PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Final report

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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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 evacuation to shore
- interconnection between 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[1].

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

[1] https://en.wikipedia.org/wiki/List_of_HVDC_projects

- 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
   - De-risked significantly grid forming operation of offshore wind power plants via comprehensive software validation, providing functional requirements, compliance procedures and grid code recommendations
   - Developed, implemented and validated generic and vendor-specific grid forming controllers for self-energization and black-start of offshore wind farms

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 progress analysis of all key technologies considered in PROMOTioN and determined that all key technologies have been advanced to 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 targeted at the 2050 goals
- 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.

LIST OF CONTRIBUTORS

Work Package and deliverable involve a large number of partners and contributors. The names of the partners, who contributed to the present deliverable, are presented in the following table.

PARTNER	NAME
DNV GL	Cornelis Plet, Maksym Semenyuk, Marga van Deelen

CONTENT

1 INTRODUCTION

This document aims to give an overview of the project, the progress that was made towards achieving the objectives, the impact that was realized, compliance with the work plan and the use of resources. Where relevant, references to the publicly available deliverables were added in the footnote. This chapter provides and overview of the project context, objectives and structure.

1.1 MAIN RESEARCH / INNOVATION

In order to unlock the full potential of Europe's offshore resources, network infrastructure is urgently required, linking offshore wind parks and onshore grids in different countries. HVDC technology is envisaged due to its ability to transport large amounts of power over large distances. So-called 'meshed' HVDC grids, in which there is always more than one path between any two points, can deliver the high required reliability and multi-functional use of both exporting offshore wind energy combined with interconnecting countries. The deployment of such meshed HVDC offshore grids was hindered by the high cost of converter technology, lack of experience with protection systems and fault clearance components, and limited by international regulations and financial instruments.

1.2 OBJECTIVES

In order to address these challenges, PROMOTioN aims to achieve the following 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
2. To develop interoperable, reliable and cost-effective technology of protection for meshed HVDC offshore grids and the new type of offshore converter for wind power integration
3. To demonstrate different cost-effective key technologies for meshed HVDC offshore grids and to increase their technology readiness level by investigating and overcoming early adopter issues and pitfalls
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
5. To facilitating the harmonization of ongoing initiatives, common system interfaces and future standards by actively engaging with working groups and standardization bodies and actively using experience from the demonstrations.

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6. To provide concrete deployment plan for “phase two” in bringing key technologies for meshed HVDC offshore grids into commercial operation in Europe, taking into account technical, financial and regulatory aspects

By building on the results of previous EU funded projects Twenties E-highways and BestPaths, PROMOTioN has overcome these barriers by increasing the technology readiness level of key technologies through development and full-scale demonstration, proposing improvements to the legal & regulatory framework, and by providing insight into how such a grid may be financed. An Offshore Grid Deployment Plan for 2020 and beyond provides an agenda to stakeholders to support optimisation of utilisation of Offshore Wind Generation. The PROMOTioN results are illustrated through feasibility studies on three concrete short-term projects which are multi-terminal extensions or DC connections of projects in operation or planning today.

1.3 PROJECT STRUCTURE

The PROMOTioN project is organized in 16 work packaged, as shown in Figure 1, bundled in 4 pathways addressing different topics. The first technology pathway focuses on meshed HVDC grid control and the impact on the onshore and offshore AC grids. Requirements and methods to guarantee satisfactory steady-state and transient performance, but also the offshore wind farms’ ability to deliver ancillary services, which are currently supplied by conventional power plants, are thoroughly analysed. The performance and compatibility of different technologies are analysed, such as the diode rectifier offshore converter which challenges the need for complex, bulky and expensive converters, reducing significantly investment and maintenance cost and increasing availability.

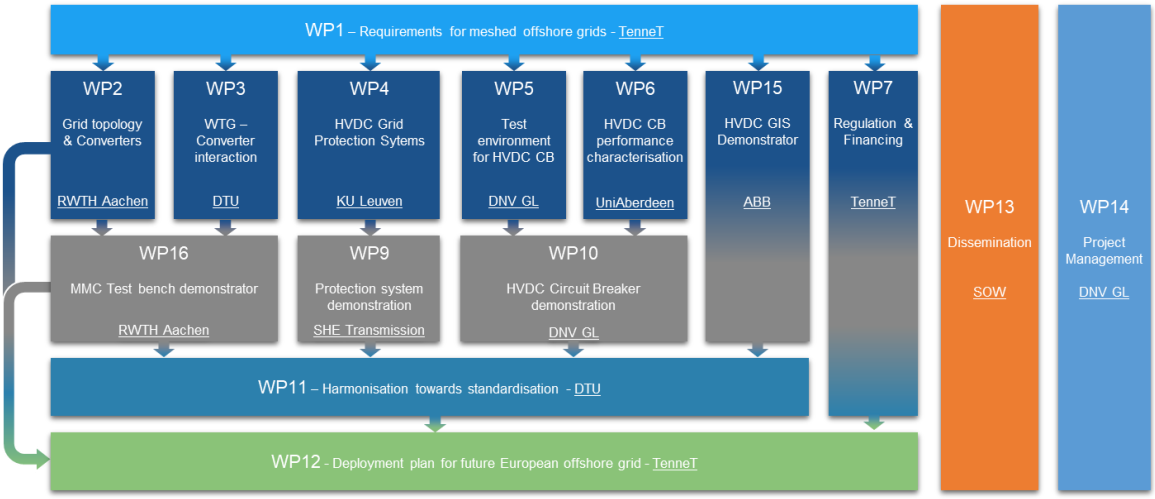

Figure 1 - Project structure

The second technology pathway addresses the HVDC network protection technology. Through a comprehensive techno-economic comparison the best performing methods were selected which

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were implemented in industrial hardware and demonstrated utilizing the SHE Transmission Multi-Terminal Test Environment to enable DC grid protection to become a “plug-and-play” solution.

The third technology pathway focused on HVDC switchgear including a first-time performance demonstration of existing DCCB prototypes to provide confidence and demonstrate technology readiness of this crucial network component, as well as gas insulated switchgear technology.

The fourth pathway is non-technical, and developed the international regulatory and financial framework, essential for funding, deployment and operation of meshed offshore HVDC grids.

Considerable effort was placed in joining the efforts in the different pathways by setting the functional requirements jointly at the beginning of the project and to merge the different efforts at the end through a joint roadmap and standardization efforts.

With 34 partners, PROMOTioN was ambitious in its scope and advanced crucial HVDC grid technologies from medium to high TRL. The consortium included all major HVDC and wind turbine manufacturers, TSO’s linked to the North Sea, offshore wind developers, leading academia, consulting companies and industry associations.

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2 REQUIREMENTS & DEPLOYMENT

To ensure cohesion and coordination between the different work packages, and ultimately in PROMOTioN's final conclusions, the requirements for all technical and non-technical tasks were defined jointly at the start of the project[2][3]. By doing so, it was ensured that the results could be readily integrated into a long-term deployment plan up to 2050.

2.1 REQUIREMENTS

A meshed offshore grid (MOG) must have sufficient transmission capacity and be reliable, stable and controllable to service market driven transmission need as it evolves into the future. To ensure long term economic expansion it must also be interoperable, both from a multi-vendor and multi-technology perspective. Additionally, there are non-functional system requirements, such as that the MOG must be economically viable and operate under a suitable regulatory framework[4].

State-of-the-art offshore grid topologies are mostly point-to-point (2-terminal) interconnectors. In principal, technology allows for multi terminal topologies, combining interconnectors and offshore wind farm connection. MOGs connect multiple terminals in such a way that loops are formed in the network topology, and thus create alternative paths of power transport. These alternative paths can be utilized at the onset of a fault to immediately reroute scheduled power flows and thereby minimize the loss of infeed in connected AC grids. Moreover, they can be used to improve availability throughout the duration of the repair of an outage. Variants and extensions on the current topologies support the discussion on requirements and ideal topology for a meshed offshore grid. PROMOTioN proposed 4 "concept" topologies are defined which illustrate different possible topology choices to facilitate conclusions around steering future grid development.

The specific interfaces between different systems in these topologies have characteristics which are defined by the system requirements. The MOG – Onshore AC grid interface puts constraints on the tolerable variations of the power output and quality, for which the ENTSO-e Network Code on HVDC Connections was taken as a starting point.

[2] D1.5 - Guiding principles / catalogue with requirements for other work packages
[3] D1.7 - Report on the reevaluation of the requirements based on results by other WPs
[4] D1.1 - Detailed description of the requirements that can be expected per work package

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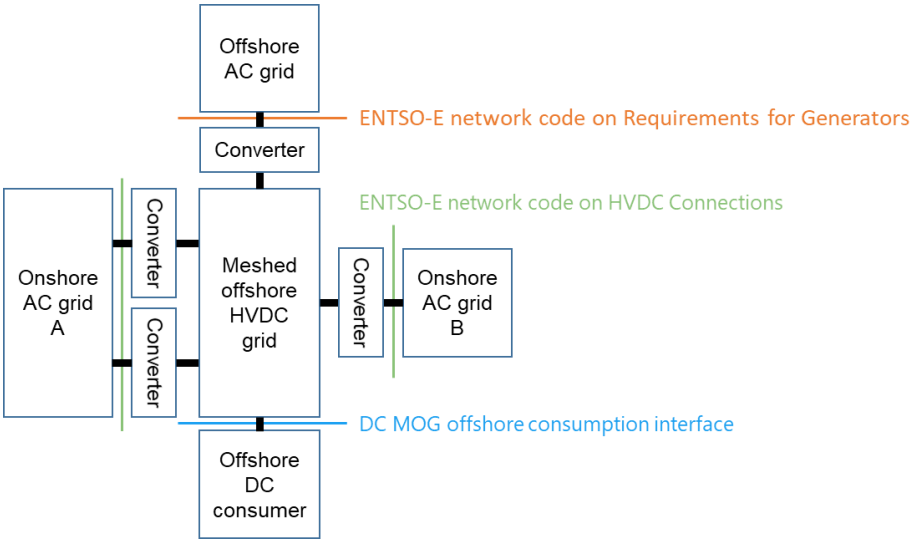

Figure 2 - Offshore grid interfaces

The MOG – Offshore generation interface puts requirements on the power output and fault ride through performance of offshore AC generation, for which the ENTSO-e code on Requirements for Generators was used as a starting point.

The MOG – DC offshore consumption interface describes possible connections to offshore consumers. Connecting offshore demand such as offshore oil & gas facilities is not the main purpose of the MOG, but could contribute to its attractiveness in certain cases. The MOG Operation interface describes the requirements for steady state and dynamic operation of the DC grid and requirements for control & protection systems of the MOG. Jointly these interfaces cover all technical aspects of the MOG. Based on this a list of requirements defined along which the work within PROMOTioN is defined. The quantification process is based as much as possible on usage of existing material and experience that the partners bring in. Gaps were identified and either addressed to the appropriate work package within the PROMOTioN project or best experience project assumptions are chosen for the quantification.

A comprehensive literature study[5] of all available previous research and feasibility studies into meshed offshore HVDC grids as well as a survey of existing projects[6] were carried out to determine the state of the art in technology, scenarios, planning approaches, market considerations, etc.

[5] D1.3 - Report with a synthesis of the available studies on offshore meshed HVDC grids and related barriers/gaps at the inception of the project
[6] D1.2 - Report documenting results of the questionnaire on best practices

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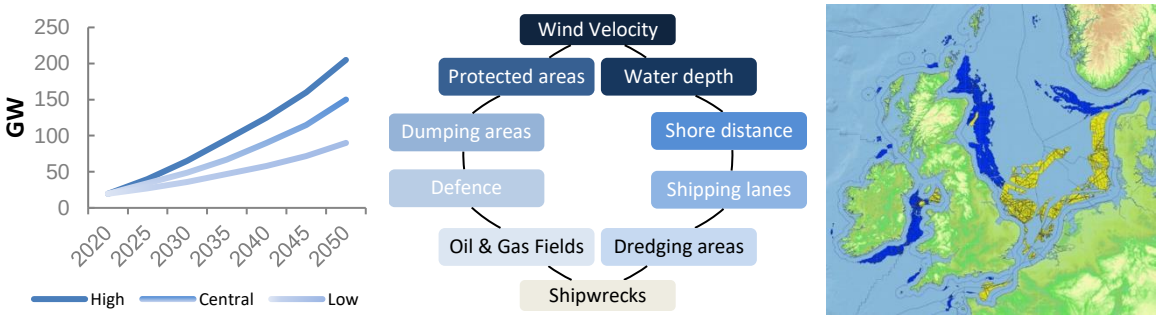
2.2 TOPOLOGY DEVELOPMENT

In order to study the types of systems that might evolve under different offshore wind capacities and international collaboration levels, an extensive scenario based spatial planning study was carried out[7]. By identifying areas with high average annual offshore wind speed and shallow water depth, and subtracting other offshore space usages, suitable wind farm sites were identified. Low, medium and high offshore wind roll-out scenarios up to 2050, based on the ENTSO-E scenarios, were developed for the North Sea countries, and distributed temporarily in 5 yearly stepwise fashion over the identified offshore wind farm sites. It was shown that realizing 200 GW offshore wind occupies all available space for fixed bottom wind turbines, and if P2X is used, even more space is required for overplanting



a) Offshore wind deployment scenarios

b) Exclusion zones

c) Identified wind farm sites

Figure 3 – Offshore wind deployment scenario development

Wind farms were clustered to form 2 GW groups. GIS study based maritime spatial planning and a large number of exclusions led to smaller than "optimal" wind farm sizes. To reach the projected amount of wind (in the high scenario) some encroachment on the national economic exclusion zones (EEZ) is necessary. This is exacerbated by national constraints.

An optimal power system planning tool was then used to identify the most optimal grid expansions to evacuate the offshore wind power to onshore AC grids. In a second power system planning optimisation, interconnection grid expansions were added to the developed topologies. The use of 525 kV rated bipole with metallic return converter configuration was assumed in the North Sea, and 320 kV rated symmetrical monopole in the Irish Sea. The current loss of infeed limits (reference incidents) of the different North Sea countries were used as constraints. Technical compatibility, interoperability and expandability were explicitly assumed in the power system expansion and optimisation.

[7] D12.2 - Optimal scenario for the development of a future European offshore grid

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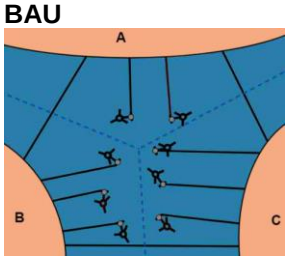
The cost of adding a protection system to the developed topologies was represented as an additional fixed percentage in CAPEX and OPEX.

The topology development was repeated for four different 'concepts' which varied regional levels of cooperation and coordination:

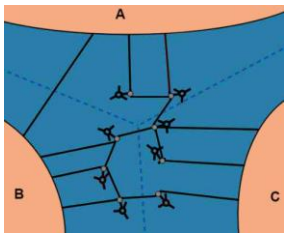
BAU



Business as usual

Point-point connections, only evacuate all wind power from EEZ to respective country, dedicated interconnectors

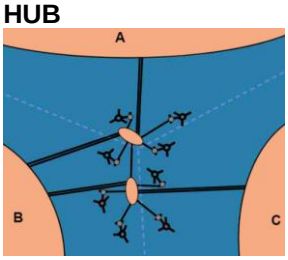
NAT



National distributed

Same as BAU, but interlinks and interconnections can be made offshore to improve utilisation and availability

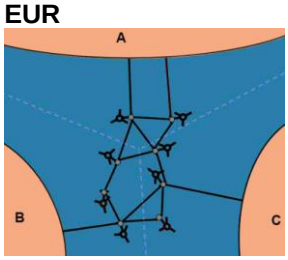
HUB



European centralised

Creation of large central (island based) hubs for offshore wind farm export and interconnection

EUR



European coordinated

Many small interconnected distributed platform-sized hubs

Figure 4 – Offshore grid development concepts

Offshore wind planning - The analysis showed that optimization of economic exclusion zones and a European approach would result in different scenarios for wind generation, probably with a similar overall capacity but with more efficient planning. A European approach to generation may also lead to offshore wind farm (OWF) planning changes between countries (e.g. more in Danish EEZ than local power consumption). PROMOTioN did not optimize wind locations per Concept even though it is anticipated that this would benefit concepts other than BAU. In particular the HUB concept, where construction of an artificial island would make the area around the island particularly valuable for offshore wind.

Onshore constraints - The PROMOTioN meshed concepts resulted in higher than expected curtailment. This was linked to greater utilization of cables – especially in the EUR model, and power being delivered to the onshore connection point closest to the offshore windfarm – rather than to high load centres. All concepts result in curtailment after 2040, linked possibly to onshore grid constraints, but more importantly because high RES availability is not confluent with consumption. Deeper analysis of the onshore power system is required to optimize the planning of an offshore grid. Reinforcement of the onshore grid is not expected to be sufficient. A significant need for storage (battery, hydro, etc.) or conversion (Power to Gas) will be required by 2045 (not material amounts in 2040) to ensure system adequacy.

