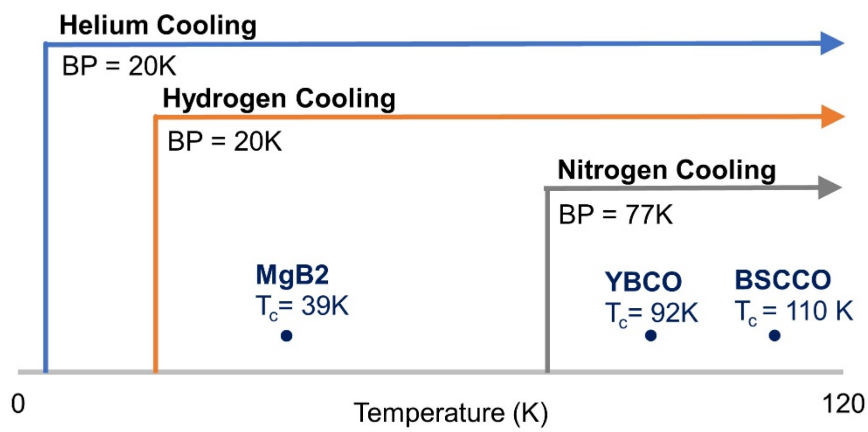


Figure 2 Coolant suitability for different superconductor types based on the coolant boiling points (BP) and the superconductor critical temperatures (T_c). $YBa_2Cu_3O_7$ is the representative YBCO superconductor, Bi-2223 is the representative BSCCO superconductor. Critical Temperatures obtained from Superconductors.org.

2.1 Cryostat

To transmit electricity resistance-free, a superconductor must be submerged in a cryogenic fluid (e.g. nitrogen or helium) and insulated by a multi-layered pipe called a cryostat. This ensures it remains in the required superconducting temperature range. The superconducting layer inside the cryostat consists of HTS tapes or wires wound around a central copper or hollow former (support tube). Outside the superconducting layer are a high voltage insulating material (dielectric) and shielding layers (or additional superconducting layers for multiple phases, see Figure 6a). The shielding layer equalises the electric field stress and provides shielding of the electromagnetic field. The inner wall of the cryostat is typically separated from the outer cryostat wall by a vacuum layer to improve insulation. An additional outer covering protects the entire structure from abrasion and other damage.

The two main categories of superconducting power cables are defined by the position of the dielectric relative to the coolant layer. In a warm dielectric cable, the electrical insulation or dielectric is outside the outer cryostat wall and is at the temperature of the external environment. In a cold dielectric design, the dielectric is inside the inner cryostat and at the cryogenic fluid temperature. Warm dielectric cables can use conventional insulation materials (i.e. cross-linkable polyethylene (XLPE) compounds) and are cheaper to manufacture. They also result in a reduced cryostat circumference that limits exposure to radiation along the cable's length and consequentially results in less heat ingress. The main disadvantage of warm dielectric cables is that currents are induced in the metallic cryostat walls during AC operation, decreasing overall efficiency. Induced currents, however, are not an issue for DC transmission where transient loads only occur during changes in loading [8].

3 Bulk power transmission

3.1 State of the art

Bulk transmission of electrical power with conventional cables uses high voltages, as it requires less current than a lower-voltage solution to deliver the same amount of power. For long-distance point-to-point schemes, HVDC transmission is preferable to HVAC transmission. HVDC transmission requires less conductor per unit distance, which reduces overall costs despite the high costs associated with the conversion equipment needed at the terminals. HVDC links typically operate in the range of 100 to 800 kV; however, a 1,100 kV ultra-HVDC link was commissioned in China in 2018. The Changji-Guquan Project is both the world's longest and most powerful transmission corridor at 3293 km in length with a capacity of 12 GW. In addition to leading the way in point-to-point bulk power transmission, China has also developed a demonstration four-terminal HVDC meshed grid in Zhangbei. This grid connects renewable (wind, solar and hydro) energy generated in three separate locations with Beijing [9].

Overhead power lines are generally not feasible for offshore wind farms, and transmission to shore must use subsea cables. Chaithanya et al. [10] present an overview of the different transmission topologies for offshore wind farms. HVAC transmission is typically used for smaller-scale wind farms and shorter distances (< 50 km) but are subject to high transmission losses as distances and voltages increase. As offshore wind farms increase in scale (>> 100 MW), it becomes more feasible to implement point-to-point HVDC connections, which require an offshore converter station or substation installed on a platform and another converter station onshore. Ryndzionek et al. [11] estimate the break-even distance (i.e. the distance at which HVDC becomes more economical than HVAC) is approximately 50 km for subsea cables, compared with several hundred kilometres for onshore transmission. Existing HVDC links include the HelWin, BorWin and DolWin transmission lines from offshore wind farms in the North Sea to Germany. Several offshore wind farm links are under construction, including two from the Dogger Bank region of the North Sea to the UK grid that are 207 km in length with a transmission capacity of 1200 MW each.

The EU Reference Scenario 2016 [12] estimates that gross electricity generation will rise from 3357 TWh in 2020 to 4064 TWh by 2050. Population growth and increasing electrification (e.g. domestic heating and transport), particularly in urban centres, will drive this demand. The global climate crisis means increased power consumption must be met with increasing renewable energy production, often in remote areas, which must then be dispatched to the load centres. The following section shows how superconductors can present a technological solution to these electricity distribution issues.

3.2 Advantages of superconductors for transmission of power generated offshore

The benefits of using superconductors for power transmission are as follows:

- Bulk transmission at medium as opposed to high voltage is possible; this dramatically reduces the cost of the offshore platforms required to house conversion equipment.
- Very low transmission losses over long distances at high capacity
- The relative cost of the cooling system decreases as transmission capacity increases.
- Reduced footprint of cables limits damage to benthic (seafloor) habitats
- No heat egress to external environment
- Potentially no electromagnetic fields

The following sections describe these benefits in greater detail.

3.2.1 Lower voltages

The primary advantage of superconductors for electricity export from offshore wind farms is that bulk transmission of power is possible at much lower voltages. An offshore HVDC connection for a large-scale wind farm (~1 GW) requires an enormous platform to house the power conversion equipment needed to transform the AC generated by the wind farm to DC for transmission. For example, the DolWin Beta is a 320 kV floating converter station with a capacity of 916 MW and weighing 23,000 tonnes which services three offshore wind farms in the North Sea. Large offshore substations have an enormous capital and installation cost: the contract for delivering the fifth iteration of the DolWin platforms, the DolWin Epsilon, is estimated at over €240 million [13]. The lower transmission voltages enabled by superconductors result in massive cost savings for the power conversion equipment required. Figure 3 compares a conceptual medium-voltage DC substation with its high-voltage counterpart.

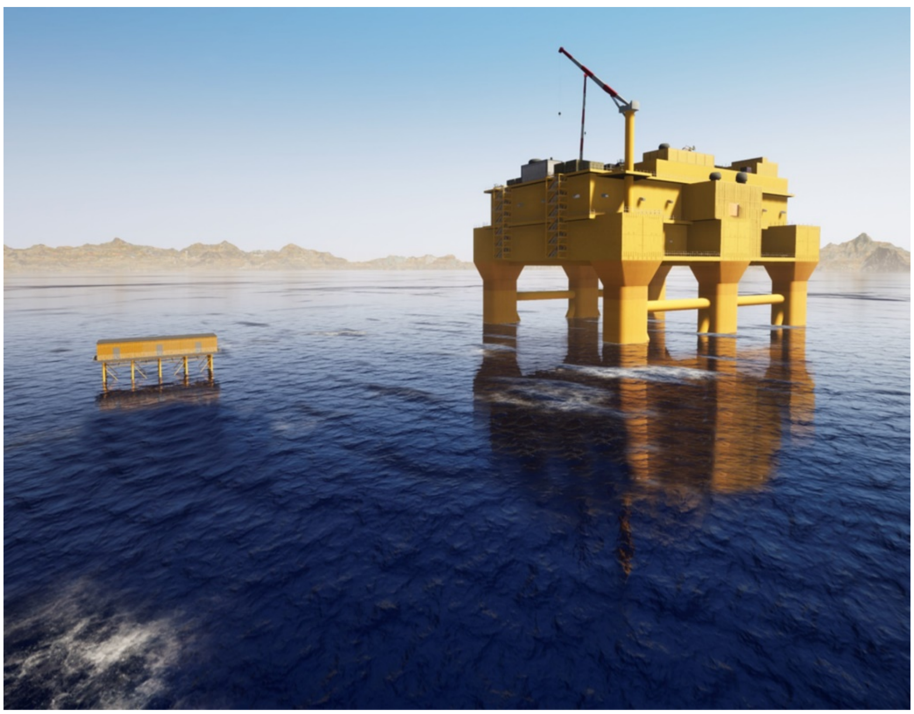


Figure 3 Typical offshore substation (right) compared to a representative substation for medium-voltage DC HTS transmission (Source: SuperNode)

3.2.2 Lower transmission losses

In traditional electricity transmission lines, resistive heating of the conducting cables is the primary mode for transmission losses. Superconductors have no heat losses in a DC application and an extremely high current density (100 times that of copper, according to [14]), meaning they have a large power transmission capacity compared to conventional cables of the same size. Furthermore, a superconducting cable's diameter tends to be small compared with the cryostat's outer diameter. Increasing the nominal current in a superconductor will not lead to a corresponding increase in the outer diameter. The heat influx into a cryogenic system and the power required to keep the cable at its operating temperature is a function of the cryostat's outer diameter and hydraulic properties.

