HVDC@70

THE PULSE OF ELECTRICITY GRIDS

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ABOUT US

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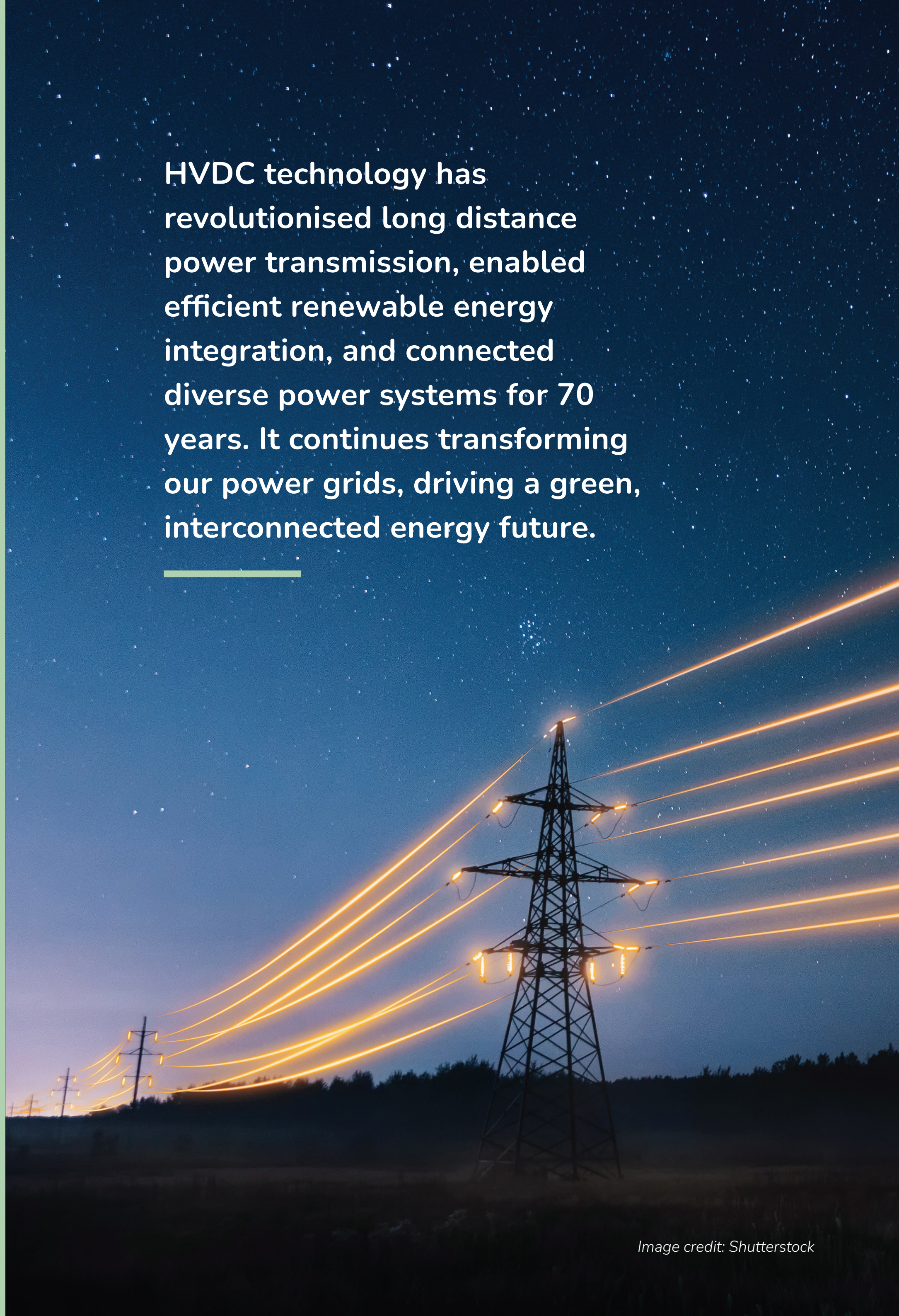

HVDC technology has revolutionised long distance power transmission, enabled efficient renewable energy integration, and connected diverse power systems for 70 years. It continues transforming our power grids, driving a green, interconnected energy future.

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Climate change is unarguably the biggest threat of our times. Our burning of fossil fuels has already emitted enough greenhouse gases to increase the average world temperature by between 1.1°C and 1.2°C. As a result, what were once subtle calls for intervention have now grown into an emphatic demand for urgent and effective measures to combat the deepening impacts of climate change. To limit global temperature rise to 1.5°C and achieve net-zero greenhouse gas emissions by 2050, swift and resolute action is urgently needed. Technology will be at the heart of this transformation.

Showcased by the World Economic Forum[1] as a technology that changed the world, high voltage direct current (HVDC) power transmission has been instrumental in the efficient transportation of electricity over long distances, the integration of renewable energy, and the interconnection of dissimilar power systems for 70 years.

The first commercial HVDC link using the first submarine HVDC cable was established in 1954 between mainland Sweden and the island of Gotland, and was recognised by the Institute of Electrical and Electronics Engineers (IEEE) as a "Milestone".

Today, there is over 375 GW of HVDC capacity installed globally, working round the clock to reduce losses, enhance grid flexibility and strengthen power system resilience.

With the push for decarbonisation accelerating over the past decade, there is now considerable momentum behind the clean energy transition and the phase-out of fossil fuels. In parallel, the transformation of the energy system is gathering pace. A new energy paradigm is emerging, driven by technologies such as solar, wind, electric vehicles, and heat pumps. These innovations are reshaping how we power our lives. HVDC is a foundational pillar of this transformation. This technology has been evolving over the years while working continuously to support a cleaner, more affordable and reliable future.

The recent global energy crisis has contributed to increasing electrification across sectors while also accelerating the deployment of clean energy technologies. As a result, electricity is fast becoming the backbone of this energy transition.

The International Energy Agency (IEA) projects that electricity's share in global energy consumption will surge from 20 per cent in 2023 to over 50 per cent by 2050[2]. Some experts estimate that this figure could be even as high as 70-80 per cent.

This fast-evolving energy landscape is posing new challenges for power grids. As power systems shift from large, centralised plants to decentralised renewables and distributed generation supported by strategically located storage, the need for more flexible and resilient grids becomes an imperative. Achieving national climate and energy goals means adding or refurbishing over 80 million km of grids by 2040[3], the equivalent of today's entire global grid. Moreover, the existing grids require major modernisation and digitalisation efforts. To deliver this, the IEA highlights that grid investments will need to almost double to exceed USD600 billion annually by 2030.

HVDC technology is poised to play a pivotal role in the evolving 2050 power system.

The origins of HVDC, which is celebrating its 70th anniversary in 2024, can be traced back to the late 19th century, to the famed “War of the Currents”. While AC prevailed because of its ability to change voltage levels and minimise losses, the introduction of HVDC in the mid-20th century provided a new, more efficient option for long distance power transmission.

The Gotland HVDC link in 1954 marked the beginning of HVDC’s transformative impact on power grids. Over the next decades, advances in semiconductor technology, control systems, cables, transformers and other grid technologies significantly improved HVDC’s performance, reliability and efficiency.

Today, HVDC is the technology of choice for overhead, underground and underwater transmission, causing minimal environmental impact and preserving natural landscapes.

The journey of HVDC is characterised by continuous innovation and transformation. While considerable progress has been made, the theoretical limits of HVDC’s core technologies still have further potential. As the technology evolved, so did its applications, with point-to-point connections advancing towards more sophisticated multivendor, multiterminal projects, laying the path for multipurpose interconnector projects and even meshed offshore grids.

These developments are critical for integrating large volumes of offshore wind in the coming years. Enabling this transition will require advances in HVDC breakers, standardisation and interoperability of equipment, regulatory frameworks, and legal and commercial structures.

70 Years of HVDC – Highlights

70+ years of rich technological journey	**> 375 GW** installed globally	**3x times** Power capacity and **30% lower** Footprint*
>3,200 km Longest HVDC project**	**12 GW ±1,100 kV** Highest capacity of LCC installed**	**5 GW ±800 kV** Highest capacity of VSC installed***

*Versus traditional HVAC

**Changji-Guquan project in China

***Kunliulong project in China

HVDC technology will continue to redefine our power grids and support a renewables-led, interconnected energy future. Achieving the critical objectives and targets set for climate action will require the collective efforts of policymakers, regulators, utilities, technology providers and consumers.

We are in the decade of delivery, and inaction is not an option. The time to act is now!

70 Years of HVDC – Key Milestones

Where it started

1954
World's first commercial HVDC link at Gotland, Sweden

1970s
Thyristor semiconductor valves replaced mercury-arc valves

1979
First microcomputer-based control equipment for HVDC

1984-87
±600 kV Itaipú project in Brazil, first of its kind

1989
World's first LCC-HVDC multiterminal, Pacific Intertie in the US

1997
World's first VSC-HVDC installation at Hällsjön, Sweden

2001
Cross Sound Cable, first US merchant transmission project

2002
Murraylink, world's longest private underground cable

2003
Modular multilevel converters introduced

2010
World's first ±800 kV UHVDC link – Xiangjiaba-Shanghai

2012
World's first offshore HVDC connection commissioned, ±150 kV BorWin1 in Germany

2012
Hybrid HVDC breaker introduced

2013
First VSC-HVDC multiterminal at China's Nan'ao Island

2014
Skagerrak 4 HVDC Interconnector, world's first VSC-HVDC at ±500 kV

2019
World's first ±1,100 kV UHVDC link – Changji-Guquan

2022
2 GW multivendor HVDC programme launched by TenneT

2023
Viking Link, world's longest undersea HVDC interconnector

2024
Europe's first multiterminal VSC-HVDC project, Caithness-Moray-Shetland

Where it is headed

Beyond 2024
Powering the grids of the future – multiterminal, multivendor, meshed, offshore hybrid systems

The adoption of HVDC has grown substantially in recent decades. An impressive 375 GW of HVDC capacity is operational today. With numerous plans and proposed projects, this capacity is set to surge, nearly doubling within the next two decades.

