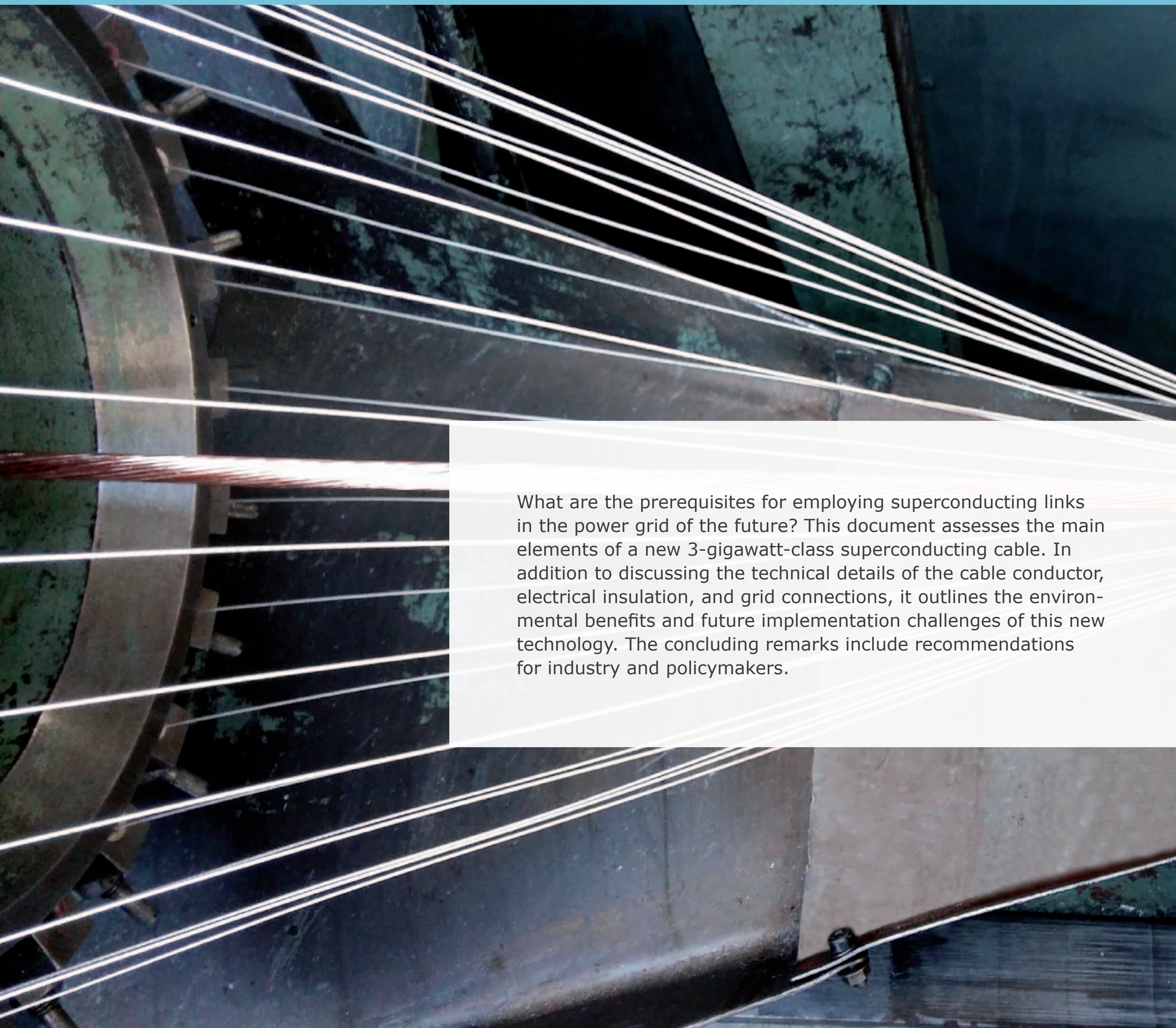
ADVANCING SUPERCONDUCTING LINKS FOR VERY HIGH POWER TRANSMISSION



What are the prerequisites for employing superconducting links in the power grid of the future? This document assesses the main elements of a new 3-gigawatt-class superconducting cable. In addition to discussing the technical details of the cable conductor, electrical insulation, and grid connections, it outlines the environmental benefits and future implementation challenges of this new technology. The concluding remarks include recommendations for industry and policymakers.

