Hornsea projects 1 and 2 – Design and Optimisation of the Cables for the World Largest Offshore Wind Farms

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ABSTRACT

In this paper experiences with the design, production, installation and commissioning of the world's two largest offshore wind farms are described.
These ground-breaking projects that until recently were thought impossible, push the limit of a cabled HVAC transmission system to almost 200 km in length.
Through extensive electrical system analysis and detailed project cable engineering the longest 220 kV cable connection to an offshore wind farm in the world was conceived and built.
This paper covers all aspects in relation to the export cable system from the onshore substation to the offshore substations including the array cable systems from the offshore substations to the wind turbines.

KEYWORDS

World's largest offshore wind farm, world's longest 220 kV cable connection to a wind farm.

INTRODUCTION

Large offshore wind farms are currently getting bigger and bigger, being built further and further from shore and come with shorter construction windows compared to previous wind farms. Even though the basic design of large offshore wind farms follows the state-of-the art known from older wind farms, the significant size and short execution time present huge challenges.

Hornsea Project One (HOW01) will be the largest offshore wind farm in the world. Once completed in 2020, it will produce enough energy to power over 1 million homes. With a capacity of 1.2 gigawatts (GW), Hornsea One will be the world's first offshore wind farm to exceed the 1 GW threshold in capacity. Following this the Hornsea Project Two (HOW02) will in 2022 surpass HOW01 as the world's largest offshore wind farm with a capacity of 1.4 GW meeting the electricity needs of a staggering 1.3 million UK homes per year.

Located off the cost of Yorkshire, England (Figure 1.), HOW01 and HOW02 will span huge areas of over 400 square kilometers each, which each is over five times the size of the city of Hull. The offshore wind farms will use 7 and 8 Mega Watt (MW) wind turbines respectively, with each one 190 meters tall – higher than the Gherkin building in London.

This paper will describe some of the challenges experienced during design and execution of the biggest wind farms in the world.

Figure 1 - Location of Hornsea Project One

ELECTRICAL SYSTEM CONSIDERATIONS

The high-level electrical design for the two offshore wind farms HOW01 and HOW02 is the same (Table 1). The Wind turbines (WTs), generating the active power, are connected to an offshore substation via the array cable system. At the offshore substations voltage is stepped-up to the transmission system level of 220kV by transformers. The generated power is exported through the export cables to the onshore substation. At the onshore substation the voltage is further increased to 400kV and connected to the two transmission interface points (TIP) at National Grid's Killingholme substation (Figure 2). The voltage profile along the export cable is optimized by including an offshore reactive compensation station. This also increase the active power transfer capability of the export cable.

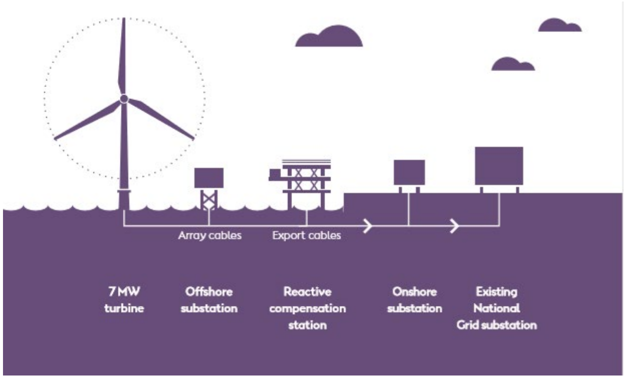

Figure 2 - HOW01 Design Layout

To obtain Grid Code compliance with the reactive power and voltage control requirements at the TIPs, three

STATCOMs are installed at the onshore substation. For operational flexibility of the wind farms, a combination of fixed and variable shunt reactors is used to compensate the reactive power generated by the export cable.
In addition, several harmonic filters are designed and installed at the onshore substation to fulfil the harmonic compliance requirement of the HOW01 and HOW02 wind farms as the long export cable in general has a low order resonance (range of 2nd-3rd order harmonic).

Another aspect of operation of a wind farm with long export cables is switching of the cables both during energization and fault clearance. One of the aspects of switching long cable is the zero-miss phenomenon [1] due to the cancellation of capacitive and inductive currents leading to significantly delayed zero-crossing. The delay of the zero-crossing can be up to a few seconds if the export cable is compensated 100% (or near 100%). The zero-miss issue can be avoided by reducing the compensation to around 50% during energization. This is mainly achieved by adjusting the variable shunt to a lower reactive power tap position than during normal operation.

