D12.1 Preliminary analysis of key technical, financial, economic, legal, regulatory and market barriers and related portfolio of solutions

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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EXECUTIVE SUMMARY

The stated goal of PROMOTioN is to land as much of the offshore generated electricity to shore as is economically and responsibly possible. Deliverable 12.1 provides a preliminary analysis on key technical, financial, economic, legal and regulatory, and market barriers and proposes a related portfolio of solutions. Solutions directed at overcoming technical barriers are being analysed and proposed in work packages (WPs) WP2, WP4, WP11, WP15, and WP16 of the PROMOTioN Project. Work packages WP3, WP5, WP6, and WP9 test new technologies and systems to increase their technical readiness and indicate potential horizons for the use of these technologies within the PROMOTioN time horizon. Potential routes to a suitable legal & regulatory framework supporting grid development and economic benefit are being developed in WP7, as are factors that facilitate financing the build of offshore grid infrastructure. This work is still ongoing. This document is a snapshot of the current understanding, rather than a final state of the analysis being performed in the PROMOTioN project. The analysis will be refined in draft and final deployment plans.

There is no unique way to develop a European offshore grid. Several strategies of development are possible and feasible, which could lead to very different offshore grid structures (topologies). The barriers for the building blocks will be dependent on the strategy applied. A prerequisite for the analysis of these building blocks is the development of possible “concepts” for a future offshore grid.

- An obvious approach to developing offshore electricity infrastructure is represented by the ***business-as-usual concept***: each country develops its own wind generation connected radially to the mainland with the sole purpose of evacuating wind generation to its own national power system, and, in parallel, point-to-point interconnectors are developed to exchange energy between countries. Although not really an “offshore grid”, this concept can be used as the reference case for comparison purposes.

Beyond the business-as-usual concept, this deliverable identifies three additional concepts:

- The first proposed concept is a “***centralised wind power hubs***” and is inspired by the “North Sea Wind Power Hub” proposed by TenneT and Energinet in 2016. In this case, OWFs are connected to large centralised connection (often >4GW and potentially up to around 35 GW) points (i.e. the centralised wind power hubs) through AC or DC connection, and power is evacuated to North Seas countries through dedicated HVDC corridors.
- In contrast with these large centralised wind power hubs, the offshore grid could be developed around several small hubs, interconnected amongst themselves to different degrees. Such an approach can branch off in a “***National distributed hubs"*** concept and in a “***European distributed hubs"*** concept[1].

[1] The Kriegers Flak Combined Grid Solution in the Baltic Sea is to connect the 966 MW offshore wind power to the national onshore transmission grids and to establish interconnection between Germany and Denmark via the offshore platforms utilizing the same and extended infrastructure and utilizing HVAC and HVDC Back-to-Back technologies [9]. This project is the first of its kind, holds the status of a ‘Project of Common Interest’ by the European Commission, receives financial support from the European Energy Programme for Recovery (EEPR), and opens for the European common approach.

This concept could be implemented through a combination of national or European policies. The national concept achieves an offshore grid based on distributed wind power hubs by promoting the development of meshed national offshore grids, weakly interconnected amongst each other. On the other hand, the European concept favours the joint development of a single Meshed Offshore Grid (MOG) integrating all the distributed hubs. Note that the national concept can eventually evolve into the European concept by increasing the integration between the national offshore grids. This requires additional legal & regulatory cooperation and will inevitably be critically examined by national and international organisations. Further cooperation may also open the market for cost-savings both in scale economies in purchasing infrastructure, but also in reducing the cost of finance to build out the grid.

For each concept, several conceptual “building blocks” will be needed and sufficiently mature to allow a European offshore grid to become a reality.

1. First, the regulatory and legal frameworks must allow the development of the European offshore grid.
2. Secondly, an offshore grid must be technically feasible, which means that the necessary technologies must be ready and that appropriate control systems must be available to operate such a grid.
3. Finally, the offshore grid must be economically viable and the financial framework must be such that the business case of the various critical stakeholders is positive.

This deliverable provides a preliminary analysis of these three fundamental building blocks for each concept and emphasizes that different issues and complexity are associated with each concept from a technical, legal, & regulatory and financial perspective.

Finally, based on the work done in the different WPs of the PROMOTioN project at the moment of writing, this deliverable reviews the main barriers hampering the development of an offshore grid in the North Seas and provides potential solutions and recommendations to address these barriers where relevant. These barriers fall into the following categories:

Economic/Financial	Legal/Regulatory	Technical
• Financing of offshore grids and the expectations of investor stakeholders. • Design and development of Market infrastructure, business models for the transmission and management of power flows. • Market interaction between the North Sea and European onshore bidding zones	• Long-term planning of offshore grids • Regulation of grid development & build, operations, and decommission • Coordination and control of standards	• Integration of DRU (Diode Rectifier Unit) technology in offshore grids to facilitate cost-efficient converter solutions • Operation and control of offshore grids • Protection of offshore grids • Test environment for HVDC circuit breakers • Use of DCCBs in offshore grids

From the analysis, it is clear that apart from technical challenges several legal and regulatory issues require attention for the development of an HVDC MOG, especially when transforming from the national business-as-usual concept which exists today to more European grid topologies.

The preliminary analysis of building blocks and barriers presented in this deliverable identifies the main issues related to each concept. It is worth mentioning that the analysis remains very general and does not provide concrete insights about the magnitude of the issues in the case of the development of a MOG in the North Seas. In addition, results from the various WPs of PROMOTioN are not yet finalised and are not fully integrated. The objectives of a deployment plan are to support stakeholder decisions in developing offshore grid infrastructure. The development of realistic (but fictive) topologies corresponding to each proposed concept highlights the alternative routes that may be taken. This document provides an introduction to the different concepts, more detailed analysis and inputs from other (as yet uncompleted) WPs are required to firm any recommendations or opinions given.

In order to enhance this analysis, WP12 will use fictive and realistic offshore grid topologies corresponding to each concept and for various load/generation scenarios, to ensure the analysis has sufficient detail and a required level of accuracy sufficient for the PROMOTioN project. Based on derived corresponding topologies and on the results of the various WPs, each concept will be evaluated from the technical, regulatory/legal, economic/financial point of view. These analyses will reveal advantages and disadvantages for each concept, universal recommendations for all concepts and specific recommendations for each concept. The topologies and the corresponding cost-benefit analyses will be published in deliverable 12.2. Preliminary conclusions and recommendations will be published under the format of a draft deployment plan (deliverable 12.3). The latter will be refined by integrating the last results of the various WPs and through stakeholder interaction to lead to the final deployment plan.

CONTENT

1. INTRODUCTION

In the course of the ratification of the Kyoto protocol in 2005, the presidency conclusions of the Council of the European Union included a proposal for “an integrated climate and energy policy” (Council of the European Union: presidency conclusions [1]). The objective of this policy is to limit “the global average temperature increase to not more than 2 °C above pre-industrial levels”. In addition, the Paris agreement reaffirms the goal of limiting the global temperature increase to not more than 2 °C, "while urging efforts to limit the increase to 1.5 °C" [2].

Besides other initiatives e.g. to lower the consumption of electrical energy, the presidency conclusions include “a binding target of a 20 % share of renewable energies in overall EU energy consumption by 2020” [3]. These targets were updated by the EU for 2030 as follows [4]:

TARGETS FOR 2030

- a 40 % cut in greenhouse gas emissions compared to 1990 levels
- at least a 27 % share of renewable energy consumption
- indicative target for an improvement in energy efficiency at EU level of at least 27 % (compared to projections), to be reviewed by 2020 (with an EU level of 30 % in mind)
- support the completion of the internal energy market by achieving the existing electricity interconnection target of 10 % by 2020, with a view to reaching 15% by 2030

The commitment lined out in directive 7224/1/07 led to the Renewable Directive in 2009, which includes inter alia the establishment of mandatory national targets “with a 20 % share of energy from renewable sources” [5]. On November 30th 2016, the European Commission presented its new energy strategy with the Energy Winter Package titled "Clean Energy for all Europeans". With this new effort, the European Commission seeks to present solutions for a Europe-Wide transition to clean energy. The ‘Winter Package’ sets a target for renewable energy of at least 27 % [6]. In November 2017 the European Parliament Committee for Industry, Research and Energy (ITRE) proposed to reach an EU binding target of at least 35 % RES by 2030 [7]. On 27 June 2018, EU ambassadors endorsed a compromise to this provisional agreement on the revision of the renewable energy directive. The agreement sets a headline target of 32 % energy from renewable sources at EU level for 2030. There is a clause to review this target in the event of changes in demand for energy consumption and to take account of the EU's international obligations [8]. In the area of electricity interconnection, the European Commission has set a 10 % target to be achieved by 2020 increasing to 15 % by 2030.

Northern Europe’s vast offshore wind potential will support these objectives. However, the connections necessary for the evacuation of the wind energy generated offshore remain a challenge on various levels. Challenges include longer lead times for the installation of capacity and connection, the development of robust technology to operate the network securely & safely and the insufficiency of the current regulatory framework to

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fully support offshore infrastructure. One option to meet the requirements in terms of climate and energy policies is the establishment of a High Voltage Direct Current (HVDC) Meshed Offshore Grid (MOG). A MOG is formed by inter-connecting OWFs with different onshore systems. The MOG could be able to combine the evacuation of offshore wind energy and facilitate the exchange of power between different countries, contributing to two of the EU strategic goals. HVDC is chosen above more widely used AC connections, as HVDC technology allows for greater distances than AC technology and at the same time reduces electricity transmission losses.

In previous research studies and EU-funded projects different challenges for the development of offshore grids have been identified:

- On a technical level there remains a lack of agreement among operators and manufacturers on system architecture, control structures, protection schemes and interfaces to ensure interoperability and multi-vendor compatibility of equipment [9] [10]
- On a regulatory level there is a lack of market rules for infrastructure investments as well as a lack of regulation regarding the operation and management of these grids from the legal, technical and market point of view [9]. Furthermore, additional barriers are linked specifically to the regulation of HVDC MOGs (e.g. control issues).

The main objective of deliverable D12.1 is to provide a preliminary analysis on the key technical, financial, economic, legal and regulatory, and market barriers along with a related portfolio of solutions. The various approaches for solutions to overcome these barriers are currently analysed in more detail by the different Work Packages (WPs 1-7, 15, 16). At the time of publication of this report, the majority of these WPs are still ongoing. Furthermore, the first projects proving feasibility, maturity and directions for solutions, such as the Kriegers Flak Combined Grid Solution in the Baltic Sea [11], are seeing daylight. Nonetheless, the analysis provided in this deliverable provides a preliminary snapshot of the current understanding. The analysis will be refined in draft and final deployment plans.

In order to provide a preliminary analysis of barriers hampering the development of a MOG and a preliminary related portfolio of solutions, this deliverable is organized as follows:

- Chapter 2 presents different concepts possible to develop an offshore grid in the North Seas
- Chapter 3 describes the conceptual building blocks needed for the development of a future offshore grid.
- Chapter 4 identifies the work of different WPs of the PROMOTioN project to analyse the specific barriers and related solutions currently under study.
- Chapter 5 looks at the way forward from this deliverable towards the remaining deliverables for Work Package 12.

The results presented in this deliverable, especially in chapter 4, are based on input from Work Packages 1-7 and have been prepared with the input of our PROMOTioN-colleagues contributing to these Work Packages. As authors of this deliverable, we thank them for their input, comments and support.

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2. CONCEPTS FOR A FUTURE OFFSHORE GRID

There is no unique way to develop a European offshore grid. Several strategies of development are possible and feasible, which could lead to very different offshore grid structures (topologies). The barriers for the building blocks will be dependent on the strategy applied. A prerequisite for the analysis of these building blocks therefore is the development of possible ’Concepts‘ for a future offshore grid. Furthermore, in the context of the liberalized electricity sector in Europe, an adequate market model will have to be developed. The market model may be influenced by the grid structure and technical constraints and can impact the regulatory/legal building blocks as well as economic/financial building blocks. Barriers and related solutions can therefore depend on the specific concept considered. The ’Deployment Plan‘ relies on the identification of solutions for remaining barriers hampering the development of an HVDC MOG. Consequently, gaps in the building blocks will have to be identified for each concept.

A future European offshore grid can be developed following different strategies that can be compared to a business-as-usual approach. A first concept, called the “centralised wind power hub concept” is inspired by “North Sea Wind Power Hub” proposed initially by TenneT and Energinet in 2016 as shown in Figure 2-1. In this case, OWFs are connected to large centralised connection points and power is evacuated to North Seas countries through dedicated HVDC corridors. However, it should be noted that due to the technical challenges involved building the artificial infrastructure (islands), this a rather long-term approach which is unlikely to materialize prior to 2030, according to its promotors (i.e. TenneT, Energinet, Gasunie and the Port of Rotterdam Authority). On the contrary, a second concept, called the ‘distributed hubs concept’, could correspond to the creation of small HVDC hubs, like the current AC substations in the onshore grid, meshed at the DC side. This concept can be divided into two sub-concepts: a MOG strongly meshed at the national level but loosely interconnected amongst countries, or a stronger interconnection between the decentralised hubs of various countries up to a level where the overall infrastructure forms a fully meshed international offshore grid.

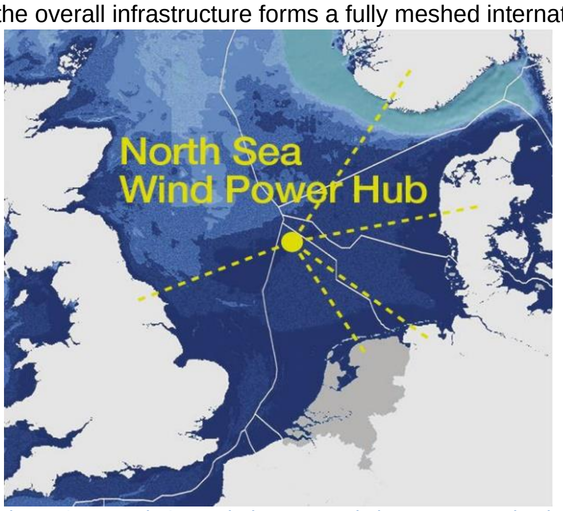

Figure 2-1. North Sea Wind Power Hub (source: Energinet).

The following subsections describe these different concepts. The concepts are sharply contrasted to make them distinctive, but they are not incompatible. Indeed, it may well be that a future offshore grid will encompass a combination of the different concepts. In concern of readability, point-to-point interconnectors are not shown in the advanced concepts, although they will remain an important part of the MOG.

The presentation of concepts provides also a preliminary analysis of the key issues linked to each concept, including but not limited to:

- Regulatory challenges concerning cross-border trading and the connection of OWFs;
- Operational complexity of the offshore grid;
- Flexibility of the offshore grid with respect to the evacuation of wind generation;
- Required level of coordination at EU level;
- Investment needs.

Exclusively for indicative purposes, the concepts are represented in figures illustrating the main ideas behind each of them. Note that these figures do not represent any results of the PROMOTioN project and may not be realistic: they only intend to illustrate different concepts. In each figure, the term ‘hubs’ is used when two or more cables converge on the same node.

2.1. BUSINESS-AS-USUAL CONCEPT

Before delving into the concepts of MOGs, it is worth considering a possible development of the offshore infrastructure in the North Sea for the ’business-as-usual”’ concept, i.e. if no action is taken to develop an offshore grid in a coordinated way. The purpose of the PROMOTioN project is to alleviate barriers hampering the development of more complex offshore grid structures (i.e. meshed grid), but the business-as-usual concept will be used as a reference case. For the business-as-usual concept, each country develops its own wind generation connected radially to the mainland with the sole purpose of evacuating wind generation to its own power system. OWFs are connected either individually to the shores or via small hubs. The offshore hubs connect the offshore generation to one country. In parallel to the evacuation of the offshore wind power, point-to-point interconnectors are developed to exchange electricity between countries. Figure 2-2 below shows an example of this business-as-usual concept.

As this concept corresponds to the standard practice of connection OWFs to shore, there is no major challenge in the operation. The further development of Diode Rectifier Unit (DRU) technology may provide a solution to decrease the costs in case of radial connection of OWFs. If this happens, the design and the operation are much more challenging as it will integrate currently untested technology. An adequate regulatory framework is already in place. However, such a system presents limited flexibility and limited perspectives towards an optimal exploitation of the wind energy resources in the North Sea.

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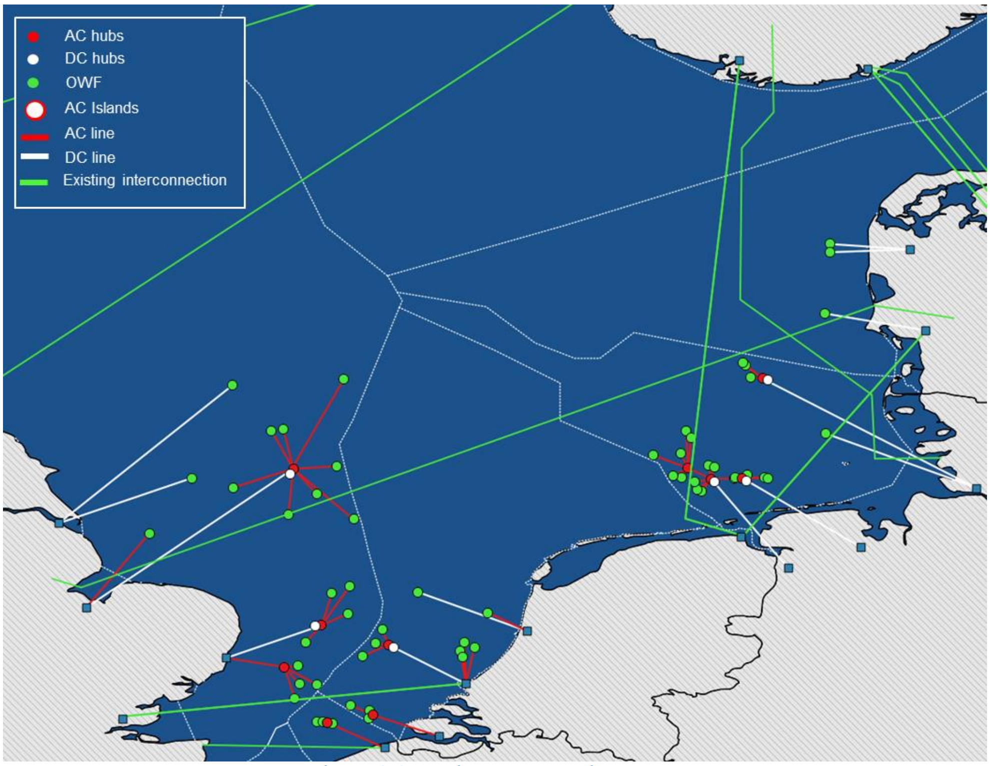

Figure 2-2. Business-as-usual concept.

2.2. CENTRALISED WIND POWER HUBS CONCEPT

2.2.1. INTRODUCTION

The concept of centralised wind power hubs describes a possible future development of the offshore grid centred on major hubs that connect multiple OWFs with a total capacity exceeding 4 GW and up to potentially 35GW. This is in line with the 'North Sea Wind Power Hub' concept. The hubs are connected to onshore grids by HVDC corridors for the evacuation of aggregated wind generation. Generally, hubs are connected typically to several countries. Therefore, these corridors can also be used to trade electricity between countries when the wind conditions allow it. Eventually, these hubs could be interconnected with each other, providing both additional evacuation routes for the OWFs.

However, there are different technical ways to develop a hub connecting OWFs and HVDC corridors towards onshore grids (or between hubs). Therefore, this concept can be divided into several sub-concepts. Without being exhaustive, three sub-concepts are identified in this document: regular AC hubs, regular DC hubs and hybrid AC/DC hubs.

2.2.2. REGULAR AC HUBS

One possibility is the development of 'regular' AC hubs working at the frequency of onshore grids, i.e. 50 Hz. Figure 2-3 provides an example of what the offshore grid could look like. OWFs are connected radially to the AC

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hubs, mainly through AC connections, but potentially through DC connections when the distance justifies it. The AC hubs are connected directly to the mainland of one or more countries through point-to-point HVDC corridors for the evacuation of aggregated wind generation.

From a technical point of view, it would also be possible to use a lower power frequency, such as 16.7 Hz, which would allow much longer submarine cables to be used, at the expense of larger and heavier transformers. In this way, an interconnected AC grid could be built offshore using 'regular' AC hubs containing transformers and AC circuit breakers. This low frequency grid would be interfaced to the onshore 50 Hz grids using frequency converter stations. The 16.7 Hz equipment is used already in railway applications but at much lower power levels (e.g. less than a few hundred MW) than what is required. Moreover, the OEMs capable of supplying high power and high voltage frequency conversion equipment are also HVDC equipment suppliers and are unlikely to support a competing technology. Hence, the option of using a lower frequency will not be considered within PROMOTioN.

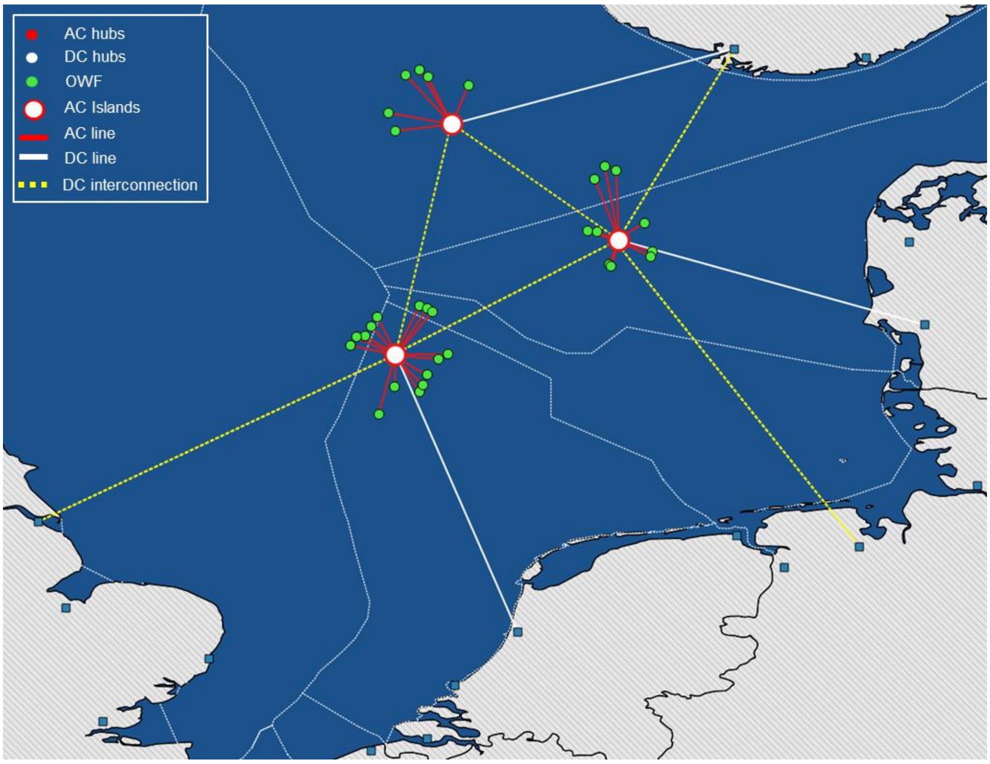

Figure 2-3. Centralised wind power hubs concept – Regular AC hubs.