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Protection - The protection technology research and CBA indicated that in principle different fault clearing strategies can be applied to different parts of the grid, resulting in a mix in technologies – interoperability was assumed. It is also recommended that larger grid structures could be split in case of faults, increasing resilience at lower cost.

Equipment - The ability to develop multi-terminal and meshed grids is dependent on the adoption of innovative HVDC technology in projects and advances from prototypes to industrially applicable equipment. The PROMOTioN work has demonstrated that the key technology elements are in principle ready for real-world application, but that a significant amount of work remains to be done on developing guidelines for their system integration. The deployment plan details recommendations for future development which are still required prior to industrial development. These grids also require suitable procurement and interoperability processes, standards and codes to be in place.

If a grid is built to evacuate 200 GW, then there is a significant industrial market for HVDC equipment as well as major substructures and construction work. PROMOTioN concludes that costing of the grid may be estimated using comparable AC equipment, and bottom-up component costing for HVDC equipment combined with experience from the oil and gas sector, compared with first HVDC platform costs for substructure costs. As much of the equipment is "new" we also conclude that a learning curve theory may be applied to some components of the HVDC grid.

2.3 COST & BENEFIT ANALYSIS

Example grid topologies in 2050 for the high scenario are shown in Figure 5. The topologies are all characterised by a large number of radial links from the offshore wind farm locations to shore, interconnected offshore between clusters and in the NAT, HUB and EUR concepts also between countries. It is clear that a strong need for interconnection capacity is required, and that this evolves a kind of backbone along the middle of the North Sea. It is expected that this effect will become stronger if interconnection is given equal weight to offshore wind export in the grid planning optimiser.

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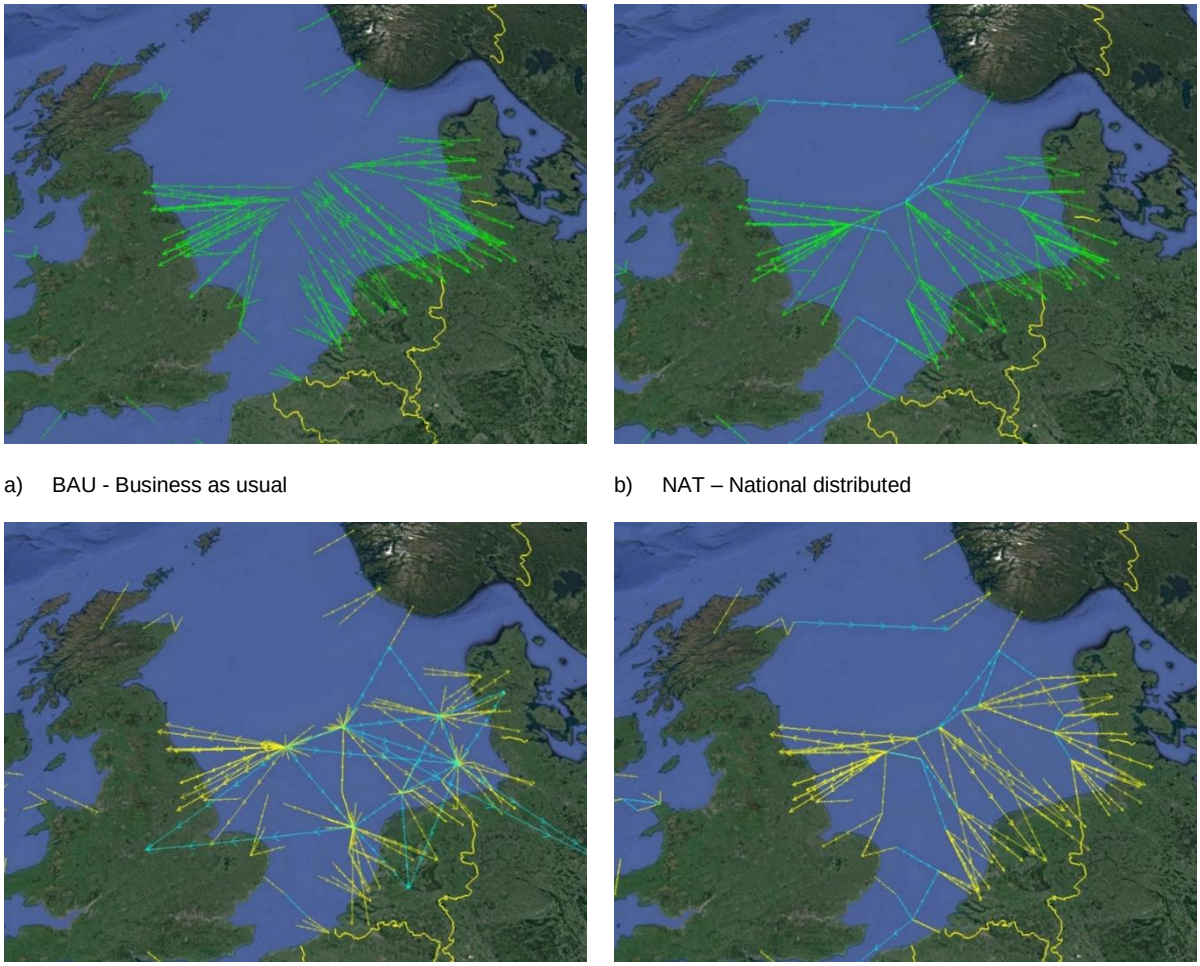

a) BAU - Business as usual

b) NAT – National distributed

c) HUB - European centralized

d) EUR - European coordinated

Figure 5 – Grid topologies in 2050 under high scenarios for different European coordination models

Benefits - The power system expansion optimiser indicated the development of meshed topologies quite earlier on already. Meshed connections appeared under specific circumstances such as scenarios with high onshore solar integration, onshore AC grid reinforcements (e.g. UK bootstrap projects, COBRA) or when cable power capacity ratings exceed onshore loss of infeed restrictions. Multi-terminal and meshed solutions all provided higher quantified social benefits than the BAU solution.

Costs - The BAU concept proposed in PROMOTioN assumes the use of 2 GW hubs and 2 GW cables and in many cases may still be the most applicable solution (depending also on the hub size). An observation is that in the early years of the development, the majority of the planned connections are point-point.

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The NAT and EUR concepts result in shorter total cable length, but the resulting reduction in cost is balanced by an increased investment in a protection system. PROMOTioN took the top end of estimated protection system costs, but there is no material difference.

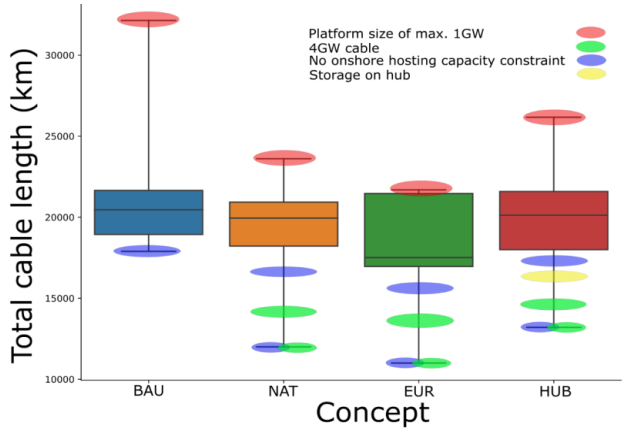

Figure 6 - Total cable length in each concept

The HUB concept indicates a reduction in total costs (CAPEX + OPEX) compared to BAU. This reduction can mainly be attributed to artificial islands replacing platforms as support structures and more efficient deployment of converters. HVDC equipment is large due to the large share of air insulated components (valves), which leads to large volume requirements and in turn will require either multiple very large platforms or an island. Due to the different cost structures, islands have a lower cost per square meter when the power rating increases beyond a certain capacity. Hence the HUB concept has largely lower anticipated overall cost compared to other concepts.

Large hubs also give the best opportunity to increase the cable power rating, which has a material impact on the required total length of cables (especially if combined with relaxation of the onshore infeed constraints)

The transmission infrastructure on the hub can be implemented as an AC hub (in which the various circuits coming into the hub are connected on the AC side of the converters) or as a DC hub (in which the various DC links coming into the hub are connected directly to one another via a DC busbar, and the OWF is connected via a converter). If the hub is used for interconnection purposes, then a DC busbar configuration leads to a reduction in the number of required converters on the hub. There is little change in the overall costs because depending on the arrangement any converter savings tend to be compensated by an increase in protection and a DC bus costs. However, the DC hub configuration is anticipated to have higher benefits due to lower losses and better availability.

Investment - Given increasing distances to shore, PROMOTioN anticipates that for full evacuation of wind, the required investment for the transmission system will be approximately €1 bln per GW – for the high scenario a total of €200 bln. This is dependent on the concept – albeit that the costs per

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concept indicate limited variation. This is in line with published current estimations for offshore transmission by OFTOs but does not reflect a measurable decline over today's costs. This may be due to increased distance to shore. However, over the PROMOTioN forecast period, costs do indicate a decline from €1.2-1.3 bln/GW in 2025 to €0.8-1.0 bln/GW in 2050. This represents almost a doubling of current rates of investment, for an extended period which is likely to place pressure on current funding models.

Hubs, meshed, and multi-terminal grids require anticipatory investment. Small hubs need to be "interconnection ready", as the grid is likely to be built incrementally. Platforms for hub structures will need to be able to expand, and where this is anticipated, space for spare connection bays should be included. This brings cash flows forwards, which requires full commitment for OWFs to be built. Within the HUB concept, PROMOTioN analysis indicates 4 of 6 proposed islands beginning construction in the period 2020-2025 and the remaining 2 of 6 in 2025-2030. This takes time and requires high investment. It requires assurance of Government.

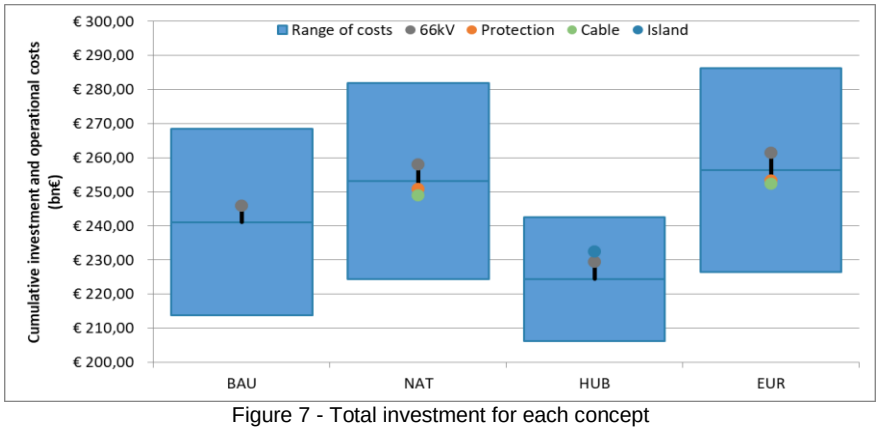

Figure 7 - Total investment for each concept

Market integration - The advantage of European cooperation in grid planning could not be proven in the cost-benefit analysis. The PROMOTioN CBA focus is primarily optimized on offshore wind energy evacuation – and only then on interconnection. Therefor specific answers regarding European cooperation are not fully proven. For example, the EUR meshed concept is optimized on evacuation and while structurally appearing to have more interconnection, this was not always usable at the right time due to priority access for energy evacuation.

We used the same wind scenarios for all concepts. These were adjusted to national requirements. Landing energy in the "wrong" country leads to higher curtailment. This may also be linked to low detail in the onshore grid models used in PROMOTioN.

Regulation - Multi-terminal and meshed grids assume a conducive legal and regulatory scheme. This may necessitate the short-term adoption of small bidding zone markets and/or Hybrid asset

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definitions. Market Model analysis concludes that the most appropriate market model, once meshing and multi-terminal grids form, is to create small bidding zones. Of the models tested (Extension of the national bidding zones to the national EEZ; Offshore Bidding Zones; Small Bidding Zones [around one or a small number of hubs]), the small zones provides the maximum social benefit. The small bidding zone model includes a transfer of benefit from OWF developers to the TSO and hence the public (Total benefit remains constant). Some form of compensation will be required to ensure OWF developers are protected/motivated, such as e.g. transmission rights, put options [right to sell energy to a bidding zone for a fixed price at a certain time], contracts for differences). The Small Bidding Zone model potentially removes the need for Hybrid Asset definition in law. As such, a potentially faster route exists to regulate pricing across bidding zones.

Coordination[8] - PROMOTioN concludes that for efficient construction of the grid, a high level of cooperation between stakeholders is required: (i) regulatory cooperation between NRAs; (ii) cooperation between (Government) policy makers and owners, (iii) cooperation between the TSOs. This may be facilitated through supranational organisations, like the North Seas Energy Cooperation, but it will need strong commitment to deliver actual projects. This has had some early success in improving approaches to long term planning and decision making (incl CBA and CBCA) which take into account meshed grid. However, results are still very nationally oriented. ACER and its RCCs have been mandated to take a greater role, but this is not yet translating into clear coordinated action. Longer term and coordinated planning may enable anticipatory investments to be made with sufficient confidence.

[8] D12.4 - Final deployment plan for future European offshore grid development

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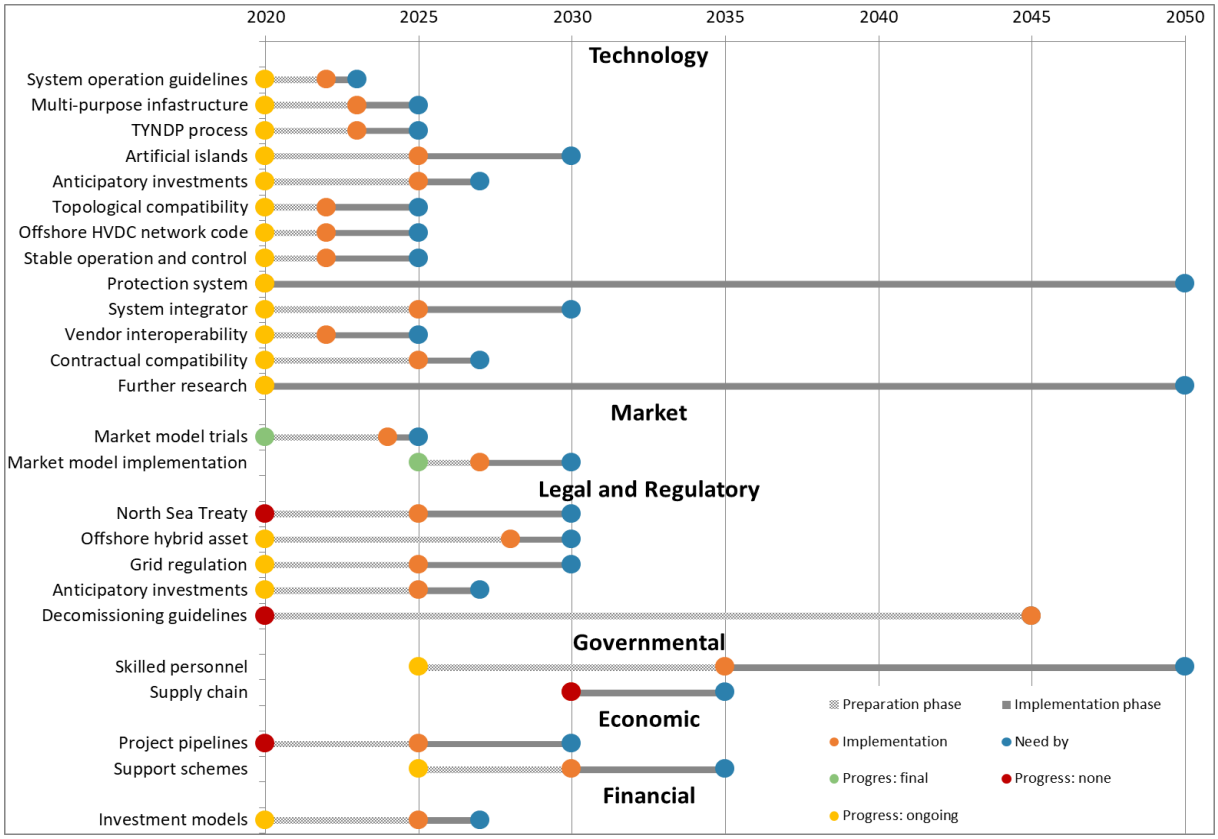

Figure 8 – Required actions sorted by stakeholder and timing

2.4 SHORT TERM PROJECTS

HVDC networks are likely to develop gradually in stepwise fashion. Apart from creating the conditions under which such extensions of existing projects are possible, it is important to identify the first possible HVDC projects where multi-terminal extension or DC connection with another project can bring a socio-economic benefit.

