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PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

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 main objective of Deliverable D12.1 is to provide a preliminary analysis on key technical, financial, economic, legal, regulatory and market barriers and direction for solutions. These solutions are currently being analysed more deeply by the different Work Packages (WPs) of the PROMOTioN project. The analyses gives a snapshot of the results to date and will be refined in the upcoming deliverables12.2 and 12.3.

In order to provide a preliminary analysis of barriers hampering the development of a HVDC Meshed Offshore Grid (MOG) and a preliminary related portfolio of solutions, this deliverable looks at:

- The conceptual building blocks for analysing challenges to the future offshore grid as identified in the different Work Packages (WPs) and possible Concepts for a future offshore grid;
- The work in various WPs, to analyse the specific barriers and related solutions, is ongoing.

Concepts

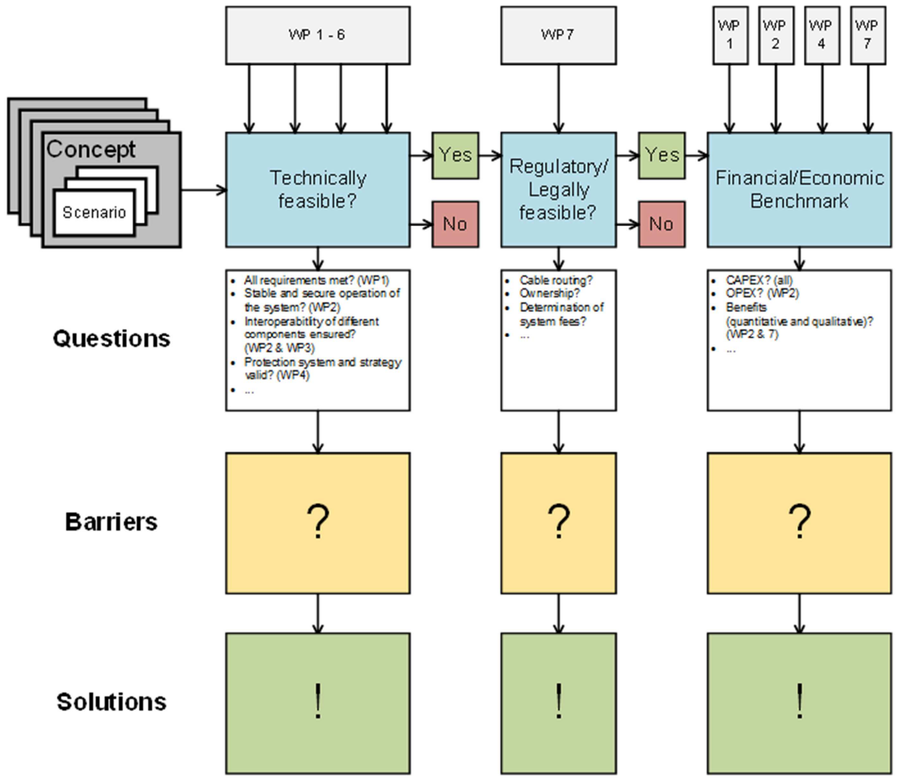
In addition to a Business-as-Usual approach which is based on national policy driven investments in the form of radially connected wind parks, a number of different approaches have been identified.

- *Centralized Wind power hubs:*
    - AC hubs with several wind farms connected (radially), DC connections for longer distances.
    - Meshing on the AC side;
    - Connection with the main land over HVDC corridors;
    - Eventually with some Interconnectivity;
    - Based on national policy.
- *National Distributed wind power hubs:*
    - Each country develops their own offshore grid;
    - Radial connections from the OWF to the hubs;
    - Meshing on the HVDC side;
    - Based on national policy.
- *European approach to Distributed wind power hubs:*
    - Integrated approach with strongly MOG developed jointly;
    - Infrastructure international, not national;
    - Meshing on either AC / DC side;
    - Based on coordinated European policy.

There are different issues and complexity with each option from a technical perspective. However, there is also a need for joint legal and regulatory action.

Evaluation of Concepts

Further evaluation of the different Concepts is needed and will be conducted in D12.2. The picture below gives an overview of the approach for evaluating the different Concepts for the development of the Deployment Plan.



Overview of the methodology to evaluate a Deployment Plan.

Analysis of barriers

On the basis of the work done in the different Work Packages of the PROMOTioN project to date an overview is given of the analysis of barriers. These fall into the following categories:

- Barriers impacting the long-term planning of offshore grids;
- Barriers related to the operation and control of offshore grids;
- Barriers hampering the integration of DRU technology in offshore grids;
- Barriers related to the protection of offshore grids;
- Barriers related to the test environment for HVDC circuit breakers;
- Barriers hampering the use of DCCBs in offshore grids;
- Barriers related to the regulation and financing of offshore grids.

From the analysis it is clear that apart from technical challenges there are a number of legal and regulatory issues requiring attention for the development of the HVDC MOG, especially when moving away from the nationally oriented Business-as-Usual approach which exists today.

Way forward

To get a better understanding from what is needed over the next few months the different Concepts will be discussed and analysed with the other Work Packages in order to the develop the understanding needed for the development of the Deployment Plan.

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1. INTRODUCTION

In the course of the ratification of the Kyoto protocol in 2005, the presidency conclusions of the Council of the European Union include a proposal for “an integrated climate and energy policy” (Council of the European Union: presidency conclusions (7224/1/07 REV1), March 2007). 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"(COP23, 2015).

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” (Renewable Energy Roadmap, 2007). 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” (EU Directive 2009/28/EU, 2009). 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% (European Commission, 2016). 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, which final outcome is expected in 2018 (European Parliament, 2017). In the area of electricity interconnection the European Commission has set a 10% target to be achieved by 2020 increasing to 15% by 2030.

In order to reach these objectives, the utilization of northern Europe’s vast offshore wind potential is obvious. However, the connections necessary for the evacuation of the wind energy generated offshore remain a challenge on different levels. It’s rather a challenge because it requires longer lead time and the regulatory framework is not there yet. One option to meet the requirements in terms of climate and energy policies is the establishment of a HVDC Meshed Offshore Grid (MOG). By inter-connecting offshore wind farms with different onshore systems, this MOG could be able to combine the evacuation of offshore wind energy with the exchange of power between different countries.

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 (Twenties, ISLES I & II, Best Pathways, e-Highways2050).
- On a regulatory level there is a lack of market rules for infrastructural investments as well as a lack of regulation regarding the operation and management of these grids from legal, technical and market point of view (Twenties; Seastart Alliance, e-Highways2050). Furthermore, additional barriers are linked specifically to HVDC MOGs (e.g. control issues).

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The main objective of Deliverable D12.1 is to provide a preliminary analysis on key technical, financial, economic, legal, and regulatory and market barriers and direction for solutions. The various approaches for solutions to overcome these barriers are currently analysed more deeply by the different Work Packages (WPs 1-7) of the PROMOTioN project. Note that, at the time of writing, these WPs are still ongoing. Therefore, the analysis provided in this Deliverable is still providing a preliminary 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 the upcoming deliverables 12.2 and 12.3.

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 describes the conceptual building blocks for analysing challenges to the future offshore grid by the different WPs as well as possible Concepts for a future offshore grid.
- Chapter 3 dives then into the work of these WPs to analyse the specific barriers and related solutions currently under study.
- Chapter 4 looks at the way forward from this deliverable towards the following deliverables for the Work Package.

The results presented in deliverable, especially chapter 3, are based on the work of the Work Packages 1-7 and have been prepared with the input of our PROMOTioN-colleagues in these Work Packages. As authors of this deliverable we thank them for their input, comments and support its preparation.

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2. 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. Firstly, an offshore grid must be feasible from a technical point of view, which means that the necessary technologies must be ready, and that appropriate control systems must be available to operate such a grid.
2. Secondly, the regulatory and legal frameworks must allow the development of the European offshore 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. The purpose of the economic / financial building blocks is to ensure its economically and financially feasibility.

