WG4: LONG-TERM VIEW FOR HVDC TECHNOLOGY

ABOUT READY4DC

The future electricity network envisioned by READY4DC will be characterized by a growing role of multi-vendor multi-terminal (MVMT) HVDC solutions within the current AC transmission networks both onshore and offshore. READY4DC is contributing to this synergistic process by enabling commonly agreed definitions of interoperable modelling tools, model sharing platforms, clear processes for ensuring interoperability, and an appropriate legal and political framework.

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Long-term view for HVDC technology

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EXECUTIVE SUMMARY

The European Commission (EC) has outlined a strategy aimed to achieve climate neutrality by 2050. This strategy involves a major shift in how electricity is generated, moving away from fossil fuels and toward wind and solar power. This transition is anticipated to introduce new power flows through High Voltage Alternating Current (HVAC) transmission networks and tap offshore wind potential, in particular in the North Sea. In response to these changes, High Voltage Direct Current (HVDC) technology is increasingly being acknowledged as the most efficient means of transporting this renewable energy.

This whitepaper describes the state-of-the-art HVDC technology, some socio-economic aspects, and the circular economy involved in the current power system. In addition, the whitepaper presents an outline of Research and Development (R&D) short- and long-term views for HVDC technology and a discussion about the end of life in the HVDC sector.

State-of-the-art HVDC technology

The state-of-the-art HVDC technology mostly concerns point-to-point HVDC links. Europe predominantly adopts the Voltage Source Converter (VSC) HVDC transmission due to its advantages over the Line Commutated Converter (LCC) technology, being the ability to use cables and reverse the power flow by changing the current direction. Also, VSC-HVDC technology is well-suited for multi-terminal HVDC systems, as compared to LCC technology. Components of HVDC systems, including cables, converter stations, and control and protection systems, have evolved to enhance efficiency, capacity, and reliability. These advancements, particularly in Cross-Linked Polyethylene (XLPE) cables and new VSC topologies, in particular the modular multilevel converter (MMC), have enabled extended transmission distances, reduced losses, and smooth integration of renewable energy. Additionally, the emergence of multiterminal HVDC systems (and at some point HVDC overlay grids) plays a vital role in the transition to renewable energy-based energy systems. As the demand for transporting remote renewable energy and connecting diverse power markets grows, the need for HVDC systems is anticipated to grow. Moreover, the introduction of HVDC DC Circuit Breakers (DCCBs) marks a potential development, ensuring system division as networks scale up. This overview underscores the critical role of HVDC technology in achieving renewable energy integration and its evolution to meet the changing demands of modern power systems. Standards play a pivotal role in the realm of HVDC technology, with the International Electrotechnical Commission (IEC) taking the lead in establishing and maintaining these standards. These standards include various facets of HVDC systems, including design, technical requisites, construction, commissioning, reliability, availability, and operation and maintenance.

WGs outcomes

The outcome of the READY4DC project includes several technical and non-technical aspects which were covered by four working groups: WG1, focused on the modeling, simulation framework, and data sharing for multi-vendor multi-terminal (MVMT) HVDC systems, detailing the requirements for successful multi-vendor HVDC demonstration projects. For instance, WG1 acknowledges the need to prioritize interaction phenomena, especially on the DC side, but notes that a comprehensive risk identification framework is lacking due to the emerging nature of MVMT DC systems. WG2 explored the legal framework required for the realization of MVMT HVDC systems, focusing on governance, standardization, intellectual property (IP) law, risk, and liability. The work emphasizes the need for clear governance, cooperation, and standardization in the development of MVMT HVDC grids. WG2 also underscores the importance of compliance with competition law and IP protection. Clear guidelines and agreements are necessary to manage risks and liabilities effectively in the evolving landscape of MVMT HVDC systems. Finally, WG3 provides insights into the multi-vendor interoperability process and demonstration definition, addressing aspects like interaction studies, workflow methodologies, and the choice of simulation tools. It outlines key steps for implementing the first MVMT demonstrator, including role clarification, legal and regulatory framework setup, standard language for MVMT projects, system adequacy studies, and a coordinated specification development process.

Socio-economic aspects

HVDC plays a role in energy markets, and it contributes to energy connectivity and resilience – and thus HVDC has socio-economic aspects. Substantial investments in HVDC technology are needed to meet future electricity generation demands and climate goals. Social acceptance, stakeholder engagement, and alignment with national and regional energy policies are important. The concept of a circular economy addresses the sustainable and efficient use of resources throughout the HVDC system's lifecycle, from raw material extraction to waste management and decommissioning. Furthermore, modularity, remanufacturing, and refurbishment are needed to achieve circularity, ultimately contributing to the sustainability of HVDC technology. Some challenges and opportunities for HVDC technology within a circular economy framework are optimizing resource use and reducing environmental impact throughout the technology's life cycle.

HVDC R&D short- and long-term

The short and long-term perspectives of R&D within the HVDC sector reflect the surge in HVDC projects, leading to resource and staff constraints, necessitating a focus on efficient deployment. Priorities include interoperability across vendors, specifying technical standards, and addressing complexities in control and protection software for grid extensions. Additionally, R&D must consider circularity and recycling, and explore higher power ratings, new functionalities, and the integration of superconducting grids. The chapter underscores the need for innovation while balancing rapid deployment, ensuring the HVDC sector keeps pace with evolving technology and industry demands.

End of life

The end-of-life phase in the HVDC sector comes with considerations for HVDC owners and utilities. There is a need for a structured framework to manage end-of-life phases and suggests drawing lessons from the Oil and Gas (O&G) sector's experience. It is important to consider financial guarantees, to address potential ownership shifts, and the role of government equity in managing electrical infrastructure during the HVDC's lifecycle. The "golden share" mechanism is explored as a strategy to maintain government influence while facilitating market investments. This chapter delves into the complexities of managing end-of-life scenarios in the HVDC sector, shedding light on practical approaches and regulatory considerations.

1. INTRODUCTION

In the pursuit of ambitious European energy targets, HVDC technology has emerged as a keystone in the transformation of power transmission systems. Traditionally employed to connect distant generation or to connect non-synchronous AC systems, HVDC technology can ease congestion and enable interconnections between previously isolated grids [1].