INTRODUCTION

Thirty per cent of the electricity in Europe is currently generated by renewable energy sources. At the present rate of growth, the proportion of renewables could reach 50 per cent by 2030 [1]. What will our future grids look like and what role can superconducting links play in them?

Recent studies have shown that additional transmission corridors extending over several hundred kilometres with capacities of 5 to 20 gigawatts (GW) are needed in the future European grid [2]. As solar and wind farms are often located far away from the consumption centres, long-distance transport lines are required, with direct-current transmission having a clear advantage in terms of efficiency.

Beyond purely technological challenges, the interplay of ecological, social and economic dimensions adds to the complexity of the system.

In this context, the EU-funded project Best Paths aimed to develop novel grid technologies to increase the European transmission capacity and electricity system flexibility. A demonstration area within Best Paths focused on validating **high-voltage direct-current (HVDC) superconducting links** capable of transporting large amounts of electricity – on the gigawatt scale [3].

This is the first time a high-voltage superconducting cable system has been designed that is capable of operating in direct current. Other projects deal with alternating current only and use high-temperature superconducting materials that are manufactured in a low-yield and complex process. By contrast, the Best Paths cable employs the superconducting material magnesium diboride (MgB_2), which is very economical to produce.

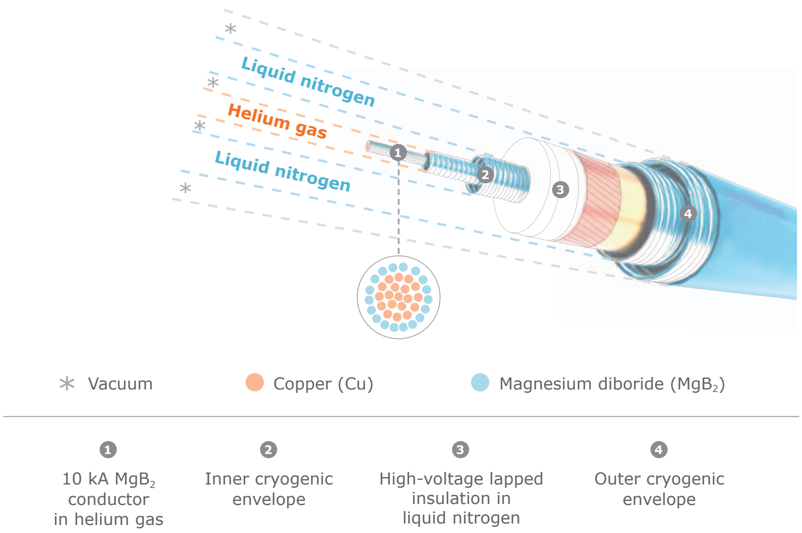
What do the main cable components look like? What can be improved in terms of costs and efficiency? Apart from testing the suitability of the MgB_2 superconductor for high-power electricity transfer, the remaining cable components – including the insulation and terminations – were also examined. Particular care was taken to employ real-grid conditions and assess the economic viability and environmental impact of the cable system.