Operational complexity is limited as each HVDC interconnector can be operated as a point-to-point connection. It is not essential to mesh on the HVDC side, although in some cases benefits may be gained by doing so, and, it may be challenging to control the AC hubs. Like the business-as-usual concept, in case of connection of OWFs through a DRU (i.e. if OWFs may need to be connected in HVDC to the AC hubs) could entail additional complexities. Note that, while operation is simplified, the flexibility of the grid for the evacuation of wind power is also limited, as only a few alternatives for diverting power flows are available.

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In the AC hub concept, multiple HVDC lines can be connected to a common AC node. Any HVDC line can exchange power with any other line connected to the AC hub. This enables the evacuation of wind power to the onshore node through different paths and energy trading among the countries connected to the offshore grid. Where there is no HVDC bridging between interconnectors, such a concept does not entail a need for HVDC circuit breakers (no meshing on the HVDC side). This is at the expense of an additional need for offshore HVDC converters. Usually relevant barriers for MOGs are limited due to the loose meshing and to the fact that most of the OWF connections are in AC, thus reducing the number of converters and DC breakers. The AC hub must have a high level of reliability, due to the large amount of wind power that must flow through it to reach the onshore grids.

Without being exhaustive, three possible sub-concepts for the AC hub are identified:

- The single node AC hub sub-concept,
- The backup node AC hub sub-concept,
- The ring AC hub sub-concept.

These sub-concepts are detailed hereafter.

Single node AC hub sub-concept

In this simple topology, the interconnectors and OWFs are all connected to the same central node, which could be an AC substation located on an artificial island. The concept is illustrated in Figure 2-4.

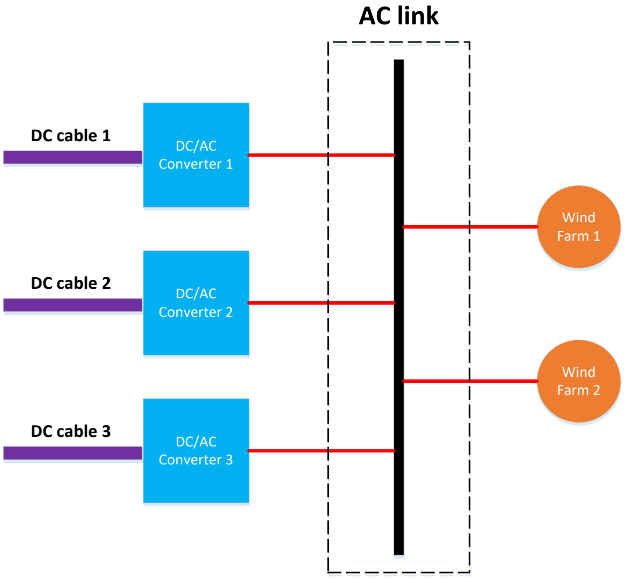

Figure 2-4. Single node AC hub topology

A slack voltage source converter (VSC) is responsible for controlling the AC voltage of the node, while the other converters could operate either in active power or in DC voltage control mode. OWFs close to the hub can be directly connected via AC connection, with an onshore step-up transformer to match the AC hub voltage. Distant OWFs need to be connected to the artificial island via HVDC connection (current minimum economic distance for HVDC transmission is around 50 km).

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The central node corresponds to an AC substation. The AC substation arrangement should guarantee high reliability, availability and ease of maintenance of the components, given the high amount of power exchange and the high costs for offshore maintenance.

The most suitable substation layouts for availability would be either double-busbar, double-breaker or breaker-and-a-half. However, these configurations come at a greater component count and complexity, which increases the capital and operational costs of the system compared to simpler configurations. Additional switching among the busbar sections could be added to enhance power routing flexibility. Alternatively, multiple busbars can be placed in parallel to increase the bus overloading capability and avoid additional switching.

The substations must be enclosed in a building to protect the equipment from the harsh environmental conditions of the North Sea. This should minimize maintenance requirements and fault probability. AIS (air-insulated) substations require large amounts of space, wide components availability and interoperability. GIS (gas-insulated) substations, require significantly less space than AIS, but have higher costs and vendor lock-in.

The single node AC hub sub-concept allows the interconnections of HVDC lines with different voltage levels and different DC link configurations. This property is exemplified in Figure 2-5. This constitutes a remarkable advantage over a DC hub, which requires the same voltage level for all the interconnected DC links, unless high voltage DC-DC converters are used (which do not exist yet and are not expected to enter the market in the foreseeable future). Any HVDC line can be easily connected or disconnected from the AC hub without affecting the operation of the others.

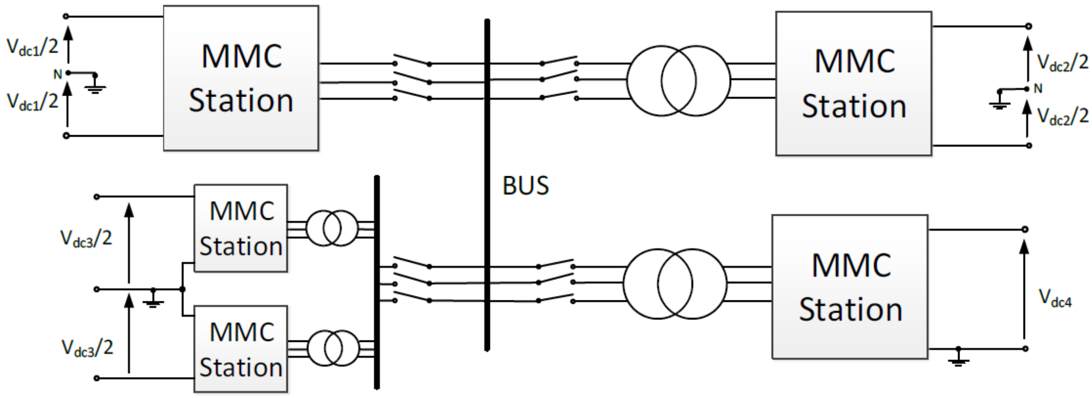

Figure 2-5. Four-port MMC-based AC hub interconnecting DC lines with different voltage levels and DC link configurations [12]

The need for DC circuit breakers is eliminated, because faults on the DC line can be cleared by opening the AC circuit breakers as it could do in existing point-to-point connections. The affected DC line can be isolated, while the rest of the system can continue to operate. However, overcurrent in the converters' valves may appear due to the slow reaction of the mechanical AC breakers Dependent on the equipment specifications, protection strategy and requirements, additional and faster DC circuit breakers may be required.

More HVDC converters are required compared to the case of pure interconnection of the DC links. If the DC voltage levels are different, additional transformers are required as well. This increases the cost of the system, as well as the space requirements and footprint of the hub. More information regarding the selection of the AC hub topology can be found in Appendix D – Literature review on AC hubs.

The AC hub introduces additional power losses compared to a direct interconnection of the DC lines, because the power transferred from a DC line to another must flow through two converters and transformers. Assuming 99.5% converter efficiency and 99.6% transformer efficiency, the losses would amount to 1.8% of the power flow.

A major disadvantage of this topology is that a substation shutdown would completely block the power flow through the hub. The 'Backup Node' and 'Ring AC hub' concepts mitigate this risk, but at the cost of increased complexity and additional space requirements.

Backup node AC hub

In this configuration, part of the incoming interconnectors and OWFs' export cables are connected not only to the main substation, but also to a back-up substation. The concept is illustrated in Figure 2-6.

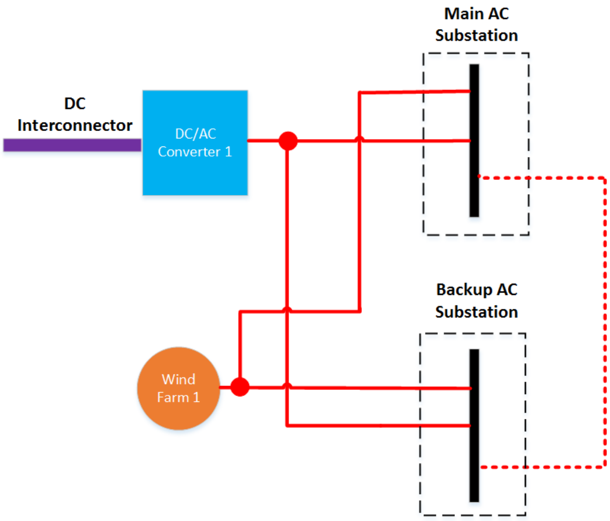

Figure 2-6. Backup substation concept

The main purpose of the back-up substation is to keep power flowing through the hub in the event of a major failure in the main substation. A direct connection between the two substations can be implemented. This way, part of the power can be routed at any moment through the backup substation if necessary.

The converter and transformer stations can be separated from the main substation. This creates another degree of independency that increases the overall reliability of the system. However, the amount of lines that need to be routed throughout the hub increases as well and this may pose a challenge for the physical implementation of the system. Costs would also increase as consequence of the higher complexity of the system.

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The backup substation does not need to have the same level of reliability of the main substation, therefore it can be designed with a simpler arrangement, e.g. as double-busbar with single breaker.
The backup substation can also serve as an expansion node for future connections in case of saturation of the main substation.

Ring AC hub

The ring AC hub consists of three independent AC substations connected to each other by AC links. The concept is illustrated in Figure 2-7.

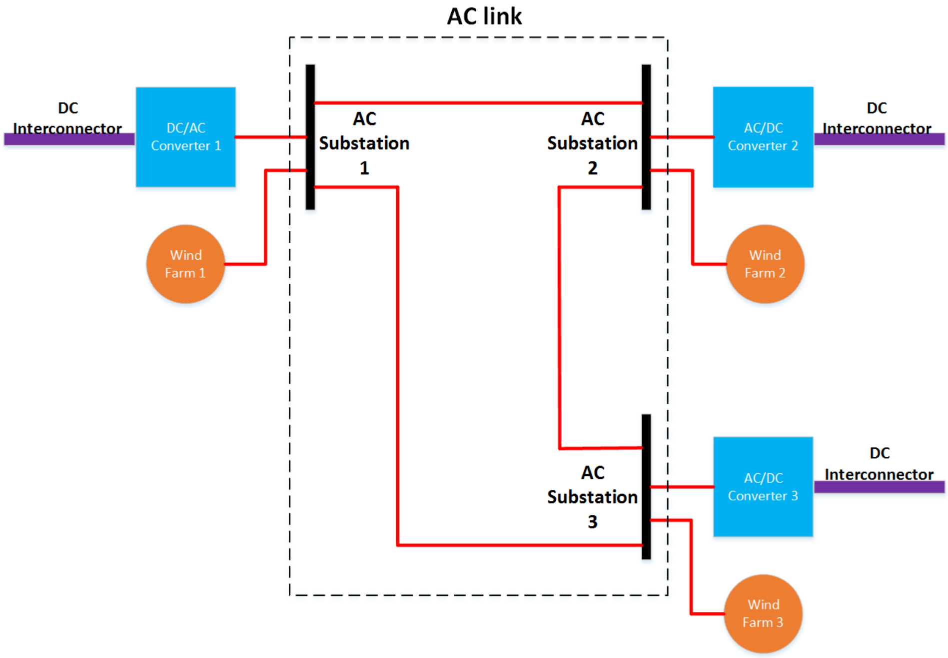

Figure 2-7. Ring AC hub concept

In this case, a substation failure would not lead to a complete shutdown of the hub, because the two healthy substations can continue to operate. Due to the ring connection, a fault in one of the AC links interconnecting the substations does not affect the operation of the system. However, the faulted AC links needs ultimately to be repaired, which adds up to the operational costs of the system.

Each of the three substations should be organized to achieve high reliability, therefore the same substation layouts suggested for the single node could be applied. However, three substations must be built and operated independently, which increases the total cost and space requirements of the system compared to the single node and backup concepts.

2.2.3. REGULAR DC HUBS

In the regular DC hub concept, all the DC lines are directly connected to each other without an intermediate AC node. Every wind farm needs to have a DC connection to the hub, which means that direct AC connection is no longer possible. The DC hub concept (for a single node topology) is illustrated in Figure 2-8.

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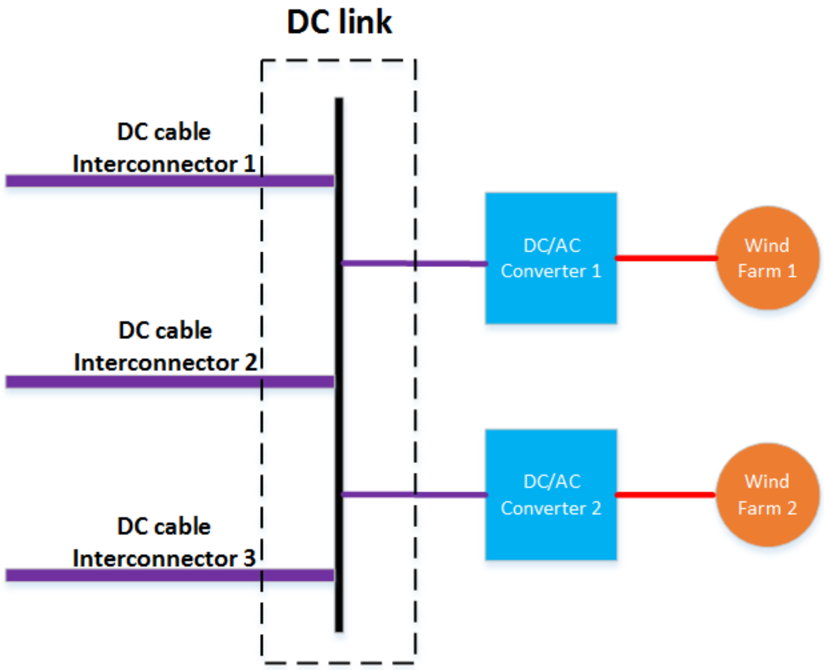

Figure 2-8. Single node DC hub topology

The DC hub reduces the need for HVDC converters and transformers, reducing the costs, volume and power losses of the system compared to the AC hub. On the other hand, this concept requires the use of HVDC circuit breakers for protection, which are not commercially available yet.

Hybrid mechanical breakers and solid-state breakers appear to be the most promising technologies due to their low fault interruption times. Hybrid breakers have a better performance and they consist of the Nominal Current Path (NCP) with low resistance that is used during normal operation, the Current Commutation Path (CCP) and the Energy Absorption Path (EAP). The structure of a hybrid circuit breaker is shown in Figure 2-9.

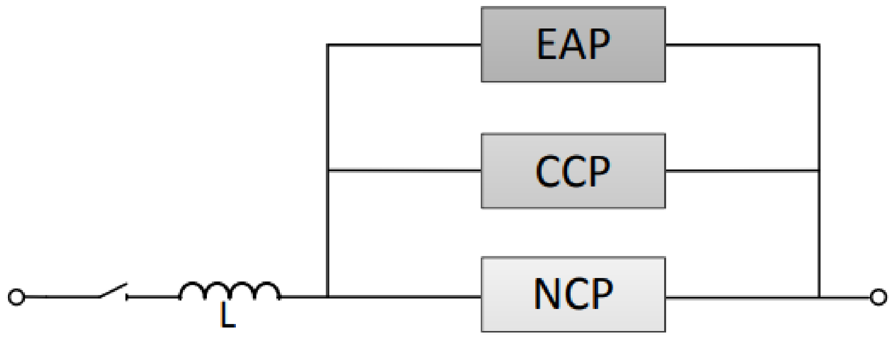

Figure 2-9. General structure of a hybrid DC breaker [13]

The cost of the hybrid circuit breakers is quite high and its use on every interconnecting line would significantly increase the overall cost of the system. For this reason, the Multi-Line Breaker (MLB) concept could be applied, as suggested in [13]. The structure of the MLB is shown in Figure 2-10. The suggested configuration minimises the number of CCP and EAP paths needed and the number of the involved switching elements within the

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breaker, offering a bidirectional fault isolation capability. Thus, the MLB optimizes the used number of protection assets by using only one unidirectional CCP and one EAP for more than one DC lines, as can be seen in Figure 2-10. The NCPs are controlled to drive the DC fault current through the main breaking paths, while at normal operation they enable bidirectional power flow in the DC grid. The design of the MLB is simple and modular, facilitating the expansion of the system and the interconnection of more DC lines. More information about the MLB concept can be found in [13].

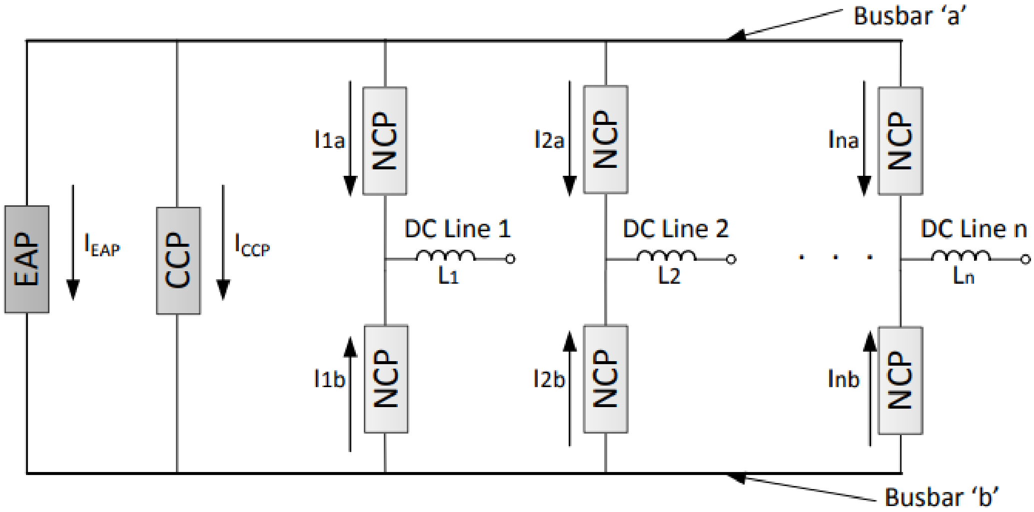

Figure 2-10. General structure of the Multi-Line Breaker [13]

The hub structures identified for the AC hub can be theoretically applied to the DC hub as well, through the extensive use of DC circuit breakers. Moreover, the immaturity of DC circuit breaker technology implies a higher risk of failure of the components, which may remarkably increase the maintenance costs of the system throughout its lifetime. The DC substation arrangement must be accompanied by suitable DC protection schemes, which are still under research.

The DC hub requires that all DC lines should have the same voltage level. This poses a limitation to the system, which cannot accommodate higher DC voltage levels in the future. Furthermore, a standardisation effort is required to determine the DC voltage of the hub.

In case of a fault on a DC line, the voltage of the DC node will tend to collapse. Moreover, all the lines will be contributing to the fault current, which means that the ratings and costs of the DC circuit breakers are closely related to the DC hub size.

2.2.4. HYBRID AC/DC HUBS

As mentioned in the regular AC hub section, a major drawback of the AC hub using transformers is the large footprint of the system. To reduce to footprint of the components of the AC side (transformers, filters etc.), a higher operating frequency could be used. On the other hand, the increase of the operating frequency results in an increase of the switching losses of the converters, lowering this way the overall efficiency of the system. For

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this reason, the selection of the frequency will be a trade-off between the footprint and the efficiency of the system. The frequency range that is recommended in academic literature is 300-500 Hz.

In case the frequency of the inner AC circuit of the AC hub is higher than 50 Hz, the offshore wind generators cannot be directly connected to the common AC bus, since the nominal operating frequency of most wind generators is 50 Hz. For this reason, two converters must be placed between the wind generator and the AC bus to reach the higher operating frequency of the AC bus, as shown in Figure 2-11. This can be done by means of a back-to-back converter on the hub, in case that the wind farm is close and an AC connection is appropriate. On the other hand, if the wind farm is located far from the hub and a DC connection is more suitable, there will only be one converter on the hub, which will convert the DC connection voltage into a high frequency AC voltage.

Although the selection of a higher operating frequency results in a decrease of the volume of the AC components, it also requires a higher number of power electronic interfaces for the connection of the OWFs to the intermediate AC link of the AC hub, as well as AC power equipment that is designed to operate at higher frequencies. Thus, the overall cost of the system will be high.