Therefore, the cooling system cost does not increase proportionally with increasing current-carrying capacity. This economy of scale makes superconductors attractive for high-power transmission applications such as large-scale offshore wind farms.

Losses from conventional DC cables become significant with increasing transmission distances. Thomas et al. [15] cite the losses for a ±320 kV HVDC XLPE underground cable at 6.5% per 1000 km at full load and the losses from ±500/800 kV HVDC overhead lines transferring 4 GW at 3.35 % per 1000 km. These losses become important as wind farms move further offshore. Thomas et al. [15] calculate electrical losses for a 4 GW and 810 km long transmission line. They compare results for a ±500 kV HVDC overhead line (OHL) and a ±320 kV HVDC buried cable with HTS and MgB_2 solutions and found superconductors are best suited to transmission at high capacities. At 100% load, all superconducting options significantly outperformed the conventional solutions: losses for the HTS line were calculated at 0.18 % compared with 2.23 % for the OHL and 5.24 % for the buried cable. At 50% load, the HTS still considerably outperformed the conventional options, and at 25% load, the HTS losses were estimated at 0.71% compared with 0.56% and 1.31% for the overhead line and ±320 kV underground cable, respectively. Long-distance superconductor cables have economic benefits, but they also have other advantages that make them more acceptable to the public.

3.2.3 Social Acceptance and Environmental Impact

Thomas et al. [16] provide a good overview of the benefits of superconducting power transmission solutions, focusing on social acceptance. Opposition to overhead transmission lines was usually related to visual impact, destruction of the natural landscape, possible impact on health, environmental impact, and reduced property values. Underground standard HVDC cabling systems overcome many of these issues but are challenging to install offshore. Taormina et al. [17] review the environmental impact of subsea power cables in the installation and decommissioning phases as well as during operation. They describe the destruction of benthic habitats due to the preparation of cable routes and the laying of both buried and unburied cables. The reduced footprint of superconducting cables will mitigate this damage. Also, the high current densities may reduce the number of cables required, even as electricity demand from offshore renewables increases. The research identifies electromagnetic fields as a particular area of concern in terms of ecological impacts, as such fields have a known negative impact on many marine species. Thermal radiation in normal operation, especially from buried cables, is also a concern as it can potentially impact benthic communities. Superconducting power cables do not generate heat, and certain configurations (i.e. cold dielectric) do not produce electromagnetic fields. Therefore, they have the potential for lower environmental impact in a marine setting than conventional technology.

3.3 Case Studies

Several demonstration projects of power transmission using superconductor technology have been deployed in recent years. Doukas et al. [7] present an overview of HTS projects implemented up to 2016 and the projects in the planning stages at the time of publication. Their review shows a trend towards longer cables and a shift from AC to DC connections. Notable AC, DC and MgB_2 projects, as summarised in Figure 4, are described in more detail in the following sections.

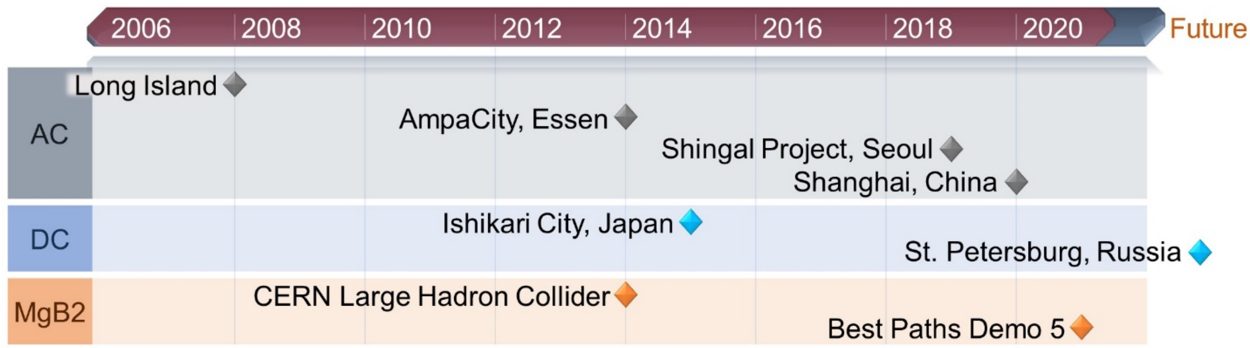


Figure 4 Sample superconducting power-transmission demonstration projects

3.3.1 AC transmission projects

There are several high-profile case studies of superconductors used to upgrade existing transmission networks. The first HTS cable used in an operational grid was installed by the Long Island Power Authority and commissioned in 2008. The 600 m long line operates at transmission voltage (138 kV) and is cooled using LN_2. The cable installation was a demonstration project to prove the suitability of HTS cables for infrastructure upgrades in highly congested areas [18]. The AmpaCity project in Essen, Germany, was commissioned in 2014 and provided a similar demonstration, as it is in a high-value area where space is at a premium. The 1 km long three-phase cable transmits 40 MVA apparent power at 10 kV, replacing a 110 kV conventional cable. It paves the way for more widespread replacement of higher-voltage systems by 10 kV superconductors, leading to a more efficient network with lower Operation and Maintenance (O&M) costs and a smaller land requirement.

The Shingal Project in Seoul is a 1 km long 23 kV HTS AC cable built to meet the demands of a growing urban area [19]. Both first- and second-generation wires in a triad configuration were used, and the system is cooled with LN_2. Further expansions of the Shingal Project are planned, including developing an AC 23 kV triaxial-cable system to reduce costs and an AC 23 kV switching station, referred to as a HTS power platform. Also under investigation is an AC 154 kV HTS transmission line and two different cooling system configurations.

A 1.2 km long 35 kV three-phase AC HTS cable demonstration project is currently under construction in Shanghai. The system is cooled with LN_2 with a cold dielectric configuration and consists of three 400 m long sections connected with superconducting cable joints. Xie et al. [20] report that the project required the development of special tools for laying superconducting cables to address differential cold shrinkage between the cable core and the insulated tube.

3.3.2 DC transmission projects

A project in Ishikari City, Hokkaido, Japan, involved constructing two superconducting DC power transmission cables: a 500 m underground cable and a 1000 m cable built on the surface [21]. Both cables were built in 2015, and cooling tests were completed by the end of 2016 [22]. The Ishikari project evolved out of previous research projects that developed a 20 m cable system followed by a 200 m long system. Yamaguchi et al. [23] used data from the Ishikari project to investigate the required thermodynamic parameters (e.g. LN_2 flow rate, system pressure, etc.) for 5 km and 10 km long pipelines.

Another important DC superconductor project in demonstrating longer cable deployments is the proposed HTS DC transmission cable in St. Petersburg, Russia [24]. The project consists of a 2.5 km long 20 kV cable capable of transmitting 50 MW of power. The cryogenic system is a closed-loop system with two circuits and cooled with liquid nitrogen. Preliminary research involved building two 30 m long cables to validate the proposed technology, followed by two full-scale 430 m long cable lengths.