Figure 1: Installed HVDC Capacity (GW)

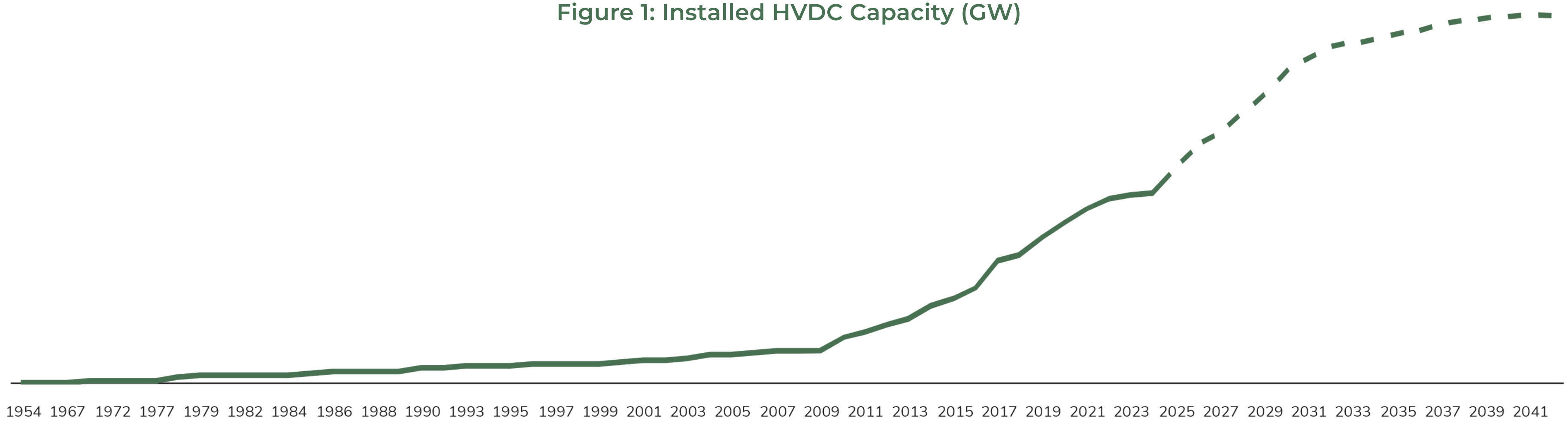
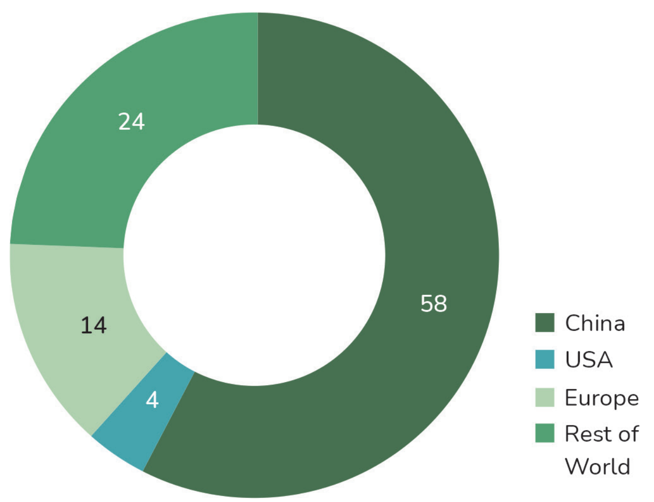
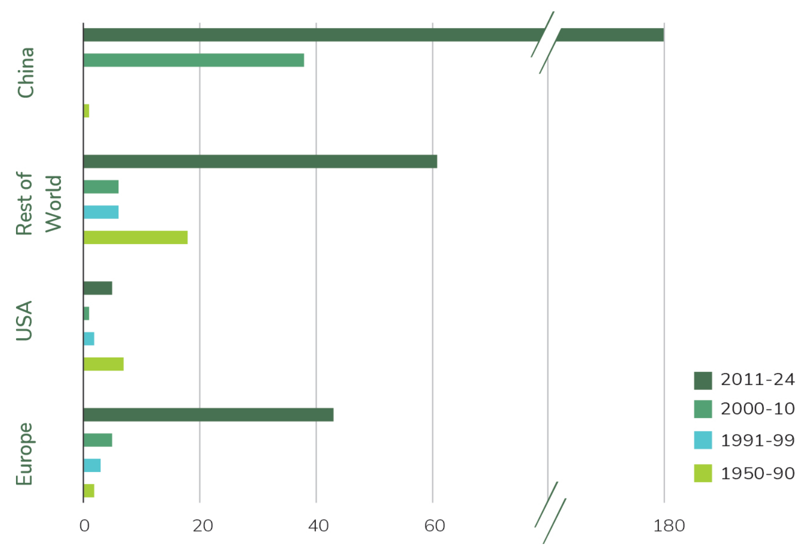


Figure 2: 2024 HVDC Installed Capacity by Region/Country (%)

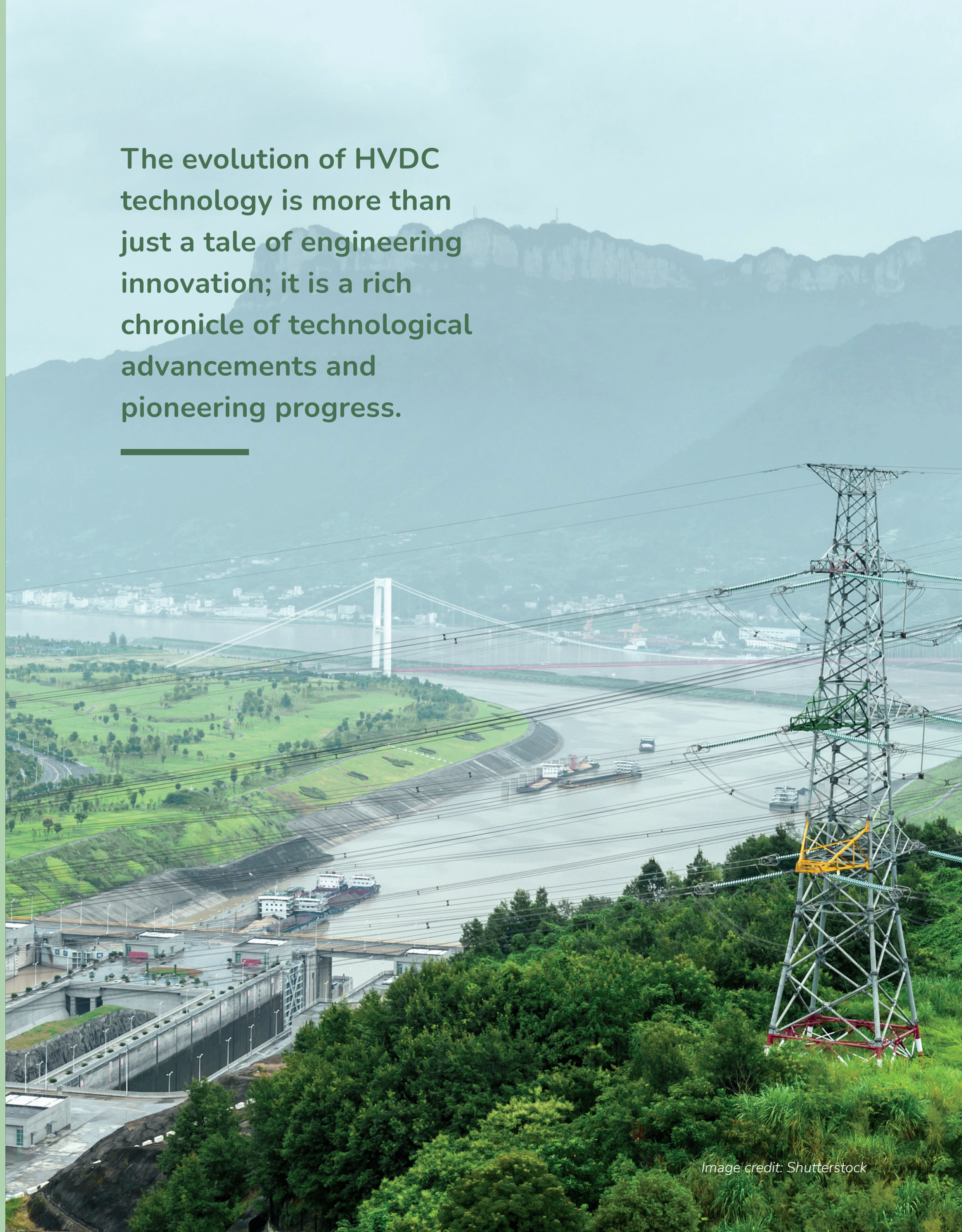


Source: Global Transmission Report

Figure 3: Growth in HVDC Capacity by Region/Country (GW)



2 ORIGINS OF HVDC: PATHWAY TO INNOVATION



The evolution of HVDC technology is more than just a tale of engineering innovation; it is a rich chronicle of technological advancements and pioneering progress.

Image credit: Shutterstock

HVDC technology, now integral to modern power transmission systems, has an illustrious history, defined by remarkable advances. To appreciate the significance and evolution of HVDC, it is essential to understand the historical context that influenced its development.

2.1 The Electrifying Battle: "War of the Currents"

The early development of HVDC cannot be discussed without mentioning the famous "War of the Currents", which captivated both the scientific and the industrial communities in the late 1880s. This was a fierce competition between Thomas Edison, a staunch advocate of DC power, and Nikola Tesla, who championed AC power, with the support of George Westinghouse.

Edison promoted DC as the safer and more reliable option, while Tesla demonstrated the efficiency and lower cost of AC. Despite Edison's extensive campaigns, Westinghouse won the contract to power the 1893 World's Fair in Chicago, showcasing Tesla's AC system, and later secured a contract to build AC generators for a hydroelectric plant at Niagara Falls. In 1896, this plant began delivering electricity to Buffalo, New York, 26 miles away, and thereby solidified AC's success in the electric power industry. In addition, AC's ability to change voltage levels using transformers made it more suitable for widespread electric power distribution at the time, ultimately establishing it as the dominant technology.

The "War of the Currents" was a defining moment in the history of electricity, and shaped the development of electrical systems and infrastructure.

2.2 Emergence of DC: Overcoming Challenges

Despite the continued success of AC, as the need for long distance power transmission grew, certain limitations became apparent. AC lines experienced significant energy losses over vast expanses and struggled with voltage stability issues when connecting remote power sources to load centres. These challenges led to a renewed interest in DC, particularly in HVDC, marking the beginning of a new era in power transmission.

The development of mercury-arc rectifiers at the turn of the 20th century commemorated an important step in the evolution of AC to DC power conversion. Further research by Dr Uno Lamm, regarded as the father of HVDC, began in 1929 in Sweden at ASEA (a predecessor of ABB and now Hitachi Energy) and laid the groundwork for HVDC technology, harnessing the potential of mercury-arc valves.

Dr Lamm's research culminated in the world's first commercial HVDC transmission link in 1954, connecting the island of Gotland with mainland Sweden[4]. This 96 km long, 20 MW, ±100 kV subsea link used a mercury-arc valve-based converter and mass-impregnated cable, marking a significant technological milestone for the electric power industry.