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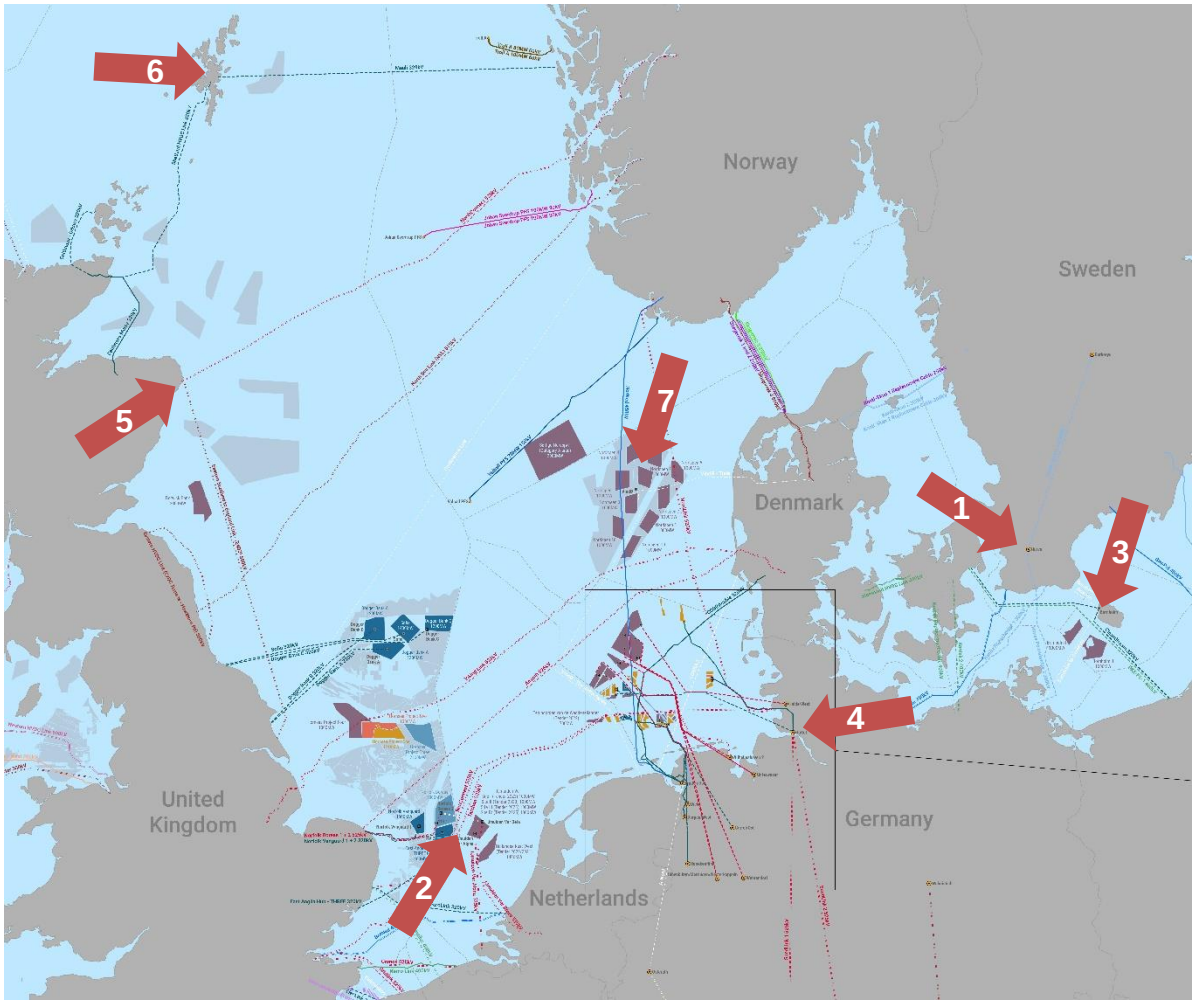

Figure 9 – Exisiting and planned HVDC links in and around the North Sea: Opportunities for beneficial mutli-terminal grid extension

PROMOTioN has made an inventory of all existing and planned HVDC connections in and around the North Sea, as shown in Figure 9 in which different colours indicate different voltage levels. Seven locations were identified where existing or planned HVDC connections have terminals at the same physical location or in close proximity, and have compatible circuit parameters (e.g. same voltage levels and converter configuration).

1. SouthWest Link – Hansa Power Bridge, 320 kV, symmetrical monopole, both have terminals in Hurva, Sweden.
2. WindConnector (UK Norfolk windfarm – NL IJmuiden Ver windfarm), 525 kV, bipole with DMR, both wind farms can be connected by a 60 km piece of cable and form a mutli-purpose and multi-terminal interconnector
3. CleanStream (Bornholm island, DK), planned offshore wind farms can be connected to interconnectors towards Denmark, Poland, Germany and Sweden via a DC hub on Bornholm island

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4. NordLink – SüdLink, 525 kV, bipole, both have terminals in Büttel, Germany. Several other 525 kV bipole links are planned to have terminals in or close to Büttel such as Südlink 2, the Tarchon interconnector to the UK, and a new offshore windfarm connection in Heide just north of Büttel
5. NorthConnect – EasternLink, 525 kV, bipole, both have terminals in Peterhead, Scotland
6. Caithness-Shetland link – Maali interconnector, 320 kV, symmetrical monopole, both links have terminals on Shetland island
7. Danish energy island in the North Sea, envisages the connection of several offshore windfarms, export links to Denmark and interconnectors to Germany and the Netherlands

For each of these connections their purposes and prevailing power flows are such that there is a significant benefit in connecting them on the DC side. It will reduce the number of converters required and thus investment, space, environmental impact and maintenance. Furthermore, it will lead to a substantial reduction in conversion losses and improve availability.

To understand the technical implementation and potential for benefit better, PROMOTioN has carried out feasibility studies[9] for the first three identified opportunities. High-level technical designs were made to enable assessment of improvement in availability and efficiency, and to estimate the investment required. Based on this cost and benefit analyses were carried out, and risk assessments completed. In all cases, a multi-terminal grid extension would result in significant benefit, even if additional costs for DC grid protection are taken into account. It is hence strongly recommended to support the real-world implementation of one or more of these DC grid building opportunities.

[9] D12.5 - Publication of the final deployment plan for future European offshore grid development

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3 TECHNICAL

In the topology development it was assumed that the technology to build meshed HVDC transmission networks is available, sufficiently mature and interoperable. PROMOTioN has analysed and demonstrated the maturity of the four key technology elements and progressed on the guidelines and standardisation that enable interoperability. The key technologies considered are:

- HVDC network control
- HVDC gas insulated substations
- HVDC network protection
- HVDC circuit breakers

HVDC cable and HVDC VSC converter technology were not further researched as they are considered sufficiently established although it is recognized that significant benefit can be unlocked through further development in terms of increasing maximum power ratings, improving reliability, reducing dimensions and reducing cost.

3.1 HVDC NETWORK CONTROL

The converters and wind farms in the offshore HVDC grids need to be actively controlled to ensure stable and reliable operation during steady state conditions and reasonable contingencies. Several control & operational strategies exist which can achieve this. Valid controller models, comprehensive yet computationally manageable system analysis techniques and controller-hardware-in-the-loop real-time simulation based validation methods are necessary to enable the TSOs and grid developers to plan and integrate the HVDC system reliably and cost-effectively.

Large AC/DC grid analysis - PROMOTioN analysed different operational strategies using a newly developed security constrained optimal power flow method for the analysis of operational strategies for large interconnected meshed AC and DC (offshore) grids, and showed that the use of curative measures (instead of preventive measures) is recommendable. Based on this, a proof of concept of simulating large interconnected AC and DC networks was delivered and a methodology for static and dynamic analyses to be performed during the HVDC grid planning phase using RMS tools was proposed.

No barriers to the controllability of large HVDC grids were identified, although power flows in cables in highly meshed grids can be become uncontrollable, necessitating the need for power flow controllers. Furthermore, control of multi-terminal grids will require some form of central controller to dispatch the converters. The physical location, governance (ownership), operation, and interoperability of such a controller remain questions to be answered.

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Diode rectifier operation - A proof of concept for Parallel operation of diode rectifiers with AC link and/or VSC links connected via the AC side has been successfully achieved, under various system conditions (Start-up, power flow changes and contingencies). Parallel operation on the offshore AC side is deemed as a good option to be further explored for HVDC systems in general. Moreover, a proof of concept was delivered for operation of diode rectifiers in combination with grid forming offshore wind parks[10] in multi-terminal and meshed DC grids taking into consideration different fault cases and contingencies.

Frequency support - Analysis of frequency reserve sharing between HVDC connected asynchronous onshore grids and frequency support via HVDC connected offshore windfarms[11] based on developed control concepts showed that the support is highly dependent on available transfer capacity of the HVDC grid. A comparison of communication-less and communication-based approaches revealed that while communication-less approaches can be used to support through HVDC grids, communication-based approaches are better suited to meet regulatory requirements.

DC fault ride through - Depending on the applied DC side fault clearing strategy, there is an impact on the offshore windfarm in case of DC faults. To achieve a fast power flow recovery after DC side faults, the wind farms have to be able to ride through the corresponding disturbance at the offshore AC connection point of the HVDC converter. A suitable control concept for the offshore windfarms including adaptions of the required grid-forming controls has been proposed and tested.

In order to enable a fast recovery of the DC grid after the occurrence of a DC grid fault, an effective power restoration scheme has to be installed which after fault clearing re-dispatches the converters to restore power flows to within normal operation ratings. Hence the restoration controller is coupled closely to the choice of grid.

Grid codes[12][13] - Alignment of existing requirements for HVDC systems at the AC connection point between different TSOs is considered to be possible, e.g. with regard to required functions from the HVDC systems or required timings such that there are more homogenous operational requirements in a future HVDC grid. To allow a multi-national HVDC grid, (future) HVDC system operators should agree on basic system design aspects[14], e.g. in a first step on standard DC voltage levels and ranges. The specifications of requirements in future grid codes should be done from a system perspective allowing the use and further development of proposed HVDC technology and control options[15].

[10] D3.4 - Operation of WPPs connected to DRHVDC
[11] D3.5 - Performance of ancillary services provision from WPPs connected to DRHVDC
[12] D2.4 - Requirements for grid code extension
[13] D3.8 - List of requirement Recommendations to adapt and extent existing grid codes
[14] D11.2 - Report on harmonization of HVDC systems
[15] D11.4 - Report on justified recommendations to grid codes

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Model validation[16] – The fidelity, accuracy and completeness of black-box models on converters and their associated control systems delivered by manufacturers are of key importance to ensure reliable grid integration. Harmonic impedance spectrum measurement by means of controller-hardware-in-the-loop real-time simulation is identified, worked out and proposed as an effective method[17] for the validation[18] of dynamic models of grid-connected VSC to prepare the grid for the electrification of future energy system.

a) HVDC system control demonstrator

b) Converter harmonic impedance model validation & black start demonstrator

Figure 10 – Control demonstrators

Demonstration - In order to verify the performance of the studied and proposed control & operational strategies, a downscaled DC grid test bench comprising down-scaled MMC converters and DC cable impedances has been realized[19] at RWTH Aachen, Germany. The MMC converters are controlled through real-time simulators allowing rapid prototyping of different control strategies. The AC grids are represented by linear amplifiers which are in turn controlled by real-time simulators enabling the mimicking the behaviour of different synchronous AC areas or of an offshore wind farm. Using this power-hardware-in-the-loop test circuit, the following aspects have been demonstrated[20]:

- The control and operational strategies to achieve stable operation and deliver ancillary services for multi-terminal HVDC grids in both steady state, dynamic and contingent conditions
- The compatibility of controllers between multi-terminal HVDC grids and offshore wind power plants in both grid following and forming control mode[21]
- Physical demonstration of DC circuit breaker based and full-bridge converter-based protection strategies

[16] D3.7 - Report with the compliance test procedures for DR and VSC connected WPPs
[17] D16.5 - Documentation of analytical approach
[18] D11.5 - Report with Recommendations to best practice for compliance evaluation
[19] D16.7 - Updated lab documentation
[20] D16.4 - Test case analysis WP2
[21] D16.3 - Test case analysis WP3

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In order to demonstrate the controller-hardware-in-the-loop converter harmonic impedance spectrum measurement as a black-box model validation method, a power-hardware-in-the-loop test-setup was created at the KEMA Flex Grid Power Laboratory in Arnhem, Netherlands. Using this power-hardware-in-the-loop test circuit, the following aspects have been demonstrated

- The harmonic impedance spectrum of the dynamic black-box model of a commercial 1 MW wind turbine converter obtained by control-hardware-in-the-loop measurement is validated by using results of a power-hardware-in-the-loop harmonic impedance spectrum measurement for the mid and low range frequency
- The harmonic impedance spectrum of the dynamic black-box model of a commercial VSC-MMC converter control replica is validated by using results of a control-hardware-in-the-loop harmonic impedance spectrum measurement
- The fault ride through of an HVDC VSC-MMC connected offshore wind power plant is demonstrated using a commercial HVDC VSC-MMC converter control replica.
- The black start capability of a commercial 1 MW wind turbine converter and controllers is verified using power-hardware-in-the-loop.

Figure 11 – Offshore wind farm control demonstrator

In order to demonstrate the control and operational strategies to achieve reliable and stable operation of and delivery of ancillary services of offshore wind farms connected to VSC HVDC converters and DRU HVDC converters, a real-time simulation test environment was set up at the University of Valencia. Wind farm and wind turbine controllers were connected to a real-time simulator in which primary HVDC transmission equipment and their controllers were simulated. Co-simulation with aero-elastic models ensured correct representation of turbine dynamics. Industrial protection IEDs were connected to be able to demonstrate protection aspects. Using this control-hardware-in-the-loop test circuit, the following aspects have been demonstrated[22]:

[22] D16.6 - WT CHIL + Protection Real Time demonstrator prototype

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- The HVAC black start capability of wind turbine and wind power plant controllers is verified using control-hardware-in-the-loop.
- The harmonic impedance of HVDC DRU connected wind power plants is characterised using a control-hardware-in-the-loop test bench.
- Grid forming controllers for offshore wind power plant in islanded operation are verified using control-hardware-in-the-loop.
- HVDC diode rectifier unit compatible wind turbine and wind power plant controllers are verified using control-hardware-in-the-loop

3.2 HVDC NETWORK PROTECTION

Multi-terminal HVDC systems will require a protection system to safely and reliably remove faults from the system so that operation can continue in the healthy remainder of the system. It has to do so whilst striking a balance between minimizing the interruption of power flow to an acceptable level and minimizing the cost of the protection system. No HVDC system protection had been applied anywhere at the start of PROMOTioN, so no consistent terminology, technology selection decision points, specification guidelines, testing standards or operational experience existed. PROMOTioN has de-risked HVDC grid protection through the development of consistent requirements, analysis models and tools and prototype equipment.

Technology selection - Vocabulary and functional requirements for fault clearing strategies for HVDC grids have been proposed, as their scope goes beyond the traditional scope of power system protection. Detailed protection sequences, including fault detection, protective actions and control actions have been proposed for each of the fault clearing strategies, clearly showing that protection and control are fundamentally interlinked. Technical key performance indicators to assess the performance of a given strategy have been proposed. The assessment of protection philosophies showed that several philosophies could serve as a viable technical solution to DC-side protection[23].

DC grid protection strategies could impact the frequency stability and the transient (angular) stability of the AC transmission systems surrounding the DC network due to a temporary nature of disturbance of the DC power flow, which can reach values of several GW for 100-200 ms. Hence the choice of fault clearing strategy is a balance between the number and type of HVDC circuit breakers[24] (speed and selectivity) on the DC network, and the cost of procuring additional frequency reserves to handle a temporary loss of infeed. A precise assessment of the AC stability issues requires detailed data of the AC system and its dynamics.

[23] D4.2 - Report on the broad comparison of protection philosophies for the identified grid topologies
[24] D4.5 - Requirements for DC switchgear

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No single protection strategy outperforms the others on all possible future grids, both on a technical and economic level, however, all the tools to evaluate them are developed.

Techno-economic assessment[25] - A risk-based cost benefit analysis is developed which allows to evaluate the cost-effectiveness of different protection strategies considering AC and DC side reliability based OPEX. Analysis of several benchmark networks showed that the additional cost of protection on a lifetime basis is 6-8% of the total network investment, and thus not considered to be prohibitive. Relaxing loss of infeed limit on temporary interruption can lead to substantial cost savings

Figure 12 - Prototype of PROMOTioN protection IED

Prototype - An academic and industrial-grade prototype IED (from Mitsubishi Electric) have been developed and used to demonstrate the principles of fast-acting protective relaying algorithms. The academic prototype IED is open-source available.

A prototype system supervisor for a non-selective protection scheme was developed.

