Technical Report

Data Specifications for HVDC Reliability Assessments

January 2026

Foreword

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the association of the European transmission system operators (TSOs). The **40 member TSOs, representing 36 countries,** are responsible for the secure and coordinated operation of Europe's electricity system, the **largest interconnected electrical grid in the world.**

Before ENTSO-E was established in 2009, there was a long history of cooperation among European transmission operators, dating back to the creation of the electrical synchronous areas and interconnections which were established in the 1950s.

In its present form, ENTSO-E was founded to fulfil the common mission of the European TSO community: to power our society. At its core, European consumers rely upon a secure and efficient electricity system. Our electricity transmission grid, and its secure operation, is the backbone of the power system, thereby supporting the vitality of our society. ENTSO-E was created **to ensure the efficiency and security of the pan-European interconnected power system** across all time frames within the internal energy market and its extension to the interconnected countries.

ENTSO-E is working to secure a carbon-neutral future. The transition is a shared political objective through the continent and necessitates a much more electrified economy where sustainable, efficient and secure electricity becomes even more important. **Our Vision: "a power system for a carbon-neutral Europe"*** shows that this is within our reach, but additional work is necessary to make it a reality.

In its Strategic Roadmap presented in 2024, ENTSO-E has organised its activities around two interlinked pillars, reflecting this dual role:

- "Prepare for the future" to organise a power system for a carbon-neutral Europe; and
- "Manage the present" to ensure a secure and efficient power system for Europe.

ENTSO-E is ready to meet the ambitions of Net Zero, the challenges of today and those of the future for the benefit of consumers, by working together with all stakeholders and policymakers.

Disclaimer

This report describes HVDC reliability-related actual experiences from European TSOs. They do not reflect any exact knowledge, but the TSOs' understanding of what occurred and the lessons thereof.

* https://vision.entsoe.eu/

Contents

1 Executive Summary

High Voltage Direct Current (HVDC) transmission is indispensable to achieving the EU's 2050 climate neutrality target. The reliability of HVDC systems will directly influence the pace of offshore wind integration, cross-border power flows, and internal system connections via embedded HVDC links, thereby accelerating Europe's long-term energy security.

Deploying HVDC systems comes with challenges in terms of reliability due to complex assets and sophisticated control mechanisms. For HVDC systems to play a key role in Europe's power system, they must address reliability wholistically: they must be adequate, secure and resilient. Reliable HVDC systems are not only a technical necessity but a strategic imperative for the resilience of European grid networks and for achieving the EU's commitment to a carbon-neutral future under the European Green Deal. As HVDC technology forms the backbone of offshore wind integration, cross-border interconnections, and large-scale renewable integration, its reliability directly underpins the continent's decarbonisation pathway.

CIGRÉ surveys (as of 2018) show HVDC systems experience an average of 7.7 trips per year and outages lasting up to 24 days per year – far above acceptable levels for critical infrastructure. Availability of HVDC links below 95 % is already considered unacceptable by leading TSOs. With over 50 HVDC projects now operating in Europe, persistent reliability gaps could lead to Europe risking repeated failures across projects, delaying offshore wind integration, weakening cross-border security of supply and potentially escalating costs and raising consumer prices.

Efforts from multiple stakeholders are currently underway to improve the reliability of HVDC systems. This includes TSOs collaborating with industry and Original Equipment Manufacturers (OEMs) to better understand needs, develop work methods, collect and share relevant data. These discussions have been strengthened under the EU Grid Action Plan[1]. Although EU-funded projects have tackled several technical and regulatory challenges, outages and failures remain above acceptable levels, threatening the scale-up of HVDC deployment. With European funded projects on the topic of HVDC nearing their end, and the ramping up of HVDC projects to more complex structures such as multi-vendor multi-terminal, a technical assessment of gaps in HVDC reliability is needed.

This report provides European stakeholders; TSOs, OEMs, regulators, policymakers and research communities, with a consolidated roadmap to improve HVDC reliability. The objective of this report is to provide a harmonised European framework and roadmap for HVDC reliability, drawing on TSO experience, to inform regulators, OEMs, policymakers, and research communities on the urgent actions required to safeguard Europe's decarbonisation pathway.

Based on a unique survey conducted to gather relevant information on HVDC development bottlenecks, this report provides a sharper technical overview of HVDC reliability, insight into TSO perspectives, and the role data specifications can play in improving reliability. Harmonised targets and collaborative actions have been compiled to ensure to address gaps in data specification and surrounding steps so HVDC technology can deliver Europe's decarbonisation and energy security goals.

1 COM (2023) 757 final https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023DC0757

Key outputs and findings of this report are:

- HVDC reliability remains below target levels: outages are frequent and prolonged, threatening offshore wind integration, cross-border power flows, and internal system connections (embedded HVDC links).
- Current HVDC reliability assessment is hindered by fragmented metrics, inconsistent definitions, and a lack of harmonised data collection. A common European framework is urgently needed to enable comparability, benchmarking, and systematic learning across projects.
- Knowledge erosion is accelerating as HVDC experts retire, and structured retention tools are urgently required.
- OEM transparency is insufficient; gaps continue to block systematic fault analysis, making regulatory support for open, standardised data sharing essential.
- Coordinated action is required among TSOs, OEMs, regulators, and policymakers to define and enforce robust, measurable reliability targets at both project and system level.
- Pan-European reporting (beyond the current Nordic/Baltic scope) is essential to achieve a full understanding of HVDC reliability challenges.

Harmonised data specifications and definitions are urgently needed to identify research and innovation gaps and to drive targeted improvements. The insights presented in this report highlight the needs and planned actions of European TSOs to enhance HVDC reliability, and call for increased collaboration with OEMs, regulators, and research communities to close the identified gaps. Only through collective action across industry, regulators, and research communities can HVDC reliability be elevated to the level required to support Europe's long-term climate ambitions and to ensure a secure, sustainable, and future-proof energy system.

2 Introduction

HVDC technology is indispensable for Europe's future electricity networks, playing a key role in the ambitions for a sustainable, low-carbon future. HVDC has been identified as a crucial enabler of EU's 2030 and 2050 climate targets, integrating large volumes of offshore wind, and safeguarding security of supply in a decarbonised system.

Today, HVDC links are primarily used to connect asynchronous AC systems and to transmit bulk power over long distances via overhead lines, underground cables, and submarine/subsea cables. Embedded HVDC systems are now emerging, such as north-south connections carrying offshore wind power, and many more are being planned.

The main advantages of HVDC over AC systems include lower operational losses, higher power transfer capability, and improved controllability. In the case of VSC technology, HVDC systems can also provide reactive power compensation and grid-forming capability, thereby strengthening AC networks through reactive power control and frequency stabilization. However, HVDC systems also have disadvantages, such as more complex components (e.g., converters, transformers, circuit breakers, and protection equipment), specialized and costly maintenance requirements, and high capital costs, particularly, for shorter transmission distances. For LCC systems, harmonics and reactive power compensation require special consideration. With over 50 HVDC projects in operation across Europe as of 2025, many in demanding offshore environments, reliability concerns have become increasingly prominent.

The complex components and sophisticated control mechanisms pose technical reliability issues in HVDC systems of today. Additionally, maintenance and availability of relevant equipment form another layer of unreliability. With HVDC systems being still less mature than HVAC, standardisation within HVDC systems is lagging, creating integration and development challenges. The rapid growth of HVDC systems calls for increased reliability of these systems as they begin to play a key role in European transmission networks.