Table 1 - HOW01 & HOW02 design concept

	HOW01	HOW02
Windfarm's Overall Capacity	1218 MW	1386 MW
No x Type of WTs	174 x 7MW	165 x 8MW
Distance from the coast	120 km	89 km
Array Cables, U	33 kV	66 kV
No of Offshore Substations	3	1
Offshore Export Cables, U	220 kV	220 kV
Onshore Export Cables, U	220 kV & 400 kV	220 kV & 400 kV
Number of Circuits to OnSS	3	3

EXPORT CABLE SYSTEM DESIGN

The HOW01 and HOW02 export cable systems are to date the longest AC offshore wind export cable systems energized / under construction, respectively, in the world.

The number of export cable circuits has been optimized to serve the windfarms' overall capacity at the transmission system voltage level of 220 kV, allowing short construction windows, cost-efficiency and securing the system reliability in both windfarms. Despite the complex installation and operating conditions along the cable route, extensive analysis of the thermal conditions and the dynamic loading concept have led to the optimum design.

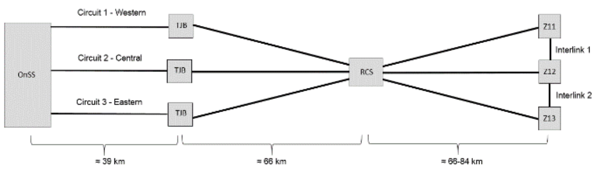

Figure 3 - HOW01 export cable layout

The export cable systems have been further optimized, thanks to the introduction of the Reactive Compensation Station in the design of both windfarms offering a balanced voltage profile and charging current compensation.

Due to the sheer magnitude of export cables systems to be manufactured and the complexity of interfaces during the design, construction and commissioning stages (Figure 3), the total supply scope has been distributed between three cable supply contracts; one for the onshore export cable and two for the offshore export cable systems (Table 2). For monitoring purposes, temperature sensing systems have been installed and commissioned (DTS), utilizing the fibres placed near the power cable conductors along the entire export cable route.

Table 2 – Offshore Export Cable Supply

	HOW01	HOW02
Offshore Export Cable Supply	NKT HV Cables (Sweden)	NKT HV Cables (Sweden)
Offshore Export Cable Supply	NKT HV Cables (Germany)	Nexans Norway
Onshore Export Cable Supply	LS Cables	LS Cables

Onshore Cable Systems

The three elements of the system are: the 220 kV onshore export cables, the 220kV/400 kV internal substation cables and the 400kV transmission cables to National Grid.

Onshore Export Cable System

The HOW01 Onshore Export cable system consists of three circuits each capable of transmitting 400 MW over approximately 37 km from the TJB where the onshore and offshore cables meet, to the new HOW01 substation. The route whilst mostly arable includes two Network Rail crossings, four major road crossings and a river crossing, all necessitating Horizontal Directional Drills (HDD's) to be considered when determining the optimum cable cross sectional area and method of bonding.

Taking account of suitable joint bay locations, access for joint bay construction, cable processing and overseas transportation lengths, final local cable delivery and cable pulling, it was determined that the optimum solution consisted of 26 cable sections with 25 joint bays. With the construction corridor of 30 m, it was determined that the cables should be installed in a flat spaced formation with 6 m between circuits allowing circuit separation to be increased within HDD sections and for an access haul road to be constructed the length of the route. For most of the route the 220 kV cables were installed direct buried, although some sections were installed in PE ducts.

Taking account of the load criteria and installation limitations a complex onshore export cable system was designed comprising elements of end point bonded, conventional cross bonded (with link boxes) and direct cross bonded sections (without link boxes). Further the phases were transposed at joint bays with the phase rotation of the central circuit opposite to that of the other two circuits to minimise losses and to optimise phase/circuit current carrying balance.