Test environment - Test procedures[26] and the requirements[27] for the required test equipment to assess primary and back-up HVDC network protection operation and to evaluate the performance of HVDC IEDs have been developed. real-time models use for benchmarking[28] performance of real IED devices using hardware-in-the loop testing were developed, including integration of DC protection systems and prototype protection IEDs and HVDC circuit breaker models.

Demonstration - Demonstrated successful operation of fully[29], partially[30] and non-selective[31] protection schemes in a controller-hardware-in-the-loop real-time simulation test setup with industrial converter control & protection replicas of a real multiterminal HVDC grid at the National HVDC Centre in Cumbernauld, UK and at Super Grid Institute in Lyon, France. This is considered to be the

[25] D4.7 - Preparation of cost-benefit analysis from a protection point of view
[26] D9.5 - Hardware-in-the-loop test environment and guidelines for non-Selective protection systems demonstration
[27] D9.2 - DC grid protection testing guidelines
[28] D9.1 - Real-time models for benchmark DC grid systems
[29] D9.3 - Selective protection systems demonstration
[30] D9.4 - Demonstration of Selective protection systems interoperability and primary and backup protection
[31] D9.6 - Demonstration of Non-Selective protection systems interoperability and primary and backup protection

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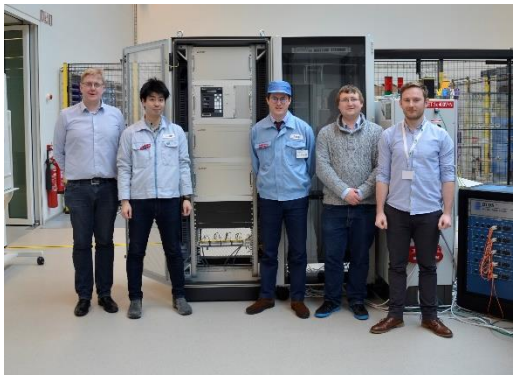
most realistic test case possible without installation on real power system. IED performance is expected to be sufficient for the potential future HVDC grids.



a) Industrial IED unit testing at KU Leuven

b) HVDC system protection testing at National HVDC Centre

Figure 13 - HVDC Network protection demonstration

Interoperability - It was shown that in principle different fault clearing strategies are compatible/interoperable with one another and grids with different protection strategies can be connected through grid splitting HVDC circuit breakers. Interoperability of the protection devices was demonstrated, proving that a multivendor protection system could be achievable, including the use of IEC61850 in some cases.

3.3 HVDC SWITCHGEAR

Switchgear and instrumentation are necessary to realize nodes i.e. substations in multi-terminal HVDC grids. For HVDC transmission networks both HVDC circuit breakers, which are capable of interrupting fault currents, and HVDC gas insulated substation equipment are necessary to create the nodes that connect the HVDC cables into a network.

3.4 HVDC GAS INSULATED SUBSTATIONS

Air insulated substation technology for HVDC is well-developed and mature, but requires a large footprint due to the necessary clearance distances, which results in large and thus costly platforms offshore. Gas insulated substation technology can reduce the volumetric space requirements by 90% and lead to a reduction of 10% of the platform costs. The technology is well-proven for AC applications but still nascent for HVDC. Moreover, SF6, the insulating gas which is traditionally used is a potent greenhouse gas, and its use is being avoided by most TSOs today. Research into the application of SF6 alternatives to HVDC systems has started but is in an early stage.

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Specifications[32] – Since there is no or little experience with HVDC gas insulated systems with TSOs and developers, PROMOTioN has developed recommendations for developing specifications for HVDC gas insulated systems in order to provide insight in how to use and apply this new technology.

Qualification[33] – As no formal testing standards currently exist for HVDC gas insulated systems, testing requirements, procedures and methods for HVDC gas insulated systems were developed based on simulation analysis, real HVDC onshore and offshore experiences, and based on CIGRE work. Most notably, a long-term so-called 'prototype installation' test programme was developed which comprises all main GIS components in one test object and represents realistic long term electrical and thermal stresses.

Monitoring[34] – Partial discharge monitoring is a well-known technique to assess the condition and diagnose degradation in AC primary equipment. The partial discharge behaviour in HVDC equipment is quite different and little experience existed. PROMOTioN researched an alternative partial discharge monitoring and diagnostics method based on magnetic detection, in contrast to the conventional capacitive detection on HVAC GIS. Concepts such as PD localization and charge estimation were investigated and proved feasible for critical offshore installation.

Alternative gases – In order to characterise the behaviour and performance of potential SF6 alternative gases in HVDC conditions, the partial discharge behaviour of artificial defects was studied. Three alternative gases were analysed and compared, their behaviour characterised and their applicability to HVDC conditions validated at Super Grid Institute. Sensitivities of several electrical and an optical partial discharge detection techniques were tested for the alternative gases, with the aim of building up a knowledge base of behavioural patterns that may enable the early detection of defects and degradation.

Demonstration – The maturity of HVDC gas insulated system technology was demonstrated through the successful testing of an industrial full-scale HVDC gas insulated system prototype test pole (Hitachi-ABB, 320 kV, 4000 A) at an independent industrial high voltage test laboratory (KEMA Laboratories).

[32] D15.1 - Document on recommendations for specifying DC GIS systmems
[33] D15.2 - Document on test requirements, procedures and methods
[34] D15.3 - Report on DC GIS diagnostic and monitoring tools and methods

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a) Long-term prototype installation test demonstrator

b) SF6 alternative demonstrator

Figure 14 – HVDC gas insulated substation demonstrators

3.4.1 HVDC CIRCUIT BREAKERS

Some HVDC network protection strategies require HVDC circuit breakers to interrupt fault currents and isolate faulty parts of the HVDC system at specific locations other than the converter terminals. HVDC circuit breakers are novel components, that differ strongly from their AC counterparts. At the start of PROMOTioN, no practical installations existed, and the technology had been proven on paper, by simulation and in small-scale lab set-ups. PROMOTioN carried out extensive literature research, modelling, analysis and demonstration of different HVDC circuit breaker technologies to gain understanding in their application, how to qualify their performance, and to mature the technology.

Modelling - A generic DC CB model, equivalent in structure for all known topologies, has been developed and comparison with detailed models concluded that accuracy is adequate for limited range of studies while simulation speed is significantly better. These models were used in the protection system evaluation studies. Simplified models for three DC CB technologies (hybrid[35], mechanical[36] and VARC) have been developed and comparison with detailed models concluded that accuracy is adequate for limited range of studies. Detailed models for three DC CB technologies (hybrid, mechanical and VARC) have been developed and analysis of test responses concluded that accuracy is satisfactory. Real time models for three DC CB technologies (hybrid, mechanical and VARC) have been developed and tested, and conclusion is that accuracy is good. These models were used in the real-time test environment to demonstrate the HVDC network protection.

A generic simulation test circuit for DC CB models has been developed and simulation verification has concluded that it can represent well all key functions of DC CB models.

[35] D6.1 – Offline models for hybrid DCCBs
[36] D6.2 – Offline models for mechanical DCCBs

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Bottom-up models were made to estimate the cost and dimensions of different HVDC circuit breaker technologies, which were used in the techno-economic comparison of HVDC network protection strategies, and in costing the scenario driven offshore grid topologies.

Small-scale prototyping[37] - The tests on lab-scale hardware DC CB demonstrators for hybrid and mechanical topologies concluded that responses and functional principles can represent the main operating principles of high-power DC Circuit breakers reasonably well.

Technology development[38] - Multiple improvements in hybrid DC CB have been proposed and simulation results together with lab-scale hardware demonstration concluded that improvements in DC CB speed and lowering costs might be possible.

The roadmap for development of mechanical DC CB and VARC DC CB to extra high voltages (525 kV) concluded that modular approach is the most suitable and feasible in a reasonable timescale.

Integration - The deployment simulation study for all 3 DC CB topologies on a relevant tests grid provided by a grid operator, concluded that performance is satisfactory for a wide range of expected DC faults.

Failure modes - The failure mode study provided insight into mechanism and consequence of failures for each major DC CB subunit and these conclusions have been confirmed on lab-scale demonstrators[39]. Generic failure modes of HVDC circuit breakers and their system impact were linked to failures of specific subcomponents.

Identification of stresses - Worst-case HVDC system short-circuit currents (ignoring travelling wave effects) can be modelled with generic passive equivalent circuits[40]. The complex waveforms of the stresses experienced by HVDC circuit breakers during short-circuit current interruption can be modelled with linear approximations[41].

High-frequency electrical and thermal measurements define stresses on vacuum interrupters and energy absorbers through experiments with an improvised DC circuit breaker up to 100 kV.

Inventory of non-standard stresses on standard components (mechanical switchgear, power electronics and energy absorbers) as applied in HVDC circuit breakers compiled. Testing dynamic

[37] D6.5 – Hardware prototypes of DCCBs
[38] D6.8 – Advanced DCCB topologies
[39] D6.6 – Demonstration and report on DC CB failure modes study
[40] D5.1 – Report describing the fault analysis severity versus fault location
[41] D5.3 – Report on fault stress analysis for the various technologies

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dielectric withstand of mechanical switchgear for insulation/interruption, especially when many are series connected, is necessary.

Test requirements - A full set of technology independent test requirements[42] for HVDC circuit breakers covering all operational stresses and standardized terminology is proposed. Test-requirements are available for (fault) current interruption, agreed among the partner-manufacturers and applied in the demonstration test campaigns.

Test circuits[43] - Due to inherent limitations in test circuit capabilities compared to real HVDC grids, HVDC circuit breaker technology qualification will consist of a series of separate tests, validating different aspects, and possibly exploiting the modular construction, together covering the complete stresses in multiple steps. Dielectric and operational tests can be carried out with existing standard test circuits already in use for testing other types of T&D equipment. HVDC short-circuit current breaking tests require significant amounts of energy which cannot be realized by existing standard test circuits. A test circuit based on AC short circuit generators operated at low power frequency together with a synthetic DC voltage source is capable of recreating the current, voltage and energy stresses required for testing the short-circuit current breaking capability of full-scale HVDC circuit breakers. A complete test environment for HVDC circuit breakers capable of providing full stress as in service is now readily available.

Demonstration - Three technologies of industrial HVDC circuit breakers up to 350 kV system voltage interrupting 20 kA of fault current have been publicly demonstrated in an independent industrial high-power laboratory[44] (KEMA Laboratories).

- ABB – Hybrid HVDC circuit breaker – 350 kV, 20 kA, 3 ms
- Mitsubishi Electric – Mechanical HVDC circuit breaker with active current injection – 200 kV, 20 kA, 7 ms
- SCiBreak – VARC HVDC circuit breaker – 80 kV, 12 kA, 2 ms

The demonstrations were the first time that independent verification of the complete fault current interruption process was carried out in a lab-simulated full-power HVDC grid environment.

[42] D5.4 – Document on test requirements
D5.5 – Document on test procedures
[43] D5.6 – Software and analysis report on candidate test-circuits and their effectiveness
[44] D10.7 - Full test set-up and documentation

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a) VARC HVDC circuit breaker

b) Mechanical HVDC circuit breaker

c) Hybrid HVDC circuit breaker

Figure 15 – HVDC circuit breaker demonstration

3.5 TECHNOLOGY READINESS LEVEL

PROMOTioN has carried out research, development and demonstration work on all four key technologies for meshed HVDC networks, thereby progressing their maturity. In order to objectively assess and quantify the actual progress made, the H2020 technology readiness level (TRL) framework with nine distinct maturity levels is used.

- The generic Horizon2020 TRL definitions are adapted to suit power transmission technology development. A distinction is made between hardware-based and software-based technologies
- An analysis of all technology research, development and demonstration steps was to assess their contribution to increases in TRL
- The technology readiness level of all key technologies was progressed to 6 or higher, which means they are ready for a real-world pilot
    - HVDC network and OWF control TRL increased to 6 ‘Technology demonstrated in industrial environment’
    - HVDC gas insulated systems TRL increased to 8 ‘System complete & qualified’
    - HVDC network protection TRL increased to 6 ‘Technology demonstrated in industrial environment’
    - HVDC circuit breaker TRL increased to 7 ‘System prototype demonstration’

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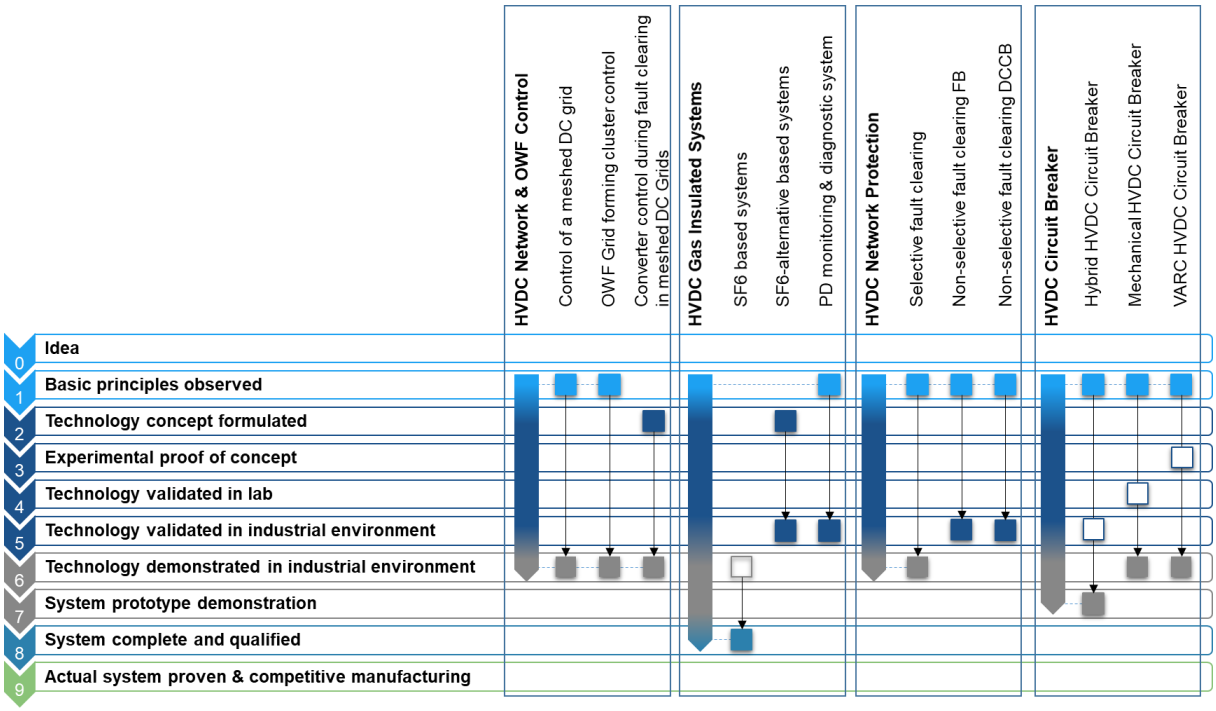

Figure 16 - TRL progressions made by PROMOTioN activities

Through the research, modelling, analysis, development and demonstration work carried out in PROMOTioN and by partner manufacturers, the technology maturity of the individual key technologies has been sufficiently matured that they are ready for a real-world pilot. Significant steps remain to be undertaken in the integration of the key technologies into a functioning system, and solve the vendor interoperability issues.

3.6 INTEROPERABILITY

In addition to sufficient technology maturity, the topology development in PROMOTioN assumed that different technologies can be integrated into one functioning HVDC system. In reality, this assumption of the interoperability and compatibility between the different systems and components from different vendors remains a major hurdle towards multi-terminal HVDC network building. This remains a challenge to which further research, development and demonstration needs to be devoted. The issue can be split into two aspects:

- Compatibility, which relates to the ability of two or more HVDC systems or HVDC components to perform their required functions while sharing the same HVDC environment
- Interoperability, which relates to the ability of two or more HVDC systems (or components) to exchange and subsequently use meaningful, actionable information across organizational boundaries

Both aspects can be further split between compatibility & interoperability between two different technologies such as converters and HVDC circuit breakers, and between two different organizations

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such as between equipment from different vendors, or grid systems from different owners. Hence and 'HVDC environment' is not purely technical but also covers operational rules, market rules, governance, etc.

Compatibility and interoperability are typically achieved through alignment of ratings and functionalities, and standardisation of interfaces. PROMOTioN has determined seven different levels on which harmonisation, standardisation or alignment is necessary in order to achieve compatible and interoperable systems. Specific recommendations for stakeholders on each level have been worked out and included in the deployment plan.