2.3 The HVDC Edge: Uncovering its Merits

As more clean electricity is funnelled through power grids across the world, electricity is poised to become the backbone of the energy system. This shift elevates the responsibility of power grids, which must not only efficiently deliver electricity to households, businesses and industries but also support new loads such as data centres and AI processing. At the

Installation of the Gotland Project in Sweden

Source: Hitachi Energy

same time, they need to manage the variability of increasing renewable energy sources, often located far from consumption centres. Power grids are also on the frontline when it comes to managing frequent extreme weather events, cybersecurity threats and physical attacks. These changing dynamics in supply and demand introduce greater complexity, necessitating a transformation in how we plan, build, operate and maintain our power grids.

This is where the benefits of HVDC technology stand out. Every country needs to expand, refurbish, or modernise its power grids to meet the demands of an evolving energy system. The IEA estimates that by 2040, over 80 million km of grid infrastructure would need to be added or refurbished – "the equivalent of the entire existing global grid". HVDC technology has a crucial role in this effort, particularly for maximising renewable energy integration, minimising energy losses and environmental impact, and enhancing grid management.

HVDC technology has proven to be economically competitive with HVAC for distances over 400 km for overhead lines, 30-50 km for underground cables, and 50-80 km for subsea cables. HVDC systems use only two conductors instead of the three used in HVAC systems, yet they can carry three times more power. They require fewer towers and a narrower right of way (RoW), making it easier to navigate a challenging terrain.

New HVDC systems can be entirely underground or a mix of overhead and underground to address siting issues and public concerns. They thus reduce the physical footprint and improve the visual impact of transmission infrastructure. Their compact design is particularly advantageous in urban or environmentally sensitive areas. Moreover, HVDC can efficiently connect grids with different frequencies (asynchronous grids), thereby facilitating electricity trade across borders or regions.

Benefits of HVDC

HVDC transmission delivers significant benefits not only from a technical power system standpoint but also from an economic, environmental and societal perspective.

Technical

- Enables high power transmission capacity, currently up to 12 GW at ±1,100 kV spanning>3,000 km.
- Minimises long-distance power losses.
- Contributes to AC grid flexibility with independent voltage and frequency control.
- Enhances grid resilience with black start capability.
- Connects grids with different frequencies (asynchronous grids).
- Manages congestion through its more precise control of power flow.

Economic

- Lowers wholesale electricity prices by integrating diverse energy markets.
- Reduces balancing and redispatch costs with improved control.
- Offers lower operational costs over its whole life cycle owing to reduced energy losses and cuts infrastructure costs with narrower RoW.
- Reduces the need for intermediate substations due to fewer voltage drops over long distances.
- Encourages generation capacity investments by improving grid reliability and stability.

Environmental

- Accelerates decarbonisation by integrating clean energy sources such as wind, solar and hydro electricity.
- Minimises landscape impact by reducing the transmission footprint (fewer towers and conductors).
- Optimises resource use by enabling the transfer of electricity from regions with surplus to those with limited generation capacity.
- Lowers electromagnetic field emissions.

Societal

- Increases ability to integrate renewables, thereby enhancing public health outcomes by improving air quality.
- Boosts the environmental well-being of local communities by reducing land use.
- Reduces the socio-economic impact of outages with black start capability, which enables the rapid restoration of grids.
- Promotes regional collaboration through energy trading.

2.4 Inside an HVDC System

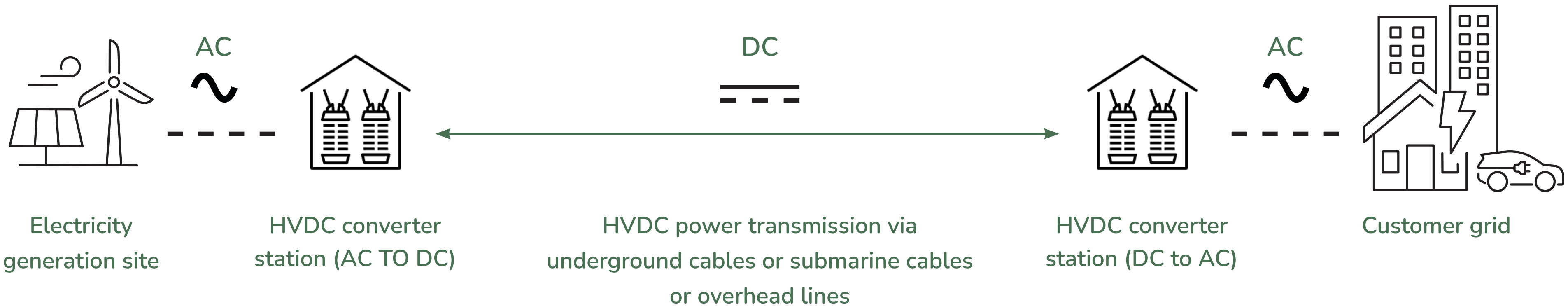
In an HVDC system, electric power is taken from one point in a three-phase AC network, converted to DC in a converter station, transmitted to the receiving point by an overhead line or cable, and then converted back to AC in another converter station and injected into the receiving AC network.

Integral to HVDC transmission systems are terminals (or converter stations) that convert AC to DC for transmission and then back to AC. Each terminal can act as either a rectifier (converting AC to DC) or an inverter (converting DC to AC). The connection between the converters may be by overhead line, cable, or both. Converter stations may be installed onshore or offshore.

The core of these terminals are converters, which serve as the interface with the AC transmission and manage the conversion process. These converters utilise controllable electronic switches called valves, whose primary function is to control the direction of current flow, ensuring it only moves in one direction. This unidirectional flow is essential for both rectification and inversion processes within HVDC systems.

Complementing the converters and valves are components such as converter transformers, filters, reactive power sources and smoothing reactors. This equipment is designed to ensure smooth operation, system stability, and secure operation by managing the flow of electricity and safeguarding against faults.

Figure 4: A Simplified Illustration of an HVDC System



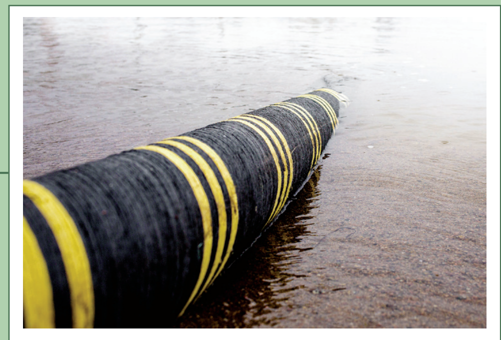
Core Components of an HVDC System

Converter Valves

HVDC Power Transformers

HVDC Station

Converter Control and Protection



HVDC Power Cables

Photos credit: Hitachi Energy and NKT

2.4.1 Converter Valves

Converter valves are essential components within HVDC converters owing to their critical function in ensuring continuous current flow. Advances in valves and converter technologies, specifically through power electronics, have greatly enhanced the efficiency, reliability and control of HVDC systems.

While electronics is the field of engineering that deals with devices that operate on low voltages and currents, power electronics deals with devices that operate on high voltages and currents. Power electronics is a multidisciplinary field encompassing power semiconductor devices, converter circuits, advanced control systems, digital signal processors and artificial intelligence techniques.

There are few components more crucial than semiconductors, also sometimes referred to as microchips or integrated circuits. They are the foundation of modern computing and are ubiquitous in our daily lives, with devices such as smartphones and laptops relying on them. Unlike household semiconductors, power semiconductors can endure high voltage and current with minimal losses. They are primarily used as switching devices and rectifiers, and for altering the voltage or frequency of electrical currents.

Following the successful energisation of the Gotland project in 1954, numerous mercury-arc valve-based HVDC projects were commissioned in the 1960s. However, despite its early successes, this technology was not without its limitations. These systems were prone to a phenomenon known as "arc-back", which could result in system instability and interruptions. In addition, their large physical size, maintenance needs and the environmental impact of mercury meant that innovation was needed.

General Electric's invention of the silicon controlled rectifier (SCR) in 1957, or thyristor as it later came to be known, marked a major technology leap and ushered in a new era of HVDC. Thyristors are semi-controllable power semiconductor switches and are used to control electric power. Throughout the 1960s and 1970s, thyristor valve-based converters, more commonly known as Line Commutated Converters (LCCs), became widely adopted, especially for connecting remote power generation sites to urban centres.

However, LCC technology too has limitations. It requires a strong AC grid for commutation (the process of switching current conduction from one of the thyristor valves to another in the same row), introduces harmonics, necessitating extensive filtering, and demands 50-60 per cent of its rating in reactive power, which requires the addition of costly equipment. Moreover, LCC systems lack black start capability, needing external help to restart after a blackout. These limitations highlighted the need for more advanced HVDC technologies that could operate independently of the AC grid and reduce the impact of harmonics.

The development of Voltage Source Converters (VSCs) in the 1990s revolutionised HVDC technology. VSCs mostly use insulated gate bipolar transistors (IGBTs), solid-state devices that provide fast switching, reduced conduction losses of 20-30 per cent and improved control over power flow. An IGBT is a fully controllable power semiconductor switch. Thanks to their smaller footprint and better control capabilities, IGBTs make VSC technology particularly suited for interconnecting new renewable sources with the grid.

More recent innovations in power semiconductors, such as Bi-mode Insulated Gate Transistors (BIGTs), have further enhanced the power handling and control capabilities of VSC-based HVDC systems. These advances, along with compact valve designs, enable efficient and space-saving configurations. One of the world's largest offshore windfarms, the Dogger Bank project, in the UK, uses the BIGT-based HVDC system.

Modular Multilevel Converters (MMCs) are the fourth generation of VSC-based HVDC technology. MMCs are fast becoming the best available solution for transmitting power over long distances through submarine cables from offshore wind farms to land. Since HVDC multiterminal systems have high requirements from control and protection systems, MMC-based HVDC systems will also play a pivotal role in the development of multiterminal projects and multipurpose interconnectors (discussed in detail in Chapter 4).

The constant evolution in semiconductor technology has enabled valves to meet market needs for ever increasing levels of transmitted power. The efficiency of the valves has improved with the continuous reduction in semiconductor losses. The amount of space required for valves has also reduced significantly over time. These advances have contributed to HVDC becoming increasingly cost competitive for power transfer.

As converter valves are some of the most expensive components of HVDC systems, research is continuing to drive innovation to reduce costs. The US Department of Energy (DOE) has launched a funding opportunity for research on driving down VSC costs . This is the first step in its HVDC COst REduction Initiative (CORE)[5], aimed at reducing the cost of HVDC systems by 35 per cent by 2035 to promote widespread adoption of the technology.

VSCs offer numerous advantages over LCCs, including:

- **Bidirectional Power Flow:** VSC systems enable power to flow in both directions through a single transmission line, unlike LCC systems, which often need separate converters for each direction, raising costs and complexity.
- **Black Start Capability:** VSC systems can restart a grid after a blackout, significantly boosting grid resilience.
- **Lower Harmonics:** VSCs generate fewer harmonics, reducing the need for expensive filtering solutions.
- **Grid Support and Stability:** VSC systems enhance voltage stability and reliability by providing reactive power support to the AC grid.
- **Renewable Energy Integration:** VSC handles variable inputs more effectively than LCC, which often needs additional voltage and reactive power management equipment.
- **Compactness and Flexibility:** The compact design of VSC stations lowers environmental impacts, making them suitable for urban installations and challenging offshore environments.