The purpose of this Chapter is to analyse these fundamental building blocks, in particular to identify current gaps in the building blocks, i.e. current barriers.

There is no unique way to develop a European offshore grid. Several strategies of development are possible and feasible, which could consequently 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. Additionally, 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 a HVDC Meshed Offshore Grid (MOG). Consequently, gaps in the building blocks will have to be identified for each Concept.

This Chapter is thus structured as follows. Section 2.1 provides possible Concepts for a future European HVDC MOG. Section 2.2 develops the technical, regulatory / legal and financial / economic building block. Finally the interaction between the WPs is defined. Section 2.3 looks at the framework for the evaluation of the different Concepts. The remainder of the chapter focusses on the approach of the work in the different Work Packages in relation to the analysis of the Concepts and the analysis of challenges and solutions.

2.1. CONCEPTS FOR A FUTURE OFFSHORE GRID

A future European offshore grid can be developed following different strategies which can be analysed against a Business as Usual approach.

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First possibility builds upon the Concepts as proposed by TenneT and Energinet with the so-called "North Sea Wind Power Hub" provided in 2016, as shown in Figure 2.1 and in Figure 2.1. In this case, offshore wind farms are connected to large centralised connection points, and power is evacuated to North Seas countries through dedicated HVDC corridors.

A second option could be the creation of small HVDC hubs, like the current AC substations in the onshore grid, meshed at the national level but loosely interconnected amongst countries.

Lastly, a third option could foresee a stronger interconnection between decentralized hubs up to a level where the overall infrastructure forms a fully meshed international offshore grid.

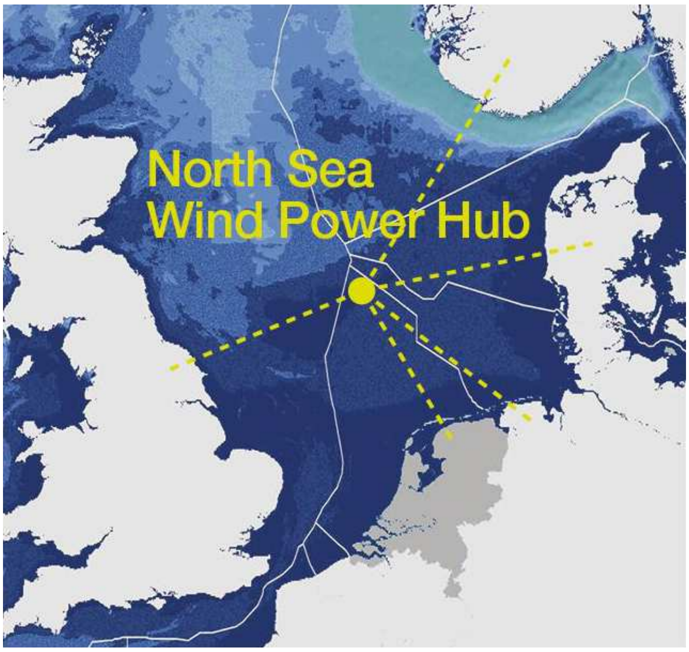

Figure 2.1. North Sea Wind Power Hub – general Concept *(source: Energinet).*

Figure 2.2. North Sea Wind Power Hub – artificial island / artist impression *(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 is expected that a future offshore grid will be the combination of different Concepts. In particular, for the sake of readability, point-to-point interconnectors are not shown in the advanced Concepts, even while they will remain an important part of the picture.

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 Offshore Wind Farms (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: however they illustrate different Concepts. In each figure, the term “hubs” is used when two or more cables converge on the same node.

2.1.1. BUSINESS-AS-USUAL CONCEPT

Before delving into the Concepts of MOGs, it is worth considering a first possible development of the offshore infrastructure in the North Sea in a “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

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will be used as a reference case. In this reference 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. Offshore wind farms are connected either individually to the shores, or via small hubs. However, offshore hubs connect only the offshore generation of the same country. In parallel to the evacuation of the offshore wind power, point-to-point interconnectors are developed to exchange energy between countries. Figure 2.3 below shows an example of this Business-as-Usual Concept.

Because this Concept corresponds to the standard practice of connection offshore wind farms to shore, there is no major challenge in the operation. The DRU might be a solution to decrease the costs in case of radial connection of offshore wind farms. In that case, the operation is 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.

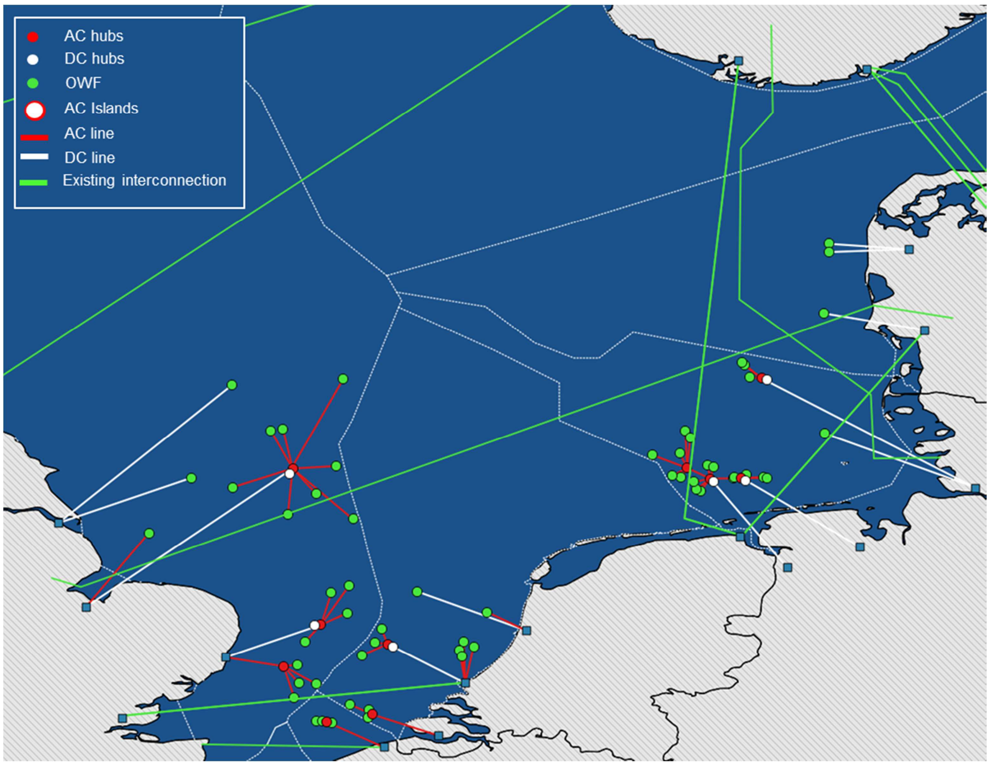

Figure 2.3. Business-as-usual Concept.

2.1.2. CENTRALIZED WIND POWER HUBS CONCEPT

The Concept of centralised wind power hubs describes a possible future development of the offshore grid polarised around AC hubs to which several wind farms are connected, in line with the "North Sea Wind Power Hub" Concept. Figure 2.4 provides an example of how such a grid could look like. Offshore wind farms are connected radially to the AC 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 bulk wind generation. Eventually, these hubs could be interconnected with each other, providing both additional evacuation routes for the offshore wind farms. Aside from the central hubs, offshore wind farms close to shore are connected radially to the mainland, or through small hubs, as per the respective national policies

It should be noted however, that due to the technical challenges involved building the artificial infrastructure (islands), this a rather long-term approach which is not likely to materialize prior to 2030/35, according to its promotors.