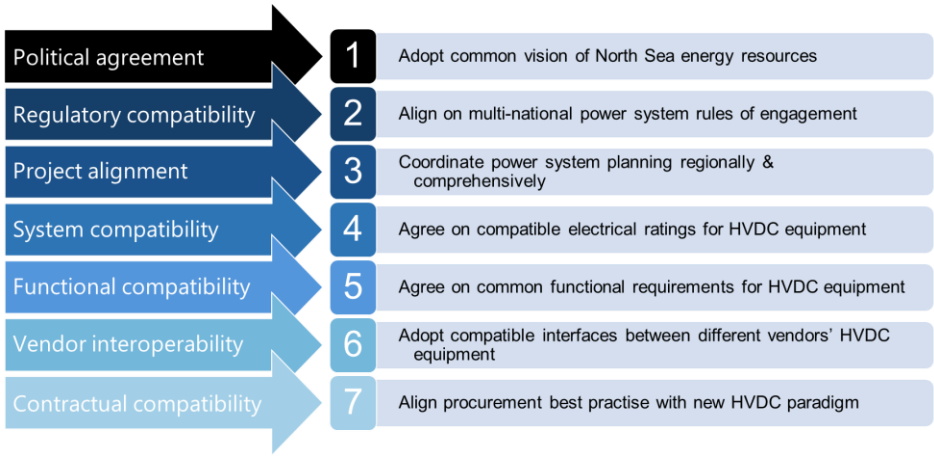

Figure 17 – Seven levels of compatibility and interoperability identified by PROMOTioN

PROMOTioN has contributed to achieving compatibility and interoperability through the following steps:

- Analysis of functional behaviours of different technologies, development of recommendations for a DC grid code, and the demonstration of different DC grid configurations, protection and operational strategies. The main challenge will be to define technology neutral requirements for events such as DC fault ride through
- Protection systems developed in PROMOTioN are published as open-source and use standardized communication protocol IEC 61850 to facilitate integration with equipment of other vendors
- Protection systems developed in PROMOTioN and the protection system developed by Mitsubishi Electric were successfully integrated and tested with industrial converter control & protection replicas in the National HVDC Centre, demonstrating that multi-vendor interoperability between control systems is in principle possible
- Testing procedures for HVDC GIS[45] and HVDC circuit breakers were developed as much as possible in a technology neutral way, agreed with all participating manufacturers, and

[45] D15.6 - White- and position papers on prestandardization of DC GIS testing

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applied to the demonstrators in an equal way, demonstrating performance of different technologies from different vendors towards common technology requirements.

- Methods for the validation of models of vendor-specific converter controllers were developed and demonstrated, to facilitate the reliable integration studies for converters of different vendors.
- Common technology and vendor neutral requirements and compliance evaluation procedures for offshore wind turbine generators and wind farms were developed and demonstrated
- PROMOTioN results were actively shared with standardisation bodies to facilitate uptake and agreement within the wider industry stakeholder community
- PROMOTioN has initiated work on assessing the opportunities for making the upper-level controllers of converters available as open source, thereby greatly simplifying integration of equipment from different vendors whilst guaranteeing a stable remuneration of vendors of the control systems

Through the results and experience gained with the above activities, PROMOTioN has contributed to a significantly improved understanding of the challenges involved in achieving interoperability, and the prerequisites and processes required to do so.

3.7 STANDARDISATION

A key aspect of achieving compatibility and interoperability, as well as being a key indicator of technology maturity, is standardisation. PROMOTioN has dedicated a specific work package to ensuring PROMOTioN results and learnings[46] are actively shared with the standardisation bodies.

- Compliance evaluation of HVDC systems relies on exchange of models and compliance test results between TSOs, project developers / owners and manufacturers of components including HVDC converter systems and wind turbines. PROMOTioN contributed with modelling and test procedures of harmonic / multifrequency impedances which will be forwarded to CIGRE and IEC standardization. PROMOTioN recommends standardization of functional requirements to EMT models.
- Standardization of functional requirements to grid forming operation e.g. for black start operation will be needed. PROMOTioN has contributed to this by simulations and HILs studies which will be input to future standardization.
- In existing commission regulations, the need for compliance tests and simulations is only specified for a few requirements. PROMOTioN recommended a more systematic approach to ensure that the needed models will be available and validated to ensure that grid operator can ensure compliance in the multi-vendor HVDC system.

[46] D11.1 – Harmonisation catalogue

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- Standardization is needed for protection systems in multi-terminal DC systems. PROMOTioN has contributed to harmonization of performance evaluation, communication, specification and functional testing of protection systems.
- Standardization of circuit breaker tests[47] is essential to develop multi-terminal DC systems based on multivendor suppliers. PROMOTioN has developed agreement among key manufacturers on test programs for HVDC circuit breakers. This experience is brought forward to CIGRE and IEC to be utilized in standardization.
- PROMOTioN has developed prototype installation test of HVDC GIS equipment and contributed to initiate standardization of test programs.
- PROMOTioN has shared test results from the technology demonstrations in order to inform and help shape the currently ongoing standardisation initiatives. The project has mapped the needs for grid code compliance evaluations to ensure stable operation of future multiterminal HVDC systems, including model needs, approaches, phases and outputs.

DC grid codes are seen as a key enabler to facilitate multi-terminal HVDC grid development. To date there is no DC-side grid code available yet. To write such a grid code in a technology-neutral way is challenging due to the broad range of proposed technologies to be used in future HVDC grids, e.g. for fault clearing. It cannot be expected that a DC grid code will be developed in one step, rather a step-wise development can be expected, with standardisation and best practices coming first.
Needed research on suitable DC grid code specification entails, e.g

- Further study the interaction between AC and DC side to be able to specify the requirements on the system in a holistic way, e.g. with regard to required energy exchange and its dynamic under contingencies in either system.
- Identifying suitable ways to specify the requirements on control modes and the converter behaviour at the point of connection, e.g. options to specify the behaviour in the frequency domain.

Work on these topics has started within PROMOTioN and the standardisation efforts with regard to functional specifications for HVDC grids, e.g. in the CENELEC TC8X WG06 between vendors, TSOs and academia have been supported by the insights gained within PROMOTioN.
During the run-time of PROMOTioN, ENTSO-E has increased work on these topics, e.g. stating the need for standardisation for cost-reduction and also the evolved DC voltage levels, of 320 kV and 525 kV, in a published position paper on offshore development. This resembles the voltage levels used in PROMOTioN for the offshore system analysis. In general, this coordination is especially needed for the proposed system development in the North Sea.

[47] D10.8 - White- and position papers on prestandardization of HVDC CB testing

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4 LEGAL, REGULATORY, ECONOMIC & FINANCIAL

A main barrier to the realisation of meshed offshore multi-terminal HVDC transmission networks is the absence of suitable legal, regulatory, economic and financial frameworks to establish governance, create a clear view on the definition and split of costs, benefits and risks, create market models that incentivize grid development, and to provide sufficient long-term stability to attract financing. PROMOTioN has carried out a desktop study of the current frameworks in the North Sea countries and based on this developed recommendations and suggestions to create a level playing field and long-term stability[48].

4.1 LEGAL[49]

4.1.1 DEFINING OFFSHORE HYBRID ASSETS

An adequate legal and regulatory framework is necessary to turn the market player's great investments in the project into viable investments. Central to the project's legal framework are hybrid assets i.e. cables between at least two countries and at least one offshore wind farm. Their current classifications as interconnector puts the asset at a disadvantage: reforms with respect to EU law (as exception for hybrid assets) or the bidding zone model are necessary and should be implemented urgently. In the short term it is recommended to adjust the Electricity Regulation to include a Hybrid asset definition. Firstly, it needs to be introduced in Recital (66) of Electricity Market Regulation; secondly, substantive law needs to be added. In the long-term it is recommended to create a common interpretation of UNCLOS by a multilateral agreement. The alternative to the hybrid asset definition can be also offshore bidding zones but that can have the drawback of a long implementation time

Legal and Governance Framework - States currently coordinate their plans bilaterally (as opposed to regionally) and most coastal states cooperate with each other in the context of the EU. There is no international agreement for the cooperation of the North Sea states to which the states participating in the MOG, as well as the EU (as the competent authority for many energy market related topics) are signatories. It is recommended to adopt a '**mixed partial agreement**' (signatories should be states participating in the MOG, as well as the EU) to set out the objectives and high-level principles of the MOG, including a structure for:

- governance,

[48] D7.9 - Final policy recommendation package
[49] D7.2 - Report establishing EU legal framework

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- liabilities,
- decision making,
- cooperation and
- dispute resolution.

This provides legal certainty for the states, the grid owners and the parties connected to the grid. In conjunction, National Regulatory Authorities (NRAs) should organize themselves in a specific regulatory coordination group to oversee grid development and operations.

4.1.2 DECOMMISSIONING

There are no guidelines supporting decommissioning of offshore assets and rules for decommissioning offshore assets vary by country, and often do not account for the fact that some aspects of an offshore wind development may have a longer lifespan than others (e.g. a hybrid transmission asset may continue to be used as an interconnector after the end-of-life of a wind farm). It is recommended to agree and adopt on a general standard process: transmission cables should left in place at the end of life of a wind farm, unless in a sensitive area with high shipping or fishing activity, changeable sea bottom or areas such as the beach. The decommissioning requirements for OWFs should be based on a case-by-case assessment by the relevant permitting agency, during the planning process. This could for example be either complete removal or foundation left in place. Any assets which remain in situ after their useful life should fall under the responsibility of the state provided that the state is compensated for potential future costs (e.g. ring- fenced fund). Any guidelines for decommissioning should be agreed upon at an international level such as International Maritime Organization (IMO) or OSPAR.

4.2 REGULATORY

4.2.1 OPERATION OF THE MOG

So far, only interconnectors and radial connections to OWFs have been operated as offshore assets by system operators, however operating a multi-connection meshed system connecting offshore windfarms to several countries and respecting the framework of the system operation guidelines is extremely complex. It is recommended to evolve the governance of system operation towards a North Sea Regional Coordination Centre. A staged approach should be adopted to support the creation of an adequate knowledge base for any operator involved in the dispatching and operation of the MOG and its interfaces with onshore systems. As part of this, the Balancing Mechanism design should be enhanced to remove barriers to entry for OWFs as BRPs as well as BSPs. For Balancing Mechanisms a single price rule, small bid sizes, gate closure close to real time as well as a liquid intraday market are needed.

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4.2.2 PLANNING: ORGANIZATION

Planning and permitting procedures are perceived as a key risk in large infrastructure projects. Permitting issues become increasingly burdensome when the projects concerned span more than one jurisdiction, with the possibility of these risks materializing in two (or more) countries. Permitting can cause offshore infrastructure projects to be delayed by several years. It is therefore recommended to streamline the permitting processes to reduce the risk of legislative change during the permitting phase. There should be no retroactive impact of legislative changes on projects that have already approved. Once granted, permits/licenses should remain valid for the duration of the construction and operation phase. A central approach for grid planning should be adopted, with strong coordination of grid development plans (timing, location) to increase the transparency of future network investments requirements and their cross-border impact. The number of and interdependency between national grid development plans should be greatly simplified. Until such centralization is established, national planning and permitting procedures should separate the processes for the wind farms from that for the cables but coordinate to ensure alignment of the projected commissioning dates.

Stakeholder objections to new OWF or transmission asset development has historically been a cause of significant delay and could prevent or hinder the deployment of the MOG. Wind farm developers and transmission system developers should use the evidence and tools presented in the literature, to develop strategies for understanding public opinion and broadening active public participation.

4.3 ECONOMIC[50]

4.3.1 PLANNING: COST BENEFIT ANALYSIS[51]

Several CBA methodologies were assessed and found not to fully account for the interdependencies of meshed grid projects. Interactions between (offshore) PCIs could thus be overlooked. It is recommended to introduce clearer criteria on when projects should be considered as part of a cluster for CBA. Furthermore, a project should be compared against two baselines (TOOT and PINT) in order to identify potential synergies between new projects.

Currently, there is a lack of transparency about costs in decision making process for PCIs which affects gaining trust and public acceptance. In order to tackle this, it is recommended to harmonize and disaggregate cost and benefits reporting (with an ambition to move towards an open source CBA model).

[50] D7.4 - Report establishing EU Economic framework
[51] D7.11 - CBA methodology for offshore grids

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Decisions about PCI investments are not always objective and based on complete CBAs. It is recommended to reducing the politics in the valuation of PCIs by carrying out a fully monetized CBA of the value of project. The eligibility and monetization criteria should be agreed upfront by all parties.

4.3.2 PLANNING: GRID TARIFFS

The regulatory handling of the grid connection costs of OWF is done differently between the North Sea countries. It is recommended to develop regionally consistent approaches about selecting wind farm locations, onshore grid access responsibility and grid connection charges.

The transmission charges paid by generators for access to the transmission network are not harmonized across Europe. Furthermore, for assets connected to more than one country there is currently no mechanism for calculating their transmission charges. It is recommended to align transmission tariffs across the North Sea countries (this would also create solutions for OWF connected to multiple countries).

4.3.3 ELECTRICITY MARKET

Currently, subsidies paid to RES are recognized only when electricity generation is effectively delivered from the EEZ in which it is generated into the respective country, thus preventing RES generation to move freely. In case of a MOG this could lead to suboptimal grid design. There are two recommendations to overcome this problem. In the short term, decouple physical electricity flows from market flows when it comes to support for RES. In the longer term, establish a joint fund (or joint support scheme) and calculate each country's contribution ex-post, based on the principle ”beneficiary pays”.

The electricity generated in one EEZ will likely flow to the EEZ with the highest price. Market structures could evolve from the current extension of country bidding zones into the offshore EEZ to small offshore zones models. The small bidding zones model contains optimal incentives for efficient dispatch, also in the presence of (hydrogen) storage or other types of consumption offshore. Similarly, it avoids the need for counter trading. A “bidding zone” was defined as an area where the electricity price is the same. Hubs close together and without congestion between them would be in the same bidding zone. This would be the case where multiple wind farms are connected to a single interconnection point. However, the more dispersed are the wind farms, the more likely is a cost-price difference between hubs, resulting in a loss of social benefit. Where there is congestion in some circumstances between hubs or groups of hubs, we would create a (small) bidding zone, with the congested links crossing the borders of the price zones.

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It is recommended to develop a joint support scheme for offshore wind farms, or at least to avoid prohibitive differences, and to implement the 'beneficiary pays principle'. At the current stage, bidding zones in Europe are mostly based on the national borders with a few exceptions[52]. This is not always optimal from the economic point of view.

4.3.4 TRANSMISSION OWNER REVENUE

The absence of a clearly defined regulatory framework increases the risk of the investment and discourages investors from investing in the grid. It is recommended to create a long term and stable regulatory framework which will increase the 'bankability' of offshore transmission assets, defining roles, responsibilities and liabilities of investors, constructors and managers; to provide institutional investors and debt and equity providers with the clarity needed to assess the investment risk.

In some North Seas countries, TSO legal ownership restrictions hinder private equity provision and the amount of debt they can leverage. TSO balance sheet constraints and often legal ownership restrictions hinder private equity provision. Offshore grid asset ownership should be designed to ensure the participation of multiple funding sources to support the challenging volume of required investments and avoid TSO financing constraints. Grant flexibility regarding access to private equity to overcome the TSOs' balance sheet constraints and optimize allocation of capital available from global investors.

Relying solely on congestion rent as investor income is not a viable long-term business model for MOG assets and would struggle to attract investment, in case MOG transmission assets were treated as exempted (merchant) interconnectors. It is recommended to allow offshore hybrid asset income based on regulated income (with incentives and adjustments to encourage good performance) rather than on congestion rent. Where offshore assets are remunerated as part of a wider regulated asset base (RAB), a possible regulatory grant of additional dedicated investment could be considered to account for the additional risk of offshore investment. Individually owned assets should receive a fixed revenue depending on the availability and performance of the assets and on market indicators (e.g. UK OFTO-regime)

4.4 FINANCIAL[53]

4.4.1 FINANCING INVESTMENT

Anticipatory investments are considered vital to prepare infrastructure for future expansion into a MOG. Currently there are no national regulatory incentives for cross-border anticipatory investments

[52] https://raport2016.pse.pl/files/aktywny_udzial/MAPA_EUROPA_2.svg
[53] D7.6 - Report establishing EU Financial (governance) framework

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regarding hybrid assets (with the exception of the WindConnector in the Netherlands). It is recommended to enable support by the EU public financing (CEF/EEPR funding) for the remuneration of the necessary cross-border anticipatory investments for the early phase of the MOG.

The construction phase entails the highest risk of a transmission project due to technical risks and potential delays arising from permitting and public processes. The regulatory framework should support the provision of revenues during construction to reduce investors' risk, to make finance more readily available at lower interest rates during these riskier periods and to reduce the interest accrued during construction.

Some North Seas countries include funding for innovation in the price controls of their TSOs however this is not common across all countries. In addition, legislation relating to transmission networks can be a barrier to deploying innovation in the grid. Support for technological innovation through EU funding at the early stage of the infrastructure development is also a key enabler and it is recommended to accompany the project deployment with a regular review of the future developments in the energy sector and its associated technologies.