Pioneering HVDC Projects

Mercury-Arc Valve Milestones

- **HVDC Cross Channel:** Undersea link connecting France and the UK.
- **Konti-Skan 1:** First interconnection between Sweden and Denmark's western grid.
- **HVDC Inter-Island (Cook Strait Cable):** Link in New Zealand bridging the North and South islands.
- **Vancouver Island 1:** A 312 MW, ±260 kV project in Canada, commissioned in 1968.
- **Pacific HVDC Intertie:** A ±400 kV transmission link from Dalles, Oregon to Los Angeles, California.
- **Nelson River Bipole (Manitoba Bipole 1):** The largest and last commercial mercury-arc valve-based system; 895 km long link with a capacity of 6.5 GW at ±500 kV; developed in 1972 in Canada.

LCC Triumphs

- **Eel River:** First fully thyristor-based ±80 kV HVDC system, transmitting 320 MW of power between Hydro Quebec and New Brunswick in Canada, energised in 1972.
- **Cahora Bassa Link:** A ±533 kV, 1,920 MW interconnector between South Africa and Mozambique.
- **Itaipú Transmission System:** A 6.3 GW, ±600 kV HVDC link in Brazil to transport hydroelectric power, the world's first of its kind.
- **CASA-1000 Power Link:** Connects Tajikistan to Pakistan, transmitting 1.3 GW at ±500 kV over 800 km, a key project under the Central Asia-South Asia Regional Electricity Market initiative.

VSC Innovations

- **Hällsjön Project:** First experimental VSC project, a 3 MW ±10 kV link in Sweden (1997).
- **Gotland:** A 50 MW, ±80 kV system, marking the commercial debut of VSC-HVDC in 1999.
- **Cross-Sound Cable:** First merchant transmission project in the US, a 330 MW, ±150 kV link between New York and Connecticut.
- **Piedmont-Savoy Interconnector:** At ±320 kV, 190 km, longest underground interconnector between Italy and France.
- **Caprivi Link:** A 300 MW, ±350 kV link between Namibia and Zambia, combining VSCs and AC lines for greater grid stability.
- **BorWin1:** A 400 MW, ±150 kV subsea link, first to showcase VSC's potential for offshore wind integration.
- **Dogger Bank:** First BIGT-based link, with 1.2 GW capacity at ±320 kV.

2.4.2 Converter Transformers

Another important element of an HVDC system is a converter transformer, which serves as the critical interface between the AC system and the DC converter. These transformers, among the largest in terms of power, voltage and complexity, face unique challenges as they handle demands from both the AC system and the DC system simultaneously. Their primary function is to insulate the DC voltage of the converter valve from the AC network, ensuring that all power flowing through the HVDC system is efficiently transformed to a suitable voltage level for the converter valve.

Initially, transformer development focused on achieving long distance transmission with minimal losses. Technological advances during the 1980s and 1990s delivered transformers capable of supporting higher power capacities and voltage levels. A notable example is the Itaipú HVDC power link in Brazil, commissioned between 1984 and 1987. This mega project pushed voltage and power capacity limits to ±600 kV and 6.3 GW.

Further research enabled voltage ratings of ±800 kV and ±1,100 kV. Hitachi Energy and Siemens Energy led the way, supplying converter transformers for the world's first two ±800 kV HVDC projects – Yunnan-Guangdong and Xiangjiaba-Shanghai – commissioned in 2010. They also supplied transformers for the first ±1,100 kV transmission link, the Changji-Guquan project, capable of transmitting 12 GW of power over 3,284 km in China. By 2013, China independently manufactured ±800 kV transformers and by 2018, developed ±1,100 kV capability.

The leap from ±800 kV to ±1,100 kV DC occurred rapidly, especially compared to the 25 years it took to move from ±600 kV to ±800 kV DC. The power rating for ±800 kV DC transmission links also increased from 8 GW to 10 GW, exemplified by China's Ximeng-Taizhou project, the world's first ±800 kV project with 10 GW capacity.

Another breakthrough relates to the AC voltage levels of HVDC converter transformers. All existing DC transmission voltage levels can now be connected with any AC voltage level. For example, the Lingzhou-Shaoxing (LingShao) project interconnects a 750 kV AC network with an 8 GW, ±800 kV HVDC transmission system, showcasing the continuous evolution and innovation in HVDC transformer technology.

2.4.3 Control and Protection Systems

Control and protection systems, often referred to as the brains of HVDC transmission, are designed to manage the flow of electricity and protect infrastructure from faults and failures. They ensure reliable power transmission under both normal and abnormal conditions, while preventing harmful interactions between the HVDC system and the AC network.

In an HVDC system, power transfer is fully controllable, meaning that the amount of power and the direction of that power flow can be adjusted on demand. To ensure this controllability, which is important for system operators, a highly responsive control system is essential, working to adjust the voltage and current in real time. A modern HVDC system comprises a collection of equipment that needs constant monitoring and control, from the semiconductor valves to the electrical and auxiliary systems. The control system is also responsible for measuring and monitoring this equipment, as well as taking automatic control actions.

Side by side with the control system is the protection system. It protects the HVDC system from faults by taking corrective action. When the fault is significant, for example if the cable has been compromised or if the HVDC transformer insulation has not been working as expected, the protection system will order the complete shutdown of the HVDC system in an effort to protect the healthy equipment and the broader grid. The shutdown results in the HVDC system being isolated from the AC grid. The speed of this response must be extremely fast, often in the order of milliseconds or less and, therefore, human intervention is not possible.

Better control and protection strategies are paramount for better HVDC performance. Hence, technology providers have been innovating on the design and operation of control and protection systems for over 30 years, ensuring operational stability, efficiency and safety. Today, the control and protection systems leverage advances in digitalisation and power electronics to enhance power transfer controllability and prolong the lifetime of legacy HVDC projects.

Modern HVDC systems often integrate telecommunications infrastructure with their power transmission capabilities. Fibre optic cables frequently run through the centre of power conductors or, at the very least, occupy the same cable tunnels. This integration enhances communication and control across the HVDC network, improving reliability and performance.

Advanced control modules, protective mechanisms and comprehensive monitoring have been fundamental to the success of HVDC technology. As HVDC systems evolve with increasing voltage and power capacities, the demand for precise and faster control and protection systems becomes critical.

2.4.4 HVDC Cables

At first glance, HVAC and HVDC cables appear quite similar; both contain a conductor (made of copper or aluminium), insulation, a water barrier and, in the case of undersea cables, armour. However, the primary distinction lies in the electrical insulation. HVDC cables use two main types of insulation – mass-impregnated (MI) and cross-linked polyethylene (XLPE). MI involves paper impregnated with high-viscosity oil, known for its reliability. These cables include steel armour for submarine use to improve mechanical performance. XLPE insulation, on the other hand, is made by chemically cross-linking polyethylene, which boosts its strength and ability to handle high temperatures and electrical stresses.

MI cables have long been preferred for HVDC transmission, especially in LCC-based projects, and can now handle voltages of up to 600 kV. MI cables of 800 kV voltage levels have also been announced. However, MI cables are heavy, with a weight of 50 kg to 60 kg per metre for subsea applications.

XLPE extruded insulation cables provide significant technical and cost benefits due to their better thermal stability, higher temperature tolerance and increased current ratings. They are more environmentally friendly, as they do not have the risk of oil leaks like MI cables. Weighing 20 kg to 35 kg per metre – about half the weight of MI cables – XLPE cables are cheaper to manufacture and install, making them ideal for HVDC offshore applications.

While XLPE cables have been commonly used at 320 kV, the 525 kV level is now available for deployment, and some manufacturers have tested 640 kV versions. These new cables are expected to boost transmission

Figure 5: Germany's Planned Corridors Project

1: A-Nord by Amprion

2: Ultranet by Amprion and TransnetBW

3 & 4: SuedLink (2 HVDC cables) by TenneT and TransnetBW

5: SuedOstLink by TenneT and 50 Hertz

Source: Ministry for Environment, Climate and Energy of Baden-Württemberg, September 2021

capacity by nearly 20 per cent while reducing cable weight and potentially lowering manufacturing and installation costs.

Other innovations in cable technology have enabled a combination of underground and overhead cables in a single HVDC project. India's federal transmission utility, Power Grid Corporation of India, commissioned its ±320 kV Pugalur-Trichur VSC-based project in 2021, combining overhead lines with underground cables and demonstrating the adaptability of these systems in complex transmission environments.