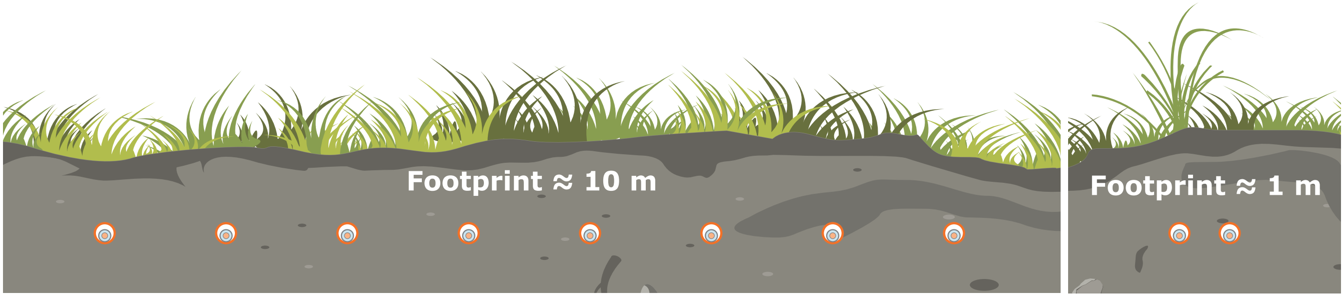
KEY COMPONENTS AND CHARACTERISTICS OF THE CABLE

The most important specifications of the Best Paths 3-GW-class HVDC superconducting cable system are summarised below. The upper part of the table lists the main nominal parameters of the cable, and the lower part shows the requirements imposed by transmission system operators for successful integration into the electricity grid. The fulfilment of these requirements was a key consideration in the design of the cable [4].

The figure on the right-hand side illustrates the basic cable configuration, with the key components labelled accordingly. Due to their large size, the electrical terminations used to provide the grid connection are not represented here.

Structure	Monopole
Power	3.2 GW
Voltage	320 kV
Current	10 kA
Cooling media	Liquid N_2 for the electrical insulation He gas for the MgB_2 conductor
Fault current	35 kA during 100 ms
AC ripples on 10 kA DC current	< 1% amplitude 50 Hz
Change of power flow direction	100 MW/s up to 10 GW/s





Resistive cables (XLPE)
8 cables (320 kV/2500 mm² Cu)

Superconducting cables (MgB_2)
2 cables (320 kV/10000 A)

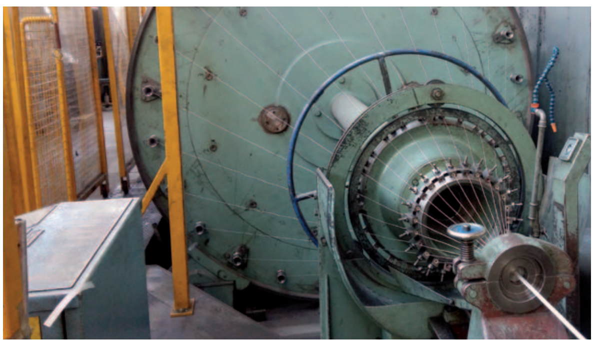
WHAT ARE THE MAIN RESULTS?

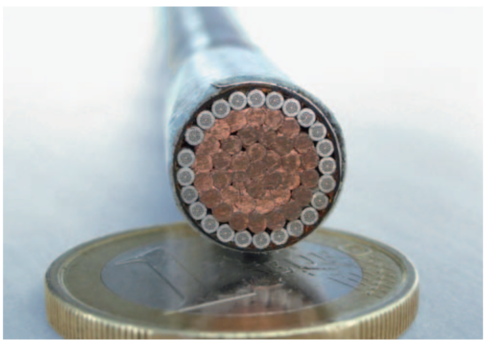
- **Wire and cable conductor:** The project confirmed that MgB_2 superconductors can carry large amounts of electricity, up to 500 times more than copper. Furthermore, the superconducting wires are manufactured in a robust and reproducible industrial process. Using these wires, 10 kiloampere (kA) cable conductors have been designed and assembled on standard cabling machines. The performance of the cable conductors has been tested and confirmed at different temperatures and magnetic fields. No degradation has been found after mechanical stress tests such as bending and pulling.

