

# D1.2: Report documenting results of the questionnaire on best practices

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks  
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# EXECUTIVE SUMMARY

Since the development of the technology and the commissioning of the first pioneering commercial projects in the 1950s, Europe has witnessed a large increase of HVDC installations. Especially during the last decade, the number of HVDC projects has rocketed. This is mainly due to the need of interconnecting countries via submarine links to transport large amounts of energy and the development of the Voltage Source Converter (VSC) technology, which has allowed the development of large offshore wind farms located far from shore.

Although most of the HVDC installations currently in operation are point-to-point links, the experience that TSOs, developers, manufacturers and other stakeholders have gathered during these years can be of great value when it comes to designing and implementing future meshed HVDC grids in Europe.

Deliverable 1.2 (D1.2) is one of the outputs of PROMOTioN Work Package 1 (WP1), which is a horizontal WP that covers the whole project and has the general objective of defining the requirements that should be met by an offshore HVDC grids and the wind farms connected to it. These requirements will be applied to all the WPs in the Project. D1.2 captures the results of *Task 1.3: Assessment and inputs from existing offshore connections and grids*. The main objective of this task is to engage with stakeholders involved in the existing European HVDC installations (TSOs, offshore wind farm developers, manufacturers, consultants, universities, research institutes and others) to gather best practices and lessons learned during the different phases of these projects. In order to do so, the PROMOTioN Task 1.3 partners organized two workshops to engage with experts and made a questionnaire that covered the main stages of an HVDC project:

1. Technical design.
2. Administrative issues.
3. Policy and finance.
4. Project management.
5. Construction.
6. Operation.

The questionnaire was distributed among relevant stakeholders (industry, academia, regulators, public entities, financing) and, although the experience with meshed grids is so far limited in Europe, it includes a chapter dedicated to HVDC grids in order to understand their views on such networks and to try to identify requirements that they would have to fulfil.

Some of the conclusions are the following:

- There are some differences in the perception of the industry and the academic/consultancy world regarding future HVDC grids in Europe. While the academic world thinks that these grids will be important to lower the costs when compared to point-to-point links, the industry thinks that the degree in which these reductions will take place has yet to be studied in depth, and considers that symmetrical

monopole point-to-point links will be the most common projects until the technical and policy barriers are overcome.

- The main drivers in the design of an HVDC project are CAPEX and reliability. The designs try to comply with N-1 requirements and reduce losses using the simplest topology. Due to the environmental laws that limit the use of earth or sea return electrodes, the most common topology in the latest projects, especially those connecting offshore wind farms, is the point-to-point symmetrical monopole.
- HVDC projects usually interconnect different countries, require a close collaboration between TSOs and wind farm developers, are unique and the technology used is often new and not standardized. This means that there must be a right organizational setup from the very beginning, with clear objectives and schedule.
- Multivendor interoperability must be ensured if HVDC grids are to be developed. During the first stages towards the full standardisation, the owners will face higher operation risks that may translate into higher costs.
- The technical design phase requires detailed simulation studies to understand the behaviour of the link and write a correct specification. In this sense, there are some issues with the simulations that involve models supplied by converter manufacturers, since the details of these models are only known to the suppliers and they are the only ones who can run software tests to solve issues related to the control.
- Existing projects perform as expected, although experience shows that the cost of the technology is larger than expected and some projects had to switch to HVAC to be competitive.
- Regulatory aspects are of vital importance for the development of meshed HVDC grids. Different European countries have different regulatory frameworks, and it is not currently clear how renewable energy subsidy schemes will fit in a generation unit using a grid that interconnects two or more jurisdictions, or who will operate this infrastructure and what the charging regimes will be. It is also necessary to have a clear roadmap for the development of meshed HVDC grids to avoid extra costs.

## LIST OF ACRONYMS

ACRONYM	MEANING
AC	Alternating Current
CAPEX	CApital EXPenditures
CATO	Competitively Appointed Transmission Owners
CBA	Cost Benefit Analysis
CfD	Contract for Difference
DC	Direct Current
DCCB	DC Circuit Breaker
DRU	Diode Rectifier Unit
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EMT	Electromagnetic Transient
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EWEA	European Wind Energy Association (now WindEurope)
FEED	Front End Engineering Design
FID	Financial Investment Decision
GIS	Gas Insulated Switchgear
HLV	Heavy Lift Vessel
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IGBT	Insulated-Gate Bipolar Transistor
IOTP	Integrated Offshore Transmission Project
IPR	Intellectual Property Rights
LCC	Line-Commutated Converter

## PROJECT REPORT

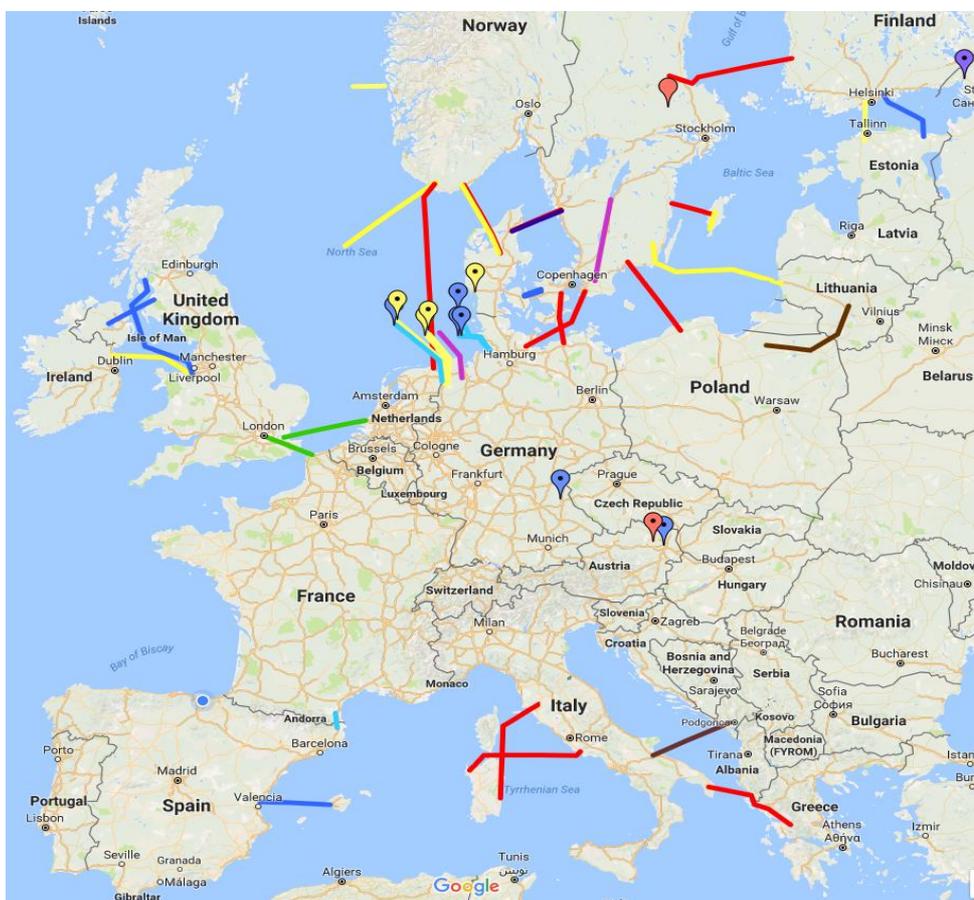
LCOE	Levelized Cost of Electricity
MMC	Modular Multi-Level Converter
NIC	Network Innovation Competition
OFTO	Offshore Transmission Operators
O&M	Operation and Maintenance
OPEX	Operational Expenditure
OWF	Offshore Wind Farm
PV	Photovoltaics
R&D	Research & Development
RIIO	Revenue Incentives Innovation Outputs
SCADA	Supervisory Control and Data Acquisition
TRL	Technology Readiness Level
TSO	Transmission System Operator
UK	United Kingdom
UoS	Use of System
VSC	Voltage Source Converter
WP	Work Package

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# 1 INTRODUCTION

Since the development of the technology and the commissioning of the first pioneering commercial projects in the 1950s, Europe has witnessed a large increase of HVDC installations. Especially during the last decade, the number of HVDC projects has rocketed. This is mainly due to the need of interconnecting countries via submarine links to transport large amounts of energy and the development of the Voltage Source Converter (VSC) technology, which has allowed the development of large offshore wind farms located far from shore.



HVDC projects in Europe.

Red: ABB LCC; Yellow: ABB VSC; Dark blue: Siemens LCC; Light blue: Siemens VSC;  
 Purple: Alstom LCC; Pink: Alstom VSC; Green: combined manufacturers

In line with the commitments taken by the EU Member States for 2020 and beyond for the decarbonisation of the European electricity sector, wind energy will become the most prominent renewable resource in Europe to contribute to greenhouse gas emission reduction by 2050. The development of onshore wind has still significant potential, but is facing the challenge that many sites with good wind resources have already been utilised in countries like Germany, Spain and Denmark, and the repowering of 'old' onshore wind farms will not be enough

to meet the set political targets. On the other hand, there is a great potential in offshore wind. However, many of the existing offshore wind farms and designated planning sites are located far from the centres of consumption. To integrate the prospected capacities of offshore wind power, European networks will have to evolve from the current meshed HVAC grids with point-to-point HVDC links to meshed HVDC grids that will act as the backbone to transmit large amounts of power across the continent. The current limitations to the development of such grids are the high cost of converter technology, lack of experience with protection systems and fault clearance components, and immature international regulations and financial instruments.

The PROMOTioN project aims to overcome these barriers with the development of a regulatory, financial and economic framework and an offshore grid deployment plan for 2020 and beyond, as well as the demonstration of three key technologies:

- Diode Rectifier Units (DRUs).
- HVDC Circuit Breakers.
- HVDC grid protection systems.

Deliverable 1.2 (D1.2) is one of the outputs of PROMOTioN Work Package 1 (WP1), which is a horizontal WP that covers the whole project and has the general objective of defining the requirements that should be met by an offshore HVDC grids and the wind farms connected to it. These requirements will be applied to all the WPs in the Project.

D1.2 captures the results of *Task 1.3: Assessment and inputs from existing offshore connections and grids*. The main objective of this task is to engage with stakeholders involved in the existing European HVDC installations (TSOs, offshore wind farm developers, manufacturers, consultants, universities, research institutes and others) to gather best practices and lessons learned during the different phases of these projects.



## 2 METHODOLOGY

Two complementary paths have been used for the identification of best practices from previous HVDC projects and of expected main trends in future HVDC meshed networks: a questionnaire was distributed among HVDC experts and two stakeholder workshops were held in the UK and in Germany, the regions where the offshore wind industry is currently most active, to capture the opinions of the main stakeholders in the area.

The results of the questionnaire and the stakeholder workshops are both described in the following sections.

### 2.1 QUESTIONNAIRE

A detailed questionnaire was designed by the partners involved in WP 1.3 and circulated among experts to gather their opinions on HVDC projects, based on their knowledge, project experience and personal opinions regarding the future of HVDC grids in Europe.

To define the content of the questionnaire, two main inputs were considered as reference. On the one hand, PROMOTioN deliverable D1.1 (TenneT TSO b.v., 2016) presents general requirements on HVDC meshed networks, therefore, the questionnaire was designed to be in line with it. On the other hand, Deliverable D17.1 of the EC FP7 'TWENTIES' project (Hansen & et al., 2011) presented a survey on offshore interconnector projects, which provided useful information to select the most relevant topics affecting HVDC projects.

The questionnaire, which can be found in Annex A, was available in two formats, a Word document and online (using *Google Forms*), and it was divided into the following sections that cover the main phases in the development of a project:

1. Technical design.
2. Administrative issues.
3. Policy and finance.
4. Project management.
5. Construction.
6. Operation.

Although the experience with meshed HVDC schemes is limited in Europe, an additional section was included in the questionnaire to inquire stakeholders about their views on such grids, with the aim of identifying the main barriers to their deployment as perceived by different parties.

For each section, a set of relevant aspects were identified by the partners in Task 1.3 and the respondent was asked to provide a numerical answer to evaluate their relevance (from 1-not important to 5-very important).



Apart from these predefined aspects, a series of questions were presented with the objective of extracting best practices from the stakeholders. In these open-format questions, the respondent was free to provide their experiences in an extended way (a recommended maximum of 300 words).

Several mailing campaigns were performed to distribute the questionnaire, and the summary of the responses is described in section 3.

## 2.2 WORKSHOPS

Apart from the questionnaire, two workshops were held to enrich the information. Since the main areas for HVDC-connected offshore wind development are located in the UK (Round 3 projects) and Germany (offshore wind farms in the EEZ of the German Bight) the workshops were held in Edinburgh on 5<sup>th</sup> October 2016 and Hamburg on 17<sup>th</sup> November 2016 to attract as many experts as possible from the industry.

Both workshops shared common contents:

1. Introduction to the workshop and description of questionnaire
2. Introduction to PROMOTioN
3. Operation and regulatory challenges from a TSO's perspective
4. HVDC technology from a manufacturer's perspective
5. HVDC grids from a wind farm developer's perspective
6. Academic perspective on HVDC grid development
7. Reporting of preliminary answers to the questionnaire

The following companies accepted the invitation to make a presentation and provide their experiences and opinions:

- TSO: TenneT
- Utility: Scottish Power / Iberdrola
- Manufacturer: ABB, Siemens, Mitsubishi
- Academia/consultancy: RWTH Aachen, Tractebel, Strathclyde University, The Carbon Trust

Twenty to thirty experts attended each workshop, and after each presentation fifteen minutes were allocated for discussion among the participants, and their opinions were captured in the minutes of meeting.



### 3 RESULTS

The main results obtained from the responses of stakeholders both through questionnaires and workshops are described in the sections below. The different aspects in each subsection have been ordered by relevance (from 5, most relevant, to 1, least relevant) and visualized in bar plots.

#### 3.1 QUESTIONNAIRE

Questionnaires were received in both text and online formats. Some of the responses were individual, but some of them came from a group of experts working for the same company. Responses came mainly from Industry and Academia/Consulting fields.

The next figure shows the amount of responses per stakeholder group.

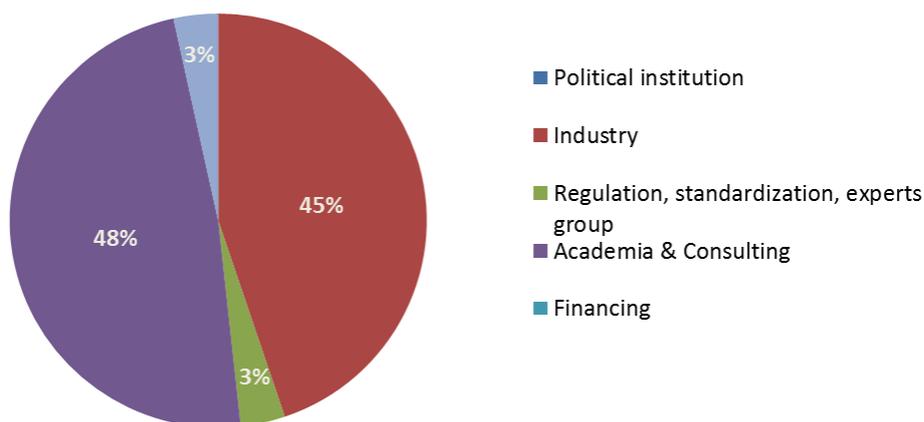


Figure 3.1. Questionnaire responses per stakeholder group

Most of the responses do not cover the total of the questions addressed. The section with highest participation is the one devoted to expectations on future HVDC networks, while the one dealing with experience on HVDC projects is mainly answered by industrial parties, due to the fact that they are the ones with the necessary experience in HVDC projects. Eleven blocks of questions needed to be assessed numerically, the summary of the level of response for each of them is presented in the following table.

BLOCK OF QUESTIONS	NUMBER OF QUESTIONS	AVERAGE % OF RESPONSES PER QUESTION
Aspects influencing the technical design of HVDC projects	34	51.2%
Main reasons for a modification in the initial design	15	30.3%
Most challenging administrative aspects	9	34.1%
Economic, financial, legal and regulatory challenges	12	36.2%
Main problems for the internal project organization	4	35.3%
Main challenges in the construction phase	23	31.6%
Main challenges of the operation of HVDC links	19	45.6%
Improvements of meshed HVDC networks with respect to point to point solutions	5	84.8%
Preferred topologies for HVDC grids	8	76.3%
Importance of systems in HVDC grids	10	85.5%
Main challenges of HVDC grids in the future	10	82.1%

The following subsections sum up the responses per topic. The last point includes a comparison between the point of view of the main two stakeholder groups that participated in the survey (industrial and academic), related to HVDC networks.