Despite HVDC systems still relatively developing technology, reliability issues also arise due to the aging of HVDC assets; many installations are approaching or exceeding 30 years of service. Additionally, advancements in technology result in obsolescence, lack of ancillary services (e.g. support for the AC grids) and inefficiencies. The impact of HVDC system failures due to such aging, obsolete or inefficient assets can result in significant consequences in terms of costs and disruption of the electricity supply.

Further factors affecting HVDC reliability include the consolidation of OEMs, many of whom have merged or shifted business priorities, reducing support for older technologies and legacy systems. At the same time, manufacturers are moving toward standardized and repeatable solutions to optimize resources and reduce delivery risks. A shortage of experienced engineering staff has also forced OEMs to prioritize ongoing projects and limit their full technical involvement until contracts are awarded; making the preferred bidder scheme a key element of their current procurement strategy. These trends, combined with the retirement of senior technical experts, increase the risk of knowledge erosion and reduced long-term support for HVDC systems.

With HVDC deployment accelerating, TSOs urgently need enhanced tools, knowledge, and frameworks to tackle these reliability challenges.

2.1 Background

Regarding reliability and availability, HVDC performance definitions and data were standardised by the International Electrotechnical Commission (IEC) in 2013 in the Technical Specification IEC/TS62672-1 "Reliability and availability evaluation of HVDC systems – Part 1: HVDC systems with line commutated converters" [1]. Overall, international HVDC performance statistics show that the reliability and availability of HVDC systems have slightly improved over time.

The only worldwide HVDC performance statistics for 2005–2016 collected by CIGRE (International Council on Large Electric Systems) show that present levels of HVDC system availability and reliability are not fully adequate, as systems suffer from rather many trips (7.7 pcs/year) and outage durations are quite long (24 days/year), in average. The trend can be seen from CIGRE worldwide HVDC performance surveys during the years 1983–2022 with the latest published in 2024 [2] as well as the ENTSO-E Region Nordic DISTAC (Disturbance Statistics and Classification) group statistics 2011–2017 [3]. Unfortunately, participation in CIGRE HVDC performance statistics has declined from approximately 50 % to 35 % during the years, as the increase in the number of new HVDC systems is much higher than the increase in the number of survey responses [4].

The latest comprehensive survey on the operational reliability of HVDC systems worldwide is available for the years 2021 and 2022 by CIGRE [2]. The report consolidates reliability data provided by system operators for 57 LCC (Line Commutated Converter) and 20 VSC (Voltage Source Converter) systems in 2021, and 58 LCC and 19 VSC systems in 2022. The data were collected using a standardised protocol that includes metrics such as energy availability, energy utilisation, forced outages, and scheduled outages. Some of the key insights can be outlined below:

- **Energy Availability and Utilisation:** Systems (on a substation level not a whole network) displayed a broad range of utilisation, from low-duty standby applications to those operating near full rated capacity. Many systems maintained high energy availability (> 95 %), indicating generally reliable converter and transmission infrastructure.
- **Outage Statistics:**
  - Forced Energy Unavailability (FEU) is predominantly associated with converter station outages, as line or cable faults are so very rare.
  - Scheduled Energy Unavailability (SEU) reflects planned outages, typically timed to minimise system impact.
  - Outages are categorized by root cause: AC and auxiliary equipment, valves, control and protection, DC equipment, and others.
  - The average forced outage duration varied significantly across systems, with some instances exceeding 500 hours per year, especially for older or complex systems.
- **Trend Analysis:**
  - A notable reduction in FEU attributable to converter transformers was observed compared to the 1983–2020 period, suggesting improved transformer reliability and condition monitoring.
  - Some systems experienced significant transmission unavailability due to converter or cable-related issues, highlighting areas for further operational optimization.
- **Cumulative Reporting:**
  - The study contributes to a long-term dataset (1983–2022) and supports benchmarking efforts for HVDC system reliability performance over time.
  - The average FEU per system was 199.2 hours in 2021 and 261.2 hours in 2022, slightly higher than the long-term values.

Within ENTSO-E, the HVDC Reliability Working Group (WG) formed in 2015 initiated among its many outputs, the systematic cataloguing of experiences gained on HVDC installations. ENTSO-E has systematically strived for enhanced efforts to improve HVDC reliability since 2015. Additionally, the aim of this WG was to set guidelines on improving HVDC system reliability in a way of helping European TSOs that have raised concerns about the actual experienced levels of reliability of existing HVDC systems. Since the inception of this WG, European TSOs have been actively investing resources in a variety of HVDC projects.

With the rapid development of new HVDC systems, there is a growing need to enhance the capability of TSOs by providing them with the necessary tools and knowledge to support overall system design, specification, and configuration decisions. Establishing high-quality standards for individual system components, each critical to the operation of the entire HVDC scheme, is essential to ensure that these systems are designed, integrated, and operated in a robust, reliable, and efficient manner.

The EU funded project, HVDC-based grid architectures for reliable and resilient WIdeSprEad hybrid AC/DC transmission systems (HVDC WISE [2]), seeks to provide the necessary framework for HVDC grid design to enable reliability and resiliency. Several of its deliverables touches upon and a definition of Reliability and Resilience, practical methodologies, use cases and developing associating tools and model needs.

Although median values are significantly better, ENTSO-E is striving to reach better availability and reliability figures. Enhanced cooperation is needed to simplify and improve the fault data collection, allowing for more in-depth data analysis, greater learning from incidents, and continuous HVDC performance improvement.

2.2 TSO efforts on building HVDC reliability

To foster knowledge sharing and address these challenges, ENTSO-E held three HVDC reliability workshops from 2015 to 2019 under the HVDC Reliability Working Group and collected experience from its members via several surveys as well as a dedicated Task Force work from 2017 to 2019. The Task Force ended its work in 2019 and resulted in two position papers: "Improving HVDC system reliability" [5] and "Recommendations to improve HVDC cable system reliability" [6]. "Improving HVDC system reliability" position paper established the foundation for cooperation among stakeholders to promote HVDC and improve its reliability a key output among the three major actions towards improving HVDC reliability that were identified:

1. Influencing the industry to better address the needs of European TSOs and owners
2. Improvements in fault data collection, analysis and the sharing of experiences and knowledge; and
3. Developing TSO work methods, HVDC resources, requirements, specifications and tools to support interaction studies as well as operation and maintenance.

Since 2018, a significant number of new HVDC links have become operational in Europe with 4 links coming to operation in 2021. Discussions between TSOs and OEMs are constantly advancing, notably strengthened under the Grid Action Plan and coordinated efforts through ENTSO-E. Working groups within ENTSO-E continue to gather availability and utilisation statistics of HVDC links (so far focused on the Nordic-Baltic region), providing clear oversight of functioning of HVDC links and major reasons for unavailability and limited utilisation.

The joint paper, published with T&D Europe and WindEurope in March 2021, lays out a clear research direction with timelines, that focus on the development, delivery and deployment of multi-vendor, multi-terminal (MV MT) HVDC systems providing connection to offshore windfarms. A technical challenge highlighted within this report is how reliability of HVDC systems can be ensured especially as development moves towards more complex HVDC systems compared to the point-to-point links currently deployed. With MV MT HVDC system construction to be planned by the end of this decade, maturing reliability metrics and enabling a harmonised understanding is prudent.