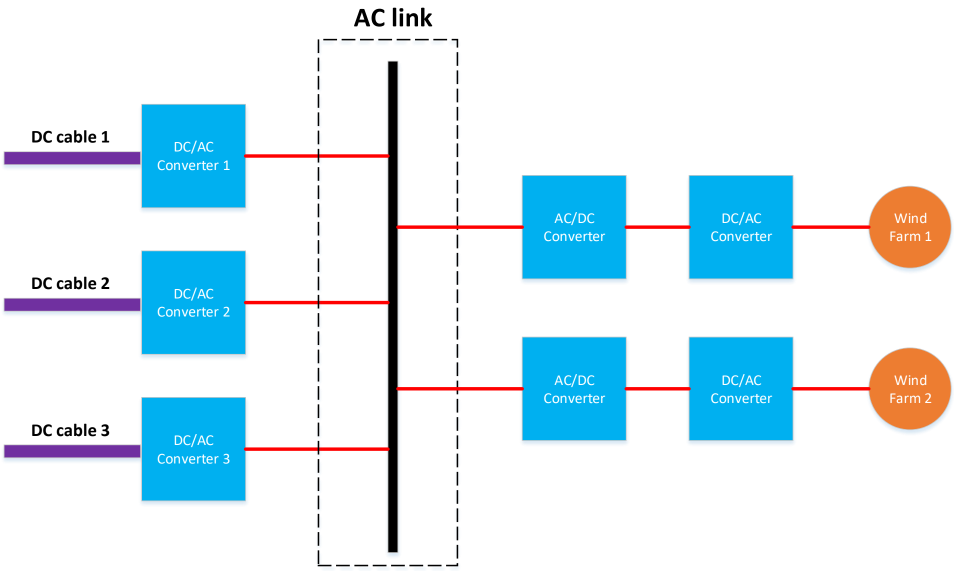

Figure 2-11. Hybrid AC/DC hub

2.2.5. DISCUSSION

From a regulatory perspective, several challenges might hamper the implementation of the centralised wind power hubs concept. The most predominant is linked to the potential connection of OWFs in the national waters or Exclusive Economic Zone (EEZ) of a 'country A' to a centralised hub located in the territorial waters or EEZ of another 'country B' which means that different grid codes and subsidy schemes might be involved. Furthermore, an additional challenge could occur if there is no direct connection between the centralised hub and the onshore

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grid of country B (e.g. in Figure 2-3: no direct connection between the Dutch centralised hub connecting German OWFs and the onshore German grid). A degree of coordination at European level is of crucial importance, albeit limited, it might be required in the form of extended connection codes, ownership schemes and support schemes, dedicated trading hubs and/or agreements, and operating agencies.

In perspective, the concept of centralised wind power hubs is open to various development paths. The interconnection between islands can be extended to form a meshed grid, and eventually these islands can be connected together to create large hubs in the longer-term horizon.

2.3. DISTRIBUTED HUBS CONCEPTS

In contrast with large centralised wind power hubs, the offshore grid could be developed in steps around several small hubs, interconnected amongst themselves to different degrees. Such an approach can be differentiated between two specific sub-concepts, based on a national or European approach related to policies for the offshore grid:

- The national concept achieves an offshore grid based on distributed wind power hubs by promoting the development of meshed national MOGs, each national MOG being interconnected with others, but weakly.
- The European concept favours the joint development of a single MOG integrating all the distributed hubs.

It is noteworthy that the national concept can eventually evolve into the European concept by increasing the integration between the national offshore grids, as discussed in [14]. The concepts are described in the following sections, with visual examples for indicative purposes. Each of these concepts may deploy a similar technological design of the hubs, albeit in a much smaller format than in the centralised wind power hubs concept.

2.3.1. NATIONAL DISTRIBUTED HUBS CONCEPT

Figure 2-12 illustrates the national distributed hubs concept. In this approach, each country develops its own national offshore grid according to national policy and regulation. The purpose of each national MOG is to evacuate all the national offshore wind power generation to the corresponding onshore national grid. With respect to the radial connections of OWFs, a MOG grants more flexibility and increased security of supply as wind power can be injected in the mainland system through different connection points depending on the state of the system. The national offshore grids may be interconnected with each other. The recently proposed “WindConnector” between the Dutch area “IJmuiden Ver” and the British “East Anglia” area[2] corresponds to this concept: the Dutch offshore grid will be designed such that it is able to evacuate all the Dutch offshore wind energy to the Dutch onshore grid, the British offshore grid will be designed such that it is able to evacuate all the

[2] https://www.tennet.eu/news/detail/tennet-and-vattenfall-to-study-potential-dutch-and-uk-offshore-wind-farm-connections/

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British offshore wind energy to the British onshore grid, but the two offshore grids would be connected by an interconnector.

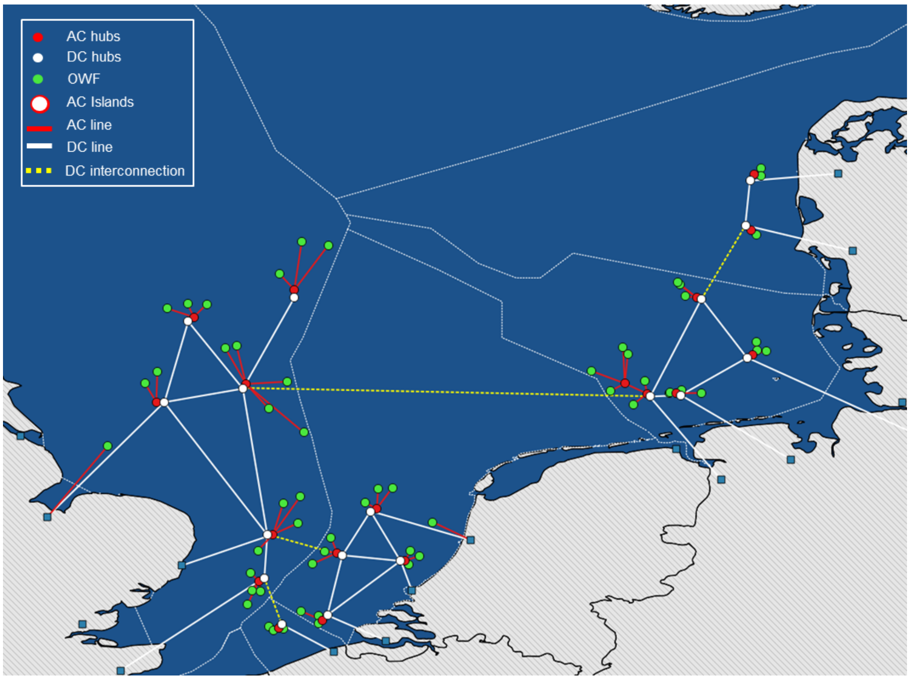

Figure 2-12. National distributed hubs concept.

The operational complexity of the offshore grid depends on its extent and degree of meshing. As the development of the grid is driven by national policies, these characteristics might change from country to country. When meshing appears on the HVDC side, control interactions between converters leading to instabilities could appear. Furthermore, the need for requirements for DC grid protection depends on the quantity of wind energy capacity connected to each part of the grid. No major regulatory challenge is anticipated because existing frameworks should be applicable to both cross-border trading and wind farm connection. With regard to the flexibility of the overall offshore grid: the weak interconnection between national grids prevents reaching the same level of flexibility as with the European approach. That said, the distributed hubs concept ideally presents more flexibility than the centralised concept, as a larger number of alternatives should be available to cope with congestion and/or outages.

2.3.2. EUROPEAN DISTRIBUTED HUBS CONCEPT

Figure 2-13 illustrates the European distributed hubs concept. In this concept, small hubs are integrated into a MOG developed jointly by the North Seas countries as international infrastructure. OWFs can be connected in either AC or DC to the most suitable node of the grid regardless of to which country it belongs. The national offshore grids are no longer designed to be able to evacuate all the national offshore wind energy to the corresponding national onshore grids, but are rather designed to be able to evacuate all the offshore wind energy to the onshore grids combined. In other words, in that concept, it is not essential for each country to scale its onshore grid to evacuate all wind generation in its corresponding offshore sector. If there is e.g. 40GW of generation in the Danish sector and its onshore grid can accept only 10GW, then the remainder may be landed elsewhere in Europe.

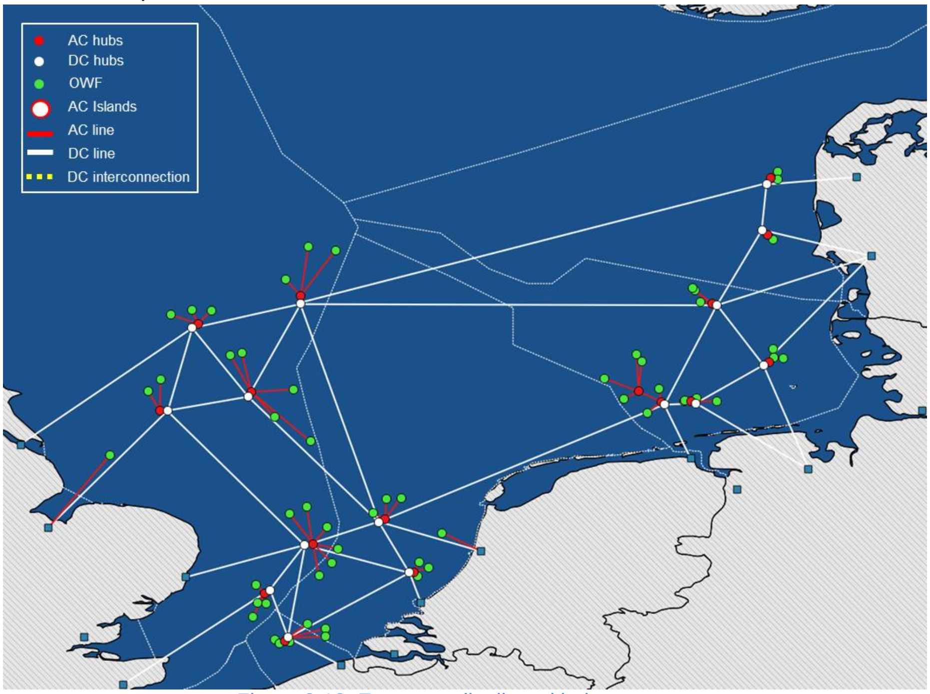

Figure 2-13. European distributed hubs concept.

The operation of such a meshed and widespread grid is complex and requires the commercial availability of key technologies and an adequate regulatory framework. A major challenge is the control and the protection of the grid, due to the high level of connectivity. Several regulatory challenges appear, in particular because OWFs of a 'country A' can be connected to the grid of a 'country B' and interconnectors are not distinguishable from other branches.

Theoretically, this concept presents the highest level of flexibility of the offshore grid, allowing efficient evacuation of wind generation but also good resilience against uncertainties. In addition, the highly coordinated development allows a better optimization of the topology and positioning of OWFs, increasing the exploitation of wind resources in the North Sea.

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3. BUILDING BLOCKS

The development of a European offshore grid can be deconstructed into several conceptual "building blocks". These blocks should be sufficiently mature at the time of deployment for the MOG to become a reality.

1. An offshore grid must be feasible from a technical point of view, which means that the necessary technologies must be commercially ready and mature, and that appropriate control systems must be available or implementable to operate such a grid.
2. The regulatory and legal frameworks must allow the development of the European offshore grid.
3. The offshore grid must be economically viable, and the financial framework must be such that the business case of the various critical stakeholders is positive. The purpose of the economic/financial building bloc[illegible]conomically and financially feasibility.

The purpose of [illegible] chapter is to analys[illegible] these three fundamental building blocks for each concept. This analysis will [illegible] the identification of cu[illegible] gaps in the building blocks, i.e. the identification of current [illegible] 4. These [illegible] blocks [illegible] dependent, influencing and interacting with each [illegible] work of this document, [illegible]es are defined according to the diagram shown in Figure 3-1.

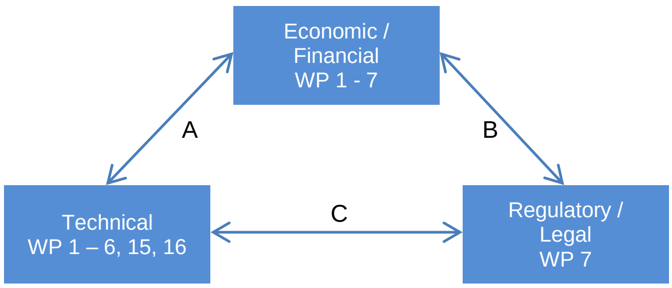

Figure 3-1. Overview interactions between building blocks.

Examples of these can be:

- The technical solutions and requirements will influence the investments and operating costs (link A);
- Economic analysis in the CBA of alternatives will influence recommendations on solutions presented, or their relative attractiveness (link A).
- Regulatory requirements will impact the business model (e.g. requirements on security, interoperability and on the structure of the market) (link B);
- Technical solutions may heavily depend on the regulatory framework (e.g. requirements on interoperability, security such as allowable loss of load) (link C)
- The regulatory framework will take into account the technical direction for the setting of regulations and requirements (e.g. grid codes) (link C). Additionally, developments in technical fields may allow for new

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alternatives in the use of assets or operating. As such, regulation may and will have to change and be adjusted over time.

Because the overall electricity market design affects the operation of the system and the business models of the different stakeholders, this chapter starts with preliminary market considerations in section 3.1. Then, the technical building blocks are developed in section 3.2. Afterwards, the regulatory/legal building blocks are analysed in section 3.3, and the financial & economic building blocks in section 3.4.

3.1. PRELIMINARY MARKET CONSIDERATIONS

3.1.1. TYPES OF ELECTRICITY MARKET DESIGNS CONSIDERED

Only the wholesale electricity market is considered in this preliminary analysis, i.e. the trading of “active” power to balance the load and the generation. Wholesale electricity markets are organized in general along three timeframes: the forward market for long-term allocations (e.g. yearly and monthly allocations), the physical/spot market (e.g. day-ahead and intraday markets) and the real-time market (balancing mechanisms).

If the electrical grid would not entail any constraint on the power flows, i.e. if the grid is a “copper plate”, there is obviously no need to consider any grid constraint in the market clearing mechanisms. However, this is a theoretical case. In general, there are three ways to manage constraints induced by the grid:

1. **Redispatch only**

   The market is first cleared without any consideration of the grid constraints, and then, if the dispatch violates one (or several) operational constraint(s) that cannot be solved through topological actions, the operator imposes deviations of power dispatch to generating units compared to what was decided by the market, i.e. they impose a redispatch. Redispatched units, i.e. units having to increase or decrease their generation, are remunerated for that service by TSOs.

2. **Zonal market with internal redispatch**

   The power system is divided into different market zones or bidding zones, with transmission constraints limiting the power exchanges between the different zones. These transmission constraints between zones can be considered through either Available Transfer Capacity (ATC) constraints or flow-based constraints. For the ATC-based market coupling, the power exchange between each pair of market zones is limited to a single value in each direction, the ATC. It corresponds to a transportation model: the power that zone A and zone B can exchange is independent of the power they exchange with zone C. It is convenient when areas are radially connected or weakly meshed. It is much less adequate in a meshed system, in particular because it is complicated to define ATCs between zones. The flow-based market coupling tries to address this limitation through an explicit representation of major transmission constraints by using Power Transfer Distribution Factors (PTDFs) between areas and major branches. Several assumptions are then needed to derive the flow-based constraints imposed to the market, among which assumptions on the geographical repartition of generation changes in a zone (Generation Shift Keys). In both cases, redispatch actions might be needed to manage grid constraints within a zone. Note that the definition of zones is supposed to limit the redispatch need, but it is not always the case.

3. **Nodal market**

   A detailed model of the transmission system is used to explicitly model major operational constraints (e.g. limits on power flows endured by transmission elements) in the market-clearing algorithm. In this way, redispatch is limited: it is only used to address operational constraints not represented in the market clearing algorithm and which cannot be solved through topological actions (e.g. specific voltage constraints). Note that a nodal market can be seen as a limit of a zonal market with flow-based market coupling, with zones corresponding to nodes.

For North Seas' countries, the market model is currently a zonal one with internal redispatch. A flow-based market coupling has been applied since 2015 for the day-ahead market in Central West Europe (CWE, covering Benelux, France and Germany) to improve the efficiency of the market because the grid is strongly meshed between these countries. An ATC-based market coupling is still used in CWE for the other timeframes and is used as well for the other North Seas' countries. When a zonal market model is used, the market areas must be defined. In Europe, for historical and political reasons, the market areas correspond often to the countries, with some exceptions (e.g., Norway is split into five market areas, and Denmark is two market areas). However, there is no evidence that this is the optimal solution.

3.1.2. RELEVANT MARKET DESIGNS FOR EACH CONCEPT

Market designs used in the framework of PROMOTioN will tend to stick as much as possible to the status quo, i.e. zonal markets organized by countries, whenever relevant. However, it is not necessarily relevant for each concept and that is why other market designs are explored. Nevertheless, in each case, the simplest relevant solution will be used.

Business-as-usual concept

For the business-as-usual concept, there is obviously no need to change the underlying market model: the current zonal market with internal redispatch can be used. In particular, OWFs are associated to the market area of their country and an ATC-based market coupling can be used between North Seas' countries, with the exception of trades between CWE countries. Furthermore, the available offshore interconnection capacity between North Seas' countries is independent of the actual generated wind energy.

Centralised wind power hubs concept

As defined in chapter 2, the offshore connection capacity of wind power hubs will be such that the overall offshore wind capacity of a country can be evacuated to the corresponding national onshore grid (without considering possible limitations entailed by the onshore grid itself). Consequently, there is no need to change the underlying market model: the current zonal market with country-based zones can be used. However, the available offshore interconnection capacity between North Seas' countries depends heavily on the amount of

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wind generated and therefore is highly dynamic. The accuracy of offshore wind power forecasts as well as the desired reliability margins influence the market efficiency and the redispatch costs. Furthermore, in case a topology is used in which the flows are not fully controllable in each branch individually (e.g. meshed structure); a flow-based market coupling might have to be used.

National distributed hubs concept

As defined in chapter 2, each national offshore grid will be such that the overall offshore wind capacity of a country can be evacuated to the corresponding national onshore grid (without considering possible limitations entailed by the onshore grid itself, due to methodological reasons). Consequently, there is no need to change the underlying market model: the current zonal market with country-based zones (i.e. OWFs in the EEZ of a country belongs to the bidding zone of that country) can be used. However, similarly to the centralised wind power hubs concept, the available offshore interconnection capacity between North Seas' countries is dynamic and the forecasts as well as the desired reliability margins affect the market efficiency and the redispatch costs. The possibility to keep an ATC-based market coupling or the need to adopt a flow-based market coupling depends on the way interconnections are integrated to national offshore grids. Indeed, if power flows on interconnections are individually controllable (e.g. through dedicated HVDC converters), an ATC-based market coupling can be kept, while if power flows on interconnections are not fully individually controllable (e.g. HVDC interconnections directly integrated in an HVDC MOG), a flow-based market coupling will have to be operated.

European distributed hubs concept

As defined in chapter 2, there is no guarantee that the offshore grid could evacuate the overall offshore wind capacity of a country to the corresponding national onshore grid (even without considering possible limitations entailed by the onshore grid itself). Therefore, current zonal market with country-based zones might become irrelevant. The creation of dedicated offshore market zones not related to countries with a flow-based market coupling might be needed in the future. In the extreme case where a division in market zones is not relevant (e.g. changing congestions), a nodal market might be needed.

Summary

Table 3.1 summarizes the preliminary analysis. For the centralised wind power hubs concept, the preferred market model is ATC-based, but a flow-based market might be needed. For the distributed hubs concepts, a flow-based market model will probably be needed, but an ATC-based market might also be possible. The preferred or objective market models will be selected and fully analysed in D12.2.

Concept	Timeframe	Offshore market model	Offshore market areas	Additional comments
Business-as-usual	Long-term	Zonal, ATC	National	
	Spot	Zonal, ATC	National	
Centralised wind power hubs	Long-term	Zonal, ATC	National	Computation of long-term available capacity based on conservative assumptions.
	Spot	Zonal, ATC (or FB)	National	Computation of day-ahead transfer capacities based on wind power forecasts and reliability margins. Additional capacity available in intraday market if better forecasts.
National distributed hubs	Long-term	Zonal, ATC	National	Computation of long-term available capacity based on conservative assumptions.
	Spot	Zonal, FB (or ATC)	National	Computation of day-ahead RAMs based on wind power forecasts and reliability margins. Additional capacity available in intraday market if better forecasts.
European distributed hubs	Long-term	Zonal, ATC	Dedicated	Computation of long-term available capacity based on conservative assumptions.
	Spot	Zonal, FB (or ATC)	Dedicated	Computation of day-ahead RAMs based on wind power forecasts and reliability margins. Additional capacity available in intraday market if better forecasts.

Table 3.1. Summary of the possible market models.

3.2. TECHNICAL BUILDING BLOCKS

From a technical point of view, a MOG can be viewed as a set of elements that have to work together to achieve a common mission. Various categories of elements will co-exist in a MOG and the technology needs to be mature for each category. The reasons for this are as follows:

- First, one of the key objectives of an offshore grid is the evacuation of offshore wind energy power (in addition to power exchanges between various countries). The presence of OWFs will be an essential requirement for the MOG. OWFs already exist, so there is no major technical challenge existing at that level.
- Second, to transport power to the shores undersea HVAC and/or HVDC cables form a second category of elements. Although there are constant technological improvements at that level (i.e. higher voltages), existing cable technologies are sufficiently mature to be part of offshore grids.
- When HVDC is needed (i.e. to transfer power over long distances), a third category of elements are converters to convert AC power (from OWFs or onshore grids) into DC power. Various technologies of converters do exist. The PROMOTioN project is targeted at improving the economic benefit of offshore generation. As such, it evaluates improvements on existing technology such as VSC, while also testing and raising the Technical Readiness Level of new technologies such as the DRU, which has the potential to transform the cost of offshore grid architecture. The VSC is a proven technology already integrated in real power systems. However, at this stage of testing, the maturity of the DRU technology is insufficient to plan directly its integration into offshore grids.

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- Finally, a further important category of elements could be DC grid control and protection technology, and in particular HVDC circuit breakers. In some cases they might be needed to interrupt fault currents in the HVDC MOG. The capability of HVDC circuit breakers to interrupt fault currents at the voltage levels and the power levels envisaged in a MOG has not yet been characterized based on standardized test procedures. The PROMOTioN project aims precisely to perform this characterization, bringing the maturity of HVDC circuit breakers to a higher level.

It is however not sufficient to have the necessary elements for a MOG: they must be able to work together to establish a system that is fully capable fulfilling the requirements. A major challenge is the operation and the control of the MOG. This is discussed in section 3.2.1. Another challenge is the development of a suitable DC grid protection methodology, able to detect and clear faults within the MOG in a cost-effective manner, which is discussed in section 3.2.2.