### 3.1.1 HVDC LINK PROJECT PLANNING PHASE: TECHNICAL DESIGN

The most important aspects in the technical design of HVDC links that the respondents identified are linked to cost, reliability/availability and converter control design, mainly at the offshore station:

- Converter station CAPEX.
- Converter station reliability.
- In the third position, six aspects are rated with similar score: interaction with offshore wind turbine generators, lessons learned from previous projects, converter station OPEX, cable reliability, maintenance and repair strategy (at the converter station), and transient/harmonic issues at the converter station.

The HVDC links are designed in order to comply with N-1 requirements or to reduce losses in the transmission, and once these requirements are met the most cost-effective solution is chosen. This means that, whenever possible, monopoles with earth/sea return are selected as preferred topology. However, due to environmental regulations this topology is no longer a viable option in most cases, so the most common topology in the latest installations is the symmetrical monopole considering cable and converter costs, especially to connect offshore wind farms. According to some experts the outage costs due to cable failure are lower than the costs of a system that can partly cover the failure of a converter or cable.



The results also show that the causes leading to the modification the initial design of the HVDC project are considered of less relevance as they are considered to be manageable. When this happens, the main issues are linked to supply chain problems and administrative delays.

The figures at the end of this subsection show the scores obtained by each of the topics in the questionnaire (out of five), sorted out from higher to lower. The red line shows the average score obtained in the question.

Regarding the best practices identified and the lessons learnt during the technical design phase of the project, the following were mentioned:

- When new technologies or topologies are considered in the project a close relationship must be maintained between the infrastructure owners and the suppliers, even more so when several countries are involved and the ownership of the link is shared. This way, a better insight into the technology is obtained, even if at the costs of some project hours. The specifications of the requirements for suppliers must be as specific and understandable as possible (e.g. including measured data like background harmonics or noise level). This avoids risk and permits to obtain lower prices.
- There is sometimes a conflict between suppliers and operators when it comes to modelling. Issues related to the control code can only be solved by the supplier as they do not provide details on it. Similarly, operators demand good EMT models to perform fault analysis, as they consider that the studies performed by suppliers are not as detailed as the operators would like in this aspect.
- It is necessary to coordinate the specifications of converters together with that of cables. Studies should be performed in parallel with those of manufacturers (based on first off-line versions of controllers provided by the manufacturers).
- Grid resonances are an important issue. They can cause instability of controllers in high frequency range and high steady state harmonic distortion. Also the energisation of transformers can be difficult.
- The controller of the converter can get into resonance with the grid. If the frequency of the resonance is changed, e.g. by a switching operation, the transient will not disappear and it will remain in steady state. In this case, the converter will generate high frequency harmonics, which cannot be prevented even by the high short circuit power provided by conventional power plants. Instead, the frequency dependent impedance has to be considered. Unfortunately, this phenomenon is mostly unknown in extra high voltage grids and no generally accepted analysis method is available.
- If a series resonance reaches very low values, because converter dominated cable grids do not provide damping, even the harmonic distortion of MMC based converters can cause high harmonic



currents. This happens if a resonance is directly located at a frequency at which the converter produces harmonics. Generally, this happens with the 5th or 7th harmonics.

- In low damped grids, the energisation of transformers can lead to inrush currents which can stay for minutes. If a resonance is located for example at the 2nd or 4th harmonic, the inrush current of a transformer will be amplified by the resonance and will keep the transformer in saturation. Already energised transformers can get also into saturation if a transformer nearby is switched on (sympathetic interaction).
- The use of the FEED approach (Front End Engineering Design) is useful. Design and project execution are optimized during the planning phase and no changes are permitted during the manufacturing and execution phases. In order for a certain technology to be accepted during the FEED phase, it is generally required it to be TRL (Technology Readiness Level) 7 (proven in a real demonstrator) to 9 (successfully proven in different installations).
- In many cases the decision to build a link depends on submitting a technical specification by a certain date. In some projects there was not enough time to perform thorough simulations, which led to over specifying a series of requirements that the real operation of the HVDC link showed that were not necessary.



PROJECT REPORT

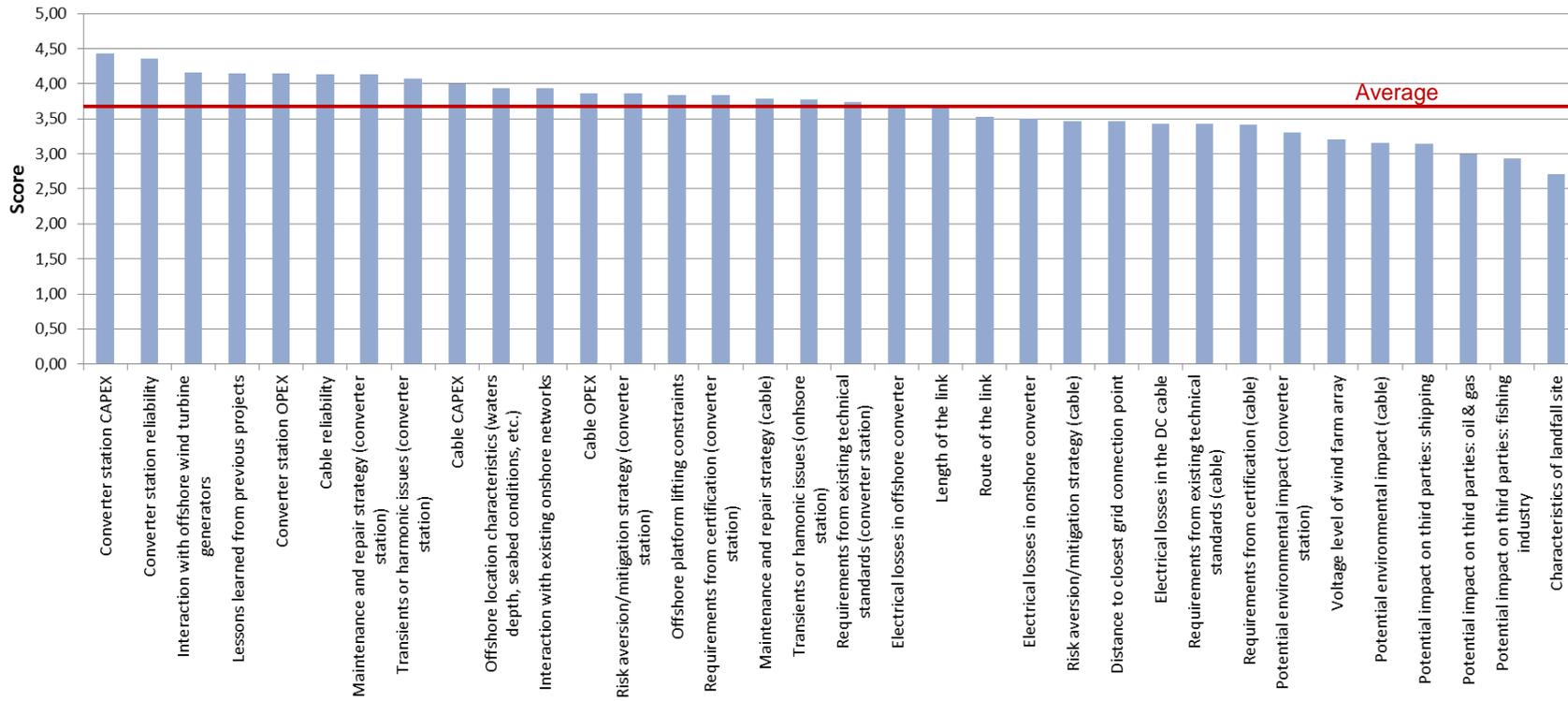


Figure 3.2. Relevant aspects influencing the technical design



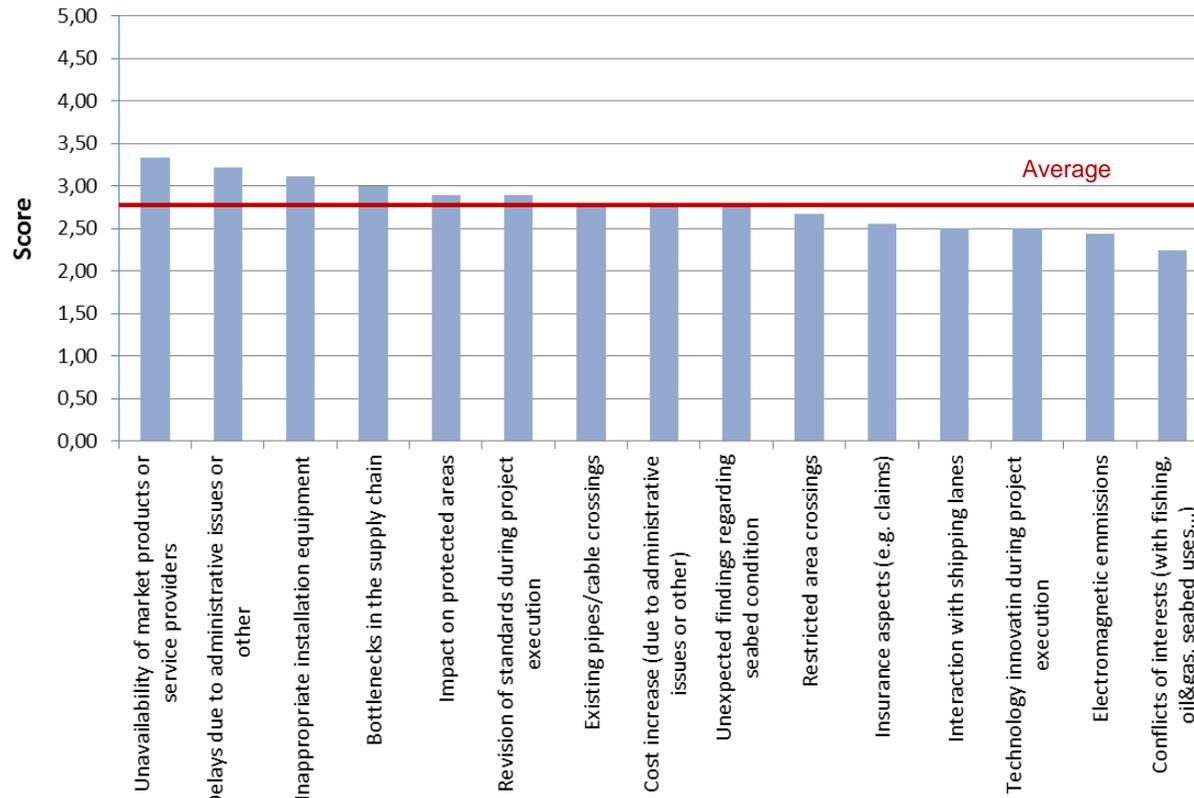


Figure 3.3. Main reasons causing the modification of the initial design

3.1.2 HVDC LINK PROJECT PLANNING PHASE: ADMINISTRATIVE ISSUES

The average scores obtained by administrative topics are lower than those addressing the technical aspects. The most important issue for HVDC projects seems to be the complexity of procedures and standards and the second, the interaction with authorities (both liaising with large number of authorities and the involvement of authorities from multiple countries). The following figure shows the overall ranking from most to least important aspect.

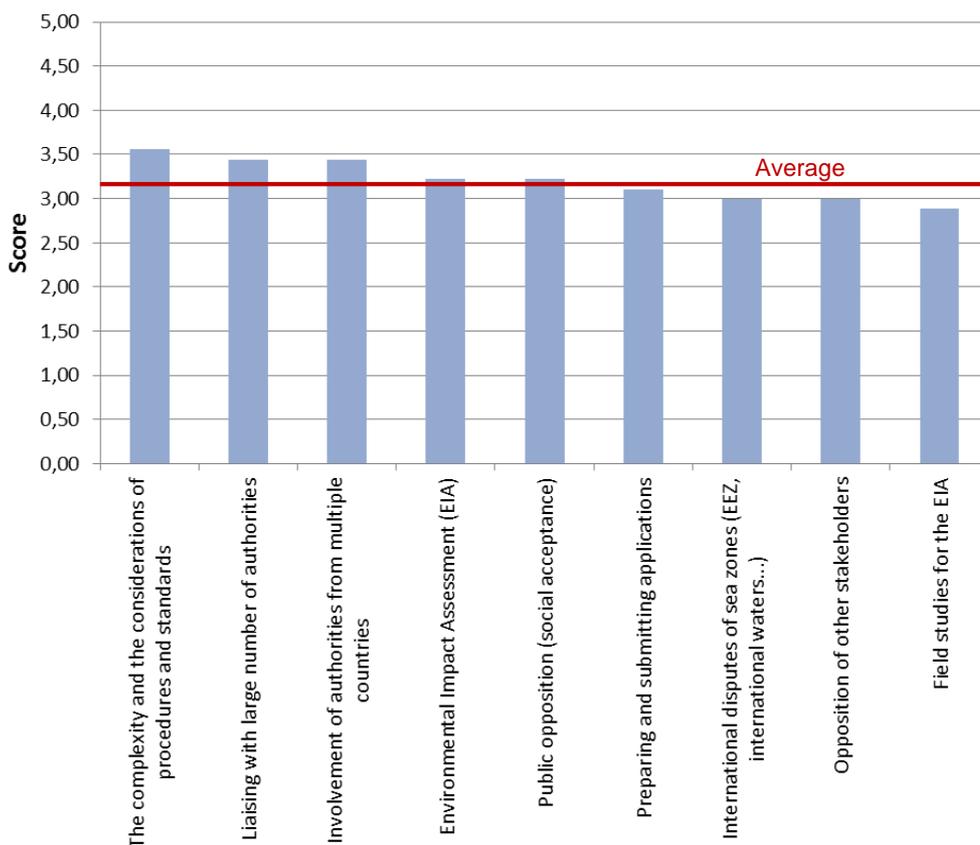


Figure 3.4. Administrative issues importance in the planning phase

According to the responses, the consenting process for a HVDC project takes between 2-3 years. Only one questionnaire provides information about the extra-costs related to administrative issues and estimates them between 1500-3000 thousand of Euros (0.02% of the total). Offshore wind farm developers calculate the consenting process to contribute 3-5% of the total costs.

The lessons learnt from previous projects were the following:

- Opposition of onshore stakeholders is possible due to the fact that nominating an onshore grid connection point always means for public that an onshore overhead line may follow. Therefore, close coordination of public consultation with onshore grid development in an early state is advisable.
- Timescales vary from country to country depending on the regulatory regime and the different regulatory bodies.

- Changing regulatory regimes are one of the main risks.
- Risks impacting on what the transmission link is connecting to should be checked.
- Each project is unique. The use of project development techniques, such as FEED, is recommended.

### 3.1.3 HVDC LINK PROJECT PLANNING PHASE: POLICY AND FINANCE

From a policy and finance point of view, regulatory instability and aspects affecting on project costs are highlighted, while the ability to participate in energy markets to provide ancillary services are considered least relevant.

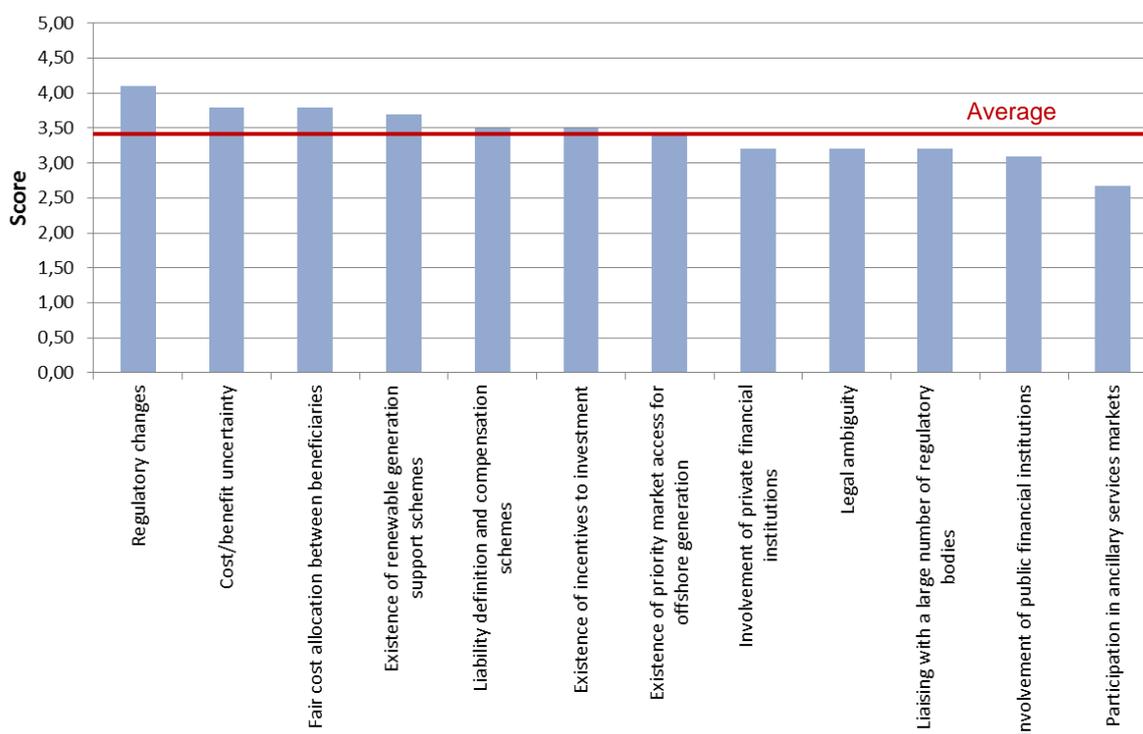


Figure 3.5. Policy and finance aspects importance ranking in HVDC projects

Convincing private investors in the profitability of offshore assets, taking into account all potential risks, is key in this topic.

