WG4-Framing the European energy system

ABOUT READY4DC

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

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Framing the European energy system

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EXECUTIVE SUMMARY

High-Voltage Direct Current (HVDC) is a technology used worldwide for transmission of large amounts of electrical power. To reach the European goals for integration of renewable energy sources integration and phase-out of thermal power plants, the number of HVDC projects is required to grow quickly, and since today's HVDC projects are solely point-to-point connections, meshed DC grids have to become a reality. This whitepaper discusses the long-term role of HVDC and meshed DC structures, especially Multi-Terminal, Multi-Vendor (MTMV) HVDC grids, in the transforming European energy system.

The EU member states have committed to transforming the EU into a climate-neutral entity by 2050 and reducing carbon emissions by at least 55% by 2030 compared to 1990. A massive expansion of Renewable Energy Sources (RES) generation capacity is required, in which offshore wind power is expected to make up a significant share, especially in the North Sea countries. HVDC cable transmission is expected to be the main technology used to bring offshore wind power to European lands. Having access to an estimated potential of 380 GW of generation capacity in the northern European waters, the North Sea countries recently agreed on offshore wind targets of at least 120 GW by 2030 and 300 GW by 2050 in the Ostend Declaration. These targets require a 10-fold increase in installed capacity from today to 2050 and dictate the magnitude of offshore wind & HVDC development. The targets also show a rising trend in recent years, possibly ramping up further.

Besides offshore wind power evacuation, HVDC has several purposes onshore and offshore. Many recently commissioned offshore HVDC projects are cross-country interconnections enabling energy trading. Interconnection projects include, for example, country-to-country connection onshore to onshore or hybrid projects that combine evacuation of offshore wind power with interconnection. Onshore HVDC is used for long-distance transmission with overhead lines or underground cables. Further, like offshore, one purpose of onshore HVDC transmission is to facilitate cross-country interconnection to cope with European power system needs as identified in the Ten-Year Network Development Plan (TYNDP) of ENTSO-E. In this context, the identified needs are grid reinforcement requirements to reach RES targets, keep security under control, and reduce the overall cost of electricity. Another use case of both offshore and onshore HVDC is replacing, to some degree, grid-stabilising functionalities of existing AC assets, such as the inertia provided by synchronous generators. With all use cases combined and keeping the current HVDC growth rates, a projection of future HVDC deployment would lead to a possible total HVDC-based transmission capacity close to 1 TW by 2050.

Generally, a stronger European transmission grid is necessary to integrate massive renewables-based power generation, balance the variable energy output of RES, and cope with the expected increase in electrical power consumption. The question emerges if there is a need for an HVDC "supergrid" spanning multiple European countries and serving as transmission infrastructure in coexistence with the pan-European AC transmission grid. In several visions for the future European grid, the role of HVDC in power transmission varies. While earlier visions came with a flavour of a top-down planning and building approach for a possible European HVDC supergrid, today, we see the first multi-terminal HVDC systems appearing that may be extended piece-by-piece. An incremental approach also seems to be the realistic way to integrate multi-terminal HVDC projects into the European grid and to realise meshed MTMV HVDC grids, rather than top-down planning of a large-scale HVDC grid, e.g., covering the North Sea area.

The challenges for the HVDC sector include scarcity of specialized HVDC engineers, fast growth rate vs supply chain, or even scheduling HVDC commissioning with many HVDC links expected to be put into operation almost simultaneously. Also, incorporating HVDC projects into the AC grid likely leads to power flow constraints limiting the usable capacity of HVDC links. Therefore, significant AC transmission grid reinforcements will be necessary to distribute the power transmitted by HVDC projects.

Despite these challenges, HVDC projects are needed with regard to the UN sustainable development goals (SDGs). Since DC transmission is more efficient than AC, HVDC improves energy efficiency and potentially lowers the cost of electricity (SDG 7). In SDG9, HVDC contributes to developing reliable, sustainable, and resilient infrastructure, including transborder infrastructure. Meshed HVDC grids are particularly relevant since they require fewer converter stations than equivalent infrastructure using several point-to-point links, potentially saving cost and raw materials.

Finally, beyond HVDC, other emerging DC technologies and concepts can also contribute to the energy transition, for example, High-Power Direct Current (HPDC) technology or Medium-Voltage Direct Current (MVDC). Here, it must be acknowledged that each voltage level and DC technology comes with specific technical aspects.

1. ROLE OF HVDC ONSHORE AND OFFSHORE

1.1 Ambition of the North Sea Countries

EU Ambitions

The European goals for the integration of renewable energy sources (RES) and electrical grid development emerge from the European Green Deal (2019) and the Fit for 55 legislation package (2020) presented by the European Commission (EC). In the course of these initiatives, all 27 EU Member States have committed to transforming the EU into a climate-neutral entity by 2050, and reducing carbon emissions by at least 55% by 2030, compared to 1990 levels [1]. One month after Russia's February 2022 invasion of Ukraine, the European Council agreed to end Europe's dependency on Russian fossil fuels in the form of coal, oil, and gas imports as soon as possible. Subsequently, the European Commission published a set of additional measures known as REPowerEU, with the overall intention of the EU becoming independent by saving energy, accelerating the deployment of renewables, and diversifying the EU's energy supply.

Further, in March 2023, the European Parliament and Council committed to increasing the share of renewables in the EU's final energy consumption to 42.5% by 2030 [2]. A massive expansion of RES generation capacity is required to reach the set targets, and High-Voltage Direct Current (HVDC)-transmitted offshore wind power is expected to make up a major share, especially in the North Sea countries. In 2020, the EC published a strategy to harness the potential of offshore renewable energy, which includes an EU-wide objective of 300 GW of offshore wind installed capacity by 2050, considering this target "realistic and achievable" [3] and a target of at least 60 GW by 2030 [4].