The paradigm shift in HVDC implementation is most evident in the growing interest in multi-terminal HVDC systems that can provide flexible power transmission, redundancy, and reduced need for infrastructure (compared to several point-to-point HVDC links). Proposals for offshore wind "hubs" where multiple wind farms channel their energy through several HVDC cables to various countries [2], exemplify this novel approach. The rationale behind this transformation is clear: meeting the ambitious EU targets outlined in the "Fit for 55" legislative package and the REPowerEU plan necessitates harnessing the potential of renewable sources on an unprecedented scale. In fact, Europe envisions 592 GW of solar photovoltaic (PV) generation and 510 GW of wind generation by 2030, demanding substantial annual additions of 48 GW for solar PV and 36 GW for wind [3].

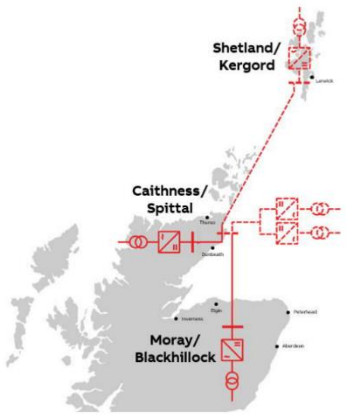
However, the growth of HVDC technology is not without its challenges, particularly in the realm of safety and grid reliability. In emerging multi-terminal DC systems, such as the North Sea Wind Power Hub program [2], ensuring that the system does not compromise critical onshore AC grid parameters like the maximum permissible power loss is imperative.

Considering these developments, HVDC technology assumes a pivotal role. Already, HVDC has demonstrated its efficacy in connecting extensive offshore wind farms (OWF) to onshore grid connection points. For instance, the German North Sea project stands as an example of HVDC's effectiveness in achieving long-distance connections for offshore wind energy. The first multi-terminal HVDC projects in Europe include the following:

1. Caithness-Moray-Shetland [4]

The Caithness Moray HVDC Link in northern Scotland is configured for a five-terminal HVDC system indicated by the straight lines in the picture and is anticipated to be entirely operational by 2024.

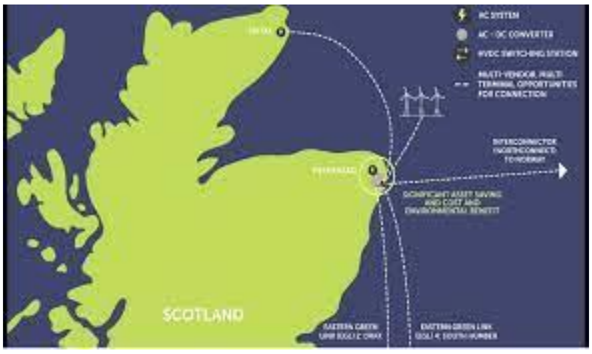
FIGURE 1-1
The Caithness Moray HVDC Link in Northern Scotland



2. Project Aquila [5]

Project Aquila represents a multi-terminal, multi-vendor demonstration project associated with the Eastern Green Link initiatives and other developments centered around the Peterhead substation in the North-East of Scotland, a collaborative effort between SSEN Transmission, industry partners, and The National HVDC Centre.

FIGURE 1-2
Project Aquila



3. Hypergrid [6]

Hypergrid is a long-term planning initiative led by the Italian transmission grid operator Terna. It involves the establishment of several HVDC links to interconnect Italy's islands and enhance the onshore transmission grid.

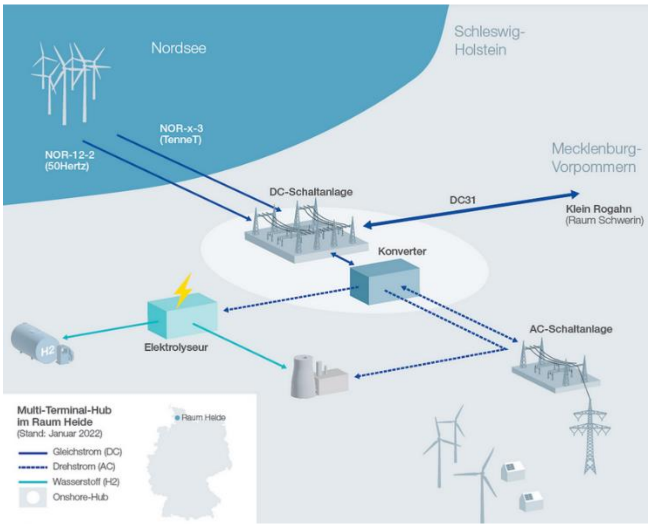
FIGURE 1-3
Hypergrid project in Italy

4. The Heide hub [7]

The planned power hub on the North Sea consists of a 4-terminal 500 kV bipole system that will link a 2 GW offshore wind farm to mainland Germany and to a land-based 2 GW HVDC connection that carries the wind power towards the southern load centers.

FIGURE 1-4

Heide hub in Germany



2. STATE-OF-THE-ART OF HVDC TECHNOLOGY

HVDC technology plays a crucial role in the efficient transmission of electricity across extended distances and facilitates the integration of renewable energy sources (RES) into the current AC energy network. In comparison to traditional HVAC systems, HVDC offers a more efficient and cost-effective means of long-distance bulk power transmission [8]. HVDC systems have key advantages over AC systems in terms of both power transmission capacity and the distances they can cover while using fewer materials [9]. Due to their fast controllability, these transmission systems are especially valuable for transferring high power over extended distances, including undersea cable connections for offshore renewable energy integration. VSC HVDC transmission is the preferred type of converter in Europe due to its advantages over LCC such as self-commutated converters, bidirectional capabilities and grid forming and grid following capabilities [10].

A typical HVDC transmission system consists of AC/DC and DC/AC converter stations and transmission lines, transformers, as well as control and protection systems, secondary equipment, and more. As the demand for transporting remote renewable energy and connecting diverse power markets grows, the number of HVDC systems is expected to grow rapidly. Furthermore, the concept of HVDC multiterminal systems is emerging, at some point potentially leading to an overlay or backbone system within the existing AC grid. In this setup, a multi-vendor aspect becomes critical to achieve.