### 3.1.4 HVDC LINK PROJECT PLANNING PHASE: PROJECT MANAGEMENT

Looking at the average score per question, this would be the least important topic for the participants in the survey. Only four questions were included in this section and the first in the importance ranking deals with the cooperation between the different Transmission System Operators (TSOs) participating in HVDC project.

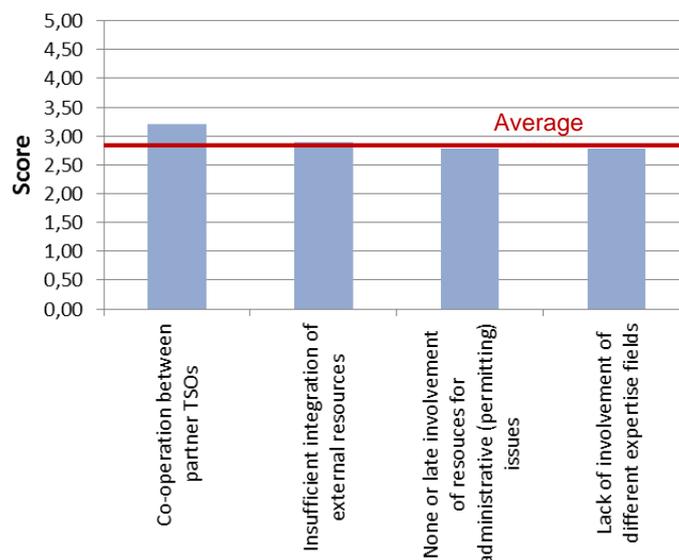


Figure 3.6. Project management issues in HVDC projects

However, during the discussions in the workshops, it was stated that the cultural differences when people from different countries are involved is often dismissed, but it can be a source of major delays in any phase of the development of an HVDC project. Even different companies in the same country have different ways to approach a project depending on their experience, therefore it is vital that the managers establish a clear and common planning and schedule.

Among the best practices to be accomplished in this phase of the project planning, the following are mentioned:

- Assigning key personnel from various stakeholders to form the project team is important, but it is also vital to steer them in the correct way to avoid delays in the technical decisions. The strategic planning is one of the core elements. The right organizational setup for all project issues, such as technical project management and project management is important for the success of the project.
- When teams of people from different cultural origins have to work together, it is important to establish clear objectives and programmes and work as closely as possible to avoid misunderstandings that could delay the project and increase its cost.
- The users of the link have interests that are largely aligned, but there could be some aspects in which the alignment is not complete. In these cases both parties have to make compromises to fulfil the programme.
- There must be an early engagement and agreement between stakeholders on the delivery model.

### 3.1.5 HVDC LINK CONSTRUCTION PHASE

Coming to the construction phase of HVDC projects, keeping to schedule and safety issues are highlighted among the set of topics proposed in the questionnaire, while document management and onshore related works are considered about the least important. This is the section with highest average ranking per question after the one devoted to the technical design.

Only one respondent answered to the question dealing with the duration of this phase and it was four years.

One of the participants in the survey, mentioned delays related to offshore converter stations in several projects due to the following reasons:

- Too ambitious time schedules.
- Quality deviations with the structure.
- Installation delays of systems and subsystems.
- Delays during the commissioning process.

The installation of offshore substations was also a matter of discussion. Some stakeholders preferred to avoid self-installing platforms, stating that heavy lift vessels (HLVs) are sometimes dismissed due to the fact that there are very few of them worldwide that could lift the substations required for this kind of projects. According to these stakeholders using large self-installing platforms with equipment that will only be used during their lifetime (transport and installation) is not as optimal as considering other designs that could be installed by HLVs and properly managing this process with people who are experienced in dealing with this kind of vessels.

The following best practices were identified in the construction phase of previous projects:

- A strong cooperation and consultation between internal and external stakeholders is very important for the success of the construction.
- From technical point of view, the technical engineering phase has been identified as an essential phase during the construction. An HVDC system for offshore grid connection systems is very complex and the used technology is mostly not state of the art, especially the platform. During the technical engineering the basis for the construction phase is built up and the system integration clarifies technical interfaces in order to construct the needed/ right HVDC system.
- For a professional construction, the right organization structure and a high maturity level on project management & technical project management is needed. Good planning and cooperation with all parties in the project results in good project execution.



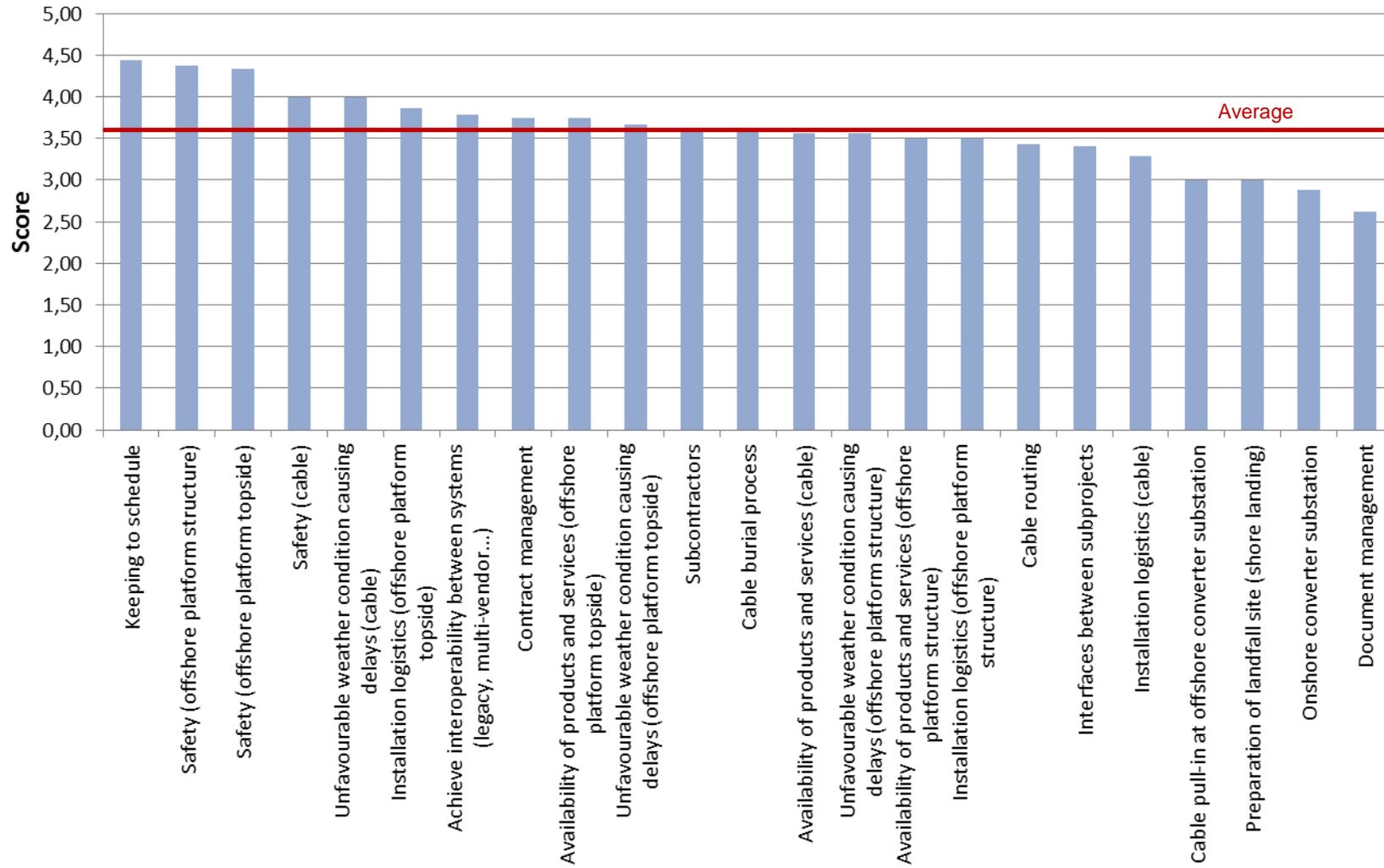


Figure 3.7. Project construction phase challenges in HVDC projects

### 3.1.6 HVDC LINK OPERATION PHASE

The operation phase challenges are led by reliability, costs of maintenance and control/stability issues. All the topics ranking is presented in Figure 3.8.

The operation parameters are established, in the first place, by grid codes and the links should meet their requirements. Most of the links reported do not provide synthetic inertia support, although links that are being currently constructed, like the Cobra Cable, do. Even if protection is integrated in the DC control, faults are cleared in the AC side and the following characteristics provided in the questionnaires:

- Use of differential protection schemes and differential protection as back up.
- A TSO reported a maximum short circuit fault clearing time of 120ms, while other mentioned around 70ms.
- Location of the fault is determined, first, by step impedance measurement in the protection relay and, second, the location of the fault in the cable using different measurement devices.
- The classification of fault types is important according to two of the questionnaires and, according to a third one, this depends on system and customer requirements (this is the case when quick restart is required). No opinion is against a classification of fault types.

Regarding the availability of the link, values between 97.5% and 98.7% were reported.

Lessons learned regarding the HVDC came mostly from TSOs and are summarized below:

- Availability is a cost driving factor, however it is worth considering how much is essentially enough.
- During operation of converter dominated grids, the harmonic protection integrated in the HVDC system is really necessary. Converters, in combination with low damped grids, can cause several harmonic problems and classical protection systems will not react on this.
- The low short circuit power of converter dominated grids will not cause high currents in case of a fault. As a consequence, overcurrent relays may not detect short circuits and their use has to be avoided. Also, the characteristic of short circuit currents might be different and some protection relays may not detect the fault. Therefore, relays of different manufactures and protection technologies should be used (e.g. distance and differential protection).
- During operation, the extra high voltage equipment is running with very good availability. Most problems are caused by auxiliary systems. As valves need to be cooled, the complete HVDC system

will fail if pumps stop operating. In case of offshore systems, the seawater cooling system is not very reliable and it needs to be redundant.



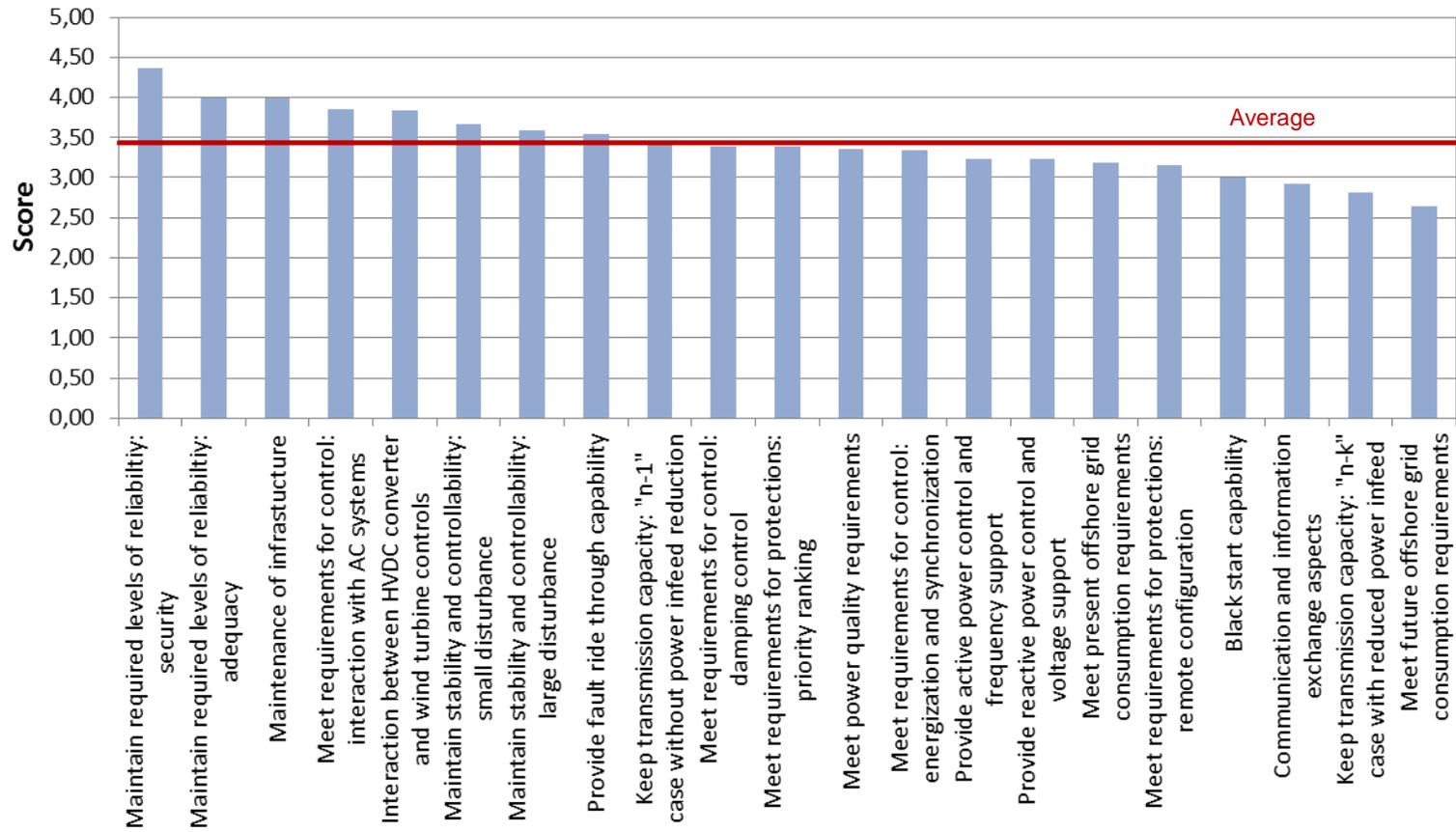


Figure 3.8. HVDC link operation challenges ranking



### 3.1.7 HVDC LINK PERFORMANCE

In the last section of the questionnaire, a general issue is raised in reference to the performance of the HVDC links and possible improvements in future projects of similar nature. According to the responses, these systems are generally performing as expected, even if there is still some place for improvement:

- The cost of offshore converter stations is higher than initially expected. Wind farm developers also comment on this, stating that in some cases the cost-benefit analysis showed that the traditional breakpoint distance of 100 km was moving farther into shore and projects that were initially designed to be connected with HVDC links were finally connected via HVAC cables.
- Building at least a DC termination facility in the point-to-point connections that are being constructed nowadays could help in the future integration into an HVDC grid.
- The insufficient incentives for the preparation of HVDC links under construction to be integrated in HVDC grids makes it difficult and they will end up being more expensive.
- Site implementation of Modular Multi Level Converter (MMC) control and protection remains a challenge.
- VSC technology, in comparison to LCC, permits advanced features such as black start, quick start and reactive power control, but its novelty means that many links had to be built using LCCs.
- Better coordination of cables and converters' specifications would be stressed if the VSC link under consideration was to be built today.

Only one response, by a TSO, stresses the fact that the performance of HVDC links is not often as expected and differs significantly from one project to the other, mostly due to the pilot character of these devices. Due to the lack of standards in the design of this kind of system, the operator has to spend a lot of time specifying in a high level of the detail its requirements, and unexpected performances require support from the supplier in order to adapt controls

### 3.1.8 HVDC GRIDS

Four blocks of questions to be ranked between 1 and 5 are included in this section, which is the one with highest number of responses.

Participants in the survey consider that the main advantages that HVDC networks will bring is the reliability improvement followed by cost reduction. On the contrary, power quality improvement seems to bring more doubts.