In January 2023, EU countries agreed on new, long-term targets for deployment of offshore renewables out to 2050 for each of Europe's sea basins, with intermediate objectives for 2030 and 2050. The resulting cumulative EU offshore goals have the following ranges: 109-112 GW by 2030, 215-248 GW by 2040, and 281-354 GW by 2050. At the end of 2022, 16 GW of offshore capacity was operating in the EU. By 24 January 2024, in accordance with the TEN-E regulation, ENTSO-E must develop and publish a Strategic Integrated Offshore Network Development Plan for Europe's sea basins to support these offshore wind capacities and ensure integration with the onshore grid. This will be part of the wider Ten-Year Network Development Plan (TYNDP) framework.

TABLE 1
'Best estimate' prognosis for RES generation capacity in Europe by ENTSO-E and ENTSO-G [5].

Type of Generation (RES)	Estimated capacity		
	2030	**2040**	**2050**
Solar	671,585 MW	1,091,031 MW	1,398,656 MW
Onshore Wind	391,462 MW	552,512 MW	618,841 MW
Offshore Wind	155,620 MW	370,084 MW	480,358 MW
Total	1,219 GW	2,014 GW	2,498 GW

Including non-EU nations such as Norway and the UK, ENTSO-E and ENTSO-G have indicated 480 GW of offshore wind capacity in 2050 as a best estimate [5]. The ENTSOs have published 'high', 'low', and 'best estimates' for all renewables, including solar and onshore wind. TABLE 1 shows the ENTSO's 'best estimates' out to 2050.

Status Quo

As of July 2023, approximately 30 HVDC Voltage-Sourced Converter (VSC) systems are operational in Europe [6]. By the end of 2022, a total of 30 GW of offshore wind power capacity had been installed in Europe (16 GW in EU-27, 14 GW in the UK), covering 3 per cent of the electricity demand in that year [7], see FIGURE 1. While today much offshore wind energy is brought to shore with AC connections, recently (with larger capacity and longer distances), offshore wind farms are more and more connected using HVDC technology. For this reason, the offshore wind (plans) can be used as an indicator for the build-out of HVDC technology. However, HVDC is not exclusively used for bringing offshore wind to shore but also serves as technology for interconnectors between countries.

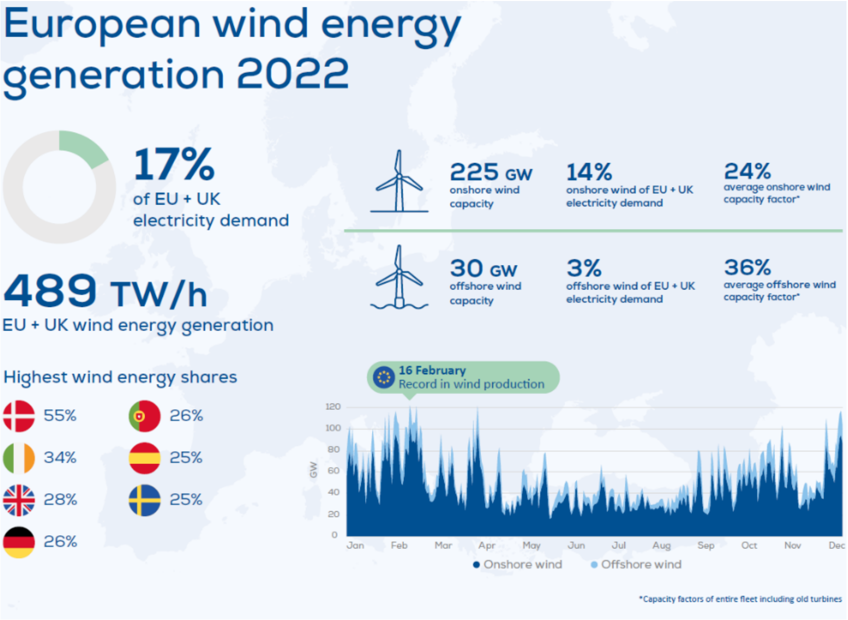


FIGURE 1
Summary of European Wind generation 2022 [7].

Unified goals of the North Sea countries

In April 2023, several European countries in proximity to the North Sea (Germany, Belgium, Denmark, Netherlands, France, Luxembourg, Norway, UK, and Ireland) signed the Ostend Declaration on the North Seas as Europe's green power plant, committing to combined targets for offshore wind installed capacity in the North Seas of at least 120 GW by 2030 and of at least 300 GW by 2050 [8]. These targets pose a significant extension to the Esbjerg Cooperation from May 2022 between Germany, Belgium, Denmark, and the Netherlands, which defined offshore wind capacity targets of 65 GW by 2030 and 150 GW by 2050 for the four countries combined (see FIGURE 2) [9].

Additionally, Norway's 2023 target is developing 30 GW of offshore wind capacity by 2040 [10]. The goals defined in the Ostend Declaration surpass the 2020 ambitions of the EC, showing a rising trend in offshore wind targets within recent years. Ramp-up is also evident in the UK's recent target for 2030 of up to 50 GW offshore wind capacity, compared to its 2020 target of 40 GW by 2030 [11]. Further, the goals define the magnitude of offshore wind & HVDC development, with a 10-fold increase in installed capacity targeted from today to 2050.