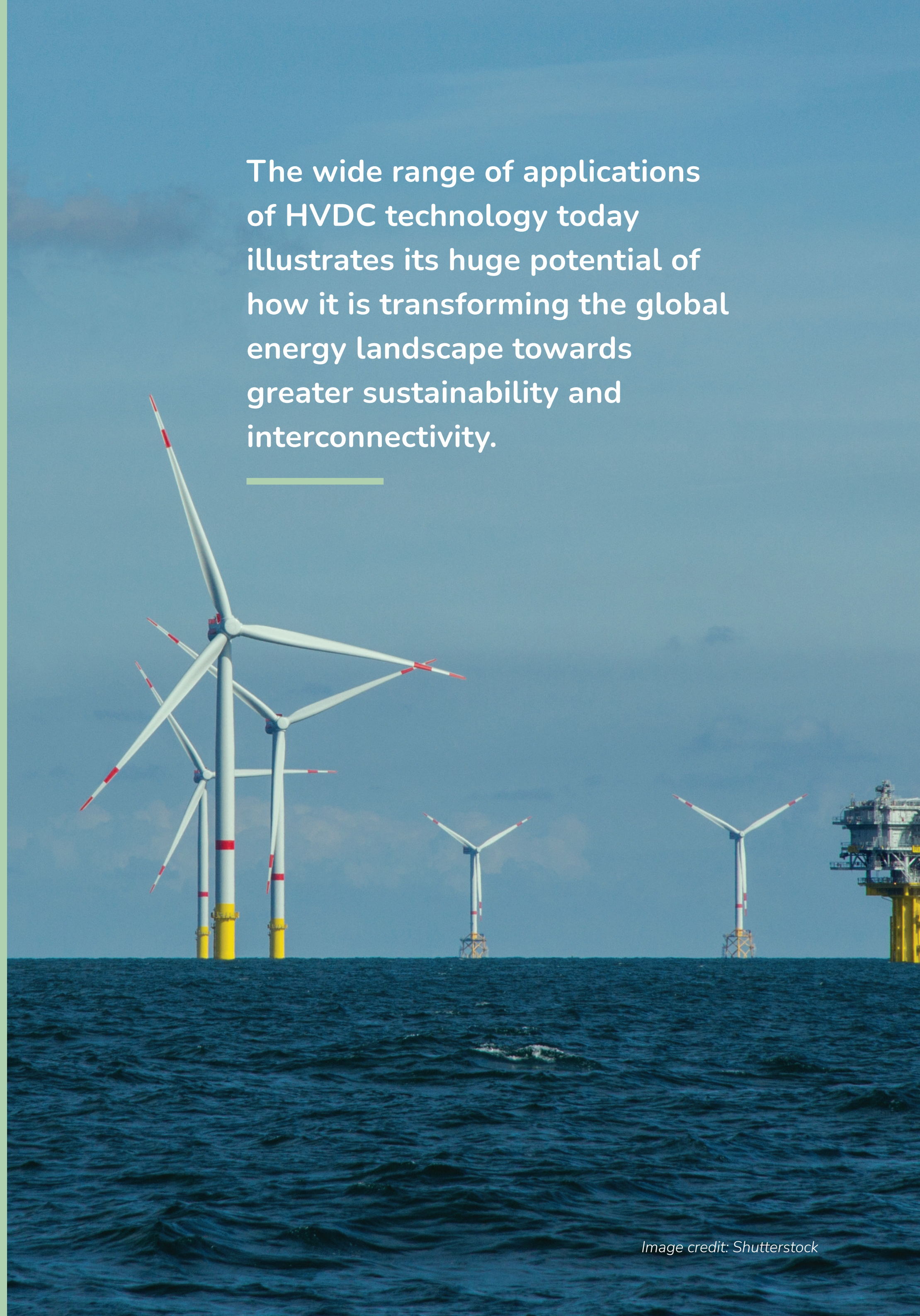
An ambitious project that will deploy higher voltage and power ratings of HVDC extruded cables is the German Corridors Project. Four German Transmission System Operators (TSOs) – TenneT, 50 Hertz, TransnetBW and Amprion – are collaborating on a bold task to build HVDC underground links and efficiently integrate them with the existing AC systems. The Corridors Project has three 2 GW, ±525 kV sub-projects – Sued Link, SuedOstLink and A-Nord – each to be completed by 2027. A-Nord will further connect to Amprion's planned Ultranet project, forming what is called the Corridor A. Ultranet is distinctive in its approach, as it will be the first to transmit both AC and DC power over the same pylons.

In a first of its kind, TenneT's ambitious 2 GW programme[6] will deploy 525 kV extruded HVDC cables for 14 grid connection systems – both onshore and offshore – in Germany and the Netherlands. TenneT is partnering with NKT, Nexans and LS Cables for these projects.

Superconducting Cables

An interesting area of research in cable technology is superconducting materials. The most promising solution for HVDC superconducting cables involves high temperature superconductors (HTS), designed to operate at extremely low temperatures (-180°C to -200°C) using liquid nitrogen. This achieves very low resistance while maintaining excellent electrical performance and mechanical stability. Nexans[7] has qualified a ±320 kV superconducting cable for currents up to 10 kA with 3.2 GW power transmission capability. This advancement highlights HTS cables' potential for HVDC applications. However, HTS technology remains expensive and requires further research and validation for commercial use.

3 MODERN APPLICATIONS POWERING THE PRESENT



The wide range of applications of HVDC technology today illustrates its huge potential of how it is transforming the global energy landscape towards greater sustainability and interconnectivity.

Image credit: Shutterstock

Key Applications of HVDC Technology


Long distance transmission


Connecting remote generation


Connecting remote loads


Offshore wind integration


Interconnecting grids


City centre infeeds


DC links in AC grids


Power from shore


Upgrades and retrofits

Photos credit: Shutterstock

The expanding adoption of HVDC technology emphasises its significance in enabling a wide array of power transmission applications. Chapter 3 describes the key areas where HVDC is a viable solution today.

3.1 Long Distance Transmission: Connecting Remote Renewables and Remote Loads

HVDC is the technology of choice when transporting substantial amounts of power across vast distances. Its significance is particularly evident when linking remote renewable energy sources, such as hydroelectric plants and wind farms, to the main grid, and when supplying electricity to distant, isolated or offshore load centres (for example, offshore oil and gas facilities). Advancements in power transformers have played an important role here, enabling ultra-high voltage levels above ±800 kV with significantly reduced energy losses. China has been a pioneer in developing UHVDC projects since 2009 and now boasts numerous ±800 kV and ±1,100 kV systems. India and Brazil have also developed ±800 kV projects.

An interesting example of where HVDC technology is used to supply electricity to offshore load centres is ADNOC's Project Lightning in the UAE. Two undersea interconnectors (140 km and 124 km) will transmit clean electricity from the UAE grid to two offshore oil and gas complexes, significantly reducing the carbon footprint of both facilities.

Figure 6: Long Distance HVDC Application Showcase

	Jinping-Sunan UHVDC Project, China	Northeast-Agra UHVDC Link, India	Changji-Guquan UHVDC Project, China	TransWest Express Project, USA
Developer	State Grid Corporation of China	Powergrid Corporation of India	State Grid Corporation of China	TransWest Express LLC
Capacity	7.2 GW	8 GW	12 GW	3 GW
Voltage	±800 kV	±800 kV	±1,100 kV	±600 kV
Line length	2,090 km	1,728 km	3,000 km	1,175 km
Commissioning year	2013	2017	2019	Expected in 2027
Lead HVDC technology providers	Siemens Energy and Hitachi Energy	Hitachi Energy, Bharat Heavy Electricals Limited	Hitachi Energy and Siemens Energy	Siemens Energy
Objective	Connects hydroelectric plants in central-west to the eastern region	World's first ±800 kV multiterminal project transporting power from northeast to central-north India	World's first ±1,100 kV project, integrating remote generation	Will transmit wind energy from Wyoming to Colorado, Utah and Nevada

3.2 Interconnecting Grids: Facilitating Electricity Trade

Interconnectors are rapidly becoming essential components of modern power systems, connecting the electricity networks of neighbouring countries or regions within a country. These links enable the efficient exchange of electrical power across borders when needed, for instance when consumption is high, or to avoid curtailment of renewables, or in the case of a technical incident. They provide a range of benefits including reducing the price of wholesale electricity, optimising the integration and use of renewable energy, and enhancing security of supply.

For linking national grids of different countries that are operating at different frequencies, HVDC is currently the only feasible technology available. Back-to-back HVDC stations consist of two converters located in the same building. The Chateauguay HVDC system, in operation since 1984, enables the transmission of electricity between Quebec, Canada (operating at 735 kV) and New York, USA (operating at 765 kV). The system is currently being modernised to increase its capacity to 1,500 MW.

Europe has greatly benefited from HVDC technology and is now one of the largest interconnected grids in the world, with over 400 interconnectors. SIEPAC, the Central American Electrical Interconnection System, is another example of a notable interconnection project that links six Central American nations. Several Asian and African countries are also building HVDC interconnectors to optimise regional resource use and strengthen energy security.

Figure 7: HVDC Interconnector Project Showcase

	BritNed, UK and Netherlands	Piedmont (Italy)-Savoy (France)	Viking Link, UK and Denmark	Saudi Arabia-Egypt Interconnector
Developer	National Grid and TenneT	Terna and RTE	National Grid and Energinet	Saudi Electricity Company and Egyptian Electricity Transmission Company
Capacity	1 GW	1.2 GW	1.4 GW	4.5 GW
Voltage	±450 kV	±320 kV	±525 kV	±500 kV
Line length	260 km	190 km (underground)	765 km	1,350 km
Commissioning year	2011	2022	2023	2025
HVDC vendors	Siemens Energy	GE Vernova	Siemens Energy	Hitachi Energy
Objective	Enhances energy security and market integration	Connects France and Italy via underground cables through a tunnel	Longest land and subsea HVDC interconnector in the world, enhancing energy trade	First multiterminal HVDC project to facilitate electricity trade between the Middle East and North Africa

3.3 City Centre Infeed: Optimising Urban Power Infrastructure

Globally, power demand is increasing in heavily populated areas such as cities. This is driving the upgrade and expansion of power networks within city limits. However, securing right of way for new infrastructure in congested urban areas is challenging due to land scarcity, as well as stringent environmental regulations and frequent community opposition.

HVDC systems, particularly those based on VSC technology with its compact equipment, offer effective solutions to meet the rising power demand in urban areas. In space-constrained urban areas, DC cables can be easily installed underground using existing rights of way. Careful planning can minimise disruption during installation. Implementing noise reduction measures further minimises environmental impacts.

Mumbai in India is one of the world's most densely populated cities, with a population of over 20 million, and has been experiencing a rapid increase in electricity consumption. Adani Energy is investing in a 1,000 MW capacity city centre infeed project, which will increase the power coming into Mumbai by almost 50 per cent. The compactness of the HVDC system and its controllability, combined with underground DC cables, were the key factors when planning this project.

Figure 8: Urban HVDC Project Showcase

	Trans Bay Cable Project, USA	New York City Hudson Transmission Project, USA	Mumbai Green HVDC Link, India
Developer	Trans Bay Cable LLC, owned by NextEra Energy	PowerBridge	Adani Energy
Capacity	400 MW	660 MW	1 GW
Voltage	±200 kV, VSC	Back-to-back AC-DC-AC converter	±320 kV, VSC
Line length	85 km of underwater and underground cables	12 km	80 km overhead and underground link
Commissioning year	2010 2018 (upgrade of the control system)	2013	2025
HVDC vendors	Siemens Energy	Siemens Energy	Hitachi Energy
Objective	Delivers additional power to San Francisco, helping to reduce congestion	Back-to-back converter station in New Jersey, to deliver power to customers in New York City	Based on VSC-MMC technology, will greatly enhance electricity supply to the metropolitan city of Mumbai

3.4 Interconnecting Large-Scale Offshore Renewable Energy: A New Leap Forward

While HVDC transmission plays an important role in connecting renewables such as large-scale hydropower, onshore wind plants and utility-scale solar plants to the grid, it will also be essential for connecting offshore wind energy.

Offshore wind energy has proven to be a promising resource to accelerate the global energy transition and achieve carbon neutrality by 2050. According to the Global Wind Energy Council (GWEC)[8], to meet a 1.5°C global warming trajectory, the world will need at least 380 GW of offshore wind by 2030 and 2,000 GW by 2050. To realise these ambitious goals, it is imperative to develop the necessary infrastructure for the effective integration of offshore wind resources. Early offshore wind projects were nearshore and primarily used AC systems to transfer electricity to onshore grids. As projects grew to GW scale and moved into deeper, more challenging marine environments, the viability of HVDC technology for interconnecting offshore wind farms came to the fore.