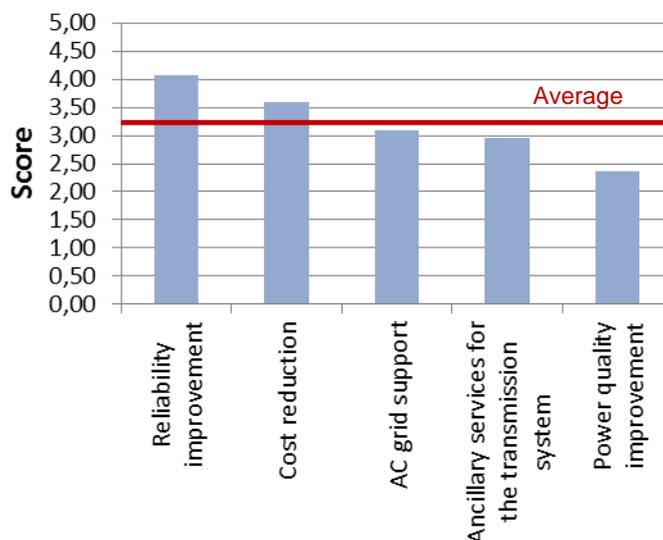


Figure 3.9. Improvements that HVDC networks will bring

Other opinions related to the improvements that HVDC networks may bring were shared in the questionnaires:

- HVDC networks will allow for clean (wind) energy generation without stability effects that are too negative. It will not so much improve current systems. Cost reduction, AC grid support, reliability, power quality and ancillary services are easily met with conventional generation.
- Size/volume will be improved.
- Higher operation flexibility.
- Improved system stability and security of supply via a larger regional distribution.

With respect to the grid topology, the meshed and radial multi-terminal got the same score at first position in the ranking. The option of DC breakers to split the network in subsystems was preferred to that of breakers in all branches and, in relation with the converter configuration, bipole and symmetrical monopole were considered best options.

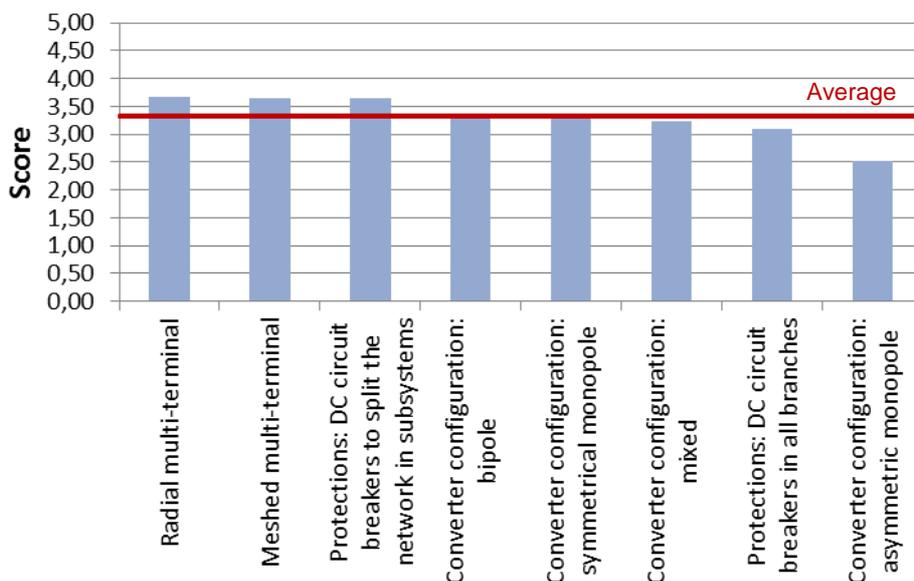


Figure 3.10. HVDC networks topology options

Questionnaire responses show that the majority of stakeholders consider that VSC technology will be key for the development of HVDC networks thanks to its inherent capabilities (black start, no voltage reversal, no need of strong AC grid, etc.), while line commutated converters (including diode-based ones) are considered of lesser relevance for such grids.

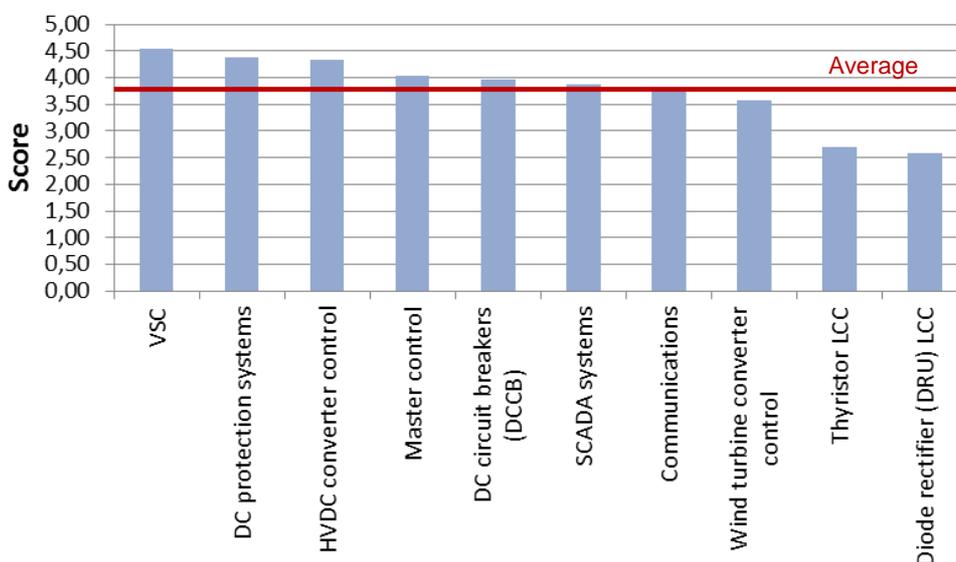


Figure 3.11. HVDC networks systems

Regulatory aspects were in the first place of the future challenges for HVDC networks, followed by financial issues. Last in the ranking, environmental impact was considered.

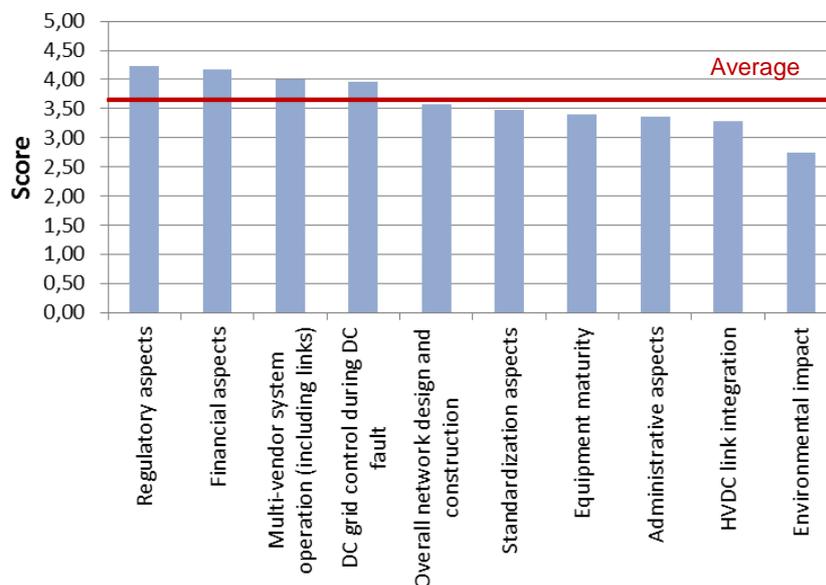


Figure 3.12. HVDC networks challenges for the future

Levelized Cost of Electricity (LCOE) calculation, DC/DC converters and suppliers capacity to face market requirements were pointed out as additional challenges of HVDC grids.

About the implications of integrating HVDC links in future meshed networks, several opinions were gathered:

- Most of the VSC connections might be integrated but converter control and protection will need to be completely adapted (e.g. in the case of one of the TSOs around 75% of the VSC links are suitable to become part of a meshed network). Cross links with additional substations should be adequately positioned and built. In addition, the overall protection strategy of the DC network should be revised and DC breakers should be installed in the new set up.
- LCC systems are not compatible.
- The modifications needed in the platforms represent a great barrier to accomplish this task:
  - In addition to circuit breakers, a new switching station is required in every platform. No spare space is likely to exist, therefore, a switching platform should be installed.
  - Systems are not running with the same DC voltages.
  - It should be checked whether state of art systems could operate in meshed grids.
  - There might not be available J-tubes for DC cables in the platforms.

The interoperability of multi-vendor links requires standardization, which is a challenging activity considering the efforts that should be put on this task: negotiation among stakeholders, Intellectual Property Rights (IPR) protection of vendors, maintenance of the standard, etc. Converter configuration and protection and control methods should be standardised to meet grid codes. It is not expected that the hardware should be modified. During the transition towards standardisation, if such interoperability is accomplished, the interface and its

management would involve higher risk and, therefore, higher costs and responsibility for the owner. Making most controls local could increase the independence of converters and would also help towards interoperability. In addition, providing clear boundaries of responsibility might also be relevant.

The most critical aspects to be taken into account for the development of future HVDC grids in Europe are the following, according to the participants in the survey:

- Systems such as protections, DC circuit breakers and DC/DC converters. DC breakers need to be efficient and not expensive or, as an alternative, converters should have the capacity of clearing a fault.
- DC load flow, converter control and small signal stability, DC fault detection and protection, turbine control.
- Development of hybrid topologies, combining VSC converters with other topologies to allow the development of cheaper and more efficient links.
- Investment sources. Convince regulators of the necessity to invest in the first projects of this kind, since their benefit is hard to justify. The benefit is visible only when the network has certain size.
- The integration of links in HVDC networks due to the voltage difference.
- Political willingness.
- Harmonization of regulation across borders.
- Regulations need to help projects be financially viable.
- Standardization.
- Fair and sustainable cost, benefit and risk allocation among stakeholders.
- Existence of a business case for the multi-terminal approach. As long as the wind farms are constructed with the same size as the rating of a symmetrical monopole, there is little incentive to go from a radial to a meshed topology. Decreasing costs of photovoltaics (PV) and storage will also influence the techno-economic feasibility of HVDC grids.
- HVDC networks should be very reliable in order to be considered the backbone of the transmission system. Currently, they do not reach the reliability level of conventional AC systems.



- To establish innovative technology solutions, demonstrators and first-of-a-kind deployment projects are needed and should be funded / supported on EU level. This will be the prerequisite to bring costs down.
- Better cooperation between manufacturers to increase customers' confidence. It is important that any problem during the lifetime of the equipment is properly and economically addressed, i.e. with the solution not being to remove vendor A hardware and install vendor B hardware (resulting in a single vendor system, or resulting in a system which is broken down in multiple and smaller “single vendor systems”).

This section permits the comparison between the opinions of two different groups of stakeholders, industry and academia, since around ten questionnaires from each of them responded to this set of questions.

With regard to the improvements that HVDC networks will bring, the academy/consulting group is more optimistic in general (higher average score) but with a short margin. The main differences exist in two topics:

- Cost reduction will be a clear improvement of HVDC networks for the academic stakeholders (second place in the ranking after the reliability improvement) while it gets a significantly lower score by industrial partners (3.0 versus 4.3).
- Power quality improvement differences are not so relevant and, in this case, industry is more optimistic (2.8 vs. 1.9).

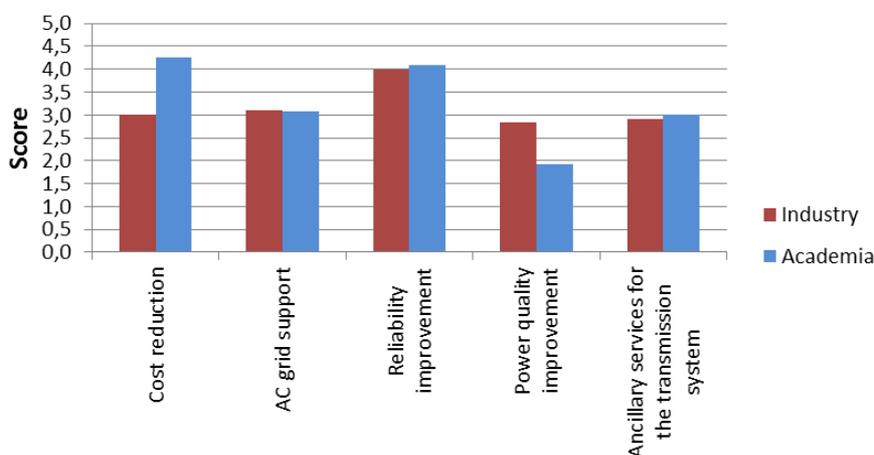


Figure 3.13. Improvements that HVDC networks will bring according to industry and academia

Topology related responses for both groups are presented in the next figure. Again, the opinions from academic/consulting stakeholders give higher scores, in this case to most of the topics. Apart from this, the same conclusions can be extracted from both groups with regard to topological issues with the exception of the preferred configuration. In this case, industry bets on the symmetrical monopole configuration while academia prefers mixed and bipole configurations.

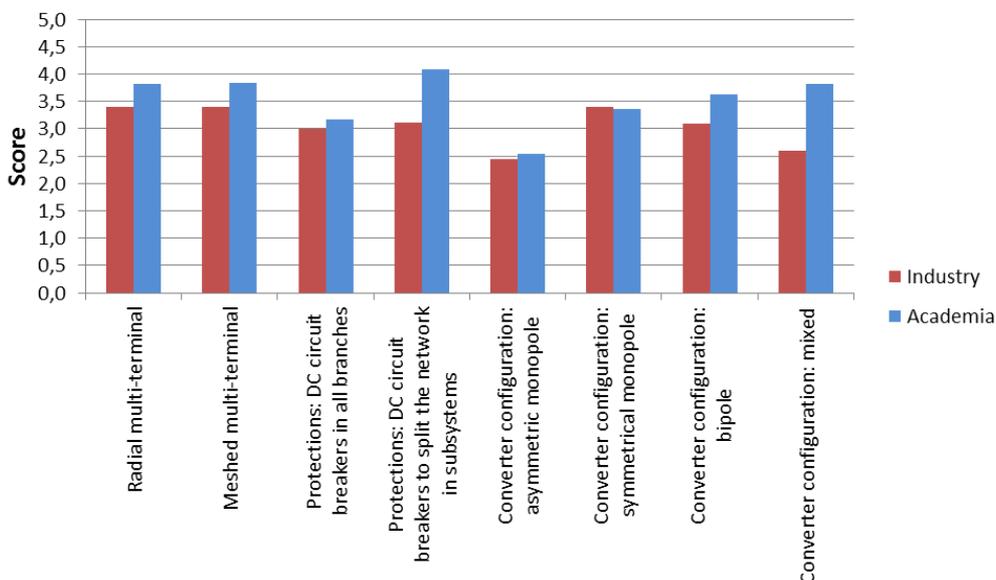


Figure 3.14. HVDC networks topology options for industry and academy/consulting stakeholders

Regarding the importance of different HVDC technologies, the opinions of the two groups of stakeholders are compared in the next figure. In general:

- Industrial stakeholders give clearly higher scores to the topics related to control (wind turbine, HVDC and master).
- Academia/consulting gives higher scores to LCC technologies and DC circuit breakers.

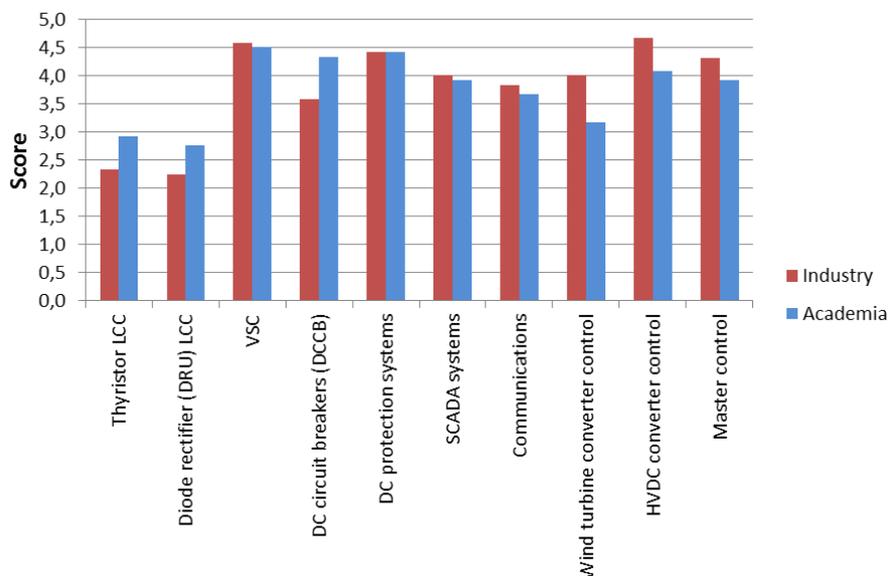


Figure 3.15. HVDC networks systems for industry and academy/consulting stakeholders

Regarding future challenges for HVDC networks, academic stakeholders give higher scores for all topics. However, their relative importance is very similar for both groups. The highest scoring differences stand out in the following topics: 'equipment maturity', 'HVDC link integration', and 'standardization aspects'.

