

EXECUTIVE SUMMARY

Offshore wind energy will play a significant role in the European Green Deal's overall objective of achieving climate neutrality. In the North Sea alone, with its strong winds and shallow waters, a total potential of over 200 GW of generating capacity could be built by 2050. Transporting this amount of offshore wind power to shore and integrating it into the onshore transmission systems is a formidable challenge, requiring high levels of interconnection between the states that border the North Sea.

Due to the remote locations of offshore wind farms and the increasingly large distances across the North Sea, traditional high-voltage alternating current (AC) transmission technology is no longer viable and high-voltage direct current (HVDC) connections must be utilised instead. Previous research projects have indicated that the most socio-economically beneficial implementation of such an HVDC transmission system is a coordinated, interconnected (meshed & multi-terminal) HVDC offshore transmission network which combines the purposes of:

- offshore wind power export to shore
- interconnection of different North Sea states
- reinforcement of onshore AC networks
- supply of offshore energy consumers

To-date however, HVDC systems in Europe have predominantly been implemented as separate point-to-point links under a single vendor, single purpose and often single owner paradigm, due to immature multi-terminal HVDC network technology solutions, large differences in national and supra-national legal and regulatory frameworks, and an absence of a suitable economic framework, resulting in financing challenges.

The EU funded Horizon2020 project PROMOTiON 'Progress on Meshed Offshore HVDC Transmission Networks' project has addressed the technical, legal, regulatory, economic and financing challenges in the development of a meshed offshore HVDC transmission network in the North Sea by working towards the following six objectives:

1. To establish interoperability between different technologies and concepts by providing specific technical and operational requirements, behaviour patterns and standardization methods for different technologies, PROMOTiON has:

- Focussed on four key technologies: HVDC network and offshore wind farm control, HVDC network protection, HVDC circuit breakers and HVDC gas insulated substations
- Defined common functional requirements for multi-terminal HVDC systems and offshore wind power plants

- Researched, analysed, simulated and compared the techno-economic performance and interoperability of meshed HVDC network topologies with different combinations of key technologies under different operating configurations and a full range of operating conditions
- Developed guidelines for technology selection and equipment specification
- Developed recommendations to achieve compatibility and interoperability on legal, regulatory, planning, technical and contractual levels

2. To develop interoperable, reliable and cost-effective technology of protection for meshed HVDC offshore networks and the new type of offshore converter for wind power integration, PROMOTiON has:

- Defined common performance requirements for HVDC network protection
- Created cost models and a cost database for HVDC equipment
- Carried out a comprehensive lifetime cost and benefit analysis of different protection strategies to determine the most cost-effective strategy for different types of HVDC transmission networks
- Developed, fully tested and validated an Intelligent Electronic Device (IED) which can be programmed with various HVDC network protection strategies
- Developed a common system interface between different protection system components (e.g. circuit breaker & IED)
- Demonstrated vendor interoperability through the successful operation of both PROMOTiON's and an industrial vendor's IED with another industrial vendor's converter control & protection replicas
- Carried out stress and failure mode analysis of HVDC circuit breaker technologies and components

3. To demonstrate different cost-effective key technologies for meshed HVDC offshore networks and to increase their technology readiness level by investigating and overcoming early adopter issues and pitfalls, PROMOTiON has:

- Developed common technology performance qualification procedures and test circuits
- Carried out semi-public full-power, full-scale and/or full-functionality demonstrations of industrial prototypes of all key technologies delivered by vendors at independent industrial test laboratories and universities based on the proposed test requirements and test circuits
- Carried out numerous lower-power, lab-scale and simulation-based technology demonstrations and test system development, which will be utilised for technology development, research and staff training.
- Created technology readiness level (TRL) definitions for HVDC transmission technology in accordance with Horizon2020 TRL framework
- Performed a dedicated TRL review progress analysis of all key technologies considered in PROMOTiON and determined that all key technologies have reached a TRL of 6 or higher

- 4. To develop a new EU regulatory framework, both in accordance with EU wide energy policy objectives and those of the Member States, and to increase the economic viability of meshed HVDC projects by providing a suitable financial framework, PROMOTiON has:**
- Performed a desktop study of international, European and national law and developed specific recommendations for identified gaps and incompatibilities
 - Proposed a definition for a new type of asset classification of wind farms connected to more than one country (i.e. hybrid assets)
 - Developed a methodology for socio-economic cost and benefit analysis for offshore transmission system development
 - Developed specific recommendations for offshore network planning, operation and decommissioning
 - Developed an offshore market design based on small bidding zones with additional measures to ensure stable revenue streams for offshore wind farm developers
 - Analysed and made recommendations for the required investment volumes, ownership models, investor income models, cross-border cost allocation as well as suitable financing strategies and instruments
- 5. To facilitate the harmonisation of ongoing initiatives, common system interfaces and future standards by actively engaging with working groups and standardisation bodies and actively using experience from the demonstrations. PROMOTiON has:**
- Inventorised all active and relevant standardisation initiatives, mapped these onto PROMOTiON results and established liaisons
 - Organized targeted harmonisation workshops on different topics
 - Developed and shared specific information packages with standardisation initiatives. In particular, test results of the demonstrators have been shared and have helped to actively drive and shape standardisation
 - Proposed and initiated standardisation activities in case of identified gaps
- 6. To provide a concrete deployment plan for “phase two” in bringing key technologies for meshed HVDC offshore networks into commercial operation in Europe, taking into account technical, economic, financial and regulatory aspects, PROMOTiON has:**
- Developed potential network topologies based on offshore wind roll out and international coordination scenarios
 - Performed a comparative evaluation based on the cost and benefit analysis for the developed topologies
 - Created a roadmap with necessary stakeholder actions and timing
 - Carried out feasibility studies of three short-term opportunities for multi-terminal HVDC pilot projects

Final conclusions

Based on the work performed, PROMOTioN concludes that there are no technological showstoppers for multi-terminal HVDC transmission network development, but that significant standardisation work is still required to enable multi-vendor HVDC network integration. TSOs and vendors need to align on common, technology-neutral functional performance requirements and adopt common communication protocols and standards for HVDC equipment. Procurement and contractual best practises must be adapted to enable multi-vendor system integration. The technologies, control systems and operating practices for HVDC grids have been developing rapidly, PROMOTioN has contributed to technology development and identified a number of directions for further performance improvement and cost reduction.

Collaboration and coordination between national governments, TSOs and other offshore space users is key to implementing regulatory and legal recommendations and to aligning national offshore renewable energy plans with transmission planning. The best way to overcome the remaining challenges and initiate the collaborations necessary to do so is through the realisation of a full-scale cross-border pilot project which would demonstrate the technology's viability, showcase international collaboration models and deliver the socio-economic benefit of multi-terminal HVDC transmission systems as compared to the current point-to-point connection paradigm.

The PROMOTioN results have been extensively disseminated through publication in international conferences and journals (e.g. CIGRE and IEEE) as well as through targeted topic driven workshops with key stakeholders such as national ministries, DG Energy, ENTSO-E, WindEurope, T&D Europe and the North Sea Wind Power Hub. The public deliverables and presentations are available on the project website www.promotion-offshore.net.