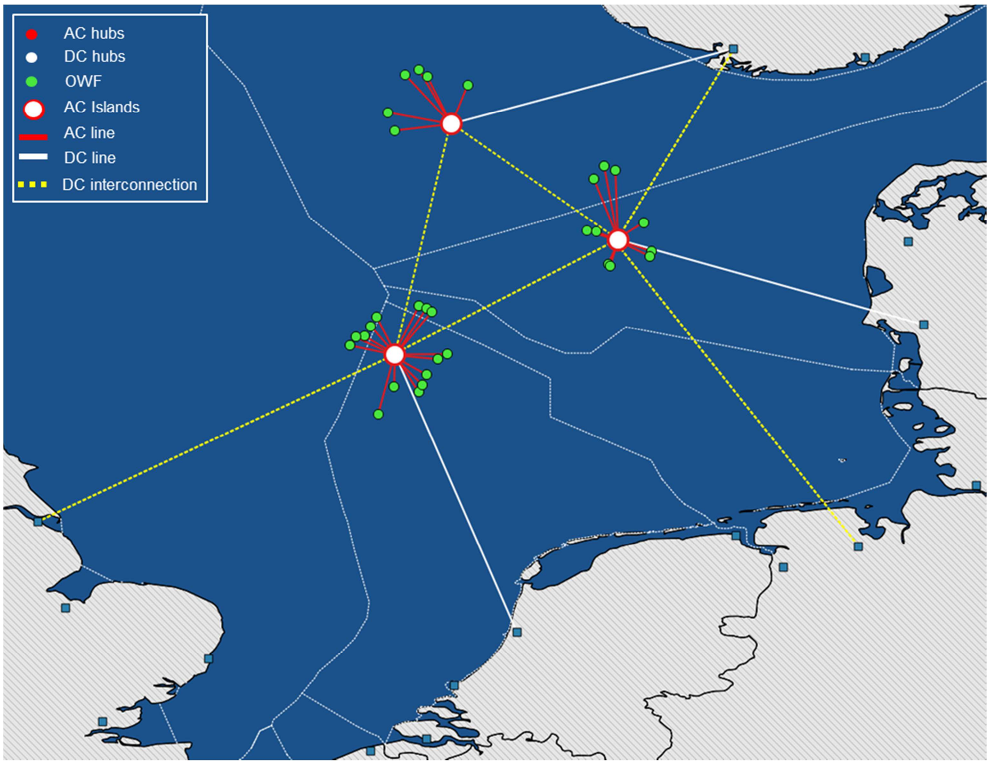

Figure 2.4. Centralized wind power hubs Concept.

Operational complexity is limited as each HVDC interconnector can be operated as a point-to-point connection. It appears thus to not mesh on the HVDC side. However, the control of AC hubs might be challenging. Similarly the Business-as-Usual Concept, in case of connection of offshore wind farms through a DRU (i.e. if offshore wind farms 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.

From a regulatory perspective, several challenges might hamper the implementation of such a Concept. The most predominant is linked to the potential connection of offshore wind farms in the national waters or European Economic Zone (EEZ) of a 'country A' to an AC hub located in the territorial waters or EEZ of another 'country B'

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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 AC hub and the onshore grid of country B (e.g. in Figure 2.4Figure 2.4., no direct connection between the Dutch AC hub connecting German offshore wind farms 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.

Regarding the investment needs, the centralised wind power hubs Concept foresees extensive auxiliary works. Nevertheless, such a Concept does not entail a need of HVDC circuit breakers (no meshing on the HVDC side). This 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.

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 strongly meshed grid, including eventually a larger number of hubs in the longer term horizon.

2.1.3. DISTRIBUTED WIND POWER HUBS CONCEPTS

In contrast with large centralized wind power hubs, the offshore grid could be developed around several small hubs, interconnected amongst themselves to different degrees. Such approach can branch off in two specific Concepts for wind power hubs, based on a national or European approach 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 offshore grid, weakly interconnected amongst each other.
- On the other hand, the European Concept favours the joint development of a single MOG integrating all the distributed hubs.

It is worth noting that the national Concept can eventually evolve into the European Concept by increasing the integration between the national offshore grids. The Concepts are described in the following sections, including visual examples for indicative purposes.

2.1.3.1. NATIONAL DISTRIBUTED WIND POWER HUBS CONCEPT

Figure 2.5 illustrates the national distributed wind power hubs Concept. In this Concept, each country develops its own national offshore grid according to the national policies. The scope of the offshore grid is to evacuate all the national offshore wind power generation to the corresponding onshore national grid. With respect to the radial connections of wind farms, a MOG grants more flexibility and increased security 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 might be interconnected with each other. The envisaged “Wind connector” Concept between the Dutch area “IJmuiden Ver” and the British “East Anglia” area corresponds to this Concept: the Dutch offshore grid would have to be designed to evacuate all the Dutch offshore wind energy to the Dutch

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

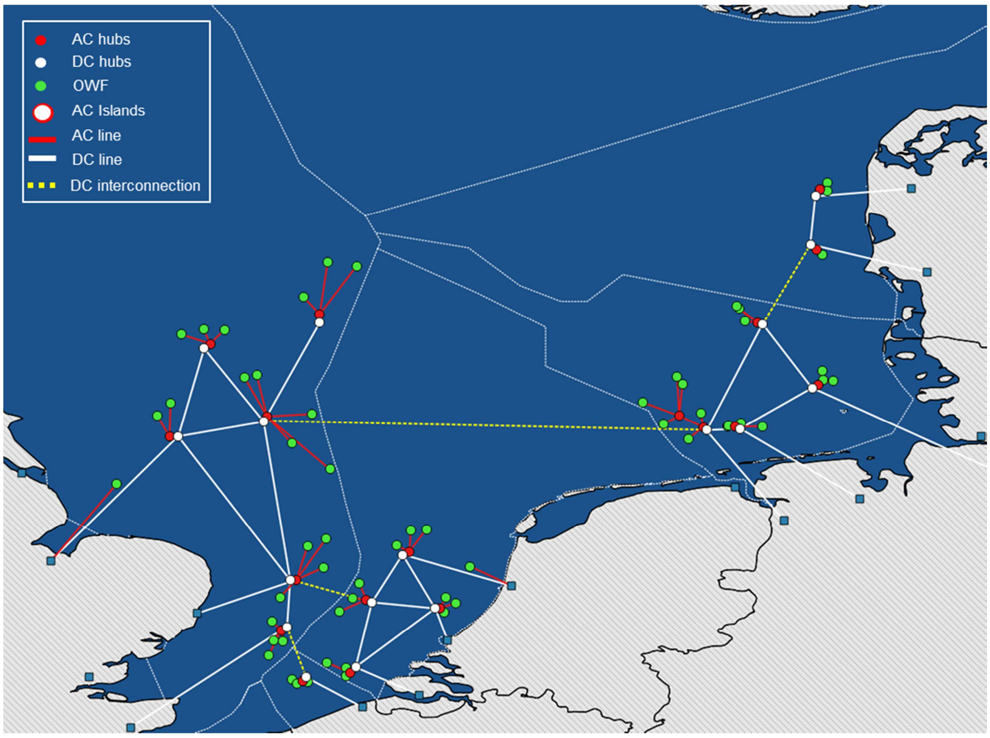

Figure 2.5. National distributed wind power hubs Concept.

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 issues could appear. Furthermore, the need for requirements for DC grid protection depend 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 both to 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 national Concept ideally presents more flexibility than the centralized Concept, as a larger number of alternatives should be available to cope with congestion and / or outages.

2.1.3.2. EUROPEAN APPROACH

Figure 2.6 illustrates the European distributed wind power hubs Concept. In this Concept, the distributed wind power hubs are integrated into a strongly MOG developed jointly by the North Sea countries as an international infrastructure. Offshore wind farms can be connected either in AC or DC to the most suitable node of the grid regardless of where it belongs to. The onshore grid is not anymore designed to be able to evacuate national offshore wind energy to the corresponding national offshore grid.