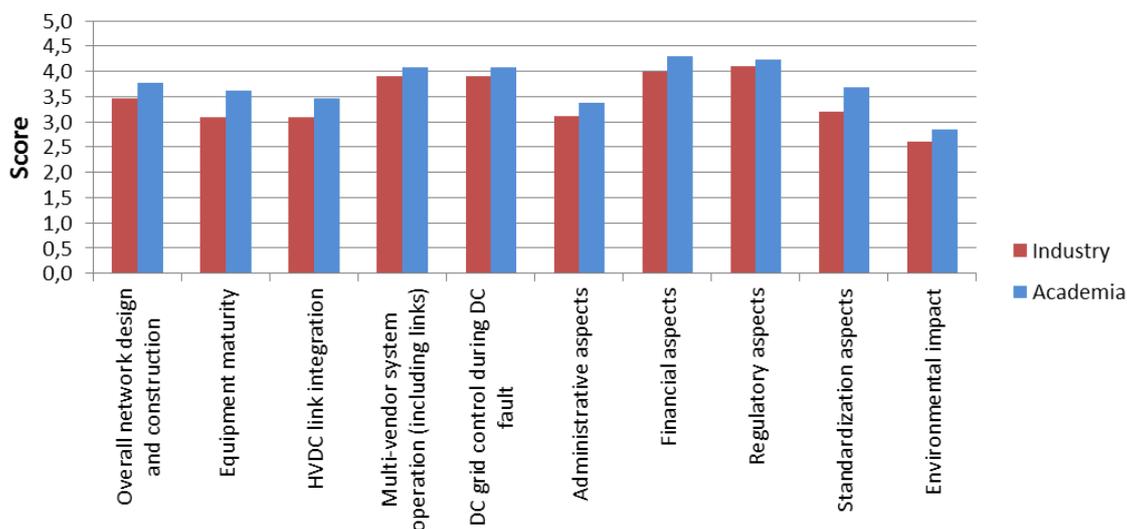


Figure 3.16. HVDC networks challenges for the future for industry and academia/consulting stakeholders

## 3.2 WORKSHOPS

Several topics related to HVDC projects were discussed in the workshops held in Edinburgh and Hamburg, and some best practices were proposed for each of them. A summary of the main conclusions is provided below in this section.

Regarding project planning phase these are some of the main aspects to be considered:

- Realistic planning (stakeholders should not push for unrealistic dates).
- Benefits of a masterplan
- Coordination with onshore parties (overhead lines face long lead times). Onshore grid connection points should not be overlooked in the planning. Both offshore and onshore developments should be integrated more systematically. Onshore networks should be able to cope with the gigawatt range supplies coming from large meshed offshore generation.
- Standardisation.
- Synergies in Operation & Maintenance (O&M) concepts.
- Clarity on liabilities and risks associated with the expense on infrastructure.

- Flexibility in design is key to permit retrofits in offshore substation and converter platforms, for example to enable future meshed connections through an extra J-tube. The issue here might be the acceptance of extra costs by the regulatory authority.
- Relatively small deployment sizes do not justify the use of HVDC links. The map of what AC can deliver is changing.

Regarding the administrative phase, and specifically about consenting issues, the following was brought up:

- It represents a high risk, along with construction, of HVDC projects.
- It may amount up to 5% of CAPEX.
- In the UK, consent is required for both the generation and transmission. The developer has to apply for the consent for grid connection together with consent for the Offshore Wind Farm (OWF) in the same time frame, which is challenging. Consent is required before acquiring a Contract for Difference (CfD) while, in Germany, consent is sought after being awarded a tariff.
- Onshore grid upgrades could be very hard to roll out due to public opposition and long planning processes.
- In Germany, there is the need to meet tight connection timeframes and penalties are applied if a connection is not developed in time.

Another of the topics that came up frequently throughout the workshop was regulation. These were some of the ideas that stemmed out from presentations and related discussions:

- The framework for offshore wind in Europe should be designed as 'umbrella legislation', allowing country specific approaches and allowing competition.
- The role of offshore transmission operators (OFTO) was analysed comparing monopoly versus an structure made up of various operators:
  - A monopoly position can unlock synergies resulting out of a well-coordinated planning approach. However, innovation might be limited because little incentives are available to take the risk associated with the introduction of new technologies.
  - A market with several operators can also block innovations due to the higher commercial risks affecting smaller businesses.
- There should be more incentives to encourage the investment decisions in new technologies.
- Regulation providing incentives should be stable and open to stakeholders of various types and sizes.



- The following issues were mentioned dealing with renewable energy subsidy schemes when generation units are connected to two or more jurisdictions:
  - This needs to be dealt with on a case by case basis.
  - All generation could be assumed to be in a single jurisdiction, i.e. market boundaries can be moved in respect to specific projects.
  - Whoever benefits should pay.
  - Work is being done by ENTSO-E on cross sharing issues.
  - Subsidy schemes are meant for developers to make their business cases positive. So subsidy schemes are part of business cases themselves.
  - There is a lot experience with onshore renewable electricity generation. Power is traded across borders without taking incentive schemes into account.

As concluded from the questionnaire results analysis, cost is one of the main concerns driving project design. It was also a recurrent topic in the workshop:

- Comparing HVAC vs. HVDC the following facts were presented: 100% for HVAC nearshore connection; 146% for classic HVDC far-shore connection. The cost benefit analysis shows that a large-scale island hub connecting tens of gigawatt wind capacity could bring cost down to 93% compared to today's HVAC grid connections. However international cooperation is key and a doubt remains about who will finance this type of project.
- Different approaches exist to cost benefit analysis. The ENTSO-E has developed a comprehensive methodology. This is a good starting point but it might be risky to rely only on one approach.

The difference in finance models was discussed between various stakeholders. There was some discussion on which model, Dutch versus UK, was better, with some seeing Ofgem as a pioneer. It was also highlighted that in some cases special purpose vehicles could be used for the financing of meshed grid projects, and then the projects once constructed could be sold to traditional financing firms.

A common mechanism for trading was requested in the workshop.

Some HVDC specific technologies were also dealt with during the workshop: DC breakers were a relevant topic of discussion:

- Various designs for DC circuit breakers were presented: active resonant scheme, passive resonant scheme and hybrid option. The DC circuit breaker with active resonant scheme is one of the candidates for multi-terminal DC networks because of its large current interruption capability and fast reaction time. Different options could co-exist but requirements might be needed to allow performing this in an optimum way.
- Technology is probably at TRL 8.



- Challenges and risks considerations need to be front ended e.g. business case needs, R&D efforts and competencies, and time constraints that align with commercial releases.
- The need for a demonstration project was highlighted for wind developers to adopt the meshed HVDC technology.
- The extent of use of circuit breakers and where these should be placed in HVDC grids remained up for discussion. It was recognised that once fully meshed, breakers will be needed to realise the main benefits of meshed network configurations.
- Fault management is clearly crucial. However, the cost for offshore protection systems (including the capability to interrupt fault current) has to be compared against the benefit to isolate a single faulted branch and leave everything else in service. In this context, it has to be considered how often faults do occur, in which time of the year (as the prevailing weather conditions determine repair time), grid downtime and the wind production curtailed as a consequence. It was then asked how offshore turbines should behave when there is a fault. Diode Rectifier Units (DRUs) could make it more complicated.
- The cost for placing a DC circuit breaker offshore is very high, while the utilisation of the asset is occasional. From UoS's perspective the best solution is an AC protected system with few or no DC circuit breakers placed offshore. As there are no offshore consumers, continuity of supply is less of an issue than for onshore transmission networks. However, the economics may change in the future and there could be a technological jump.

DC/DC converters were proposed as future solution to cope with the foreseeable co-existence of different voltage levels in HVDC implementations. DC/DC converters are currently not commercially available at reasonable cost, so this remains an area for further improvement.

Some opinions were also expressed in the workshops referred to HVDC networks:

- Following the case study of East Anglia wind farm project, it was suggested that there is little benefit to increased coordination and offshore interconnection between the planning sites in the area. It was instead suggested that onshore interconnection (reinforcement of existing lines) could provide greater benefit.
- A meshed DC grid should be first demonstrated onshore in order to save costs and minimise economic risks.



## 4 CONCLUSIONS

This document reports the answers to the questionnaire on best practices received from different kinds of stakeholders, most of them coming from the industry and academia. There are some differences in the perception of these two stakeholder groups regarding future HVDC grids in Europe. While the academic world thinks that these grids will be important to lower the costs when compared to point-to-point links, the industry thinks that the degree in which these reductions will take place has yet to be studied in depth, and considers that symmetrical monopole point-to-point VSC links will be the most common projects until the technical and policy barriers are overcome. Existing projects fulfil the design requirements set by the companies operating them, although experience shows that the cost of the technology is larger than expected and some projects had to switch to HVAC to be competitive.

The main drivers in the design of an HVDC project are CAPEX and reliability. The designs try to comply with N-1 requirements and reduce losses using the simplest topology. Due to the environmental laws that limit the use of earth or sea return electrodes, the most common topology in the latest projects, especially those connecting offshore wind farms, is the point-to-point symmetrical monopole.

HVDC projects usually interconnect different countries, require a close collaboration between TSOs and wind farm developers, are unique and the technology used is often new and not standardized. This means that there must be a right organizational setup from the very beginning, with clear objectives and schedule.

The technical design phase requires detailed simulation studies to understand the behaviour of the link and write a correct specification. In this sense, there are some issues with the simulations that involve models supplied by converter manufacturers, since the details of these models are only known to the suppliers and they are the only ones who can run software tests to solve issues related to the control.

Interoperability must also be guaranteed in the future grids. This is a challenging issue because it requires a lot of negotiation among different stakeholders to respect the intellectual property rights of vendors and standardise protection and control methods to meet grid codes. During the transition towards the standardisation the operators will face higher risks that may translate into higher costs.

Regulatory aspects are of vital importance for the development of meshed HVDC grids. Different European countries have different regulatory frameworks, and it is not currently clear how renewable energy subsidy schemes will fit in a generation unit using a grid that interconnects two or more jurisdictions, or who will operate this infrastructure and what the charging regimes will be. It is also necessary to have a clear roadmap for the development of meshed HVDC grids to avoid extra costs. Most of the existing VSC connections are suitable to become part of a meshed network, but converter control and protection will have to be completely adapted and,



in addition to circuit breakers, additional space has to be allocated in every platform to allow future upgrades for it to become a node in the grid.

Most of the concerns expressed by the experts consulted in Task 1.3 will be tackled in PROMOTioN and it is expected that the outcomes of the project will help make a significant step towards the realization of an Europe wide DC network that will increase the penetration of renewable energy and allow the commercialization of energy at a higher scale among the member countries.



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## 6 ANNEX A: QUESTIONNAIRE FOR BEST PRACTICES ON HVDC PROJECTS





**PROMOTiON**  
 PROGRESS ON MESHED HVDC  
 OFFSHORE TRANSMISSION  
 NETWORKS

# QUESTIONNAIRE

# BEST PRACTICES ON HVDC PROJECTS

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## 1. PERSONAL AND PROJECT INFORMATION

Name	Position	Company	Stakeholder group <sup>1</sup>

HVDC project/s used as reference for the information provided in the questionnaire	Link to general information on the project

Would you agree to be contacted by the project team for follow-up?  Yes  No

Please indicate preferred contact:  e-Mail address: .....

Telephone: .....

<sup>1</sup>Six **stakeholder groups** have been identified as target groups for this questionnaire; each question is initially addressed to one or more stakeholders, but feel free to answer any of the questions where you have knowledge or opinions. The six stakeholder groups are as follows:

- Political institutions
- Industry
- Regulation, standardization and expert groups
- Academia & Consulting
- Financing
- Public



PROMOTiON – Progress on Meshed HVDC Offshore Transmission Networks

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

## 2. PROJECT PLANNING: TECHNICAL DESIGN

### I. Please help to identify relevant aspects influencing the technical design of the HVDC projects?



From Not important (1) to Very important (5)

	1	2	3	4	5
Offshore location characteristics (water depth, seabed conditions, etc.) .....	<input type="checkbox"/>				
Potential impact on third parties: shipping .....	<input type="checkbox"/>				
Potential impact on third parties fishing industry.....	<input type="checkbox"/>				
Potential impact on third parties: oil & gas.....	<input type="checkbox"/>				
Interaction with existing onshore networks .....	<input type="checkbox"/>				
Voltage level of wind farm array .....	<input type="checkbox"/>				
Lessons learned from previous projects .....	<input type="checkbox"/>				

Cable

Length of the link .....	<input type="checkbox"/>				
Route of the link.....	<input type="checkbox"/>				
Cable CAPEX.....	<input type="checkbox"/>				
Cable OPEX .....	<input type="checkbox"/>				
Cable reliability .....	<input type="checkbox"/>				
Electrical losses in the DC cable .....	<input type="checkbox"/>				
Requirements from existing technical standards .....	<input type="checkbox"/>				
Requirements from certification .....	<input type="checkbox"/>				
Risk aversion / mitigation strategy .....	<input type="checkbox"/>				
Maintenance and repair strategy .....	<input type="checkbox"/>				
Potential environmental impact.....	<input type="checkbox"/>				

HVDC converter station

Converter station CAPEX .....	<input type="checkbox"/>				
Converter station OPEX .....	<input type="checkbox"/>				
Converter station reliability .....	<input type="checkbox"/>				
Electrical losses in offshore converter .....	<input type="checkbox"/>				
Offshore platform lifting constraints .....	<input type="checkbox"/>				
Interaction with offshore wind turbine generators .....	<input type="checkbox"/>				
Requirements from existing technical standards .....	<input type="checkbox"/>				
Requirements from certification .....	<input type="checkbox"/>				
Risk aversion / mitigation strategy .....	<input type="checkbox"/>				
Maintenance and repair strategy .....	<input type="checkbox"/>				
Transients or harmonic issues.....	<input type="checkbox"/>				
Potential environmental impact.....	<input type="checkbox"/>				

Onshore station

Characteristics of landfall site .....	<input type="checkbox"/>				
Distance to closest grid connection point.....	<input type="checkbox"/>				
Transients or harmonic issues.....	<input type="checkbox"/>				
Electrical losses in onshore converter .....	<input type="checkbox"/>				

II. If a modification to the initial design was required during the subsequent phases of the project, what were the main reasons?



From Not important (1) to Very important (5)

	1	2	3	4	5
Impact on protected areas .....	<input type="checkbox"/>				
Electromagnetic emissions .....	<input type="checkbox"/>				
Restricted area crossings .....	<input type="checkbox"/>				
Existing pipes/cable crossings.....	<input type="checkbox"/>				
Interaction with shipping lanes.....	<input type="checkbox"/>				
Conflicts of interest (with fishing, oil & gas, other seabed uses...) .....	<input type="checkbox"/>				
Delays due to administrative issues or other .....	<input type="checkbox"/>				
Cost increase (due to administrative issues or other) .....	<input type="checkbox"/>				
Unavailability of market products or service providers.....	<input type="checkbox"/>				
Unexpected findings regarding seabed conditions .....	<input type="checkbox"/>				
Inappropriate installation equipment.....	<input type="checkbox"/>				
Technology innovation during project execution.....	<input type="checkbox"/>				
Revision of standards during project execution .....	<input type="checkbox"/>				
Bottlenecks in the supply chain .....	<input type="checkbox"/>				
Insurance aspects (e.g. claims) .....	<input type="checkbox"/>				

**2.1 What were the main drivers behind the choice of the topology used in the project?** (Referred topology examples: monopole earth return, monopole metallic return, symmetrical monopole, bipolar earth return, bipolar metallic return, monopoles connected to a bipolar grid)



**2.2 Which suppliers were used for the converters and the DC cable? Was the main reason for choosing them technical or economic?**



**2.3 Please comment on the best practices and lessons learned during the technical design phase of the project.** (Stress most important issues and include other aspects not considered in the previous questions. Consider 300-400 words as illustrative maximum length of your description).