- **High-voltage insulation:** A novel HVDC insulation operating at cryogenic temperatures has been designed and successfully tested within the project. The insulation consists of multiple layers of paper immersed in liquid nitrogen. In case of an electrical breakdown, the nitrogen automatically fills any gap in the paper and the insulation properties are thus recovered. Tests on the nitrogen-impregnated insulation proved its very high electrical performance and reliability, confirming its suitability for future use in the electricity grid. The results were shared with the international electrical insulation community [5].

- **Terminations:** Managing the connection between the superconducting cable and the existing grid is one of the most challenging technical aspects due to the high current and voltage levels involved. Hence, the innovative design of the terminations aims to separate the current and voltage functionalities. The terminations are therefore split into two independent parts: In the upper part, the current is injected through special current leads connected to the cable conductor, while the high-voltage gradient is managed in the lower part. With this design, the performance of the superconducting cable system can be easily adapted to the grid voltage and current without the need for any new development work.

The high-voltage testing was carried out at a dedicated test platform on a 30-meter superconducting loop connected to two terminations. It was conducted at up to 592 kilovolts (kV), which is the testing voltage required to qualify 320-kV-class systems. These pioneering tests of superconducting cables have set benchmarks for future HVDC standards.





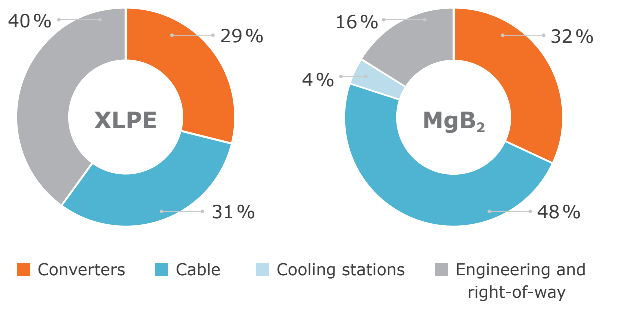
Impressions from the industrial manufacturing process

KEY ENVIRONMENTAL BENEFITS

The advantages of superconducting cables over conventional HVDC cables are:

- No heat leakage into the surrounding soil
- Significantly smaller overall size – one pair of high-power superconducting cables has the same transmission capacity as eight conventional cables (see footprint figure to the left), which translates into:
  - Lower impact on the soil during installation
  - The possibility of using narrow or existing corridors
  - Reduced impact on nature, especially in forested or pristine areas.

CAPITAL COSTS FOR A 6.4 GW LINK OF 500 KM LENGTH



In terms of their overall costs, resistive and superconducting links are very similar. As seen above, the cost of the converters that deliver 320 kV and 10 kA is comparable for both solutions. Due to the small footprint of the superconducting link, expenditure on engineering and right-of-way can be reduced by a factor of 2.5. Surprisingly, the cost of the cooling stations is not that significant. It is, in fact, the cryogenic envelope that accounts for the main cost share. This figure is, however, based on existing production lines. More efficient production lines will be needed to install links that are several hundreds of kilometres long. And the costs of the cryogenic envelope are expected to decrease by at least 30 per cent as a consequence of this industrialisation.

IMPLEMENTATION CHALLENGES

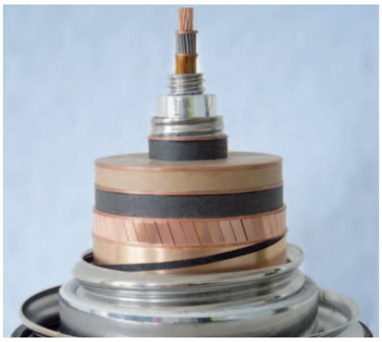
Superconducting cables can transmit high currents at flexible voltage levels that can be tailored for optimal performance. This makes high power transmission possible even at moderate voltages (up to 320 kV) and holds great promise for the next generation of electricity grids.