3.3.3 MgB_2 projects

Since MgB_2 was only discovered as a superconductor in 2001, it is in an earlier development stage than other superconductors. The European organisation for nuclear research (CERN) in partnership with Columbus Superconductors, has led recent research into this technology. Their High-Luminosity Large Hadron Collider project developed two 20-metre long prototype MgB_2 cables and in 2014 obtained a world-record current transmission of 20 kA at 24 K [25]. This project was significant as it led to the development of MgB_2 wires. These wires are more suitable for cable formation than the tapes that were the only available solution before project commencement. Following on from their prototype testing, CERN is currently developing longer cables to power the Collider's superconducting magnets. These Superconducting links will each be around 100 m long and rated for currents up to 18 kA.

Another significant MgB_2 project is the Best Paths Demo 5 project, which Nexans is leading in conjunction with nine other industrial partners, including CERN and Columbus Superconductors [26]. Best Paths Demo 5 is a Joint-Industry project to design and test a full-scale HVDC superconducting loop. The 30-metre-long demonstration cable and associated terminations and cooling systems were tested under high voltage and in realistic scenarios (normal operation, overvoltage, polarity reversals, etc.) to demonstrate the technical and economic feasibility of HVDC cables. The high cooling cost notwithstanding, the low manufacturing cost makes MgB_2 an attractive proposition for long-distance cables.

4 Engineering challenges for the deployment of subsea superconductors

Superconductors for overland use are proven technology, even if questions remain over their cost-effectiveness. Deployment of subsea conductor cables over long distances subsea requires merging existing onshore superconductor technology with subsea engineering experience from the oil and gas pipeline engineering community. Figure 5 shows the key aspects of subsea superconductor design. The following sections consider how to approach each of these design aspects, beginning with the critical challenge of maintaining cryogenic temperatures over long distances in a subsea environment.

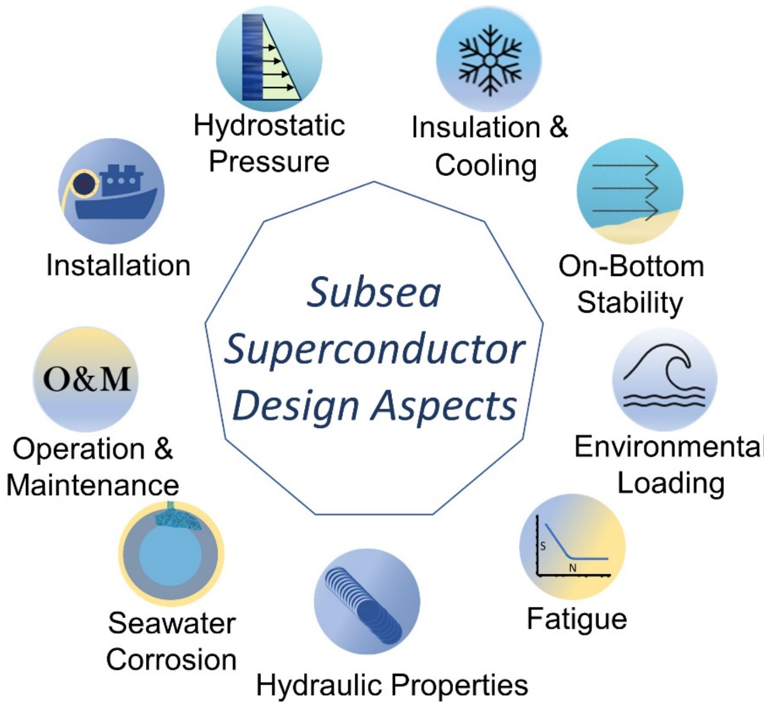


Figure 5 Aspects of Superconductor Design for Subsea Deployment

4.1 Thermo-hydraulic performance: Maintaining temperature and pressure

Maintaining cryogenic temperatures over the pipe's length is crucial to preserving the electrical cable's superconducting state. State-of-the-art cryostats typically have thermal losses in the range of 0.1 to 2 W/m, depending on the cryostat's diameter, with more significant losses associated with larger diameters [27]. The Ishikari project team considered different multi-layer insulation wrapping methods (up to 21 layers) in the cryostat; the measured heat leak was in the range of 0.73 to 1.51 W/m [28]. The amount of heat ingress depends on the insulation method and cooling system employed [29]. The following sections examine various heat-loss mitigation methods in superconductor cables, including passive insulation, active cooling systems and minimising frictional heat loss using smooth profiles.

4.1.1 Insulation systems

Superconductor cables need best-in-class insulation measures to maintain the required temperature differential between the cryogenic pipeline and the surrounding seawater. This temperature differential ranges from 160 - 200°C for liquid nitrogen. Overland superconductor cables favour a vacuum-insulation layer over thermal coatings to achieve the necessary thermal-insulation levels. However, there are issues in maintaining vacuum integrity subsea, which are discussed in detail in Section 4.3.2. The offshore oil and gas industry places a high value on robustness and has favoured alternatives to vacuum-insulated pipes.

Knowledge about insulating cryogenic liquids in a marine environment comes from the experience of transporting Liquefied Natural Gas (LNG). Here, the traditional approach uses rigid pipes supported on trestles for transport over short distances via offloading jetties. A 2007 Fluor Corporation study discussed several different insulation systems for rigid LNG pipes, including vacuum-insulated, Aerogel-filled annulus, and Polyurethane-insulated pipes and the cost-effectiveness of each solution [30]. The system they selected as the most cost-effective used Nanogel® Aerogel from Cabot Corporation for annular insulation, although vacuum Pipe-in-Pipe with bulkheads and Nanogel® blankets also scored well. The Fluor rigid pipe design is further described in [31]. Cabot Corporation is not the only organisation researching innovative annular insulation materials. InTerPipe developed a pipe-in-pipe solution consisting of two coaxial pipes with an Izoflex® annular-insulating layer and were able to achieve the required level of insulation with just 40 mm of insulation [32]. A rigid pipeline is a cost-effective solution for LNG pipelines as it enables large diameters and higher volumetric flow rates; this is not a factor for superconductor conduits. Rigid superconductor conduits would have the complication of installing a continuous superconducting wire within pipe sections welded together offshore. A spoolable flexible cable greatly simplifies the installation process and is a more appropriate solution for subsea superconductor cables.

In the LNG industry, flexibles hoses have advantages over rigid pipes in allowing jettyless and vessel-to-vessel LNG offloading and a wider weather window for operations, prompting companies to start exploring their use. Cryoline® floating flexible hoses have a three-layer structure comprising a corrugated inner layer, insulation layer and outer protective layer [33,34]. These pipes have transferred cryogenic fluids over distances up to 150 m with sizes up to 500 mm. Magma and Shell are currently working on a project to certify a flexible Single Polymer Composite pipe for cryogenic applications at temperatures down to -196 °C [35]. Their pipe, M-pipe®, is made from just two raw materials, carbon fibre and PEEK (Polyether ether ketone), which are fused in a complex manufacturing process. PEEK is both a thermal and electrical isolator and so has potential for use in superconductor cables. The LNG flexible pipe industry is still in its infancy, with SBM Offshore developing the first flexible LNG hose in just 2011. Much research and development is still being undertaken in this area.

LNG pipe insulation systems provide useful insights into using flexible pipes containing cryogenic fluid in maritime environments, but they have not been employed over long lengths. The thermal insulation requirements for a subsea superconductor cable would be higher due to the pipe's length and the colder internal temperature required (LN_2 is liquid at -196°C compared to LNG at -160°C).

Figure 6 provides a summary of existing pipe insulation systems, not all of which are qualified for cryogenic usage. Improvements in current subsea insulation values coupled with improved cooling system design are necessary for subsea superconductor cables to become a reality.