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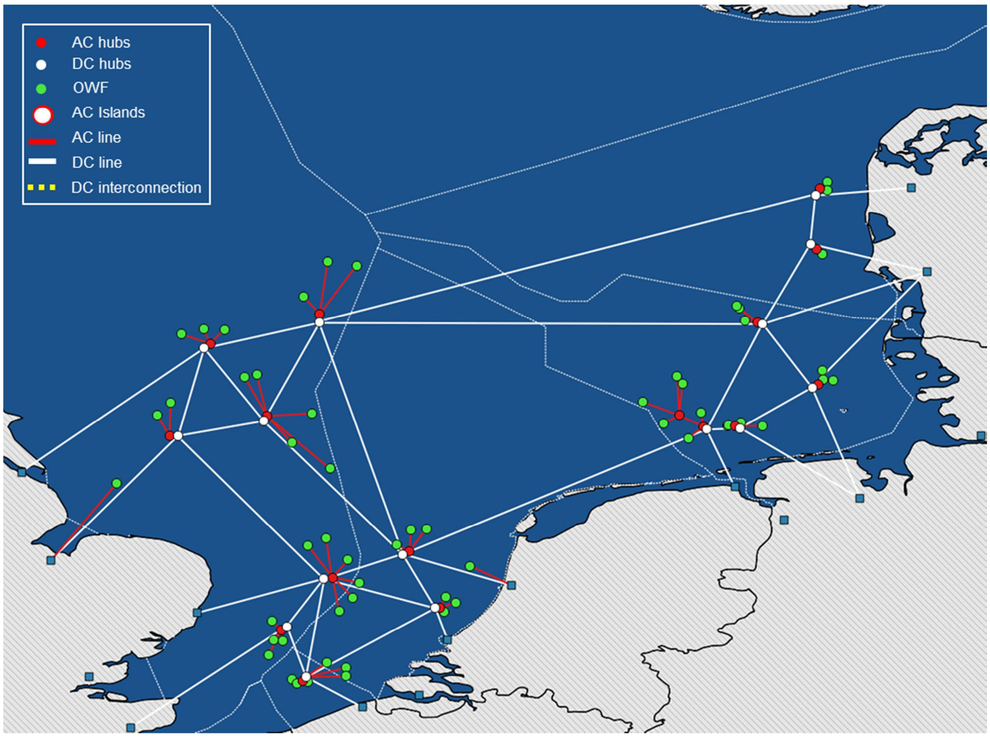

Figure 2.6. European decentralized wind power hubs Concept.

The operation of such a meshed and widespread grid is complex and requires the readiness 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 offshore wind farms of a 'country A' can be connected to the grid of a 'country B' and interconnectors are not distinguishable from other branches.

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 offshore wind farms, increasing the exploitation of wind resources in the North Sea.

2.1.4. CONCEPT EVALUATION

The above Concepts will be evaluated against key characteristics to get insight into the relative complexity of the individual Concepts. The figure below gives an example of what the evaluation may look like. Please note this is only an initial set up that can be refined as part of during future and more detailed analysis, it included for insight and not as presentation of final results. For the purpose of the final results an approach for relative grading will be formulated.

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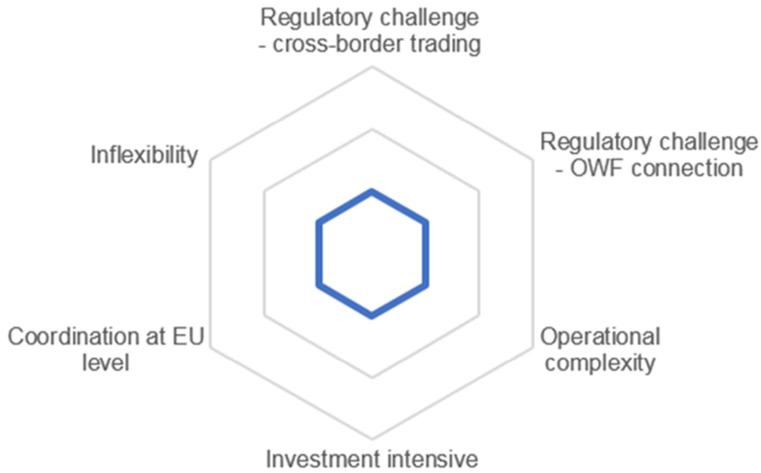

Figure 2.7. Possible structure for analysing and comparing Concepts based on key Characteristics.

2.1.5. DEVELOPMENT OF SCENARIOS

From the Concepts, the further analysis in the next phase of WP12 will analyse scenarios for further evaluation. This will be taken forward in D12.2, and will act as input for the development of the Deployment Plan in the report of deliverable D12.3. Scenarios will include feedback from the other WPs on the Concepts for the development of appropriate scenarios.

2.2. DEFINITION BUILDING BLOCKS

The PROMOTioN Project builds on different studies that have already partly addressed the development of a MOG and the associated technical, financial, regulatory and market barriers. In this section, an overview of the definitions *technical, financial, economic, legal, regulatory and market barriers* are provided. In addition, the related portfolio of solutions" and the related dependencies between the barriers are elaborated.

2.2.1. TECHNICAL BUILDING BLOCK

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:

- Firstly, one of the key objectives of an offshore grid is the evacuation of offshore wind energy power, wind farms will constitute a first essential category of elements. Offshore wind farms already exist, so there is no major technical challenge existing at that level.
- Secondly, 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.

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- When HVDC is needed (i.e. to transfer power over long distances), a third category of elements are converters to convert AC power (from offshore wind farms or onshore grids) into DC power. Various technologies of converters do exist. The PROMOTioN project will concentrate on the VSC[1] (specifically MMC) and on the DRU[2]. The VSC is a proven technology already integrated in real power systems, but not yet the DRU. Hence, the level of maturity of the latter might currently not be sufficient for a direct integration in offshore grids.
- Finally, a fourth important category of elements could be DC grid control and protection technology, and in particular HVDC circuit breakers. Indeed, 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 thus 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 thus the control of the MOG. This control depends strongly on the structure of that grid, and thus on the Concept envisaged. For the Business-as-Usual Concept, control challenges are mainly expected for DRU connections of offshore wind farms. Indeed, other parts of the Concept (e.g. point-to-point interconnectors, VSC connections of offshore wind farms) already exist in real power systems. Control challenges for DRU connections of offshore wind farms are being studied by WP3. For more complex Concepts, especially when meshing appears on the HVDC side, the coordinated control of converters is challenging. This control is studied by WP2. 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. This is studied by WP4.

In summary, at the exception of HVDC circuit breakers and, to some extent, with the exception of DRU, components do exist to build a MOG. However, to the contrary, the control of such a grid, including interactions between converters and offshore wind farms, appears much to be much more challenging. The PROMOTioN project is thus addressing mainly the barriers linked to HVDC circuit breakers and to the control of the MOG. These barriers are looked at in the next chapter.

2.2.2. REGULATORY / LEGAL

Electricity transmission is a regulated business in Europe. This means that the legal / regulatory framework in within which it operates has a profound impact on earning back of long-term investments and on creating the right investments incentives. Therefore, the regulatory framework plays an instrumental role in stimulating investment and has an impact on the financeability of projects. On the other hand, the regulatory framework also influences the market design of a MOG, and influence on the standard technological specification for various technologies.

[1] VSC – Voltage Source Converter
[2] DRU – Direct Rectifier Unit

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2.2.3. FINANCIAL & ECONOMIC

The financial and economic components 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 get a clear overview what aspects could be the bottleneck 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. Cross border offshore grid investments come at high costs and risks, due to high technical risk and high uncertainty of the profits. This means that the regulatory framework has a role to play in terms of predictable and timely cost recovery, by mitigating financial risks, and by providing for sufficiently attractive returns that reflects the risk associated. Attracting debt capital 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, equity financing may be subject to constraints as it is related to State ownership of TSOs (in most of the cases), as the anticipated investments needed will be substantial. This means that next to improving the attractiveness of debt financing, equity enhancing solutions need also to be considered and developed.

