CIGRE-445

2021 CIGRE Canada Conference & Expo
Toronto, Ontario, October 25-28, 2021

Offshore substation platform expandability

C.A. PLET[1], M.S. ZADEH[1] & N. ROUXEL[2]
DNV Energy Systems
[1]Canada, [2]United States

SUMMARY

With the increasing number of offshore wind farms being planned in North America in the next decade or so, many jurisdictions including New York State Energy Research & Development (NYSERDA) are looking into possibilities of requiring future expandability of offshore substations to enable future connection of radial export transmission links into an interconnected offshore grid. In Europe, several HVDC projects are currently being built that have so-called 'multi-terminal readiness' as a built-in feature. In addition to ensuring compatibility of the system ratings such as voltage levels, frequency, earthing/grounding etc., the offshore substations themselves must be designed with future expansion factors in mind due to the restricted space on offshore platforms.

Offshore grid expansions can be realized to achieve redundant capacity, redundant auxiliary power and they can enable offshore substations to act as 'stepping-stones' for more remote offshore substations. They can also be used to service different purposes such as connecting offshore loads to wind farm collector systems, or to create potential additional transmission capacity between two onshore points of interconnection in addition to exporting offshore wind power. Depending on these different types of offshore grid expansions and the technology of the existing export link, different technologies such as medium voltage AC, high voltage AC or even HVDC can be used.

The different types and technologies of offshore grid expansions require different levels of preparation for offshore substations that have to be made in order to enable this expandability. Some must be taken into account at very early system design stages, some preparations must be made at the time of designing and manufacturing of the equipment at the factory and/or building the platforms at the yard, others can be made at a later stage during onsite installation. The platform readiness to accept additional cable connection(s) also determines the required upfront (anticipatory) capital investment. In particular, the availability of space is an issue on platforms which are typically optimized for an initially envisaged application. Depending on the certainty of the future expansion, different levels of preparedness, and thus different levels of associated anticipatory investment, can be chosen in order to manage the risk of stranded/unused assets.

In this paper, a classification of different levels of expandability preparedness is proposed. The proposed index ranges from the absolute minimum provisions that must be made to enable the minimum levels of future expansion, to offshore substations that are already fully equipped and 'Plug & Play' ready for future expansions. The proposed index is intended to be used as an indicator to planners, lenders and developers of how much additional effort and investment would be needed to realize a certain extension to an already existing offshore substation platform.

KEYWORDS

Offshore wind, offshore transmission, offshore substation platform, offshore platform, expandability

Cornelis.plet@dnv.com

Introduction

In early offshore windfarms, the wind turbine generators could be connected directly to the onshore grid by extending the medium voltage submarine array cables. Today, driven by ambitious renewable energy targets, offshore wind farms have grown in capacity and are often located increasingly further from shore. In order to transmit the generated wind energy to shore, wind turbine generators are connected to an offshore substation, where the medium voltage is stepped up to a high voltage, primarily to reduce losses, and transmitted to shore via a smaller number of high power long distance submarine export cables. For very large and/or relatively remote offshore wind farms, HVDC transmission is used, which means that the offshore substation also houses a converter. To date, these high voltage AC and DC transmission links have predominantly been point-point connections. In order to save costs, these connections are often built enough to meet minimum requirements and without provisions for future expandability (This typically means that no offshore HV busbar is present) s.

As more offshore wind farms are being built in closer proximity to each other and to other electrical system users, the next step in offshore power system development is the expansion of point-point export systems, into more complex networks. Expansions can be made for different reasons such as increasing the number of wind farm array cables, connecting offshore loads, realizing redundant capacity between adjacent offshore wind farms, etc. These expansions often take place after the realization of the first point-point export link. To enable the expansion, additional electrical equipment and structural elements are necessary. Some of these provisions have to be in place from the very initial project stages, resulting in the need for anticipatory investment. In case a potential expansion is not realized, these provisions become so-called stranded assets. Different levels of preparedness for future expansions require different levels of anticipatory investment which can be chosen based on the likelihood of the need and realization of a future expansion.