2.1 Cable

The majority of the HVDC systems in operation today in Europe are cable-based [11]. XLPE cable technology is advancing to enhance efficiency, capacity, and reliability in long-distance power transmission, progressing alongside converter technology. This evolution has seen voltage levels grow from 80 kV to 640 kV, offering extended transmission distances with reduced system losses and lightweight, high-voltage-qualified cables [12]. XLPE insulated cables are increasingly favored for new installations due to their cost-effectiveness and superior thermal performance [11]. However, a significant challenge lies in recycling XLPE and achieving circularity. Furthermore, novel extruded cable technologies featuring polypropylene are emerging, boasting higher thermal ratings and a simplified manufacturing process compared to XLPE. These developments, once established as reliable technologies, have the potential to lower HVDC cable costs [13].

2.2 Converter station

The shift from LCC-HVDC technology to predominantly VSC converters in Europe has been driven in part by the change in the traditional power system [9]. LCC technology relies on high-power thyristors and high AC system strength, making it unsuitable for offshore wind projects [13]. In contrast, VSC converters employ high-power insulated-gate bipolar transistors (IGBTs), offering controllability and the ability to black-start and operate in islanded mode, making them ideal for offshore wind connections [14]. In particular modular MMC VSC converters can produce smooth HVAC voltages with minimal harmonics, reducing the need for filters. VSC HVDC technology furthermore provides flexibility in controlling active and reactive power, making it suitable for urban areas and offshore applications. The technology can serve as a "Grid Follower Converter" or "Grid Forming Converter" to address grid manageability and RES integration challenges. Different VSC types, such as Half Bridge Type MMC and Full Bridge Type MMC offer different functionalities. The Half-bridge MMC-HVDC transmission technology comes at a lower hardware cost due to a smaller number of power semiconductors, whereas the Full Bridge MMC (with more power semiconductors and higher losses) can offer fault-blocking capability [15]. The differences and trade-offs have been addressed by national and EU-level R&D initiatives and projects.

2.3 Control and protection

HVDC converters are equipped with sophisticated control and protection systems. These systems comprise a complex blend of hardware components, such as Digital Signal Processors, Field Programmable Gate Arrays (FPGAs), I/O boards, transducers, and more, all governed by embedded software logic [13]. In contrast to traditional passive HVAC assets, these control systems play a defining role in how HVDC systems operate and interact with HVAC networks.

In HVDC multi-vendor setup, a notable challenge emerges - interoperability. The control and protection software used by different vendors is highly specific to each vendor and tightly integrated, making it challenging to coordinate and achieve interoperability. As multi-vendor HVDC systems become more of a necessity, the importance of conducting in-depth studies on control and protection system coordination and interoperability grows significantly [16].

Key areas for innovation include multi-vendor interoperability, grid-forming mode, enhanced ancillary services for DC grids, improved capabilities for AC grid ancillary services, AC and DC side protection, firewalling, and communication protocols tailored to hybrid AC-DC systems [10]

2.4 HVDC DC circuit breakers (DCCB)

While DCCBs are not seen as absolutely required in today's multiterminal HVDC systems as the Caithness Moray HVDC project demonstrated, DCCBs are anticipated to be required in larger HVDC systems in the future to ensure a system division following a fault. In parallel with this anticipation, DCCBs have moved from a concept to a commercial possibility in HVDC systems[17]. In the PROMOTioN project, tests were conducted with three different DCCBs:

- Mitsubishi's DCCB at 160-200 kV, 16 kA, 7 ms [18]
- Hitachi's DCCB at 350 kV, 20 kA, 3 ms [19]
- SciBreak's DCCB at 80kV, 15kA (2ms) and 12kA (<1.5ms) [20]

The exact requirements for DCCBs are subject to the specific HVDC system.

2.5 Standards

The IEC plays a crucial role in setting and maintaining standards for the field of HVDC technology above 100 kV [10]. These standards cover a wide range of aspects, including design, technical requirements, construction, commissioning, reliability, availability, and operation and maintenance of HVDC systems and equipment.

Several standards are established, for example, the following:

- IEC 60633 [21]: This standard outlines the terminology for HVDC transmission, encompassing HVDC substations with line-commutated converters. This standard has seen 71 updates, featuring 31 new terms and amendments, particularly focusing on converter units, valves, operating conditions, HVDC systems, substations, and equipment.

- IEC 62747 [22]: Addressing VSC for HVDC systems, this standard primarily deals with IGBTs in VSC technology, but its applicability extends to other controllable semiconductor devices.
- IEC TS 63291-1 and 2 [23]: These standards pertain to HVDC grid systems and connected converter stations, providing guidelines and parameter lists for functional specifications. They offer guidance for planning, specifying, and executing multi-vendor HVDC grid systems, with the terminology "HVDC grid systems" or "HVDC grids" referring to systems involving more than two HVDC stations. These standards are relevant to high-voltage systems with nominal DC voltages exceeding 50 kV.

Future work includes further work on HVDC multi-vendor interoperability but also the consideration of DC/DC converter stations, representing an evolving aspect of HVDC technology standards.

3. WORKING GROUP OUTCOMES

3.1 WG1: Modelling, simulation framework and data sharing for multi-vendor HVDC interaction studies and large-scale EMT simulation [24]

In WG1, the whitepaper offers a detailed analysis of interaction studies in MVMT HVDC grids, addressing various aspects, including interaction phenomena, workflow methodologies, stakeholder roles, openness of the converter control and protection, and the choice of EMT simulation tools. It emphasizes the need for prioritizing interaction phenomena and developing risk assessment rules for MVMT HVDC systems. The proposed step-by-step workflow aligns with industry standards and testing procedures, fostering effective collaboration among stakeholders. Furthermore, the whitepaper does not propose a definite 'one-fits-all' simulation approach, instead it offers a detailed analysis of various pros and cons, providing a comprehensive understanding of the available options. This approach empowers the entity responsible for these simulations, equipping them with the knowledge to decide what works best for their specific needs, all with the WG1 whitepaper as a valuable reference. In addition, the importance of selecting the EMT simulation tools for multi-vendor interaction studies is emphasized. The choice of tools depends on factors like model availability and the project's development stage. Standardized tools are encouraged to ensure consistency and reliability in these studies with a call for collaboration between software and hardware providers, Transmission System Operators (TSOs), and vendors. The whitepaper lays the groundwork for defining new frameworks for interaction studies, with the goal of advancing MVMT HVDC systems.