### 3. PROJECT PLANNING: ADMINISTRATIVE ISSUES

III. Please identify the most challenging administrative aspects for the development of HVDC projects?



From Not important (1) to Very important (5)

	1	2	3	4	5
Environmental Impact Assessment (EIA) .....	<input type="checkbox"/>				
Field studies for the EIA.....	<input type="checkbox"/>				
Liaising with a large number of authorities.....	<input type="checkbox"/>				
The complexity and the considerations of procedures and standards .....	<input type="checkbox"/>				
Involvement of authorities from multiple countries .....	<input type="checkbox"/>				
International disputes of sea zones (EEZ <sup>1</sup> , international waters...)	<input type="checkbox"/>				
Preparing and submitting applications.....	<input type="checkbox"/>				
Public opposition (social acceptance).....	<input type="checkbox"/>				
Opposition of other stakeholders .....	<input type="checkbox"/>				

IV. What were the expected and real durations of the consenting process? ..... / .....months



V. What were the incurred extra costs due to administrative issues (in euros)? .....k€



VI. What were the incurred extra costs due to administrative issues (as a percentage of planned cost)?.....%



**3.1 Please comment on the main barriers encountered during the planning and licensing phase of the project and how they were dealt with. What were the lessons learnt for future projects?**  
 (Stress most important issues and include other aspects not considered in the previous questions. Consider 300-400 words as illustrative maximum length of your description).



<sup>1</sup> Exclusive Economic Zone

## 4. PROJECT PLANNING: POLICY AND FINANCE

VII. Please identify the challenges of HVDC projects focussing on economic, financial, legal and regulatory aspects?



From Not important (1) to Very important (5)

	1	2	3	4	5
Involvement of public financial institutions .....	<input type="checkbox"/>				
Involvement of private financial institutions.....	<input type="checkbox"/>				
Legislative ambiguity .....	<input type="checkbox"/>				
Regulatory changes.....	<input type="checkbox"/>				
Liaising with a large number of regulatory bodies.....	<input type="checkbox"/>				
Existence of renewable generation support schemes .....	<input type="checkbox"/>				
Existence of priority market access for offshore generation .....	<input type="checkbox"/>				
Participation in ancillary services markets .....	<input type="checkbox"/>				
Liability definition and compensation schemes .....	<input type="checkbox"/>				
Cost/benefit uncertainty .....	<input type="checkbox"/>				
Fair cost allocation between beneficiaries .....	<input type="checkbox"/>				
Existence incentives to investment.....	<input type="checkbox"/>				

**4.1 Please comment on the best practices and lessons learned on policy and finance issues.** (E.g. public-private partnership, evaluation of investment and operation risks, specific financial products or services, authorities support... Consider 300-400 words as illustrative maximum length of your description).



# 5. PROJECT MANAGEMENT      PLANNING:      PROJECT

VIII. Please help to identify the main sources of problems for the internal project organization:



From Not important (1) to Very important (5)

- |   |  |
|---|--|
|   | 1 2 3 4 5  |
| None or late involvement of resources in administrative (permitting) issues ..... | <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> |
| Lack of involvement of different expertise fields .....                           | <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> |
| Insufficient integration of external resources .....                              | <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> |
| Co-operation between partner TSOs .....   | <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> |

**5.1 Please comment on the best practices and lessons learned on project organization.** (E.g. creation of specific working groups, strong project management and responsibilities distribution, use of specific methodologies for project management... Consider 300-400 words as illustrative maximum length of your description).



## 6. CONSTRUCTION

### IX. Please help to identify the main challenges of the construction phase?



From Not important (1) to Very important (5)

- |  | 1                        | 2                        | 3                        | 4                        | 5                        |
|--|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Keeping to schedule .....  | <input type="checkbox"/> |
| Achieve interoperability between systems (legacy, multi-vendor.....) | <input type="checkbox"/> |
| Interfaces between subprojects .....                                 | <input type="checkbox"/> |
| Subcontractors .....   | <input type="checkbox"/> |
| Document management .....  | <input type="checkbox"/> |
| Contract management .....  | <input type="checkbox"/> |

Cable

- |  |                          |                          |                          |                          |                          |
|--|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Availability of products and services .....          | <input type="checkbox"/> |
| Cable routing .....                                  | <input type="checkbox"/> |
| Cable burial process .....                           | <input type="checkbox"/> |
| Cable pull-in at offshore converter substation.....  | <input type="checkbox"/> |
| Installation logistics.....                          | <input type="checkbox"/> |
| Safety .....   | <input type="checkbox"/> |
| Unfavourable weather conditions causing delays ..... | <input type="checkbox"/> |

Offshore platform structure

- |  |                          |                          |                          |                          |                          |
|--|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Availability of products and services .....          | <input type="checkbox"/> |
| Installation logistics.....                          | <input type="checkbox"/> |
| Safety .....   | <input type="checkbox"/> |
| Unfavourable weather conditions causing delays ..... | <input type="checkbox"/> |

Offshore platform topside

- |  |                          |                          |                          |                          |                          |
|--|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Availability of products and services .....          | <input type="checkbox"/> |
| Installation logistics.....                          | <input type="checkbox"/> |
| Safety .....   | <input type="checkbox"/> |
| Unfavourable weather conditions causing delays ..... | <input type="checkbox"/> |

Onshore station

- |  |                          |                          |                          |                          |                          |
|--|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Onshore converter substation.....                  | <input type="checkbox"/> |
| Preparation of landfall site (shore landing) ..... | <input type="checkbox"/> |

### X. What were the expected and real durations of the construction phase?



...../.....months

**6.1 Did you suffer any significant delays during the cable routing? What were the causes for these delays and how were they managed?**



<b>6.2 Did you suffer any significant delays during the construction of the converter stations (offshore and onshore)? What were the causes for these delays and how were they managed?</b>	<b>I AC</b>

<b>6.3 Please comment on the best practices and lessons learned regarding the construction of the HVDC link.</b> (E.g. how to deal with cable routing and converter construction, how to integrate legacy and multi-vendor systems... Consider 300-400 words as illustrative maximum length of your description).	<b>I AC RS</b>



## 7. OPERATION

### XI. Please help to identify the main challenges of the operation of HVDC links?

I AC RS

From Not important (1) to Very important (5)

	1	2	3	4	5
Keep transmission capacity: "n-1" case without power infeed reduction .....	<input type="checkbox"/>				
Keep transmission capacity: "n-k" case with reduced power infeed .....	<input type="checkbox"/>				
Maintain required levels of reliability: adequacy .....	<input type="checkbox"/>				
Maintain required levels of reliability: security.....	<input type="checkbox"/>				
Maintain stability and controllability: small disturbance .....	<input type="checkbox"/>				
Maintain stability and controllability: large disturbance .....	<input type="checkbox"/>				
Provide active power control and frequency support .....	<input type="checkbox"/>				
Provide reactive power control and voltage support .....	<input type="checkbox"/>				
Provide fault ride through capability.....	<input type="checkbox"/>				
Meet requirements for control: energization and synchronization.....	<input type="checkbox"/>				
Meet requirements for control: interaction with AC systems .....	<input type="checkbox"/>				
Meet requirements for control: damping control .....	<input type="checkbox"/>				
Meet requirements for protections: priority ranking.....	<input type="checkbox"/>				
Meet requirements for protections: remote configuration.....	<input type="checkbox"/>				
Black start capability .....	<input type="checkbox"/>				
Meet power quality requirements.....	<input type="checkbox"/>				
Communication and information exchange aspects .....	<input type="checkbox"/>				
Meet present offshore grid consumption requirements.....	<input type="checkbox"/>				
Meet future offshore grid consumption requirements.....	<input type="checkbox"/>				
Interaction between HVDC converter and wind turbine controls.....	<input type="checkbox"/>				
Maintenance of infrastructure .....	<input type="checkbox"/>				

### XII. What are the operational limits of the link?

I AC

<b>7.1 What is the minimum power that the link can transmit?</b>
<b>7.2 What are the voltage limits in which the link operates?</b>
<b>7.3 What are the frequency limits in which the link operates?</b>
<b>7.4 What are the fault ride-through requirements for the link?</b>
<b>7.5 Does the link provide synthetic inertia support? In which range?</b>

XIII. What is the protection strategy used in the link?

I AC

<b>7.6 How are short-circuit faults detected and cleared? What are maximal fault clearance times?</b>

<b>7.7 How is the fault location determined in case of a line fault?</b>

<b>7.8 Are classifications of fault types important after fault clearance?</b>

XIV. What is the expected/real availability<sup>2</sup> of the system?...../.....

I AC

<b>7.9 Please comment on the best practices and lessons learned regarding HVDC link operation.</b> (E.g. use of redundancy, protection strategy, short circuit fault detection and location... Consider 300-400 words as illustrative maximum length of your description).

I AC RS

<sup>2</sup> Percentage of time that the system is available without considering planned downtimes

## 8. FUTURE HVDC GRIDS

XV. In general terms, what improvements will meshed HVDC networks bring with respect to point to point solutions?

I AC RS

From Not important (1) to Very important (5)

	1	2	3	4	5
Cost reduction .....	<input type="checkbox"/>				
AC grid support.....	<input type="checkbox"/>				
Reliability improvement.....	<input type="checkbox"/>				
Power quality improvement .....	<input type="checkbox"/>				
Ancillary services for the transmission system .....	<input type="checkbox"/>				
Others (specify) .....	<input type="checkbox"/>				

XVI. Which of the following will be important with respect to HVDC grid topology options in future grids?

I AC RS

From Not important (1) to Very important (5)

	1	2	3	4	5
Radial multi-terminal .....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Meshed multi-terminal .....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Protections: DC circuit breakers in all branches .....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Protections: DC circuit breakers to split the network in subsystems.....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Converter configurations: asymmetric monopole.....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Converter configurations: symmetrical monopole.....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Converter configurations: bipole .....	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Converter configurations: mixed .....	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

XVII. Please rate the importance of the following systems in HVDC grids?

I AC RS

From Not important (1) to Very important (5)

	1	2	3	4	5
Thyristor LCC .....	<input type="checkbox"/>				
Diode rectifier (DRU) LCC .....	<input type="checkbox"/>				
VSC .....	<input type="checkbox"/>				
DC circuit breakers (DCCB).....	<input type="checkbox"/>				
DC protection systems.....	<input type="checkbox"/>				
SCADA systems .....	<input type="checkbox"/>				
Communications.....	<input type="checkbox"/>				
Wind turbine converter control.....	<input type="checkbox"/>				
HVDC converter control.....	<input type="checkbox"/>				
Master control.....	<input type="checkbox"/>				

XVIII. Please help to identify the main challenges of HVDC grids in the future? I AC RS PI F P

From Not important (1) to Very important (5)

	1	2	3	4	5
Overall network design and construction .....	<input type="checkbox"/>				
Equipment maturity .....	<input type="checkbox"/>				
HVDC link integration .....	<input type="checkbox"/>				
Multi-vendor system operation (including links) .....	<input type="checkbox"/>				
DC grid control during DC fault .....	<input type="checkbox"/>				
Administrative aspects .....	<input type="checkbox"/>				
Financial aspects .....	<input type="checkbox"/>				
Regulatory aspects .....	<input type="checkbox"/>				
Standardization aspects .....	<input type="checkbox"/>				
Environmental impact .....	<input type="checkbox"/>				
Others (specify) .....	<input type="checkbox"/>				

**8.1 To what extent do you consider that the HVDC link (or links) in which your company has been involved would be able to become part of a meshed DC grid? What modifications would be required for it to be connected?** I AC

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**8.2 What would be the requirements for the interoperability of multi-vendor links? What do you estimate would be the cost of these requirements?** I AC

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**8.3 Please provide your view and concerns on the development of the future meshed HVDC grids in Europe, and specify the most critical aspects that you consider that should be taken into account for the successful deployment of such grids.** I AC RS PI F P

Consider 300-400 words as orientative maximum length of your description.

---

XIX. When do you think that HVDC networks will become reality? I AC RS PI  
 In.....years



## 9. CLOSING QUESTIONS

**9.1 In general terms, and according to your experience, do HVDC links perform as expected? What would be the main changes you would make if the project (or projects) in which your company was involved were constructed today?**

I AC

**9.2 The Promotion project will hold a workshop in Madrid on 1<sup>st</sup> September 2016 to discuss HVDC links and share experiences and lessons learnt from different stakeholders. Would you be interested in attending this event? What are the aspects you would like to be addressed at the workshop?**

I AC RS PI F P

## 7 ANNEX B: EDINBURGH WORKSHOP MINUTES

**Workshop date:** 5 October 2016

**Attendees:** Andrzej Adamczyk (Alstom), Waqas Ahmed (ORE Catapult), Urban Axelsson (Vattenfall), Keith Bell (University of Strathclyde), Ramon Blasco-Gimenez (IEEE), Salvador Ceballos (Tecnalia Corporación Tecnológica), Geraint Chaffey (Imperial College London), Thomas Donders (TenneT), Niek de Groot (TenneT), Othmane El Mountassir (ORE Catapult), Gavin Greene (Scottish Power Renewables), Guy Henley (Carbon Trust), Inigo Azpiri Irazabal (Iberdrola), Callum MacIver (University of Strathclyde), Luis Martin (Iberdrola), Peter McGarley (DONG Energy), Samer Oukaili (Mitsubishi Electric Europe), Andre Rauwerda (DNV-GL), Jonathan Ruddy (University College Dublin), James Sinfield (Carbon Trust), Kamal Siriwardhana (Arup), Michael Smailes (ORE Catapult), Claudia Spallarossa (Mitsubishi Electric Europe), Tobias Verfuss (Carbon Trust), Konstantin Vershinin (GE), Bo Westman (ABB)

**Workshop aim:** To convene relevant stakeholders from (Northern) Europe in order to collect knowledge from existing HVDC projects and to enrich stakeholder feedback on the questionnaire that was developed in PROMOTioN Task 1.3

### Workshop agenda

- 09.30 - Registration and coffee
- 10.00 - Intro to the workshop and welcome to Edinburgh (James Sinfield, Carbon Trust)
- 10.10 - Introduction to PROMOTioN (Niek de Groot, TenneT)
- 10.30 - HVDC Development (Thomas Donders, TenneT)
- 11.30 - Coffee Break
- 11.45 - Technology from the utility perspective (Gavin Greene, SPR)
- 12.45 – Lunch
- 13.30 -Technology from the manufacturers perspective (Claudia Spallarossa, Mitsubishi)
- 14.30 - Academic perspective (Keith Bell, University of Strathclyde)
- 15.30 - Regulatory environment (Guy Henley, Carbon Trust)
- 16.00 - Reporting on questionnaire and literature review (Inigo Azpiri Irazabal, Iberdrola)
- 16.30 - Closing remarks (James Sinfield, Carbon Trust)



## Proceedings

### 1-Introduction and welcome (James Sinfield, Carbon Trust)

This workshop is aimed at enriching the information gathered by the questionnaire which was developed within PROMOTioN Task1.3 (<https://goo.gl/JSwvFE>), to collect knowledge from existing projects, increase the awareness about PROMOTioN, and disseminate data from the questionnaire.

### 2-Introduction to PROMOTioN (Niek de Groot, TenneT)

An introduction to PROMOTioN was provided. Project duration 4 years, 34 consortium partners, €39.3m EU funding under Horizon 2020 programme. Motivation to initiate the project derived from European climate targets, massive deployment of renewable energies needed. Huge wind potential in Europe's marine environment thus project focus on offshore wind. Project comprises technology development and demonstration as well as development of a roadmap (deployment plan for future European offshore grid) as a final outcome. A brief introduction to technical, financial and regulatory challenges was given. The rationale for meshed grids to connect offshore windfarms was briefly touched upon, including (i) the large wind resource in the North Sea (ii) less stakeholder concerns with offshore deployment of wind energy and (iii) the need to bring the costs down.

#### Discussion:

- Synergies and potential for learning from the Cenelec working group. It was raised by an industry stakeholder that to date coordination between PROMOTioN and Cenelec hasn't occurred on a sufficient level. This point was answered by Mitsubishi and TenneT that PROMOTioN WP11 "Harmonization towards standardisation" will cover this area, and that engagement with other stakeholders and working groups already happens in the project (as much as these stakeholders are in the PROMOTioN consortium, e.g. ABB) or invited to join and participate. It was discussed whether this should be front ended, or whether formal steps and processes could be taken to ensure cross findings were discussed and worked upon where appropriate. It was mentioned that steps could be taken to ensure protection, breakers and control findings from Cenelec were incorporated.
- The industry stakeholder went on to state that other technical meeting groups operating in the HVDC space (e.g. Cenelec, CIGRE) could help to prioritise efforts across PROMOTioN, avoid repetition and meet industry needs. In particular, Cenelec should be involved in the process to define (functional) requirements. In addition it should be recognised that aspects such as standards are fluid, and therefore there could be value for PROMOTioN to challenges other working groups findings.