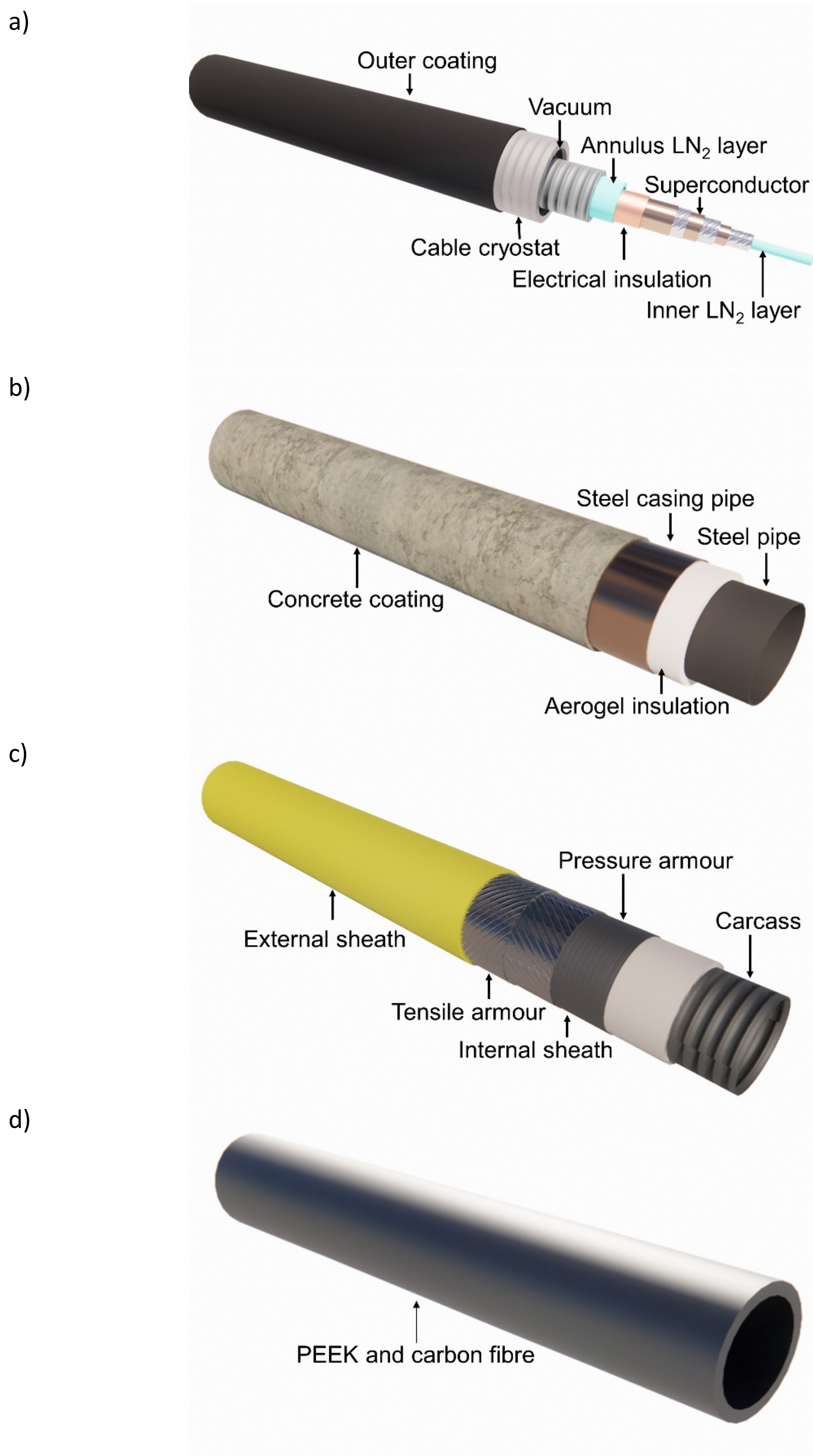


Figure 6 Pipeline Insulation: a) Overland superconductor with vacuum layer; b) LNG rigid pipe with Aerogel Insulation; c) Unbonded flexible pipe with external coating for insulation; and d) Flexible composite pipe with polymer insulation.

4.1.2 Cooling systems

A cryogenic fluid surrounds the superconducting cable to bring it below the superconducting critical temperature. As the cryogenic fluid flows along the cryostat, it gradually heats up due to heat generated by friction within the cryostat and heat penetration from the external environment. A cooling system must either replenish the cryogenic fluid (open-loop) or reliquefy the gas (closed-loop) to maintain the HTS cable in the correct temperature and pressure range. Researchers such as [36] and [37] cite the cooling system as the major barrier to long-distance superconductors. Current cooling system capabilities limit transmission distance to the region of 1 km. Cooling systems for very long HTS cables will require multiple cooling stations.

Cooling schemes that mix liquid oxygen with LN_2 lower the cryogenic fluid's freezing point and, therefore, the achievable feed-in temperature [38]. This lower input temperature facilitates a greater distance between cooling stations. Kottonau et al. [29] investigate the thermo-hydraulic performance of a HTS AC cable with four different cooling configurations to determine the maximum cable length achievable within the operating limits of LN_2 (temperature <78 K and pressure >3 bar). Table 1 summarises their results and shows that there are trade-offs between cooling distance obtained, pipe diameter and cooling system simplicity and cost. Pipeline hydraulic parameters need optimisation to achieve greater distances between cooling stations for cost-effective long-distance transmission.

Table 1 Cooling System Options [29]

Cooling Option	Outflow	Return Flow	Maximum Length (km)	Comment
1	Inside Former	Annulus	2.6	Single cable for easy installation, especially subsea.
2	Inside Former and Annulus	External to Cryostat	3.8	Best cooling performance but needs external pipe for return.
3	Inside Former	External to Cryostat	2.6	Smaller cryostat diameters but needs external pipe for return.
4	Inside Former	Annulus: Separate coolant system for return flow	3.6	Extra Cooling System adds cost and complexity.

Several researchers have worked to understand the maximum distances that could theoretically be achieved by increasing flow rates and pipe capacities. Yamaguchi et al. [23] show that extrapolating the Ishikari project experimental data leads to acceptable thermo-hydraulic performance in a 5 km pipeline, but conclude that it is not possible to achieve a distance of 10 km using the parameters of the original experiment. They then present a thermo-hydrodynamic analysis for a 50 km and a 100 km land-based DC cable using heat leak data from the Ishikari project but with large-diameter pipes and a smoothbore to achieve acceptable thermo-hydraulic performance. Key to the analysis is the cryostat design, which includes a radiation shield that splits the pipeline into two sections: one to house the HTS cable and the other to accommodate the return flow of LN_2. The pipeline construction means that heat ingress from the external pipe predominantly affects the return pipe resulting in minimal heat leak in the HTS cable pipeline. This design achieves a temperature rise in the HTS cable of only 1 K per 50 km; the temperature rise in the return pipe is much higher (25 K per 50 km) due to the cryostat design. The researchers estimate that 100 km between cooling stations is achievable by inputting LN_2 at both ends of the pipe. 100 km between cooling stations was also deemed achievable by [8], who modelled a 3600 MW/$\pm$200 kV HTS DC cable. The key to achieving these long distances is ensuring friction losses are minimised; here, the use of a smoothbore pipe in place of the traditional corrugated bore used for onshore superconductors is critical.

4.1.3 Profile of the inner cryostat

The profile of the carcass has a significant impact on the thermo-hydraulic performance of the pipe carrying the cryogenic fluid. Overland superconductor cables use a corrugated internal carcass, which has good internal pressure resistance and flexibility but results in a greater pressure drop than a pipe with a smooth inner surface. Similarly, most offshore flexible pipes also use a metallic, rough-bore carcass so that they can flex in response to dynamic loading. A corrugated inner bore would appear to be a good solution for short subsea cable as they can flex in response to dynamic loading. However, the steel typically used in unbonded flexible pipe structural components is carbon steel and not the austenitic steel that is qualified for cryogenic temperatures. The impact of introducing new cryogenic materials on the pipe’s structural performance, particularly under dynamic loading in an offshore environment, is unclear.

Several studies have investigated the thermal and hydraulic performance of HTS cables with corrugated pipe cross-sections, including [39] and [40]. The latter investigated a counter-flow cooling system for long-length HTS cables using Computational Fluid Dynamics simulations; they showed large pressure drops attributed to turbulence in the corrugated pipes. The friction heating effects caused by a rough inner bore will likely prove significant over longer pipeline lengths, and smoother inner bores would provide enhanced thermo-hydraulic performance. One possible solution to improve hydraulic performance is to use rigid pipes with a smooth metallic inner layer for parts of the pipe that are not subject to significant dynamic motion. Smooth metallic cores would not be flexible enough to allow spooling except at small diameters (for reference, coiled tubing used in the offshore industry have diameters less than 100 mm to enable spooling [41]). Rigid pipelines are commonly used in the offshore oil and gas industry, particularly on the seafloor where dynamic loading is minimal. In line with common practise in the offshore oil and gas industry, a potential solution would be to use rigid superconductor conduits on the seafloor and combine these with shorter flexible riser sections to connect with a surface platform. The primary disadvantage of using rigid pipe sections is the requirement to weld sections together during installation, the potential for thermal losses at the joints.