This paper proposes an index to describe the degree of preparedness of an offshore substation for future expansion to aid different project stakeholders such as system designers and investors. First, different reasons for offshore system expansions are discussed and, where applicable, illustrated with real world examples. This is used as a baseline to determine the different provisions that need to be in place to enable these expansions. The provisions will be classed based on their relative cost and their ability to be realized at a future date. This ranking is then used to classify substation expandability on a scale, ranging from not expandable to plug & play ready.

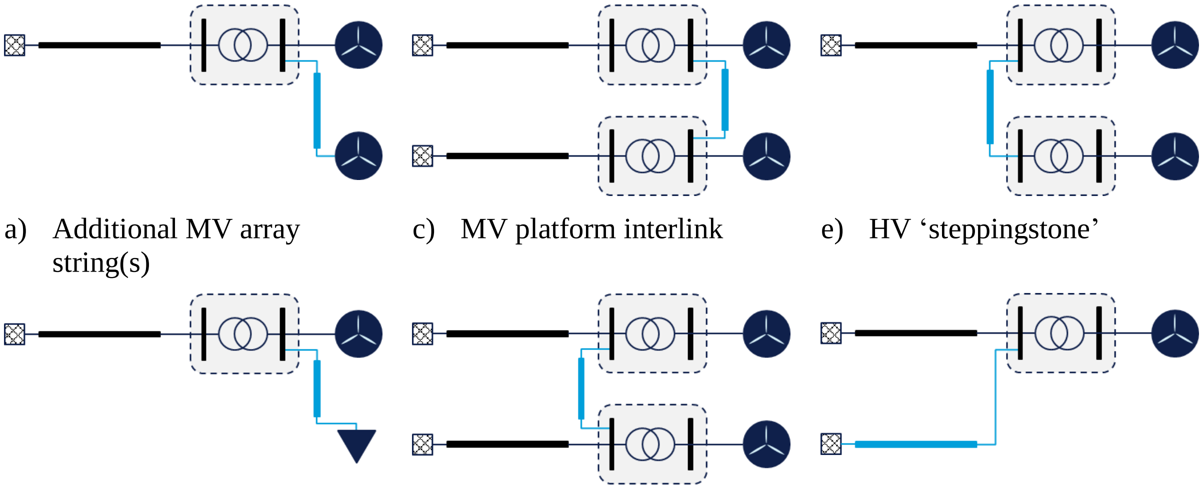
Offshore grid expansions

In general, offshore power system expansion provisions can be made to the offshore substation on the wind farm array side (medium voltage level) or on the export side (high voltage level), depending on the purpose of the expansion, as shown in Figure 1. The following describes each option:

Additional MV array string(s) – to increase the offshore wind farm capacity (e.g. due primarily to repowering) by connecting additional array cables to the offshore substation, as shown in Figure 1 (a). This will require additional medium voltage switchgear bays and sufficient additional capacity of the export link system.

Supply to offshore load – to provide power from shore to offshore energy users such as oil & gas platforms or island communities, by connecting an additional MV cable, as shown in Figure 1 (b). This requires an additional MV switchgear bay. Examples of this type of expansion are the Danish Anholt wind farm which supplies the nearby Anholt island [7], and the Dutch electrification of oil & gas platforms [9]. Connecting both wind turbines and consumers can lead to different requirements for the availability and reliability of the offshore power system compared to when the link only functions as export system [8].

MV platform interlinks – to realize a redundant supply of auxiliary power to the offshore platform and offshore wind turbine generators in case of an export link outage, by connecting an MV cable to an offshore substation of an adjacent offshore wind farm, as shown in Figure 1 (c). This requires an additional MV switchgear bay. Due to the limited capacity of this type of interlink it generally cannot



a) Additional MV array string(s)

c) MV platform interlink

e) HV ‘steppingstone’

b) MV supply to offshore load

d) HV platform interlink

f) HV transmission to different onshore substation

Figure 1 - Offshore AC power system expansion purposes

be used as redundant transmission path. An example of this type of expansion is the link between the Danish Horns Rev 2 and 3 offshore wind farms [1] and the Dutch ‘Net op zee’ 700 MW AC offshore substation design standard [2].