3.2 WG2: Legal framework for the realization of a Multi-vendor HVDC systems [25]

In the WG2, the Whitepaper's final conclusions provide insights on the governance, coordination between companies and standardization, IP law and HVDC grid development, risk, and liability. The governance of an MVMT HVDC grid requires clear legal and regulatory frameworks in both public and private law. In developing an MVMT HVDC grid, companies must cooperate while respecting EU competition law.

For standardization, a collaborative process is essential. Key considerations include transparency, non-discrimination, and the need to avoid anti-competitive agreements. For situations with multiple vendors and varying IPs, there are different standardization options, each with pros and cons. These choices affect the risk of competition law violations and IP use. Access to IP should be fair and non-discriminatory (FRAND) to ensure competition law compliance. Standard-setting organizations can help, but it's crucial that specifications are open and reasonable. The extent of IP sharing should align with interoperability needs. The question is whether stakeholders can adopt a shared approach and how specifications can accommodate this. In summary, navigating IP law in HVDC standardization requires vendors to balance protecting sensitive information, adhering to FRAND requirements, and determining fair licensing fees.

Transitioning from turn-key HVDC systems to MVMT HVDC systems affects risk and liability distribution. Turn-key systems involve a single vendor with clear responsibility for system failures, simplifying liability. In multi-vendor systems, responsibility is shared among vendors and the entity managing interoperability, raising the potential for interoperability issues and complex liability allocation. To manage risks and liabilities in early MVMT HVDC development, initially connecting multiple turn-key systems can reduce potential problems. Clear roles and responsibilities outlined in procurement contracts, along with robust system integration and testing guidelines, are essential to minimize risks. Thorough interoperability testing helps detect and address faults before they escalate into major issues. Establishing a clear plan for liability allocation in case of faults or damages is crucial to minimize disputes and ensure accountability.

3.3 WG3 Multi-vendor interoperability process and demonstration definition [26]

In WG3, the final whitepaper provides background information on MVMT HVDC systems and outlines challenges in realizing multi-vendor HVDC demonstration projects. The whitepaper builds on previous R&D projects, reports from industry associations, and regulatory requirements. The report offers guidelines for integrating a multi-vendor HVDC demonstration project into the European transmission grid, including selection criteria that present two concepts for selecting projects, emphasizing the need to consider the needs of all stakeholders and ensuring that promising projects are not excluded prematurely. The identified candidate projects are Bornholm Energy Island, North SeaEnergy Island, Project Aquila, and a Generic MVMT system hub. The candidate projects align with existing interoperability standards and aim to contribute to standards and regulations. The whitepaper outlines key milestones for implementing an MVMT demonstrator, from preconditions such as clarification of key roles, legal and regulatory framework, and planning to project-specific requirements, defining stakeholder roles, and a common pathway. The document discusses the requirements for achieving future expandability of MVMT projects, for instance, system rating as a technical requirement, policy maker as a role of key actors, the definition of technical terms and descriptions as a planning standard, and finally cyber security as further requirements. In addition, the whitepaper offers insights into extending multi-vendor to the medium voltage level. Lessons learned from stakeholder management reviews are also presented such as collecting the planned projects and comparison of these lead to an aligned basic topology and a better understanding of the complexity of DC MVMT systems to mention a few.

4. SOCIO-ECONOMIC ASPECTS

As technology advances it is important to analyse the socio-economic aspects of HVDC that follows the development of the technology. The socio-economic factors shape the adoption, success, and sustainability of this advancement. This chapter discusses the EU targets and infrastructure investment plan, the benefit of HVDC technology, investment considerations, and societal implications.

As the energy landscape evolves, HVDC technology is being actively integrated into the future HVDC grid to accommodate the integration of offshore wind resources [27]. This integration not only addresses the growing demand for renewable energy sources but also reinforces the role of HVDC in transforming energy markets.

The impact on energy markets is clear with examples like the Caithness-Moray link. This project demonstrates how HVDC can enhance grid stability and reduce curtailment, leading to economic benefits in being connected to interconnected markets [4]. Furthermore, HVDC allows for the connection of independent grids that cannot be merged into a single synchronous system. The North Sea Link is an example, facilitating energy flow between Norway's grid and Britain's National Grid. The modern VSC-based conversion brings greater flexibility and control to HVDC systems, enables offshore wind farms to link multiple grids and optimize power distribution, and allows for bidirectional power flows [1].

Therefore, cross-border and national projects play a vital role in enhancing energy connectivity and resilience. The TYNDP (10-year network development plan) studies suggest that by 2030, an additional 64 GW of cross-border reinforcements, following the 2025 developments, would be cost-efficient, requiring around two thousand million euros of annual investment. Such capacity increases are projected to contribute significantly to the region's socio-economic welfare, with a yearly expected boost of approximately 5 thousand million Euros [27]. Moreover, it's worth noting that national investments, like Germany's initiatives, also play a vital role by connecting stronger areas with weaker ones, achieving a similar effect. Looking at the near future, by 2025, there are plans to build around 23 GW of new cross-border reinforcements, in addition to the existing grid. These projects are already ongoing, with many of them already under construction, and they form the starting grid for further analysis [28].

The ambitious Vision 2050 proposes substantial investments in power conversion and storage devices, upgrades to the pan-European transmission and distribution networks, and the implementation of digital solutions [29]. In line with this effort is the Green Deal's objective to achieve an offshore capacity of 100 GW by 2030 and several hundreds of GWs by 2050. New investments, coordination, regulatory conditions, and interoperability processes represent areas that require attention to achieve these goals effectively.