3.2.1. OPERATION AND CONTROL

The market clearing does not lead necessarily to a unique way to set the active elements of the offshore grid, i.e. mainly the converters. Indeed, although the active power flows through each converter depend strongly on the results of the market clearing for each offshore wind generator and for cross-border flows, there might be several ways to set the active power flows in line with the market clearing (e.g. in case several converters connect an offshore grid to a country) as well as voltages (in both the AC and the DC grid). The scheduling process is the link between the market system and the settings of the converters. Several practical aspects that should be taken into consideration by the scheduling process:

- Controlling power flows. The scheduling process will define the power and/or voltage setpoints of the converters (onshore and offshore), similarly to setpoints sent to conventional generation. By doing so, it is possible to control the flows on the DC grid. A way of doing that could rely on a constrained optimal power flow algorithm to provide the optimal setpoints to each converter.
- Optimizing the DC grid topology. Depending on planned outages and the forecasted wind production, changing the DC grid topology could be required, similar to what is done in AC grids. It is not expected to change the topology for every dispatch, it might be needed in some cases to avoid congestion. Therefore, the scheduling process should consider the possibility to change the DC grid topology, either in a manual way or in an automatic way (i.e. optimal transmission switching).
- Consideration of AC and DC constraints. The scheduling process will have to consider constraints on the DC grid but also on the AC system. This requires a coordinated approach that should optimize power flows in both the DC grid and the AC grid. Depending on the concept for future offshore grids, the dispatch algorithm can optimize the dispatch within one part of the DC grid or throughout the entire HVDC grid. This depends on the presence of AC hubs or DC/DC converters.
- Compensating imbalances. Imbalances can occur in an offshore grid due to forecast errors and due to the intrinsic variability of offshore wind within a scheduling period. Any imbalance in the offshore grid will lead to a voltage drop/rise at some DC-buses. To cope with small imbalances, a local control can be implemented at the converter sides. This control involves a droop control that will adapt the active

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power setpoint depending on the voltage deviation from the setpoint. If correctly implemented, the voltage droop control will guarantee that voltage limits are not violated and can contribute to keep the system within its thermal limits. After the action of local droop controls, a centralised algorithm could coordinate and re-optimize the setpoints of each converter.

- Operational security of the grid. It is usually not deemed sufficient for a grid to be in a state fulfilling flows and voltage constraints: it must also have some degree of security. Security of a power system can be defined as its ability to withstand disturbances arising from faults and unscheduled removal of equipment without further loss of facilities or cascading failures. The management of the security of an offshore HVDC grid will differ from the management of the security of an onshore AC grid for two main reasons: almost no load is expected within an offshore HVDC grid, and HVDC circuits might not be protected fully individually (i.e. HVDC circuit breakers might not be installed at all line extremities) because HVDC circuit breakers are expected to be expensive. In particular, the N-1 security rule must be adapted for offshore grids. Following the UCTE philosophy, it appears desirable to ensure that the loss of any single element must not endanger the security of the onshore grids and must not lead to uncontrolled cascading outage. In particular, any single contingency must not lead to load shedding. In the reverse situation, it is assumed acceptable to temporarily curtail wind generation or limit the evacuation of wind energy following an onshore N-1 contingency. Like AC grids, it is expected to use both preventive and corrective actions in a DC system to manage the security and to maintain flows and voltages within acceptable bounds. Note that the use of corrective actions increases the capacity available for power flows, compared to the use of preventive actions. In an offshore HVDC grid, just after an outage, local voltage droop control of each controller will lead to a new steady state. An optimisation of that local control (e.g. through optimization of the droop constants) could help to keep power flows and voltages within acceptable bounds. In case the new steady state presents overloads and/or unacceptable voltage conditions, fast corrective actions could then be taken through a master controller sending automatically new setpoints to the converters. In addition, or in complement, slow corrective actions could be taken manually.
- Partial restoration of the grid after a fault. One specific constraint of the HVDC meshed grid is the restoration of the grid after a fault. If HVDC circuit breakers are not installed at the extremities of each line (e.g. because the cost of HVDC circuit breakers is high), a part of the HVDC grid will have to be blacked-out just after the occurrence of the fault. Then, the topology will have to be changed to isolate the faulty element and the healthy part of the HVDC grid will have finally to be reenergized. This requires the implementation of a reliable remote-control system able to change the configuration of each DC bus (when de-energized). This question is linked to the protection philosophy discussed in section 3.2.2.

The following paragraphs discuss these considerations for each concept.

Business-as-usual concept

For the business-as-usual concept, there are few degrees of freedom between the results of the market clearing and the operation of the grid. Indeed, HVDC systems connecting OWFs evacuate the generated offshore wind energy and point-to-point interconnectors transfer the cross-border power flows resulting from the market. As

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there is no possibility to change the topology, the optimization of the DC grid topology is irrelevant. However, AC grid constraints can lead to offshore wind curtailment, as well as the limited ampacity of HVDC systems in case of overplanting. Furthermore, in case several HVDC interconnectors connect two areas, the power flow on each interconnector can be set to minimize the losses while satisfying the operational criteria, including AC grid constraints. The N-1 security rule in the business-as-usual concept simply means that an HVDC system cannot transfer more power from/out of a synchronous area higher than the available primary reserve. Note that, control challenges might be expected mainly for DRU connections of OWFs. Indeed, other parts of the concept (e.g. point-to-point interconnectors, VSC connections of OWFs) already exist in real power systems. Control challenges for DRU connections of OWFs are being studied by WP3.

Centralised wind power hubs concept

In this concept, the hubs are decoupling points. Indeed, OWFs will be connected radially (in AC or through a point-to-point HVDC system) and hubs will be connected to the onshore grids through point-to-point HVDC systems and will be connected together through point-to-point HVDC systems. Like the business-as-usual concept, power flows in transmission elements (including converters) are almost a direct consequence of the market clearing result. AC grid constraints can also lead to offshore wind curtailment. Note that the topology of the AC parts of the hub could be changed, but no benefits are expected from such a possibility, especially because power flows are already individually controllable. However, because several OWFs are connected to several HVDC systems, the compensation of imbalances is not straightforward and will require the definition and implementation of a control strategy to share these imbalances between the different converters. The N-1 security rule means then not only that an HVDC system connecting a hub to an onshore grid cannot transfer more power than the available primary reserve (i.e. Frequency Containment Reserve) in the area, but also that outages of transmission elements connecting OWFs to the hubs and connecting hubs together must be managed to avoid undesired consequences in the onshore grid. Note that the outage of a transmission element will induce a power imbalance on one or several hubs and thus a unique control strategy can be used to deal with both forecast errors and outages. In addition to that, the security of the system following faults and outages within the AC hub must also be ensured. Finally, the question of the partial restoration of the grid after a fault is irrelevant in this concept because HVDC systems can be protected individually.

National distributed hubs concept

For the national distributed hubs concept, there is a broader gap between the market clearing and the setting of converters. Firstly, as an offshore HVDC grid could have several connection points in a specific bidding area (e.g. in a specific country), there are several possible ways to set the power flows through converters such that the offshore wind energy is evacuated and that cross-border flows are met. Furthermore, topological actions are possible to influence power flows in the grid. As the national offshore and the onshore grids are strongly interrelated for specific countries (i.e. the power sharing between converters impact both the offshore grid and the onshore grid), the scheduling process must consider in a joint way these two grids, which could be accomplished either with a single TSO or with two different TSOs with a coordination entity. Secondly, the compensation of imbalances due to forecast errors and wind generation variability can be performed on a national basis and necessitates a specific control strategy as well as reliability margins on transmission

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elements. Thirdly, the N-1 security criterion can affect strongly power flows within the grid and the need to optimize voltage droop control to maximize the available transfer capacity. A fast master controller can be used at a national level to quickly redispatch and/or curtail wind after a contingency to avoid sustained overloads and unacceptable voltage conditions. Finally, specific switching strategies are needed to quickly restore the grid after a fault.

European distributed hubs concept

The operation and control considerations for the European distributed hubs concept are similar to the ones related to the national distributed hubs concept, with the additional complexity that they cannot be managed nationally anymore. Therefore, either a specific TSO must be in charge of the control, or several TSOs with a strong coordination. Furthermore, a fast master controller might have to be used at an international level quickly redispatch and/or curtail wind after a contingency to avoid sustained overloads and unacceptable voltage conditions[3].

3.2.2. PROTECTION PRINCIPLES

Power systems are regularly subjected to faults on transmission elements (e.g. cables). In order to ensure a safe, continuous and reliable operation of power systems, these faults must be quickly detected, located and cleared. In AC transmission systems, protection systems and circuit breakers usually protect individually each transmission element. When a fault occurs in an AC transmission system, the specific faulty element can be isolated from the rest of the system in tens of milliseconds. Protection of DC transmission systems is much more challenging for two main reasons. First, DC faults lead rapidly to high currents and must be interrupted much more quickly than AC faults because components have a limited overload capability. It implies that they must be detected, located and cleared in a couple of milliseconds. Second, DC faults do not exhibit periodical zero-crossing, contrarily to AC faults, and their interruption is thus much more challenging. This means that DC circuit breakers are expected to be much costlier than AC circuit breakers. Consequently, it might be unaffordable to adopt an identical fault clearing strategy like the one for AC transmissions systems and to protect each HVDC circuit individually using DC breakers, i.e. to adopt a fully selective fault clearing strategy. Hence, two other strategies are then possible: a non-selective strategy consisting in de-energizing the entire DC grid in case of fault (through AC breakers or fault blocking converters), and a partially selective strategy consisting in splitting the grid using DC breakers in case of fault to de-energize a portion of the DC grid with the faulty element. Note that a non-selective strategy could reveal itself expensive due to higher frequency reserve requirements in onshore grids[4]. PROMOTioN's WP4 is studying in detail the pros and cons of the different fault clearing strategies. A short preliminary analysis is provided below for each concept.

Business-as-usual concept

[3] Note that the experience of the Kriegers Flak Combined Grid Solution has shown that the master controller is required for operation of the interconnector and enabling several operation regimes including normal operations and N-1 regimes [12].
[4] An increase of the frequency reserve requirements can also lead to a decrease of the generation system adequacy.

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In the business-as-usual concept, HVDC systems connecting OWFs or interconnecting countries are exclusively point-to-point systems. Consequently, the overall HVDC point-to-point system can be isolated in case of fault on an HVDC transmission element by opening circuit breakers on the AC side. There is thus no major issue to protect individually each transmission circuit, i.e. dedicated algorithms and HVDC circuit breakers are not needed.

Centralised wind power hubs concept

In the centralised wind power hubs concept, only HVDC point-to-point systems are used. Therefore, each transmission circuit can be protected individually by opening circuit breakers on the AC side in case of fault. There is thus no major issue to protect individually each transmission circuit, i.e. dedicated algorithms and HVDC circuit breakers are not needed.

National distributed hubs concept

Protection principles for the national distributed hubs concept are more complex, because the offshore grids are potentially meshed on the DC side. Nevertheless, a non-selective strategy could be possible without extra costs for specific portions of the offshore grid. These portions must form an HVDC island (i.e. isolated from the rest of the offshore HVDC grid), must be connected to the onshore grid of a single country (to avoid consequences of an event beyond boundaries), and must connect an amount of offshore wind lower than the current frequency primary reserve of the linked synchronous area. Note that offshore grids will evolve in steps over time: a specific portion of the offshore grid could first connect an amount of wind lower than the current primary reserve, and afterwards an amount higher than the reserve. The protection strategy could thus have to evolve over time. In that concept, the offshore grid could also have national portions weakly connected to each other. In that case, interconnectors could be considered as natural splitting points for a partially selective strategy. By this way, the protection of the grid could be still managed nationally, in line with the UCTE N-1 security principle "no cascading with impact outside my border". If the maximum of the sum of the evacuated offshore wind energy and the imports is lower than the current primary reserve of the corresponding synchronous area, such a partially selective strategy could be sufficient to ensure system security. On the contrary, the selectivity or the primary reserve will have to be raised.

European distributed hubs concept

Protection principles for the European distributed hubs concept are similar to the ones of the national distributed hubs concept, with the exception that interconnectors between countries are no longer natural splitting points. Although isolated portions of the offshore grid could still be managed through a non-selective strategy, partially selective or fully selective strategies necessary for portions of the offshore grid connecting significant amount of offshore wind will have to be designed in a centralised manner to guarantee a sufficient level of security for all North Seas countries.

3.2.3. PLANNING PRINCIPLES

Transmission planning consists in defining the way to develop the transmission system as economically efficient as possible while ensuring an acceptable reliability level. The required reliability level is defined by the planning

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criteria. Traditional planning criteria are deterministic. PROMOTioN's D1.6 proposes a set of planning criteria for offshore grids. In the case of offshore grids, transmission planning will include the following tasks:

- Selection of technologies (AC/DC) and voltage levels for transmission equipment,
- Development of grid topology,
- Definition of the protection strategy and of the substation configuration.

Note that a prerequisite for offshore grid planning is the forecast of the development of offshore wind energy, as well as the forecast of the evolution of load and generation in the North Seas countries (and neighbouring countries). The complexity of these tasks will depend strongly on the concept. A short discussion is provided hereafter.

Business-as-usual concept

For the business-as-usual concept, the planning process is eased by the very weak coupling between different offshore transmission projects. Indeed, HVDC OWFs connections and interconnectors are not connected to each other on the DC side. Consequently, the selection of technology and of voltage level can be performed on a case-by-case basis to optimize the costs (investment cost, maintenance cost, and losses). For that reason, several voltage levels are used for HVDC systems evacuating offshore wind energy or interconnecting countries. For example, the voltage of the NorthConnect and the NordLink interconnectors is 500 kV, the voltage of COBRAcable interconnector and of DolWin HVDC links is 320 kV, the voltage of HelWin1 HVDC link is 250 kV and the voltage of BorWin1 HVDC link is 150 kV. The Cigré TB684 "Recommended voltages for HVDC grids" provides guidelines for the selection of voltage level for specific projects. Beyond costs, the two main driving factors for the selection of a voltage level is the power to transfer and the distance. In the business-as-usual concept, the development of grid topology is performed individually for the evacuation of offshore wind energy and for interconnectors. Even if OWFs were initially connected individually to the shore, a coordinated approach tends to be adopted to cluster OWFs to reach a critical size and to evacuate their generation through a shared connection to the onshore grid (AC or DC). Note that shared DC connection has been standard practice in the German EEZ of the North Sea after 2009 (cf. BorWin1). The planning of offshore wind farm connections requires a forecast of the development of offshore wind energy, including its location, such that the capacity of the system to evacuate offshore wind energy can match the planned offshore wind capacity that will be connected[5]. Note that the planning of offshore wind grid connections does not require forecasts about the evolution of load and generation in the North Seas countries. Furthermore, the planning of offshore wind farm connections can be performed on a national basis and does not require coordination between the North Seas countries in that concept. On the other hand, the development of interconnectors in the business-as-usual concept is motivated mainly by economic reasons (e.g. increase of the socio-economic welfare and security of supply). The planning of interconnectors requires forecasts about the evolution of load and generation in North Seas countries and their neighbours to demonstrate the economic viability but does not require detailed information (beyond a split per country) about the expected location.

Centralised wind power hubs concept

[5] In some cases, an overplanting is allowed.

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Since OWFs connections and HVDC systems to evacuate the offshore wind energy to the shores and to interconnect countries are point-to-point in the centralised wind power hubs concept, the selection of technology and of voltage level can also be performed on a case-by-case basis to optimize the costs (investment cost, maintenance cost, and losses). Planning principles for offshore wind farm connections to the centralised hubs can also be similar to the ones of the business-as-usual concept: it can be done individually for each cluster of OWFs reaching a sufficient capacity, and it requires only a forecast of the development of offshore wind energy, including its location. On the contrary, HVDC systems connecting centralised wind power hubs to the shore (and between themselves) combine the evacuation of offshore wind energy with the interconnection function. Therefore, the sizing of these systems requires a forecast of both the development of offshore wind energy and of the evolution of load and generation in North Seas countries and their neighbours. Note that the determination of the needed transfer capacity could be performed in two steps. In a first step, the minimum transfer capacity needed to evacuate offshore wind energy can be computed based on the offshore wind energy forecast. In a second step, transfer capacity can be increased beyond that value if it is economically viable.

National distributed hubs concept

In the national distributed hubs concept, the planning process is complicated with numerous OWFs integrated into a unique meshed offshore grid. However, the process for evacuation is kept simple as the offshore grid is developed into zones that evacuate into one country's national onshore grid. National offshore grids can first be planned to evacuate the corresponding offshore wind energy and interconnectors can then be implemented when motivated by economic reasons. Nevertheless, DC/DC converters will be much more expensive than AC transformers; a unique standardized voltage level will be needed for such concept, in order to allow meshing on the DC side. A prerequisite will be the agreement among all North Seas countries about the voltage level to use, including the line configuration (i.e. monopolar, bipolar). If different voltage levels are used, two AC/DC converters might be used at an AC decoupling node (e.g. with an offshore wind farm) to connect portions of offshore grids from different countries. Note this could increase the cost and ensure that the offshore grid is not competitive compared to an independent interconnector with converters located onshore. Another possibility could be to connect offshore grids of different countries directly on the AC side. Note that the way to interconnect portions of offshore grids from different countries could influence the development of national offshore grids. Therefore, coordination between countries in the planning process is essential.

European distributed hubs concept

The European distributed hubs concept requires an integrated planning process for all the North Seas countries and cannot be organized on a national basis with a weak level of coordination. In particular, in this case, the definition of a unique standardized voltage level is of particular importance from the outset of the planning process, because the offshore grid will no longer exhibit natural decoupling points at national boundaries. Furthermore, because the evacuation of offshore wind energy and the transfer of electricity between countries are strongly intricate in that concept, the development of the offshore grid will be based in a coupled way on both the development of offshore wind energy and the evolution of load and generation in North Seas countries and their neighbours.

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks

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3.2.4. CONCLUSIONS

Although technical building blocks are mature for the business-as-usual concept, it is not yet fully the case for more advanced concepts. In particular, the control and the protection of advanced concepts appear challenging. The PROMOTioN project is thus addressing mainly the barriers linked to HVDC circuit breakers and the control of the MOG. These barriers are analysed in the next chapter.

3.3. REGULATORY/LEGAL BUILDING BLOCKS

Electricity transmission is a complicated and regulated business in Europe. The regulatory/legal framework, both on EU-level and on national level has a significant impact on the return of long-term investments in offshore transmission assets and thus on the attractiveness of these investments. Therefore, the regulatory framework plays an instrumental role in incentivising an investment and has an impact on the financeability of projects. Furthermore, the regulatory framework influences the market design of a MOG (the tasks and responsibilities related to dispatch, congestion and other revenue streams) and the standard technological specification for various technologies. The regulatory/legal building block may be conveniently divided amongst the life-stages of an offshore grid, from project planning through operation, market design and decommissioning. However, first, the jurisdiction regimes over the different components within an offshore grid are defined from international law.

3.3.1. JURISDICTION

The sea is divided into multiple zones which influence States' jurisdiction. The first zone seen from the coast, the territorial zone, extends to 12 nautical miles (22.2 kilometres) from the shore. This zone is seen as an extension of the land territory, thereby extending the full territorial sovereignty that States have on their land territory. The second zone, relevant to all North Seas states, is the EEZ. States' jurisdiction is limited to *functional jurisdiction*, allowing states to regulate only the activities related to the economic exploration and exploitation of the natural resources. Beyond the territorial zone all states enjoy the freedom to lay submarine cables. For all concepts, this means the following jurisdiction regimes can be identified:

- The jurisdiction regime over the OWFs is defined as:
  Under the UN Convention on the Law of the Sea (UNCLOS), the production of energy is explicitly mentioned as falling under economic exploration and exploitation, entailing coastal States to functional jurisdiction over OWFs in their EEZ. In the EEZ, states also have exclusive jurisdiction over artificial islands and over installations and structures constructed for the purpose of economic exploration and exploitation.
- The jurisdiction regime over the connecting cables of radial topologies is defined as:
  - If the OWFs are located in the EEZ of the state they are connected with, this coastal state has jurisdiction over the cable and can legislate over all aspects relating to the economic exploitation of the OWF, including the cables.

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- If the OWFs in the EEZ of one state are connected only to another state's shore, the cable will fall under the functional jurisdiction of the state in whose EEZ the OWF is in until it crosses the sea frontier to the continental shelf of the other state. There, it will fall under the freedom to lay cables, with very limited jurisdiction.

- The jurisdiction regime over an interconnector is defined as:

A state has full jurisdiction over its interconnector within its territorial zone. As the interconnector is not part of an activity that is associated with the economic exploration or exploitation of the natural resources in the EEZ, states do not have full jurisdiction outside its territorial zone. However, states may legislate over safety and environmental criteria and have to approve of the delineation of the cable within its EEZ.

In a MOG, the distinction in function of a cable is not as clear. It is then possible for cables to fulfil either the function of a cable that evacuates energy from an OWF to shore, or to transport energy from one shore to another. This means that these cables can be classified as 'hybrid assets', for which no regulatory framework is set yet.

Further, from antecedent cases, EU law appears as much applicable as national jurisdiction; it has full competence where states have sovereign rights and where national jurisdiction is limited by international law, so is EU jurisdiction. Therefore, EU law is considered also applicable to certain activities in the North Seas. As Norway is not part of the EU but only of the European Economic Area (EEA), the legal status is slightly different. The majority of EU law is also applicable in the EEA, under the condition that it is adopted in the Annex of the EEA Agreement. So far, most EU acts are also incorporated into the Annex. Whether or not the United Kingdom (UK) remains part of the EU or EEA creates legal uncertainty for a MOG.

3.3.2. PLANNING AND CONSTRUCTION

For MOG planning and construction, multiple EU directives apply for the planning procedure and several EU-wide regulations are in place for construction. Next to this, there are differences between North Seas countries in national policy regarding licensing and permitting and grid connection a MOG.
The EU Directives relevant for offshore electricity transmission infrastructure mainly focus on the environmental and spatial impact of the constructions. Both the Habitats Directive and Birds Directive may be of large influence of MOG planning, as they designate several areas specifically to the conservation of habitats and wild flora and fauna and wild birds. These may potentially overlap with OWF locations.
For construction, the designated MOG area is listed as a priority area on the list of Projects of Common Interest (PCIs) under the Regulation on guidelines for Trans-European energy infrastructure (TEN-E Regulation). Projects that are listed as PCIs have the benefit of accelerated planning and permitting granting processes. Also, the Inter-TSO Compensation (ITC) Mechanism is applicable to a MOG. The mechanism is mostly in place to compensate TSOs for the losses they have as a result of cross-border flows through their networks and the extra costs incurred by infrastructure reinforcement in order to accommodate these flows.
For licensing and permitting procedures, North Seas states have different procedures in place. Legal barriers for an offshore grid in the context of licensing and permitting procedures could start to exist when a cross-border

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project encounters a multitude of different permit requirements that are not streamlined in terms of time and procedure. For example, when there are long delays in the decisions to award licenses for an OWF that should form part of a hub-to-hub construction, the entire project including the cross-border grid connection may face delays. Further research by WP7.1 will answer how the process of planning and permitting can be streamlined to mitigate this regulatory risk, especially with regard to cross-border projects. From a developer's point of view, one practical method to decrease the risk is to decrease the time between the planning stage, the permit and license application and the financial close of the project. This decreases the risk that there are legislative changes in the meantime.