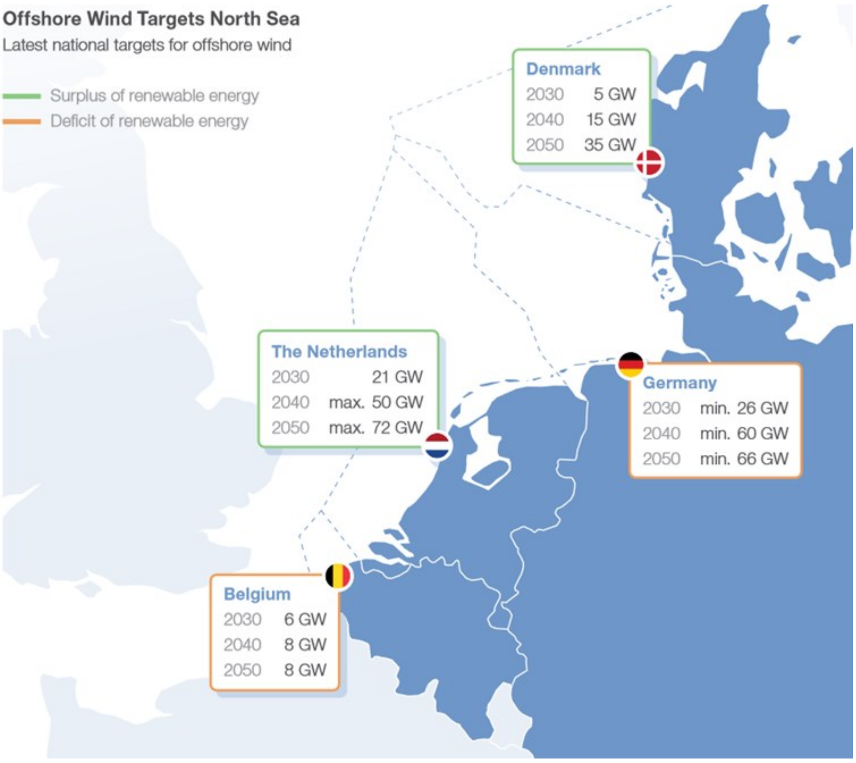
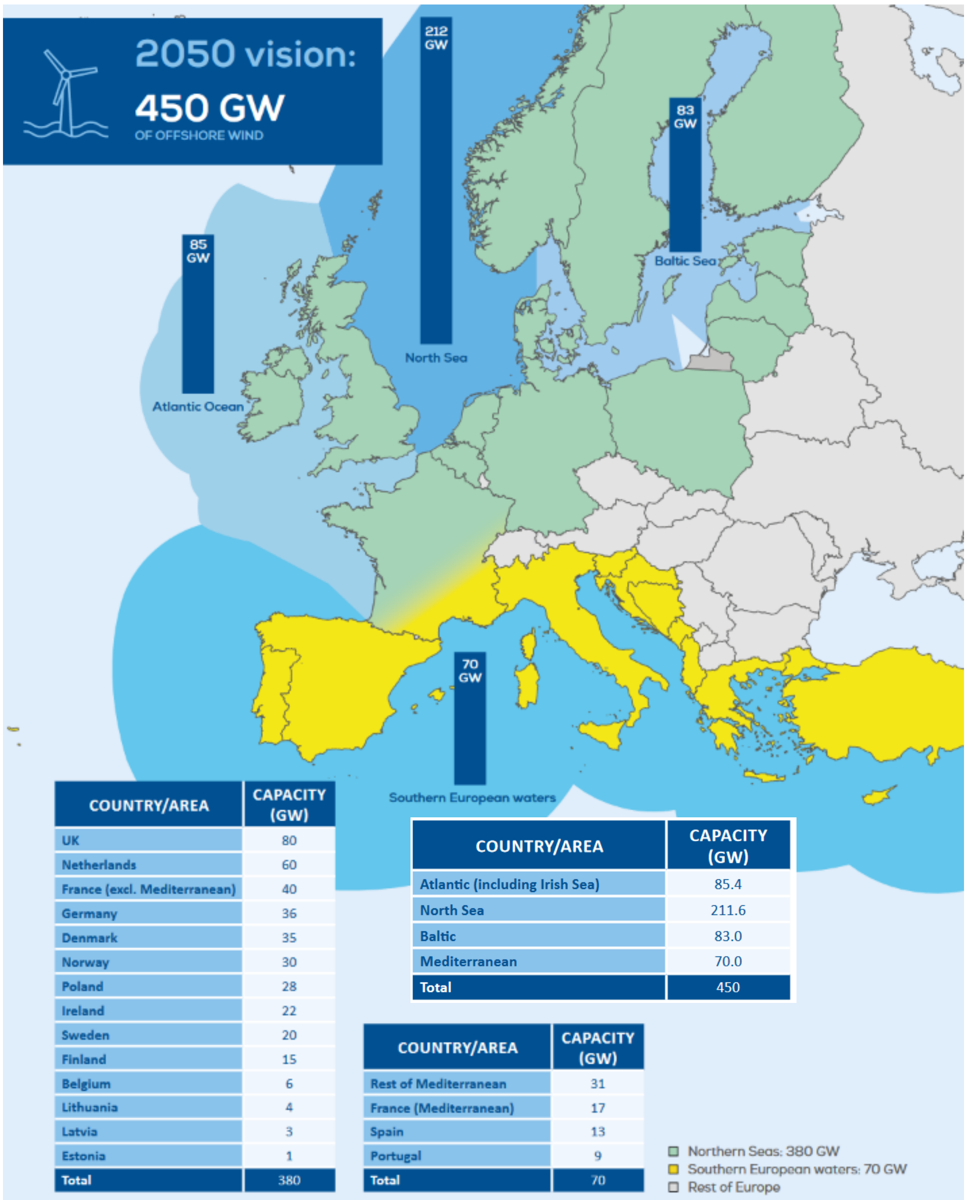


FIGURE 2
Esbjerg cooperation targets [9].