Section a – consisted of a single point bonded section with the earth continuity conductor transposed at the mid position and maximum standing voltage of 128 V

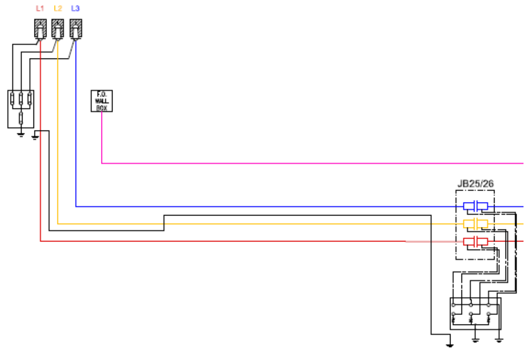

Figure 4 - Cable end point bonding

Section b - consisted of a cross bonded section both minimising losses but still permitting path to earth under lightning strike conditions by way of SVL's in the proximity to the substation location and of approximately equal section lengths to cancel the induced voltages.

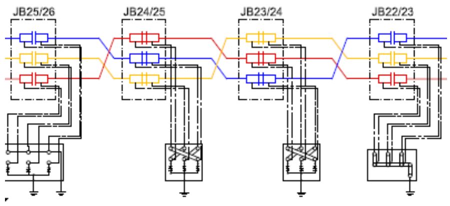

Figure 5 – Cable cross bonding over 3 sections

Section c – consisted of three major cable sections each of cable sections direct cross bonded at approximately equal section lengths with induced voltages cancelled out.

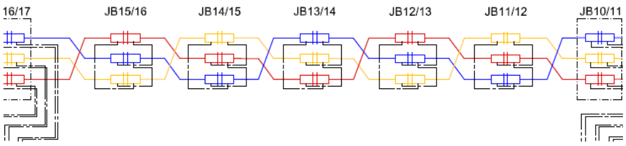

Figure 6 – One major cable section with direct dross

Section d – consisted of 4 cable sections direct cross bonded but with the final two sections being approximately equal in length in total, to those of each of the preceding two sections, thus allowing for a straight through joint while still cancelling out the induced voltages.

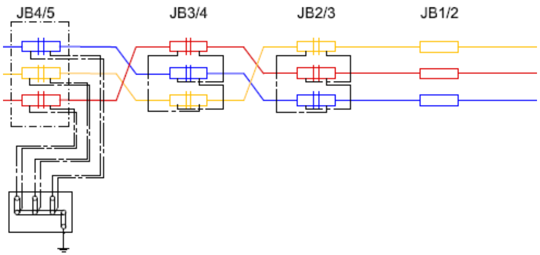

Figure 7 - Cable Direct Cross Bonded 4 cable sections

1600 mm^2 aluminium conductor, XLPE insulated, welded aluminium screen/water barrier, PE sheathed cable was chosen to meet the current carrying capacity requirements in the specified installation conditions, although an 1800 mm^2 conductor was utilised for seven of the sections

Internal Substation Cable System

Within the new HOW01 substation the internal cables consisted of a combination of 220 kV as transmitted from offshore and 400 kV as stepped up within the substation by way of three super grid transformers (SGTs). These cables were typically installed in lengths of 100 m to 200 m.

220 kV cables were of 1800 mm^2 aluminium conductor, XLPE insulated, welded aluminium, PE sheathed as the export cable route and a combination of solidly bonded and end point bonded arrangements were chosen to meet the operating current of the different electrical equipment connected by way of underground cable and connecting switchgear, reactors, harmonic filters and transformers.

400 kV cables in the substation were of 2500 mm^2 copper conductor, XLPE insulated, welded aluminium screen/water barrier, PE sheathed design as the grid connection cables. These were used to connect the harmonic filters and were solidly bonded. All internal cables were installed in free air within the substation cable basement or in buried ducts.

The cables connecting the 220 kV switchgear to the SGTs was the most highly loaded and due to further space limitations within a substation, necessitated where in ducts being installed in a proprietary low TR surround concrete with Bentonite filled ducts.

Grid Transmission Cable System

The export connection from the new HOW01 substation to National Grid substation for national transmission was made by way of a two circuit 400kV cable connection.

Whilst under normal operating the load is shared between the cable circuits, under contingency operation a single circuit can be required to carry the full 1.2 GW.
Between the two substations the 400 kV cables were installed in flat spaced formation in Pe ducts with 4 m circuit centre spacing. Installed in a proprietary low TR concrete.

