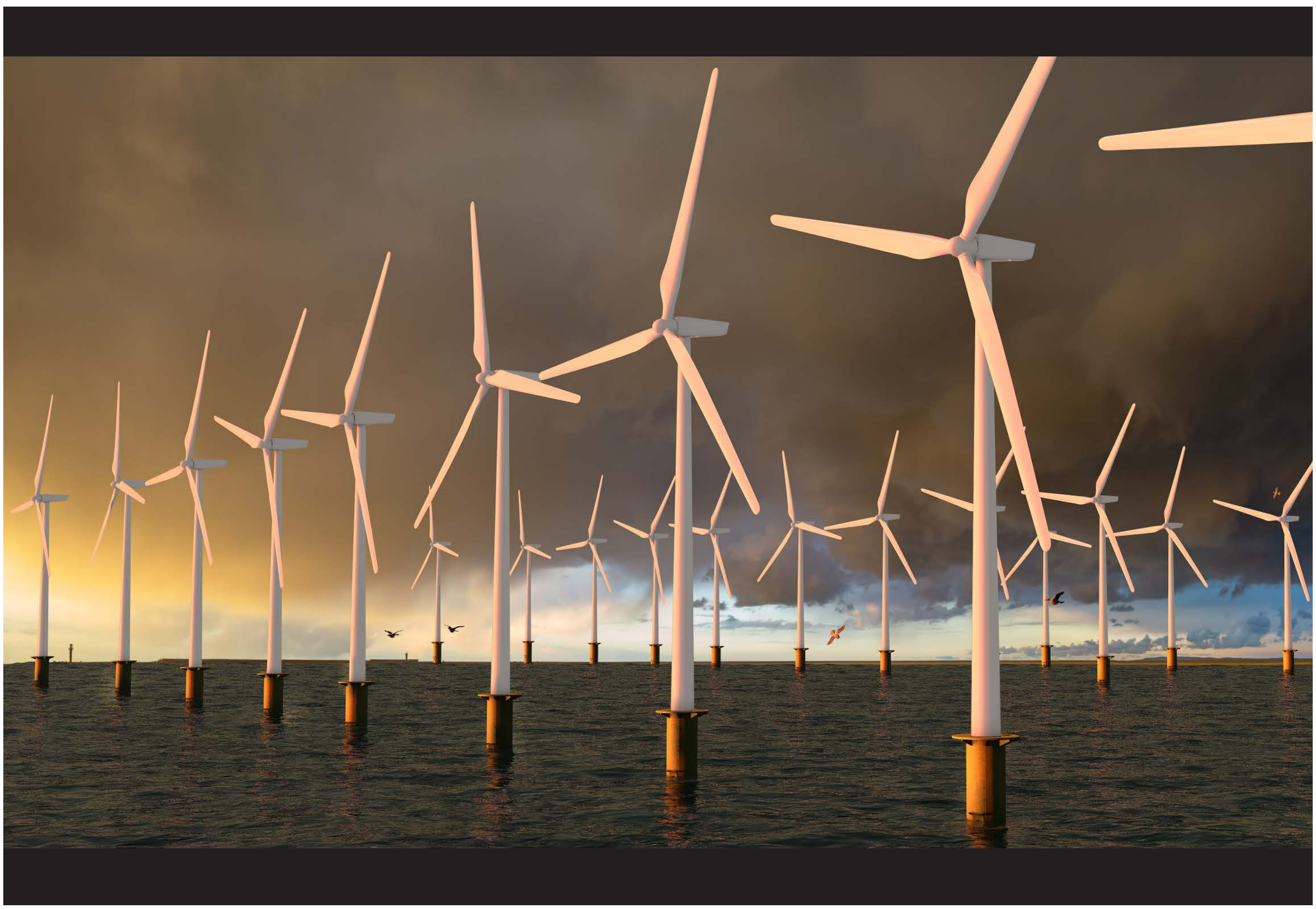
ELECTRIC POWER RESEARCH INSTITUTE

PLANNING FOR THE INTEGRATION OF OFFSHORE WIND GENERATION



March 2020

Key Points

- Price reductions are driving new policy targets for offshore wind.
- Countries who were second movers in Europe were able to draw on experience of neighboring countries. Similarly, the US can draw on European experience.
- Radial grid development remains dominant however the concept of backbone or meshed offshore grids is generating more and more interest from the stakeholders.
- Offshore wind integration onshore is not without its technical challenges, injections at the onshore POI can be large and contain multiple offshore wind plants and can often be considered the single largest infeed.
- Integration challenges such as voltage control, frequency control, dealing with variability and grid stability are as relevant to offshore installations as they are to onshore renewable integration.
- Cable routing does not have to be direct to nearest point on shore, or even nearest high voltage bus. It is possible with coordinated planning to circumvent onshore constraints by routing cables into load centers.
- Floating offshore wind turbines have the potential to revolutionize the offshore wind industry even further opening deeper waters closer to major load centers like California.

Introduction

This whitepaper is intended to provide an overview of the offshore wind transmission industry, how it is beginning to impact the US east coast utilities and an overview of some of the advancements that have taken place around the world in the offshore wind industry. The energy industry in the United States is turning quickly to offshore wind to meet increasingly ambitious renewable energy targets. Since 2016 when the first US offshore wind farm was installed (Block Island wind farm, 30 MW) there have been ambitious targets set in New York (9 GW by 2035), New Jersey (3.5 GW by 2030) and Massachusetts and Rhode Island have awarded 1200 MW of offshore contracts. Table 1 shows the number of projects in the pipeline for the US East coast according to the Bureau of Ocean Energy Management (BOEM).

Year	Project	Power (MW)	State
2020	Coastal Virginia Offshore Wind	12	VA
2021	Vineyard Wind	800	MA
2022	South Fork	130	NY
2022	Ocean Wind	1100	NJ
2022	Bay State Wind	800	MA
2022	US Wind	250	MD
2023	Revolution Wind	400	RI
2023	Skipkjack Windfarm	120	MD
2024	Sunrise Wind	880	NY