Furthermore, since estimates indicate that by 2050, the world will require four times the current electricity generation and three times the transmission capacity, significant investments are required [1]. All this investment creates economic opportunities such as R&D development, manufacturing, and installation of HVDC systems creating new job opportunities and economic growth.

HVDC projects also align with national and regional energy policies and strategies to achieve climate goals and energy diversification and financial schemes play an important role in the project development. An example of this is the NeuConnect project [30] (the first direct power link between Germany and Great Britain that will become one of the world’s largest interconnectors, their policy scenario has been developed using a range of third-party projections, TYND, FES, NECP among others). Their source of funding includes private investment and they operate under Ofgem’s "Cap and Floor" regulations that encourage investment in interconnectors while safeguarding consumer interests [31].

In addition, the successful deployment and integration of HVDC technology heavily rely on achieving social acceptance among local communities, stakeholders, and the general public [28]. The significance of involving these key groups in decision-making processes cannot be understated, as their support and cooperation are essential to the smooth implementation and long-term success of HVDC projects.

New technologies that are less obtrusive, more efficient, have higher transfer capacity, use less raw material, and can be delivered expeditiously with public acceptance to support electrification are sorely needed. In the face of changing requirements and challenges, such as exploiting renewable energy sources from different regions and managing fluctuating generation, HVDC stands out as a key technology to address the future of power transmission.

4.1 Circular economy- challenges and opportunities in HVDC technology

The concept of a circular economy has been applied in different sectors. Its core objective is to optimize the use of materials, components, and products. The goal of the circular economy is to effectively manage resources to sustain or improve social well-being and environmental quality for present and future generations. Many sectors support the idea that without the implementation of a circular economy, meeting climate goals becomes a hard challenge [32].

For HVDC technology the circular economy implies the sustainable and efficient use of resources throughout the lifecycle of HVDC systems. The concept includes raw material extraction, product design, production and remanufacturing, and waste management-decommissioning of HVDC infrastructure to minimize environmental impact [33]. We can summarize how the concept of circular economy can be applied to HVDC technology:

Extraction of materials

When building all anticipated HVDC systems, the construction will require consumption of substantial quantities of key metals and minerals, including aluminium and copper to mention a few [34]. The availability of raw materials will become a significant bottleneck for reaching Net-Zero in time, as it will be key for e.g. the deployment of electric vehicles and increasing the capacity of the transmission and distribution system. In scenarios developed by S&P3, annual copper demand is expected to double by 2035 (from 25 MMt to 50MMt) and continue to grow until 2050 (53 MMt). According to the International Energy Agency (IEA), 152 million km of electricity transmission cable is needed to meet net zero emissions, requiring 427 million tons of copper or largely half of total global copper reserves, estimated at 870 million tons. If such an amount of copper were to be used for electricity transmission, there would not be enough copper available for those wind turbines, batteries, and other clean technologies needed for net zero. Copper can to some extent be substituted by aluminum. Nevertheless, innovative solutions with improved raw material use – whether compared to copper or aluminum cables - are emerging, including higher capacity cables and superconducting cables for long-range bulk transmission of power without energy losses. In addition, raw material use for related infrastructure would be significantly lower. For example, a modern 2.4 GW, 525 kV offshore collector station weighs more than 15,000 tons and costs up to € 1 billion. A collector station for a superconductor cable that can carry the same amount of energy would operate below 100 kV and weigh and cost less than half.

In addition, steel is used in the construction of the platform structures, which are often over-scaled to withstand offshore weather conditions. However, steel platforms can be designed for potential life extension and refurbishment, aligning with circular economy principles. The raw material dilemma also exists regarding copper cables, with the question of whether fully depreciated or non-active cables should be left on the seabed or removed. New insulation materials aim to make these cables more environmentally friendly, but an opportunity cost is present that is associated with not re-using the copper. However, cables traditionally outlive their planned economic life, which provides the possibility of requiring less of the total anticipated raw material at a certain point in time. It is important to note that aluminum remains a costly metal to produce and recycle which is important to consider for sustainable material management in HVDC projects.

Design for circularity

By designing HVDC systems to be modular and upgradeable, with a focus on modularity, it becomes easier to replace or refurbish specific components, thus extending the overall lifespan of the technology. Efforts towards modular design are accompanied by efforts towards reduced footprint and increased power density, with significant achievements of up to 40% less footprint over the last 6-7 years. However, it's important to address environmental concerns, such as the use of lead and the leakage of SF6 - the most common gas used - which is a significant contributor to greenhouse gas pollution. While several substitute gases have been explored, some environmental limitations persist. For example, in the PROMOTioN project, one work package was dedicated to finding alternatives [35]. There are advocates for a return to air insulation due to the environmental limitations of current substitutes, highlighting the ongoing challenge of achieving true circularity in HVDC technology. As part of this effort, companies are exploring the potential to enhance the circularity design of power transformers by replacing conventional oils with renewable or re-refined oils.

Remanufacturing and refurbishment

To avoid discarding entire HVDC systems when certain components reach the end of their useful life, remanufacturing and refurbishment are needed. Manufacturers can reclaim and restore components through different processes, reducing the need for new raw materials and lowering environmental impacts. For instance, an innovative refurbishment scheme [36] has been proposed, focusing on transitioning from the traditional LCC to the more contemporary VSC technology. Initially, LCC served as the primary converter for long-distance transmission until the advantages of VSC gained more prominence. This scheme advocates for the replacement of LCC valves at the receiving end with VSC valves, resulting in significant reductions in the submodule capacitor and current capacity demands, ultimately leading to cost savings. Additionally, within the context of HVDC components like DCCBs, industrial design considerations are aimed at facilitating the quick replacement of sub-assemblies and parts. This approach proves beneficial in terms of maintenance turnaround and parts refurbishment, thereby contributing to the overall sustainability of HVDC systems. In addition, according to ENTSO-E TYNDP 2018, around 37,000 km of extra high voltage (EHV) power lines on land as well as at sea will need to be built/refurbished by 2030. As already mentioned, Europe's electricity network needs significant expansion and improvement, with a focus on underground and submarine cables, especially HVDC technology, approximately 42,666 km of HVDC land and submarine cables are estimated to be required over the next ten years to enhance electricity supply reliability in the region [11].