2.3. EVALUATION OF DIFFERENT CONCEPTS

The impact and viability of the different Concepts introduced in section 2.1 depend on the environment and the framework determined by the building blocks discussed in section 2.2 of this document. Adjustments and modification of the different environments and frameworks can be carried out by changing parameters of the mathematical models representing them. A combination of different parameters is defined as a scenario in the course of this document. Therefore, the evaluation of different Concepts requires the consideration of different scenarios for each Concept. An overview of the methodology for the evaluation of different Concepts is provided by Figure 2.8.

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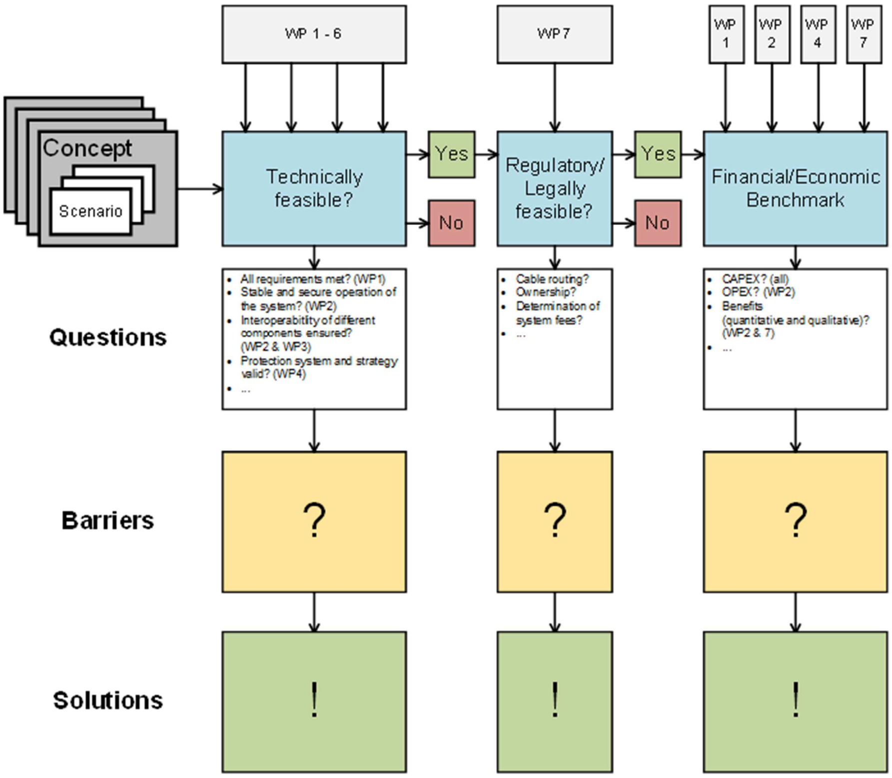

Figure 2.8. Overview of the methodology to evaluate a Deployment Plan.

A defined scenario for one of the four Concepts serves as input for the methodology. In line with the three building blocks identified, the first step addresses all aspects relevant to answer the overall question, if the Concept for the scenario defined is feasible from a technical point of view. The numerous detailed questions, which are related to an answer for the global question, have to be addressed by the technical Work Packages 1 through 6. In particular more detailed questions could unveil barriers for a MOG. These barriers require adequate solutions. The second step of the evaluation covers all questions related to regulatory and legal issues. Again, detailed questions will have to be answered in order to provide an answer to the overall question, if a Concept is feasible assuming a defined scenario determining the environment and the framework. Finally, a financial and economic assessment of the Concept allows the comparison of different Concepts and, therefore, represents the basis for the development of a final deployment plan for a MOG.

2.4. RELATED PORTFOLIO OF SOLUTIONS

The "related portfolio of solutions" are solutions and recommendations defined for specific barriers and challenges identified by the different WPs (see Figure 2.9). The solutions and recommendations are based on the current knowledge and will be updated in the upcoming months.

Please note that in this deliverable only preliminary portfolio solutions are incorporated from WP 1-7.

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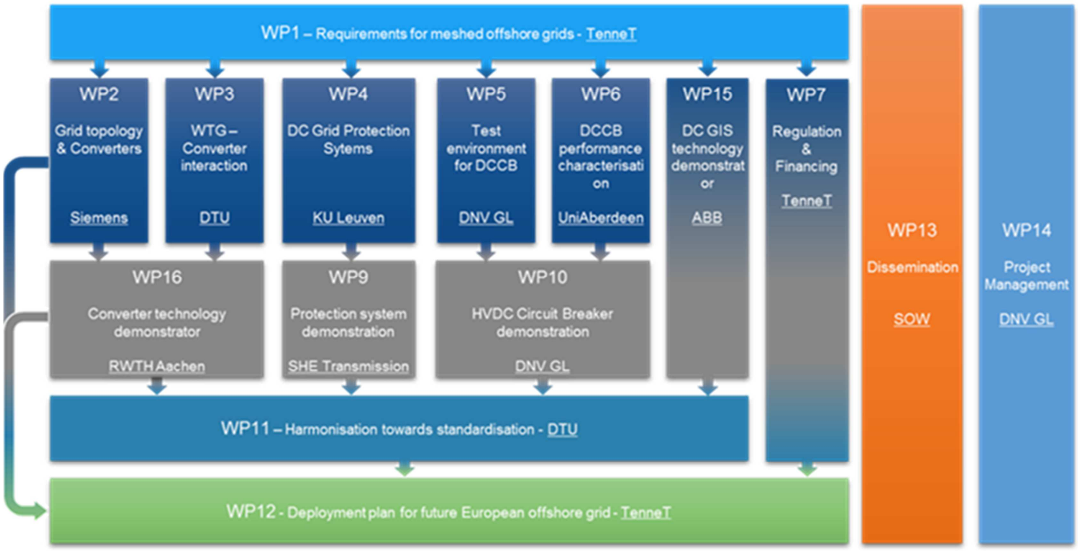

Figure 2.9. Possible structure for analysing and comparing Concepts based on key Characteristics.

2.5. INTERACTIONS BETWEEN BUILDING BLOCKS

The building blocks for a MOG are separated into different groups which are introduced in the previous sections of this chapter. These blocks are linked to each other and are interacting. In the framework of this document, the interdependencies are defined according to the diagram shown in Figure 2.10. An important aspect that should be taken into account is that the market design is not mentioned as a specific building block. Market design is partly touched upon in the "regulatory / legal-" and "financial / economic building block". In addition, it is assumed that the market design will follow after a MOG is build.

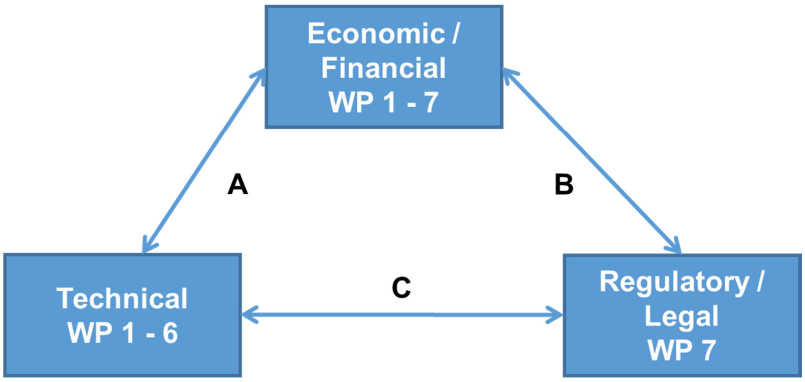

Figure 2.10. Overview interactions between buildingblocks.

The above lines between the different building blocks reflect the fact that these do not stand on their own. The analyses of the various factors are strongly interdependent and influencing each other.