Further, the North Seas states have multiple options for grid connection. The three possibilities are either the developer connects to the onshore grid, and is responsible for the export cable, or there is a separate entity between the OWF and the onshore grid (OFTOs in the UK), or the TSO provides the connection until the converter station. The latter option is most favourable with regard to clustering of offshore windfarms. Other factors that significantly affect the possibility of clustering OWFs are the geographical location, and thus spatial planning, and the timing of delivery of the different OWFs to be connected.

3.3.3. OPERATION

The operation of a grid encompasses many different issues, such as grid safety, access rules, balancing responsibility, rules on dispatch and capacity allocation & congestion management. For the currently existing grids these issues are mostly regulated on a national level through national grid codes. Nevertheless, the main focus of this research project is an HVDC offshore electricity grid, whereas most national grid codes are designed specifically for the currently existing AC grid. There is an EU Network Code specifically for HVDC connections but changes may have to be made to the national network codes as well. Even though the European Network Codes have all been developed in recent years, several issues which are relevant for future developments are not yet addressed (e.g. there is a need to prevent disruption of the onshore grids and the "N-1" security standard. While regulation to maintain this level of security offshore may be excessive, it is important for TSOs that disruption of the onshore network is prevented. This is of increasing importance as offshore wind energy takes an increasing proportion of the total supply). This could form a legal barrier to developments towards an offshore grid.

According to the Renewable Energy Directive, electricity from renewable sources should either get priority access or guaranteed access. Whether it is possible to reconcile priority access, causing a variable remaining capacity for interconnection, with the rules on cross-border capacity allocation and congestion management is expected to be clarified shortly. There is a chance that Priority access and Priority in dispatch will be removed.

In a MOG, where connection of OWFs is mixed with interconnection between countries, clear agreements have to be made. For example, it should be decided whether the full capacity of the cable is available for transportation of the offshore generated electricity (which means that this electricity always has priority access), or whether part of the cable is separated in some way and reserved for interconnection, as is suggested in some studies.

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3.3.4. MARKET DESIGN

The regulatory/legal framework concerning market design consists of (1) support schemes, (2) transmission and connection tariffs, (3) congestion revenues, (4) bidding zones, (5) balance responsibility, (6) priority of dispatch (potentially this will end), (7) priority of access (potentially this will end), (8) capacity allocation and (9) gate closure time and imbalance settlement period.

North Seas countries differ significantly in market design components 1 through 5 and 9, which has its implications on a MOG. As these components differ between states, OWFs that are connected to different states have different rules to deal with. Therefore, these differences hamper the development of a MOG. Elements 6 and 7 are different between states, but this is easily harmonised and as there are few non-renewable grid connections. A regulatory framework is in place for capacity allocation (element 8), but a common methodology has yet to be defined.

3.3.5. DECOMMISSIONING

Installations, such as wind turbines and converter stations, need to be removed when they are not in use anymore. It can be discussed whether electricity cables would also need to be removed after use. The purpose of the removal obligation is the safety of navigation, according to UNCLOS. As cables lie in the sea bottom, there is much less danger compared to installations that reach to or above the water level and that form a collision danger. Nevertheless, the removal should also take into account the duties under environmental law and the rights of other states: if there are too many cables in a certain area, the right of other states to lay cables might be limited.

It has to be noticed that there are differences between decommissioning of OWFs and decommissioning of cables in the seabed. First of all, they may have a different lifetime: whereas OWFs normally have an economic life of between 20 and 30 years, modern subsea electricity cables can have a much longer lifetime. In the context of the development of an offshore HVDC grid, this is an important difference: what will happen when an OWF is decommissioned halfway through the lifetime of the connecting cable? Will a new OWF be constructed at the same place or will the cable also have to be removed even though it is still economically and technically sound?

Secondly, they have a different impact on the space use, and thus the reasons for decommissioning or not are different. OWFs and grid equipment such as converter stations are decommissioned because they can form a hazard for other users of the sea, such as navigation or tourism, and because they take up space that could perhaps be used otherwise. At the same time, cables that are buried are much less of a disturbance to other sea users. However, leaving cables in the seabed after the end of their economic life could lead to a ‘spaghetti scenario’ in which it is difficult to lay new cables due to the existing abandoned cables. However, from an environmental impact perspective, it could also be the case that leaving the cable buried in the seabed causes less negative environmental impact than digging up the cable and disturbing the seabed.

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3.3.6. CONCLUSIONS

The regulatory/legal framework has shown that some issues are first to be resolved on an international level, especially concerning the jurisdiction over hybrid assets. Further, there are large discrepancies in the regulatory/legal framework of the North Seas states. Although these can be found already in the planning and construction of OWFs and a grid, this mostly has its implications in the operation and market design of the grid. Therefore, the largest focus is on harmonising this framework throughout North Seas states.

3.4. FINANCIAL & ECONOMIC BUILDING BLOCKS

The financial and economic requirements focus on the uncertainties with regard to the bankability of investments and the applicable rules for grid operations. An analysis will be provided in order to understand what aspects might constitute bottlenecks for financing a deployment plan.

For this deliverable financeability is defined as: the ability of transmission operators and/or other potential investors to attract capital at a 'reasonable' cost. To date there have been no major financing challenges. The market has shown great interest in investing in grid infrastructure. PROMOTioN research indicates that it is viewed by investors as a low risk investment with an acceptable return. The major risk offshore in the development of a grid is the lack of a (consistent) regulatory/legal framework supporting investments in a MOG. Regulatory risks, related to the cost recovery and the remuneration of the investors, have a significant impact on their ability to finance a MOG. The regulatory framework defines the remuneration terms to support predictable and timely cost recovery and helps to mitigate financial risks around volatility of generation and transport. The regulatory framework aims to allocate the various risks among the actors involved and therefore, to determine the level of remuneration/rate of return for the investors. Cross border offshore grid and MOG investments involve high costs and risks. This is mainly attributed to the technological challenges and risks which are related to the failure or damage of the equipment due to internal or external reasons as well as the uncertainties regarding the estimation of infrastructure costs and maintenance requirement for innovative technology (e.g. DC circuit breakers, etc.). Here the EU has facilitated financial support instruments to promote investment.

Large volumes of debt and equity have to be raised in order to finance a MOG in the North Sea. Attracting debt is in the foreseeable future not likely to impose a significant financial barrier (given the current liquidity of funds on the international capital markets). However, increasing debt financing could lead to higher gearing ratios of the TSOs, resulting in a lower credit rating and thus, higher financing costs. Internal and/or external equity injection is also needed. However, equity financing may be subject to constraints, especially in the case of state owned TSOs (as it is related to state ownership of TSOs (in most of the cases), and as the anticipated investments needed will be substantial). This could be due to government's budget constraints and legal restrictions on access to private equity, when the government is not willing to dilute their rights. Also, the political will of governments to finance what may be cross-border assets or support multinational ownership may be limited. Therefore, next to improving the attractiveness of debt financing, equity enhancing solutions also need to be considered and developed.

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Currently, there are different governance models for the ownership and operation of the offshore electricity transmission assets (OWF connections and interconnectors) among the countries surrounding the North Seas. The prevailing approach is that the national TSOs are the owners and also responsible for the operation of the offshore grid (OWF grid connections and interconnectors) within their EEZ. In the UK, the generator builds the connection to the onshore grid and then transfers it to the Offshore Transmission Owner (OFTO) who is the owner of the asset. The operation of the whole offshore grid in the UK is the responsibility of the System Operator: National Grid. In the case of the interconnectors, the owner could be a TSO (regulated approach) or a third party (merchant or cap & floor approach).

The various governance models indicate different allocation of grid responsibilities among the actors involved. Therefore, the governance models have an impact on the liabilities of the investors (TSOs, private investors, etc.) as well as the level of risk they will have to bare.

Unlike the European onshore electricity transmission grid which is a mature and established network, a MOG in the North Sea, which is expected to combine the evacuation of offshore wind energy with energy trading among several countries, is a new concept which is not yet developed. Therefore, in order to ensure the development of a reliable, economic efficient and financially viable MOG the various options for governance models need to be explored and evaluated.

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4. ANALYSIS OF BARRIERS AND POTENTIAL SOLUTIONS

This chapter reviews the main barriers hampering the development of offshore grid in the North Seas. The different barriers are combined in the following categories:

Technical	Legal/Regulatory	Economic/Financial
• Barriers impacting the long-term planning of offshore grids (section 4.1) • Barriers related to the operation and control of offshore grids (section 4.2) • Barriers hampering the integration of DRU technology in offshore grids (section 4.3), • Barriers related to the protection of offshore grids (section 4.4), • Barriers related to the test environment for HVDC circuit breakers (section 4.5), • Barriers hampering the use of DCCBs in offshore grids (section 4.6).	• Barriers related to the regulation of offshore grids (section 4.7). o Long-term planning of offshore grids (4.7 – 1) o Regulation of grid development & build, operations, and decommission (4.7 – 2) o Coordination and control of standards (WP11)	• Barriers related to the financing of offshore grids (section 4.7). o Market interaction between the North Sea and European onshore bidding zones (4.7 – 3, 4) o Design and development of market infrastructure, business models for the transmission and management of power flows. (4.7 – 5, 6, 7) o Financing of offshore grids and the expectations of investor stakeholders.(4.7 – 8, 9)

These barriers are addressed by the PROMOTioN project and the categorisation is in line with the Work Package structure of the project. For some barriers, potential solutions and recommendations have already been developed from the PROMOTioN project, while for others further analysis is required. Where relevant, the obtained solutions and recommendations are presented. In addition, the interdependencies between the various categories of barriers are briefly analysed. Each section is organised as follows. First, a description of the relevant barriers and the manner of addressing them by the corresponding WP(s) is provided. Second, specific barriers and related solutions are analysed. Finally, the links with other categories of barriers are discussed where perceived relevant.

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4.1. BARRIERS IMPACTING THE LONG-TERM PLANNING OF OFFSHORE GRIDS

4.1.1. GENERAL ANALYSIS

The long-term planning of a MOG requires several factors. The first factor is the definition of the missions that should be performed by the overall offshore grid and the requirement on the quality of service, i.e. the definition of functional system requirements. The second factor is the definition of working conditions for the different components of the system, i.e. the requirements that should be met by the components. The third factor is the knowledge of the technical capabilities (current ones and expected in the future) of the components that could be used in an offshore grid.

A key objective of PROMOTioN WP1 is to define the requirements that need to be met by an offshore grid and the OWFs connected to it at the system level and component level. This resulted in three successive deliverables (D1.1, D1.5 and D1.7). D1.7 consists of a revision and evolution of D1.1 and D1.5. Work Package 1 included in three further deliverables: D1.2 was a collation of lessons learned from existing offshore connections and grids, D1.3 compiled and analysed past and ongoing studies about offshore grids, and D1.6 derived a draft roadmap for the evacuation of offshore renewable generation.

Since completion of WP1 several of the key barriers impacting the long-term planning of offshore grids have been resolved. The system requirements have been largely defined. However, the definition of required behaviour of components on the DC side of a MOG is challenging. No standards for a meshed grid exist and the choice of specific detailed requirements can impact the business case for an offshore grid. For these reasons, requirements are not fully defined, but the simulation work performed by other WPs of the PROMOTioN project should lead to a more complete set of requirements. Furthermore, the functional system requirements (e.g. in terms of transfer capacity or reliability) can also impact the costs and the benefits of a MOG. A first proposition has been formulated in WP1 for the purpose of the PROMOTioN project, but the definition of functional requirements for an actual offshore grid is a political decision. Without such a decision, it will be difficult to plan a MOG. Finally, the technical capabilities of converters (in particular DRUs) and HVDC circuit breakers are not yet fully known, but several WPs of the PROMOTioN project will provide a better characterization of these elements.

4.1.2. FOCUS ON SPECIFIC BARRIERS AND RELATED SOLUTIONS/RECOMMENDATIONS

This section has a specific focus on issues from a technical and regulatory perspective.

Technical

1. Need for innovative planning criteria

The planning of onshore grids is currently based on deterministic criteria (e.g. N-1 security rule). These deterministic planning criteria can be transposed to offshore grids, but the relevance of such criteria might be limited. Offshore grids will be very different from onshore grids (e.g. no significant load) and the direct transposition of deterministic criteria for planning could lead to over-costly solutions and may not always be

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relevant. Cost-effective offshore grids might require innovative planning criteria, e.g. probabilistic planning criteria.

2. **Need for a coordinated planning between onshore and offshore grids**

The limited capabilities of onshore grids to transfer power from the shore to the load centres in the mainland could strongly impact the grid topology: it might be cost-effective to extend the HVDC grid up to onshore consumption centres, rather than connecting OWFs to the closest onshore connection point. In the planning stage, it could be of importance to consider both the onshore grid and the offshore grid in a more coordinated planning approach.

3. **Need for a clear understanding of DRU capabilities**

Currently it is unclear for which grid topologies a DRU could be used. The technical capabilities and the cost of DRUs could also significantly impact the potential development of offshore grids. According to the supplier, DRUs might lead to cost reductions compared to equivalent VSCs. However, technical capabilities and costs are still unclear. Currently, WP2 and WP3 are analysing potential options to integrate DRU in radial multi-terminal and meshed topologies (see in particular section 4.3).

4. **Need to establish a set of standard models and values that could be used in the long-term planning phase**

Long-term planning for some scenarios requires assumptions about power system elements that do not currently exist and are not even in the development phase. For traditional onshore grids, this is in particular the case with future power plants.

Assumptions on the electric machines, on the frequency control and on the voltage control are needed to verify that the planned power system complies with the planning criteria, in particular the stability criteria and the constraints on the short-circuit levels. Usually, generic models and typical values of parameters are used in the simulations, which is justified as the actual values are close to typical values. For example, the frequency droop parameter of a (conventional) power plant is typically between 4% and 6%, which means that the frequency stability of a power system can be studied in long-term planning by using values in that range.

For offshore HVDC grids, there are no “standard values” for the different parameters that can be used in control loops. For example, there is no indication of what a realistic range for the voltage droop parameter of HVDC converters could be. The lack of typical values could hamper the planning of offshore HVDC grids. It is of importance to establish a set of standard models and values that could be used in the long-term planning phase.

The ongoing work in the various WPs of PROMOTioN should lead to a more informed understanding about the assumptions that could be made during the long-term planning phase.

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5. **Need for a clear understanding of the DC circuit breaker capabilities**

In AC grids, the requirement of having a maximum short-circuit current lower than the circuit breaker interruption capacity can significantly impact system topologies. It is expected that the same phenomenon will apply to offshore HVDC grids. The DC circuit breaker's capabilities and costs will drastically impact the business case of coordinated solutions such as meshed grids.

If only hybrid DC circuit breakers are technically viable for the voltage and power levels present in the offshore grid, only offshore windfarms far from the shore (i.e. significantly more than 100 km) will be part of the offshore grid. On the contrary, if mechanical DC circuit breakers can also be used (much cheaper than hybrid circuit breakers), OWFs closer to the shore could be integrated as well. The ongoing work in WPs 5, 6 and 10 should lead to a better understanding of DC circuit breakers capabilities (see sections 4.5 and 4.6).

Regulatory

6. **Need for more understanding on the level of appropriate legislation and regulation for the installation and management of assets**

The procedures and legislation around hybrid assets, DC infrastructure, etc. in cross border situations requires clarification and harmonisation, especially on Network Code level. The mixed jurisdiction nature of European infrastructure projects may benefit from alignment of legislation and mechanisms that support solution of conflicts. Recommendations for the regulatory/legal framework will be made in WP7.

7. **Need for more insight on how markets will be organized**

With the current regulatory systems, the costs and the calculation (method) of the regulated return on offshore grid assets impact the benefits of a MOG. Equally important is compatibility of national support schemes for offshore windfarms and national grid connection requirements. Different schemes might be implemented to define the bidding areas (e.g. national bidding areas, offshore bidding areas) and different market models might be used (ATC-based, flow-based). Long-term planning relies on cost-benefit analyses and thus needs assumptions on the market organization. Uncertainty on the market organization is a barrier impacting the long-term planning of offshore grids.

4.1.3. MAIN IMPLICATION FOR INTERACTION WITH OTHER WPS

WP1 forms the starting point for the work performed in WP2 - WP12. So each barrier is expected to be looked at in those WPs.

4.2. BARRIERS RELATED TO THE OPERATION AND CONTROL OF OFFSHORE GRIDS

4.2.1. MAIN OBJECTIVE

This section is based on the work performed in WP. The main objectives of the WP are:

- To compare and perform a trade-off analysis of different topologies of the MOG;
- To develop control and operational concepts for different configurations of the MOG to ensure interoperability;
- To define recommendations on onshore and offshore power systems for existing grid codes; and
- To study and demonstrate the interconnection of VSC and DRU HVDC system in realistic scenarios.

The two deliverables completed by WP2 so far include a list of grid topologies to be used e.g. for DRU and VSC studies and component model specifications as well as a detailed specification list for models in each simulation tool relevant for the work to be carried out in WP2 (see Deliverable D2.1). Moreover, the relevant operation and control objectives are addressed in deliverable D2.1. Deliverable D2.2 deals with the specifications of scenarios and test cases, which are also of interest for WP3. The main part of the deliverable consists of a PSCAD model and library for electromagnetic transient (EMT) simulations and the defined specification list of investigated scenarios. A validation of EMT and average value (RMS) models has been carried out. Furthermore, open research questions have been identified and coordinated with WP1. An overview of the framework of the investigations is presented in Figure 4-1.

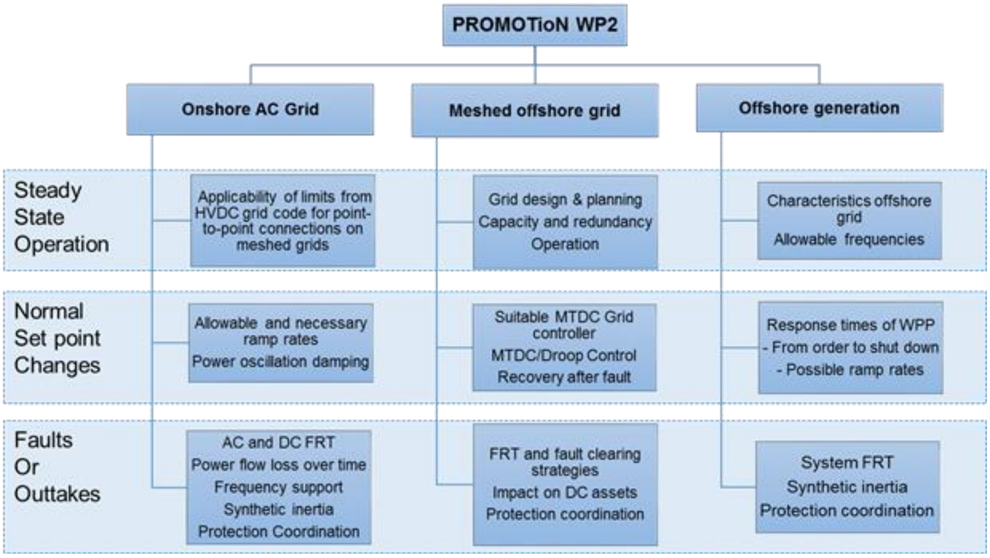

Figure 4-1. Clustering of research aims.

4.2.2. MAIN BARRIERS AND PROVIDED SOLUTIONS/RECOMMENDATIONS

The main objectives mentioned in the previous section are associated with (potential) barriers for the establishment of a MOG. Given the fact that today's HVDC systems are point-to-point connections in Europe, the control and operation of a meshed structure includes a number of challenges, if not barriers.

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- First of all, the point-to-point connections usually consist of plants and equipment assembled by one company. Therefore, the interaction of the different types of equipment has been tested in advance and is not expected to cause any problems in terms of interoperability. However, a widespread MOG will more than likely feature equipment from a number of different manufacturers. In addition, the interaction and dependencies have not been tested as yet – especially when it comes to the interoperation with new technologies. Hence, the resulting interoperability will not be guaranteed. Even if it is analysed and simulated in the framework of WP2, there is no guarantee that the models used or to be used will cover all relevant phenomena. A comparison or benchmark of the models and simulations with a "real" system is not possible since such a system does not exist (at this time).
- The second potential barrier arising from the objectives of WP2 is the selection of parameters for the models. Due to the absence of operational experience, the tuning of the parameters is a challenge and assumptions are essential for the simulations to be carried out. Consequently, the provision of operational strategies is more of a best guess based on reasonable assumptions rather than a ready-to-use proposal.

These assumptions will be discussed to the best of existing knowledge between research institutes and vendors.

The definition of recommendations for onshore and offshore power systems on existing grid codes suffers from the gaps identified in WP1. Due to the inability to quantify all relevant requirements for a MOG, a "definition" of recommendations is a major challenge and could become a barrier for WP2 and the eventual development of a deployment plan for MOG. Furthermore, one of the results from the analysis conducted by WP1 is that existing technical codes cannot be simply used for (meshed) DC topologies. The adjustments and modifications required are addressed by several other institutions and initiatives, but progress made in recent years is limited amongst others due to the complexity of the task.

Finally, the integration of innovative technologies such as DRUs in a MOG is not only a challenge from an operational point of view. It is reasonable to expect DRUs, once this technology is available on the market, to reduce the costs of connections of OWFs significantly. However, the operation of a system including VSC and DRU technologies, which will be investigated in WP2, represents a challenge or barrier. Considering the identification of reasonable parameters mentioned above, the identification and definition of "realistic" scenarios, which are inevitable for the study and demonstration of systems including both technologies, could become a barrier as well. Furthermore, the significant number of factors influencing the scenarios and the uncertainty related to these factors, is increasing the complexity of the task.