HV platform interlinks – to realize redundant transmission capacity in case of an export link outage, by connecting HV cable(s) to offshore substation(s) of adjacent offshore wind farm(s), as shown in Figure 1 (d), which requires an HV busbar and additional HV switchgear bay(s). This makes sense in case of clusters of nearby offshore wind farms. Examples of this type of expansion are the Dutch GEMINI [3], German OstWind [4], the Belgian Modular Offshore Grid [5], and the British Hornsea ONE [6] offshore grids. Some of the German offshore HVDC stations in the North Sea have HV AC platform interlinks.

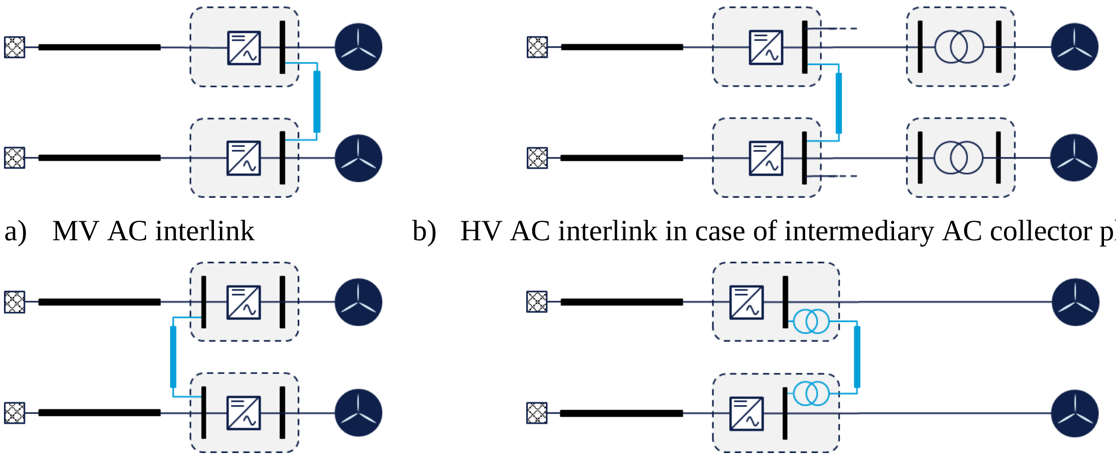
HV steppingstone – to connect another, often more remote, offshore substation and offshore wind farm, as shown in Figure 1 (e). This will require an HV busbar with an additional switchgear bay and sufficient capacity of the export link components. This type of topology could also be an operational configuration or a first development step of the HV platform interlink topology. An example of such an arrangement is the Belgian Belwind wind farm which is connected to shore via the Northwind offshore substation [7].

HV Transmission – to provide transmission capacity to a second onshore substation to improve the availability of the export system, and to realize transmission capacity between the two onshore substations via the offshore power system at times of low wind, as shown in Figure 1 (f). This requires an HV busbar and additional HV switchgear bay(s). This type of expansion is typically beneficial if the offshore wind farms are located on or close to the route of an interconnector between two states. An example of this type of expansion is the Kriegers Flak Combined Grid Solution between Denmark and Germany (which also requires a frequency changer due to its connection of two separate synchronous zones) [10], the HVDC WindConnector between the UK and the Netherlands [2], and the HVDC Nautilus link between the UK and Belgium [11]. This type of dual purpose functionality of the infrastructure often requires specific agreements and/or regulation to be put in place between the different owners/users and regulators.

HVDC – In case of offshore HVDC converter platforms, similar considerations of AC platforms apply, with some notable differences:

MV AC platform interlinks - as shown in Figure 2 (a) can be applied to realize a redundant auxiliary power supply. This requires an additional MV switchgear bay.