Cross-border investments will only be taken up by investors if adequate financing structures like tenders or SPVs are allowed and liabilities are clearly allocated for all types of investors

4.4.2 CROSS-BORDER COST ALLOCATION

As cross-border grid development such as envisioned in a MOG is unprecedented in Europe, a significant scope for improvement exists in application of cross-border cost allocation (CBCA) in the offshore context. The key areas to be considered are:

- Use of significance threshold for CEF
- Conducting Market tests
- incorporate binding contracts
- Consider project interactions
- Innovative approach to CBCA
- Reach complete CBCA decisions

PROMOTioN has developed four recommendations in this regard. Firstly, it should be ensured that CBCA decisions are complete, considering how costs would be allocated between nation states, both with and without a contribution from the EU's Connecting Europe Facility (CEF). Secondly, CBCA decisions for complementary projects should be coordinated by taking a clustered approach e.g. a single CBCA agreement for a group of projects. Thirdly, the CBCA agreement should be a binding contract between the involved parties, with a clear specification of non-compliance penalties to formalize the cooperation, especially with respect to commissioning dates, ensuring greater commitment towards the project and construction of stranded assets. Lastly, the interaction between

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the significance threshold and EU funding should be revisited, for more effective cost allocation by encouraging complete CBCA decisions as well as enable effective EU funding allocation.

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5 IMPACT

By achieving its main objectives, PROMOTioN aims to contribute maximally to the expected impacts of the 'Competitive Low Carbon Energy' call topic 5 'Innovation and technologies for the deployment of meshed offshore grids'. The main aim of LCE is to make Europe's energy system cleaner, more secure and more efficient. One of the sub-goals for this is to increase the levels of integration of renewable energy, especially of offshore wind. Meshed offshore HVDC transmission networks are seen as a key enabler for this. The realisation of such a network will lead to improved productivity of European industry, improved competitiveness, lower energy prices and reduced environmental impact.

5.1 CONTEXT

The PROMOTioN project has taken place during a period 2016-2020 of rapid development and growth in both the offshore wind as well as the multi-terminal HVDC network sectors. This had an impact on both the relevance, scope and impact of the project. Acting on developments and ensuring the focus of the project remained aligned with the state-of-the-art, PROMOTioN has both had an impact on and been influenced by several global events and initiatives.

EU Energy Targets[54] – At the start of PROMOTioN in 2016, the official EU energy targets were to have 27% of the energy consumption in 2030 to be generated by renewable energy sources. Since then, this figure has increased to 32% and is likely to increase again as the commission as proposed to increase the CO2 reduction target from 40% today to 55% reduction in 2030 compared to 1990 levels. At the same time, the interconnection target has increased from 10 to 15%. These upwardly changing targets place an increased relevance and urgency behind the results of projects such as PROMOTioN to deliver the enabling technologies and regulatory frameworks to achieve this.

North Sea Energy Cooperation[55] – Starting in 2016, the North Seas Energy Cooperation, the ministers of the North Sea countries and Luxembourg have committed to jointly work on removing hurdles to large scale offshore wind development by addressing maritime spatial planning, planning & permitting, offshore grids, etc. PROMOTioN has had regular and targeted stakeholder interactions with the NSEC and presented at the North Sea Energy Forum, as well as joint stakeholder meetings. As such, PROMOTioN results and conclusions have been actively shared and discussed with NSEC and have helped steer and shape the discussions and ensuing actions.

[54] https://ec.europa.eu/clima/policies/strategies/

[55] https://ec.europa.eu/energy/topics/infrastructure/high-level-groups/north-seas-energy-cooperation_en

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North Sea Wind Power Hub[56] – Announced in 2017, the initiative by TenneT, Energinet, Gasunie and Port of Rotterdam to build hubs on islands and combine this with power-to-X has put a strong spotlight on the choices to be made in offshore grid development. With two of the involved parties being part of the PROMOTioN consortium, technical and regulatory specialists from the NSWPH have taken part in PROMOTioN, both as contributors as well as in dissemination events such as workshop and technology demonstrators, ensuring PROMOTioN results are well known and accessible by them.

WindConnector[57] – In 2017 TenneT announced the possibility for building a link, the 'WindConnector' from the Dutch IJmuiden Ver offshore windfarm, to either the UK Norfolk windfarms or directly to the UK shore, thereby creating a hybrid asset. Realising this type of asset requires addressing both technical and regulatory barriers. Representatives of PROMOTioN partners were involved in the studies into the feasibility of the concept, ensuring the direct application of PROMOTioN legacy. Futhermore, PROMOTioN has carried out a short-term feasibility study on the placement of an HVDC circuit breaker in the WindConnector and actively liaised with the WindConnector team on this topic.

Small Bidding Zones[58] – Starting 2018, PROMOTioN has developed the small bidding zones market model, as opposed to the current approach of using EEZs as bidding zones. This market model is the most economically optimal and reduces regulatory issues. To guarantee a stable revenue stream for wind farm operators, additional measures are foreseen to reduce the low price risk. The small bidding zone model discussion has since been presented with partner TSOs, national miniseries, the NSEC, ENTSO-E, NSWPH and WindEurope. It is now adopted as the preferred vision for the North Sea grid by many of these stakeholders.

TenneT (2 GW 525 kV) platform standardisation[59] – In line with (but not necessarily as a result of) PROMOTioN recommendations, TenneT is developing a standardised multi-terminal ready 2 GW 525 kV HVDC platforms for use in the IJmuiden Ver and other future offshore windfarm connections. The technical personnel from TenneT has taken part in PROMOTioN tasks and dissemination events, and hence PROMOTioN technical learnings, with a focus on the use of gas insulated switchgear has been directly accessible, facilitating the uptake of the technology and the low cost implementation of the platform. Furthermore, in line with PROMOTioN recommendation, the Dutch government has approved the anticipatory investment for additional space to connect an additional bay for multi-terminal expansion of the platforms.

[56] https://northseawindpowerhub.eu/

[57] https://www.tennet.eu/news/detail/study-suggests-a-windconnector-linking-dutch-and-gb-electricity-markets-and-offshore-wind-farms-coul/

[58] https://northseawindpowerhub.eu/wp-content/uploads/2020/06/NSWPH-Discussion_Paper_Market-Setups-for-Hybrid-projects1.pdf

[59] https://www.tennet.eu/news/detail/tennet-develops-first-2gw-offshore-grid-connection-with-suppliers/

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Hybrid asset classification[60] – PROMOTioN has developed specific recommendations for hybrid assets i.e. wind farms that are connected to more than one country, to be included as a separate asset class in the EU electricity regulation. This is important for projects such as the WindConnector, and now the Nautilus link which foresee the possibility of connecting a wind farm in the middle of the interconnector. Without it, the connection is either seen as an interconnector, which means 70% of its capacity must be freed up for the market, or as an offshore wind farm export link, which means that it cannot be used for trading electrical energy. The Kriegers Flak project is the first such project in the EU and received an exemption to the rule. PROMOTioN has actively engaged with the NSEC and the EU to include a separate asset definition to create clarity, resulting in a recital (66) in the recast electricity regulation in 2016. This is considered a step in the right direction, but requires the addition of substantive law.

EUROBAR[61] – In 2020 Amprion presented its EUROBAR concept for offshore grid development. The concept essentially foresees in modular technically standardised HVDC converter platforms which can be initially be built radially and later interconnected, first in national EEZ's and then across borders. This would result in an offshore HVDC backbone network in the North Sea, distributing renewable energy sources across North Sea and Channel countries.

ENTSO-E: Offshore development position paper[62] – In 2020, ENTSO-E published its offshore grid development position paper echoing the PROMOTioN conclusions of the need for coordination, modularity & standardisation, step-wise development, need for interoperability, need for innovation and above all the need for a future proof regulatory framework. PROMOTioN has closely liaised and interacted with ENTSO-E as a key stakeholder, and many of PROMOTioN's partners are also part of ENTSO-E. Hence PROMOTioN findings and conclusions have all been brought to ENTSO-Es attention and helped inform ENTSO-Es position on offshore grid development.

Danish energy islands[63] - PROMOTioN work has concluded that clustering offshore wind farms in offshore hubs has the potential for the lowest cost. These results were actively shared in a targeted workshop with the Danish ministry of Climate, Energy and Utilities, Energinet and with the Danish Energy Agency. In parallel, PROMOTioN has carried out a feasibility study on the CleanStream[64] project which foresees in using the existing Bornholm island as an offshore wind hub with connectors to both Denmark and Poland. In 2020, the Polish government announced its commitment to building two offshore energy islands, one in the North Sea and one on Bornholm island. PROMOTioN work

[60] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0943&from=EN

[61] https://www.amprion.net/Press/Press-Detail-Page_25536.html

[62] https://www.entsoe.eu/2020/05/29/entso-e-position-on-offshore-development/

[63] https://in.reuters.com/article/us-climate-change-denmark/denmark-plans-to-create-energy-islands-in-baltic-and-north-sea-idINKBN22W1NC

[64] https://www.promotion-offshore.net/fileadmin/PDFs/D12.4_STP_Supplement_Bornholm.pdf

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has given useful input and a direction for possible future implementation thereby expediting the deployment of these islands.

UK offshore coordination[65] - PROMOTioN has actively engaged the key UK stakeholders through general and targeted dissemination. In 2020, OFGEM and NG ESO announced the intention to investigate the feasibility and benefits of more coordination of offshore grid connection deployment for offshore wind and interconnection. PROMOTioN results are therefore known and can be directly used to inform this process and speed-up uptake.

ENTSO-E: proposal for multi-vendor HVDC systems[66] - One of PROMOTioN's main recommendations is to address the issue of compatibility, DC system integration and vendor interoperability of HVDC systems. In 2020, ENTSO-E has started development of a proposal for a workstream to address this. PROMOTioN was consulted on the contents of the proposal and several PROMOTioN partners take part in the preparation, so PROMOTioN conclusions, results and recommendations for further work have been well represented.

Chinese multi-terminal HVDC projects[67] – Multi-terminal HVDC systems have also been in rapid development in China. Three multi-terminal HVDC transmission systems, Na'nao, Zhoushan and Zhangbei have now been commissioned and are in operation, including HVDC system protection. In order to ensure an up-to-date awareness of the Chinese developments, PROMOTioN has actively engaged with Chinese stakeholders in joint dissemination seminars and standardisation initiatives. One of PROMOTioN's partners was also directly involved as supplier of equipment to the Zhangbei meshed HVDC grid, potentially exploiting and benefitting from PROMOTioN results in the progress.

5.2 SOCIO-ECONOMIC IMPACTS

The work carried out in PROMOTioN has shown that meshed HVDC offshore transmission networks are no longer an academic concept but a possible future reality. The technology is now seen as a serious enabler and has the potential to accelerate the energy transition in Europe. The impact of the PROMOTioN work can be analysed[68] along three different dimensions; science, economy & society and policy, which can each be subdivided in short-term and long-term impacts, and direct and indirect impacts.

65 https://www.ofgem.gov.uk/system/files/docs/2020/08/increasing_the_level_of_coordination_in_offshore_electricity_infrastructure.pdf https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project
66 https://windeurope.org/wp-content/uploads/files/policy/position-papers/20200602-WindEurope-response-to-ENTSOE-workstream-proposal-on-HVDC-multi-vendor-systems.pdf
67 https://www.tdworld.com/grid-innovations/transmission/article/20971926/worlds-first-hvdc-grid-enabled-in-china
68 Airaghi A., Busch N.E., Georghiou L., Kuhlmann S, Ledoux M.J., van Raan A.F.J. and Viana Baptista J. (1999): Options and Limits for Assessing the Socio-Economic Impact of European RTD Programmes, ETAN, Commission of the European Communities, January 1999

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5.2.1 SCIENCE

Even though in essence a technology demonstration project, a good deal of scientific research has been carried out in PROMOTioN in order to advance technology or develop different solutions. Examples are new types of HVDC circuit breakers, new insulating gases for HVDC, or new control strategies. Apart from improving academic standing of European HVDC research institutes as evidenced by the large number of journal and conference publications, it has provided impetus to HVDC product and technology development, and contributed significantly to a growing body of knowledge on how to design, realize and operate meshed HVDC transmission grids.

Indirectly, the cutting-edge research done by the many academic partners in PROMOTioN has led to an improved understanding and thereby to improved teaching. This is a key impact of PROMOTioN as a large number of PROMOTioN students, motivated by the high-class teaching and research work and connected to their European peers, are now transferring to jobs in the transmission industry and take their understanding of meshed HVDC grid technology with them, thereby changing the overall thinking and culture at these companies in favour of meshed HVDC grids and accelerating their uptake.

In the long term, the methods, skills and tools that were developed to address the technical and legal questions that were solved in PROMOTioN, are lifelong attributes of the people and partners that carried out the work. Even after realizing results in PROMOTioN, these attributes will continue to deliver value by being applied to different, new problems. In addition, technologies developed for the purpose of meshed HVDC grids may also find use in different perhaps unexpected fields of application. An example is the SCiBreak HVDC circuit breaker which due to its fast operating speed has also been shown to benefit certain AC applications.

5.2.2 ECONOMY AND SOCIETY

The analysis carried out in PROMOTioN has led to an improvement of the technologies necessary for meshed HVDC transmission networks. The realization of full-scale test objects for demonstration forced OEMs to further the development and industrialisation of their concepts, in addition the scientific research identified additional improvements such as novel hybrid circuit breaker control methods. In the long term, the experience gained though all the PROMOTioN work has led to substantially improved technical know-how, which is translated into best practises and standardisation, but most importantly in lowering perceived technical barriers to multi-terminal HVDC grid development.

Due to the long time scales involved in HVDC grid realisation, the improvements in technology and the improvements in technical know-how have in the first instance led to increased productivity with

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the offshore grid planners. All North Sea countries are now considering and planning offshore HVDC grid infrastructure and seriously considering the benefits that multi-terminal and meshed implementations could unlock. This spurs activity in the entire HVDC grid ecosystem, starting with the feasibility and CBAs already being carried out by consultants, and ultimately leading to new product orders and requests for technology testing. PROMOTioN has developed the tools and methodologies to enable them to do this. The scale required to build the grid to connect just the offshore wind ambitions will lead to a tremendous growth the in manufacturing and offshore construction industry, and after commissioning a huge maintenance and operation industry.

Ultimately, this will lead to improved competitiveness of European companies in the European HVDC grid technology sector and the according job growth. The technologies and methods developed in European projects can be applied globally to solve the changing and simultaneously increasing transmission need. If properly implemented, the meshed offshore HVDC transmission network can also play a key role in achieving the most cost-effective and reliable transmission option for a clean energy future, giving European countries and there industries a competitive edge in a world where carbon will in the future come at a price.

5.2.3 POLICY

With regulation and policy often being seen as the main hurdles to the realization of the energy targets, PROMOTioN has made a significant impact in improving the understanding and raising the awareness of the gaps and short-comings in different national regulatory frameworks, the interactions, and unwanted side effects due to differences or unforeseen applications.

Building on the experience gained in the desktop studies of the regulatory shortcomings, a problem-solving approach could be adopted by PROMOTioN and concrete recommendations for overcoming the hurdles were made. Several of these recommendations have been taken up and are being discussed and considered for adoption by key stakeholders.

By creating more awareness of the differences in national approaches, and how these can lead to suboptimal deployment of renewable energy sources and thereby hinder the realization of socio-economic benefit, the work done by PROMOTioN can foster improved European collaboration. Removing regulatory barriers enables the integration of energy markets, lowering energy costs, improving reliability, reducing environmental impact and thereby improving general satisfaction of the European consumer.

5.3 EXPLOITATION OF RESULTS

The main outcomes and results of PROMOTioN will be exploited by the participating operators, developers and manufacturers through uptake in their natural business, during the project and in the

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near future. The HVDC innovations worked on in PROMOTioN are already within the core strategic domains of all involved operating, developing and manufacturing companies.

PROMOTioN has deployed the H2020 Support Services of Exploitation of Results (SSER) as key vehicle to advance on delivering project key exploitable results (KERs). Their Exploitation Strategy Seminars (ESS) provide excellent means to mobilizing organizations on their KER-efforts like methodologies and a common language; Project and the research work done or to be done in the future are considered in terms of key exploitable results. These are results, which have commercial and/or societal significance. The results selected for the discussion during the ESS are characterized from a viewpoint which is exploitation only, how they will be used to generate an impact. This is the market/customer demand or societal needs/user point of view. For each of them, risks connected to exploitation are then mapped and prioritised.

In the table below the 37 KERs which were identified in PROMOTioN are indicatively and individually scored on their contributions to the different project objectives as outlined in section **Error! Reference source not found.**. Some KERs contribute in several objective areas; a bold **x** is used when one objective clearly stands out for the respective KER contribution.