While the measures identified are continuous and ongoing efforts by TSOs, there is continued scope to further enhance understanding on HVDC reliability, form a harmonised outlook on defining reliability and identify challenges to building competency on HVDC systems. Key challenges largely stem from issues concerning data availability, harmonised specifications and standardised work methods. This report will highlight avenues to effectively address these critical aspects.

2 https://hvdc-wise.eu/

2.3 Scope of this report

Since the start of the HVDC Reliability Working Group, European TSOs have invested resources in numerous HVDC projects. These systems need to be designed for robust and efficient operation and their operational life extended where possible. As these systems are specified, awarded, and built, design decisions regarding the robustness and efficiency of future operations need to be made. Such decisions must be supported by practical analytical methods, harmonised data, and conceptual frameworks that allow decision-makers to evaluate reliability consistently.

Reliability and availability are no longer optional: they are pre-conditions for security of supply, offshore wind integration, and consumer trust. Immediate action is required to tackle risks from aging assets, OEM dependency, and knowledge erosion.

HVDC reliability encompasses the full lifecycle: design, specification, procurement, testing, commissioning, operation, maintenance, spare parts, knowledge retention, and long-term planning.

This report builds on ENTSO-E's 2018 position paper [5] and expands the analysis to today's accelerated deployment context. Its scope is focused on defining the data requirements and actions needed to ensure HVDC reliability, by:

- Providing a sharper technical overview of HVDC reliability challenges,
- Identifying prevailing bottlenecks that prevent reliability improvements,
- Exploring data specifications and current gaps and;
- Outlining future actions (such as preparing provisions for technical documentation) required to establish harmonised European reliability frameworks.

The report covers the full asset lifecycle, with a particular focus on data specification gaps across HVDC assets (excluding cables and OHL). The actions proposed constitute a research and innovation agenda for 2025 and beyond, to be updated as technology, regulation, and market needs evolve. The report focuses on HVDC systems irrespective of Line commutated convertor (LCC) or voltage commutated convertor (VCC) technology employed.

3 Reliability of HVDC Systems

3.1 Defining system reliability

A system is defined as "reliable" when it possesses sufficient available generation and transmission resources to feed the load with a suitable margin (adequacy), even during the most limiting contingencies. It must also withstand disturbances (security), i.e. it continues to supply all the customers fulfilling suitable requirements, for the category of contingencies which satisfy a credibility criterion [7]. Furthermore, it must also limit its functional degradation (resilience) for those contingencies that do not satisfy the credibility criterion adopted by the TSO (such as extreme events). The classification of "reliability" across these terms is show in Figure 1.

Resilience is a good compromise for reliability attainment in case of extreme events as it can specify the "standards for the service supply" in terms of maximum duration and severity of degraded performance of the system when it is struck by extreme events for which security cannot be assured.

Figure 1: Classification of system reliability as per CIGRE [9]

A resilient system is not necessarily reliable, as it may fail to meet service quality standards (e.g., limits on the number and duration of supply interruptions) under credible contingencies. Conversely, a system that is reliable with respect to credible events (i.e., adequate and secure in the conventional sense) may still lack resilience to other, including extreme, events. However, a truly reliable system should possess a sufficient level of resilience to extreme events; otherwise, it would not satisfy the general definition of reliability under such conditions.

3.2 HVDC reliability and overall system reliability

The performance of HVDC links directly influences system-level reliability. From a TSO perspective, HVDC assets are single points of high impact failure, though infrequent, their outages can lead to significant operational and economic consequences. They are increasingly vital to TSO networks for enabling:

- Long-distance, low-loss transmission (e.g., offshore wind integration, internal system connections via embedded HVDC links),
- Grid interconnections across asynchronous areas,
- Flexibility and controllability in congested corridors.

TSOs operate their grid with an acceptable level of availability, for instance, certain TSOs currently aim at grid availability of 99.9994 % and 99.99988 %. Similarly, acceptable availability thresholds are key to ensuring HVDC reliability. TSOs and project developers typically define minimum performance levels in procurement and operational contracts. Key implications include:

Redispatch and curtailment: HVDC outages necessitate costly redispatch or renewable energy curtailment.

- **Security of supply:** HVDC links often form part of the N-1 contingency planning. Their outage can lead to reduced operational security margins.
- **Market efficiency:** Interconnector outages disrupt price convergence and increase congestion.

While the frequency of HVDC failures is moderate, their severity (in terms of MW loss and duration) can be substantial, particularly for single-pole or monopolar configurations. It is therefore important for TSOs to consider a clearly defined acceptable availability level for HVDC systems. Table 1 provides potential target availabilities and supporting reasons:

HVDC system type	Target availability	Reason
Design values for the HVDC stations (cables excluded)	≥ 98 – 99 %	Industry best practice; achievable with proactive maintenance and monitoring
Operational target	≥ 95 %	Common contractual minimum: values below this are typically unacceptable (except temporarily e.g. during major refurbishments)
Observed averages (CIGRE 2021 – 2022)	95 – 99 %	Most systems perform within this range; some exceed 99 %

Table 1: HVDC system availability targets and observed averages

Availability below 95 % is generally unacceptable for interconnectors or major grid-supporting HVDC links, especially when these are critical for N-1 security or market operations. For TSOs, maintaining HVDC system availability at or above 95 % is essential for ensuring secure, reliable, and economical operation of the power system. Continuous efforts in design, monitoring, collaboration, and data standardisation are key to meeting these expectations as the role of HVDC expands in future power networks.

3.3 HVDC reliability metrics

The definition of "failure" is often open to interpretation, leading to inconsistencies in data collection and reliability assessments. Some organisations define "asset failure" as any incident that results in lost production, while others might consider a downtime below 100 % uptime as acceptable. In addition, many manufacturers exclude specific events categories from being considered part of the total number of failures because they believe they do not affect the product's reliability.

However, to accurately calculate an asset's true availability, every type of event that impacts its operational uptime must be included. A high Mean Time Between Failures (MTBF) generally indicates fewer problems and lower costs for an asset, whereas a lower MTBF suggests more frequent failures and increased expenses. MTBF metrics can be significantly improved through choice of quality, quality assurance, process enhancements, data standardisation, and rigorous root cause of failures. Multiple metrics exist with respect to reliability; Table 2 lists some commonly used reliability metrics in HVDC systems.

Reliability Metric	Description	Data required
MTTF	Mean Time to Failure describes the average time, in which a failure is expected to occur, this value is also known as the average live time of a system or a component. Often used for not repairable systems or components.	› Total operating time of HVDC link › Number of failures
MTTFF	Mean Time to First Failure, describes the average time, before the first failure arises at a system or component.	› Total operating time of HVDC link › Number of failures
MTBF	Mean Time Between Failure, means the average time between different consecutive failures, the average time duration between two failures including the MTTR, referring to IEC 60050-191, the expected value of operation between two consecutive failures.	› Total operating time of HVDC link › Number of failures
MTTR	Mean Time To Repair, Mean Time To Restore, means the average time to repair the failure of the system or component, before operation could be continued.	› Total repair time of HVDC link › Number of failures (or repairs)
MTBM	Mean Time Before Maintenance describes the time between the regular maintenance intervals.	› Total operating time of HVDC link › Scheduled and unscheduled maintenance events
FR	Failure Rate describes the fraction of units which have a failure in relation to the total number of units in operation within a defined time interval, this value is often named as Lambda.	› Total operating time of HVDC link › Number of failures
Reliability Function	This function is defined as the integral of failure rate function over the time value, dependent on the assumption for the probability distribution function of the failure rate.	› Total operating time of HVDC link › Number of failures › Probability distribution function
Fault tolerance	Ability of a system to ride through a fault and stay in operation.	› Total operating time of HVDC link › Number of failures › Desired level of resilience

Table 2: Most commonly used HVDC reliability metrics

3.4 HVDC reliability block diagram

HVDC systems consist of a combination of series and parallel segments where the design engineers often apply very convoluted block reliability formulas and use relevant software calculation packages. In such cases, the underlying statistical theory behind the formulas is not always well understood, leading to errors or misapplications that may occur. Thus, a reliability model that includes the whole complexity of the entire HVDC system would be nearly impossible to implement. The analysis would be far too complex, and the results would be very difficult to interpret. To make it simpler, granular and interpretable, the Reliability Block Diagram is identified as a trusted approach [9].