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Examples of these can be:

- Link A:
    - The technical solutions and requirements will influence the investments and operating costs;
    - Vice versa, economic analysis in the CBA of alternatives will influence recommendations on solutions presented, or their relative attractiveness.
- Link B:
    - Regulatory requirements will impact the business model (e.g. requirements on security, inter-operability and on the structure of the market);
- Link C:
    - Technical solutions heavily may depend on the regulatory framework (e.g. requirements on inter-operability, security such as allowable loss of load);
    - The regulatory framework will take into account the technical direction for the setting of regulations and requirements (e.g. grid codes). Additionally developments in technical fields may allow for new alternatives in the use of assets or operating. As such regulation may and will have to change and be adjusted over time.

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3. ANALYSIS OF BARRIERS AND POTENTIAL SOLUTIONS

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

- Barriers impacting the long-term planning of offshore grids (section 3.1),
- Barriers related to the operation and control of offshore grids (section 3.2),
- Barriers hampering the integration of DRU technology in offshore grids (section 3.3),
- Barriers related to the protection of offshore grids (section 3.4),
- Barriers related to the test environment for HVDC circuit breakers (section 3.5),
- Barriers hampering the use of DCCBs in offshore grids (section 3.6),
- Barriers related to the regulation and financing of offshore grids (section 3.7).

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 still needed. 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 organized as follows. Firstly, a description of the relevant barriers and the manner of addressing them by the corresponding WP(s) is provided. Secondly, specific barriers and related solutions are analysed. Finally, the links with other categories of barriers are discussed.

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

3.1.1. GENERAL ANALYSIS

The long-term planning of a MOG requires several ingredients. First ingredient 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. Second ingredient is the definition of working conditions for the different components of the system, i.e. the requirements that should be met by the components. Third ingredient 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 major objective of PROMOTioN WP1 was the definition of the requirements that should be met by an offshore grid and the wind farms connected to it, both at a system level and a component level. This objective resulted in three successive deliverables (D1.1, D1.5 and D1.7), and the latest one, D1.7, constitutes a revision and combination of the first two. Note that Work Package 1 resulted in three other deliverables, D1.2 collecting

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lessons learned from existing offshore connections and grids, D1.3 compiling and analysing past and ongoing studies about offshore grids, and D1.4 deriving a draft roadmap for the evacuation of offshore renewable generation.

At the time of writing of this Deliverable (December 2017), the work of WP1 is finishing and several barriers impacting the long-term planning of offshore grids have been alleviated. Indeed, most system requirements have been defined. However, the definition of required behaviour of components on the DC side of a MOG is challenging. Indeed, standards do not exist yet and the choice of specific detailed requirements can drastically impact the business case of an offshore grid. For these reasons, requirements are not yet 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, of 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.

3.1.2. 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. Indeed, offshore grids will be very different from onshore grids and the direct transposition of deterministic criteria for planning could lead to over-costly solutions and may not always be relevant. Cost-effective offshore grids might thus 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 shores 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 load areas, instead of connecting offshore wind farms to the closest onshore connection point. In the planning stage, it could thus be of paramount importance to consider both the onshore grid and the offshore grid in a more coordinated planning approach.

3. **Need for a clear understanding of DRUs 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. DRUs are expected (by the

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supplier) to have a lower cost compared to equivalent VSCs, but they might be limited to purely radial connections within an offshore grid. Under that specific set of assumptions, radial connections might have an economic advantage compared to meshed grids. On the contrary, if DRUs can be integrated as well in meshed grids, these meshed grids will equally benefit from that cost reduction. Currently, WP2 and WP3 are analysing this potential options (see in particular section **Error! Reference source not found.**).

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 making assumptions about power system elements that do not yet exist and are not even in the development phase. For traditional onshore grids, this is in particular the case with future power plants.

Indeed, 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 could be a realistic range for the voltage droop parameter of HVDC converters. The lack of typical values could hamper the planning of offshore HVDC grids. It is thus of paramount 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 better understanding about the assumptions that could be made during the long-term planning phase.

5. Need for a clear understanding of the DC CBs (circuit breakers) 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 DCCBs capabilities and costs will drastically impact the business case of coordinated solutions such as meshed grids.

If only hybrid DCCBs 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 DCCBs can also be used (much cheaper than hybrid circuit breakers, but they might have to be used only in conjunction with full-bridge VSCs), offshore wind farms 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 DCCBs capabilities (see sections 3.5 and 3.6).

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Regulatory:

6. Need for more insight on how markets are organized

The way the electricity market is organized can drastically impact the benefits of an offshore grid. 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.

3.1.3. 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.

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

3.2.1. MAIN OBJECTIVE

This section is based on the work performed in Work Package 2, 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 about the framework of the investigations is presented in Figure 3.1.

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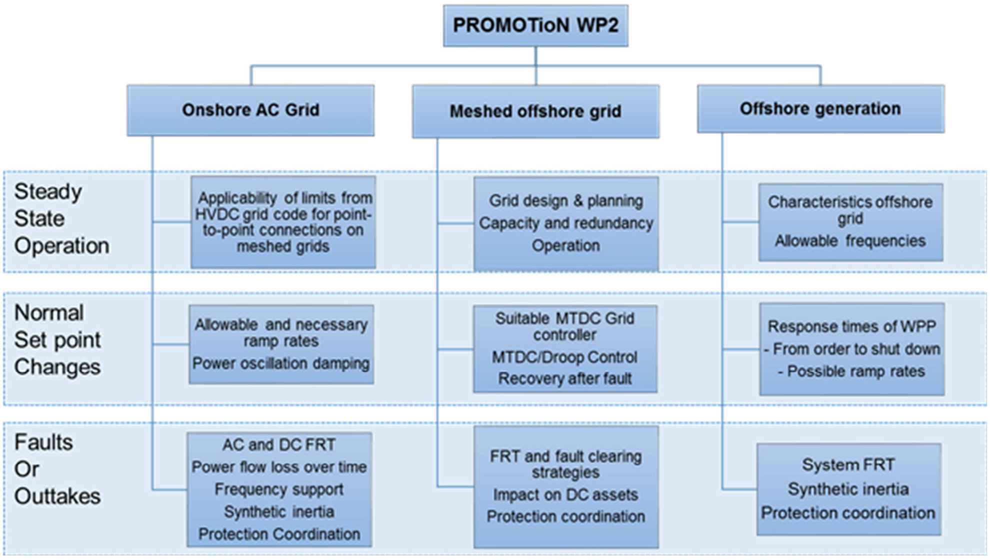

Figure 3.1. Clustering of research aims.

3.2.2. MAIN BARRIERS & 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.

- 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.

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The definition of recommendations on onshore and offshore power systems for existing grid codes suffers from the gaps identified in WP1. Because of 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, finally, the development of 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 the 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 offshore wind farms 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 amount of factors influencing the scenarios and the uncertainty related to these factors, is increasing the complexity of the task.

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

3.3.1. GENERAL ANALYSIS

The work related to these barriers, as analysed in Work Package 3, aims 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 (Work Package 3): diode rectifiers (DR) 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 Diode Rectifier Units (DRUs) are presented below.

3.3.2. MAIN BARRIERS & PROVIDED SOLUTIONS / RECOMMENDATIONS

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

<u>Technical:</u>

1. **Need to define offshore system topologies that allow the integration of diode rectifiers (DR)**

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In WP3, a comparison is made between the well-known VSC-VSC point-to-point connection and the DR-VSC point-to-point HVDC connection for the connection of offshore wind farms. 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, shut-down, 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 DR-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 wind farms connected with the DR 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 DR unit, as it is a passive element. Therefore an additional auxiliary AC voltage source is required during the start-up of the wind farms 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 DR-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, in-puts and out-puts, 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 (e.g. frequency support and power oscillation damping control) with the DR interconnected wind farms, it is required to obtain accurate measurements from the onshore AC power system that needs support. In the currently considered DR-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 currently 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 wind farms 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

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analysing the existing standards, development of procedures for compliance evaluation is one of the main tasks in WP3.

Legal / regulatory barriers:

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.

3.3.3. INTERACTION WITH OTHER TYPES OF BARRIERS

The barriers related to the DRU connection of wind farms 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).