2025	Dominion Commercial Lease	2600	VA
2025	Empire Wind	816	NY
2026	Atlantic Shores	2500	NJ
2027	Kitty Hawk	2500	NC

From a network planning and operations perspective there are several research challenges. Unlike onshore wind, offshore wind will be connected close to major cities. The selection of the landing point for the offshore wind farm connection is an issue which network planners will need to decide. AC cables connected into load centers

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which already have a significant amount of cable infrastructure could cause undesirable harmonics and voltage issues if not planned and managed properly.

Recent advances in turbine technology and size, use of high voltage collector systems and Figure 1 shows the contracted bid price of a number of offshore wind plants in Europe in the past 10 years. It can be clearly seen that the price has dropped considerably in the past 3-4 years compared to the years previous[1]. The bid price in the UK includes the cost of the transmission cost to shore, compared to the prices in the other European countries where only the wind farm and the offshore collector network are considered in the price. An NREL study has found that the approximate cost of transmission for an AC connected offshore wind farm can be assumed to be 20 $/MWh for comparison, obviously that price is dependent on a number of factors including distance and transmission technology[2].

In March 2018 and March 2019 two Dutch wind plants bid a zero dollar per MWh subsidy price, meaning they will receive the market price for energy. It is worth noting again that transmission costs are not included here. The reduction in costs can be attributed to a number of factors:

- Larger wind turbines installed offshore. 10-13 MW offshore wind turbines are now available.
- Project sizes are increasing providing projects with economies of scale.
- Increase to 66kV collection networks. All offshore wind plants built to date use 33kV collection networks offshore. Increasing this voltage has significantly reduced losses in the offshore collection network and reduced prices.
- New installation methods and vessels.
- Increased investor confidence and access to finance has become easier.

The third round of renewable energy auctions in the UK took place in September 2019. The trend of reducing contract for difference prices in offshore wind continued with prices ranging from £39.65-£41.61 ($51.50 - $54.04) per Mwh.