European Offshore Wind Potential

The offshore wind targets could, in theory, ramp up further up to the limit of European offshore wind potential. A 2019 report of WindEurope envisions a joint European offshore wind capacity of 450 GW by 2050, which would meet 30% of Europe's electricity demand in 2050 when assuming a 50% increase in demand compared to 2015 due to electrification. In this scenario, 380 GW of capacity are expected to be developed in the North Seas (the Atlantic off France, Ireland and the UK, the North Sea, Irish Sea, and Baltic Sea) based on wind resource availability and proximity to demand. The remaining 70 GW are expected to be located in the Southern European waters, as shown in FIGURE 3 [12].

In WindEurope's report, HVDC links are assumed to make up a large proportion of the grid, both offshore and in onshore interconnections. While HVDC transmission is expected to be the main technology for transporting offshore wind energy to European lands, this application is just one use-case among others, e.g., interconnectors.



COUNTRY/AREA	CAPACITY (GW)
UK	80
Netherlands	60
France (excl. Mediterranean)	40
Germany	36
Denmark	35
Norway	30
Poland	28
Ireland	22
Sweden	20
Finland	15
Belgium	6
Lithuania	4
Latvia	3
Estonia	1
Total	380

COUNTRY/AREA	CAPACITY (GW)
Atlantic (including Irish Sea)	85.4
North Sea	211.6
Baltic	83.0
Mediterranean	70.0
Total	450

COUNTRY/AREA	CAPACITY (GW)
Rest of Mediterranean	31
France (Mediterranean)	17
Spain	13
Portugal	9
Total	70

FIGURE 3
Overview of European offshore wind potential by marine area [12].

1.2 Comparison of HVDC offshore and onshore

Offshore role of HVDC

In addition to offshore wind power evacuation, one main purpose of recently commissioned offshore HVDC projects, such as the North Sea Link between the UK and Norway, is cross-country interconnection to enable energy trading. Such interconnection projects include:

- Country-to-country connections (onshore to onshore)
- Offshore hub to onshore in multiple countries
- Hybrid projects for evacuation of power generated offshore and interconnection
- Offshore hub to offshore hub connections
- Offshore to onshore inland location direct

Further, there are bootstrap links, i.e., offshore links for (inland) power transport north to south or east to west, with the purpose of avoiding the building of land links. Offshore HVDC projects that provide transmission capacity otherwise required to be built onshore will be increasingly needed in the future. Specifically, in the TYNDP 2022 of ENTSO-E, it is stated that wide-meshed offshore grids will be required to accommodate the future high volumes of transit power flows [13].

Offshore and onshore HVDC projects can be closely related, e.g., land links may join hubs close to or at landing points to inland consumption points either directly or via onshore hubs.

Onshore role of HVDC

HVDC connections fulfil the needs for long-distance transport to inland sights, both with overhead lines and underground cables. Some examples are the German power corridors A-Nord, Südlink and Südost-Link, which will be built as HVDC cable connection, and the Ultranet power corridor for which existing pylon systems will be used to realise its HVDC overhead lines [14].

Similar to offshore, a main purpose of onshore HVDC transmission is to facilitate cross-country interconnection to cope with European Power system needs. In the TYNDP 2022, system needs are defined as areas in which grid reinforcements are necessary to reach decarbonisation targets, keep security under control and reduce the overall cost of electricity [15].