HVDC platform interlinks - as shown in Figure 2 (c) can be applied to realize redundant transmission capacity. This requires a DC busbar/switchyard. HVDC GIS is currently under development, with the



a) MV AC interlink

b) HV AC interlink in case of intermediary AC collector platforms

c) HVDC interlink

d) HV AC interlink using dedicated transformers in case of direct connection of wind farm strings

Figure 2 - Interlinks for HVDC platforms

first systems being placed in operation in the next few years. Special consideration needs to be given to the need for HVDC circuit breakers, as the knowhow on system integration of such devices is limited. HVDC interlinks cannot be used for supplying auxiliary power to another HVDC platform to replace the presence of an emergency diesel generator, because it is not economically feasible to tap relatively small amounts of power from an HVDC link. Furthermore, HVDC converters require specific control and protection systems to be able to operate in a so-called multi-terminal network configuration such as the stepping stone and the offshore transmission configurations such as those shown for AC in Figure 1 (d), (e) and (f) [13]. The vendor specific implementations of these control & protection systems complicate the interconnection of HVDC systems from different vendors.

HV AC platform interlinks – Early offshore HVDC export systems made use of intermediary AC collector substations, which means an HV AC busbar is present on the HVDC converter platform and, at the expense of an additional HV AC switchgear bay, could be used to make a platform interlink to improve the availability of the offshore grid, as shown in Figure 2 (b). An example of this is the 155 kV AC connection between TenneT's DolWin1 and DolWin3 offshore converter platforms in the German North Sea [15]. In modern offshore HVDC converter stations, the wind farm strings are directly connected to the converter station, and an additional transformer or winding on the converter transformer is necessary to be able to create an HV AC platform interlink, as shown in Figure 2 (d).

Provisions for expandability

The provisions that are necessary to enable the future expansion of an offshore substation depend on the type of offshore grid expansion that is envisaged, and can largely be classed in substation related aspects and system related aspects. In order to enable an offshore grid expansion, an offshore substation must have some or all of the following provisions:

Primary equipment – to enable the physical connection of an additional cable:

- HV busbar is necessary in case of an HV connection, which is not usually foreseen in offshore substations for straight point-point connections
- Additional switchgear bay is needed to connect the additional cable to the offshore power system. In case of MV or HV AC connections, this is typically a GIS circuit breaker bay with associated disconnectors and earthing switches. In HVDC, both AIS and GIS implementations are possible, but are unlikely to include an HVDC circuit breaker on the same topside due to its large size
- Additional power cable realizes the offshore power system expansion. As such, this cable is typically installed at the time of expansion

Secondary equipment – to enable the electrical operation of the primary equipment

- Bay control & protection units are needed for each additional switchgear bay

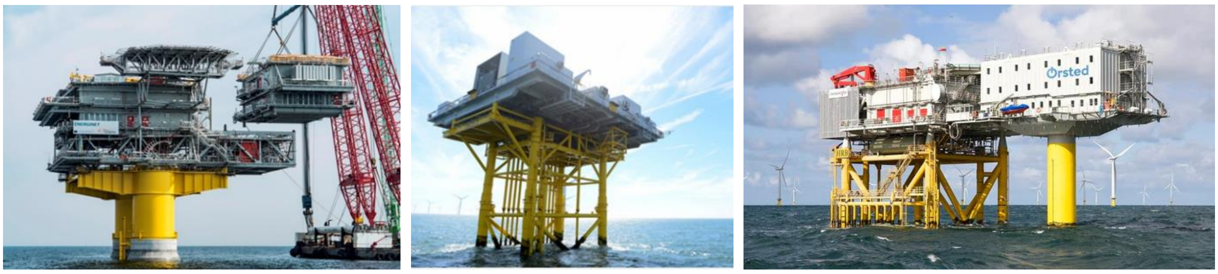
- Metering is needed to enable dispatch and market settlement of any additional power system user that is connected as part of the offshore grid expansion
- Instrumentation wiring is needed to connect the additional primary and secondary equipment. In modern digital substation design the need for additional wiring can be kept to a minimum by using substation bus systems