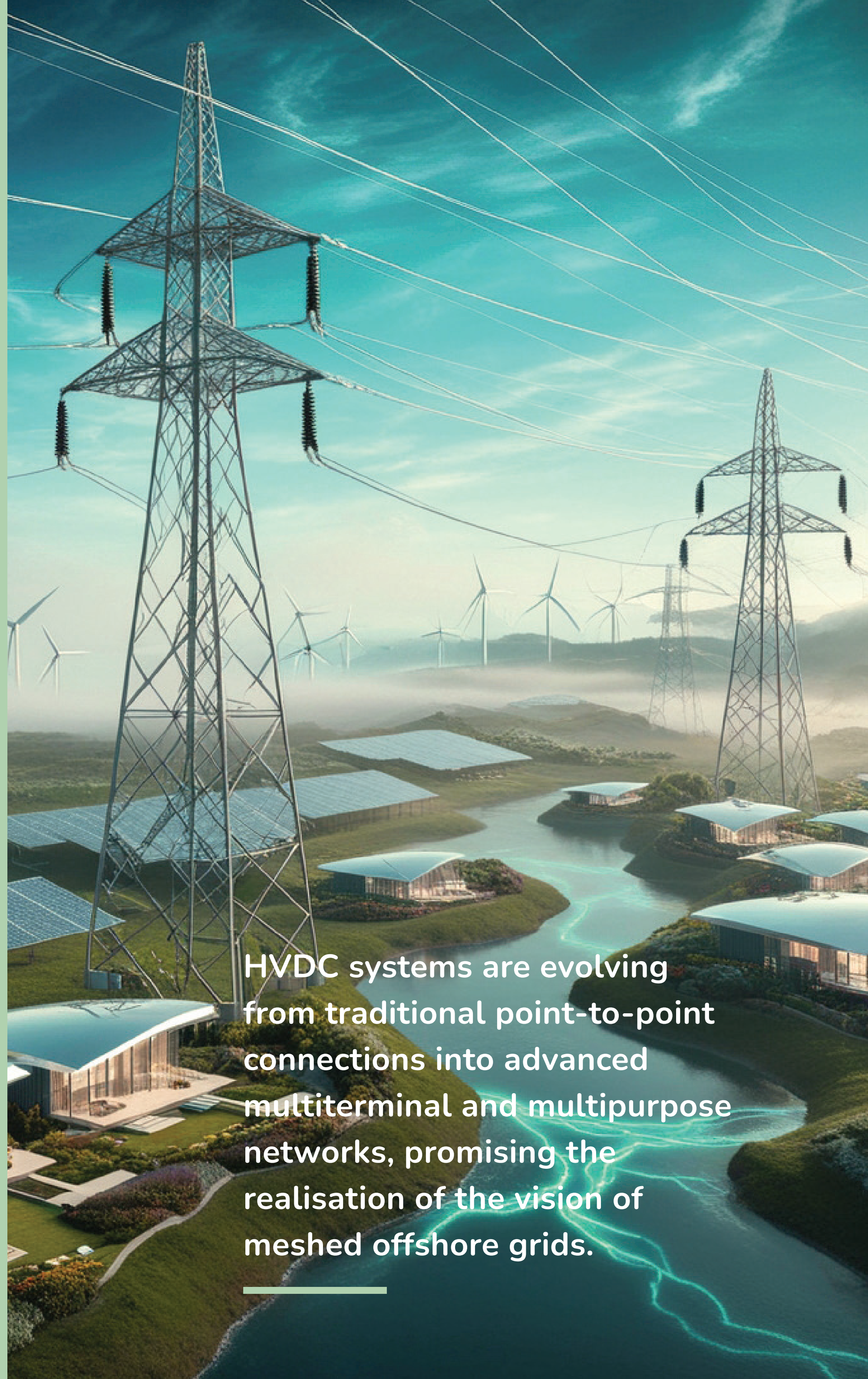
In 2012, Germany's BorWin 1 became the world's first offshore wind farm to use HVDC technology with a ±150 kV connection, demonstrating its technical feasibility for offshore grid infrastructure and setting a precedent for future projects. This success sparked a wave of HVDC projects across Europe. Germany soon implemented several offshore connections using ±320 kV HVDC, and the UK followed with the Dogger Bank A project in 2023, its first use of ±320 kV HVDC technology.

Meanwhile, TenneT's latest 2 GW programme, featuring ±525 kV HVDC technology in collaboration with several vendors, is establishing a new benchmark for offshore wind transmission systems.

Figure 9: Offshore Wind Integration Application Showcase

	BorWin 2, Germany	DolWin 3, Germany	Dogger Bank A, B, C, UK
Developer	TenneT	TenneT	JV of SSE Renewables, Equinor, Vårgrønn
Capacity	800 MW	900 MW	3.6 GW
Voltage	±300 kV, VSC	±300 kV, VSC	±320 kV, VSC-MMC; three offshore and three onshore converter stations
Line length	200 km submarine and land cables (including 75 km onshore)	83 km of submarine cable and 79 km of underground cables	680 km of submarine and underground cables (205 km for Phases A and B, 270 km for Phase C)
Commissioning year	2015	2018	2023, 2024 and 2026
HVDC vendors	Siemens Energy	GE Vernova	Hitachi Energy-Aibel consortium

4 REVOLUTIONISING FUTURE GRIDS



HVDC systems are evolving from traditional point-to-point connections into advanced multiterminal and multipurpose networks, promising the realisation of the vision of meshed offshore grids.

While onshore transmission grids are usually designed and developed as meshed networks, offering multiple pathways for power flow, offshore grid infrastructure has been, until recently, developed as point-to-point links radiating out from the onshore AC grid.

With global offshore wind capacity projected to increase from about 75 GW at the end of 2023 to over 2,000 GW by 2050, significant grid development is anticipated. China alone aims to install 1,500 GW by 2050. The EU member states along with Norway and the UK target 496 GW in operation by 2050. Japan is aiming for over 100 GW by 2050. The US envisions a pathway to deploying 110 GW or more by the same year. With this comes the need to evolve transmission approaches to bring power from offshore projects to our homes, businesses and industries.

This transformation is advancing HVDC systems from basic point-to-point connections to sophisticated multiterminal and multipurpose networks and further towards meshed offshore grids, ushering in a new era of electricity transmission.

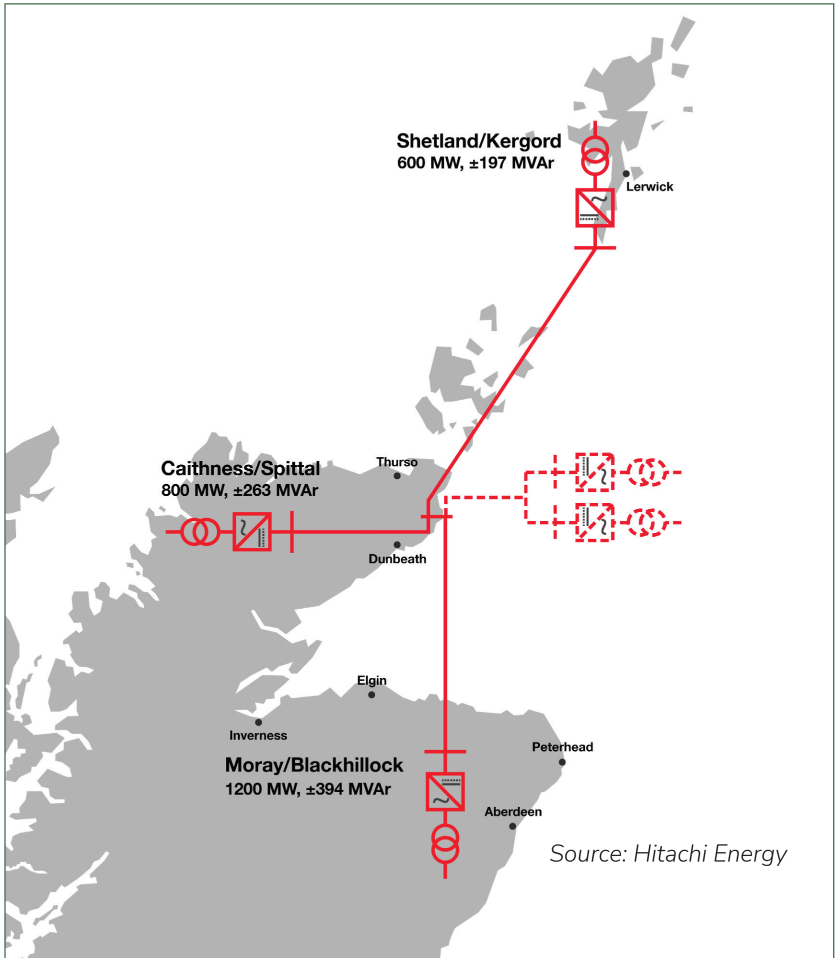
4.1 Multiterminal HVDC Systems

Whereas with a point-to-point connection there are two separate converter stations connected together by a single HVDC transmission line, multiterminal HVDC systems use multiple transmission lines to connect multiple converter stations (or terminals).

The early multiterminal projects were based on LCC systems such as the ±450 kV, 2 GW Québec to New England interconnection, commissioned in 1992. Another example is the SACOI (Sardinia-Corsica-Italy) interconnection, built in 1967 with two mercury-arc valve-based converters and later expanded to include an LCC-based converter station. Further advancements allowed for the development of much higher capacity and voltage LCC-based multiterminal systems. An example of this is India's Northeast-Agra link, which stands as the world's first ±800 kV UHVDC multiterminal system.

The UK's 600 MW, 260 km, ±320 kV Caithness-Moray-Shetland link,

Figure 10: Caithness-Moray-Shetland Project Layout



Source: Hitachi Energy

commissioned in August 2024[9], is Europe's first VSC-based multiterminal project. Developed by SSEN Transmission, a new link to Shetland connects to the existing ±320 kV Caithness-Moray line, creating a three-terminal HVDC system. The HVDC link has been designed as a five-terminal system, with further extension possible.

The Saudi Electricity Company and the Egyptian Electricity Transmission Company are building the first ever large-scale HVDC interconnection between the Middle East and North Africa, enabling the exchange of up to 3,000 MW of electricity at ±500 kV – much of which is expected to be generated from renewable energy sources in the future. The 1,350 km HVDC interconnection will use overhead power lines and a subsea cable across the Red Sea. Power will be able to flow in multiple directions among the three terminals – for instance, from Tabuk to Badr, but also simultaneously from Tabuk to Medina.