In theory, a system is formed as a series, parallel or complex (combination of series and parallel) connection. A series system is a configuration such that, if any one of the system components fails, the entire system fails. Conceptually, a series system is one that is as weak as its weakest link. A parallel system is a configuration such that, if not all the system components fail, the entire system works. Conceptually, in a parallel configuration, the total system reliability is higher than the reliability of any single system component. Some systems are made up of combinations of several series and parallel configurations. The way to obtain system reliability in such cases is to break the total system configuration down into homogeneous subsystems. Then, consider each of these subsystems separately as a unit, and calculate their reliability. Finally, put these simple units back (via series or parallel recombination) into a single system and obtain their reliability. Table 3 illustrates the different types of system connection and their associated reliability (R_s). The probability of failure (P_f) is complementary to reliability, i.e. $1-R_s$. Table 3 provides a detailed evaluation of reliability (R_s) across linear (series or parallel) and complex systems.

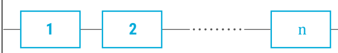
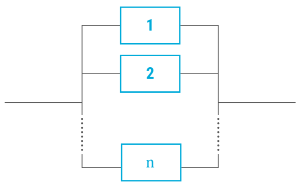
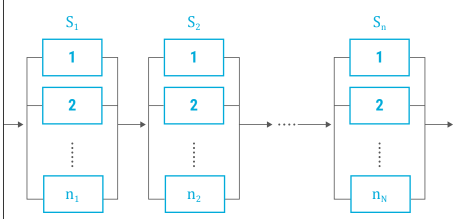
System	Series	Parallel	Complex
Block Diagram			
Reliability calculation	$R_s=R_1\times R_2\times\ldots\times R_n$ (for n-different individual reliabilities) $R_s=[R_i]^n$ (for n-identical individual reliabilities)	$R_s=1-\sum(1-R_i)=1-[(1-R_1)\times(1-R_2)\times\ldots\times(1-R_n)]$ (for n-different individual reliabilities) $R_s=1-\sum(1-v)=1-[1-R]^n$ (for n-identical individual reliabilities)	Reliability is calculated by breaking the total system configuration down into homogeneous subsystems. Each of these subsystems (S_1, S_2, …, S_s) is separately considered as a unit, and their individual reliability is calculated. Lastly, combination of each unit (via series or parallel recombination) into a single system gives the reliability of the complex system.

Table 3: Classification of system and their reliability (R_s)

For any system, both linear and complex, the Reliability Block Diagram (RBD) can be used to identify potential areas of poor reliability and where improvements can be made to lower the failure rates for the equipment. Literature study dates to the 1970s when the first study was performed on HVDC components [10], [11], [12]. In these studies, the HVDC system is modelled in a reliability block diagram with several key components for the HVDC. Later in 2000, the IEEE task force published a guidebook IEEE Std 1240–2000 for the evaluation of the reliability of HVDC converter stations [13]. This guide promotes the basic concepts of reliability, availability, and maintainability (RAM) in all phases of the HVDC station's life cycle. The intention of introducing these concepts of RAM in HVDC projects is to provide help in: (i) improving RAM for stations in service, (ii) calculating and comparing RAM for different HVDC designs, (iii) reducing costs, (iv) reducing spare parts and (v) improving HVDC converter specifications [14].

A generic schematic of a HVDC system is shown in Figure 2. For reliability studies, a single line schematic is transferred to a reliability block diagram with a few key components.

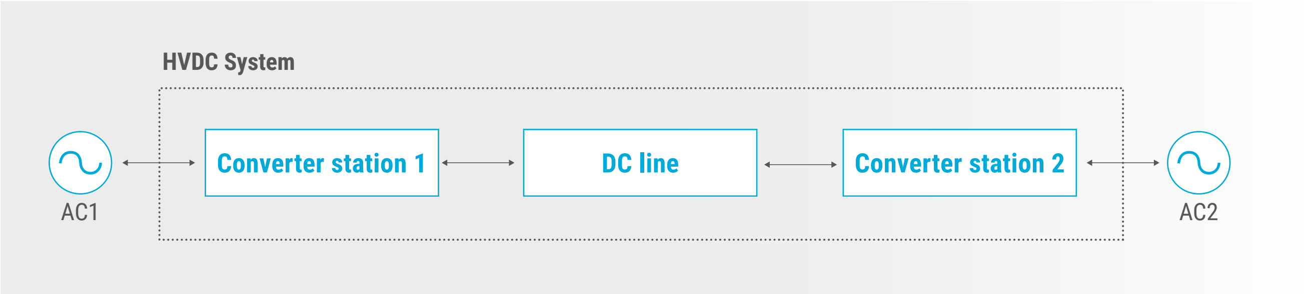


Figure 2: Generic schematic of a HVDC system [9]

Figure 3 shows a HVDC single line schematic transferred to a reliability block diagram with a few key components. It can be used in both the design and operational phase to identify poor reliability and provide targeted improvements.

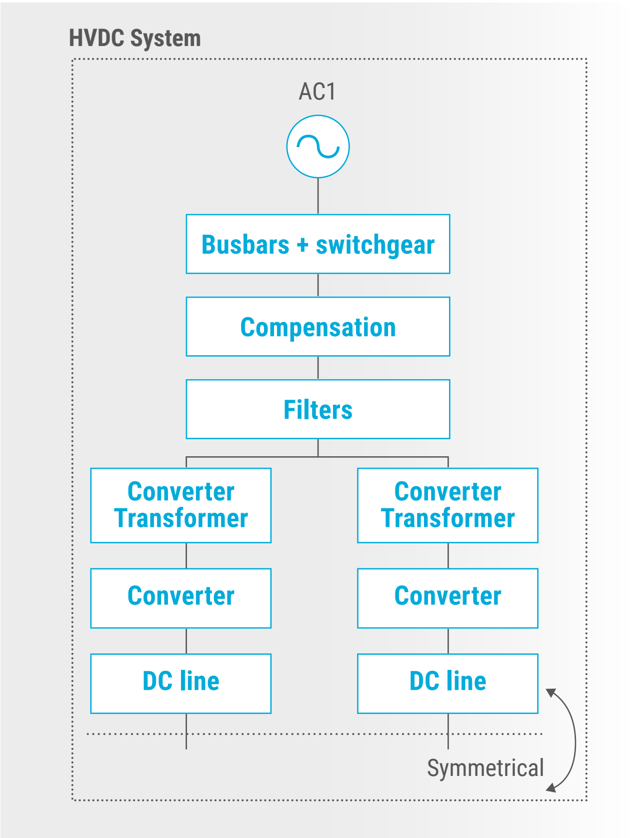


Figure 3: Single line block diagram of a HVDC system [9]

Most HVDC systems consist of both series and parallel arrangements, reflecting the layered dependencies of converters, cables, auxiliaries, and controls. By associating each block with its failure rate (λ), Mean Time To Repair (MTTR), or other reliability metrics (MTBF, MTTF), system-level reliability indices can be calculated. In the design phase, RBDs help identify critical components where redundancy or spares would most effectively improve system reliability. For example, introducing parallel paths or spare transformers can significantly increase availability although the financial aspect is always discussable. Similarly in the operational phase, RBDs support condition monitoring and maintenance prioritisation by showing which components contribute most to system unavailability. This enables targeted asset management strategies.