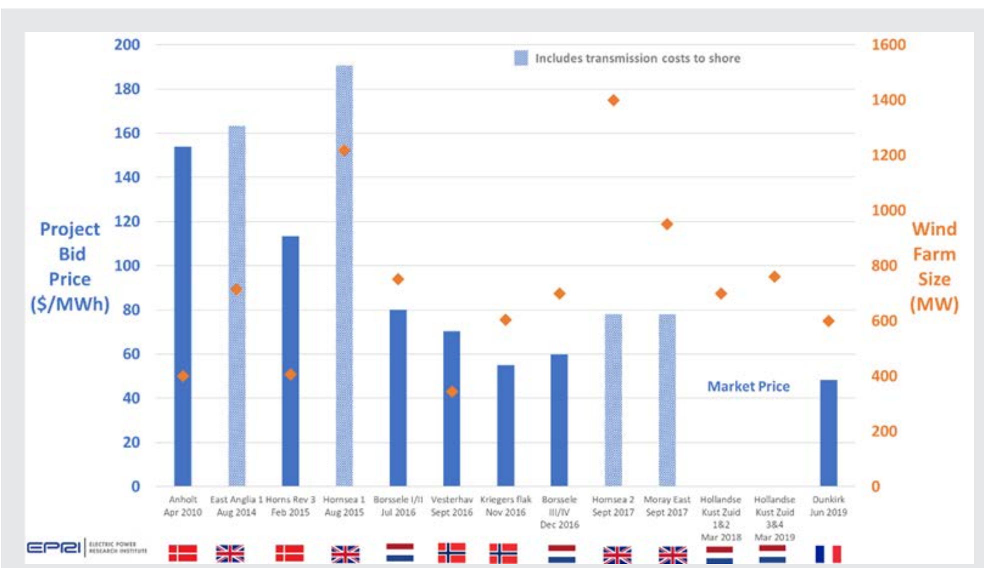

Figure 1. Bid price of selected offshore wind plants and wind plant size in Europe

[1] *Renewable Insights: Cost and Performance Trends of Wind*, EPRI. Palo Alto, CA: 2019. 3002016186.
[2] *An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030*. NREL. Golden, CO: 2017. NREL/TP-6A20-67675.

Connection Options for Offshore Wind

Offshore wind turbines are strung together using 33 kV or 66 kV AC cable arrays in the offshore collection network. There are two main options for connection directly to shore, HVAC or HVDC transmission.

HVAC transmission comprises a HVAC substation offshore to step up from the collector voltage to the HVAC cable voltage and HVAC cables to connect to the onshore substation. Capacitive charging is much higher for AC cables than AC overhead lines. Thus, for long AC cables there is a need for reactive compensation, in the form of shunt reactors, to maintain an acceptable steady-state voltage profile along the cable. If the cable is so long that compensation on each end is not sufficient, then compensation at the mid-point may be required to extend the feasible HVAC transmission distance. In the UK the first Reactive Compensation Station (RCS) offshore is in operation for the Hornsea Project One wind park which is a 1.2 GW installation, 120 km (70 mi) from shore. The traditional break even distance between HVAC and HVDC offshore cables would have previously been considered to be much shorter than 120 km, however advancements in mid point compensation have significantly increased the feasible HVAC distance. The question of whether to use HVAC or HVDC in this case becomes an economic comparison between extra reactive compensation stations offset against the cost and benefits of a HVDC link.

A HVDC Interconnection will require an offshore AC substation and an offshore HVDC converter station (these can be on one platform or separate platforms). DC cables then connect to an onshore HVDC converter station which converts to AC onshore. DC connections have essentially no limit to the distance offshore. To date the only offshore wind plants connected by DC connections have been connected in Germany. Generally, those HVDC connections have collected power from multiple offshore wind plants rather than one individual plant.

Several considerations make up the pros and cons for the comparison of HVAC and HVDC. Some are more relevant to the developer and some more relevant to the onshore grid.