Auxiliary systems – to ensure the required operational conditions for the additional primary and secondary equipment:
- HVAC, firefighting & lighting in any additional space that is necessary to host additional primary & secondary equipment
- LV wiring is needed for the power supply to the additional primary & secondary equipment
- Diesel generator and UPS capacity (e.g. additional batteries) are required to serve the increased auxiliary load demand due to the additional primary & secondary equipment, and due to additional HVAC & lighting requirements

Structural support – to host the additional primary, secondary and auxiliary equipment:
- Space for additional primary, secondary & auxiliary equipment. Sufficient footprint and headroom must be available for the installation, operation and repair of the equipment. The location of the additional space must be chosen such that it easily facilitates the integration of any additional equipment with existing systems. This includes the availability of free space for cables and wiring in sealed wall crossings, additional space for power cable installation & routing and in instrumentation & LV wire trays
- J-tubes are required to enable the pull in of additional power and communication cables. The spare J-tube will need to be designed with sufficient room and bending radius to accommodate the future expansion cable. Sufficient space must be available on the cable deck to pull-in the additional cable
- Seabed cable arrangement must leave sufficient space for the installation and repair of an additional submarine cable
- Support structure design must be sufficient to support the installation of additional weight, and offer space and support points to host any additional modules.

SCADA system upgrades – to integrate the functionality of additional equipment. Special control modes necessary for the operation of more complex offshore grid topologies must be enabled, especially in the case of HVDC. Limited interoperability of control & protection systems of different vendors should be taken into account.

System ratings need to be compatible with the foreseen offshore grid expansions:
- Basic insulation level and rated voltage of offshore grid expansions need to be the same, or additional transformers and overvoltage protection equipment are necessary.
- Power ratings of transformers and cables need to ensure sufficient margin for any possible additional loads resulting from future expansions is present.
- Reactive power compensation of additional cable(s) must be present to comply with grid code power factor requirements. This can be realized through additional shunt reactors, variable reactors with tap changers or dynamic reactive power compensation systems such as SVCs and STATCOMs
- Current ratings of busbars, switchgear and instrumentation need to ensure sufficient margin for any possible additional currents resulting from future expansions.
- System earthing design must be sufficiently flexible to accommodate more complex offshore grid topologies where multiple earthing points could be possible, and ensure changes in short-circuit currents due to system expansions are compatible with equipment and protection settings
- Harmonic stability could be affected by the connection of additional equipment (cable capacitance, shunt reactance) and require retuning and possible additional filter equipment
- Circuit energization equipment ratings such as pre-insertion resistors need to be sufficient to accommodate the connection of additional equipment, or operational philosophies need to be adjusted



a) Modular topside add-on (Kriegers Flak, Denmark) b) Shared support structure (Humber, UK) c) Adjacent platforms (Horns Rev 2, DK)

Figure 3 - Offshore substation expansions

In addition to the above provisions, the need for platform certification in certain jurisdictions, and any requirements (and costs) for recertification following from an offshore substation expansion, would have to be considered.

Substation expansions

There are three possibilities to install additional provisions necessary for offshore substation expansions:

- On the same support structure, <u>within</u> the existing topside:
    - Plug & play: All necessary provisions are installed during manufacturing and ready to use at the time of expansion
    - Expandable: Only minimum provisions such as space, structural support and interfaces for necessary equipment are installed during manufacturing and available and accessible for future installation
- On the same support structure, <u>adjacent</u> to the existing topside:
    - By installing an additional module onto the existing topside, as shown in Figure 3 (a).
    - By installing a separate additional topside onto the same support structure, as shown in Figure 3 (b)

In both cases, space, structural support and interfaces for the future installation of the module must be present from the start.