In Germany, TenneT and 50Hertz are building the country's first ±525 kV HVDC multiterminal hub in the Heide region. The NordOstLink (NOL) project aims to transmit 4-12 GW of wind energy from the coast to Mecklenburg-Western Pomerania, and via the planned SuedOstLink+ to the urban and industrial areas in the south by 2032. The US is also exploring a multiterminal HVDC proposal to integrate planned offshore wind farms in the Atlantic. With targets to develop 30 GW of offshore wind by 2030 and 110 GW by 2050, the US Department of Energy's Atlantic Offshore Wind Transmission Study (AOSWTS)[10], released in March 2024, indicates that multiterminal HVDC technology will be necessary for interregional and backbone topologies on offshore platforms by 2035.

To date, multiterminal projects have been primarily built on land and the system operator could manage the system impact of a sudden loss of the complete multiterminal system. As power transfer limits increase side by side with the number of terminals, there is an increasing need for an HVDC circuit breaker that could isolate faults in particular areas of the system, allowing other sections to continue transmitting power.

4.2 Offshore Hybrid Assets/Multipurpose Interconnectors

Pushing ambition further and building upon multiterminal architecture would entail the development of offshore hybrid assets (OHA), also known as multipurpose interconnectors (MPI). The European Commission's offshore renewable energy strategy defines an OHA as a system that

Kriegers Flak Combined Grid Solution

An early version of a hybrid interconnector is the Kriegers Flak Combined Grid Solution (CGS), notable for several pioneering features. This project deploys a back-to-back HVDC station at Bentwisch in Germany, enabling the connection of the asynchronous AC power grids of eastern Denmark (150 kV) and Germany (220 kV), a first of its kind in Europe. It is also the first project in the world that links offshore windfarms (600 MW Kriegers Flak in Danish waters and Baltic I and II with 336 MW in German waters in the North Sea) to two national transmission grids.

Europe's Key Planned OHAs/MPIs

Denmark has planned an energy island in both its sea basins – the North Sea and the Baltic Sea – each designed to host 3 GW of offshore wind capacity. The Bornholm Energy Island (BEI) project in the Baltic Sea is progressing rapidly and is due to be completed by 2030, with Denmark's TSO, Energinet, collaborating closely with Germany's TSO, 50 Hertz.

Belgium is moving fast on its 3.5 GW Princess Elisabeth Island (PEI) project. The Danish government plans to connect its North Sea Energy Island (NSEI) to PEI via the Triton Link. This would be the world's first subsea connection between two artificial energy islands, spanning over 600 km.

The UK has proposed connecting to the PEI via the 1.4 GW Nautilus Link and to the Netherlands via the LionLink.

Estonia has signed a letter of intent with **Germany** to develop a 750 km hybrid interconnector, the Baltic WindConnector. This 2 GW project will link Estonia's mainland coast to the Mecklenburg-Western Pomerania coast, transporting electricity from offshore wind parks in the Estonian Baltic Sea.

integrates offshore energy generation with interconnection. An OHA would link clusters of offshore wind farms to interconnectors between two or more countries, optimising future offshore grid infrastructure development and offering greater demand and supply flexibility.

Given their efficiency, hybrid projects are anticipated to serve as a precursor to the envisioned European offshore meshed grid (explained later in this chapter). The European Commission's offshore renewable strategy acknowledges that "hybrid projects will constitute an intermediate step between smaller-scale national projects and a fully meshed, offshore energy grid".

Europe is preparing to develop multiple OHAs. Its first Offshore Network Development Plan (ONDP), published in January 2024 by the European Network of Transmission System Operators for Electricity (ENTSO-E)[11], envisages the development of 25 GW of offshore hybrid transmission infrastructure in European sea basins by 2040. The North Sea is expected to host most of the offshore hybrid infrastructure.

4.3 Overlay Grids and Meshed Grids

As the energy network becomes more digitalised and incorporates substantial variable renewable energy sources, continuously expanding the existing AC systems may not be the most cost-effective strategy for achieving energy transition goals.

DC overlay systems can be designed as radial multiterminal systems or as meshed systems. A radial multiterminal system is a system that connects N terminals (or converter stations) with one power-flow path between two terminals of the DC grid. Alternatively, similar to an AC meshed grid, a DC meshed grid functions like a web, where multiple nodes are interconnected and provide multiple power-flow paths between terminals, thereby enhancing redundancy and flexibility.

The evolution of energy systems is set to take a significant leap forward with the development of DC meshed grids. In parallel, however, extensive research is focused on overcoming the technical challenges of integrating DC overlay grids into AC grids to leverage the advantages of both technologies.

China is probably the most advanced power market when it comes to expanding its grids using meshed DC configurations. The first step has already been taken with the completion of the ±500 kV Zhangbei project in 2020, which is considered the first truly meshed HVDC grid in the world.

Europe is also moving quickly. The EU-funded PROMOTioN[12] (Progress on Meshed HVDC Offshore Transmission Networks) project, completed in 2020, focused on advancing HVDC technology for designing, building, operating and protecting meshed grids. Alongside its technological research, the project proposed regulatory and financial frameworks necessary for the planning, construction and operation of meshed grids. Since then, several of its recommendations are being actively pursued across the policy, regulatory and industry levels.

While the techno-economic challenges of integrating DC meshed grids into AC grids are still being addressed, the vision of HVDC overlay grids is now emerging, with a number of conceptual plans already available.

TenneT has drafted the blueprint for its Target Grid 2045[13], outlining a plan for an integrated onshore and offshore HVDC grid infrastructure with energy hubs and significant upgrades to the existing AC grid. Italian grid operator Terna has unveiled its vision for the future national grid, known as the HyperGrid[14], comprising five backbones, to enhance the onshore AC grid.

The development of DC overlay grids may one day also allow various electricity networks to be interconnected on an intercontinental or even transcontinental scale. Although some of these proposals might seem futuristic today, they clearly demonstrate that HVDC technology will be the cornerstone of future power grids, efficiently connecting diverse power systems and enabling a more integrated energy network.

4.4 Key Enablers to Accelerate the Evolution Towards Meshed Grids

Transitioning from point-to-point connections to meshed offshore grids, involving multiple terminals, vendors, wind farm clusters and markets, will be complex. Some key enablers across the pillars of technology, policy and regulation, business models and frameworks can drive this evolution forward.

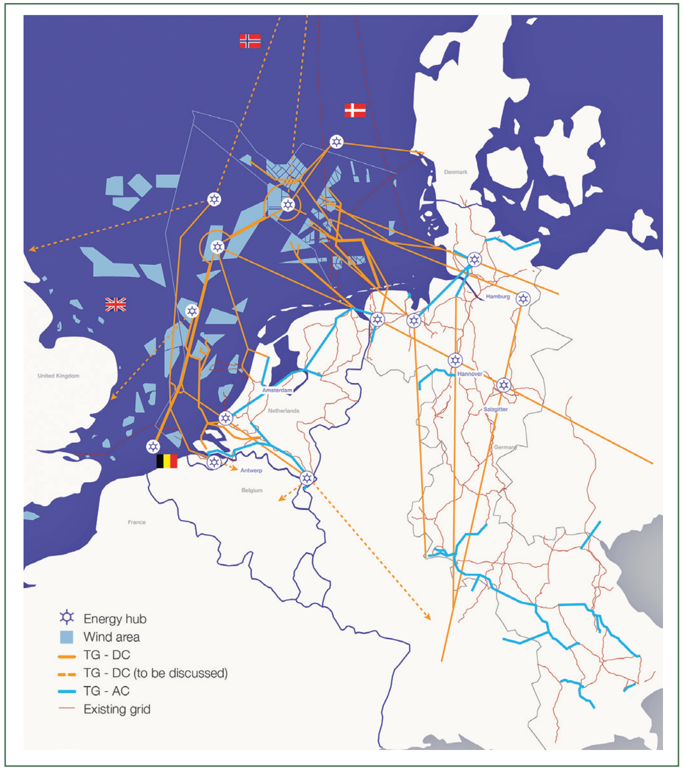
4.4.1 Technology

High Voltage DC Circuit Breakers – Guardians of Interconnected DC Grids

For large-scale multiterminal and meshed grids to become commercially viable, high voltage DC circuit breakers (DCCBs) are essential. In current

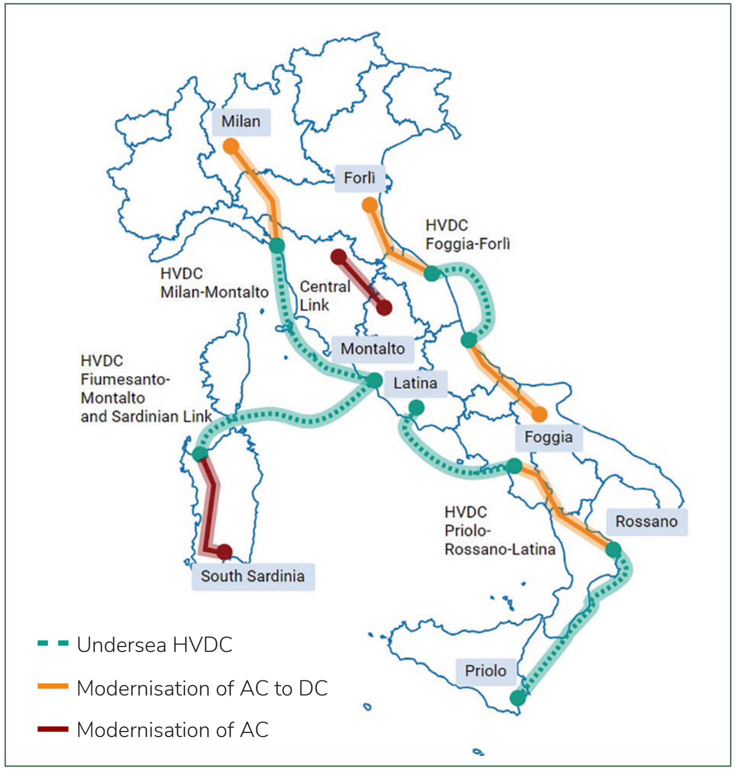
Figure 11: Showcase of Visionary Projects

TenneT's Target Grid



Source: www.tennet.eu/target-grid

Terna's Hypergrid



Source: Terna's 2023 Development Plan

point-to-point HVDC projects, DC faults are managed by opening circuit breakers on the interfacing AC side. This approach is inadequate for interconnected multiterminal HVDC systems. The stakes are high here. If a fault is not promptly cleared, it can result in system instability, potentially causing widespread blackouts and disruption.

Large-scale multiterminal systems and meshed grids will require high voltage DCCBs capable of rapidly interrupting current and isolating faults on the DC side. Unlike conventional AC circuit breakers, DCCBs must address the unique challenges of the continuous and unidirectional flow of DC. They need to efficiently manage high voltages and currents, ensuring rapid fault clearance, often within a few milliseconds, to maintain system stability and minimise energy loss.

There are three main types of high voltage DCCBs – mechanical, solid state (based on semiconductors) and hybrid (combining features of both). The market introduction of Hitachi Energy's hybrid high voltage DCCB in 2012 marked a major milestone in HVDC history.