- Typically, below a certain break-even distance, AC transmission has lower CAPEX than DC transmission for offshore wind.
- Fewer DC cables are required to transmit the same power level as AC. As an indicative example: a 1 GW link will require 3 AC cables at 220 kV or two DC cables at 320 kV DC.
- AC connections provide significant challenges with reactive power requirements onshore. Reactive charging current from AC cables make it necessary to manage the voltage profile at various injection levels. Onshore compensation may be required like Statcom/SVC/Synchronous condenser.
- HVDC connections provide a DC buffer between the onshore grid and the offshore wind park. VSC HVDC does not contribute reactive charging current onshore inherently. VSC's can also provide reactive power control independent of the active power flowing on the HVDC link. HVDC controls can also be configured to provide system services such as balancing, frequency response and blackstart.
- HVAC cables introduce low resonant frequencies to the AC system which can be costly to filter out as lower frequency filters are larger and more expensive than high frequency ones. The equipment may be exposed to temporary overvoltages for a longer duration due to the low resonant frequency.
- VSC HVDC with MMC technology requires little to no filtering on the AC output. If harmonic filters are required, they are usually very high order harmonics from the converter switching.
- A disadvantage of HVDC is the complexity of the power electronics system, AC does not have this complexity issue.
- With HVDC there is the possibility for control interactions between the offshore wind turbines and the HVDC station. Controls need to be tuned appropriately to avoid these issues.

From a technical point of view, onshore, HVDC provides significant benefits to the onshore network compared to the challenges posed by HVAC offshore connections, however these benefits generally come at a cost. While evaluating the cost comparison between different solutions it is important to consider the onshore implications of the offshore transmission system and any costs that may be incurred due to those. Evaluating the cost of offshore wind transmission interconnection can be difficult to generalise, even for the same connection points. The cost of interconnection could be low for the first offshore wind farm (first mover) intending to connect to an onshore POI, but after that connection the POI may reach an injection limit (active or reactive power) where significant investment is needed to facilitate more connections. Conversely, the initial investment could be high for the first mover to a POI which has limited injection capacity and the investment made by the first mover can make further interconnection easier for the next plants aiming to connect.

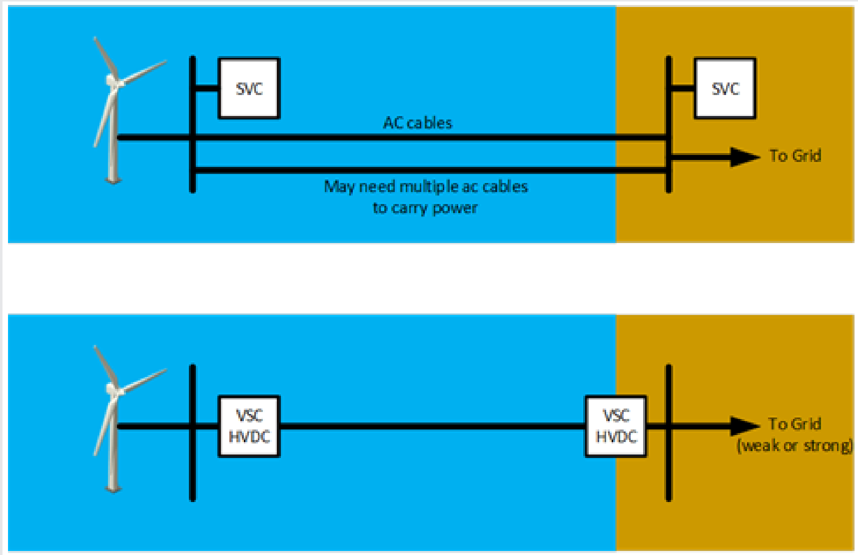

Figure 2. HVAC and HVDC connections for offshore wind

Point to Point Connections vs. Coordinated Offshore Grid

The concept of a coordinated offshore grid collecting offshore wind power and delivering to shore across several POI's has been around for a number of years, however to date most planned interconnections are tied directly to land via a single transmission cable. Figure 3 shows the main different options for offshore transmission to shore. Radial connections describe a single offshore wind plant connected directly to the onshore point of interconnection (POI) via offshore and onshore substations. An offshore wind developer may decide to connect to two POIs onshore via a split connection to increase the availability of the offshore wind power. A more complex option is the concept of a backbone grid running parallel to the coast collecting wind power from several offshore plants and connecting to a number of POIs onshore. This option provides a high level of redundancy and will be discussed in more detail further in the paper. The final option displayed in the figure is the concept of a meshed offshore grid with much higher levels of meshed connection than the backbone grid. Currently most of the wind plants in Europe are radially connected directly to shore, particularly those with AC connections. This is partially because developers build the offshore plant and the onshore transmission direct to the POI onshore. In Germany the HVDC connections tend to connect 3-4 offshore wind plants to shore, still only utilising a single HVDC link.