If improved thermo-hydraulic performance is critical, flexible pipes using non-metallic materials for the inner bore are a potential solution. One flexible pipe manufacturer describes several issues in designing a large diameter (350 mm) smoothbore flexible pipe [42] for offshore use. These include the manufacturing process for the inner tube and ensuring that damage to the external sheath will not result in the external hydrostatic pressure being applied directly to the inner tube. An additional challenge for superconductor pipes would be ensuring any polymer used is suitable for cryogenic use.

Several papers have outlined the design requirements for plastics used in cryogenic environments, including [43] and [44]. Plastics cooled to cryogenic temperatures become harder, stiffer, and more brittle. In the context of a flexible pipe, this would lead to a greater likelihood of cracking of the inner sheath, especially when subjected to bending loads.

Another challenge with designing for cryogenic temperatures is the relatively high coefficient of thermal expansion of polymers compared with metals, leading to differential shrinkage of adjacent layers. Cryogenic temperatures also impact the friction properties of a polymer. Several polymers are suitable for cryogenic usage. PCTFE or Polychlorotrifluoroethylene is a popular choice for cryogenic applications [45]. Plastics can be filled with other materials such as glass fibres, graphite, or molybdenum disulphide to reduce the coefficient of thermal expansion of base polymers [43]. DuPont™ Vespel® [46] and VICTREX CT™ 200 [47] are two polymers that have used this technique, and they claim better thermal expansion properties compared with PCTFE polymers. Providing a smooth internal carcass can significantly enhance the thermo-hydraulic performance of the coolant fluid. The materials to create such a smoothbore already exist; the question is can they withstand the dynamic loading encountered in an offshore marine environment.

4.2 Structural integrity: Loading in a marine environment

When dealing with land-based superconductor cables, thermo-hydraulic performance is a key focus area. These issues are also critical for the successful deployment of marine superconducting cables. However, the subsea environment presents an additional range of issues to consider, such as hydrostatic pressure, dynamic loading from waves and current, as well as cable installation and operation and maintenance procedures. The oil and gas industry represents state of the art in terms of subsea pipeline design, and we consider their approach to subsea pipe design in the following sections.

4.2.1 Hydrostatic pressure

The external pressure experienced by pipes subsea is substantially more than that experienced in atmospheric conditions. Atmospheric pressure is around 1 bar at the ocean surface, with the hydrostatic pressure increasing by 1 bar for every additional 10 m of water depth. Pressure differentials between internal and external pressure induce hoop stress in the pipe’s layers (i.e. stresses tangential to the pipe circumference). If the internal pressure exceeds the external pressure, the pipe might burst. If the external hydrostatic pressure exceeds the internal pressure, collapse may occur. The collapse resistance depends on the pipe diameter, wall thickness, and material properties (e.g. Young's modulus, yield strength and Poisson's ratio) and is a critical consideration in the initial sizing of a subsea pipe [48]. If a vacuum layer provides the insulation for a superconductor cable, the outer cryostat layer will carry the external pressure with no counteracting internal pressure. High-density polyethylene (HDPE), Polyamide 11 (PA11) and high-strength Polyurethane (PU) are typical materials used for the outer sheath layers of subsea pipelines; these materials are known to perform well when saturated and subjected to high hydrostatic pressures [49]. Additional collapse resistance can be provided by a structural layer inside the protective outer sheath. The outer cryostat in a vacuum-insulated system, for example, will provide such resistance. Flexible pipes in the offshore oil and gas industry have been used at depths over 2000m, so the likely depths for a superconductor used for offshore energy transmission are considered shallow: ~150 m for much of northwest Europe, as shown in Figure 7. However, the lack of internal pressure means the net pressure is higher, so the risk of pipe collapse remains a consideration.

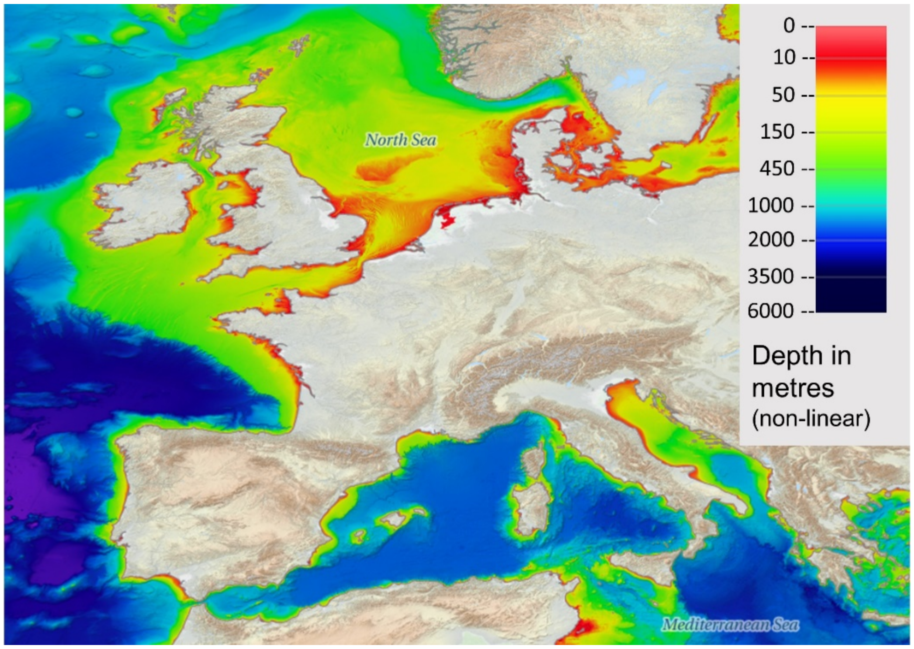


Figure 7 Mean Water Depth in Europe (Source: https://portal.emodnet-bathymetry.eu/)

4.2.2 Wave, current and vessel motions and the need for flexibility

Environmental conditions introduce dynamic loads in offshore pipes, especially in pipes connected to a floating vessel/platform (known as risers). Current loading varies over the water depth and, along with direct loading on the pipe, will also cause movement of any floater to which a riser may be connected. Currents at the seabed may be an issue for pipeline stability. Currents are defined by their speed and direction and are relatively static over short durations. Waves dissipate quickly with depth, so direct loading on the riser is significant near the surface only. Wave-induced motion of floaters is calculated based on the Response Amplitude Operators (RAOs) of the floater. Waves are defined by their height, period, and direction and are dynamic even over short durations. The waves and current loading and platform motions introduce stress into the superconductor system.

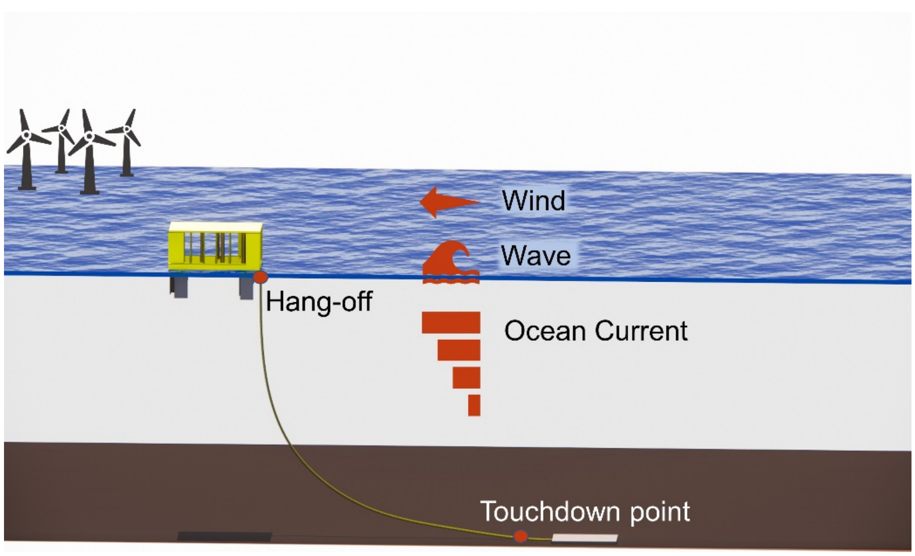


Figure 8 Marine Environmental Loads on Superconductors

The three main types of stress of concern to an offshore pipeline engineer are axial tension/compression, bending stress and hoop stress. The software tools (e.g. [51,52]) used to numerically analyse subsea pipes consider the coupled effects of these stresses. As an example, bending will increase the tension on the outside of a pipe curve and increase the compression on the inside. Section 4.2.1 discusses hoop stress and its role in pipe collapse or bursting. Axial loading and pipe bending are further discussed here.