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4.3. BARRIERS HAMPERING THE INTEGRATION OF DRU TECHNOLOGY IN OFFSHORE GRIDS

4.3.1. GENERAL ANALYSIS

WP3 analyses barriers to identify and specify appropriate analyses and tests to demonstrate the interoperability of the wind turbine and wind farm controls with two different types of HVDC systems: DRUs and VSC converters. The main goals are:

- To analyse the functional requirements for WPPs connected to DR and VSC HVDC connections;
- To identify and specify general control algorithms;
- To define and demonstrate compliance evaluation procedures by simulations and tests.

Identified barriers related to integration of DRUs are presented below.

4.3.2. MAIN BARRIERS AND PROVIDED SOLUTIONS/RECOMMENDATIONS

This section separately focusses on issues from a technical and legal/regulatory perspective.

Technical

1. Need to define offshore system topologies that allow the integration of DRUs

In WP3, a comparison is made between the well-known VSC-VSC point-to-point connection and the DRU-VSC point-to-point HVDC connection for the connection of OWFs. A set of minimum requirements for the windfarms and HVDC connections are proposed. Several test cases are described to analyse the operational states of the connection and windfarm (e.g. the start-up procedure, normal operation, AC system support, shutdown, etc.). However, an extensive analysis of the impact of the DC system topology on the different controls has not yet been performed. Several options for the DC system topology are possible, varying from several parallel DRU-VSC and VSC-VSC point-to-point connections between an AC offshore island and the onshore grid, to a fully meshed DC offshore grid. It is crucial to identify which parts of the controls are topology independent and which are not, to avoid that the OWFs connected with the DRU technology form a limitation for the future DC system development.

2. Need to provide offshore AC voltage during start-up

The offshore AC voltage cannot be formed with the DRU, as it is a passive element. Therefore, an additional auxiliary AC voltage source is required during the start-up of the OWFs and DC connection. Several options are possible to deliver this AC voltage, e.g. an umbilical AC cable from onshore, offshore diesel generator, a battery system, etc. However, each technology has advantages and disadvantages. As the focus is currently on the umbilical AC cable, one limit could be the maximum length and capacity of this AC cable.

3. Need to clearly distinguish the functions of the new controllers and coordinators

In WP3, a control hierarchy is designed to operate the windfarm and its DRU-VSC DC connection. The control hierarchy contains wind turbine controllers, wind farm controllers, a wind farm group controller and a wind farm – offshore grid controller/coordinator. As such, it is required to identify the functional requirements of each controller block, inputs and outputs, their dependency on the DC grid topology and its owner. Especially the functionalities and ownership of the wind farm – offshore grid controller/coordinator need to be clearly defined.

4. Need to compare different communication procedures

To be able to provide ancillary services to the onshore grid (e.g. frequency support and power oscillation damping control) with the DRU interconnected OWFs, it is required to obtain accurate measurements from the onshore AC power system that needs support. In the currently considered DRU-VSC point-to-point DC connection, the wind farm receives the status of the onshore system after communicating the onshore measurements via dedicated on-to-offshore communication channels. It is advised to analyse the impact of different DC grid topologies on the current proposed communication methodology and the possibility to make use of a more decentralised communication strategy.

5. Need to define additional requirements for the offshore wind farms

The OWFs need to be equipped with additional control loops, to be able to form and control the AC offshore voltage. Therefore, new requirements as grid code recommendations for such a new approach of operation need to be defined. Based on the technical requirements proposed and the simulations performed in WP3, and analysing the existing standards, development of procedures for compliance evaluation is one of the main tasks in WP3.

Legal/regulatory

6. Need to define the ownership of the different control structures

The role and ownership of the wind farm – offshore grid controller/coordinator in more complex topologies, needs to be clarified. Additionally, responsibility and ownership of the auxiliary AC voltage source (e.g. umbilical line) needs to be clarified as well.

4.3.3. INTERACTION WITH OTHER TYPES OF BARRIERS

The barriers related to the DRU connection of OWFs and their integration in the offshore grid, have a direct impact on the barriers related to the long-term planning of the grid (WP1) and the operation and control of the offshore grid (WP2).

4.4. BARRIERS RELATED TO THE PROTECTION OF OFFSHORE GRIDS

4.4.1. GENERAL ANALYSIS

The work performed in WP4 aims to develop multivendor DC grid protection system. The goals are:

- To develop a set of functional requirements for various DC grids: from small scale to large overlay grids and for a variety of system configurations and converter topologies;
- To analyse a wide range of DC grid protection philosophies on a common set of metrics;
- To identify the best performing methods for the systems under study;

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- To develop detailed protection methodologies for the selected methods;
- To develop configurable multi-purpose HVDC protection intelligent electrical devices (IEDs) to enable testing of the methodologies to investigate the key influencing parameters of protection systems on the cost-benefit evaluation.

Developing and designing a proper protection system for meshed HVDC offshore grid is challenged by more important topics such as need of interoperability, need of proper models, need of proper design criteria, need of considering future extension possibilities, need of considering the right choice of converter configuration, lack of sufficient standardisation and grid codes and, finally, a lack of mature components for some important parts of the protection system.

4.4.2. MAIN CHALLENGES AND POSSIBLE SOLUTIONS

This section separately focusses on issues from a technical and economical perspective.

Technical

1. **Need to ensure interoperability of protection methods**

Conventional AC protection systems are designed based on a fully selective philosophy, which means only those protective devices closest to a fault will operate to remove the faulted component and power flow in the rest of the grid remains uninterrupted. However, various DC grid protection philosophies exist and the applicable protection philosophies to a certain DC grid depend on the impact of the DC grid to the connected AC systems. In D4.1 and D4.2, the DC grids are classified as “low, medium and high impact”.

The higher the impact of the DC grid, the higher the requirements are of the DC grid protection system. Multivendor interoperability in the context of DC grid protection is defined as the characteristics of the DC grid protection system that allow protection equipment (such as relay, DC circuit breaker and converter) from any vendor to be able to “plug-and-play” within *multiple protection philosophies.* In order to achieve multivendor interoperability, a common set of requirements/specifications on the DC grid protection systems/components should be defined. DC grid protection systems/components fulfilling these requirements should be interchangeable/interoperable in a multivendor and multi-strategy DC grid. Therefore, it is important to define the functionalities and requirements of the DC grid protection systems/components, including their operating ranges. Multivendor interoperability at the system level defines the functionalities and requirements of the interfacing device connecting two sub-grids and the behaviour of the sub-grids in the event of a DC fault.

Within the sub-grids, different protection philosophies can be implemented. Multivendor interoperability within one protection philosophy includes the following aspects:

- Requirements on the measurement device, relay, DC circuit breaker and converter;
- Requirements on the communication system for protection and restoration control.

Solutions/recommendations

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A subtask is dedicated to the investigation of the interoperability of protection systems within WP4, task 4.3. It is expected that a significant part of the issue can be addressed by either developing (pre)-standards and grid codes (see barrier 6) or 'smart' design options of the grid.
However, a balance needs to be analysed between standardisation and overrating of converters to serve a greater volume, as both will influence costs.

2. Need to understand models and controls needed for studies

Stability in the context of power systems is defined as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with the system variables bounded so that practically the entire system remains intact. However, in multivendor and multi-terminal HVDC schemes, research on stability issues include studies to de-risk the interconnected DC system from the point of view of resonances, power flow and possibility of control interactions and interoperability under steady state and dynamic operation conditions. De-risking the interoperability of the multivendor DC grids is performed by offline EMT simulations with the converter and cable models from the manufactures, and if required in later stages of the projects with real time simulation with hardware in loop.

Availability of validated open models will greatly simplify the solution of any potential issue detected during the simulation analysis and can simplify the design process. However, at the current stage none of the HVDC manufactures provides their open models to the outside or third parties. It is however also considered a reasonable scenario where only black box models are provided with the possibility of tuning most relevant system parameters. This could offer an additional layer of non-disclosure guarantee to the manufacturers but it then becomes more critical to discuss in advance their degree of support in assisting in the solution of the issues that are detected and in providing updated models. To perform the simulations with reasonable accuracy, it is expected that models provide access to most relevant input and output parameters of the converter. As none of the HVDC converter and cable manufacturers provides their reasonably open models for their customers or third parties, it is impossible to perform the necessary analysis and de-risk the interoperability of multivendor DC grids.

Solution/recommendation

An initial list of inputs and outputs for the converter model should be accessible. In addition, the model should include the details of the electrical components, converter capacitors, reactors, transformers, filters and converter protection equipment's and settings. In case such details are not available, generic values shall be adapted from literature or manufacturer recommendations.
In case only a black-box model is available, the tuning of most relevant system parameters shall be made available.
In order to ensure trustworthy black-boxed and open models, there is a need to define the needed level of accuracy of the models. Methodology to evaluate the accuracy needs to be defined or adapted from standards.

3. Need for reliability expectation of a MOG, its extensibility and planning

When developing a DC grid, design choices are made with respect to expected functionality of the grid. Within those choices, there are a number of related DC grid protection systems, such as: relative size compared to the

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size of the connecting grid(s), grounding (see separate barrier), busbar configuration, reliability expectations, insulation coordination and cable/overhead lines. This could amongst others lead to different choices of protection philosophy, the expected time delays associated with protection devices and measurement requirements. Once the choice is made, it might no longer be possible to simply alter these decisions without a fundamental overhaul. For instance, if the system is not developed with extensibility in mind, offshore substations might not have sufficient space available to accommodate the expansion.

An example is the transition of a (small) offshore grid (no need for breakers or full bridge converters) to a large impact offshore which requires breakers or fault blocking converters. Pre-emptive investments might be needed to accommodate such changes. On the other hand, these additional investments might become sunk investments if they do not materialize. For this, it is important that a reliability expectation for offshore grids be established. Questions raised include for example: What is the expected service provided at a given node? Will the system be operated according to N-1 operating principles (or others)?

Solution/recommendation:
During the planning phase, it needs to be clear which potential barriers are linked to given network design options and choices. These are linked to the actual grid situation, and not all barriers are relevant in all situations. As such, WP4 has the ambition to clearly stipulate these potential grid extensibility concerns.

4. Need for decision to go for a bipolar/monopolar configuration

This barrier is related to choice of configuration will be MOG. Future HVDC grids could be based on either monopolar or bipolar configuration. The majority of the existing VSC HVDC point-to-point links (interconnectors) are nowadays based on the monopolar configuration, while bipolar configuration is mainly used in large existing LCC links. Regarding future Multi Terminal Direct Current (MTDC) grids, the choice of the configuration depends on techno-economical aspects such as availability of needed technologies, ambition to combine OWFs and AC interconnectors, opportunity to trade energy into several countries etc. In Appendix A, an overview is provided of the technical and economic barriers of a monopolar/bipolar configuration.

Solution/Recommendation:
This barrier is strongly related to the other barriers and depends on requirements coming from the DC grid operator. The choice of the optimized configuration requires an in-depth analysis taking into account technical constraints, cost and reliability. As support, cost-benefit analysis tools and EMT studies can be performed. In part, this will be addressed in WP4 (task 4.5).

5. Need for a standardisation of the grid codes

In order to pave the road for future multivendor DC grids, a certain degree of standardisation should be expected at the initial design stage. The DC grid is likely to be developed with different components coming from different manufacturers, using different technologies, implementations and control schemes. Ultimately, all of them should be able to interoperate with each other, given that they remain within predefined operating margins.

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In a DC grid, it should be possible to add new lines and converter stations without fundamentally influencing the existing grid, its controls and protection. Moreover, adding a new circuit that changes the topology of the network should not lead to changes in the overall protection philosophy, even if some AC or DC protection retuning would be required.
Alternatively, such transitions should be clearly known and understood from the conception of the project (start small, but understand that if we pass certain boundaries, fundamental changes are required).

Solution/Recommendation:
The DC grid projects should establish minimum and maximum values for the power exchange in a DC node based on the security of the network. These values have to be observed especially by new users connecting to the DC grid.

The topology of the DC grid should be defined in advance, as introducing an asymmetric solution to an existing DC grid with symmetric design will have serious consequences for the fault detection and protection of the grid. Pre-definition of DC grid insulation levels for the components should be defined in advance. It is expected that the DC voltage (nominal, steady-state and transient range), Fault Current Contribution, Multi-terminal DC Protection strategy and the Multi-terminal DC control strategy needs to be predefined. Additionally, the minimum and maximum DC fault current breaking time should be defined for each project in advance. Standardisation and grid codes will take time and so will an open discussion with all involved stakeholders.

Economical

1. **Need to gain clarity on cost for protection devices/immaturity of technology**

HVDC grid protection components have to deal with constraints in the physical behaviour of DC grids (i.e. no zero crossing currents, propagation of very high speed for both current and voltage waves). In addition, specialised power components will be required. More particularly, current suppression devices, such as DCCBs, would rely on the association of high-speed mechanical switches and power electronics components, within a quite complex structure. It could then be expected that the costs of these components are higher than those of classical AC protection components. Furthermore, some of these protection components are new components. Then, the pending question of the level of maturity of these new components (reliability) is clearly raised and should be characterized.

The overall cost of the HVDC grid protection system will depend on the costs of individual protection components, but also on the selected protection strategy architecture, depending on the acceptable level of performances for the protection system.

Solution/recommendation
Currently a cost-modelling subtask has been set up within task 4.5 to develop better understanding of component costs. Currently a cost data task (under the lead of DNVGL, within WP12) has been set-up, in which WP4 (and in particular T4.5) participates to develop a database for cost data.

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4.5. BARRIERS RELATED TO THE TEST ENVIRONMENT FOR HVDC CIRCUIT BREAKERS

4.5.1. GENERAL ANALYSIS

Several manufacturers have proposed and developed HVDC circuit breaker technologies and built prototypes. The behaviour of these prototypes has been verified internally through a range of development tests in the manufacturer's own labs.

Testing of HVDC circuit breakers is fundamentally different from that of AC circuit breakers, as both voltage across and current through the circuit breaker exist at the same time, leading to an energy absorption requirement. Therefore, the next step is to demonstrate the performance of the HVDC technologies proposed by the different manufacturers at an independent short-circuit laboratory.

A meaningful demonstration of the HVDC circuit breaker technology can only be achieved when the applied tests accurately reflect realistic fault conditions in multi-terminal HVDC networks. The goal of WP5 is to, based on fault analysis of multi-terminal HVDC networks, develop suitable test requirements and a test programme, as well as realising a test circuit based on AC short-circuit generators.

The initial objectives identified are:

- To identify worst case situations of faults from grid simulations in an internationally recognised benchmark meshed DC grid;
- To produce dynamic, black-box models of DC circuit breakers of technologies as applied by the partners, including their relevant function;
- To embed these models in the benchmark system to quantify the electrical stresses (current, voltage, energy) to which high-voltage DC circuit breakers are subjected in case of a fault;
- To design, by simulation, test circuits that produce the stresses equivalent to those in service, based on existing high-power generator source, e.g. as present at DNVGL;
- To realise real high-power test-circuits including the necessary equipment specifically needed for DC testing.

4.5.2. MAIN BARRIERS & PROVIDED SOLUTIONS/RECOMMENDATIONS

This section separately focusses on issues from a technical and economical perspective.

Technical

1. **Need to identify the fault behaviour**

In D5.1, existing technical literature on HVDC network fault behaviour and analytical fault analysis techniques were reviewed and simulation studies on a benchmark study network were carried out to identify the factors determining the fault currents in meshed multi-terminal HVDC networks. The main factors are:

- Before the blocking of the converter, the submodule capacitors discharge and have a significant impact on the fault current behaviour.

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- After blocking, the DC output current of the converter is determined by the DC resistance between the fault, the converter impedance, the converter transformer impedance and the AC network strength.
- The insertion of series reactors at the ends of cables reduces/limits the rate of rise of fault currents. The higher the inductance of the reactor, the slower the rate of rise of current. Consequently, the voltage drop at the converter before blocking will be smaller. Inserting series reactors also increases the time it takes for converters to block, with remote converters blocking later than the ones located close to a fault.

Fault behaviour can be characterised well by means of EMTP simulation using software such as PSCAD. However, as no common approach on the design of HVDC grids exists to date, there are still many unknown design variables such as the choice of transient interruption voltage, or the blocking characteristics of converters in an HVDC grid. These parameters can greatly affect the stresses experienced by an HVDC circuit breaker. In this work package some suitable assumptions have been made to arrive at somewhat realistic stresses.

2. Need to develop PSCAD models of the circuit breakers

Deliverable 5.2 describes the PSCAD models of three different concepts (mechanical circuit breaker with active current injection, IGBT based hybrid circuit breaker and thyristor based hybrid circuit breaker), that are used in deliverable 5.3 to determine the electrical stresses on the circuit breaker.

It is important to note that HVDC circuit breakers typically have a modular construction, in which the full line voltage (referred to as full pole) rating is achieved by series connecting several identical modules which individually have a voltage rating between 40 – 80 kV depending on the technology used. The modules consist of several parallel paths that each has a different function but that can be broadly divided into:

- Normal current path;
- Auxiliary/commutation path;
- Energy absorption path.

The components in the modules may be interconnected at each module terminal or may be arranged in such a way that they are interconnected at the full pole circuit breaker terminals.

The components and modules may be placed on one or more support structures. The support structures may be in the form of a ‘dead’ tank i.e. earthed enclosure; ‘live’ tank i.e. enclosure at potential of prorated line voltage, or air insulated. The support may be realised by suspending the components from the ceiling or on insulating supports.

HVDC circuit breaker ratings are determined based on their specific application in a grid. No standardised current, voltage, breaker operation time and energy ratings have been formalised. As such, an HVDC circuit breaker should be seen as a tailor-made system, rather than as a standardised component, as compared to AC circuit breakers.

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3. Need to identify the stresses on the circuit breaker

In D5.3, the circuit breaker simulation models have been embedded in a multi-terminal HVDC study grid model, to identify the stresses on the models of the circuit breakers during interruption under varying conditions. This allows identifying requirements that can be used as a guideline to design proper test circuits for practical HVDC circuit breakers in a high-power laboratory.

For each of the HVDC circuit breakers considered, it is necessary to have a series DC current limiting reactor. However, assuming the presence of a fast enough protection system, the size of the reactor used along with each circuit breaker technology depends mainly on the breaker operation time (the time from trip order until the circuit breaker can withstand a transient interruption voltage (TIV)) of the circuit breaker. In general, the DC current limiting reactor is chosen to:

- Limit the magnitude of the fault current occurring in the protection zone of the circuit breaker to within the interruption capability of the circuit breaker during fault current neutralisation time.
- Ensure continued controlled operation of the healthy part of the system by avoiding the voltage collapse of the entire DC grid during the fault neutralization time. In doing so, the series DC current limiting reactor also provides more time for the protection system to detect and locate the fault.

The electrical stresses that are extended onto HVDC circuit breakers can be divided into four periods (i.e. normal operation when the breaker is in closed position; Fault current commutation period; Fault current suppression period; Normal operation when the breaker is in open position) and are elaborated in Appendix B.

Currently, there is no publicly available information about the exact way that a full pole HVDC circuit breaker is realised in terms of module arrangement, enclosures and support structures. For many manufacturers, this is still in development. In the absence of this information, it is not possible to prescribe specific testing procedures, but only generic guidelines.

4. Need to standardise the requirements and test procedures for HVDC circuit breakers

As no international standards describing the requirements, applicable tests and test procedures for HVDC circuit breakers are available, a general guideline is provided for a list of tests to be applied to HVDC circuit breakers. D5.4 is composed by using AC circuit breaker standards, CIGRE technical brochures, VSC converter valve standard and Chinese draft standard for HVDC circuit breakers as references.

In D5.5 the type of tests, sequence of execution, number of tests and pass/fail criteria are described to verify the test requirements defined in deliverable 5.4. It is a non-exhaustive list of tests (categorised into dielectric, operational, making and breaking and endurance tests), describing the main categories of tests that can be applied to HVDC circuit breakers. Please see for more information Appendix C, for types of test that are needed for HVDC breakers.

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5. Need to test the circuit breakers in the lab

In August 2017, mechanical HVDC circuit breakers have been tested for the first time in an independent test laboratory. It has been shown that AC short circuit generators running at low speed (16,67Hz) can be used to deliver carefully controlled test currents and energy levels to the test object to mimic DC current interruption stresses. Several methods exist to apply dielectric DC voltage stress after current suppression. The ability of the reduced frequency AC short-circuit generator based method to apply the correct stresses was verified by testing the DC current interruption capability of a Mitsubishi Electric HVDC circuit breaker 80 kV prototype at DNV GL's KEMA Laboratories, which managed to successfully interrupt 16 kA with an 8.5 ms breaker operation time and absorbing 3,6 MJ of energy. However, the main goal of the test was to verify the ability of the test circuit which was successful. The demonstration proved that it is possible to test DC fault current interruption of HVDC circuit breaker (modules) using standard equipment which should be available in conventional AC short-circuit laboratories which use short-circuit generators.

6. Need to identify limitations of the test environment

Due to the physical size of a complete HVDC circuit breaker, due to the amount of power required (e.g. 18,75 GW for a 25 kA 500 kV breaker) and due to the required test circuit, it is not possible to directly test the complete DC circuit breaker "as a whole" in the test environment. As such the test environment is designed to test the largest functional building block of a DC circuit breaker, which is one (or more series-connected) submodule(s) of the HVDC circuit breaker. Therefore, it is required to identify the possible impact of combining these blocks on the functionality of the breaker and its correct operation. For some tests, in case only one submodule is tested, it is necessary to represent the electrical impact of the other submodules to ensure a correct distribution of electrical stresses. For example, this can be done by dummy impedance, the value of which is determined by the physical construction of the eventual full pole HVDC circuit breaker. Special arrangements may need to be made in order to pre-condition the HVDC circuit breaker prior to the fault current interruption tests to mimic the effect of normal load current or a recent opening operation (for example in a reclosing sequence), or provide auxiliary power to systems which would normally derive their power supply from the line voltage. Functionality such as re-closing, although theoretically possible, cannot currently be tested directly (i.e. full ratings and functionality in one test from one test source) in the existing testing infrastructure. Different methods to verify the ability of an HVDC circuit breaker to successfully reclose are developed in which functionality and ratings are tested separately.