### 3-HVDC Development (Thomas Donders, TenneT)

Overview of TenneT's offshore wind activities in Germany (DE) and The Netherlands (NL). Windfarms are currently being connected both via HVAC and HVDC links. Brief description of lessons learned and best practice including (i) Realistic planning (stakeholders shouldn't push for unrealistic dates), (ii) NBenefits of a masterplan, (iii) Coordination with onshore parties (overhead lines face long lead times), (iv) Standardisation (v), Synergies in O&M concepts, (vi) Clarity on liabilities and risks associated with the expense of infrastructure.

In order to meet European renewable energy and climate change targets it is needed to step up offshore wind deployment rapidly. In NL parties have established an 'Energy Agreement' which suggests the deployment of 3.5GW offshore wind capacity. TenneT was appointed as



offshore grid operator through this agreement as it was deemed this would result in the greatest efficiencies and bring down cost. As examples for recent cost degression, Vattenfall's Vesterhav Nord & Syd project in Denmark (€64.0 per MWh, excluding transmission cost) and DONG Energy's Borssele 1+2 project in NL (€72.7 per MWh, excluding transmission cost) were mentioned as examples.

Schematics on projects within NL and DE were presented. Cost efficiencies were obtained in NL from the use of HVAC technology, leaner infrastructure (substations without helideck, elimination of backup diesel generator on platform), introduction of 66kV array voltage requirement and standardisation, i.e. roll out of five identical offshore transformer platforms and standardised connections between platforms and windfarms. Synchronising the development of the grid with the generation units could make significant reductions to overall capex.

Illustration of 'island hub' concept. Planning horizon 2024-2035 for planning area 'Ijmuiden Ver' (next to British East Anglia zone), and 2050 for Dogger Bank island. Cost of energy comparison: 100% for HVAC nearshore connection; 146% for classic HVDC farshore connection (current technology). Cost benefit analysis show indicate that a large-scale island hub connecting tens of GW wind capacity could bring cost down to 93% compared to today's HVAC grid connections. However, international cooperation is key.

Discussion:

- It was discussed between various stakeholders how regulatory challenges can be addressed. It was concluded that the framework for offshore wind in Europe should allow be designed as 'umbrella legislation' allowing country specific models and enabling competition. It was stressed that not every detail needs to be harmonised.
- An industry stakeholder mentioned that onshore grid connection points are important factors that are often overlooked in planning for offshore windfarms.
- It was asked by an industry stakeholder if the design of the offshore substations at Borssele follows a standard design. TenneT clarified that the NL substation designs differ from DE designs as different requirements apply. As such the cost savings realised at Borssele are not fully transferable to other countries and in particular not to farshore sites.
- An industry stakeholder commented that it remains unclear who would finance the proposed 'island hub' as the connected windfarms would belong to different countries.
- It was discussed between various stakeholders how the Dutch approach compares with the UK model. In general there is a need to integrate offshore development with onshore development more systematically. The Dutch model seems more stringent with regard to long-term planning. In the UK, Offshore Transmission Operators (OFTO) compete on financing, based on operation and maintenance, but they need to ask for onshore grid connections from National Grid. The UK transmission capabilities are old, some of the systems in the UK need upgrades, but who should pay for the cost. In NL, TenneT was given greater freedom and the current setup allowed them to link offshore windfarms to onshore connection points that were already available, i.e. new ones did not need to be built. It remains however unclear which is more cost effective approach. A TSO in a monopoly position can unlock synergies resulting out of a well coordinated planning approach, but other examples show that monopoly structures are not great for innovation as there are little incentives to take the risk which is associated with the introduction of new technologies. On the other hand, a market with several smaller grid operators can also block innovations as smaller businesses are exposed to higher commercial risk and tend to rely on proven technology.

- It was asked by an academic stakeholder how lessons learnt on items like stability, coordination, long term planning, and standardisation can be incorporated elsewhere? Another industry stakeholder commented that for longer term planning the onshore grid will struggle to integrate very large meshed generation sites with generation capacities in the GW range, and that it will be hard to upgrade the onshore system to cope with such large intakes. Grid codes for technical connections for large links is not easy. In the UK onshore infrastructure is not geared for large GW at least cost. Importantly it is not clear who is going to fund the hub i.e. Where will the money come from, and at what cost. Although there has been precedents for joint large scale funding as seen with northern EU gas connections. PROMOTioN WP12 should be able to develop a deployment plan, but talking about 70GW may be too big.
- It was mentioned by an industry stakeholder that a monopoly network provider will try to maximise the size of the asset base, because they get a return on size of the asset base. So they have fragmented decision making, and insufficient drivers to take a longer term view.
- The difference in finance models was discussed between various stakeholders. One is based on price cap, and rate of return. It was mentioned that other countries are looking to the UK interconnector model as it is deemed front running. The Revenue Incentives Innovation Outputs (RIIO) model, income adjustment factors were debated, and it was unsure if these were effective at present. Note: there was some discussion on which model (Dutch versus UK was better), with some seeing Ofgem<sup>3</sup> as a pioneer.

#### 4-Technology from the Utility perspective (Gavin Greene, SPR)

SPR presented the challenges for new technology from a utility perspective. To do this it learnt upon experience derived from the East Anglia windfarm project (700 MW substation, 66kV array voltage). Findings from the Integrated Offshore Transmission Project (IOTP) were briefly presented<sup>4</sup>. Following an analysis across the East Anglia stakeholders it was suggested there is little benefit to increased coordination and offshore interconnection between the planning sites in the East Anglia zone. It was instead suggested that onshore interconnection (reinforcement of existing lines) could be cheaper realised and provide greater benefit. For increased offshore interconnection several questions need to be addressed: (i) who is going to coordinate planning and construction, (ii) who manages the asset, and (iii) who invests?

**Consenting** was singled out as a large part of the risk (along with construction). i.e. in the UK consent is required for the transmission and the generation unit, but the UK Government is also very concerned about onshore requirements. Consenting cost up to 5% of CAPEX, in UK the developer has to apply for the consent for grid connection together with consent for OWF in the same timeframe which is challenging. Consenting requirements include:

- Design options
- Routing alternatives
- Environmental Impact Assessment (EIA)
- Planning application
- Stakeholder engagement
- Landowner agreements
- Feasibility
- Master plan is required for forward planning

<sup>3</sup> Office of Gas and Electricity Markets - the UK regulator

<sup>4</sup> See Future Energy documents here: <http://www2.nationalgrid.com/uk/industry-information/future-of-energy/>

- Route selection is required 6-7 years in advance (onshore) and think about new connections

Planning for future connections is challenging, especially in terms of developing and financing capital intensive offshore platforms. It was highlighted that the time frame for the consenting process was key. The German/Dutch model offers a streamlined and holistic approach. In Germany there is the need to meet tight connection timeframes, and compensation is provided if a connection is not developed in time. In the UK, with OFTO and now 'Competitively Appointed Transmission Owners' (CATO) it is much more fragmented. No one has gone for the 'OFTO build' option so far. The situation is getting very complex with CATOs. From the utility perspective the complex interface management is introducing new risks. The OFTO/CATO model may reduce transmission costs (but these are fairly low) and sensitivity of reducing them is low versus significant delays.

#### Discussion:

- With regard to the proposed onshore interconnection of the East Anglia sites it was commented by TenneT that experience in Germany demonstrated onshore grid upgrades could be very hard to roll out due to public opposition and long planning processes.
- It was questioned by TenneT whether retrofits of offshore substation platforms and converter platforms are feasible to enable future meshed connections, similar to what occurs in the oil and gas sector. It was responded by SPR that flexibility in design is key. However, any additional design option (e.g. extra J-tube) is particularly dependent on Ofgem's acceptance of the extra costs and also is contingent on the nature of the consent, i.e. a few extra words in your consent with options for interconnector could be sufficient. If these aren't present then a lengthy secondary process is required.
- It was asked by an industry stakeholder, if the CATO is introducing extra risk. This point was answered by SPR and Mitsubishi Electric. The risk profile from one CATO to another is very different. Different CATOs would attract different investor groups. It was highlighted that the late CATO model could best accommodate developer risk. Consent is required before acquiring a Contract for Difference (CfD). In Germany consent is sought after being awarded a tariff.
- A discussion then ensued on AC cables. East Anglia went for AC at 120 km cable length at 66kV. It was suggested that industry is converging towards 66kV which offers economic benefits (10-12% CAPEX reduction associated with switch from 33kV to 66kV according to outcomes from a Carbon Trust study on 66kV cables done by Arup). This was chosen for competitive reasons, and technology limits of DC today, but in particular at the time of design. 220kV was set for the connection back to shore. There is a moving map in terms of what AC can deliver. Perceptions are being challenged about length of AC deployment, although feasibility and proven technology are also key considerations. In addition, part of the reason that AC is chosen in the UK is due to the relatively deployment levels parcelled up within the CfD allocation. Relatively small deployment sizes do not justify the need for HVDC links, and to date prospected windfarm projects remain relatively close to shore. Optionality of switching from 33kV to 66kV has also helped with AC longevity. However, the risks with HVDC are decreasing, although the UK is somewhat adverse to it given the technical and financial risk. There is a different view in Germany. In addition, long AC connections can cause problems onshore, e.g. the introduction of transients and harmonics. This might result in a need to deploy filters, but who will then bear the extra cost? Especially for the UK, in regards to CATOs this may create issues. PROMOTioN demonstrations should help alleviate the concerns with DC. However, it may not be delivered in time for some projects that are being considered to date, e.g. East Anglia 3, although it was considered for East Anglia 1. All technology

choices have to be finalised at the time a project comes to Financial Investment Decision (FID).

- It was added by an industry stakeholder that one should take into account very long lead times for offshore converter platforms. For instance HVDC has 4yr+ lead time. This does not align very well with the UK CfD regime which requires build in 4 years. Developers have to order the cable straightway (with current lead times) and then show significant financial commitment very quickly to the Low Carbon Contracts Company.
- It was questioned whether comparison between technologies is available. It was highlighted that a CBA will be carried out as part of WP4.
- It was then mentioned that 1 GW offshore platforms account for significant proportion of the transmission assets costs.

### 5-Technology from the manufacturer's perspective (Claudia Spallarossa, Mitsubishi Electric Europe)

This session covered in detail the evolution of HVDC technology from the first converter technologies to the development of circuit breakers to facilitate the operation of meshed offshore grids. As in AC systems, DC meshed grid would require DC circuit breaker to ensure system stability in normal operations. One of the aims of PROMOTioN is to increase the technology readiness level of such devices from lab scale to commercialization. In the last decades a rising interest in HVDC application was observed, for example a faster innovation cycle which is driven by market needs (China – Ultra High Voltage DC; Japan – 6.5kV IGBT; DC circuit breakers). In DC Gas Insulated Switchgear (GIS) the 'Kii channel' in Japan is the first project worldwide with a 49km subsea cable between Anan and Yura and a 51km overhead line between Yura and Kihoku. The presentation covered various designs for DC circuit breakers: The 'active resonant scheme', the 'passive resonant scheme' and a 'hybrid option'. The DC circuit breaker with active resonant scheme is one of the candidates for multi-terminal DC networks because of its large current interruption capability and fast reaction time. (LCC are not applicable in meshed offshore DC grids).

#### Discussion

- Various stakeholders raised points on timing versus cost saving.
  - Questions were posed on whether different options could co-exist, e.g. hybrid and mechanical with active resonant scheme. From Mitsubishi Electric Europe's point of view it was highlighted that they could. An industry stakeholder stressed that technical requirements need to be set to allow coexistence.
- It was stated the technology is probably at TRL 8. In addition, it was mentioned that challenges and risks considerations need to be front ended, including the business case needs to be clearly stated, R&D efforts and competencies, and time constraints that align with commercial release.
- It was recognised that without a demonstrator project offshore windfarm developers will be hesitant to adopt meshed HVDC technology. Likewise without orders, manufactures have less incentive to finalise R&D. PROMOTioN will help to overcome existing barriers.

### 6-Academic perspective (Keith Bell, University of Strathclyde)

The purpose of this session was to give a perspective on HVDC-related activities at UK universities. A number of other projects were highlighted, including:



- **TWENTIES**<sup>5</sup> project 2009-2013 ->WP 5 and WP 11 - can be found on EWEA
- **Transformation of the Top and Tail** project<sup>6</sup> - includes continent-scale and offshore wind but also DC but at low voltage
- UK academics' participation in **CIGRE** working groups
- **BestPaths** project.

Among the issues that UK academic are addressing in respect of HVDC are:

- High voltage, high current power electronic devices
  - Includes MMC converter switched at low frequency
- High voltage DC cables
- Converter topology and control
  - Physical size, losses, behaviour under fault conditions, controllability
- Fault management
  - Detection and location of faults
  - Fault clearance / DC breakers / system recovery
- Operation and control of multi-terminal HVDC grids
  - Includes inter-operability (vendors and converters)
  - Coordination of converter control and protection devices
  - Real-time simulation of large scale DC networks
- Design of HVDC grids
  - Operability and impact of faults on AC grids
  - Extensibility
- DC/DC conversion

In addition, coordination issues and cost options were discussed. It was mentioned that the extent of use of circuit breakers and where these should be placed still remained up for discussion (e.g. will circuit breakers at each end be mandatory?), although it was recognised that once fully meshed, breakers will be needed to realise the main benefits of meshed network configurations.

Discussion:

- It was questioned how to deal with cable faults in a meshed offshore grid? It was highlighted by UoS that fault management is clearly key. However, the cost for offshore protection systems (including the capability to interrupt fault current) has to be compared against the benefit to isolate a single faulted branch and leave everything else in service. In this context it has to be considered how often faults do occur in which time of the year as the prevailing weather conditions determine repair time, grid downtime and the wind production curtailed as a consequence. It was then asked how offshore turbines should behave when there is a fault. Diode Rectifier Units (DRUs) could make it more complicated.
- It was asked by an industry stakeholder how one can justify the huge cost for placing a DC circuit breaker offshore? A main blocking point is the utilisation of the asset – a DC circuit breaker is waiting for something to happen. It would be a different story if this component was placed onshore. From UoS's perspective the best solution is an AC protected system with few or no DC circuit breakers placed offshore; as there are no offshore consumers, continuity of supply is less of an issue than for onshore transmission networks. However, it was recognised that the economics may change in the future and there could be a technological jump. Various stakeholders discussed

<sup>5</sup> TWENTIES: Transmission system operation with a large penetration of wind and other renewable electricity sources in electricity networks using innovative tools and integrated energy solutions

<sup>6</sup> <http://www.topandtail.org.uk/>

then that the cost of an option is very high versus having stranded assets. It was mentioned that the UK regulator leaves it up to the licensee to make a financial judgement. A multi-terminal solution can maximise and adapt power flows to maximise utilisation to 'cost per MWh' by the assets as a whole.

- As every project has a bespoke design the future will see different DC voltage levels. It was therefore questioned whether it makes sense to define a standard DC voltage level? It was commented that the soon to report CIGRE WG C1.B4.65 has come up with some ball park standard voltages which could be useful for PROMOTioN. It was also stated that DC/DC converters would allow different voltage levels to be interconnected. However, DC/DC conversion does currently not receive much attention, neither in PROMOTioN. University of Aberdeen (Prof Jovicic) and RWTH Aachen (Faculty of Electrical Engineering and Information Technology; Prof. De Doncker) are looking into this as well as Chinese research institutes. If DC/DC converters were commercially available at reasonable cost then they could be used. This is as an area for future works.
- It was suggested to leverage findings with regard to 'interoperability' from the TWENTIES Project in the PROMOTioN project.
- An industry stakeholder stated that a meshed DC grid should in the first step be demonstrated onshore in order to save cost and minimise the economic risk (and such a demonstration is promised in China in 2018). If the technology for meshed HVDC solutions was found to be reliable then the industry should consider an offshore demonstrator. In this context it was mentioned that a true meshed grid is different from interconnections. Managing the loops is important.
- An academic stakeholder stated that there is the need to remove the technological risk from the TSO and windfarm developers. Mitsubishi Electric Europe added that the business case which was created for HVDC technology in Germany was very helpful for manufacturers. Hope to copy this model for multi-terminal solution.
- An industry stakeholder stated that a massive extension of the offshore grid would lead to losing inertia of the network. It was then discussed how inertia could be maintained. The MIGRATE<sup>7</sup> project will also examine zero inertia systems. Tennet Germany is involved in this project.