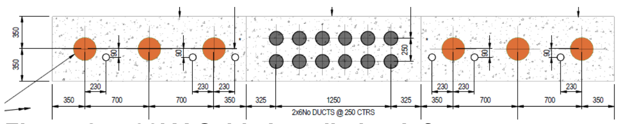

Figure 8 - 400kV Cable Installation Infrastructure

2500 mm^2 copper conductor, XLPE insulated, welded aluminium, PE sheathed cables with Milliken conductor design including insulated copper wires was used to achieve the load requirements and to further optimise the current carrying capacity cable circuits were installed end point bonded with an ECC transposed at mid-point and phase rotation alternated between the two circuits.

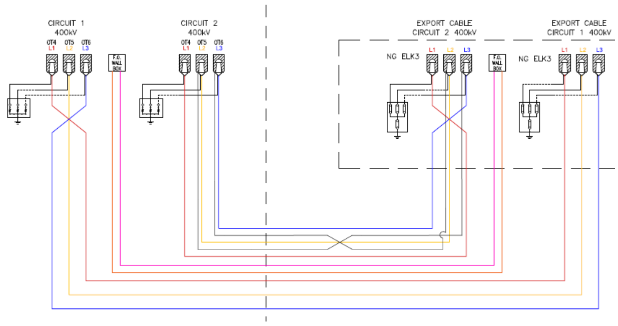

Figure 9 - 400kV Cable Circuit Configurations

Offshore Export Cable Systems

The overall HOW01 offshore export cable system comprises of three independent offshore export cable circuits, each one consisting of the following main subsections:

a) Offshore export cable between the offshore substations and the reactive compensation substation, transferring the power coming from the array cable system

b) Offshore export cable between the TJB and the reactive compensation substation, transferring the power to the onshore export cables via the transition joints

220 kV AC single-core cable circuits have also been designed and installed in the offshore substations and the reactive compensation substation, to accommodate the internal connections to the electrical components; i.e. Transformers and Shunt Reactors.

To increase the system's reliability and minimize its limitations, the 3 offshore substations have been connected to each other through two interlink offshore cables, as shown in Figure 3, allowing power transfer through any of the three cable circuits, and to maintain the entire park energised during faults and maintenance.

HOW02 is quite like HOW01, however there are certain differences, e.g. the offshore cable route is slightly shorter and there is only one offshore substation, where all three individual export cable circuits are connected to, without any interlink offshore cables.

Each offshore export cable circuit consists of the following subsections:

a) Approximately 66 km of offshore export cable between the transition joint bay and the reactive compensation substation

b) Approximately 62 km of offshore export cable from the reactive compensation substation to offshore substation.

HOW01 Cable Design

The design and length freeze of the offshore export cable systems has been based on the extensive analysis of a composite but well-captured setup of interfaces:

All offshore export cable systems have been optimally designed in compliance with the relevant Ørsted and IEC specifications [2] and CIGRE TB design / testing requirements [3], to meet

a) the installation conditions;

Extensive seabed surveys and studies have been performed to identify the seabed thermal properties and sand-wave migration profile during the lifetime of the windfarm. Similar attention has been paid to the analysis of the thermal conditions along the shore sections, due to the increased burial depth (HDD) as well as the shorter distance between the cable circuits. The water depth of approximately 60 m has also been considered for the mechanical and electrical design of the cables.

On the offshore substations, the cable arrangement has been also thoroughly examined, due to the numerous cables to be pulled-in through J-tubes and terminated to the GIS; e.g. 6 offshore export cables among 3 internal cable circuits on the Reactive Compensation Station. The more complex interfaces on the offshore substations, where array cables are also connected, have been secured with the introduction of straight joints, ensuring a balanced solution for the construction and operation period (easier installation off shore vs. risk of an extra joint)

The engineering works that were carried out for the cable installation campaigns, including the mapping of boulders and crossings, seabed's morphology, HDD profiles and spare strategy, finally determined among others the location of the offshore joints as well as the length of the cable sections.

b) the operating conditions;

The voltage and current profile along the offshore route have been the key features that have been mostly studied for the cable sizing of the offshore export cable systems. To achieve the optimum setup, optimization techniques have been implemented, including the dynamic loading concept described in [4] and [5] (Figure 10), that is based on extensive analysis of wind data, as well as control of the overall electrical capacitance of the cables (charging current).