4 TSO Identified Bottlenecks to Improving HVDC Reliability

To better understand the current challenges and opportunities surrounding HVDC system reliability in Europe, a survey was conducted in 2025 by the HVDC Reliability Working Group among the European TSOs. The responses reflect perspectives of most TSOs with active HVDC systems in operation. Although the primary objective was to capture practical insights, institutional needs, and readiness for collaboration across the sector (both TSOs as well as manufacturers), the survey also aimed to assess the importance of harmonised practices, understand the challenges in data sharing, and identify opportunities for collaboration and knowledge retention. This section summarises the key findings from the survey:

Bottleneck	Survey Insights
Lack Harmonised understanding of HVDC Reliability	Many European TSOs considered **it important to have a harmonized understanding of HVDC reliability with consistent definitions, metrics, and interpretations of reliability.** It is seen as a foundation for improving operational reliability and supporting coordinated European grid planning.
Data Sharing and Vendor Transparency	**There is limited exchange of relevant data among stakeholders.** Lack of contractual obligations for OEMs to provide detailed root cause analysis remains a critical obstacle. TSOs cannot learn systematically from faults, especially from similar faults occurring on other TSO's systems. Common failure points identified included converter stations, cables, auxiliary systems and control systems.
Institutional knowledge and tools retention	Survey outcomes pointed **out risk of loss of institutional knowledge** due to limited internal tools or methods for retention over time, particularly as staff change or projects evolve. No significant use of standardised training, documentation platforms, or knowledge databases was reported suggests a vulnerability in maintaining long-term expertise.
Fault data granularity	TSOs highlighted the **urgent need for detailed subsystem-level fault data. Current aggregated data is insufficient for root cause analysis or preventive maintenance strategies,** either due to technical limitations, lack of contractual obligations from OEMs or in some cases due to lack of sufficient data collection.
Regulatory and OEM transparency	Survey highlights OEMs limited obligation to disclose detailed root cause analyses or fault histories, restricting TSOs' ability to learn from incidents. **Regulatory support to establish standardised obligations for OEMs to share such data with TSOs/owners by using more open data environments** could be beneficial for all stakeholders and, thus, also improve reliability of HVDC systems.
Value of a central repository and collaboration	Overwhelming **support shown for a central ENTSO-E repository to store and disseminate lessons learned, best practices, and failure case studies.** While some TSOs expressed clear willingness to participate or were already involved in initiatives like ENTSO-E DISTAC, others indicated that resource allocation would depend on the perceived value or alignment with internal priorities. Some respondents also proposed regular webinars and working groups to maintain ongoing engagement and learning.

Table 4: TSO identified bottlenecks and insights on data specifications for improving HVDC reliability

The survey revealed a high level of awareness and motivation among TSOs to improve HVDC system reliability through harmonised methods, transparent data sharing, and collaborative platforms. At the same time, it identifies critical gaps, particularly in institutional tools, fault data accessibility, and OEM accountability. Addressing these through regulatory alignment and ENTSO-E-led initiatives could yield significant improvements in system resilience and operational efficiency.

From the survey some key findings for improving/keeping up HVDC system reliability and availability are listed below:

- **Proper specifications and design:** The initial design and specifications of the HVDC system play a pivotal role in determining its long-term reliability. A well-thought-out design can mitigate potential operational issues down the line.
- **Level of redundancy:** The presence of redundancy within the system, including backup components or subsystems, is essential for maintaining reliability. Redundancy can help minimise disruptions in the event of component failures.
- **Availability of spares:** The timely availability of spare parts is critical for swift repairs and minimising down-time during outages. Adequate spare part management is a key factor in reliability.
- **Speed of response:** The responsiveness to failures or disruptions is a crucial determinant of system reliability. Swift response times can significantly reduce the impact of outages.
- **Training and experience:** The expertise and experience of human operators and maintenance personnel are vital. Well-trained professionals can identify and address issues more effectively, contributing to system reliability.
- **Manufacturer support:** Collaborative support from equipment manufacturers is instrumental in maintaining the reliability of HVDC systems. Manufacturers can provide technical expertise and spare parts support.
- **Good documentation:** Comprehensive and well-maintained documentation is essential for troubleshooting, maintenance, and system reliability. It ensures that all stakeholders have access to critical information.
- **Cooperation between utilities, TSOs and owners:** Effective collaboration and communication between utilities, TSOs and system owners are paramount. Such cooperation ensures a unified approach to addressing issues and maintaining the reliability of HVDC systems.

In addition to these, software reliability has emerged as a critical aspect of HVDC system performance. Potential software-related failure modes can range from:

- Firmware bugs in Intelligent Electronic Devices (IEDs) and Remote Terminal Units (RTUs), which may lead to protection maloperations or false tripping events.
- Configuration errors, such as incorrect relay logic, protection settings, or coordination issues across subsystems, often stemming from human oversight.
- Human errors during software updates or parameter tuning, which can introduce vulnerabilities or cause operational instability.
- Cybersecurity vulnerabilities could, if exploited, compromise the integrity, availability or confidentiality of protection and control systems

These gaps are systemic and require coordinated European action, regulatory intervention, and stronger OEM accountability.

5 Data Requirements for HVDC Reliability

The reliability of HVDC systems is influenced by a combination of robust engineering design, operational preparedness and coordinated system management. While traditional factors such as hardware redundancy, spares availability, and operator expertise remain foundational, the growing complexity and software-dependence of modern HVDC infrastructure introduces new potential failure modes. Addressing issues related to firmware, configuration, human error and cybersecurity is increasingly vital to ensure that protection and control systems remain dependable. As such, a comprehensive approach to reliability, one that integrates both physical and digital risk management, is essential. In addition, while the ENTSO-E and CIGRE Reliability Surveys provide valuable insights, there is a growing need for more detailed and inclusive reliability data that captures both traditional hardware failures and software-related issues. Expanding the scope of reliability data is essential for enhancing system resilience and guiding the development of future standards and operational practices.

5.1 Relevant data for better reliability assessment

The increasing criticality of HVDC systems in modern power grids underscores the need for more reliable, data-driven assessments. As discussed, utilities face challenges of managing risk, optimising operations and ensuring the longevity of HVDC equipment. The current availability of reliability data is falling short. To address these challenges, a more sophisticated approach to data collection and analysis is needed, one that enhances the utilities' ability to make well-informed decisions.