The impact of axial force on pipes depends on whether the net force is compressive or tensile. Offshore cables can be subjected to substantial tensile loads at vessel or platform hang-off due to their self-weight and the motions of the structure to which they are attached. Subsea flexible pipes contain a tensile layer to resist such loading. In designing superconducting cables for overland use, tensile loading is not a significant consideration. Existing overland cable designs may not have adequate tensile resistance for offshore use. Axial compression can also cause issues for seabed pipes, especially as a factor in the lateral buckling of the pipe. Pipeline engineers often refer to the effective axial force, which includes the effect of internal and external pressure on the walls of the pipe. It is this effective force that is considered in lateral buckling analysis [53,54]. Another source of axial stress in superconducting pipes is the axial contraction of layers at cryogenic temperatures. Superconductors can experience thermal contractions of the order of 0.3% compared to ~0.1% thermal expansion for conventional cables [55]. The Ishikari Project reported contractions of ~0.3% when the temperature was reduced from 300 K to 70 K [56]. The challenge with designing for cryogenic temperatures is the relatively high coefficient of thermal expansion of polymers compared with metals [43]. Usually, a plastic layer of a pipe shrinks significantly more on cooling than an adjacent metal layer. Such differential shrinkage causes issues when the layers are terminated at an end fitting and may lead to end fitting pull out or excessive stresses on metal layers. A suitable superconductor cross-section design will consider all axial loading effects, including axial stress, induced buckling, and differential expansion/contraction of component layers.

Along with hoop and axial stress, a subsea engineer must also pay close attention to the bending stress caused by the initial configuration or environmental loading. Flexible pipes used by the offshore oil and gas industry have low bending stiffness in comparison to axial stiffness to allow them to flex in response to this loading. These pipes are defined by an allowable Minimum Bend Radius; overbending them leads to ovalisation and eventually pipe collapse. In traditional unbonded flexible pipes, overbending can also lead to the unlocking of the pressure armour layer. Critical areas for bending are at the seabed Touchdown Zone and the hang-off region. Bend stiffeners and bend restrictors ensure the pipe does bend beyond the minimum bend radius. Numerical simulations and analysis can determine if such structural components are required. As well as ensuring that any superconductor conduit can withstand extreme environmental events, such as a 100-year wave or current, the impact of continual cyclical loading and the fatigue response must also be evaluated.

4.2.3 Fatigue, including Vortex-Induced Vibrations (VIV)

Fatigue damage occurs readily in a marine environment, especially due to the cyclical nature of wave loading. Repetitive loading can cause brittle cracking due to fatigue damage even if no single cycle exceeds the material's absolute strength. The potential sources of fatigue in pipelines include temperature cycling, pressure cycling, slugging (due to gas-liquid separation), bending fatigue and vibrations. Since a superconductor cable's successful operation requires the constant flow of coolant, it is reasonable to assume that the pipeline's internal conditions will remain relatively stable, and no significant pressure, temperature, or slugging fatigue occurs. The primary driver of fatigue damage in flexible risers is usually the wave-induced motion of floating platforms or vessels to which they are attached.

Flexible pipes can withstand harsh environmental loads due to their ability to flex in response to wave, current, wind and vessel loading [50]. However, the repeated sliding of the flexible pipe layers relative to each other due to prolonged repetitive motion may lead to fatigue damage and the wear of the metallic structural layers. Existing onshore superconductor cable systems use corrugated, welded stainless steel layers as the inner and outer tubes to provide both fluid containment and hoop stress resistance [57]. The fatigue resistance of such a corrugated layer when subjected to non-uniform wave, current and platform motion would need to be established using appropriate numerical modelling and Factory Acceptance Testing. Particular attention should be paid to the welds' performance under dynamic loading as existing flexible pipe armour layers use an interlocking structure rather than a welded design. The failure modes of flexible pipe armour layers (unlocking of the layers, fretting wear [58] and fatigue [59]) are relatively well understood, so using a new type of pressure layer adds to the design uncertainty.

Another type of fatigue loading, Vortex-Induced Vibrations (VIV), is caused by current loading. VIV is not considered significant in flexible riser design due to the damping effect of the multi-layered system, hydrodynamic damping, and lack of coherent vortices [49]. However, long-distance flexible pipes on the seabed are not common (usage is typically for short jumpers connecting subsea equipment), so the likelihood of VIV occurring in unsupported superconductor spans should be considered if a flexible superconductor design is selected. VIV is a known issue for flexible subsea umbilicals [60,61], which is an indication that VIV could potentially be an issue for superconductor cables. As well as causing VIV, the seabed currents can also affect the stability of the pipe on the seabed.

4.2.4 On-bottom stability

Depending on in-situ conditions and water depth, pipelines on the seabed may be subject to wave and current loading forces. These may destabilise the pipe leading to floatation or lateral movement [62]. Lateral motion is resisted by soil friction force and by the passive soil resistance, which is dependent on the pipe embedment. Superconductor cables can have small diameters and high levels of lightweight insulation. They will likely require some method of enhancing their on-bottom stability due to their low weight. These may include adding weight to the cross-section, adding ballast elements or anchoring. The pipes' low mass may have an adverse impact on the installation process, and a specific gravity of at least 1.1 is recommended to avoid floatation [63].

4.3 Marine environment

4.3.1 Installation

As well as designing pipes for in-situ operating conditions, pipes must also handle the stresses that occur in the installation phase. Ease of installation is one of the key drivers for using flexible, spoolable pipes rather than rigid pipes. Rigid pipes need welding before deployment, which is a time consuming and expensive operation. Subsea superconductor cables introduce the additional complexity of installing a continuous length of superconducting cable within the rigid pipe ensemble after welding. A flexible pipe solution appears to be a good option for a subsea superconductor pipeline. Such pipes are stored on spools and deployed overboard via a chute or using a Flex-lay system. Careful installation of the flexible pipe avoids any damage to the external coating, excessive tensile forces and bending the pipe beyond its specified Minimum Bend Radius.

4.3.2 Operation and maintenance

Subsea systems need to be robust and designed for minimal maintenance. Although vacuums provide better thermal insulation compared to other insulation systems, there is a cost price in higher maintenance costs and increased risk of complete failure. Adding a vacuum layer to a subsea pipe produces challenges in maintaining the vacuum long-term, especially if vacuum ports are underwater. If the vacuum is compromised, this effectively eliminates the thermal insulation effects. Nexans, a manufacturer of onshore superconductors, guarantee the vacuum in their cryogenic cables for two years [57]. The short length of this guarantee would imply a regular monitoring and maintenance system for the vacuum system would be required. Standard flexible pipe designs contain a venting system for the annulus layer to deal with any gases permeating through the polymer inner sheath. Adaption of these venting systems could provide a solution for venting a vacuum layer in a cryostat design. Southwire Company provided some positive news on a vacuum layer's long-term performance when they tested the integrity of the vacuum spaces on a HTS cable system that had been in operation for six years in Columbus, Ohio [37]. While all the vacuums had degraded, none had done so to a level that compromised the system's cooling capability. The most degradation occurred in one of the cable-terminal joint enclosures, where the vacuum pressure had increased to 0.04 mbar compared to an optimum level of 0.013 mbar. The cable tested was short (200 m), and this level of vacuum pressure loss might not be acceptable for a longer line. Additionally, even if the natural vacuum degradation does not compromise the superconductor cables' functionality, there remains the risk of accidental damage resulting in vacuum breach and loss of superconducting ability. A sacrificial outer sheath is one means of mitigating this risk of accidental damage; this was the solution employed by Technip in developing a large diameter smoothbore flexible pipe that was at high risk of failure if outer sheath damage occurred [64].

Another potential area for consideration in cryogenic system maintenance is the need for de-icing exposed components. Effective insulation should make this unnecessary, but ice build-up should not compromise the operation of components such as valves. Due to the difficulty accessing subsea equipment, systems should ideally have built-in redundancy in case a crucial component fails. Designing with redundancy may mean, for example, using two 50% pumps in parallel rather than a single pump which would be a critical failure mode. Another option is to use twin cables in a cryostat or two parallel cables to deal with HTS failure or cryostat failure, as shown in Figure 9. Levelized Cost of Energy calculations will determine the most cost-effective superconductor configuration with consideration of manufacturing, installation, operation, maintenance, and decommissioning costs.