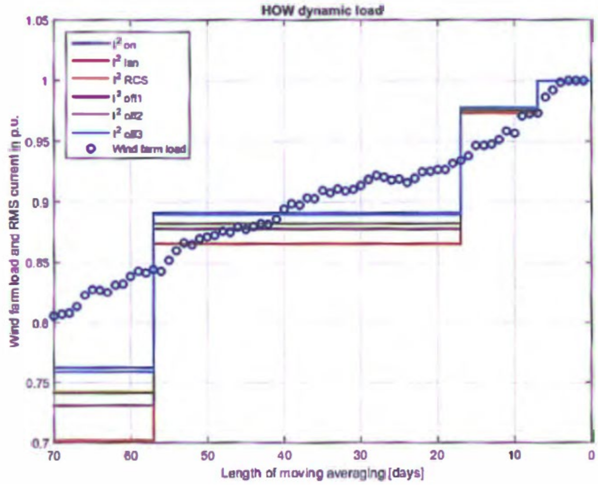

Figure 10 - Dynamic loading profile for different locations (and thus capacitive current)

Apart from the requirements and interfaces described above, the compatibility of the cable designs with the HV components, the compliance of the integrated FOC designs with SCADA specifications as well as the compatibility of the offshore and onshore cables with the transition joints had to be properly examined and secured.

On HOW01, four different dry-type cable designs of three-core cables, meeting the latest cable technology standards, have been selected for the offshore sections of the project, ensuring the optimum solution for the execution and operation stages.

All designs have been based on a typical three-core XLPE cable design with 2 integrated FOC, with few basic differences between the conductors, armour and FOC designs. 2 Non-magnetic armour designs were proposed and finally chosen for HOW01, since the project specific design advantages were identified, evaluated and secured.

a) 220 kV 3-core cable of 1000 mm^2 Cu conductor, XLPE insulation, lead sheath and stainless steel/plastic armour wires for the Eastern and Western offshore export cable circuits

b) 220 kV 3-core cable of 1000 mm^2 Cu conductor, XLPE insulation, lead sheath and sea grade aluminum armour wires for parts of the Central offshore export cable circuit

c) 220 kV 3-core cable of 1200 mm^2 Cu conductor, XLPE insulation, lead sheath and galvanized steel/plastic armour wires for the rest of the Central offshore export cable circuit

d) 220 kV 3-core cable of 950 mm^2 Al conductor, XLPE insulation, lead sheath and galvanized steel armour wires for the Interlinks

Internal Offshore Substation Cable System:

The cable design that has been selected for the internal connections is the same on all offshore substations, including the reactive compensation substation, offering increased flexibility during the construction period.

Three-phase circuits of 220 kV 1-core cable of 800 mm^2 Al conductor, XLPE insulation, copper wire screen and PE oversheath have been installed and terminated. Due to various lengths along the internal connections, the bonding of the metallic screen has been either solid or single-point.

HOW01 Cable accessories

Additional engineering and testing works were carried out post contract signing for the optimization of the offshore accessories; such as the rigid sea joints and the bend restrictors, pulling heads and cable protection systems, to de-risk the construction period.

Amongst others, the following cable accessories were designed and installed for the development of the HOW01 project under various time windows, significantly affected by the weather:

- 9 rigid sea joints, compatible with both in-line and omega jointing setup
- 9 straight joints on the substations
- 9 transition joints at the TJB
- 75 GIS terminations for offshore and internal cables
- 18 Shunt Reactor terminations
- 18 Transformer terminations
- 13 hang-offs on the substations

PROJECT EXECUTION

The execution of both projects is based on a multi contract approach, meaning that cables supply, and installation have been procured separately. Therefore, the amount of interface coordination done in the project by Ørsted is significantly higher and more complex, compared to a turn-key based solution. Especially the interface between offshore export cable supply and cable installation has been challenging because of the number of delivery lengths, installation vessels and limited whether windows. Despite of this, all project site activities have been completed on time.

Onshore Export Cable Systems

Execution of the project necessitated the manufacture and subsequent handling of approximately 360km 220kV cable and 5 km 400 kV cable, as well as the production of the 225 off 220 kV joints, 63 off 220 kV terminations, 24 off 400 kV terminations, the associated bonding, earthing and FOC system from multiple production facilities and including the associated logistics of moving cable drums of up to an individual 4.5 m height and 35 T weight.