Economical

7. Need to limit costs related to the DC breaker

The topology and design of the HVDC meshed grid and its protection system, as well as limitations posed by the HVDC circuit breaker technologies themselves, determines the requirements of the HVDC circuit breaker. The breaker type required for a specific HVDC topology and its associated cost, can determine whether the topology is economically feasible or not. The cost of testing HVDC circuit breakers is strongly related to whether or not it is acceptable to the end user to verify its ratings and functionality modularly or not. It is the opinion of WP5 participants that modular and synthetic testing is an adequate method to do so.

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4.5.3. MAIN IMPLICATION FOR INTERACTION WITH OTHER WPS

The results of WP5 may affect:

- WP4 task 7 which deals with a socio-economic comparison of protection schemes. The cost of testing an HVDC circuit breaker must be incorporated in the total cost.
- WP7 deals with the regulation and financing. The need for complex or large test schemes can increase the cost of testing the breakers.
- WP10 deals with the circuit breaker performance demonstration. The test circuit design can limit the conclusions that can be drawn from the circuit breaker performance demonstration.

4.6. BARRIERS HAMPERING THE USE OF DCCBS IN OFFSHORE GRIDS

4.6.1. GENERAL ANALYSIS

Adequate DC circuit breaker models are required, to understand and analyse the behaviour and stresses imposed on the DC circuit breaker during fault clearing. The level of detail required in the model strongly depends on the type of study to be performed. When performing a DC system study, using a component level model would result in very long simulation times. However, when simplifying the model, it is important to maintain the characteristics of the breaker that play a role on the system behaviour in the model. Similarly, when studying the consequences of failure modes, a system level model would not provide the necessary information. As such, this work package is developing different HVDC circuit breaker models, which meet the level of detail required for the different studies. The aim is to develop the following type of models:

- System level models for hybrid (IGBT and thyristor) and mechanical DC circuit breakers;
- Component level real time models for hybrid and mechanical DC circuit breakers.

The work package will also develop kW-size hardware models for both hybrid and mechanical DC circuit breakers. This allows a further validation of the developed models. Subsequently DC circuit breaker failure modes will be shown on these kW-size hardware models.

The current available DC circuit breakers are in the range of 80-100kV. In the framework of a meshed offshore DC grid, it is required to upgrade the voltage rating of these DC breakers to a value in the order of 500kV. Therefore, the final aspect dealt with in this work package is the design of a roadmap to scale up the hybrid and mechanical DC breaker models to extreme high voltage DC (EHV DC). This roadmap will contain performance specifications, integration investigations and simulation studies.

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4.6.2. MAIN BARRIERS AND PROVIDED SOLUTIONS/RECOMMENDATIONS

This section separately focusses on issues from a technical perspective.

Technical

1. **Need to design system level models**

Using a component level model for system studies would lead to very long simulation times. Therefore, it is required to develop a system level model for each type of circuit breaker model, which includes the system level characteristics. Deliverable 6.1 describes a system model for the hybrid circuit breaker, while deliverable 6.2 describes the mechanical circuit breaker system model. D6.1 and D6.2 were delivered in December 2016.

2. **Need for standard DC CB model verification plan and Real-time DC CB models**

During the work on T6.1 and T6.2, it has become clear that there is significant difference in the understanding of the operating conditions of DC circuit breakers between the three manufacturers. In addition, DC circuit breaker prototype testing at manufactures has been completed for some but not for all expected operating conditions. The discussions at WP6 meetings have revealed that it is important to have a unique DC circuit breaker model-testing plan applicable to all DC circuit breakers, and therefore T6.9 was introduced as a new task. In addition, real-time DC circuit breaker models for two key DC circuit breaker topologies are required for system level studies. Deliverable D6.9 outlines these models.

3. **Need to design component level and real-time simulator models**

To analyse the consequences of failure modes, it is required to develop accurate electro-mechanical, switching transient and thermal models at component level. These models should become complemented with models for real-time simulator studies. This work will be described in D6.3 and D6.4.

4. **Need to validate the proposed circuit breaker models**

With the current models, it is only possible to analyse and guarantee the functional behaviour of the circuit breaker. To use the quantitative results of simulations, it is required to perform an extensive validation of the models against the measurements of actual tests in a power laboratory.

5. **Need for a lab model**

A kW-size hardware model will be designed to validate the models proposed and to implement and test new circuit breaker designs and controls. Furthermore, this model allows analysing the impact of internal component failures of the circuit breaker at the system level protection. A kW-size hardware model has been implemented and the first analyses of new control strategies as well as circuit breaker designs have been initiated in T6.5. Several papers on this topic are expected during the project.

6. **Need to develop a roadmap to scale up the circuit breaker designs**

The full-scale DC circuit breakers available from manufacturers are in the range of 80 to 100 kV. The wide deployment of these units will require upgrading to ratings in the order of 500kV. Therefore, the final aspect of

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this work package is to develop a roadmap for scaling DC circuit breakers. This roadmap should identify all technical, economic and regulatory challenges that could obstruct the deployment of the DC circuit breaker in a MOG. Currently, this task is at an early stage. However, it is crucial for the development of a MOG that DC circuit breakers at a higher rating are available in the near future.

4.6.3. INTERACTION WITH OTHER CATEGORIES OF BARRIERS

The results of WP6 have a direct impact on:

- WP4 deals with the development of a multivendor DC grid protection scheme. The DC circuit breaker models developed in this work package are expected to be used in WP4.
- WP9 deals with the demonstration of DC grid protection. The DC circuit breaker real time simulation models need to be integrated in the RTDS environment. Without these models, WP9 will be delayed.
- WP5 and WP10: testing of DC circuit breakers and test circuit development is based on simulation studies using verified DC circuit breaker models.

4.7. BARRIERS RELATED TO THE REGULATION AND FINANCING OF OFFSHORE GRIDS

4.7.1. GENERAL ANALYSIS

WP7 looks at the appropriate European regulatory target framework from a legal, economic and financial perspective in order to develop an integrated offshore electricity transmission infrastructure with the following aims:

- Foster efficient investments across North Seas states by creating a level playing field, undistorted by regulatory differences;
- Coordination of the offshore grid development and the connection of OWFs; and
- Ensure projects are financially viable.

The framework and regulatory principles should be applied to the North Seas offshore grid. The final framework could also be valuable for other regions where current or future (integrated) offshore electricity grid developments are taking place, such as the Baltic Sea.

4.7.2. MAIN BARRIERS AND PROVIDED SOLUTIONS/RECOMMENDATIONS

1. **Need for legal certainty regarding North Sea grid jurisdiction**

In order for parties to consider investments in cross border electricity infrastructures (including offshore assets), parties need legal certainty in terms of which rules and regulatory frameworks apply to their offshore assets. In order to create legal certainty, clarity is needed on which Member States can claim jurisdiction over the offshore assets (or parts of it) and under which conditions they can do so. A passive approach (self-restraint) does not constitute the required legal certainty as individual country-specific interests may change over time.

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Solutions/recommendations

First, increase the coordination for the development of a (joint) jurisdiction with predictable legal behaviour. Second, harmonise the rules and the regulatory framework with higher level of integration of assets and markets.

2. Need for coordinated offshore and onshore grid planning

a. Need for coordination on the siting of offshore wind farms

In the context of planning offshore wind development, locational requirements for RES support can be described by the question “where should a wind developer site an offshore wind farm?” The decision to develop an offshore wind farm needs to consider a variety of constraints. These may consist of social, environmental, economic and technological limitations. Therefore, during the planning stage, effective coordination of various agencies is required both domestically, internationally, and even across borders. Moreover, the location of OWFs has a direct consequence on the development of the offshore grid and especially its access to the onshore network. It makes the siting of the wind farm a critical issue from the perspective of efficient offshore-onshore grid development planning. Current national policies vary in their approach. Different policies exist in different countries:

Open door approach	Developer initiates development on a site proposed by him. He has researched the location.
Single siting approach	Site is defined by the governing authority and tendered to developers. The locations are researched and documented by the tendering authority.
Zone approach	Developers can tender for sites within a specific zone. Limited research of the quality of each site is done by the tendering authority.

b. Need for allocating offshore grid responsibilities.

In the North Seas countries, there are differences between the states in terms of the responsibility of the grid connection and other activities related to the development of hybrid assets or a MOG (i.e. including both wind farm connections and interconnection). Furthermore, there are differences in the incentives embedded in the respective regulatory frameworks resulting in different investments structures. Additionally, this framework and these incentives can change over time.

Depending on the responsibility for the offshore grid connections, in the case where the TSO has responsibility for providing the offshore grid connection, the wind farm developers do not incur the construction costs related to the offshore transmission assets (except for a super shallow or shallow connection charge). Instead, the construction costs for the grid construction are borne by the TSO, which means that the investments are included in their regulatory asset base as part of their regulated revenues (including a reasonable rate of return on the investments). The national regulatory authority ensures that only the efficient costs are remunerated.

In Great Britain, the offshore responsibility is more asset-specific. This is in contrast to the approach taken by most of the other North Seas countries where the TSO has more of a system wide grid responsibility

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(onshore/offshore grid and interconnection). Under the OFTO regime in the UK, the generator builds (under the generator approach) the offshore transmission assets needed to connect its windfarms to the onshore grid which is under the grid responsibility of National Grid. After construction, the assets are transferred to a competitively appointed OFTO[6].

Such differences in offshore asset responsibility might pose challenges for the coordination of cross-border offshore infrastructure. The above described example regarding the regulatory framework in Great Britain arguably delivers infrastructure earlier and at lower overall cost for individual assets and in a form that is easier to defend towards financial investors (the cost-benefit of each construction is isolated within specific projects), however it risks encouraging asset specific optimisation (due to different offshore responsibilities). Promoters of a more planned TSO system-wide approach argue that this is more suitable for long-term coordination of offshore grid assets [15]. Within a planned grid, the cost benefit of each grid reinforcement is also the result of cost-benefit analysis and investments may be considered with a forward-looking perspective to support offshore asset development. The approach taken by the UK was also intended to separate heavily regulated onshore assets with lightly regulated offshore assets and increase the number of asset owners.

Solutions/recommendations

To ensure a successful implementation of an integrated approach to cross-border offshore grid development in the North Seas, both models are deemed valid but require coordination amongst a range of stakeholders. There is an interaction between onshore grid development, traditionally performed by TSOs, and the development of offshore grid infrastructure (performed by TSOs, generators or OFTOs). A lot of thought has gone into both models and both may be justifiable. However, we can see increased coordination required both between different/multiple onshore and offshore parties as there is increased coupling of markets and supply, and increased coordination between the different offshore parties when the expected meshing develops. If permitted, this is likely to result in a potential consolidation of asset owners offshore or the growth of an umbrella organisation to coordinate development and support coordinated operations. A legal/regulatory framework should be in place to support and ensure that orderly markets develop.

c. Need for using super shallow grid connection charges

Grid connection charges are related to the question "which part of the offshore infrastructure is paid for by the offshore wind developers?" This policy choice does not only have an impact on the decision of the offshore wind developer to invest in an offshore wind project but also on the incentive of this offshore wind developer to connect the OWFs to the shore at a connection point where the incremental cost for the network is minimal. In the broader system perspective, it is critical to have the right coordination between the actor responsible for grid access and the one that is responsible for paying the grid connection costs. The grid connection costs can be attributed to the wind generation developer based on *three connection charge policies* as shown in Figure 4-2.

[6] An alternative approach where the OFTO itself builds the asset is also possible but as yet has not been implemented.

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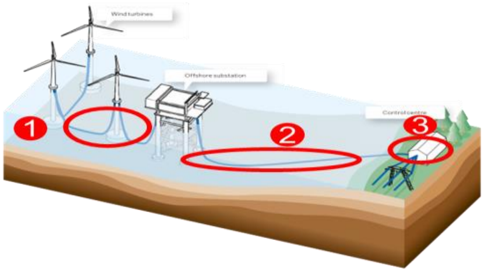

Connection policies

1. Super shallow charges (wind developer pays 1)
2. Shallow charges (wind developers pays 1+2)
3. Deep charges (wind developers pays 1+2+3)

Figure 4-2. Connection policies *(source Vattenfall)*.

The different approaches are based on the extent to which the developer is exposed to the costs of building the offshore grid connection and the necessary reinforcements that may be required to the onshore network.

Solutions/recommendations

To create transparency and a level playing field for offshore wind developers in an increasingly integrated electricity market, coordination will support harmonisation of the planning of OWF investments, clear and harmonised rules on parties' responsibilities and the determination of connection charges.

3. Need to align national support schemes with a multinational cooperation mechanism for RES support

The support scheme arrangements for wind farm developers vary in type and level of support among the North Seas countries. The current regulatory framework for wind farm developers required the OWFs to connect to the respective national markets.

However, in combined grid solutions (and thus fully meshed solutions) the wind farm developers might feed into two or more countries. As a result, different national support schemes may apply and the developers might be exposed to differences in support and charging schemes (grid connection or transmission charges). This means that legal certainty is needed on which support and charging scheme will apply in order for parties to consider offshore wind investments, as these schemes will have a considerable impact on the business cases for wind farm developers.

An important element of the Clean Energy Package Proposals presented by the European Commission in November 2016 is the obligation to open up national support schemes to projects from other Member States for at least 10% of the newly supported capacity between 2021 and 2025, and 15% between 2026 and 2030.

The energy produced across the border should in principle count towards the RES targets of the funding country. Opening up of the support schemes could help in diminishing the legal barrier that exists for connecting

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offshore wind in hybrid or combined solutions (i.e. connecting OWFs to interconnectors). However, there is a great political challenge to this as countries are less willing to pay for renewable energy if it flows to other countries.

This cross-border flow issue is relatively straightforward if it is one-way e.g. RES in Country A supplies Country B, therefore national support scheme from Country B is available to the generator. The more challenging issue is when RES in Country A supplies both Country A and Country B (and possibly others), potentially at relative shares that are not known in advance at the time of the investment decision.

It should be noted that some of the recent offshore wind developments in Germany and the Netherlands provide zero subsidy bids, showing the rapid cost decline and increase in scale efficiencies in the offshore wind industry. These developments may remove the barrier of differences in national support schemes by the time these combined or meshed grid solutions might be implemented (from 2025 onwards).

Solutions/recommendations

Coordination and harmonisation of market rules, network charging schemes and incentive schemes will help to prevent nationally oriented suboptimal choices, reducing the overall costs and increasing overall social welfare if implemented carefully. Investors may be given more certainty in their business case, especially for investments to more than one country.

4. Need for reconsidering RES priority operational dispatch

It remains a relevant discussion for the offshore grid when considering rules on system access: when OWFs and interconnection are combined in one cable, the capacity available for interconnection would vary according to how much electricity is produced by the OWFs and how much capacity is needed for that electricity to access the system. Whether it is possible to reconcile priority access, causing a variable remaining capacity for interconnection, with the rules on cross-border capacity allocation and congestion management is still unclear in the context of an offshore grid (although it is clear for the CGS) [7].

Additionally, the Renewable Energy Directive stipulates that Member States shall ensure priority for RES concerning *dispatching*. This means that when TSOs decide over which generation installations will meet the system load and which will be disallowed to deliver energy, RES have priority over conventional energy sources. There is one important condition to priority dispatch for RES: the rule only holds “in so far as the secure operation of the national electricity system permits”. The Directive further obliges Member States to ensure the minimisation of curtailment of RES electricity through grid and market-related measures. However, with an offshore grid, all electricity produced in that grid will be from renewable sources, while at the same time there is little to no demand for electricity at sea (only in the onshore grids). Therefore, it is not possible to speak of priority dispatch in the offshore grid as such.

[7] These rules are stipulated in the Network Code on Capacity Allocation and Congestion Management (CACM) which is dealt with in PROMOTioN's D7.1.

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks

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Solutions/recommendations

The rules on priority access and dispatch reduce the risk on investments for RES, as the certainty that the generated electricity can be sold on the market is increased when access to the grid is prioritised.

Priority access is not anticipated to be a major regulatory problem as offshore connections are planned well in advance of construction and there are no other loads connections with which OWFs compete offshore.

Priority dispatch onshore should be replaced with a market-based measure. The decision around which measures to take will be made by ENTSO-E. For the offshore grid though, it is important that offshore wind production has priority over the interconnection flows in order to keep a level playing field with other electricity producers and to ensure the primary function of the grid. Asset owners are more likely to assess and maximise overall financial benefit of the connection. Interests of stakeholders will need to be balanced and agreements made to formalise these. In a MOG where connection of OWFs is also mixed with interconnection between countries, these agreements are more complex . For example, it should be decided whether the full capacity of the cable is available for transportation of the offshore generated electricity (which means that this electricity always has priority access), or whether part of the cable is separated in some way and reserved for interconnection, as is suggested in some studies[8].

5. Need to improve ENTSO-E CBA methodology for evaluating investments

A Cost Benefit Analysis (CBA) is a well-established tool to guide investment decisions in various sectors including the energy sector. However, only in recent years, we have seen the development of an EU-wide standard methodology. The most well-known use of CBA methodologies in the EU energy context is the CBA methodologies for energy infrastructure published by ENTSO-E and ENTSOG. According to EU Regulation No 347/2013, ENTSO-E and ENTSOG received the task to develop these methodologies which are subject to public consultation and ACER comments and are finally to be accepted by EC and published in official EC documents. There are multiple ways of performing a good CBA, but as the goal is to compare and select projects to prioritise, it is of foremost importance that these are evaluated using the same methodology.

The harmonised system-wide CBA methodology is applied by the ENTSO-E to provide objective information uniformly about the projects taken up in the Ten-Year Network Development Plans (TYNDPs). In addition, the CBA methodology is highly relevant for:

- Establishing a regional list of projects of common interest (PCIs);
- Submission of investment requests by PCI promoters to National Regulatory Authorities (NRAs);
- Decisions of NRAs on granting incentives to PCIs;
- Providing evidence on significant positive externalities for the purpose of EU financial assistance to PCIs (ACER, 2017).

[8] See, for example, NSCOGI Market Arrangements Paper, 31-7-2014, p. 5/6 (virtual case 1).

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Solutions/recommendations

The CBA methodology is developed further within WP7.11 to allow for a uniform and generally accepted manner for performing evaluations on a system-wide basis, including agreement on its uniform application as to allow for like-to-like comparison of investments.

6. Need to improve framework for cross border cost allocation

A MOG will be achieved by the joint investment in infrastructure, as is the case for interconnectors nowadays. Each of these assets has a cost that eventually must be recovered from its users. Considering the multi-party characteristics of these assets, their costs may follow a slightly more complicated path until they reach the final user. The CBA for evaluating the costs and benefits of European infrastructure investments is expected to provide decision-makers with geographic disaggregated costs and benefits. Consequently, a Cross-border Cost Allocation (CBCA) process is conducted in which costs and benefits are split and/or negotiated among the (North Seas) countries involved. When the costs are allocated among the countries involved, it is up to the member states how these costs are redistributed nationally. The most common way is that the costs are borne by the TSO and recovered from system users (these can also be generators) who are obliged to pay the transmission charges.

Solutions/recommendations

As with the need for a uniform CBA, there is a need for a uniform and agreed approach for allocating the benefits and the costs for cross-border assets. A fair CBCA should lead to projects and participation from different countries, in order to create an overall win-win for all parties involved. A coordinated approach has been initiated by the North Seas Countries' Offshore Grid Initiative (NSCOGI) [16].

7. Need for harmonisation of transmission tariffs

Transmission tariffs ('G--charges') and connection tariffs ('C-charges') divide costs amongst grid system users. The different (national) transmission and connection tariff designs are expected to have an impact on the development of OWFs. Although grid tariffs represent only a smaller fraction of the total costs of an offshore wind project, it may have an impact on the location and business case of these projects. The (offshore) tariff design is still not harmonised across the North Seas countries. Both the amount of transmission costs levied on generation and the form of transmission and connection charges vary considerably.

Generators are also grid users and beneficiaries of transmission lines; therefore, there are arguments to say that they too should be responsible for the cost incurred for developing the grid (dependent on the transmission levy model). Currently, G-charges are often seen as unnecessary, as the cost is passed to the consumers. However, besides recovering the cost of the grid, transmission tariffs can be used, if desired, to send a locational signal for the siting of new capacity. Therefore, G-charges are internalized in the investment decision of developers leading to efficient siting of the new capacity from a grid development perspective.

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Solutions/recommendations

The tariff setting approach may benefit from coordinated approach in order to steer the rational behaviour of investors in their business case, with the objective of maximizing overall benefit. However, G-charges may be perceived as counter-productive in the goal to speed investment in offshore capacity – or may lead to further distortions or subsidy requirement as locations become more distant. In any case, some form of levelling may be required to provide a reasonable cost of grid connection.

8. Need to provide sufficient investment incentives

The framework for investment incentives is provided with in D7.4 and the results are expected in April 2019. A framework that facilitates and promotes the required infrastructure investment is a crucial element to the success of a MOG.

9. Need to develop a tailor made regulatory framework for hybrid assets

A challenge is the legal qualification of the offshore assets. Depending on the type of transmission assets (onshore grid, offshore grid and interconnectors), different regulatory frameworks apply with different rules and requirements. A key characteristic of a combined or meshed solution is a modular approach. This means that an asset is built with a specific purpose or functionality, for example as a connector for offshore wind generation, with specific rules and regulations. However, over time this asset may be combined as an interconnector. At that point, it is unclear which rules and regulation applies and which functionality prevails (generation capacity vs. interconnection capacity). For example, the current arrangement for interconnector development in the UK is based on the project developers (not being the SO or an OFTO) incurring the construction and operational costs. Here, the regulated revenue model for the interconnector is solely based on the use of the congestion revenues of the interconnector. There is no financial incentive for such interconnector operators to provide access to wind farm developers as this would lower the trade capacity of the interconnector, nor a legal obligation to provide a connection to parties seeking access. Furthermore, it is questionable whether interconnector developers are even allowed to connect generation, as it remains unclear whether the offshore assets (still) qualify as an interconnector or whether the hybrid solutions should be qualified as an offshore grid, shifting the asset responsibility and changing the applicable regulatory framework. For regulated assets in Europe, transmission operators receive regulated revenues and the congestion revenues according to EU law (although in the NL they have decided that the congestion rents should be clawed back against the tariffs; this is a deviation from EU law).