Some TSOs are beginning to move away from a "developer build" concept to a "TSO build concept." The Belgian TSO Elia has recently developed a modular offshore grid infrastructure to interconnect four offshore wind plants via two centralized AC offshore platforms and AC cables to shore. Prior to this offshore wind plants in Belgium were radially connected directly to shore. Similarly, TenneT, the Netherlands TSO will build out the offshore transmission infrastructure for a number of future offshore wind plants. Further concepts of a backbone connection or offshore grids have been proposed both in Europe and the US.

A "backbone" type offshore grid off the US east coast (either AC or DC) could provide efficiencies and advantages to integrating offshore wind. Some of these advantages include:

- Interconnection is one of the largest risks for an offshore wind development. Coordinated offshore transmission development could provide an opportunity to de-risk interconnection of offshore wind plants.
- Potential reduction in cost of energy.
- Reduction of number of landfall points.
- Potential for reduced environmental impact of offshore transmission routes.

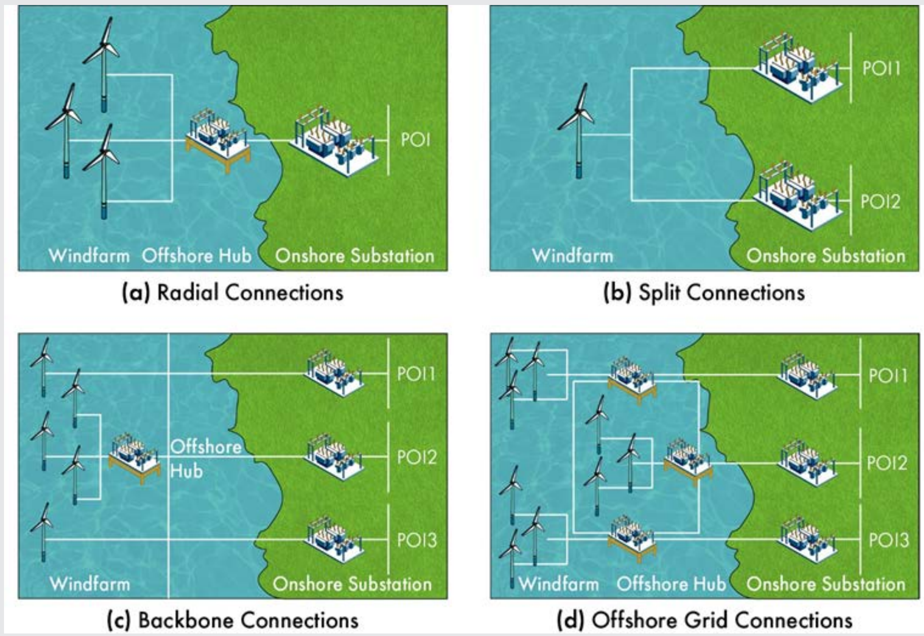

Figure 3. Figure sowing possible connection options for offshore wind

- Enhancement of offshore grid connection redundancy and therefore reliability.
- De risks offshore development from landfall permitting.

However, several concerns and challenges exist.

- There are concerns over cost allocation for the offshore backbone grid.
- Potential for overbuilding of offshore transmission – who bears this risk?
- Developers concerned over defining and locking developers into a specific technology which may not be the most cost effective.
- If the backbone grid were to cross multiple states, then regulatory differences in how offshore wind is procured could cause issues.
- For larger projects at 1 GW or more, it may be more efficient and reliable to connect these direct to shore due to maximum infeed requirements of utilities.
- Using a direct connection can spread the offshore wind penetration across multiple interconnection points.