3.4. BARRIERS RELATED TO THE PROTECTION OF OFFSHORE GRIDS

3.4.1. GENERAL ANALYSIS

The work performed in Work Package 4 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;
- To develop detailed protection methodologies for the selected methods;
- To develop configurable multi-purpose HVDC protection 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.

3.4.2. 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 systems. Multivendor interoperability, in the context of DC grid protection, is defined as the characteristics of the DC grid protection system which 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 on 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

A subtask is dedicated to the investigation of interoperability of protection systems within WP4, task 4.3. It is expected that a significant part of the issues can be addressed by either developing (pre)-standards and grid code (see barrier 6) or ‘smart’ design options of the grid.

2. Need to understand models and controls needed for studies

Stability in the context of power systems as defined by is 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 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. But at the current stage none of the HVDC

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manufactures provide their open models to the outside or third parties. However, it is also 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 becomes then 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. However, at the current stage, none of the HVDC converter and cable manufacturers provides their reasonably open models for their customers or third parties. Hence 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.

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 size of the connecting grid(s), grounding (see separate barrier), bus bar 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 is established. Question 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 that are not well established yet. 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 standardization of the grid codes.

In order to pave the road for future multivendor DC grids, a certain degree of standardization 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 inter-operate with each other, given that they remain within predefined operating margins.

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.

Topology of the DC grid should be defined in advance. Since 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 as well. It is

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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. Standardization 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 constrains in the physical behaviour of DC grids (i.e. no zero crossing currents, propagation of very high speed for both current and voltage waves). Also specialised power components will be required. More particularly, current suppression devices, such as DC CBs, 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 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.

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

3.5.1. 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 Work Package 5 is

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to, based on fault analysis of multi-terminal HVDC networks, develop suitable test requirements and a test programme. As well as realizing a test circuit based on AC short-circuit generators.

The initial objectives identified are:

- To identify worst case situations from 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 realize real high-power test-circuits including the necessary equipment specifically needed for DC testing.

3.5.2. 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.
- 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. As a consequence, 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 a HVDC grid. These parameters can greatly affect the stresses experienced by a HVDC circuit breaker. In this work package some suitable assumptions have been made to arrive at somewhat realistic stresses.

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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 realized 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 standardized component, as compared to AC circuit breakers.

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 neutralization time.

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- 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 realized 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 (categorized 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 which are needed for HVDC breakers.

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

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Due to the physical size of a complete HVDC circuit breaker, the amount of power required (e.g. 18,75 GW for a 25 kA 500 kV breaker) 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 a 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 the work package participants that modular and synthetic testing is an adequate method to do so.

3.5.3. MAIN IMPLICATION FOR INTERACTION WITH OTHER WPS

The results of WP5 may impact:

- WP4 task 7 which deals with a socio-economic comparison of protection schemes. The cost of testing a 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.

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3.6. BARRIERS HAMPERING THE USE OF DCCBS IN OFFSHORE GRIDS

3.6.1. 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 (CB) 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 currently 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 DC voltages (EHV DC). This roadmap will contain performance specifications, integration investigations and simulation studies.

3.6.2. MAIN BARRIERS & 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**

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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 CB between the three manufacturers. Also DC CB 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 CB model testing plan applicable to all DC CBs, and therefore new task T6.9 was introduced. Also, Real-time DC CB models for two key DC CB topologies are required for system level studies. Deliverable D6.9 is expected in December 2017.

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 this work package is to develop a roadmap for scaling DCCBs. 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.

3.6.3. 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 CBs and test circuit development is based on simulation studies using verified DC CB models.

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

3.7.1. GENERAL ANALYSIS

Work Package 7 looks at the appropriate European regulatory target framework from a legal, economic and financial point of view in order to the development an integrated offshore electricity transmission infrastructures with the aim of:

- Fostering efficient investments by creating a level playing field;
- Coordinating the offshore grid development and the connection of wind farms; and
- Ensuring its financial viability

The framework and regulatory principles should be able to be applied to the Northern Seas offshore grid, but could be valuable for other regions where current or future (integrated) offshore electricity grid developments are taking place.

3.7.2. MAIN BARRIERS & PROVIDED SOLUTIONS / RECOMMENDATIONS

1. Need for a 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 will do so. A passive approach (self-restraint) does not constitute the required legal certainty as individual country-specific interests may change over time.

Solutions / recommendations

Firstly, increase the coordination for the development of a (joint) jurisdiction with predictable legal behaviour.. Secondly, harmonize the rules and the regulatory framework, with higher level of integration of assets and markets. This will require more and a wider scope of harmonisation.

2. Need for coordinated offshore and onshore grid planning

a. Need for steering offshore wind siting

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?”. While deciding upon a site for developing an offshore wind farm various constraints need to be taken into consideration. These may consist of social, environmental, economic and technological limitations. Therefore, during the planning stage, effective coordination of various agencies is required, even across borders. Moreover, the location of offshore wind farms 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. Currently, different policies (Open door approach, Zone approach and Single siting approach) have been implemented by the countries around the Northern Seas.

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b. Need for allocating offshore grid responsibilities.

In the North Sea countries, there are differences between the states in terms of the responsibility of the grid connection and other activities related to the development of combined or MOG (e.g. interconnection). Furthermore, there are differences in the incentives embedded in the respective regulatory framework for the different investments types.

Depending on the responsibility for the offshore grid connections, in case of a TSO 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 born 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, whereas in most other North Sea countries the TSO has more of a system wide grid responsibility (onshore / offshore grid and interconnection). Under the Offshore Transmission Owner (OFTO) regime in the UK, the generator builds (under the generator approach instead of the OFTO led approach) the offshore transmission assets needed to connect its windfarms to the onshore grid (under the grid responsibility of the TSO, i.e. National Grid). After construction, the assets are transferred to a competitively appointed offshore transmission owner (OFTO).

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 encourages asset specific optimisation (due to different offshore responsibilities) whereas the TSO system-wide approach seems more suitable to coordinate and build offshore grid assets.

Solutions / recommendations

One of the keys to a successful implementation of an integrated approach to cross-border offshore grid development in the North Seas is the coordination among various 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). To this extent, there are a number of onshore-offshore coordination issues that may impact the development of the required offshore transmission infrastructure and the necessary onshore grid reinforcements (and associated costs).

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 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 wind farms 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

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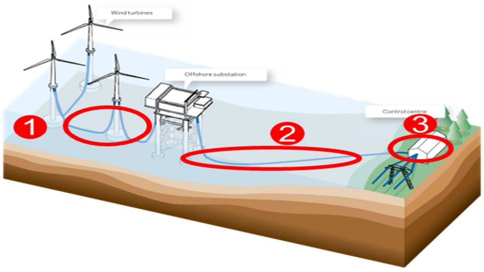
grid access and the one that is responsible for paying the grid connection costs. The grid connection costs can be attributed to the wind generation developer based on *three connection charge policies* as shown in Figure 3.2.



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 3.2. 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 a clear and level playing field in increasingly integrated electricity market coordination will support moving to coordination and as such harmonisation of the planning of the OWF investments, clear and harmonised rules on parties' responsibilities and the determination of connection charges.

3. Need for use of cooperation mechanism for RES Support

The support scheme arrangements for wind farm developers vary in type and level of support among the North Sea countries. Currently, the regulatory framework for wind farm developers required the offshore wind farms to be connected to the respective national markets.

However, in combined grid solutions (or even full meshed solutions) the wind farm developers might be feeding 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 considerably affect the business cases of 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 offshore wind in hybrid or combined solutions (i.e. connecting OWFs to interconnectors). However, there is a

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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 considering RES priority operational dispatch

Priority access is very relevant for the offshore grid when it comes to 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 thus how much capacity will be 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 (it is clear for the CGS) [3].

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 turned off, 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 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.

Solutions / recommendations

[3] These rules are stipulated in the Network Code on CACM is dealt with in PROMOTioN, D7.1.