- On a separate adjacent support structure and topside
    - Connected by a bridge, as shown in Figure 3 (c), if the offshore substations are closely located e.g. several 10s of meters apart. The bridge will allow for easy personnel accessibility between the platforms, and can be used to support connections such as HV cables, GIL, LV power supply, communications, and other amenities.
    - Connected by submarine cable, if the offshore platforms are located too far away from each other to be connected by bridge.

In both cases, space on the seabed, and additional electrical switchgear bays for the future installation and connection of the additional offshore substation must be present from the start.

Anticipatory & retrofit expenditure

The future expandability of an offshore substation depends on the degree to which provisions (e.g. equipment, system and structure ratings, dimensions, SCADA integration, …) necessary to enable a future expansion are present, and how this affects the relationship between the amount of anticipatory and retrofit expenditure that is necessary to realize these provisions, as illustrated in Figure 4.
Some of these provisions must be in place at the time of manufacturing of the platform and result in a need for anticipatory expenditure (ANTEX). Without these minimum provisions, such as sufficient space for the installation of an additional cable and switchgear bay, the platform is simply not expandable. This would be a suitable choice of design for offshore substation locations where no plans and no potential for future expansions exist.

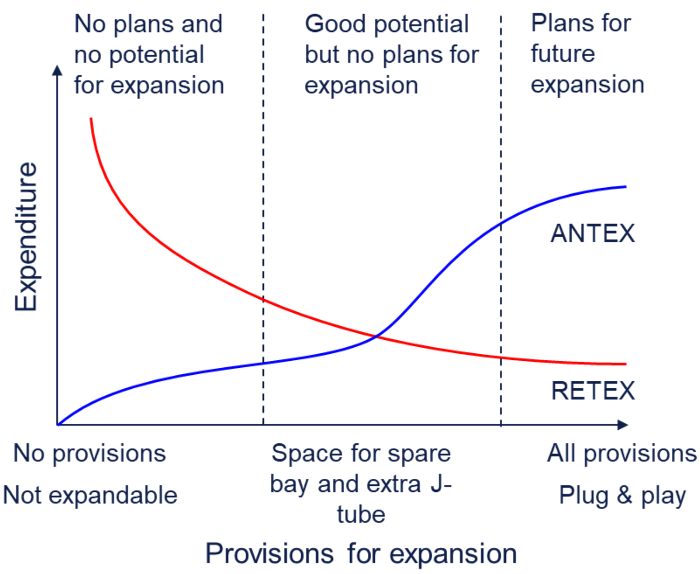


Figure 4 – Anticipatory expenditure (ANTEX) vs retrofit expenditure (RETEX)

Provided the basic requirements for expandability are in place, other provisions can be installed during a future retrofit and require retrofit expenditure (RETEX). The offshore retrofitting of the installation and connection of the additional equipment, modules or topsides is typically more expensive than if it was done in the harbor during the original construction, but reduces the initial required ANTEX. This would be a suitable design choice in case of offshore substations in an area where there is good potential for future expansions, but no certain plans. In a Plug & Play offshore substation, all the necessary provisions for a future expansion are in place from the start, leading to the highest ANTEX, but in return requiring the lowest future RETEX when the expansion is realized.

Different levels of preparedness for future power grid expansions can be identified based on the anticipatory availability of the necessary provisions as illustrated in Table 1.

Table 1 - Classification of offshore substation expandability - (X) = limited impact

Provisions	Impact on initial CAPEX investment	level of expandability			
		Integration on same support structure			Separate support structure
		Plug & play	Modification of existing topside	Separate topside (module)	
Additional J-tube & space on seabed and cable deck for additional cable	$$	X	X	X	
Space and structural provisions for additional switchgear bay	$	X	X	X	X
Space in cable trays and provision for new cable routes	$	X	X	(X)	(X)
Space and ampacity for additional UPS batteries & diesel genset	$	X	X		
HV busbar	$$	X	X		
Additional HV switchgear bay	$$	X			
Additional MV switchgear bay	$$	X			
Additional platform cable	$$			X	X
Additional bay control & protection unit	$	X			