Coordinated Onshore Grid Planning

An alternative to the backbone grid is coordinated onshore grid and landfall planning to provide offshore wind connections with defined landing points and cable routes in the planning stages. This could take the form of onshore transmission construction with the goal of interconnecting offshore wind, similar to the CREZ lines developed in ERCOT to enable onshore wind connections[3]. It could also take the form of coordinated landfall tunnels with capacity for several cables from several projects connecting to nearby interconnection points. This has the major advantage of requiring only one construction phase onshore and one interruption for communities at the landfall sites. The investment required for this type of onshore coordination would be a fraction of the investment required of coordinated offshore backbone grid.

Project Focus

To look in more detail at several the different connection options, three projects are described here to provide the reader with a reference point for projects which have utilized novel technologies, controls and ideas to push the boundaries of offshore wind.

[3] Competitive Renewable Energy Zones ("CREZ"), http://www.ettexas.com/Projects/TexasCrez.

Hornsea One and Two

Hornsea Project One and Hornsea Project Two are the largest offshore wind plants in operation and in development at 1200 MW and 1400 MW respectively. The wind plants are located 120 km off the UK coastline and have a further 49 km of 220 kV AC cable onshore connecting to the point of interconnection. Each project uses three 220 kV AC cables to connect directly to shore. These projects are unique because they use midpoint reactive power compensation stations to extend the feasible transmission distance for AC cable transmission. Mechanically switched reactors are used to reduce the required ratings of STATCOMs used to provide dynamic reactive power compensation[4]. Prior to this project it had been commonly assumed that projects beyond 60-70 km would be implemented using HVDC transmission although research conducted in 2016 indicated that AC connections are still significantly cheaper than HVDC for distances of between 120 km and 160 km utilising inductive reactive compensation at both ends and the midpoint of the HVAC cable[5].

Kriegers Flak Combined Grid Solution

Kriegers Flak is a unique combination of an interconnector between two countries (Denmark and Germany) with separate synchronous systems and an interconnector of multiple offshore wind farms. In the Baltic Sea between Denmark and Germany, three offshore wind plants were built (two German and one Danish). The proximity of the plants to each other made connecting them together an attractive option. This hybrid interconnector can be used to transfer power from one synchronous area to the other when the offshore wind plants are not at full output. The offshore network is operated as part of the Danish synchronous system. At the German side, onshore, a Back to Back converter station de couples the two systems. This DC converter station also employs a master controller for interconnector operation to control the flow of power[6]. The power transfer is calculated based on offshore wind power forecasts and equipment ratings considering any unavailability of assets or onshore grid congestion. This back to back converter has additional modes of control which can be utilized by the grid operator. When the BtB converter is in any of the following modes the master controller has no control over the flow of power.:

- Emergency power control
- Runback
- STATCOM mode
- Blackstart

North Sea Wind Power Hubs

A number of partners in the Netherlands and Germany, led by TenneT, are exploring the concept of an offshore island hub in the North Sea to collect and distribute 30 – 40 GW of offshore wind power. The island hubs will be connected to multiple countries using multi terminal HVDC transmission. Like the Kriegers Flak implementation described above, the HVDC links can also be used as interconnectors between countries. The island concept relies on a modular hub and spoke concept where additional wind plants could be added. The concept is currently 'under consideration' by ENTSO-E for inclusion in the Ten Year Network Development Plan[7]. It is envisaged that one of the key benefits of using the island hub will be the ability to store the energy using Power to Gas technology on the islands.