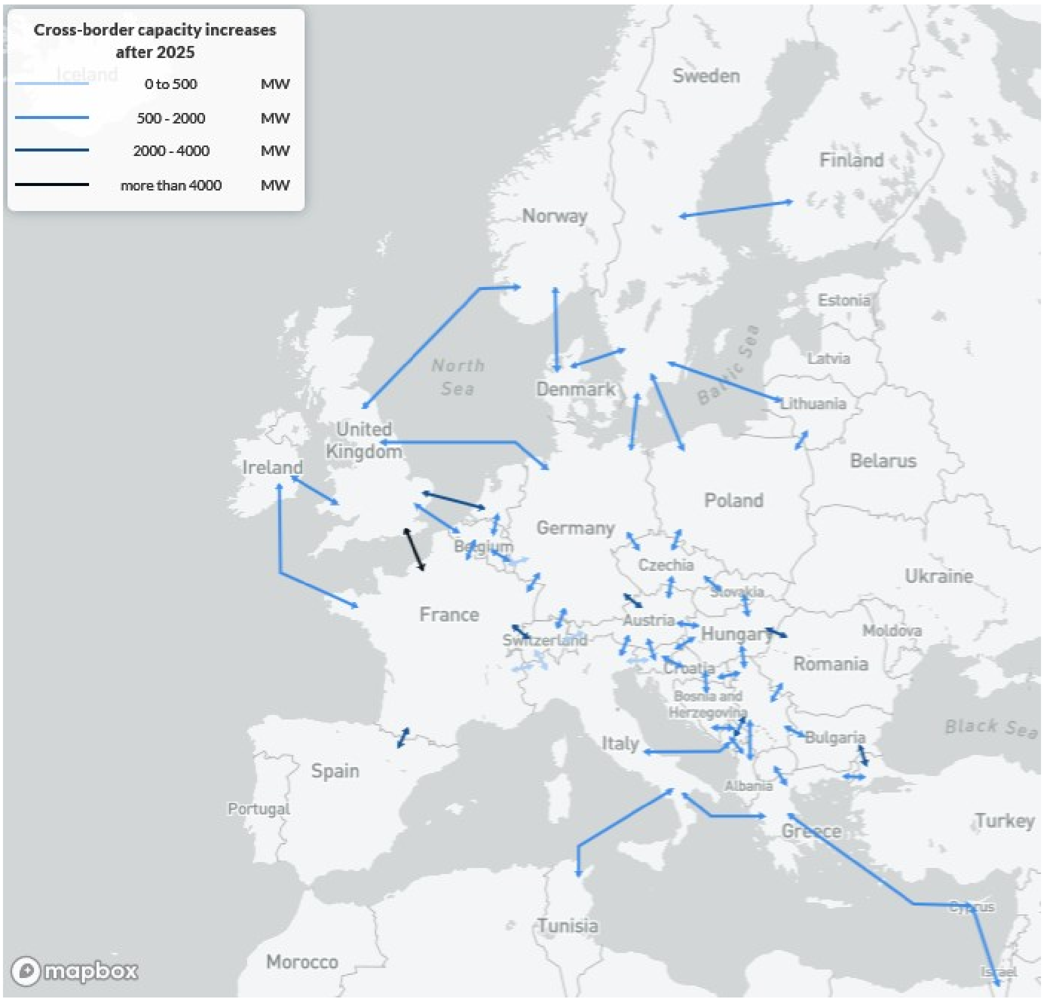


FIGURE 4
Cross-border system needs after 2025, as identified in the TYNDP 2022 [16].

More specifically, identified system needs are potential cross-border interconnection capacities which minimise total power system costs, composed of generation cost and cost of interconnection infrastructure, including costs of necessary internal grid reinforcements associated with the interconnection projects - while taking into account the uptake of renewable energy sources and system flexibilities predicted by national trend scenarios for 2030 and 2040.

According to the current TYNDP System Needs Study, a more efficient use of the European generation mix would translate into a significant reduction in carbon emissions and also a reduction of generation costs by 9 billion € per year in 2040, leading to lower cost of electricity for consumers. The European power system currently has 93 GW of cross-border transmission capacity [17]. The identified system needs in Europe are a total of 64 GW cross-border transmission capacity on more than 50 borders in 2030. By 2040, 24 GW of additional cross-border capacity increases were identified on top of the increases identified for 2030 [15]. FIGURE 4 gives an overview of the system needs in Europe, representing interconnection capacities between neighbouring countries onshore as well as cross-border offshore capacities.

Role of HVDC in Power System Stability

The TYNDP scenarios furthermore show that the future power system will have more renewables at all voltage levels, more power electronics both in generation and due to HVDC connections, a more variable mix of generation as well as highly variable power flows with more interconnections between different synchronous areas. These trends lead to technical challenges in several aspects of real-time power system operation, such as frequency and voltage control.

Frequency variations in AC power systems are caused by mismatches between active power generation and demand. The energy stored in the rotating masses of synchronous generating units can instantaneously balance the mismatch by harnessing the units' intrinsic mechanical inertia. This inertial response is essential for stabilising the power system. Presently, an immediate inertial response can only be met by synchronous generators. Since more and more synchronous generators are being replaced by power electronics-based RES generation, new capabilities will be necessary, such as grid-forming converters, which are power electronics devices designed to support the operation of an AC power system. Here, utilising the converters of HVDC links is identified as a practical way to introduce grid-forming capabilities. Thus, another use case of both offshore and onshore HVDC is replacing, to some degree, grid-stabilising functionalities of existing AC assets [13].

Overview of European HVDC Projects

At what scale are HVDC projects expected to contribute to the European transmission grid? The TYNDP 2022 contains transmission projects with over 43,000 km of potential additional cables and lines, of which 25,000 km (58 %) are DC [15]. Moreover, HVDC projects, which are currently in the planning or construction phase, are mainly VSC-based. As stated earlier, with all use cases combined, approximately 30 (VSC-based) HVDC projects are already operational in Europe [6], as shown in FIGURE 5 on the left. If the current growth in HVDC continues, a projection of future deployment based on the past and planned deployment would lead to the trend shown in FIGURE 5 on the right. A projection to 2050 shows a possible total installed capacity in the magnitude of 1 TW, assuming the growth rate remains similar to currently experienced growth rates (up to 2030). After discussing the role of HVDC in general, the following chapter deals with the role of HVDC grids in overall infrastructure.

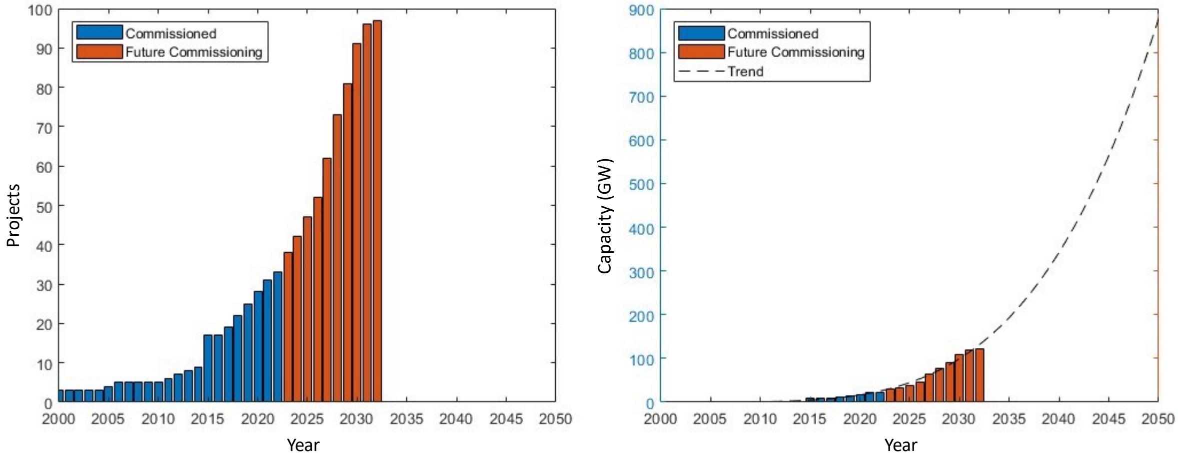


FIGURE 5
Trend of European HVDC-VSC projects. Left: cumulative projects by year; right: cumulative installed capacity. Data source: [6].