Waste management/recycling and decommissioning

When an HVDC system reaches its end-of-life, valuable resources need to be extracted through recycling processes, minimizing waste and the need for new raw materials. In the case of offshore oil and gas platforms, recycling oil and gas equipment, such as pumps and valves, helps conserve resources and reduces waste sent to landfills. In Appendix A, Table 4 of [37] provides an overview of the equipment commonly found on offshore oil and gas platforms in the North Sea, along with indications of their potential for re-use or re-sale. The table demonstrates that a substantial portion of the assets and equipment can be considered for re-use, re-sale, or recycling. In addition, the asset inventory in Appendix shows a diverse range of assets and equipment, including items beyond the usual accommodations and canteens, which could be useful in other industries. Decommissioning and end of life aspects are discussed more in detail in Chapter 6.

5. HVDC R&D SHORT AND LONG TERM VIEW

The massive increase in HVDC projects leads to financial, resource and staff scarcity [38] It is important that R&D reflects this scarcity and focuses on how to efficiently achieve deployment. "Getting the infrastructure up and running" is firstly about modularization, standardization of components, and assembly of interfaces, all contributing to interoperability. However, also R&D into further efficiency gains leading to reduced cost (footprint, weight, power,...) and circularity are needed.

The HVDC community has already consolidated its view on R&D priorities in several detailed reports. From the READYA4DC community contributing to this whitepaper, we only want to highlight and discuss some aspects brought up in these reports.

The EU project PROMOTioN consolidated the projected R&D needs in Sept 2020 with a focus on specific technologies needed in HVDC grids [39] . OFGEM released their view on R&D priorities in July 2021 and sorted different R&D needs into several themes. Similarly to [39], OFGEM Theme 1 on upscaling HVDC manufacturing innovation addresses the need for new components. However, the recently increasing need for rapid deployment and associated increasing production capacity should also be highlighted in this context. OFGEM Theme 4 on leveraging technical expertise, skill development, and resourcing is becoming more and more relevant in light of staff scarcity [38]. Finally, OFGEM Theme 5 focuses on learnings from the O&G sector in particular with regard to recycling. The Implementation Plan HVDC [10] sorted different R&D needs into the topics of primary and secondary equipment, control and protection, operation, and planning. For each, the short (-2027), medium (2027-2035), and long-term (2035-2050) activities are presented. Finally, the need for coordinated long-term planning of a busy industry sector is addressed in [40] published Aug. 2023.

The HVDC sector is rapidly evolving and justifies the short and long-term R&D needs put forward in the above reports. However, since the HVDC deployment goals were recently massively increased [24] the READY4DC community contributing to this whitepaper would like to strengthen and add the following aspects:

It is the first priority to get the infrastructure up and running and that comes with two engineering R&D fields, i.e., interoperability across vendors, and technical specifications and standards [26], touching upon topics such as multi-vendor control and protection integration, coordinated DC grid control, resolving interactions AC and DC, onshore and offshore, power flow control tools to include DC grids, grid-forming, ... just to name a few. These engineering R&D needs go hand-in-hand with managing interoperability in light of massive deployment demands and results in R&D needs in, e.g., modular design, manufacturing scalability (volume, not rating), easy documentation, or functional modeling in multi-vendor setups as a vendor-agonistic way to organize multi-vendor projects. Furthermore, the development of a fair division of risks and rewards, and research into the (legal) forms of cooperation that can support interoperability is needed. Notably, while the first priority is to get the infrastructure up and running, it is equally important to focus R&D efforts on the following two aspects.

Firstly, future incremental HVDC grid extensions need to be done efficiently, i.e., without falling back into the project development stage. Due to complex dependencies in control and protection software, and hardware, adding an extension to an existing HVDC system is not straightforward – even less in a multi-vendor setup. An R&D need for HVDC grid extension is already mentioned in [10] but there needs to be more focus on this topic, considering for example, "the need to think the end game from the start", the level of independent design/building of grid elements and finally HiL/SiL testing for the new grid extension approaches.

Secondly, for financing reasons, it is equally important to address R&D needs regarding circularity and recycling already today. For example, an offshore platform has a lifetime of at least 50-60 years and learnings can be observed from the oil & gas industry. However, circularity and recycling already become relevant in Wind farms after 20-25 years. In the industrialisation of HVDC systems, today, circularity and recycling are not a top priority, arguably since the life cycle of HVDC equipment is perceived just as long as for AC equipment (economically planned for 25 -30 years but once deployed - maybe for 40-60 years or longer. However, in industrialising new HVDC equipment an R&D priority should be on refurbishing parts of the equipment and how we can extend the life of systems in a sustainable way.

After the above, R&D into higher power ratings and new functionalities appears reasonable, e.g., an operating strategy for large pan-European HVDC grids, WAMS/WA Control optimization across AC and DC, first truly embedded AC DC grid, including robust control, such as done in [41].

At a later stage, R&D into HVDC control & protection retuning may become relevant. The READY4DC community contributing to this whitepaper wants to highlight this topic in addition to the above reports on R&D priorities, touching upon, e.g., control & protection re-tuning of setpoints, modes, control gain parameters; offline vs. online re-tuning e.g. as done in [42], [43] and new ideas for partially open control and protection software [39], [44] Ultimately, for the overall emerging DC technologies also more converter topologies (DC/DC, mixed topologies) and interlinking with medium-voltage DC (MVDC) will need R&D [45]

Ultimately, while there are R&D priorities due to the massive need for deployment, the HVDC community also has to ensure we do not prevent innovation.