			Objectives					
SHORT NAME	KER #	TYPE OF EXPLOITATION	**1**	**2**	**3**	**4**	**5**	**6**
DNV GL	1	Service	x			**x**		
KEMA	2	Service	x	x	**x**			
ABB	3	Product			x			
KU Leuven	4-7	Service Development of a new standard Further research/ education		x		 x	 x	
KTH	8	Product/further research	x	**x**				
EirGrid	9	Increased knowledge		**x**	**x**			
SGI	10-12	Services/ Products/ Further contract research	 x x	 **x** **x**	x **x** x			
DWG	13	Service				x		x
MEU	14-15	Products	x	**x**	**x**			
SvK	16	Increased knowledge		**x**	**x**			x
UniAbdn	17	Patent		x				
RTE	18	Development of a new standard					x	
TU Delft	19	Services		x				
Equinor	20	Increased knowledge	**x**					x
SOW	21	Consultancy services	x	x	x	x	x	x
Siemens	22	Increased knowledge			x			

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			Objectives					
SHORT NAME	KER #	TYPE OF EXPLOITATION	**1**	**2**	**3**	**4**	**5**	**6**
DTU	23	Service	x				x	
RWTH Aachen	24	Service	**x**	x	x			
UPV	25	Contract research	**x**	x	x			
FGH	26	Product/Service - software	x					x
Ørsted	27	Development of a new standard					x	
Carbon Trust	28	Consultancy services	x	x				
Tractebel	29	Consultancy services	x					**x**
EUI	30	Policy recommendation				x		
T&D Europe	31	Increased knowledge and competence			x			x
USTRAT	32	Service		x	x			
RUG	33	Policy recommendation				x		
MVOW	34	Development of a new standard					x	
Energinet	35	Increased knowledge	x			**x**		
SHE Transmission	36	Services	**x**	x	x			
SCiBreak	37	Product			x			

For a more detailed analysis and explanation of the KERs please refer to deliverable D14.5.

5.4 COMMUNICATION

The goal of PROMOTioN is to lower barriers to the implementation of meshed offshore HDVC transmission networks. It is therefore of paramount importance to communicate this message and explain its reasoning to the key stakeholders through targeted dissemination of the results of the technical, legal, regulatory, economic and financial analysis and demonstration. PROMOTioN has placed specific emphasis on a clear, structured and effective dissemination campaign.

5.4.1 PROJECT IDENTITY

PROMOTioN has developed a clear, recognizable and appealing project identity characterized by the project logo. Based on this, a clean and authoritative house style has been developed for all reports, letters, releases, presentations and roll-up banners and used in all communication to stakeholders to support the pursuit of consistency and coherence in PROMOTioN work and communication.

PROMOTioN
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5.4.2 STAKEHOLDER MEETINGS

PROMOTioN has drafted a communication list with contacts of key stakeholders. 17 open **stakeholder group meetings** have been organized in which intermediate research results were presented to a general stakeholder group to gain feedback and direction for the further research steps. These meetings were often organized alongside major industry events such as WindEnergy Hamburg

A reference group was formed with representatives of selected key stakeholder organizations and 6 closed meetings have been organized to discuss the project progress and intermediate results. These **reference group meetings** were typically organized next to specific industry events such as ENTSO-E conferences. The reference group meetings were split between technical and non-technical topics. With an increasing complexity of the research conducted over the project's duration, these relatively general meetings were substituted for more targeted dissemination measures to better tailor the different research topics to their respective audiences.

Several **stakeholder workshops and demonstration events** have been organized on specific topics such as HVDC circuit breakers, HVDC gas insulated switchgear, HVDC system operation, standardisation, regulatory aspects, etc. These workshops were well attended and helped serve the purpose of getting industry consensus on aspects such as testing or requirements. For example, each technology demonstration was accompanied by a dedicated workshop, in which selected key stakeholders from TSOs, developers, lenders engineers, and national ministries were invited.

Figure 18 - Regulatory reference group meeting in June 2018 in Amsterdam, Netherlands

Several of these workshops were organized as side events of well-known industrial conferences or meetings such as the CIGRE Paris session, WindEurope conferences such as the Hamburg Offshore Wind event and ENTSO-E conferences such as InnoGrid.

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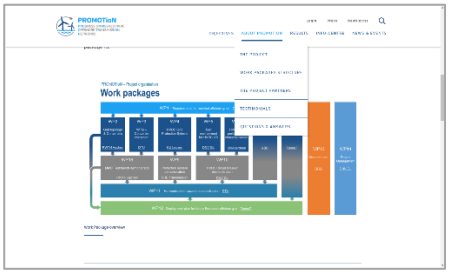
In order to guarantee the delivery of key PROMOTioN recommendations to the main stakeholders, a series of 7 **targeted dissemination visits** have been organized to selected key stakeholders such as National ministries and regulatory authorities of the Netherlands, Germany, Denmark and the UK. In addition, dissemination workshops were organized with stakeholders such as ENTSO-E, the NSWPH and T&D Europe.

Figure 19 - Targeted dissemination visit to the German ministry of Economic Affairs and Energy in January 2020

5.4.3 WEBSITE

A professional looking website has been created which gives an overview of the project and its partners, provides links to public deliverables, publications, presentations, contains an agenda of upcoming events, and a news section.



The website went online on 23 June 2016 and had already an average number of monthly visitors of around 300 at the end of December 2016. Between 2018 and 2020, the website had a total of 17166 unique users visiting, of which 15.5% (2660) were returning visitors, creating a total of 26855 sessions (1.6 per user).

The website had a substantial increase of traffic from mid-August 2020 onwards (07.08.2020-07.09.2020), where several key attributes showed significant increase when compared to the previous month (06.07.2020-06.08.2020): the number of users increased by 55% (1926 vs 1237), the number of sessions by 71.48% (3018 vs 1760) and the number of page views gained 77.75% (7901 vs 4445). This nicely reflects an increased interest in PROMOTioN due to the imminent start of the project's capstone event series.

Overall, by far the most visitors arrived from English speaking countries (US, UK; 56%), followed by Germany (11%) then The Netherlands, Denmark and France (4%, respectively). It is notable that close to 3% of traffic came from China/Taiwan.

To provide public access to the data and material created in PROMOTioN, SOW is committed to host PROMOTioN's web-presence even beyond the project's duration, thus satisfying EC standards on Open Access publishing and dissemination of project results.

5.4.4 PRESS-RELEASES

In order to bring special attention to certain key events or project results, several press releases have been issued to the relevant press outlets (15 Press Releases, more than 55 articles in print-

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and online media). This was done with every major first-time demonstration of a key technology, with major project events, and with the entry of new partners. The press releases were reviewed and approved by the PMG. In total 14 press releases were issued during the project time.

5.4.5 NEWSLETTER

Regular newsletters have been distributed to a wide group of interested stakeholders. The total number of stakeholders fluctuated during the time, from around 1000 in December 2016 to at its peak (December 2018) 1325 stakeholder contacts. During 2019, the number of contacts dropped to 1210, mainly due to changes on the recipient side (e.g. changes of positions and/or employers, based on autoreply email feedback after sending out stakeholder emails). By August 2020, the total number of unique contacts reached 1294 again. Overall, this is reflecting a steady and continuous interest by a large and diverse set of stakeholders in the project.


PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Dear readers and subscribers,

Frantic COP climate negotiations amidst growing social unrest about the dangers of global warming and the perceived lack of action of global leaders, set the scene for the announcement of the new European Green Deal: to be the first continent to become entirely carbon neutral by 2050. WindEurope estimates that 450 GW of offshore wind capacity in European waters is believed to be necessary to meet this target, with over 200 GW installed in the North Sea alone - an ambitious goal in line with the PROMOTioN high scenario.

To realize this goal in the most cost-effective way for the European consumer, it is clear that international cooperation and collaboration is a must to create a pipeline that allows not only the offshore wind industry, but also the offshore transmission equipment industry to achieve cost reductions by scaling up. At the same time, it should be clear that reducing cost should not come at the cost of European manufacturing and jobs creation. As a tangible example of international coordination, in 2019 PROMOTioN has started a collaboration with the H2020 funded project AURES II on working out a framework for cross-border auctions in international offshore energy hubs.

How to shape such international collaboration, most notably forming a North Sea Treaty on offshore grid development, is discussed in deliverable 7.9, one of PROMOTioN's key milestones which outlines a legal, regulatory, economic and financial framework. The analysis is summarized in 33 key recommendations which, in the deployment plan, will be

The newsletters gave updates on the project research, provided an overview of the context of the project, brought the readers' attention to upcoming PROMOTioN events and contained a list of PROMOTioN publications. Each newsletter was introduced with an editorial provided by either the coordinator or the dissemination work package leader.

5.4.6 CONFERENCES

PROMOTioN has organized two conferences dedicated to disseminating PROMOTioN's results and bringing the stakeholder community together. One conference was organized at the project midpoint, and the other one at the end. In both conferences, the results of all work packages were shared, keynote speeches by speakers from government and industry were given, and a panel discussion with prominent speakers and representatives of all stakeholder sectors led to lively and interesting discussion. The **midterm conference** was a physical meeting held in Amsterdam. A meeting of the North Seas Energy Forum was planned adjacently, ensuring the attendance of key stakeholders. The conference was well-attended with over 150 participants from all stakeholders and received a satisfying amount of press-coverage. Real displays of the HVDC GIS

Figure 20 - Mid-term conference in Amsterdam, Netherlands

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prototype and the protection IED were present to give attendees a first-hand experience with these new technologies.

The **final conference** was intended to be a two-day lunch-lunch event held at the Brussels Museum for Fine Arts. The program was planned to be similar to that of the mid-term conference but now with complete results and a deployment plan presentation. Due to the COVID-19 pandemic the final conference was held online, spread out over 4 weeks with weekly break-out sessions on HVDC network technology, HVDC network technology qualification, HVDC network legal, regulatory and economic framework and offshore HVDC grid planning, all leading up to a final capstone event. The final event, which was attended by over 300 people, featured keynote speeches by decision makers from DG Energy, the state secretary of the German ministry for economics and energy, and the CEO of WindEurope. An interesting panel discussion with C-level speakers from key offshore grid stakeholders, moderated by DG Energy, was closed by the secretary-general from ENTSO-E. The messages from all speakers aligned very well with the key conclusions from PROMOTioN and further underlined the need for governmental cooperation between different countries and the need for urgency.

Figure 21 - Final conference panel speakers

For the main event “North Sea Grid for the European Green Deal” on 21.09.2020 a total of 482 individuals registered, with ultimately 302 individuals attending (63% attendance rate) the day of; again, a number within the expected margins for online events. All over, 23 questions were posted by the audience while 6 polls gauged the audience’s opinion over the course of the event. The live panel discussion on the future development of MOGs in Europe with C-level representatives of the industry from 1pm-2:30pm that day showed the highest rates in attentiveness (71%), i.e. viewers actively followed the discussion with our stream being on top of all other applications, as opposed to the ones where our stream was minimized or ran in the background. A full recording of the final conference day is available on the PROMOTioN website.

Overall, by shifting the event from a location-based to a digital online event, PROMOTioN actually attracted a larger audience than we could have expected from a physical conference – in comparison, the physical event at the Museum of Fine Arts in Brussels was aimed to gather about 200 attendees from the sector over the course of two days. The online event series created a much larger and more diverse audience for our message, with the additional benefit of the live recordings, which will continue to be accessible online and keep up engagement way beyond the immediate event itself. On a downside, it needs to get noted that online events are not able to recreate the spontaneous exchange, casual dialogue and direct networking opportunities that come along with regular conference activities. Given the limited options to host such an event, especially

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internationally, in an event industry heavily impacted by the COVID-19 pandemic, the chosen online solution appears to be an adequate, albeit very different, alternative solution.
The videos created for this event series are hosted via YouTube and were well received by our audience. Over the course of the event series (24.08.2020 – 21.09.2020), the number of unique views increased from 11/month by the end of July 2020 to 1460 views/month by September 2020. During this period alone, viewers totalled 101.5 hrs of playback time.

5.4.7 PUBLICATIONS & ARTICLES

Many partners contributed to the dissemination activities by giving presentation on many conferences as CIGRE, IEE PES General meeting, Wind Europe Offshore Conference, IEEE Transactions on Power Delivery, Wind Energy Science conference, IET DPSP, and many more. In total 198 conference papers and presentations were given during the project time (Target: 50 until the end of the project).
Further multiple journal articles and journal papers were published of which 61 publications in peer-reviewed scientific journals (Target: 25 until the end of the project).

5.4.8 PROJECT MEETINGS

An important benefit of formation of a consortium like PROMOTioN is the strong network building and sharing of know-how, analysis results and discussion between representatives of different partners that happens within. To foster this type of internal communication, PROMOTioN has structurally organized periodic physical meetings.

General assemblies – Twice per year a physical general assembly was organized along a plenary session in which intermediate results of all work packages were presented. The meetings were organized at the premises of different, mostly academic, partners, and accompanied by project dinners typically sponsored by one of the industrial partners.

Figure 22 - Half yearly project meeting in December 2019 at DTU in Roskilde, Denmark

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Project management group meetings – The project management group (PMG), consisting of the work package leaders, coordinator and R&D coordinator has been very active. Four physical meetings per year have been organized and monthly telcos in between. The PMG meetings have been used to keep track of progress on the deliverables and milestones, identify and mitigate risks, discuss and coordinate large changes to the consortium or scope of work, and agree on participation in large dissemination events. The coordinator has strived to maintain a good balance between different stakeholders (e.g. industry, TSOs and academia) in the composition of the PMG.

Figure 23 - Quarterly PMG meeting in January 2018 in Amsterdam, Netherlands

Work package meetings – Numerous work package and task force meetings have been organized, enabling partners to exchange expertise, discuss analysis results and chart next steps on specific topics. Typically, work package meetings would be organized at least four times per year, twice alongside the General Assembly, and twice in different partner locations.

Figure 24 - Work package 6 meeting in June 2016 at the University of Aberdeen, Scotland

5.5 LIAISON WITH OTHER EU PROJECTS

Several other EU funded projects address aspects of transmission or renewable energy that are complementary or somehow related to the PROMOTioN scope. Active coordination with these projects was carried out to ensure compatibility in geographical scope of analysis, avoid overlap and exploit complementarities in scope of content, and to streamline dissemination.
Coordination takes place through partners taking part in both projects, dedicated liaison meetings, active participation in each other's dissemination events, having joint dissemination events, and having joint task forces.

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The BRIDGE project is the overarching programme that brings all Horizon2020 funded projects together and explores common themes such as business models, data management, regulations and customer engagement. The programme is most suitable for projects relating to technologies at the distribution level, so PROMOTioN being a transmission project was exempted from participation. However, in order to ensure (vertical) coordination with the other energy projects, and to provide a transmission perspective, PROMOTioN representatives have taken part in annual BRIDGE meetings and regularly provided input to the BRIDGE newsletter.

The BestPaths project is PROMOTioN's predecessor which also covered aspects of HVDC grid technology development such as novel VSC-HVDC converter technology, HVDC network control, multi-vendor interoperability, HVDC circuit breakers. To avoid overlap or large gaps between these two Horizon2020 projects, several coordination meetings were organized between the project management groups. Further coordination was achieved by the fact that several PROMOTioN partners also took part in BestPaths

The MIGRATE project started simultaneously with PROMOTioN and addressed the impact of a growing share of power electronics interfaced generation in the existing AC grid. MIGRATE and PROMOTioN coordinated closely by holding joint dissemination events, sharing partners, and regular project management interactions.

Baltic InteGrid was a very similar project to PROMOTioN but then focused on the Baltic Sea. It also included maritime spatial planning and market & supply chain and environment & society in its scope which PROMOTioN didn't. PROMOTioN, in turn, focused on the technology development and demonstration, which Baltic Integrid didn't. The projects are thus considered to be nicely complementary in scope and geographic applicability. Several PROMOTioN partners to part in Baltic Integrid and the projects participated in each other's dissemination events.

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AURES II (AUctions for Renewable Energy Support) aims at ensuring the effective implementation of auctions for Renewable Energy Sources (RES) in EU Member States. This topic is complementary to PROMOTioN scope but aligns well with it. Hence a joint task force was created between AURES II and PROMOTioN. In addition, several of PROMOTioN's partners were also part of AURES II.

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6 PROJECT MANAGEMENT

Due to the highly integrated nature of PROMOTioN (many interactions and dependencies between different work packages) and the need to deliver one consolidated message at the end, effective project management has been indispensable. Moreover, due to the macro-economic changes affecting the participating countries and partners, the PROMOTioN project had to face several large and defining disturbances and manage to integrate these into the project in a meaningful way. The day to day project management was carried out by the work package leaders, meeting monthly at the PMG meetings and telcos, and the coordinator DNV GL, whose team held weekly internal meetings to discuss progress, risks and action items.

6.1 COMPLIANCE WITH THE WORK PLAN, DEVIATIONS AND CORRECTIVE ACTIONS

Several major changes to the original work plan have taken place during the project.