Communication & LV power supply wiring	$	X	X		
Additional HVAC, lighting & firefighting capacity	$$	X	X		
Additional UPS capacity	$$	X	X		
Inclusion of additional equipment in the SCADA	$	X			
Control system vendor interoperability	$	X	X		
Provision for increased capacity of life saving equipment (life rafts, muster stations…)	$		X	X	
Additional capacity in HV systems (transformer, cables, shunt reactors)	$$$	X	X		
Support structure architecture and structure ready for extension	$$$			X	X
Additional space for support structure in the subsea layout	$				X
Accessibility for the handling of new equipment (crane, hatches, doors and corridors size)	$		X		

Conclusions

The rapid growth of offshore wind power, and the increasing supply of power from shore for offshore users is driving the development of offshore transmission infrastructure. To date, most offshore transmission links have been built as single point-to-point connections, but as more and more of these links are built in ever closer vicinity, they can be connected or expanded offshore to initiate the realization of offshore transmission networks. Several different types of offshore power system expansions exist and can be classified on their functionality, technology and voltage level. Unlike onshore power systems, offshore footprint comes at a premium and is limited once an offshore substation has been built. Hence, sufficient space and structural support for the equipment necessary for future offshore substation expansions must be considered from the start. Other provisions such as primary, secondary & auxiliary equipment can be installed during platform manufacturing or the in future as part of a retrofitting campaign, requiring different amounts of anticipatory and retrofit expenditure, respectively. Offshore substation expansions can be realized in different ways, depending on if they will use the same topside and the same support structure as the original offshore substation. Different levels of preparedness for future offshore power system expansions, i.e. the offshore substation expandability, can be chosen, the choice of which ultimately depends on the likelihood of that expansion and whether the required anticipatory investment to do so can be justified.

BIBLIOGRAPHY

[1] https://renews.biz/36553/dong-vattenfall-link-horns/ <accessed on 6th of June 2021>

[2] https://www.tennet.eu/our-grid/offshore-grid-netherlands/dutch-offshore-grid/ <accessed on 6th of June 2021>

[3] https://www.geminiwindpark.nl/ <accessed on 6th of June 2021>

[4] https://www.50hertz.com/en/Grid/Griddevelopement/Offshoreprojects/Ostwind2 <accessed on 6th of June 2021>

[5] https://www.elia.be/en/infrastructure-and-projects/infrastructure-projects/modular-offshore-grid# <accessed on 6th of June 2021>

[6] M. Lehmann et al., 'Active Filtering in a Large-Scale STATCOM for the Integration of Offshore Wind Power', 17th Int'l Wind Integration Workshop, Stockholm, Sweden, 17-19 Oct. 2018

[7] http://www.nobelwind.eu/ <accessed on 12th of June 2021>

[8] https://www.offshorewind.biz/2012/11/13/offshore-wind-farm-to-connect-anholt-island-to-danish-grid/ <accessed on 12th of June 2021>

[9] https://www.4coffshore.com/news/anholt-suffers-cable-issues-nid4871.html <accessed on 12th of June 2021>

[10] https://www.tennet.eu/our-grid/offshore-grid-netherlands/programme-2030/ <accessed on 6th of June 2021>

[11] https://www.50hertz.com/en/Grid/Griddevelopement/Offshoreprojects/CombinedGridSolution <accessed on 6th of June 2021>

[12] https://www.nationalgrid.com/group/about-us/what-we-do/interconnectors-connecting-cleaner-future/nautilus-interconnector <accessed on 6th of June 2021>

[13] https://windeurope.org/newsroom/news/6-ways-to-enable-hybrid-projects-in-the-north-sea-windeurope-ceo-urges-action-at-horizon-2020-grids-conference/ <accessed on 12th of June 2021>

[14] S.B. Müller, 'TenneT Offshore - 2 GW Offshore HVDC Grid Connection System', Offshore Power Transmission & HVDC - Virtual Conference, 19th of January 2021

[15] https://www.pfisterer.com/case-studies/dolwin-3-project-successfully-in-operation <accessed on 12th of June 2021>