6. END OF LIFE

End of life is a critical and complex topic that concerns HVDC owners and utilities. From a financial perspective, in situations when an asset falls within a regulated asset base, the revenue encompasses remuneration for life extension and end-of-life investments, a standard practice in many countries. This could potentially change for commercial assets and the remuneration could need to include a reserve for end-of-life investment. It's worth noting that this adjustment might not be immediately apparent through standard accounting checks. Over the asset's lifecycle, it is necessary that the owner establishes a deferred liability on their balance sheet to cover eventual expenses related to dismantling or removing infrastructure as stipulated by national environmental regulations. This deferred liability ties up a significant amount of capital, which can incentivize asset owners to seek alternatives. In this context, it is crucial for both governments and the industry to draw lessons from the O&G sector, which has faced challenges in effectively managing the end-of-life phase for offshore O&G assets, as detailed in the next paragraph. This drives to consider whether the European Commission should play a role in addressing this issue. Given the multinational nature of new assets, which might be shared or moved across Exclusive Economic Zones (EEZ) without necessarily crossing national waters, the question of EC involvement becomes relevant.

In the case of O&G platforms, the ownership of assets often changes over the asset's lifetime, making it challenging to assess the final owner's capacity to fund disposal. When considering the offshore vision in the PROMOTioN project, it's important to recognize that it extends significantly into the future, given the minimum 25-year lifetime of such projects, where the preference would be towards life extension over disposal. Nevertheless, from a parallel perspective, it is possible to draw insights from the offshore O&G sector, where regulations were not well-structured from the beginning. The precedents set by O&G platforms can serve as a valuable reference in shaping regulations regarding the potential dismantling of offshore substations.

Offshore wind infrastructure lifecycle

For decommissioning and removal of OWFs and grid infrastructure, lifetime extension is more logical than removal. The challenge, as observed in the PROMOTioN project, is a mismatch between the cable lifetime (around 50 years) and the OWF lifetime (25-30 years). In cases where a new OWF is established at the same location, recycling the existing cable infrastructure becomes a common practice. However, it is often the case that much more capacity is needed for the new OWF, as technology improves in the three decades of an OWF. Additionally, when discussing about a grid instead of a radial connection, both the cables and converter stations become essential for interconnecting multiple OWFs.

Under international law, there is a removal obligation for installations such as wind turbines and converter stations, yet the same obligation does not apply to cables. Furthermore, different countries have different rules. For instance, some might require removing the cables that are buried in the seabed while allowing those on the seabed surface to stay. On this matter, few things to consider: Are the cables made of rare or expensive metals? If so, it might be more important to remove them. What is the environmental impact of removing them, for example, disturbing the seabed, versus leaving them in place and the potential for material leakage? What is the area going to be used for after removal? If it is going to be the site of a new OWF, it is probably better to remove the cables to make the construction process smoother. But if there is no specific plan for the area, it might not be extremely necessary to remove everything.

In this context, even though copper is not the rarest of metals, the consideration for cable removal arises because they are insulated with materials that may not be environmentally friendly. Currently, there is limited experience on this topic – perhaps it could be available from the early interconnectors between France and the UK.

Transmission grid

In the context of an offshore HVDC grid, there are substantial platforms or islands that demand nearly continuous maintenance. These structures are of considerable size and are typically engineered with an intended 25-year operational life. However, they are designed to withstand formidable forces, such as a "100-year wave," which inherently extends their engineered longevity to a span of 40–50 years, provided they receive appropriate maintenance. Additionally, it is also likely to use the proposed island structures, each characterized by unique designs and technologies.

Offshore cables in the O&G sector

The prospect of removing steel pipelines in the offshore O&G sector may be assumed impractical. Cables, however, present a different scenario due to their unique composition. If a cable remains undisturbed, it can operate for 40 to 50 years, as previously mentioned. Yet, the cables have a considerable weight and, on occasion, sink into softer seabed regions. This submersion can lead to cable breakages, however more often near the terminals.

To prevent cable submersion, cables may be fitted with "floats" to maintain them at a fixed depth, depending on the composition of the seabed where they are positioned. The longitudinal stresses in a cable are crucial. These offshore cables may have a shorter life compared to onshore cables due to mechanical reasons rather than other factors.

One additional potential weak point could be the J-tube might require more frequent renewal. The J-tube provides vital cable protection and constitutes an integral component of every offshore wind foundation structure. Anything located on a platform or connected to it is constantly subjected to mechanical stresses. There will certainly also be new mechanical aging challenges in a floating offshore infrastructure. Much of the infrastructure needs to be insulated from the seafloor, however, traditional ceramic insulators used to support cables and other HVDC equipment are typically rigid. Therefore, innovative solutions to withstand the battering of 30-meter-plus waves in such environments may be required.

Regulatory considerations

End-of-life management should be an integral component of the initial Cost-Benefit Analysis (CBA) and be subject to legislative and government contract considerations, ultimately shaped by governmental policies. Typically, environmental permits required for construction already include this aspect, although it needs special attention.

For OWFs, there exists a requirement for financial guarantees. However, in the context of state-owned TSOs, this may not be as relevant. The relevance of this obligation reemerges when grid components are owned by market entities. Ambiguities or a lack of transparent contractual policies can lead to a situation where no single party assumes responsibility at the end of the asset's life cycle, a scenario that investors understandably wish to mitigate.

In the context of life extension, due consideration must be given to the alteration of end-of-life provisions in cases where no explicit end-of-life sanctions are applicable. This requires the calculation of regulated remuneration, typically including a combination of planned and agreed Capital Expenditure (CAPEX) and operating costs. This calculation might also include a limited markup for funding costs. The method used can be either cash-based or accounting-based, contingent on specific circumstances.

Market models and government equity

In current practice, a notable shift towards phased ownership models is underway within the industry. This involves consortiums managing the project during the development phase and subsequently divesting or reselling portions of the project during its later lifecycle. This approach draws parallels with the O&G sector, where specialized companies engage in late-life field operations. For example, major corporations like Shell and BP initiate primary development activities and subsequently transfer ownership to companies that take over as the fields enter later phases, such as tertiary or even fourth-phase recovery.

This strategic approach allows major corporations to mitigate end-of-life risk, an advantage not as readily accessible to smaller companies, which may face challenges in the event of field closures. Given these dynamics, there's a growing need to explore alternative strategies for managing electrical infrastructure.