- At the end of the first reporting period, Siemens decided not to go ahead with the planned diode rectifier converter demonstrator at the Klim windfarm, Denmark. Consequently, work package 8 was prematurely terminated as no substitute demonstrator for this technology was finally proposed by Siemens
- Following the Siemens decision, linked third party Siemens Wind Power and partners Iberdrola and ADWEN have withdrawn from PROMOTioN. The tasks of these partners have been taken over by other partners. The withdrawal of ADWEN is due to its merger into Siemens-Gamesa. No new specific ADWEN technology will be developed and hence the need for studies into vendor interoperability has expired
- A new work package was created with the aim of increasing the technology readiness level of gas insulated switchgear (GIS) technology for HVDC. The work package will develop guidelines and requirements for specifying and testing HVDC GIS, compare and demonstrate the performance of alternative insulating gases, develop and demonstrate condition monitoring and diagnostic techniques for HVDC GIS, and demonstrate a 320 kV HVDC GIS product prototype by long-term test. The new work package is carried out by a mix of partners from industry (OEM, TSOs and consultancy) and academia
- ABB Switzerland was added as linked third party in relation to the demonstration of the 320 kV HVDC GIS prototype
- A new work package was created with the aim of demonstrating meshed HVDC grid control strategies and investigating harmonic interactions between converters. A scaled low voltage meshed DC grid with scaled MMC converters connected to linear amplifier interfaced real-time simulators of offshore windfarms and onshore AC grids will be used to study the impacts of

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different types of faults and grid recovery strategies. Furthermore, a 1 MW wind turbine converter will be used to demonstrate harmonic model validation.

- A new partner SCiBreak joined the consortium. SCiBreak is a Swedish start-up company developing a novel concept for HVDC circuit breakers. SCiBreak will contribute by sharing knowledge and expertise in work package 6 and by supplying a prototype HVDC circuit breaker module for testing in work package 10.
- The task structure of work package 6 was changed to accommodate the analysis of the SCiBreak HVDC circuit breaker topology and to develop a common HVDC circuit breaker model verification plan
- A task was added to develop a cost-benefit analysis methodology for meshed grid development for use in work package 12. The current ENTSO-E methodology is focussed on point-point link projects, limited in scope and time, and hence not suitable for the analysis of grid development. The new methodology will be based on the current ENTSO-E methodology and take into account the previously made recommendations
- A task was added to WP9 to demonstrate non-selective fault clearing strategies and thereby complement and complete the original WP9 scope of demonstrating selective fault clearing strategies. The new task was led by SuperGrid Institute
- An informal task was added to WP12 to develop a market model based on small offshore bidding zones. The new task was led by TU Delft
- An informal task was added to WP12 to define technology readiness levels for transmission equipment and assess the progress made in PROMOTioN. The task was led by DNV GL
- An informal task was added to WP12 to carry out feasibility studies on short-term project opportunities. The new task was led by DNV GL.
- A substantial budget transfer from mostly DNV GL was affected towards ABB, Mitsubishi Electric and SCiBreak, to enable them to deliver more full-scale HVDC circuit breaker prototypes and thereby enable the progression of the TRL to higher levels than previously envisaged
- The end date of the project was extended by 9 months to allow for completion of more ambitious demonstrators and publish the results at key industrial events such as the CIGRE session

Following the decision not to go ahead with the diode rectifier converter demonstrator, an extensive analysis of the impact of this decision on PROMOTioN's ability to achieve the project objectives was carried out. As a result, new proposals to mitigate and remedy the impact were presented to the EC, finally resulting in the two new work packages. The changes to the work plan have been formalized in 5 amendments of the Grant Agreement Annex 1 (part A & part B) and Annex 2 carried out during the 2nd reporting period.

Apart from the above large changes, the work carried out during the project has largely been carried out in accordance with the work plan in terms of scope and planning. Some minor delays were reported on the submission of deliverables. These delays were in most cases attributable to the additional time required to achieve agreement on the deliverable's contents by a large number of

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partners, or to staffing difficulties. All minor changes were carried out in dialogue with the coordinator. In each case the impact on the other work packages and deliverables was considered and negative impact minimized as much as possible by shifting tasks to other partners. The changes were formally registered in the last amendment or in the upcoming amendment. In all cases, the delay in submission date did not adversely affect any other work within PROMOTioN.

Several partners changed their names and/or were acquired by other companies, reflecting the trend of shifting from conventional fuels to renewables in the generation sector,

- DONG → Ørsted
- Statoil → Equinor

…and a general trend of consolidation and move away from EU-based manufacturing in the transmission equipment manufacturing sector:

- Alstom → GE Power Grids
- Siemens → Siemens-Gamesa & Siemens Gas & Power
- KEMA Laboratories → CESI
- ABB → Hitachi-ABB

These changes in most cases did not affect the work delivered by PROMOTioN but do give an indication of the large undercurrents in the industry at the moment.

6.2 CONTRACT MANAGEMENT

In order to appropriately accommodate some of the larger changes to the work plan or partner situations, DNV GL as coordinator effected ten amendments of the Grant Agreement annexes A & B. Amendments were carried out for the Siemens No-Go, creation of new work packages, partners leaving, partners joining, partner name changes, large budget transfers between partners and deadline extensions of both deliverables and the project as a whole.

6.3 RISK MANAGEMENT

In order to enable the timely identification of risks to the project schedule, budget or scope and formulate suitable mitigation actions, a risk register has been maintained throughout the project. The risk register was updated on a quarterly basis during the PMG physical meetings. For each risk, a likelihood and impact were estimated, and the effectiveness of mitigation measures was assessed. The risk management helped to get an early overview of potential dangers and steer the project around these.

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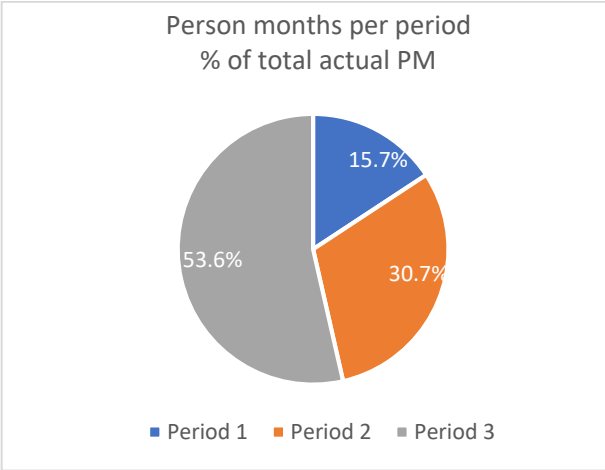
6.4 QUALITY CONTROL

In order to ensure high quality and coherent deliverables and communication, a review process has been set-up and adhered to review all deliverables and publication prior to being made available to ECAS or the public website. Each deliverable has been reviewed by two members of the PMG in a staged review process, commenting on approach, document structure and quality of content. On the whole, the quality review system, as well as the excellent work delivered by the partners, has led to a very high level of quality of the deliverables, although it in some cases also led to some delays in the sake of quality.

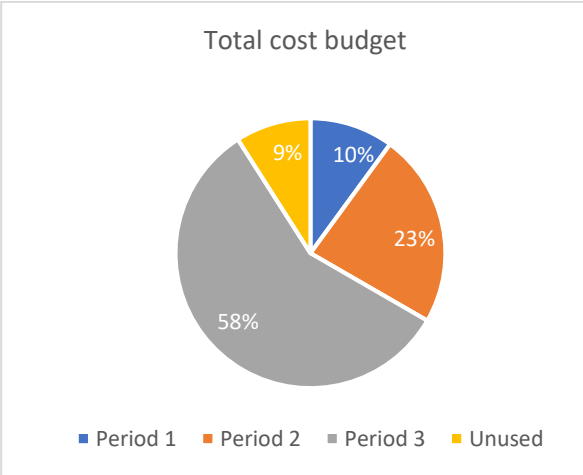
6.5 USE OF RESOURCES

The total PROMOTioN project has a person month budget of 2714 person-months, but at the end of the project 2931 person-months were made, this means that 217 months, 7% more work was done as planned.

The total actual costs budget is EUR 42,691,662.81 of which EUR 38,835,029.91 has been used, which means an underspending of 9%. The requested EU contribution is 31,756,252.18.



a) Person-months budget use



b) Actual cost budget use

Figure 25 – Use of budget

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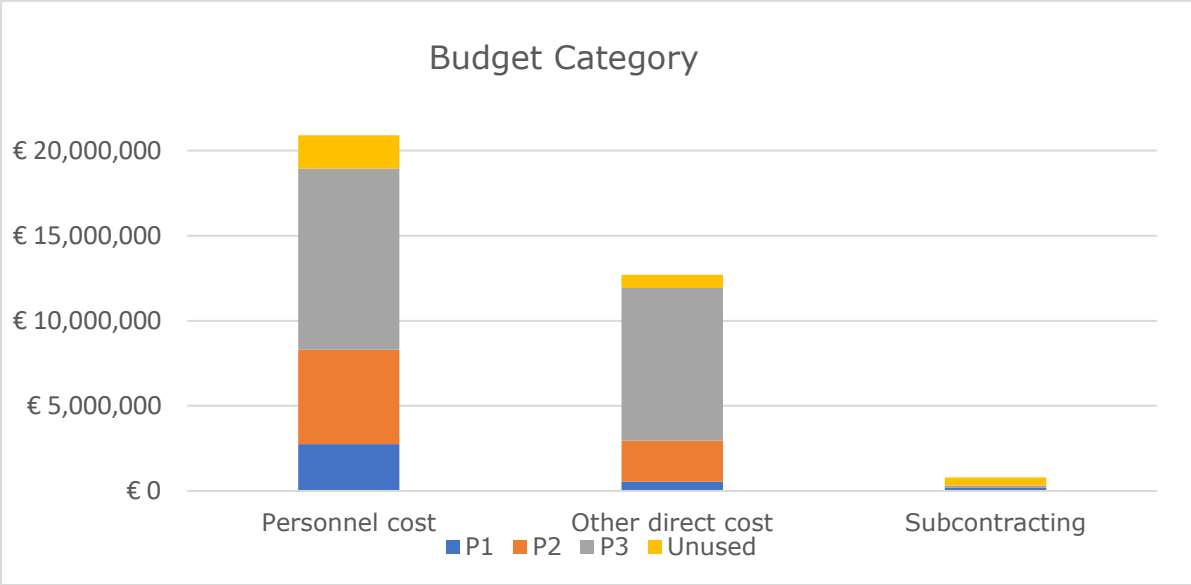

Figure 26 – Categorised budget use

With respect to the actual budget spend, it should be remembered that the more budget intensive activities, the demonstrations, have started in the second half of the project. Therefore, a significantly larger proportion of costs across all categories was encountered when the demonstrations started taking place in the 3rd reporting period.

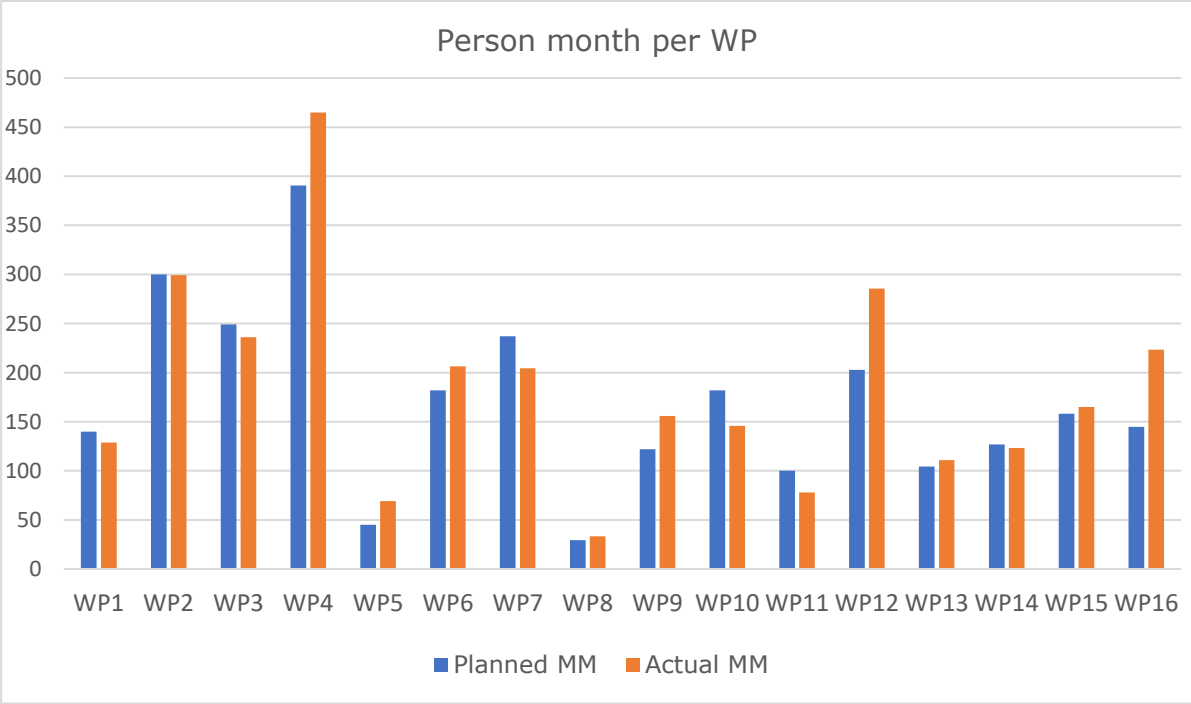

Figure 27 – Use of person-month budget per work package

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The spent person-months budget can be broken down and shown per work-package, as in the above figure. It can be seen that work packages 4, 6, 12 and 16 have exceeded their planned number of person months which is likely the utcome of their intensive work in the final period of the project being most directly involved in shaping the final report. Other work packages show good alignment between the actual and planned person-month expenditure, with work packages 1, 3 and 7 showing minor underspending.

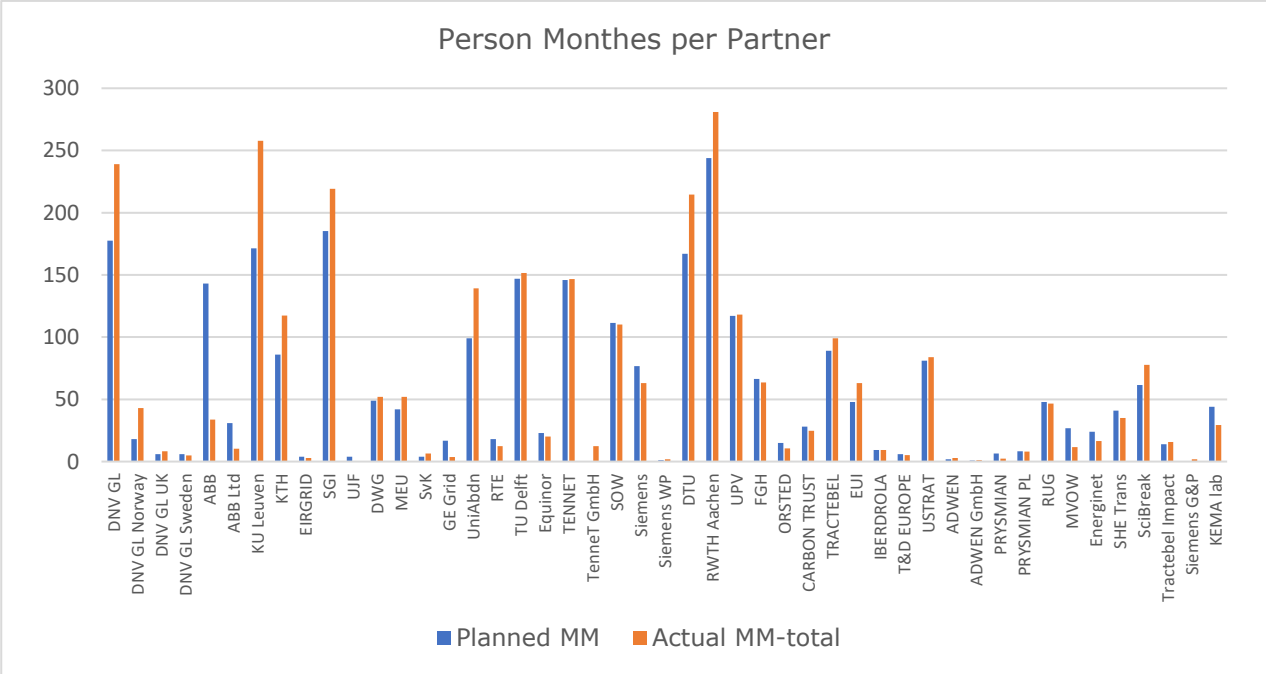

Figure 28 – Use of person-month budget per partner

The person-month budget expenditure is plotted per partner, as shown in diagram above. It can be seen that some partners have significanty exceeded their plannede level of person-month expenditure which can be linked with the information presented in the previous figure Figure 27. DNV GL, KU Leuven, SGI, UniAbdn, DTU, RWTH Aachen and SCiBreak were all active members of the above -mentioned work packages that have exceeded their budget. In contrast, a number of partners has nto reached their planned level, again, in accordance to how their respective work package activity has evolved.

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