Achieving this requires enhanced data-driven insights into HVDC reliability in several critical areas:

- **Improved Service Life Understanding:** Most utilities are keen on gaining deeper insights into the service life of HVDC equipment to manage risks effectively. Yet, the availability of generic reliability data falls short of meeting the current decision support requirements, necessitating a more comprehensive and specific approach.
- **Industry-Wide Equipment Performance Databases:** Establishing industry-wide databases dedicated to equipment performance is of paramount importance. These databases serve as a foundational resource, compiling a wealth of information on the performance of various equipment types, groups, and subgroups.
- **Past Performance Insights:** The careful collection and analysis of historical data furnish a valuable perspective on the past performance of equipment groups and subgroups. This historical data, in turn, offers insights into the factors that have influenced their performance, enabling operators and owners to make informed decisions.
- **Future Performance Projections:** With a sufficiently large and robust dataset at our disposal, it becomes possible to make informed projections about the future performance of HVDC equipment. These projections provide a crucial basis for decision-making regarding operations, maintenance and asset management.
- **Tools for Operations, Maintenance and Asset Management:** The combination of both historical and future performance data serves as a versatile tool for utilities. It aids in optimising operations, streamlining maintenance efforts and making well-informed asset management decisions, ultimately contributing to the enhanced reliability of HVDC systems.

Effective management of HVDC systems requires a more comprehensive and data-driven approach to reliability assessment. By focusing on critical areas such as improved service life understanding, the development of industry-wide equipment performance databases, and leveraging both past performance insights and future projections, utilities can make more informed decisions.

	Future Actions
Short Term	› Scope of reliability calculation can be broadened. Evaluating benefits of broadening scope beyond just the asset level, ranging from asset to a sub-system level through the project level to the region. › **Approaches other than block diagram needs to be evaluated,** considering the various scopes possible.
Medium Term	› **Setting up reliability targets during the pre-planning stage could be a means to steer the requirements for HVDC implementation contracts,** e. g. as warranty, bonus/penalty clauses as well as design and technical solutions, including e. g. redundancy, by-passing possibilities for faulty main equipment and spares.

5.2 Data granularity for reliability calculation

The data granularity used for reliability calculations plays a critical role in accurately assessing the performance and lifespan of HVDC system components. Granularity refers to the level of detail at which data is collected and analysed, which directly impacts the accuracy of reliability assessments, especially for components with complex failure modes and uncertain lifespans. For some components, determining useful life and end-of-life failure can be particularly challenging. This is especially true for long-serving components like thyristors, which have been in operation for over 35 years and yet show few signs of reaching the end of their service life, except in cases of design or quality issues.

ENTSO-E DISTAC working group's HVDC utilisation and unavailability statistics provide useful information, including commissioning year, HVDC converter type, transmission length, power rating, and statistics on unavailable technical capacity and system unavailability on monthly and annual scales, including utilisation statistics. The data is typically presented at a high level, without linking specific failure mechanisms to recorded unavailability. Building HVDC reliability requires accurate monitoring of existing links and causes for outages/failures from a technical perspective. This yearly report provides clarity on key operational/asset availability of HVDC links predominately in the Nordic and Baltic region. The report aims to go deeper into classification, consequences and outage reasons. However, the data is typically presented at a high level, without linking specific failure mechanisms to recorded unavailability and does not delve into root causes of the outage.

Due to the asset/operations perspective of the HVDC utilisation and unavailability reports, there are some key differences in the approaches from the Bidding Zone Review (BZR) with respect to capacity. Losses within the ENTSO-E DISTAC reporting are capacity deductions where the BZR has more complex market modelling considerations to losses (through market-coupling algorithm factor, influencing prices and flows rather than the reported cross-zonal capacity). BZR has more granular classification of losses and outages. Like the ENTSO-E DISTAC working group outputs, CIGRE HVDC reliability surveys have made important contributions to benchmarking HVDC system performance, but they too lack the granular detail required to support more advanced reliability modelling and targeted mitigation strategies.

	Future Actions
Short Term	› ENTSO-E DISTAC working group outputs cover only 26 of the more than 50 HVDC projects in Europe today as only the Nordics and Baltics are covered. Expansion of reporting to all HVDC projects in Europe would be of great value. The required data and submission template already exists, which should provide easy adoption. **TSOs are encouraged to engage with the ENTSO-E DISTAC working group to ensure such relevant data can be collected from all of Europe.**
Medium Term	› **Development of reliability metrics can rely on these existing definitions presented in the HVDC utilisation and unavailability statistics**, that is able to explain or incorporate them within reliability calculations. A reliability metric can address these outages; a higher reliability score meaning lower number of expected outages (excluding planned maintenance outages and planned limitations). › To improve reliability predictions and strengthen operational resilience, there is a clear need to build upon and expand these valuable initiatives. Long term actions should aim to **include more detailed classifications of failure modes, especially for protection and control systems, as well as clearer links between unavailability events and their underlying causes.** This would support a more detailed understanding of system behaviour and enable more effective maintenance, design improvements and standard development.

5.3 Data sharing for collective upskilling

ENTSO-E Task Force on HVDC Reliability (2017–2019) concluded that HVDC industry should strive for improved HVDC system reliability in general. One main factor that could contribute to it would be to seek for more efficient experience and knowledge sharing between all the HVDC industry stakeholders. Currently, several obstacles hinder this critical exchange, including:

- limited available HVDC resources and expertise;
- lack of systematic fault data collection; and
- lack of experience and knowledge sharing.

The most significant barrier to experience sharing seems to be from the fear of owners that they would violate any non-disclosure agreements or intellectual property (IP) rights if they share detailed fault information. Recent survey within ENTSO-E highlights data sharing as a key bottleneck among TSOs. The best spaces for sharing of data over the last ten years have been:

- Annual Hitachi (ABB) HVDC user Conferences: These conferences have been spaces for free experience sharing from each manufacturer and TSO through short presentations and discussions.
- Siemens HVDC User Conferences Interconnector Owners Group (IOG) meetings and member website: IOG have the space to share relevant data regarding HVDC projects in quarterly and annual meetings. However, only summaries/main messages brought up to Siemens in their biennial User Conferences.
- TSO/Owner & Manufacturer annual OEM meetings (but usually held only for those with OEM support contract).
- CIGRE HVDC Performance Surveys (general availability data and not so detailed technical descriptions).
- ENTSO-E DISTAC Group HVDC Utilisation and Unavailability statistics Surveys (general availability data, usually not so detailed technical descriptions and cover only Nordics and Baltics). The ENTSO-E DISTAC statistics allow for more detailed data in the free data field for descriptions of events, but these are available for further analysis only by the participants and on a limited basis.
- Any other form of regional or asset type-based groups of TSOs and owners.

As a first step, a common understanding, accepted by all relevant stakeholders, on sharing necessary information for fault clarification, root-cause analysis and experience sharing within the industry (and only published upon OEM explicit permission) is crucial to improving HVDC reliability.

The detailed contents and definitions of ENTSO-E’s HVDC disturbances and fault data sharing permissions are provided in Table 5 below:

Item	Allowed	Not Allowed	Note
Description of event that occurred with event timelines	×		
Description of consequences of fault	×		
Description of fault tracing findings	×		
Description of fault tracing process	×		
Starting the device ID & type(s) of faulty device(s)	×		
Stating the root causes of the fault and any factors that led to the fault with its consequences	×		
Showing photos of faulty device/consequences taken by owner/owner’s representative (consultant) e.g. at site or by owner’s representative (3rd party e.g. laboratory)	×		
Showing vendor photos of faulty device/consequences		×	To be shared between owner and OEM only
Showing OWS views of the event/consequences	×		
Showing event & alarm list around the time of fault	×		
Showing SLD/overview diagram with highlighted fault location		×	To be shared between owner and OEM only
Showing circuit diagram with highlighted fault location		×	
Showing logic diagram with highlighted fault location		×	
Showing parts of the O&M manuals with highlights relevant to the fault		×	
Stating the lessons learned from the fault	×		
Other plant documentation relevant to explanation of the fault		×	To be shared between owner and OEM only

Table 5: Definitions of ENTSO-E HVDC disturbances and fault data sharing permissions. Explanation: 1) generally not allowed, unless (e.g. some parts) separately accepted by OEM to be shared (upon request of owner)

It is very important to systematically improve experience and knowledge sharing relating to issues found in the operation of HVDC systems. Efficient sharing of information will significantly help to increase the overall skills level of all stakeholders. To facilitate better data sharing to improve HVDC reliability, TSOs and owners need sufficiently detailed data and accepted data sharing frameworks.