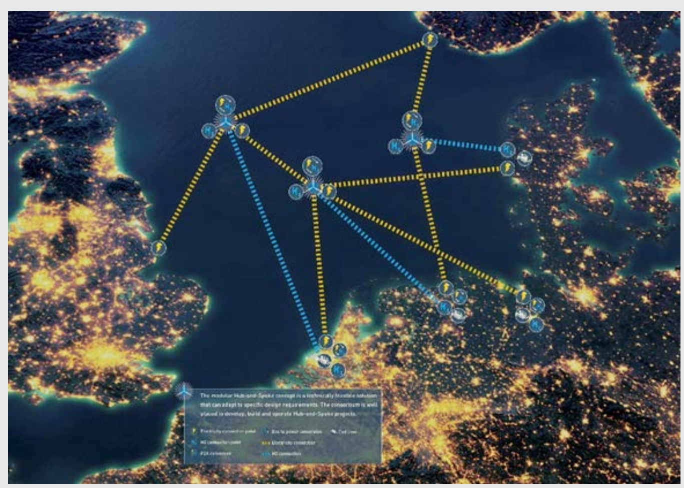

Figure 4. North Sea Wind Power Hubs concept illustration. Image Credit: TenneT

[4] J. Hjerrild et al., *Hornsea Projects One and Two – Design and Execution of the Grid Connection for the World's Largest Offshore Wind Plants*. Paper 155, CIGRE Symposium Aalborg, Denmark 4-7th June 2019.
[5] D. Elliott et al., *A Comparison of AC and HVDC Options for the Connection of Offshore Wind Generation in Great Britain*, IEEE Transactions on Power Delivery, vol. 31, no. 2, pp. 798-809, April 2016.
[6] A. Marten, T Sorensen, *Kriegers Flak Combined Grid Solution – Combination of Interconnector and Wind Power Collector using a Back-to-Back and a Master Controller*. CIGRE Paris session 2018 (B4-129).
[7] A. Alefragkis et al., *Design Considerations for the electrical infrastructure of the North Sea Wind Power Hub*. Paper 143 CIGRE Symposium Aalborg, Denmark 4-7th June 2019.

Reliability and Planning Studies

The subset of studies performed at planning stage usually varies among grid authorities and regions. A non-extensive list of the typical studies performed at planning stage is provided below for reference. Additional studies may be required depending on grid code requirements and known local system performance/response characteristics, such as areas of low short circuit MVA (weak grids), areas with series compensation, among other aspects.

- Production cost and congestion evaluation – often performed to identify preferred locations for plant siting, potential impact on on-shore system congestion and overall production cost of electricity.
- Steady state transfer capability analysis – often used to determine if area near plant being interconnected is capable of exporting power without violating transfer capability limits (thermal, voltage or stability limits).
- Steady state contingency analysis – often used to evaluate how the new plant impacts system reliability, especially under various event conditions.
- Voltage stability analysis, frequency stability analysis and transient stability analysis – often performed to determine impact of plant on overall system voltage stability, help coordinate voltage control settings, impact on system frequency stability, transient stability, etc.
- Short circuit analysis and protection studies – often performed to identify and verify protection settings and potential upgrades to circuit breaker ratings near the plant being commissioned.
- Harmonic study and mitigation analysis – often performed to verify if plant is compliant with level of harmonic injection allowed by local grid codes.
- Interactions studies both in sub and super synchronous ranges – often performed to evaluate the potential for unwanted equipment interactions and potential resonances at frequencies below or above fundamental frequency; potential for interaction is directly dependent on nearby grid equipment.
- Dynamic EMT analysis (especially in grid locations with low gird strength or fault current availability) - often performed to evaluate various aspects that cannot be addressed with the use of transient stability models, such as transient voltage recovery (over and under voltages), stability of detailed controls.

Conclusions

Policy targets in North America mean that offshore wind is on its way and will be built at speed. The experience gleaned from Europe and the rest of the world has already meant that the US in general will skip the installation of smaller pilot wind plants, with the exception of Block Island Wind Farm. Current wind plants planned off Massachusetts are expected to be 400 MW each, with further developments tending towards GW scale. The offshore wind industry can move fast when it begins to develop an offshore wind farm. Offshore wind has higher capacity factors, more predictable wind speeds and tends to blow during the day, these factors combine to provide the effect that in some sense, offshore wind can be considered baseload wind.

To help utilities with the new challenges associated with offshore wind integration, in 2020, EPRI launched its Offshore Wind Interest Group, this is an initial 1-year effort aimed at engaging key industry stakeholders and paving the way for future R&D in the offshore wind sector. The interest group will meet 4/5 times in 2020 via web conference and present research on various R&D topics. All EPRI members are eligible to participate

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Offshore Wind Integration

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