Solutions/recommendations

New legal terminology needs to be adopted for hybrid assets with a dual use as connection for OWFs and as interconnector. This will have to be adjusted in national legal systems as well, in order to create a clear and uniform basis regulating the assets as well as a level playing field for potential investors/operators for the same type of assets.

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4.7.3. MAIN IMPLICATIONS WITH OTHER WORK PACKAGES

The outcome of the regulatory framework is important for to steer the outcome of the different concepts. These concepts will be used in the different WPs as a basis for the decisions around technical system design and grid security and protection. Hence, the outcomes of the legal/regulatory framework have a major impact on the other WPs. Standardisation of technical standards which will influence interoperability and, potentially, grid investment and operational costs is handled in WP11.

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5. TOWARDS A DEPLOYMENT PLAN

5.1. PURPOSES OF THE DEPLOYMENT PLAN

One of the main objectives of the PROMOTioN project is to produce a Deployment Plan for a future European offshore grid. This plan will clearly define all the required technical, regulatory, economic, financial, legal and market actions to facilitate and support the development of an offshore grid in the North Seas. As developed in chapter 2, the multiple methods to develop an offshore grid are illustrated by the different proposed concepts. The final selected actions will be contingent on a range of factors. Note that these factors are not mutually exclusive: they may be combined. Nevertheless, some concepts might be more desirable than others, depending on the degree of maturity of the required technology, on the related costs and benefits, on the legal, regulatory and financial barriers hampering their implementation, etc. Before issuing recommendations about the actions to take to allow the development of an offshore grid in the North Seas, the Deployment Plan will first aim at providing a thorough analysis of the different concepts. For each concept, this analysis will have two outcomes: a multi-criteria evaluation of the pros and cons of each concept, and a list of proposed actions to ensure progress on the development of that specific concept. The multi-criteria evaluations will lead to recommendations about concepts that are deemed most suitable for implementation. The Deployment Plan will finally gather actions to take to allow the development of concepts that are deemed as relevant for the North Seas by stakeholders, based on the multi-criteria evaluations.

5.2. LIMITATIONS OF THIS PRELIMINARY ANALYSIS

The preliminary analysis provided in this deliverable is based on a high-level description of concepts. Consequently, although it identifies the main issues related to each concept, this analysis is very general and does not lead to concrete insights about the magnitude of these issues in the case of the development of an offshore grid in the North Seas. In addition, results from the various WPs of PROMOTioN are not yet finalized and cannot be fully integrated. In order to reach the objectives of the Deployment Plan, the analysis will have to be deepened through the development of realistic (but fictive) topologies corresponding to each concept. It will allow to provide an overview of expected costs and benefits as well as a detailed analysis of the technical, regulatory and financial challenges for each concept.

5.3. WAY FORWARD

In order to enhance this analysis, WP12 will first derive offshore grid topologies corresponding to each concept for the North Seas for the period 2020-2050. There is a high degree of uncertainty about the evolution of the European power system over this period. Furthermore, the scope of PROMOTioN is not to plan an offshore grid. Consequently, the exercise consists in deriving fictive but realistic offshore grid topologies such that the analysis has a suitable level of detail and accuracy. The uncertainty about the evolution of the European power system

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(e.g. development pace of offshore wind energy) is considered by using three different load/generation scenarios (low, medium and high). Therefore, each concept will have results for three different offshore grid topologies. Based on derived corresponding topologies for the different load/generation scenarios and of the results of the various WPs, each concept will be evaluated from the technical, regulatory/legal, economic/financial point of view. These analyses will reveal the advantages and disadvantages for each concept, universal recommendations for all concepts and specific recommendations for each concept. The topologies and the corresponding cost-benefits analyses will be published in deliverable 12.2. Preliminary conclusions and recommendations will be published under the form of a draft Deployment Plan (deliverable 12.3). The latter will be refined by integrating the last results of the various WPs and through stakeholder interaction to lead the final Deployment Plan (deliverable 12.4).

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LIST OF FIGURES

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GLOSSARY

The overview below gives key terms for the understanding of the document.

Key terms:

Building Blocks: The building blocks are the fundamental components for the development of a European Offshore Grid. Those components consist of:

- Technical building block, which comprises all aspects relevant for the technical feasibility of a meshed DC offshore grid. It covers the plant and equipment of a future offshore system as well as the control systems required for a safe and reliable operation of such a system.
- Regulatory and legal building block, which includes all regulatory and legal frameworks that should be in place to allow the development of an offshore grid.
- Economical building block, which means that the offshore grid must be viable, and the financial framework must be such that the business case of the various critical stakeholders is positive.

Concepts: The project includes different approaches/options that can be used for the development of a future grid topology (grid layout), and the manner of its operation and connection to the markets.

Deployment plan: The final deployment plan will define the all required technical, regulatory, economic, financial, legal and market actions. The final Deployment Plan (D12.4) will provide an overview of what will be needed for the development of a MOG, as well as an evaluation of the benefits of doing so. It will be based on the findings throughout the PROMOTioN project.

Finance-ability: The ability of entities to attract capital on the basis of business rational.

Hubs: Hubs are nodes where two or more cables converge. The connection of several nodes is a requirement for a meshed system.

Scenario: A scenario is the combination of certain assumptions for the different parameters influencing the evaluation of a concept. The relevant parameters include e.g. the use of the system (both on- and offshore), the market design and mechanism (e.g. flow-based market coupling etc.), the regulatory and legal framework and the operational strategy. The feasibility of a concept can differ dependent on the scenario. Furthermore, the impact of the relevant parameters can be assessed based on investigations of different scenarios.

System-Use-Case: The combination of all loads and in-feeds for a defined point in time forms a system-use-case. In terms of a future meshed HVDC offshore grid, the in-feed of electrical energy by OWFs is the dominant parameter determining a system-use-case. System-Use-Cases are one of the key parameters for a scenario.

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ABBREVIATION LIST

AC	ALTERNATING CURRENT
C-Charges	Connection Charges (Connection Tariffs)
CACM	Capacity Allocation and Congestion Management
CBA	Cost Benefit Analysis
CB	Circuit Breaker
CBCA	Cross Border Cost Allocation
CGS	Combined Grid Solution
DCCB	Direct Current Circuit Breaker
DRU	Diode Rectifier Unit
EEZ	Exclusive Economic Zone
EHV DC	Extreme High DC voltages
ENTSO-e	European Network of Transmission System Operators
EMT	Electric Magnetic Transients
EMTDC	Electromagnetic Transients including DC
EMTP	Electric Magnetic Transients Program
G-charges	Grid Chargers (Transmission Tariffs)
HVDC	High Voltage Direct Current
IED	Intelligent electrical devices
IGBT	Insulated Gate Bipolar Transistor
MOG	Meshed Offshore Grid
MTDC	Multi Terminal Direct Current
NRA	National Regulatory Authorities
NSCOGI	North Seas Countries' Offshore Grid Initiative
OFTO	Offshore Transmission Owner
OWF	Offshore Wind Farm
PCI	Project of Common Interest
PSCAD	Power System Computer Aided Design
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
VSC	Voltage Source Converter

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APPENDIX A – WP4 BIPOLAR/MONOPOLAR CONFIGURATION

In the table below an overview is provided of the differences between a Monopolar and Bipolar configuration of the MOG. In this table the technological an economical barrier are provided.

	Monopolar	**Bipolar**
Grounding	Grounding through star point reactor: - Complexity of star point reactor design - Choice of converter stations that need to be grounded through the star point.	In case of metallic return: - How to perform grounding at each converter station in order to avoid DC current flow through ground. - Placement of metallic return, cost related to separated trench in order to improve reliability. - Choice of voltage insulation level of the metallic return.
	Grounding through converter transformer: - Transformer neutral point treatment.	In case of grounding return: - Grounding electrodes have to be installed at each converter station. - Problems related to high permanent DC current flowing through the ground (corrosion, induced voltage in metallic structure…) during asymmetric operation
Fault management	Pole to ground fault: - High overvoltage (2pu) on the healthy pole, leading to insulation coordination issues. - Need to perform voltage rebalancing of the grid, complexity and cost of voltage rebalancing devices.	Pole to ground fault : - High prospective fault current, choice of protection strategy, breaking devices and limiting devices. - Impact of perturbation arising on the healthy pole
	Pole to pole fault: - High prospective fault current, choice of protection strategy, breaking devices and limiting devices. - Need of dedicated protection strategy for pole to pole fault.	Pole to pole fault: - High prospective fault current, choice of protection strategy, breaking devices and limiting devices.
Insulation coordination	Highly dependent on the grounding and protection strategies, cost related to higher insulation requirements.	
Converter transformer	Choice of winding arrangement	- Complexity and cost of dedicated HVDC converter transformer - Choice of winding arrangement
Control		How to manage current flow to the metallic return (or ground) during asymmetric configuration.

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In the table below an overview is provided of the components for an overall cost of HVDC grid protection system.

	Devices	Comments	Expected Cost consideration	Level of maturity
Breaking devices	High speed hybrid DC CB	High complexity with high number of PE components, very fast mechanical switch…	Prototype cost is surely high - Would remain quite high even with some standardisation (effect of learning curve)	Low (no industrial product, only prototypes)
	Lower speed mechanical DC CB/Scibreak DC CB	Lower complexity, still require many PE components but rely on simpler mechanical device	Prototype high cost – Expected lower than high speed hybrid DC CB	Low (no industrial product, only prototypes)
	Full Bridge MMC		Some extra CAPEX (regarding Half bridge MMC) due to more PE IGBTs, some extra losses	Medium, could be expected similar to Half Bridge MMC
Limiting devices	DC reactor	High number could be required	Cost would mainly depend on number	High
	SCFCL (Superconducting fault current limiter)	New and highly prospective component, but could be considered as a not critical component as many protection solutions would not require SCFCL	Would be probably high cost	Low (No prototype for HV application - no industrial product for HV applications)
Disconnecting devices	HSS (High speed switch)	New component due to higher required speed regarding standard DC disconnector	Expected limited extra cost	Medium (maybe derived from existing disconnector technologies?)
Control and measurement devices	Relay	Would require high speed performance	Would not be the most impacting	Medium (high speed could require specific hardware)
	Voltage and current sensors	High number could be required	Cost would mainly depend on number	Medium
Restoring devices	DBS (Dynamic breaking system)	Required in case of symmetrical monopole scheme for voltage rebalancing after fault clearing - Could be seen as a specific HVDC converter	Significant extra cost: would need to withstand full HV: At first approximation could be equivalent to one leg of HB MMC	High/Medium (non-existing product but would be probably derived from classical converter technologies)

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APPENDIX B – WP5 TYPES OF TESTS HVDC CB

Elaboration of the four periods electrical stresses that are exerted onto HVDC circuit breakers

The electrical stresses that are exerted onto HVDC circuit breakers can be divided into four periods:

Normal operation when the breaker is in closed position

- This period characterises the behaviour of an HVDC circuit breaker during normal operation prior to the occurrence of a fault. During this period the breaker will experience stresses due to normal load current, temporary overload, and the related thermal rise. As the breaker is in closed position, the voltage between the breaker terminals will be very low or negligible. In addition, it will experience the line voltage and temporary overvoltages across its support structure to ground. Any shunt connected elements such as charging systems or auxiliary power supply components will be stressed by this line voltage.

Fault current commutation period

- This period characterises the behaviour of the HVDC circuit breaker between the moment of occurrence of a fault and the moment when the breaker applies the transient interruption voltage. During this period, the fault current through the breaker rises somewhat linearly. Depending on the situation, different rates of rise of fault current in both forward or reverse direction can be experienced, with an upper limit determined by the series reactor.

Fault current suppression period

- This period characterises the behaviour of the HVDC circuit breaker between the moment when the breaker applies the transient interruption voltage and the operation of the residual current breaker. During this moment, a voltage (the transient interruption voltage) and a current exist across the HVDC circuit breaker, leading to a high energy dissipation. The effect of the transient interruption voltage is to suppress the fault current to zero with a rate of decay which depends on the magnitude of the transient interruption voltage and the circuit inductance. Once the fault current has been suppressed, a mechanical circuit breaker, also known as residual current breaker, connected in series with the HVDC circuit breaker will open to galvanically isolate the faulty line. The transient interruption voltage magnitude is determined by the 'knee-point' voltage of the surge arrestors which are part of the HVDC circuit breaker. This voltage is typically chosen as part of the insulation coordination study of the rest of the HVDC network.

Normal operation when the breaker is in open positon

- This period characterises the behaviour of the HVDC circuit breaker in open position. During this period, the line voltage appears across the open residual current breaker. Depending on the order of the series connection of the various components in the HVDC circuit breaker, the line voltage appears across the support structure(s) to ground.

APPENDIX C – WP 5 ELABORATION TYPES OF TEST FOR HVDC CB

Elaboration of the types of tests for HVDC circuit breakers

In general, HVDC circuit breakers need to be subjected to the following types of tests:

- Dielectric testing – Verify the ability of an HVDC circuit breaker to successfully withstand long duration and transient (over) voltage stresses across its support structure and across its terminals when open. This type of tests can be carried out with standard equipment.
- Operational tests – Verify the ability of an HVDC circuit breaker to successfully withstand long duration and temporary (over) current stresses through its normal current path components. The operating temperature of the components should stay within the maximum limits. Efficiency of the HVDC circuit breaker, especially if it contains power electronic components in the normal current path, should be verified in this test. This type of tests can be carried out with standard equipment.
- Making & breaking tests – Verify the ability of the HVDC circuit breaker to successfully interrupt a range of bidirectional DC currents ranging from less than nominal current to rated current interruption capability, and to re-energise a line. Re-closing and fault current limiting functionality is included in these tests. These tests cannot be carried out using conventional test circuits, a goal within PROMOTioN is to develop these test methods.
- Endurance tests – Verify the ability of the HVDC circuit breaker to successfully repeat operations. This may be related to mechanical parts which can be tested without electrical power, but in case of HVDC circuit breakers may also include the ability of the surge arrestors to successfully withstand multiple DC current breaking operations without changing characteristics.

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APPENDIX D – LITERATURE REVIEW ON AC HUBS

The main target of the energy hub (artificial island in the North Sea) is the interconnection of multiple HVDC lines and OWFs in the North Sea. Major challenges in DC systems are the DC fault protection as DC breaker technologies are not yet mature;. also, compared to AC grids, there is an absence of common standards and of an established grid code. Since most of the existing HVDC connections were implemented by the same manufacturer, there was no need for standardisation. This resulted in HVDC lines operating at different voltage levels and with different DC grid configurations [17].

For all the aforementioned reasons, a multiport DC-DC converter should be placed on the artificial island to interconnect multiple HVDC lines with different characteristics. To interconnect more than two lines with different characteristics, two main solutions can be identified. One solution is to use DC-DC converters for the interconnection of each pair of lines. As can be seen in Figure 0-1, in case three HVDC lines need to be interconnected, three DC-DC converters should be used. If an extra interconnection is necessary, three additional DC-DC converters need to be used. This makes the protection more complex and increases the cost. For this reason, this academic concept is considered unreliable with limited design modularity [17].

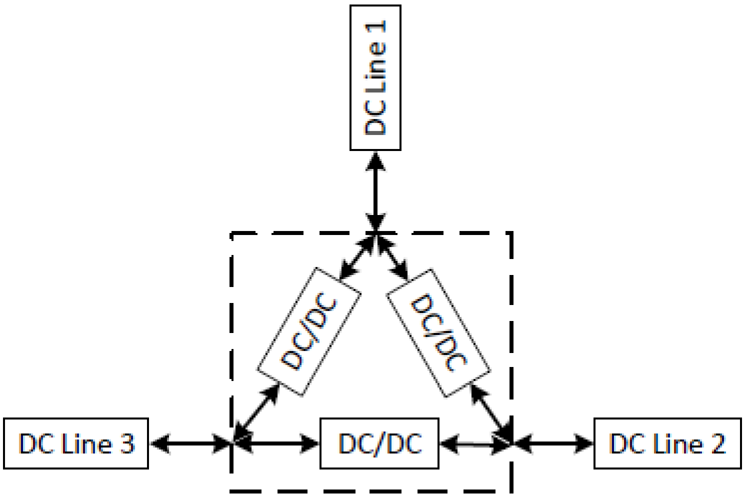

Figure 0-1 Multiport DC-DC converter [17]

A more suitable approach would be to include an element that enables the interconnection of all the HVDC lines on a common node, as shown in Figure 0-2. In fact, the AC hub concept is a multiple DC-DC converter topology that can be used for the interconnection of multiple HVDC lines and OWFs. This element can be placed strategically in a DC grid and it offers DC voltage transformation, fault ride-through ability through the intermediate AC link and more control options. The main objectives of the AC hub are [17]:

- Interconnection of multiple HVDC lines operating at different voltage levels and with different DC grid configurations.
- Any HVDC line can exchange power with any other line connected to the AC hub.
- DC fault clearance using the AC breakers on the AC lines of the hub
- Any HVDC line can be easily connected or disconnected from the AC hub without affecting the operation of the others
- It offers connection points to allow the interconnection of multiple HVDC lines and OWFs

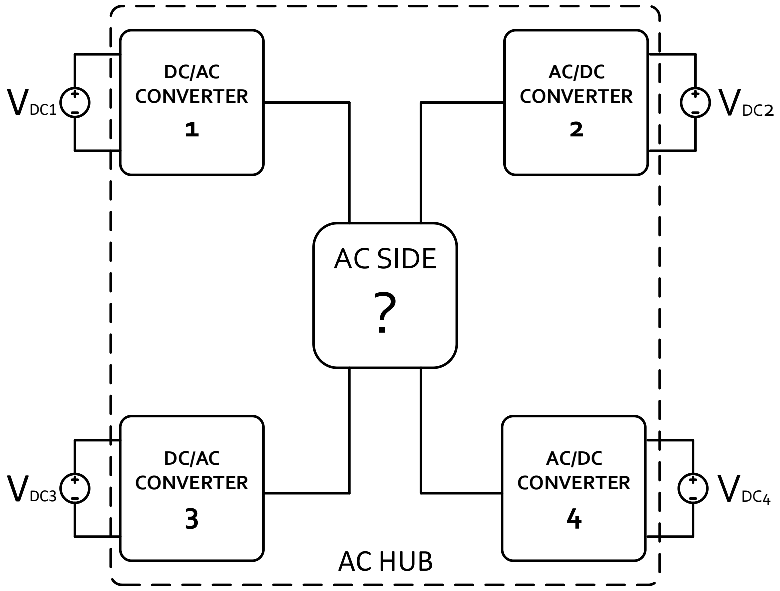

Figure 0-2 AC hub concept [12]

As can be seen in Figure 0-2, the two port AC hub is practically a DC-DC converter including an intermediate AC link. Thus, the DC-DC converter constitutes the building block of the multiport AC hub.

The DC-DC converter topology which could be used as the building block of the AC hub should have the following characteristics [12]:

- **High power transfer capability:** the DC-DC converter should have high power rating and should be able to withstand high voltage and current stresses.
- **High transformation ratio:** the DC-DC converter should be able to interconnect HVDC lines operating at different voltage levels.
- **Bidirectional power transfer capability:** the DC-DC converter should be able to transfer power in both directions, since the interconnected HVDC lines exchange power and any HVDC line could either export or import power from the interconnected system.
- **Modularity:** The topology of the multiport DC-DC converter should offer connection points to allow the interconnection of more lines

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The DC-DC converters can be categorized as:

- Two-stage (or front-to-front) converters
- One-stage converters

In the two-stage converter topology, the DC lines are interconnected through an intermediate AC link and two DC/AC converters are used. In the one-stage topology, there is no distinct AC link. The main advantage of the one-stage topology is that only one converter is used. As a result, the number of semiconductor devices is lower, resulting in lower weight, cost and volume. However, the one-stage converters do not have modular structure and thus, cannot be used as the building block of the AC hub. For this reason, only two-stage converters will be considered.

Several DC-DC converter topologies which could be used in high power applications are recommended in the literature [12] [17] [18] [19] [20] [21].

The most suitable DC-DC converter topology which meets all the aforementioned requirements is the MMC-based DC-DC converter using transformer, and its schematic is given in Figure 0-3.

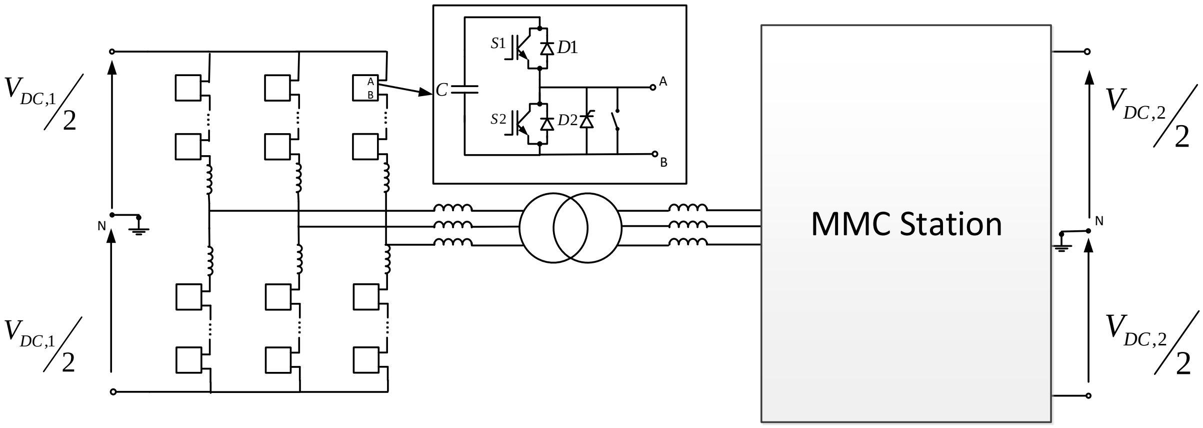

Figure 0-3 MMC-based DC-DC converter using transformer [17]

This converter type has high and bidirectional power transfer capability. Due to the use of transformer, it can be used for the interconnection of multiple HVDC lines operating at different voltage levels. Therefore, this DC-DC converter topology could be used as the building block of the AC hub.

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