	Future Actions
Short Term	› **Most relevant detailed data can be collected, shared and discussed regularly between the owners of each station and the manufacturer.** It is then beneficial to share higher level (less detailed) data between all TSOs/owners of stations implemented by the same manufacturer. › **Higher level data collection should be provided to performance data collection entities** like CIGRE SC B4 AG04 (worldwide HVDC performance surveys), ENTSO-E DISTAC group (under System Operation Committee / SOC), and Working group Probabilistic Risk Assessment as applicable. › **Any other data collection can be arranged by other expert groups and entities, like ENTSO-E, on voluntary basis and as agreed by the participating parties.** Bilateral and e.g., regional owner groups have been formed to share experiences/data, like a HVDC WG within Nordic Asset Management Group (Nordic TSO participation).
Medium Term	› A clear framework for transparent data sharing among relevant stakeholders to increase reliability, trust and collaboration. **A joint effort by all stakeholders to realise a harmonised framework** would help standardised sharing practices.

5.4 HVDC interoperability frameworks

Most European HVDC links are single-vendor and point-to-point. This creates vendor lock-in, raises costs and limits the move towards multi-terminal grids. Interoperability is essential to integrate offshore hubs efficiently, allowing greater volumes of offshore renewables to be connected in a cost-efficient manner. ENTSO-E has delivered clear tasks for TSOs, OEMs and policy makers to move the needle forward on HVDC interoperability in 2021 through the position paper [18] "ENTSO-E Position on Offshore Development Interoperability". A clear roadmap with research directions to solve technical challenges on the way to developing and deploying multi-terminal, multi-vendor HVDC systems is provided by the joint paper [19] (developed by ENTSO-E, T&D Europe and WindEurope) "Workstream for the development of multi-vendor HVDC systems".

While significant progress can be seen also with EU funded projects such as InterOPERA[3], there is a need to highlight reliability considerations within these complex HVDC system configurations. When realizing interoperability of HVDC systems, the reliability of these must still be considered as primary focus. These steps are directly aligned with ENTSO-E's Offshore Roadmap and Future-Proof Grids agenda[4].

	Future Actions
Medium Term	› **Developing open, vendor-independent standards for control and protection; testing multi-vendor interoperability in pilot projects (e.g. North Sea hubs); and advancing multi-terminal DC grid control strategies.**

5.5 Training of experts

An HVDC system is a complex combination of standard equipment, custom-designed equipment and specialised control and protection systems. One of the keys to attaining the full design life from an HVDC system is a firm commitment on behalf of the owner to train and maintain skilled staff, capable of carrying out required maintenance and repair. The level of support available from the original supplier can be expected to decline as time goes on and the technology becomes obsolete, thus possibly, as a worst scenario, leaving the owner in the position of having the only trained staff for a given generation of technology.

Sometimes partial replacement can have undesirable long-term consequences. For instance, if improvements such as control replacement, synchronous condenser controls, cooling upgrades, etc., are undertaken using suppliers other than the original supplier, then the burden of design responsibility and sourcing of spares becomes more difficult. In the event of such changes, the original supplier may no longer be able to provide support, and the responsibility for technical support to maintain performance would shift to the owner.

	Future Actions
Medium Term	› **Structured and forward-looking training programs should be developed.** These programs could cover not only original system architecture, but also any subsequent upgrades, third-party integrations, and emerging software or cybersecurity practices. Training should be ongoing, role-specific, and aligned with system evolution, ensuring continuity of expertise and minimising reliance on external OEMs over the system's lifecycle.

3 https://interopera.eu/

4 ENTSO-E Offshore Roadmap 2025

6 Conclusion

The increasing integration of HVDC systems into European power networks underscores the urgency of improving their reliability. As these systems become more central to the energy transition, enabling bulk power transfer, offshore wind integration, and interconnection of asynchronous grids, the consequences of failures are becoming increasingly significant. This report has analysed the technical, operational, and institutional factors affecting HVDC reliability and set out a clear roadmap for coordinated European action.

Key findings emphasize that while HVDC technologies offer many operational advantages, they also introduce unique vulnerabilities. These include complex power electronics, bespoke control systems and extended repair times, which, if not well-managed, can compromise overall system resilience.

Industry-wide surveys, including those by CIGRE and ENTSO-E, show that although HVDC system availability has improved over time, outages remain too frequent and too long, leaving availability in some cases below the minimum acceptable threshold. An availability threshold of ≥95 % is generally considered the minimum acceptable, especially for interconnectors and grid-critical assets, with best-performing systems achieving ≥98 – 99 %.

TSOs across Europe are taking commendable steps through collaborative working groups, task forces, and targeted training programs. But systemic challenges persist, notably:

- Lack of granular, harmonised data, especially on failure categorisation and root causes;
- OEM transparency gaps, which block systematic learning and undermine risk management;
- Accelerating knowledge loss, as experienced HVDC engineers retire without structured knowledge transfer tools;
- Fragmented definitions and metrics, which prevent benchmarking and complicate project design.

The way forward requires harmonised practices, enforceable data-sharing frameworks, and the effective use of a central ENTSO-E reliability repository. Furthermore, data-driven approaches such as Probabilistic Risk Assessment (PRA) [20] offer significant promise, but require consistent data collection, robust modelling methodologies, and regulatory alignment to be effective.

This report recommends a roadmap of five pillars:

1. Expanding pan-European HVDC statistics collection (e.g., beyond the Nordics as in ENTSO-E DISTAC),

2. Formalising training and certification pathways for HVDC specialists,

3. Enhancing regulatory and contractual frameworks to enforce availability and data transparency obligations including data sharing,

4. Integrating software reliability and cybersecurity into HVDC reliability assessments,

5. Promoting joint research and innovation to improve forecasting, fault tolerance, and long-term asset management.

Improving HVDC reliability is not only a technical task, but also a strategic imperative to secure Europe's energy transition. ENTSO-E therefore calls on OEMs, regulators, policymakers and researchers to act jointly – making HVDC reliability a binding condition for Europe's decarbonisation and energy security.