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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 the access to the grid is prioritised. However, 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[4].

5. Need to improve ENTSO-e CBA Methodology for evaluating investments

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 Regulation (EU), No 347/2013 ENTSO-e and ENTSOG received the task to develop these methodologies. 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).

Solutions / recommendations

The CBA methodology should be developed further 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 apples-to-apples comparison of investments.

6. Need to improve framework for cross border 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

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

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(North Sea) 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 born 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.

7. Need for harmonisation of transmission tariffs

Transmission tariffs ('G-charges') and connection tariffs ('C-charges') divide costs once more, now among grid system users. The different (national) transmission and connection tariff designs are expected to have an impact on the development of offshore wind farms. 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 Sea 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 thus beneficiaries of transmission lines; therefore they too should be responsible for the cost incurred for developing the grid. Currently, G-charges are often seen as unnecessary, as the cost will be passed to the consumers anyway. However, besides recovering the cost of the grid, transmission tariffs can be used to send a locational signal for the siting of new capacity. Therefore, G-charges will be internalized in the investment decision of developers leading to efficient siting of the new capacity from a grid development perspective.

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.

8. Need to provide sufficient investment incentives

The framework for investment incentives is dealt with in D7.4 and is planned for April 2019 release.

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

A challenge is the legal qualification of the offshore assets. Depending of 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 an interconnector, with specific rules and regulations. However, over time this asset may be combined with offshore wind generation. 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

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that project developers (not being the TSO or an OFTO) incur the construction and operational costs. 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.

Solutions / recommendations

Harmonisation may help to establish a level basis for assets that are currently classified differently under different regimes, but have the same functional use. This will 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.

3.7.3. MAIN IMPLICATIONS WITH OTHER WORK PACKAGES

The outcome of the regulatory framework is important for the outcome of the different Concepts. Those Concepts will be used in the different WPs as basis hence WP7 has a major impact on the other Work Packages.

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4. WAY FORWARD

4.1. CURRENT STATE OF THE ANALYSIS

4.1.1. ANALYSIS OF BARRIERS AND SOLUTIONS

The main aim of Deliverable 12.1 is to give an overview of the barriers identified in the Work Packages and show how they influence the key technical, financial, economic, legal and market buildings blocks for creating a MOG. And show what possible solutions are already provided. The preliminary solutions are based on the results from the Work Packages for the period up to early November 2017. Further analysis may provide further insights that will be considered when working on the next deliverables of WP12.

4.1.2. ANALYSIS OF CONCEPTS

Current analysis of a possible future MOG have provided an insight into possible directions for its development in the form of topology Concepts. The Concepts will be discussed with the members of the other Work Packages to see if different Concepts can be identified for further study.

4.2. WAY FORWARD

At this stage we conclude that the following steps are needed to get a better view on the Concepts and possible barriers & solutions:

- Discuss the Concepts with the different Work Packages, in order to identify additional viable Concepts;
- Discuss the different Concepts to identify what:
    - Questions need to be looked at in more detail for each of the different areas; technical, legal / regulatory and from an economic / financial perspective;
    - Identify specific barriers or challenges may be related to each different Concepts;
    - Identify the solutions, and any possible limits to these.
- Attention will be given to the factors that will be of importance for developing scenarios for further evaluation of the Concepts in deliverable D12.2.

The result generated will give a better understanding of the barriers and solutions for the different Concepts as discussed in this deliverable. And to act as input for the analysis in the upcoming deliverables, that will build on the results in this deliverable going forward. In the end, this will be part of the analysis for developing the Deployment Plan in deliverable D12.4.

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5. BIBLIOGRAPHY

Best pathways (2012). Offshore wind reduction pathway studies. Available on the World Wide Web *https://www.thecrownestate.co.uk/media/5493/ei-offshore-wind-cost-reduction-pathways-study.pdf.* Retrieved on 3 January 2017.

Commission Expert Group on electricity interconnection targets (2017). Electricity interconnection targets. Available on the World Wide Web: ***https://ec.europa.eu/energy/en/topics/projects-common-interest/electricity-interconnection-targets/expert-group-electricity-interconnection-targets****.* Retrieved on 5 March 2017.

Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions A policy framework for climate and energy in the period from 2020 to 2030 (2014). Available on the World Wide Web: *http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:52014DC0015.* Retrieved on 5 March 2017

E-Highways2050 (2015). Available on the World Wide Web: *http://www.e-highway2050.eu/e-highway2050/.* Retrieved on 10 March 2017*.*

European Commission (2016). Clean Energy for all Europeans – Unlocking Europe's growth potential. *European Commission press release IP/16/4009.*

European Commission (2016). Energy Efficiency Directive Winter package 2016. Available on the World Wide Web***:*** *https://ec.europa.eu/energy/en/content/energy-efficiency-directive-winter-package-2016*. Retrieved on 1 August 2017.

European Parliament (2017). Review of the renewable energy directive 2009/28/EC to adapt it to the EU 2030 climate and energy targets. Available on the World Wide Web: *http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=consil:ST_15120_2016_INIT*. Retrieved at 1 December 2017.

European Parliament (2017). Cleaner Energy: New binding targets for energy efficiency and use of renebales. Available on the World Wide Web*: http://www.europarl.europa.eu/news/en/press-room/20171128IPR89009/cleaner-energy-new-binding-targets-for-energy-efficiency-and-use-of-renewables*. Retrieved on 1 December 2017.

EU Directive 2009/28/EC (2009). Available on the World Wide Web***:*** *http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32009L0028. Retrieved on 10 March 2017*

ISLES (2013). Irish Scottish Links on energy Study. Available on the World Wide Web: *http://www.islesproject.eu/* Retrieved on 22 January 2017.

NSEC agreement (2016). North seas countries agree on closer energy cooperation. Available on the World Wide Web: *https://ec.europa.eu/energy/en/news/north-seas-countries-agree-closer-energy-cooperation****.*** Retrieved on 8 May 2017.

Presidency conclusions (2007). Council of the European Union: presidency conclusions (7224/1/07 REV1), March 2007. Available on the World Wide Web: *http://register.consilium.europa.eu/doc/srv?l=EN&f=ST%207224%202007%20REV%201.* Retrieved on 12 March 2017.

Renewable Energy Roadmap (2007). SEC 2006 1720 / Sec 2007 12. Renewable Energy Road Map in the 21st century: building a more sustainable future. Available on the Word Wide Web*:* ***http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:l27065*****.** Retrieved on 12 April 2017.

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

Twenties (2013). Transmission system operation with a large penetration of wind and other renewable electricity sources in electricity networks using innovative tools and integrated energy solutions (TWENTIES). Available on the World Wide Web:
http://www.ewea.org/fileadmin/files/library/publications/reports/Twenties_report_short.pdf. Retrieved on 12 March 2017.

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6. GLOSSARY OF TERMS

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, governmental 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.

Related portfolio solution: Solutions and recommendations defined for specific barriers of challenges identified by the different Work Packages within the PROMOTioN project.

Scenario: A scenario is the combination of certain assumptions for the different parameters impacting 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.

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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 offshore wind farms 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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7. ABBREVIATION LIST

AC	Alternative current
C-Charges	Connection Charges (Connection Tariffs)
CBA	Cost Benefit Analysis
CB	Circuit Breaker
CBCA	Cross Border Cost Allocation
CGS	Combined Grid Solution
DRU	Diode Rectifier Unit
EEZ	European Economic Zone
EHV DC	Extreme High DC voltages
ENTSO-e	European Network of Transmission System Operators
EMTDC	Electromagnetic Transients including DC
EMTP	Electric Magnetic Transients Program
G-charges	Grid Chargers (Transmission Tariffs)
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
MOG	Meshed Offshore Grid
MTDC	Multi Terminal Direct Current
NRA	National Regulatory Authorities
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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8. 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 barriers 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 standardization (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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9. 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 a 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.

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10. 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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