Furthermore, considering the practical scenario where decommissioning costs outlined in bank guarantees are notably higher, it may be prudent to consider adopting a state-owned infrastructure approach. State-owned TSO models present certain advantages, although it's important to note that not all countries follow the same model. For instance, Germany and Belgium have listed TSOs, albeit with some degree of government ownership. In contrast, the United Kingdom has private companies operating the grid, although the government may retain a "golden share" and strictly regulates them.

As the asset base expands, the government may need to provide equity funding to balance the increasing debt required for asset acquisitions. This is a critical consideration, particularly at a time when many onshore assets have reached full depreciation while offshore assets still require substantial investments. This expansion carries not only financial implications but also represents a theoretical risk for governments.

Governments, like corporations, have credit ratings. Any increase in risk exposure could lead to a credit rating downgrade, resulting in higher borrowing costs. If grid expansion progresses too rapidly, such as with anticipatory investments where immediate cost recovery from consumers is infeasible, it may lead credit agencies to downgrade government ratings. This is a scenario that needs to be carefully managed, as it can affect not just grid-related debts but the overall national debt with escalated interest costs.

This is of particular concern for governments dealing with financial recovery post-COVID-19. It is essential to recognize that this risk is tangible in specific European nations.

In this context, the "golden share" mechanism emerges as a potential strategy to allow market investments while retaining government influence over key decisions. Nevertheless, it's crucial to acknowledge that the extensive use of "golden shares" in various sectors, including telecommunications, has occasionally prompted legal challenges at the European Union Court. Therefore, if the "golden share" approach is to be further explored in future projects, a comprehensive analysis of the conditions required for its implementation within the EU framework will be necessary.

7. CONCLUSION

HVDC has emerged as a pivotal component in the dynamic landscape of the energy sector, addressing the increasing demand for renewable energy sources and transforming energy markets. Chapters covering the standards, multi-vendor interoperability, end-of-life considerations, and socio-economic implications collectively underline the complex nature of this technology's integration into the current energy systems.

The socio-economic implications of HVDC technology are a critical consideration, particularly as this technology plays a pivotal role in meeting climate goals and energy diversification. Investment in HVDC offers economic opportunities in terms of R&D development, manufacturing, and installation, creating new jobs and driving economic growth. Ensuring social acceptance among local communities and stakeholders is fundamental to the successful deployment and integration of HVDC systems, highlighting the importance of involving key groups in decision-making processes.

Furthermore, the concept of a circular economy, which emphasizes the sustainable and efficient use of resources throughout the lifecycle of HVDC systems, presents a compelling framework for addressing challenges and opportunities in the technology. From the extraction of materials to design for circularity, remanufacturing and refurbishment, to waste management and recycling, the principles of the circular economy can lead to more sustainable and environmentally friendly HVDC technology.

In addition, it's crucial to align research and R&D with efficient deployment. Priorities include expandability, standardization, interoperability, and efficient infrastructure operation. Notably, managing multi-vendor projects, enabling and optimizing HVDC grid extensions, and exploring circularity and recycling are emerging R&D needs. Future focuses should encompass higher power ratings, advanced functionalities, and control and protection refinement. While deployment is key, fostering innovation remains an essential principle in this evolving field.

Finally, the end-of-life phase of HVDC systems presents unique challenges. Strategies borrowed from sectors like O&G can provide valuable insights into effectively managing the decommissioning of HVDC infrastructure. The allocation of responsibilities, financing for end-of-life expenses, and the potential involvement of government bodies, like the European Commission, become central themes in ensuring the smooth transition of HVDC systems beyond their operational lifespans.

ABBREVIATIONS AND ACRONYMS

AC	Alternative current
CB	Circuit Breaker
C&P	Control and Protection
DC	Direct Current
DCCB	Direct Current Circuit Breaker
EU	European Union
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
EMT	Electromagnetic Transients
EHV	Extra High Voltage
EEZ	Exclusive Economic Zones
FRAND	Fair and non-discriminatory
HVDC	High-Voltage Direct Current
HVAC	High-Voltage Alternating Current
IEC	International Electrotechnical Commission
IP	Intellectual Property
IEA	International Energy Agency
IGBT	Insulated-gate bipolar transistor
LCC	Line Commutated Converter
MMC	Modular Multilevel Converter
MT	Multi Terminal
MV	Multi Vendor
OWF	Offshore Wind Farm
OFGEM	The Office of Gas and Electricity Markets
O&G	Oil and Gas
PV	Photovoltaic

R&D	Research and Development
RES	Renewable Energy Sources
REPowerEU	Affordabe, secure and sustainable energy for Europe
SSEN	Scottish& Southern Electricity Network
SF6	Sulphur hexafluoride
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VSC	Voltage-Sourced Converter
XLPE	Cross-Linked Polyethylene
WG	Working Group

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APPENDIX

Offshore Oil and Gas Decommissioning: Platform inventory & re-use / recycling [37]

Table 4: Extract from Appendix C

Module	Re-use options at module level?	Assemblies	Re-use options at assembly level?	Equipment	Re-use options at equipment level?	Re-sale to specialist	Recycle
Accommodation block	Re-use on other platform. Temporary accommodation onshore.	HVAC	No	Fans			Y
				Ducting			Y
				Dampers			Y
				Motors		Y	Y
				Insulation			Y
		Living quarters / ablutions	No	Soft furnishings			Y
				Partitions / ceilings			Y
				Beds			Y
				Showers / toilets etc.			Y
		Catering equipment	No	Ovens / hobs			Y
				Dishwashers			Y
				Preparation tables			Y
				Fridges / freezers			Y
				Dining furniture			Y
				Serving counters			Y
		Fresh water generator	Yes if built as a small module	Vessels	Re-sale if stainless steel	Y	Y
				Pipework			Y
				Pumps		Y	Y
				Filtration			Y
				Valves			Y
							Y
		Fresh Water Distribution	No	Storage tank	Re-sale if stainless steel	Y	Y
				Distribution pumps		Y	Y
				Coalescer units		Y	Y
				Filter units		Y	Y
				Pipework			Y
				Valves			Y
		Sewage treatment system	No				Y
		Lifeboats and lifting / release equipment	Yes if built as a small module	Lifeboats	Yes - if to current standards		Y
							Y