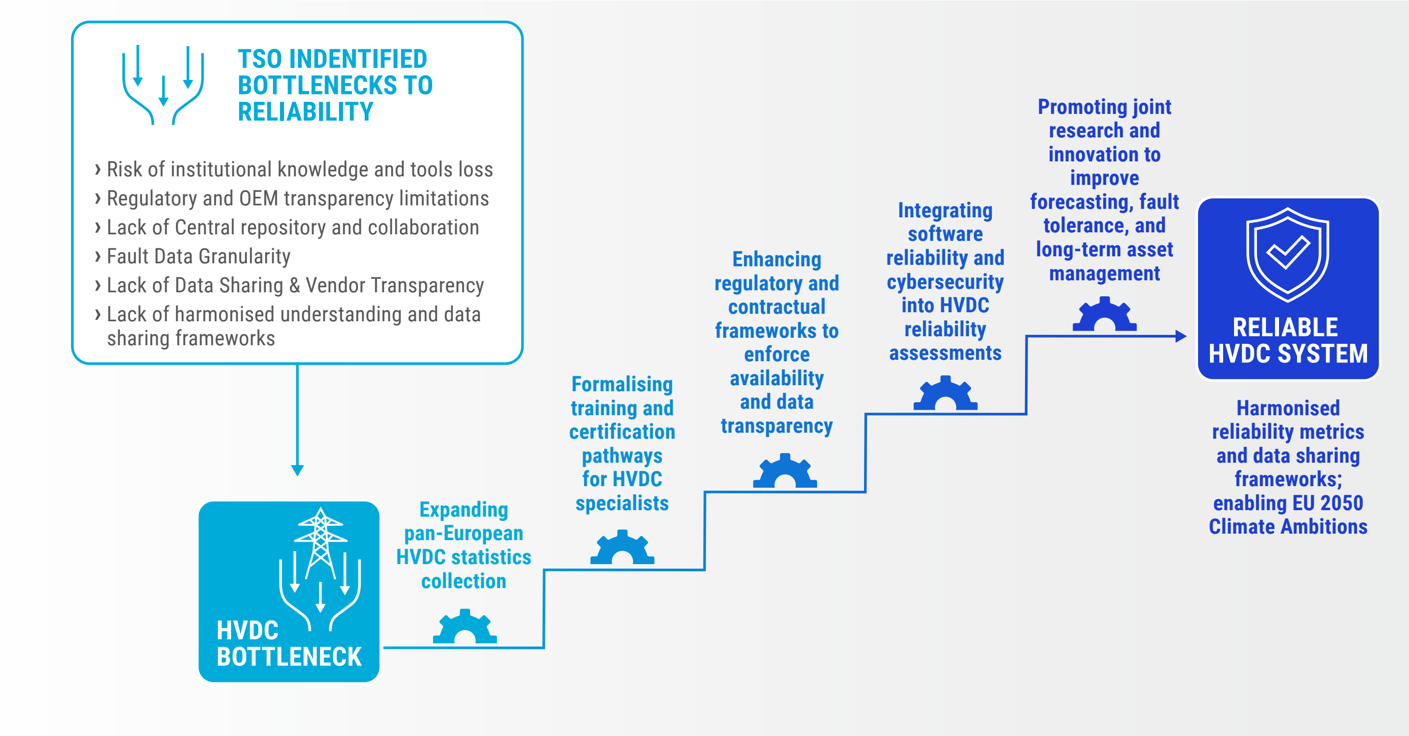


Figure 4: Five pillared roadmap for achieving reliable HVDC systems

Bottleneck	Future Actions	
Lack of Harmonised understanding and Data sharing Frameworks	**Short Term**	› **Scope of reliability calculation can be broadened.** The benefits of broadening scope beyond just the asset level, ranging from asset to a sub-system level through the project level to the region need to be evaluated. › **Approaches other than block diagram needs to be evaluated,** considering the various scopes possible.
	Medium Term	› **Setting up reliability targets during the pre-planning stage could be a means to steer the requirements for HVDC implementation contracts,** e. g. as warranty, bonus/penalty clauses as well as design and technical solutions, including e. g. redundancy, by-passing possibilities for faulty main equipment and spares. › **Developing open, vendor-agnostic standards for control and protection; testing multi-vendor interoperability in pilot projects (e. g. North Sea hubs); and advancing multi-terminal DC grid control strategies.**
Data Sharing and Vendor Transparency	**Short Term**	› **Most relevant detailed data can be collected, shared and discussed regularly between the owners of each station and the manufacturer.** It is then beneficial to share higher level (less detailed) data between all TSOs/owners of stations implemented by the same manufacturer. › **Higher level data collection should be provided to performance data collection entities** like CIGRE SC B4 AG04 (HVDC performance surveys), ENTSO-E DISTAC group (under System Operation Committee / SOC), and Working group Probabilistic Risk Assessment as applicable. › **Any other data collection can be arranged by other expert groups and entities, like ENTSO-E, on voluntary basis and as agreed by the participating parties.** Bilateral and e. g., regional owner groups have been formed to share experiences/data, like a HVDC WG within Nordic Asset Management Group (Nordic TSO participation).
	Medium Term	› A clear framework for transparent data sharing among relevant stakeholders to increase reliability, trust and collaboration. **A joint effort by all stakeholders to realise a harmonised framework** would help standardised sharing practices.
Institutional knowledge and tools retention	**Short Term**	› **Structured and forward-looking training programs should be developed.** These programs could cover not only original system architecture, but also any subsequent upgrades, third-party integrations, and emerging software or cybersecurity practices. Training should be ongoing, role-specific, and aligned with system evolution, ensuring continuity of expertise and minimising reliance on external OEMs over the system's lifecycle.
Fault data granularity	**Medium Term**	› To improve reliability predictions and strengthen operational resilience, there is a clear need to build upon and expand these valuable initiatives. Medium term actions should aim to **include more detailed classifications of failure modes, especially for protection and control systems, as well as clearer links between unavailability events and their underlying causes.** This would support a more detailed understanding of system behaviour and enable more effective maintenance, design improvements and standard development.
Regulatory and OEM transparency	**Short Term**	› Collaborate and discuss with OEMs on viable data sharing opportunities for mutual benefit.
	Medium Term	› Discuss with policy makers and regulators alongside OEMs to establish regulation on data sharing on HVDC fault.
Central repository and collaboration	**Short Term**	› ENTSO-E DISTAC working group outputs cover only 26 of the more than 50 HVDC projects in Europe today as only the Nordics and Baltics are covered. Expansion of reporting to all HVDC projects in Europe would be of great value. The required data and submission template already exists, which should provide easy adoption. **TSOs are encouraged to engage with the ENTSO-E DISTAC working group to ensure such relevant data can be collected from all of Europe.**
	Medium Term	› ENTSO-E to continue to **facilitate information exchange among TSO and knowledge sharing platforms** through the HVDC reliability working group.

Table 6: Actions to tackle TSO identified bottlenecks to HVDC reliability

By addressing today's shortcomings through shared data, stronger regulation, and collaborative innovation, Europe can build a robust, resilient, and HVDC-enabled power system that underpins the Green Deal and long-term energy security.

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Glossary

BZR	Bidding Zone Review
CIGRE	Conseil International des Grands Réseaux Electriques
DISTAC	Disturbance Statistics and Classification
ENTSO-E	European Network of Transmission System Operators for Electricity
FEU	Forced Energy Unavailability
FR	Failure Rate
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IOG	Interconnector Owners Group
IP	Intellectual Property
LCC	Line Commutated Converter
MTBF	Mean Time between Failure
MTBM	Mean Time before Maintenance
MTTF	Mean Time to Failure
MTTFF	Mean Time to First Failure
MTTR	Mean Time to Repair
PRA	Probability Risk Assessment
OEM	Original Equipment Manufacturer
RAM	Reliability, Availability and Maintainability
RBD	Reliability Block Diagram
RTU	Remote Terminal unit
SEU	Scheduled Energy Unavailability
TSO	Transmission System Operator
WG	Working Group
VCC	Voltage Commutated Converter
VSC	Voltage Source Converter

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