That said, the further development of superconducting lines faces a number of challenges. In particular, the need to combine two technologies – electricity transmission and cryogenics – introduces a new complexity. This is why within Best Paths substantial work was dedicated to elaborating a viable concept for very long superconducting links. The different options still need to be thoroughly evaluated. Some of the remaining challenges include:

- Setting up production lines on a scale required to manufacture the cryogenic envelopes needed for link lengths of several hundreds of kilometres;
- Qualifying field joints for both the cable conductor and the high-voltage insulation;
- Examining appropriate coolants for long-distance links, in particular in areas with steep inclines.

One issue that is often mentioned in conjunction with very high-current links is the absence of converters with a rating above 2 kA. However, a current rating of 5 kA is expected to become available within the next five years, and converters operating in parallel are expected to overcome this barrier in the future.

Finally, the system's reliability and availability still need to be accepted by grid operators. Even though superconducting cables are based on proven and safe technologies and have been successfully tested for more than five years with 100 per cent availability, gaining the acceptance of transmission system operators remains a challenge.



WHAT HAPPENS NEXT?

Within Best Paths, the operation of an HVDC cable system was demonstrated on test platforms. Significant efforts were made to integrate the knowledge gained in this project into the Cigré Working Group WG D1.64 (Cryogenic electrical insulation) and various Standardization Technical Committees such as TC 90 (Superconductivity) & TC 20 (Electric cables). This will ensure that the Best Paths results contribute to setting the HVDC standards of the future.

The next step will be to develop testing guidelines for high-voltage direct-current superconducting cables to guarantee safety and quality standards. A consortium of manufacturers and transmission system operators would need to be formed and further develop the testing procedures.

Furthermore, a set of new standards and availability is needed for equipment operating at high current and moderate voltage in substations. This includes not only the converters, but also circuit breakers to protect the grid and switchgear to operate it.

Ultimately, the insertion and operation of a short MgB_2-based link in the electricity grid will demonstrate the potential of this technology in a definitive way. Particular attention and specific case studies should be devoted to the implementation constraints identified in the socio-economic evaluation related to load rate, link length, and repair time. Demonstrable success in real-life operating conditions will help to convince grid operators.

PROJECT RECOMMENDATIONS

In Best Paths, gigawatt-scale superconducting cables were investigated and shown to be technologically mature and cost-competitive for the transmission of large amounts of electricity. Thanks to their high efficiency, compact size, and reduced environmental impact, superconducting cables are likely to find higher public acceptance than overhead lines and conventional cables. **In order to deploy this new technology, appropriate de-risking instruments should be put in place within the framework of European energy-climate policies.**

In the long term, superconducting links are expected to transport large amounts of electricity over long distances. In the short term, the most suitable applications are areas where civil work is expensive, but also urban areas where space is limited. Here, a short superconducting cable could serve as a 'bridge' connected to resistive cables or overhead lines. **For feasibility studies and tenders of new transmission projects, it is recommended to take the superconducting option into due consideration.**

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ABOUT BEST PATHS

BEST PATHS stands for 'BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems' and involves 38 partners from 11 European countries. The project was funded by the European Commission within the 7th Framework Programme for Research, Technological Development and Demonstration under grant agreement no. 612748.

The project united experts around five large-scale demonstrations to validate the technical feasibility, costs, impacts, and benefits of the tested grid technologies. They have found solutions for the transition from HVDC lines to HVDC grids, to upgrade and repower alternating-current parts of the network, and to integrate superconducting high-power DC links.

The superconducting demonstration encompassed expertise from transmission system operators as well as industry and research organisations from the fields of material sciences, cryogenics, energy systems, and electrical engineering:

Nexans France (Leader) • CERN • Columbus Superconductors • ESPCI Paris
IASS Potsdam • Karlsruhe Institute of Technology • Nexans Germany
Nexans Switzerland • Ricerca sul Sistema Energetico • Réseau de Transport d'Électricité
Technische Universität Dresden • Universidad Politécnica de Madrid

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