2. HVDC GRIDS IN OVERALL INFRASTRUCTURE

Since RES-based power generation is inherently volatile, the question emerges if there is a need for a "supergrid" which will facilitate a future where, at times, northern Europe can compensate the European south or vice versa, depending on the real-time availability of various RES types. Several visions for the future transmission grid have been presented in the literature to date. In such visions, the role of HVDCs in power transmission varies.

A stronger European high-voltage transmission grid is necessary to integrate massive renewables-based power generation, especially offshore wind, balance the variable energy output of renewable sources and cope with the expected future increase in electrical power consumption. Particularly, power transmission connections from offshore areas to inland regions, such as southern Germany, need reinforcements. A solution based on upgrading the existing High-Voltage Alternating Current (HVAC) grid is difficult because of public opposition and legal and environmental concerns. A vision paper from 2012 states that in most of central Europe, the most promising alternative for a fundamental upgrade of the power system is an HVDC grid since using HVDC would allow a relatively straightforward underground grid implementation. Such an HVDC grid could be of the magnitude of a supergrid, i.e., a transmission system that spreads electric power across national borders or more extensive, and it would serve as an additional transmission structure besides the existing HVAC grids. A desirable topology is a meshed DC grid, as mentioned in [18], with multiple connections between the AC and DC grid because it requires fewer converters compared to a point-to-point-based system and provides redundancy.

Another vision paper states that a possible European supergrid will not be completely built in one project. Analog to the construction of the 400 kV AC transmission grid in the 1950s and 1960s, a step-by-step development is much more likely. A potential scenario is first to realize point-to-point HVDC links, which can be later interconnected to different links by additional HVDC lines. Later, several of these smaller multi-terminal systems could be connected to form a larger-scale HVDC grid. Further, it is stated that the development of an HVDC supergrid might start simultaneously in multiple locations, and "whether emerging independent grids should be connected to form one overlapping supergrid or rather remain independent DC grids remains an open question." Coupling between these grids solely through the AC power system is thinkable [19].

A more recent vision paper from 2021 for the future transmission system states that offshore wind integration and power flow between asynchronous grids require increasing HVDC transmission. However, HVDC point-to-point links, which are incorporated into the AC grid, possibly face power transfer capacity limitations due to power flow constraints of the AC grid, among other drawbacks. A proposed alternative is to incorporate multi-terminal HVDC "power corridors" into the transmission grid to allow for high-efficiency long-distance transmission without bulk power flow through multiple AC-DC conversion stages and greater flexibility in control of power flows. The resulting system would be a robust hybrid AC/DC transmission grid. Some critical questions for the role and development of (multi-terminal) HVDC grid technology on the path to such a hybrid grid are [20]:

- How should HVDC connections contribute to AC grid stability?
- How to cope with HVDC faults?

In China, the built and planned HVDC projects may result in a nationwide supergrid interconnecting China's six regional grids while using bulk, long-distance HVDC transmission between areas with massive renewable power generation in the north and west and the densely populated load centres in the east. However, many high-capacity HVDC links are intentionally operated below their designated power rating, leading to significant curtailment of renewable power generation. Restricting the DC power flows aims to ensure that the HVDC connections do not destabilize China's regional AC grids in case of faults. China's State Grid is additionally strongly reinforcing its AC grid with sets of ultra-HVAC lines to help eastern China's regional AC grids distribute the output from the ultra-HVDC lines and to keep the grid operational [21].

An apparent common ground of the mentioned visions is that a large number of HVDC systems is necessary to reinforce the existing transmission grid and that these systems have to be included in a way that results in a resilient and reliable AC/DC power system. Resilience is usually related to the quick recovery following a low-probability, high-impact event, while reliability is related to handling high-probability events. When HVDC systems are incorporated, new inherent threats for the overall AC/DC system security appear, such as high-power converter outages. On the contrary, while the primary objective of new HVDC systems is to provide transmission capacity, the high controllability and fast response of HVDC systems can be used to provide support to AC grids and minimize the risk and impact of different threats.

An incremental approach to integrating multi-terminal HVDC projects into the European transmission grid, as presented [20], is seen as the realistic vision by this working group. From today's standpoint, the limited remaining time to reach targets for 2030, regulatory considerations, and staff scarcity in the HVDC industry may delay the planning and building of a larger-scale HVDC grid, e.g., in the North Sea area. According to a recent report by the UK's electricity networks commissioner, strategic transmission projects are expected to take 12 to 14 years from the identification of need to commissioning, while building associated wind generation is achievable in half the time. Many specialized engineers and technicians are required to realize and implement necessary (HVDC) transmission projects and engineering institutions have identified an already present engineering skills gap. Further, HVDC equipment and cables are likely to be short in supply for years or decades [22]. Currently, higher active power ratings than 2 GW for HVDC transmission are not considered, as the cable ratings are based on a 2-kA limit. In the future, higher power capacities may be available through new technologies like higher voltage cables or higher current cable technology, such as superconductor-based transmission and their respective power conversion systems. Additional challenges for HVDC grids in the overall infrastructure include the need for headroom or hardware margins in converter stations in order to minimize the risk of cascading converter failures in emergency situations. Furthermore, the mere scheduling of commissioning and start of operation of the upcoming HVDC systems already puts heavy demands on the power system operators that need to provide staff and timeslots where safe commissioning can be done one project at a time. Also, the regional rules for operation of HVDC (super-)grids need to be coordinated across borders and across different grid zones, potentially leading to a "super-system-operator". Lastly, incorporating more and more HVDC projects into the AC grid using an incremental approach likely leads to AC power flow constraints limiting the usable capacity of HVDC links. Therefore, significant AC transmission grid reinforcements are necessary to distribute power transmitted by HVDC projects [17].