In 2022, the IEA assigned a Technology Readiness Level (TRL) of 8 for the HVDC breaker, indicating that the breaker can be considered "First of a Kind Commercial." The Technology Readiness Level (TRL) of 8 can be attributed to the success of several projects: the Zhoushan project in China, where the world's first ±200kV DCCBs for a five-terminal VSC-HVDC system were installed; the 2020 Zhangbei project, which implemented ±500kV DCCBs; and the promising test results from the EU's PROMOTioN project on DCCBs.

Outside of China, only a few projects have been announced to incorporate DCCBs. However, in July 2024, the four German TSOs, 50 Hertz, Amprion, TenneT, and TransnetBW, launched an innovation partnership with Siemens Energy, GE Vernova, and Hitachi Energy. This collaboration aims to establish a common European standard for smart power hubs, transitioning from point-to-point connections to a DC grid, and enabling the efficient transmission of 70 GW of offshore wind capacity from the German North Sea by 2050. The first multiterminal hubs, featuring converter stations and DCCBs, will be built in Northern Germany.

Progress on DCCBs in China and the EU

Despite its slow start, China has made remarkable progress with multiterminal projects incorporating DC circuit breakers (DCCBs).

In 2013, the Nan'ao Flexible DC Grid Project[15] implemented a ±160 kV mechanical DCCB, developed by the Southern Power Grid Research Institute, Huazhong University of Science and Technology, and Siyuan Electric Co., becoming the first to use a mechanical DCCB.

In 2014, the Global Energy Interconnection Research Institute developed a ±200 kV hybrid DCCB with a breaking capacity of 15 kA in 3 ms, which was installed in the Zhoushan Flexible DC Grid Project in 2016, the world's first hybrid DCCB in an HVDC grid.

In 2020, ±500 kV DCCB became operational in the Zhangbei flexible DC grid, setting a world record for the highest voltage level and strongest breaking capacity. Shortly after, China commissioned its first UHVDC multiterminal project, Kunliulong (Wudongde). This ±800 kV, 8 GW project spans 1,452 km, has three converter stations, and is the world's first HVDC project to combine LCC and VSC technologies.

In the EU, full-power demonstrations of DCCBs were conducted under the PROMOTioN project. These included three types of industrial HVDC circuit breakers: Hitachi Energy's hybrid breaker (±350 kV, 20 kA, 3 ms), Mitsubishi Electric's mechanical breaker with active current injection (±200 kV, 20 kA, 7 ms), and SCiBreak's VSC Assisted Resonant Current (VARC) breaker (±80 kV, 12 kA, 2 ms).

Control and Protection Systems

Today's HVDC converter stations in point-to-point links rely on sophisticated control and protection systems, a far cry from the simple electromechanical relays of the past. These systems integrate complex software and hardware to ensure the smooth operation and interaction of HVDC systems with broader AC networks.

However, multiterminal HVDC links are the most efficient means of transporting electricity from large offshore wind farms. An expandable multiterminal HVDC grid with multipurpose interconnectors offers greater flexibility and cost efficiency but also significantly increases the complexity of control and protection systems, which must cover both AC and DC grids. Current R&D is focused on expanding HVDC grids efficiently, tackling the intricate dependency on control and protection technologies.

Adding multiple vendors to a multiterminal setup introduces further challenges, especially in terms of interoperability. A master controller will oversee the entire multivendor, multiterminal grid, coordinating the individual control and protection systems at each converter station. However, variations in vendor-specific software make seamless communication and interoperability difficult to achieve.

Functional requirements for HVDC grid protection, converter fault-ride-through behaviour and DCCBs will be essential for future multiterminal grids. The EU's InterOPERA[16] project has developed a functional framework to ensure the expandability and interoperability of HVDC systems, focusing on control and protection systems. The next critical step is to implement a full-scale HVDC multiterminal, multivendor, multipurpose application by 2030 to mitigate interoperability risks.

4.4.2 Policy and Regulation

Grid Code Updates

Grid codes define the criteria for connections to the grid to ensure its safe and efficient operation. Accommodating higher levels of renewable energy, especially offshore wind in Europe, through interconnected multiterminal and multivendor HVDC systems, creates new system requirements. These needs must be addressed through well-defined grid codes. At present, grid codes for HVDC systems primarily focus on the connection to the AC grid interface, and do not cover the situation where the HVDC system connects to a DC point of connection.

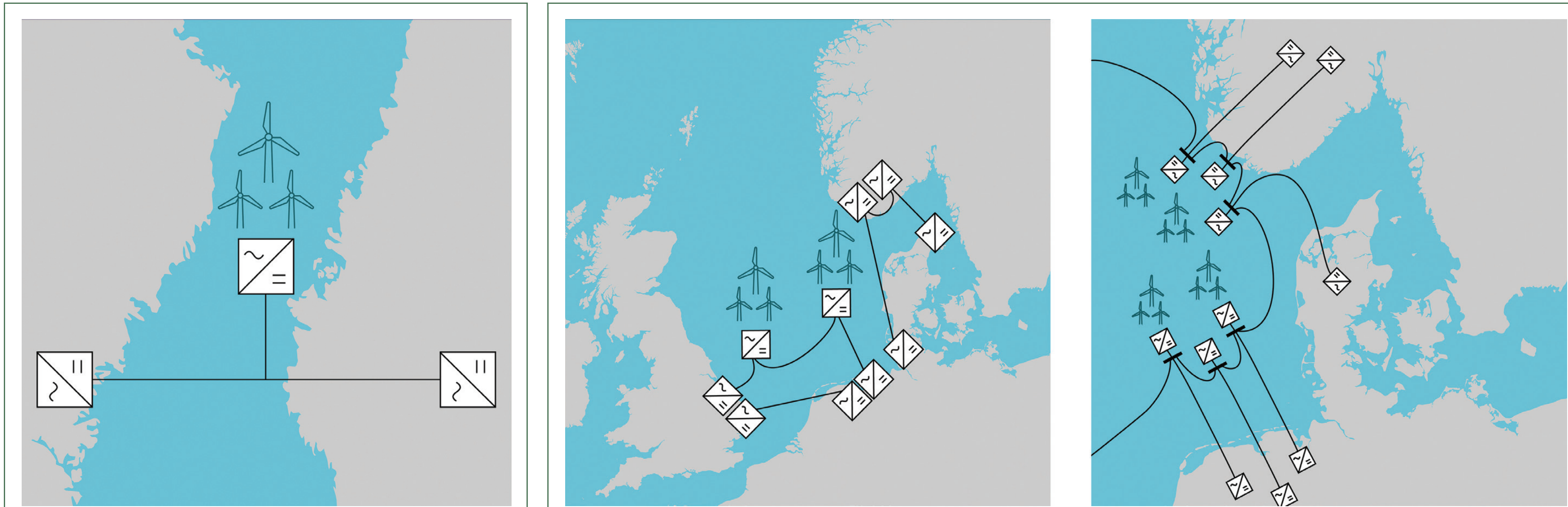
Given the pace of HVDC deployment, many regions are reviewing their approaches. In the EU, the Agency for Cooperation of Energy Regulators (ACER) has initiated a consultation on what is known as the HVDC network code, last revised in 2016, and is expected to present its recommendations to the European Commission before the end of 2024[17]. The UK is also reviewing its grid codes to reflect the changing system requirements driven by HVDC technologies, and particularly multipurpose interconnectors.

4.4.3 Business Models

Multiterminal Links and Offshore Grids

With rapid expansion of offshore wind projects in regions such as Europe over the next 25 years, multiterminal links and offshore grids

Figure 12: Transitioning to Future Multiterminal, Multivendor, Meshed Offshore Grids



Today
Single vendor hybrid multiterminal HVDC link

Tomorrow
Multivendor multiterminal meshed HVDC systems

Source: InterOPERA (interopera.eu/objectives/)

will quickly become a valid option for optimising grid infrastructure. The UK's Electricity System Operator has published two documents – Holistic Design Network for Offshore Wind (HND)[18] and Beyond 2030 – to integrate 50 GW of offshore wind by 2030 and reach 86 GW by 2035. The network designs, which consider factors like cost, deliverability, and environmental impact, are expected to save billions of pounds in costs compared to a point-to-point approach.

Various investment models, including public-private partnerships, merchant investments, and the regulated asset base model, are being explored for developing these grids. Belgium and Denmark are already creating energy islands as hubs to channel electricity from multiple offshore wind farms to different markets. While complex, these strategies will enhance power system flexibility, asset utilisation, and grid infrastructure efficiency.

Multivendor HVDC Projects

Early multiterminal HVDC projects, involving a limited number of terminals, may rely on a single vendor. However, as the industry advances towards integrated multiterminal HVDC systems, standardisation and interoperability among various vendors' equipment will be essential. This approach will help investors avoid technology lock-in and ensure greater flexibility and efficiency in their systems.

The move to multivendor, multiterminal systems will shift a part of the design and execution responsibility to grid owners and operators. Design errors could impact individual converter stations or the entire multiterminal system, including the onshore AC network. Therefore, procurement processes and contracts must adequately allocate liability and warranty risks. A new generation of multistakeholder collaboration between system operators, technology providers and engineering, procurement and construction (EPC) contractors will be essential to ensure the successful design, delivery and operation of offshore grids.

4.4.4 Frameworks

Legal and Governance

For multivendor, multiterminal HVDC grids to work, strong governance and robust legal frameworks will be crucial.

The Ready4DC EU-funded project[19] sets out some key requirements for the governance of multiterminal, multivendor HVDC grids. Firstly, there must be a clear division of roles and responsibilities. Specifically, roles and responsibilities around offshore grid ownership may need to be flexible initially to accommodate various solutions. These roles and responsibilities may evolve over time, particularly after the first few pilot projects.

Next, it is worth noting that the current legislation has been designed for AC grids. Amendments to existing directives and regulations will be needed, as well as new legislation to cover aspects such as financial regulation of TSOs (given the risks associated with offshore grids) and technical coordination between AC and DC grids. In addition, the legal framework must address the specific needs of offshore multiterminal grid development based on HVDC technology, differentiating it from traditional grid investments. It should cover standardisation, protection of intellectual property (IP), and risk and liability management.

One of the main challenges in multivendor projects is standardisation, which directly impacts the IP strategies of vendors. Laws to adequately protect IP while enabling interoperability within the multivendor grids are critical. Clear guidelines for standardisation processes are necessary to balance innovation protection and collaborative development. Cooperation must be aligned with competition law.

Finally, cooperation agreements among all stakeholders will be vital in setting targets, approaches and principles for collaboration.

The transition to meshed offshore grids is not just a technological challenge; it also requires coordinated efforts across policy, regulation, business models and legal frameworks. Together, these elements will be fundamental to securing investment and enabling a stable environment for the deployment of HVDC technology.

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