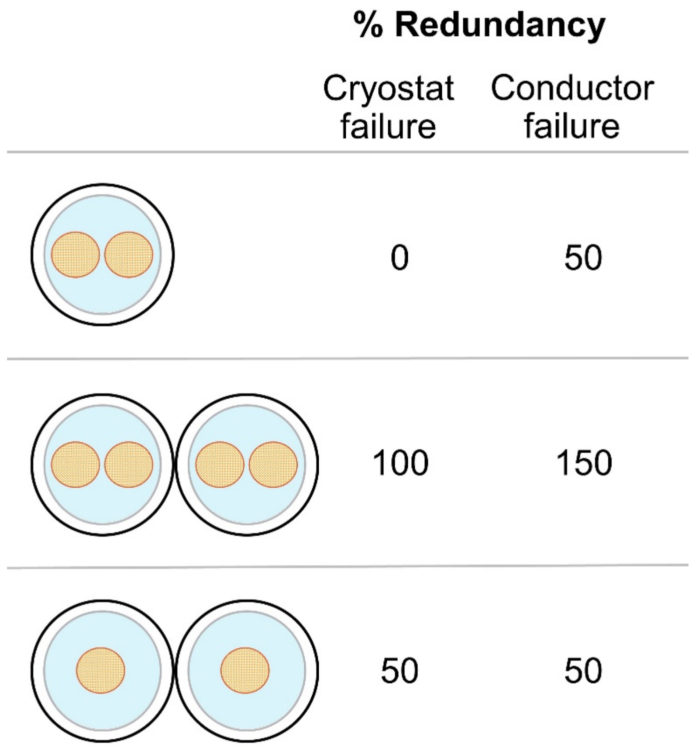


Figure 9 Redundancy in a Superconductor Cable (Source: SuperNode)

4.3.3 Corrosion

Corrosion is a key consideration in the design of offshore pipes as saltwater is an excellent electrolyte and speeds up the corrosion process. Any areas of exposed steel need mitigation measures to limit the damage caused by corrosion. Even though an outer sheath protects the pipe, it may be damaged accidentally, resulting in the inner layers experiencing saltwater conditions. Figure 10 shows that external sheath damage and associated corrosion is the most common failure mode for both flexible subsea pipes and subsea power cables [65,66]. The outer sheath may become damaged during installation or operation, resulting in saltwater ingress. Abrasion may cause damage, particularly during installation or at interfaces with ancillary equipment such as bend stiffeners/restrictors or tether clamps. Surface water is a highly oxygenated environment due to the absorption of oxygen from the atmosphere and oxygen generated by algae's photosynthesis. As a result, a critical region for potential corrosion is the hang-off point where damage may occur due to the use of ancillary equipment (I-tube, bend stiffener, etc.).

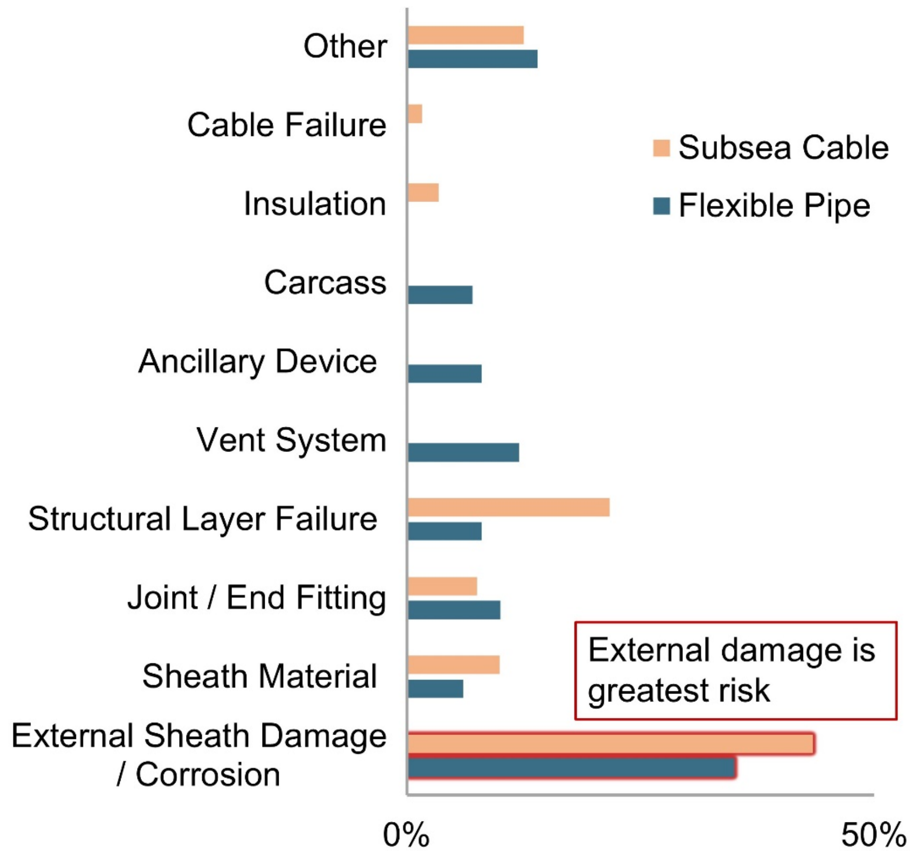


Figure 10 Failure modes for subsea pipes and cables (based on data from [66] *and* [65]*)*

Traditionally, subsea designers have dealt with the threat of corrosion by selecting corrosion-resistant materials and by using cathodic protection measures. Existing onshore superconductor cables, for example [57], use austenitic stainless steel for the carcass layers due to the steel's good structural properties at low temperatures. This type of steel generally has good corrosion resistance but is susceptible to Chloride Stress cracking [64]. Austenitic stainless steel may not be suitable for subsea use if there is a risk of seawater exposure.

5 Research and development pathway

Onshore superconducting technology is not suitable for subsea deployment and must be adapted to deal with the challenges of the marine environment discussed in Section 4. These challenges are summarised in Table 2.

Table 2 Summary of Subsea Superconductor Design Challenges

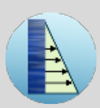
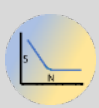
Symbol	Name	Challenges
	**Insulation & Cooling**	- Risk of total failure of vacuum insulation if outer sheath is breached - Alternatives to vacuum insulation unproven for long distances - Cooling system needs optimisation for long distances
	**Hydraulic Properties**	- Limited subsea experience of smoothbore flexible pipes - Materials with cryogenic suitability required for low-friction bores
	**Hydrostatic Pressure**	- Vacuum system offers no internal pressure resistance to pipe collapse
	**Environmental Loading**	- Bending and tensile stresses are higher in a marine environment
	**Fatigue**	- Low-cycle due to spooling during installation - High-cycle due to wave loading and second-order platform motions - Susceptibility to VIV of new cross-section unknown
	**On-Bottom Stability**	- Lightweight insulation system means additional measures to add weight to the system are likely to be required
	**Installation**	- Ensuring tensile strength is adequate to sustain self-weight - Flushing with liquid nitrogen post-installation
	**Operation & Maintenance**	- Vacuum-insulated system is difficult to maintain subsea - Subsea cooling stations may need to be hermetically sealed, which would prevent in-situ maintenance
	**Corrosion**	- Austenitic Stainless steel used for cryogenic transportation is susceptible to corrosion in seawater

Table 3 summarises how each of the key engineering challenges is addressed by existing pipeline technology. The table highlights where research effort must be focused, especially in developing a smoothbore superconductor conduit that has a suitably robust insulation system to make it viable for subsea use.

In addition to the challenges in superconductor cross-section design, research must be conducted into the development of cooling systems that enable the deployment of very long superconducting pipelines, i.e. > 100 km.