3. VISION FOR SUSTAINABILITY OF DC GRIDS

HVDC transmission largely contributes to two of the 17 UN Sustainable Development Goals (SDGs), SDG 7 ("Access to affordable, reliable, sustainable and modern energy for all") and SDG 9 ("Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation"). The roadmap for accelerated SDG 7 action in support of the 2030 Agenda and the Paris Agreement specifically defines the action "Rapidly transitioning to decarbonized energy systems". In this action, HVDC projects help reach the following targets: reduction of greenhouse gas emissions by 45 % below 2010 levels by 2030 and reaching net zero emissions by 2050; global energy efficiency improvements must increase significantly; the phase-out of coal power generation needs to be accelerated globally [23]. Here, it is also mentioned that the higher efficiency of HVDC power transmission compared to HVAC not only leads to lower carbon emissions but might also lower the cost of electricity. In SDG9, HVDC transmission mainly contributes to the development of reliable, sustainable, and resilient infrastructure, including regional and transborder infrastructure, for example, with large-scale cross-country interconnection.

HVDC cable transmission, in particular, contributes to SDG3 ("Good health and wellbeing") as it is the most efficient solution for integrating large-scale remote RES, such as offshore wind, into the existing AC grid and the most environmentally compatible solution for building large-scale inland transmission projects [24].

Following the adoption of the recast Energy Efficiency Directive in the 2023 COD Ordinary legislative procedure [25], EU member states must ensure that the Energy Efficiency First Principle (EEFP) is assessed in planning, policy and major investment decisions of energy systems, in particular by means of "more efficient conversion, transmission and distribution of energy, whilst still achieving the objectives of those decisions." This will apply from October 2025 to all planning, policy and investment decisions on energy systems with a value of more than €100,000,000 (Article 3). The EEFP is defined by the EU Governance Regulation. The application of the Energy Efficiency First Principle will mean that raw material resource use and circularity will become an integrated part of future purchasing and tendering processes for large-scale infrastructure projects such as power grids. Here, the reader is referred to the work of this working group on the long-term view on HVDC technology [26].

Diving into more detail, an arising question is: What are the sustainability gains of HVDC grids compared to point-to-point HVDC transmission? Here, it is crucial to mention that a grid topology with only point-to-point HVDC links requires a higher amount of converter stations compared to a meshed HVDC grid. This is a critical aspect since converters are expensive, sensitive, and lossy components of HVDC transmission infrastructure, furthermore requiring space (e.g., a complete offshore station). As a rule of thumb in large (AC) grids, it can be assumed that the number of branches is usually 1.5 times the number of nodes. If applied to HVDC, therefore, using only point-to-point links would require three times as many converters as the number of DC nodes in the grid, considering two converters per link. A meshed HVDC grid on the other side would require one converter per HVDC node. Roughly estimated, two in three converters could be omitted in a large, meshed DC grid compared to state-of-the-art point-to-point transmission [19]. For illustration, FIGURE 6 shows an example configuration of two AC grid areas and an OWF connected by HVDC links. For the same number of branches, the meshed DC grid configuration (left) requires far fewer converters than the point-to-point-based configuration (right). In addition, meshed HVDC systems provide the potential to save cables and, thus, raw materials compared to several point-to-point HVDC connections. For a more detailed analysis, please see [26].

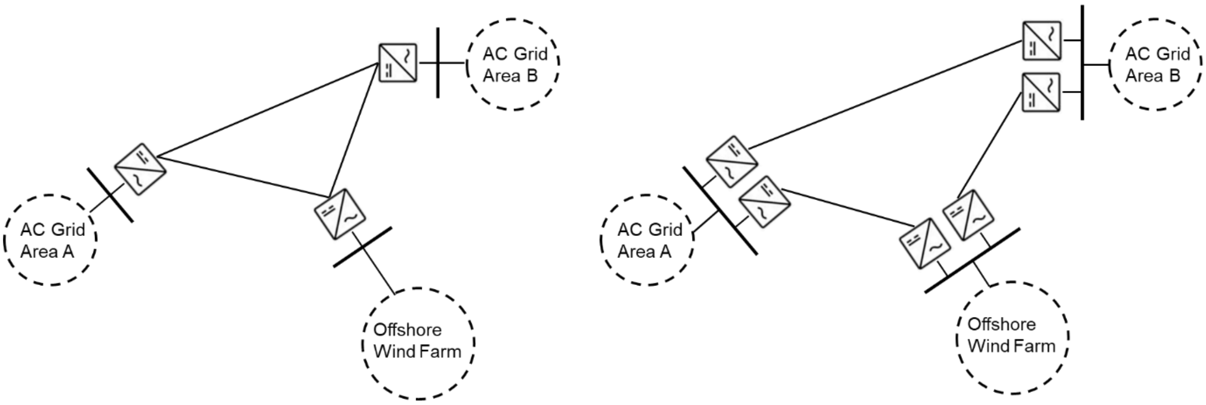


FIGURE 6
Illustration of the number of converters needed in a DC grid. Left: meshed DC grid; right: point-to-point DC transmission.