## 7-Regulatory environment (Guy Henley, Carbon Trust)

This session introduced the topics to be covered in PROMOTioN WP7. The workshop audience was divided into four groups. The session then asked the groups to discuss specific questions amongst themselves and report back the findings to the moderator for discussion. The following is a short recap of the themes that emerged:

**Question 1:** *What is the best approach and challenges for investing in transmission assets, as these vary in how they are framed from a regulatory perspective across jurisdictions?*

- From an academic perspective the UK system (OFTO & CATO) has way too many layers and restrictions. There should be more incentives to encourage investment decisions in new technologies. For example, the Belgian TSO contributes €25m to the cost of financing for the offshore grid connection which is developed by the windfarm developer. It was added that the regulation around the yearly 'Electricity Network

<sup>7</sup> MIGRATE: Massive InteGRATion of power Electronic devices

Innovation Competition<sup>8</sup> (Electricity NIC) changes with Ofgem every year. The Electricity NIC should not be restricted to three big transmission owners (SSE, SHE, NG), but open to a wider range of stakeholders including the OFTO, technology developers and research institutes. However, it was mentioned the NIC recently invited a wide range of stakeholders. The group discussion then turned to what is the best approach to transmission innovation investment from the UK perspective.

- From an industry perspective the German/Dutch model seems very beneficial as the TSOs can decide on several projects that they can interconnect. It gets more complicated with OFTO regime.
- It was highlighted that the Contract for Difference (CfD) auctions limits options for heavy investment and innovation. In addition it was queried how Brexit will affect funding opportunities and highlighted that EU funding could provide support.
- It was also highlighted that there are different approaches to cost benefit analysis which doesn't make comparability easy. ENTSO-E<sup>9</sup> has a comprehensive methodology developed, this is a good starting point. However, if you have only one methodology it becomes your bible and it may leave other aspects aside. Could be difficult with different societal benefits for different countries.
- Lessons can be learnt from the 'Kriegers Flak' project where an interconnector is spliced with offshore wind farms in Danish and German waters. In this case both Germany and Denmark invested. It is understood that wind power which is produced in the Danish windfarm goes to Denmark (vice versa for the German windfarm) and then load flow balances occur. However, it is unclear what would happen when a third country would join.
- Getting buy-in from stakeholders is key, and firstly understanding what are the functional requirements of each group. It was suggested that buy-in occurs only when the benefit is understood.
- In addition, some workshop stakeholders suggested that the perception that stakeholders won't change their structures to accommodate meshed grids could be misplaced. Especially when talking about developments in 5, 10 or 15 years. It was highlighted the UK works in 8 year cycles.
- It was also highlighted that in some cases special purpose vehicles could be used for the financing of meshed grid projects, and then the projects once constructed could be sold to traditional financing firms.

**Question 2:** *How do renewable energy subsidy schemes fit in with a generation unit connected to two or more jurisdictions - should it be generic or case by case?*

- It was suggested this needs to be dealt with on a case by case basis.
- It was mentioned that in the ISLES-I<sup>10</sup> project assumed all generation to be in a single jurisdiction, i.e. market boundaries can be moved in respect to specific projects.
- It was suggested whoever benefits should pay.
- It was highlighted that work is being done by ENTSO-E on cross sharing issues.
- Subsidy schemes are meant for developers to make their business cases positive. So subsidy schemes are part of business cases themselves.

<sup>8</sup> The Electricity NIC is an annual opportunity for electricity network companies to compete for funding for the development and demonstration of new technologies, operating and commercial arrangements.

<sup>9</sup> ENTSO-E: European Network of Transmission System Operators for Electricity

<sup>10</sup> ISLES-I: First phase of the Irish Scottish Links on Energy Study

## QUESTIONNAIRE

- It was mentioned that there is a lot of experience with onshore renewable electricity generation. Power is traded across borders without taking incentive schemes into account.

**Question 3:** *Who should operate the scheme and what is the framework for trade? - access and charging regimes*

- A common mechanism for trading should be developed.

### 8-Literature review and questionnaire (Inigo Azpiri Irazabal, Iberdrola)

This session provided an overview of the literature review and findings to date from the questionnaire which was developed for PROMOTioN Task 1.3 (online version: <https://goo.gl/JSwvFE>).



## 8 ANNEX C: HAMBURG WORKSHOP MINUTES

**Workshop date:** 17 November 2016

**Attendees:** Iñigo Azpiri (Iberdrola), Hendrik Berends (E.ON), Pierre Breton (Technofi), Alexander Broy (Siemens), Hermann Gangl (TenneT), Pierre Henneaux (Tractebel), Hasan Jørgensen (Semco Maritime), Nils Janko (ABB), Philipp Kalweit (SOW), Frank Knappe (8.2 Consulting AG), Esther Kraft (Senvion), Thilo Krupp (SOW), Teresa Maestu (Adwen), Andreas Menze (TenneT), Sebastian Menze (SOW), Ryan Motz (Adwen), Liliana Oprea (Fichtner), Sebastian Papanagiotou (ABB), Cora Petino (RWTH Aachen), Saeed Salehi (50Hertz Transmission), Xiongfei Wang (Aalborg University), Eduard Wiebe (Innogy), Klaus Würflinger (Siemens), Walid Ziad El-Khatib (Energinet.dk)

**Workshop aim:** To convene relevant stakeholders from Europe in order to collect knowledge from existing HVDC projects and to enrich stakeholder feedback on the questionnaire that was developed in PROMOTioN Task 1.3

### Workshop agenda

- 09.30 - Registration and coffee
- 10.00 - Introduction to the PROMOTioN Project and Questionnaire (Iñigo Azpiri, Iberdrola & Sebastian Menze, SOW)
- 10.15 - The operational challenges of HVDC Offshore Grids from a TSO's perspective (Andreas Menze – TenneT Offshore GmbH)
- 11.00 - Manufacturers view on meshed HVDC grids [1] (Nils Janko – ABB AG)
- 11.45 - Coffee Break
- 12.00 – Manufacturers view on meshed HVDC grids [2] (Dr. Klaus Würflinger – Siemens AG)
- 12.45 – The Developer perspective on HVDC Technology (Iñigo Azpiri – Iberdrola)
- 13.30 - Lunch
- 14.30 - Academic perspective on HVDC Development (Cora Petino – RWTH Aachen)
- 15.15 - Reporting on the questionnaire and literature review & Discussion (Iñigo Azpiri – Iberdrola, Pierre Henneaux – Tractebel Engie)
- 15.30 - Wrap Up (Iñigo Azpiri – Iberdrola)
- 16.45 - End of the Workshop



## Proceedings

### 1-Operational challenges (Andreas Menze, TenneT)

A general presentation of TenneT is made.

The system in the North Sea will be an answer to the offshore generation scenarios. The system needs to be suitable, non-discriminatory, efficient and take nature into account. Different technologies available (HVDC LCC & VSC, HVAC...). There is not a clear view on the framework and the long-term failure rates.

The n-1 planning principle is not usually implemented in offshore systems, they are mainly built following n-0 philosophy. There is a risk the link could fail and they try to minimize it. Only one cable but redundancy in transformers and auxiliary systems. Mother-daughter concept. Platforms are built close to each other so that one can supply auxiliary services in case the other fails.

Challenges:

- Offshore grids are weaker than onshore AC grids
- High amounts of power electronic devices controlled by software lead to interactions that have to be investigated. TenneT has learned that classical control strategies do not work as in onshore.
- Long cables lead to high capacitive currents shift resonances down (lower resonance frequencies).
- Resonances can reach values below 5 Ohm.
- Missing loads cause low damping on the grid. Resonances reach very high/low values (TenneT have seen 200-250Hz resonance frequencies)
- Strong dependency of resonance frequency to the switching topology; a (dis)connection of one string of wind turbines is sufficient to shift the resonance to a critical frequency
- Currently, there is a limited experience in the operation of power electronics installed to connect offshore wind farms, that should operate for 30 years
- Limited market, installation equipment (mainly vessels) and expertise in Germany.
- No standardization. Every project is custom built.
- Long emergency responses because of the long distances to the coast.
- Although ordnance areas are clearly marked, the submarine currents have spread them all across the sea, this means additional costs in protection of personnel and environment.
- Environmental restrictions mean that work at sea is only allowed under tight time constraints (e.g. construction only outside nesting period later than July) and with noise reduction measures for marine animals.

Expansion in the North Sea can be fostered with realistic development goals, with a detailed schedule on how developing the meshed grid in a modular way and describing different scenarios. This would help the industry to invest in finding solutions for the market.

Discussion:

- Major causes for delays? The main issues TenneT had were related to stability but they have been already solved. Also supply chain and cable laying (finding ammunition buried in the soil) are causes for delays.

- The main sources of delays were not related to the HVDC equipment itself, but related to the platform and the auxiliary equipment that is required (huge valve halls needed for insulation, need of clean air,...). There is a limited experience in Germany with Oil&Gas platforms and the weather conditions have to be very good.
- Tight requirements for platforms. There are a few places in Europe that can build such structures.
- Things like a misfiring of a fire alarm or people operating the platform getting sick mean that the entire platform must be shut down.
- TenneT platforms are manned because according to their experience small problems that can be easily solved could otherwise cause long downtimes.
- For HVDC hubs to connect offshore wind farms it is difficult to design the platforms in a modular way (smaller platforms installed next to each other or sharing the same foundation), because it is not always known from the beginning how many or what kind of wind farms will be connected.
- DC breakers are mainly important if the converters are half bridge and with meshed, it is not clear when it will be a critical infrastructure, and besides their size is considerable and would require an additional platform.
- In current TenneT platforms there is no space allocated in the DC side for future connection to multiterminal grids but there is some reserve in the AC side. It is difficult to plan these things in advance, not only because it is unclear how the multiterminal grid will evolve, but also the future space requirements for a technology that is constantly evolving.
- Connecting an existing converter to a multiterminal grid means a change in its operation that could lead to unexpected resonances and other issues. Who would be responsible for this?

## 2-Technology from the manufacturer's perspective (Nils Janko, ABB)

The meshed HVDC grid is a stepwise development very similar to the AC network development done in the past.

Right now the projects are tailored to the requirements of the customer. HVDC will need to be flexible and handle the connections of different technologies.

In answer to TenneT, ABB sees the need for DC circuit breakers, not for each and every line of the grid, but they will be needed to divide it in smaller sectors.

An artist's impression is presented to show the size of an HVDC breaker in comparison with an onshore MMC converter. They have not yet evaluated the space requirements in an offshore substation.

Different levels of meshed grid "preparedness"

- Multi-terminal prepared: data for additional converter in the RFQ (Request For Quotation) can be minimum & space for equipment needed in the next phase (control cubicles, arresters...) is part of the first phase
- Multi-terminal ready: all equipment designed and cost optimized for the final configuration. All data for additional converters needs to be included in the RFQ. Further development of control systems and standardization is required.

ABB talk about their participation in European R&D projects: BestPaths and PROMOTiON

### Discussion

- Currently 900 MW converter projects. In the future 1,4GW. More power will mean higher voltages and platforms will get bigger. Answer: not a linear process, 500 kV may be a state of the art in the future but no major change is currently expected in the offshore platform, manufacturers are trying to achieve manageable sizes.
- General thought: meshed grid needs common voltage level. Requires additional power electronics. Why not mesh in AC? --> if you are connecting different countries with submarine cables you still need HVDC grid.
- It may be easier to start developing onshore meshed grids rather than offshore meshed grids.
- Manufacturers questions:
  - What are the regulatory set-ups? Do we have any feeling on how e.g. ENTSO-E sees meshed grids? Who is responsible there?
  - Issue that comes as a result of a gradual development of the HVDC grid: a manufacturer is sometimes expected to take the responsibility of equipment installed by another manufacturer when they step in a project. As of today this is not possible --> the risk is taken by the owner but costs could be increased for the energy customer --> WP7 should take these things into account.

### **3-Technology from the manufacturer's perspective (Klaus Würflinger, Siemens)**

First stages of HVDC grid development: small grids connecting a few converter stations. Full bridge MMC in combination with fast disconnectors provide selective fault clearing and fast recovery.

In subsequent stages, these small grids become interconnected. This may require additional fast switching devices like fault current limiters or DC breakers.

The step-by-step growth of HVDC grids requires standardisation of design and operating principles.

If full bridge MMC converters are used, DC disconnectors are enough to isolate faulty parts of the system, because FB converters are able to extinguish DC fault currents.

System recovery: who will manage it?

Workable solutions need alignment of system aspects and switchgear capabilities. DC Breakers can only provide fault current interruption and fault isolation functionality.

### Discussion:

- Nowadays, even meshing 2 HVDC links from the same supplier by AC is difficult.
- According to Siemens there is still need of technological development to achieve meshed grids. Is it not possible to integrate existing grids in future meshed grids? Answer: it cannot be guaranteed that the technology nowadays will be compatible with the developments in 20 years or the cost of the necessary refurbishments. The available space in the substations is also a concern.
- Multivendor interoperability: which kind of models and data must be exchanged? – tbd
- Fault handling has to be clarified with all involved parties

#### 4-Technology from the Utility perspective (Iñigo Azpiri, Iberdrola)

Iberdrola presented Wikinger, their first German offshore wind farm. It is located 90 km from shore and has a total capacity of 350 MW, so it is near the breakpoint between AC and DC. Although HVDC was considered to connect this wind farm with the onshore grid, it was finally built in HVAC due to changes in the auction process, the tight grid connection timescales and the lack of clarity on the future cluster.

Wikinger topside and foundation are shared between Iberdrola and the TSO (50Hertz). The topside is separated into two parts and can be installed with a heavy lift vessel. This may lead to additional costs in engineering, construction and O&M but are compensated with the benefits of having more vessels to choose from (avoids self-installing platforms or the use of the largest vessels in the world, which are few and have very tight schedules).

East Anglia 1 also initially considered as an HVDC project but finally built in HVAC due to changes in the auction process (CfD instead of ROC) that required a substantial reduction in costs.

New technologies must reach TRL 7-9 to pass the pre-FID phase in Iberdrola.

Findings from the Integrated Offshore Transmission Project (IOTP) were briefly presented. Following an analysis across the East Anglia stakeholders it was suggested there is little benefit to increased coordination and offshore interconnection between the planning sites in the East Anglia zone. It was instead suggested that onshore interconnection (re-reinforcement of existing lines) could be cheaper realised and provide greater benefit. For increased offshore interconnection several questions need to be addressed: (i) who is going to coordinate planning and construction, (ii) who manages the asset, and (iii) who invests?

Consenting was singled out as a large part of the risk (along with construction. It cost up to 5% of CAPEX.

Planning for future connections is challenging, especially in terms of developing and financing capital intensive offshore platforms. Although they will provide benefits to developers in terms of availability and redundancy, It is not clear how HVDC grids will be implemented. It is necessary to have a detailed planning to know what kind of future upgrades will be required.

#### Discussion:

- The higher the power to be evacuated, the larger the onshore cable will be, because the AC nodes near the shore have usually low short-circuit power.
- Cultural differences are not to be dismissed when different countries are involved in a single project (different ways of approaching the tasks). These can lead to increased costs and delays, so they require a correct management and clear schedule.
- The interests of developers and TSOs are not always aligned, so this may cause difficulties in their relationships.
- TenneT in the North Sea is limited because of the Watten Sea → have to minimize number of cables.
- TenneT: wind generators should be capable of black start, the amount of power electronics in the grid is increasing. The risk of blackouts will increase. WP3 should consider this issue.

### 5-Academic perspective (Cora Petino, RWTH Aachen)

Germany's Energiewende goals:

- 35% share of renewable energy in power generation mix (2020).
- Share of renewable energies in consumption of primary energy >50% (2050).

Reduction of nuclear generation in Germany --> change from local infeed based on fixed schedules to remote infeed of volatile energy sources.

North sea HVDC projects: up to 230 km distance and up to 900 MW rated power at  $\pm 320$  kV, with higher voltage levels expected.

Future HVDC corridors across Germany will require new or extended protection concepts. Initial plans talk about using cables to avoid new overhead lines. Hybrid AC/DC corridors (AC and DC lines sharing transmission towers) are also under investigation to study interactions between both systems.

First multiterminal and multivendor (Chinese vendors) system in China: 5 MMC half-bridge converters with DC breaker installation scheduled for December 2016.

Research activities:

- New cable designs to increase DC voltage.
- Control and protection
- New fault management strategies: detection and localization, system recovery.

Questions that need to be answered:

- How can multi-terminal systems can be protected with respect to selectivity?
- How will multi-terminal systems be controlled?
- What are constraints in the operation and fault handling of hybrid AC/DC overhead lines systems?
- Are DC/DC converters required for offshore application?
- How can a future HVDC offshore grid be realized? What are the first steps?
- Which technology requires which fault management strategy?
- What has to be agreed on in terms of interoperability?
- Which extent of communication infrastructure is required?

Discussion:

- More openness of manufactures in case of protection levels needed
- To make realistic assumptions
- Have to be more standardised

### 6-Literature review and questionnaire (Inigo Azpiri Irazabal, Iberdrola & Pierre Henneaux, tractebel)

This session provided an overview of the literature review and findings to date from the questionnaire which was developed for PROMOTioN Task 1.3 (online version: <https://goo.gl/JSwvFE>).