Table 3 Suitability of Existing Systems for use as Subsea Superconducting Cables

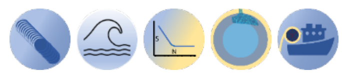
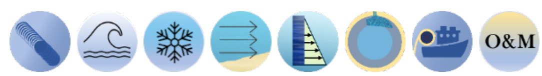
	Unbonded Flexible Pipe	LNG Flexible Hose	Composite Pipe	Onshore Superconductor
Flexibility	✓	?	✓	✓
Insulation	✗	?	?	✓
Tensile Capacity	✓	✓	?	?
Smoothbore	?	?	✓	✗
Cryogenic Suitability of Materials	✗	✓	?	✓
Corrosion resistance in Seawater	✓	✓	✓	?
Hydrostatic Pressure Resistance	✓	?	?	?
Maintainability	✓	✓	✓	✗

The Ishikari Project presents a potential roadmap to go from the present to a scenario where superconductors are deployed in a marine environment. This project began with a 20 m cable system followed by a 200 m long system; these smaller cables paved the way for deploying a 500 m underground cable and a 1000 m surface cable. A similar incremental development path could be adopted for subsea superconductors. Of course, the incremental development of subsea cables will not just be concerned with the cable length. It will also have to consider the impact of increasing water depth and harsher environmental conditions. The following sections outline the key areas for R&D that will bring subsea superconductors from the conceptual design stage (Technological Readiness Level or TRL 2) to proof of concept (TRL 3) and further up the scale toward full commercialisation (TRL 9).

5.1 Key areas for R&D

The key areas recommended for R&D are summarised in Table 4, along with the key engineering challenges that are addressed by each area. The following sections explore the research that is required in these areas.

Table 4 Summary of key areas for R&D

R&D area	Challenges addressed
Thermo-hydraulic and structural rig testing	
Material development and testing	
Vacuum system development	
Subsea cooling system development	
Open-water testing	

5.1.1 Thermo-hydraulic and structural rig development and component testing

Small-scale prototype testing in a laboratory setting can provide information about the performance of proposed superconductor cross-section designs. Specially designed thermo-hydraulic rigs can be used to test the thermal and hydraulic performance of a small-scale conduit prototype. It may not be practical to use liquid nitrogen for small-scale hydraulic testing. If water or an alternative liquid is used, pressurisation to mimic the Reynolds number and flow dynamic of liquid nitrogen is needed. At the same velocity and diameter, liquid nitrogen has a high Reynolds number than water and is more susceptible to turbulent flow.

In parallel to the thermo-hydraulic testing, initial feasibility testing of a subsea superconductor conduit design will include basic structural testing. The main loads likely to be experienced in a subsea environment are applied using structural rigs. A bending moment rig could test the conduit's bending stiffness and establish its minimum bend radius. A tensile rig could test the cables performance under tension. Even static seabed cables will need to withstand tensile loads during the installation phase. The results of prototype testing can calibrate numerical Finite Element Analysis models of the subsea conduit.

An extension to basic structural testing is the inclusion of fatigue testing. Fatigue should be considered early in developing a subsea superconductor conduit as it is a known issue for offshore pipes subject to dynamic environmental loads. The presence of new cryogenic material and possibly new material profiles (e.g. corrugated layers) adds to design uncertainty. Fatigue testing may include testing individual components' performance or full-scale fatigue testing using a resonance testing rig to apply high-frequency loading to a prototype conduit.

5.1.2 Insulation system development

State-of-the-art insulation requires a vacuum layer surrounding the coolant layer in a superconductor conduit. The feasibility of maintaining such a vacuum underwater needs study as vacuums will naturally degrade with time. Subsea pipes are in an uncontrolled environment, so there is a high likelihood of external sheath damage. This risk is so high that the API 17J flexible pipe design specification [67] requires that service-life, fatigue, and thermal insulation calculations account for the case of a flooded annulus. Any vacuum-insulated subsea line is only feasible if retaining that vacuum for the cable's expected life is achievable. Therefore, this problem needs consideration early in the design process. Unknowns include the permeability of new cryogenic materials and cryostat configurations, as well as the best design for a robust subsea vacuum system. Further sensitivity analysis is required to understand the trade-off between a continuous vacuum with access at the ends only or shorter sections isolated by bulkheads that increase robustness but complicate maintenance.

An ideal subsea insulation system would not be dependent on the maintenance of vacuum and could potentially use another more robust insulation method, such as aerogel insulation or a high-performance insulating polymer. The research and development work done by the LNG industry should be studied to establish if these types of insulation can satisfy the onerous insulation requirements of long-distance subsea superconducting cables.

5.1.3 Material development and testing

While materials for cryogenic usage exist, their suitability for dynamic use needs verification. Any structural embrittlement at low temperatures raises the possibility of increased susceptibility to cracking, especially when subjected to cyclical loading. Fatigue testing would confirm a material's suitability for a dynamic cryogenic environment and allow the development of appropriate SN (stress versus the number of cycles to failure) curves for materials. Any analysis must consider both low-cycle fatigue (during spooling and unspooling) and high-cycle fatigue (during operation in the subsea environment).

5.1.4 Subsea cooling system development

After establishing a subsea superconductor design's initial suitability, the focus of research can move to longer distance deployments (> 1 km). Some form of subsea pumping and cooling maybe necessary to move beyond the distances dictated by the input temperature and pressure. The development of subsea compression stations proves the technical feasibility of subsea stations to some extent - these stations were at TRL 7 in 2017, according to AKER Solutions [68]. AKER Solutions delivered the first such station in 2015, located at 260 m water depth with a 40 km tie-back to shore.

The focus in adapting a cryogenic pump for subsea deployment will be maximising the robustness and reliability of components, as once installed, maintenance options will be limited and costly. Subsea compressors use adapted technology to minimise the number of moving parts – one example is using magnetic bearings to eliminate the need for lubrication and reduce power requirements. The AKER Åsgard system also uses a dual-train system, with compressors, pumps, scrubber, and coolers on each train, to improve overall reliability, and components are modular to facilitate replacement. One of the major design decisions for any subsea pumping and cooling unit will be whether to hermetically seal the entire unit or leave it accessible for inspection and maintenance. Microsoft has done useful research in this space in Project Natick [69], which saw the deployment of a subsea prototype data centre housed in a watertight cylindrical shell and supported on a steel foundation. The project tests the feasibility of using seawater to cool a data centre. The development was in relatively shallow water (50 m) and located near the shore. Nonetheless, the unit size (12 m length and 2.8 m diameter) and power requirements (240 kW) are similar to those likely to be required to house and power a cryogenic cooling and pumping station.

5.1.5 Open-water testing

A first step to employing the cables in a realistic subsea environment will involve component demonstration, e.g. subsea pumping station using a dedicated open-water test. This testing may be followed by a system demonstration at scale, e.g. connecting an offshore energy converter to the grid with a subsea superconductor. Such a deployment would bring subsea superconductors to TRL 5. A longer-term test campaign (> 1 year) would establish the full system performance in a complete range of environmental conditions and allow for environmental monitoring. Long-term deployments enable the study of phenomena such as marine growth and ice formation, which can affect cable lifetime and performance. Upon completing scaled deployments, full-scale deployments of subsystems can then proceed and, finally, a full-scale demonstration of the complete system. Grid-connected test sites for full-scale deployments are available in Hawaii, Wave Hub in Wales, and the European Marine Energy Centre in Scotland, for example.

Following on from such a test campaign, the development of large-scale pre-commercial demonstration projects would bring subsea superconductors to TRL 8-9. Such a demonstration project may involve a superconducting export cable solution for a floating offshore wind farm of the order >100 MW in a high-energy environment such as the Irish Atlantic coast.

6 Conclusions

A significant portion of energy in 2050 will be generated by offshore wind farms. This paper has outlined how superconducting technology can potentially be used to meet Europe's 2050 decarbonisation targets by facilitating the transmission of large amounts of renewable power over very long distances with minimal losses. This paper has presented the state of the art in onshore superconductor technology and bulk power transmission. The key engineering challenges that must be addressed to deploy superconductors in a marine environment, using learnings from the oil and gas sector, have been examined. These challenges relate to the thermo-hydraulic properties of the conduit, the structural loading experienced in the marine environment, and marine operations such as installation and O&M. A research and development pathway has then been identified that describes how these challenges can be investigated and addressed. The key research areas that have been outlined include the development of pipes suitable for cryogenic usage that can withstand the dynamic loading encountered in a marine environment; robust, low-maintenance insulation systems suitable for subsea use; and the development of cooling systems that will enable the deployment of very long superconducting pipelines, i.e. > 100 km. Although the primary focus of this research has been on superconductor cables, the information is also applicable to other subsea conduits requiring cryogenic temperatures such as 'green' hydrogen.

7 Acknowledgements

This research was funded by Science Foundation Ireland (SFI) through MaREI, the SFI Research Centre for Energy, Climate, and Marine [Grant No: 12/RC/2302_P2], with supporting funding obtained from SuperNode Ltd.

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