4. BEYOND HVDC

Firstly, while the ambition of going ”beyond HVDC” is needed and urgent, it has to be ensured that the actual HVDC topic is well-disseminated at universities and the general public to qualify/attract more power systems and control engineers for the HVDC industry. As a critical technology for the energy transition, HVDC should receive the same attention as, e.g., hydrogen, in particular, in light of staff scarcity [27]. This aligns with the need for integrated planning and operation of a potential pan-European (meshed) HVDC infrastructure [28].

However, beyond HVDC, other DC-related technologies and concepts appear that can also contribute to the energy transition. In addition to HVDC technology, High-Power Direct Current (HPDC) technology is emerging that could transfer high volumes of power at medium or even low voltage, e.g., using high-power or superconducting cables. The first superconducting distribution grids are already commercially available, and companies on both sides of the Atlantic are working on extending the scope and application of existing superconducting cable technology by developing long-distance, superconducting transmission technology for both terrestrial and offshore applications that would be commercially available from around 2030. Superconducting electricity transmission reduces the materials use of energy transmission dramatically. To carry one kA one metre, superconducting cables require seven times less copper than conventional power cables. Alternatively, the technology can transfer the same amounts of energy at a much lower voltage level. This would be associated with far fewer environmental impacts and raw materials use.

As regards the usage of conventional cable technology, Medium-Voltage and Low-Voltage Direct Current (MVDC and LVDC) concepts promise, at first glance, synergies in, e.g., control, communication, and protection approaches. However, similarly to the existing AC infrastructure that needs solutions adapted to the specifics of the voltage level (high-voltage transmission grid vs. low-voltage distribution grid), DC voltage levels also come with differences in control, communication (delays), protection [29], and grid structure. For that reason, it is not possible to simply "copy-paste" solutions between different voltage levels, though it should be noted that MVDC vs. HVDC technology and LVDC vs. MVDC technologies are more similar to each other compared to, e.g., LVDC vs. HVDC.

Finally, even using established HVDC technology requires the power system community to "think beyond" established approaches and power system concepts. Firstly, the sheer number of HVDC systems to be commissioned is a real practical challenge (e.g., available operators, having redundant power lines available, do not commission several links at the same time, etc.). Given these challenges – with careful planning - it has to be avoided that the power system ends up in a "surgery at the open heart" situation. Secondly, the increasing capacity of HVDC systems means that at some point, a loss of infeed may be too large for an AC system to handle, thus pushing the n-1 criterion to the edge. At the same time, the HVDC reliability is extremely high, such that thought experiments appear in the community as regards the maximum loss risk for HVDC links. There may be situations (e.g., in industrial grids) where building redundant HVDC infrastructure may be hard to justify, and instead, an unlikely outage could be accepted. Ultimately, this also means that energy storage may be required (e.g., gas, hydrogen, batteries) that could buffer an HVDC outage, such that the disconnection of a large amount of renewable generation offshore will be mitigated.

5. CONCLUSION

This whitepaper presented a vision for the role of on- and offshore HVDC infrastructure and meshed DC structures in the European energy system, including sustainability aspects. Additionally, topics going beyond HVDC technology were discussed.

The up-ramping offshore wind targets in the European countries require a 10-fold increase in installed generation capacity from today to 2050 (Ostend declaration) and dictate the magnitude of HVDC development in Europe because HVDC is expected to be the main technology for offshore wind energy connection. Further, on- and offshore projects facilitate cross-country interconnection and provide similar grid-stabilising functionalities as existing AC assets. Onshore HVDC also fulfils needs for long-distance power transport. In addition, wide-meshed offshore grids will be required to handle the high volumes of transit power flows in the future European power system. All use cases combined - if the current HVDC growth rates continue - a projection of HVDC project deployment to 2050 shows a capacity close to 1 TW.

While earlier visions for the European HVDC supergrid may have resulted in the impression that a top-down planning and building approach for the complete infrastructure may be a way to move forward, today, the HVDC community sees the first multi-terminal HVDC systems appearing that are extended piece-by-piece. This incremental approach appears to be the way forward to achieve integration of multi-terminal HVDC projects into the European grid rather than top-down planning of a large-scale HVDC (super)grid. However, in the long term, a centralised operation appears useful for an HVDC Supergrid.

Already today, a high number of HVDC systems is necessary to reinforce the existing transmission grid, and these systems have to be included in a way that results in a resilient and reliable AC/DC power system. While HVDC generally contributes to sustainability in aspects such as improving energy efficiency and lowering the cost of electricity, meshed HVDC grids, specifically, require fewer converters than state-of-the-art point-to-point links, potentially saving cost and raw materials.

Beyond HVDC, other emerging DC-related technologies and concepts can also contribute to the energy transition, for example, HPDC technology, MVDC, or LVDC. Here, it must be acknowledged that each voltage level and DC technology comes with its own specific technical aspects. Finally, in light of the staff scarcity in the HVDC sector, it has to be ensured that HVDC is well-disseminated at universities and the general public to attract more technicians and engineers to the HVDC industry. HVDC is a critical technology for the energy transition, and it would be desirable that HVDC technology is equally well known to the public as, e.g., hydrogen or artificial intelligence.

ABBREVIATIONS AND ACRONYMS

Abbreviation	Description
EC	European Commission
EEFP	Energy Efficiency First Principle
HPDC	High-Power Direct Current
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current, as defined in, e.g., IEC 60633 or IEC 62747
LVDC	Low-Voltage Direct Current
MTMV	Multi-Terminal, Multi-Vendor
MVDC	Medium-Voltage Direct Current
RES	Renewable Energy Sources
SDG	Sustainable Development Goal
TYNDP	Ten-Year Network Development Plan
VSC	Voltage-Sourced Converter

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