The onshore export cable excavation consisted of three parallel trenches and to push the boundaries of safe working, Orsted sought for innovative processes to be developed and utilised during the installation process. This drive for safety sets the installation contractor a challenge in developing a system where by the entire process of excavation, cable installation and reinstatement could take place wherever possible without the need for any personnel to enter a trench and utilised such plant and techniques as:

V Bucket – A customised excavator bucket was utilised to optimise the profile of the excavation giving the minimum cut at the base where a sand bed would be laid, and cables installed, whilst maintaining a stable trench side. Different profiles were used for different ground conditions.

Sand cart – a remotely operated vehicle operated from above the trench, capable of transporting and installing selected sand for the bed and cable surroundings, including compacting

Roller design – traditional single rollers were modified to be able to be lowered in to and removed from the trench by excavators and special three-way roller boxes were developed to control the installation over bends and changes of ground profile where traditionally personnel would have been required to maintain cable on rollers to prevent cable damage

Duct lube applicator – a device was fabricated to allow the application of installation lubricant within HDD ducts to prevent the need to apply by hand.

New cable identification marker board – where traditionally in the UK individual marker boards are put across the top of cables to identify the asset below and to provide some level of protection, on the HOW01 project this would have necessitated the installation of circa 400,000 individual boards. A method of a coil-able rigid marker tape was adopted allowing the marker tape to be applied continuously from small wooden drums.

The use of these techniques and others prevented the need for construction staff to enter and work within the excavations minimising installation related safety risk.

All of the onshore export cables were successfully installed with the transposition, phasing and bonding verified as 100% correct at the time of commissioning. All circuits were subjected to a full site acceptance test regime in line with IEC and Orsted site test requirements, with all circuits passing HVAC resonance testing and with no Partial Discharge measured upon any of the accessories.

Offshore Export Cable Systems

On HOW01, the construction phase of the project, including the installation, jointing and termination campaigns related to the offshore export cables, has followed the manufacturing and testing process in the manufacturers' premises.

Totally 15 offshore cable lengths of nearly 500 km were manufactured and tested in less than two years, allowing secure planning of the offshore works.

Due to the large number of accessories and in order to optimize the execution period and minimize the offshore installation risk, the internal cables were manufactured, delivered, installed, terminated and tested in topsides at the fabrication yard in Denmark prior to their sail away.

Before the commencement of the load-outs and all site works, HIRA workshops were held as key HSE safeguards. Furthermore, trenches were created along the offshore cable route post a tremendous campaign of boulders' clearance, minimizing the risk of delays during the actual cable works.

The jointing works at the TJB followed the extensive cable pulling through the HDD and barges, equipped with tensioners, whereas the offshore cable installation was carried out by three installation vessels and included several joint installation and deployment campaigns.

The schedule of the CPS installation, cable pulling through the J-tubes and the rerouting and termination / jointing campaigns on the substations was adjusted to their readiness, offering huge flexibility and optimum efficiency to the commissioning of the project.

All site works, including the successful OTDR, TDR and soak-testing of all offshore export cable systems (24 hr at 220 kV) and commissioning of DTS, were completed ahead of schedule, in approximately one year, despite the large number of delivery lengths, the complex setup of the installation vessels and the challenging weather windows.

ARRAY CABLE SYSTEM DESIGN

HOW01

The windfarm is the world's largest offshore windfarm by a considerable margin the sheer scope of the project warranted some new thinking regarding array cables.

The array cables on Ørsted projects have in the past, typically, been supplied by means of framework agreements with cable suppliers. This given the fact that the array cables are typically seen as standardized cables within a standardized cross-sectional range. These suppliers were Nexans and JDR, both suppliers of conventional semi dry XLPE insulated cables. The array cables in general consisted of:

Water tight Stranded compacted copper conductors, semi-dry XLPE insulation, Cu wire screen, swellable tape Aluminium laminate water barrier, PE sheath, with Galvanised steel wires, and PP yarns sewing.

Although the conventional cables, this was the first time that two cable suppliers had been nominated to supply array cables to the same project. This was new terrain for Ørsted, since all previous wind farms had only one array cable supplier and this indeed changed the size of the array scope for Ørsted twofold. Especially, in consideration to the multifaceted task of aligning, from an installation and termination perspective.

The reasoning for employing two array cable suppliers were several, mostly economical. Although one notable reason, given the size of the project, was the sheer scope of cable length that was to be produced to form the array cable grid, in total around 380 km of array cables where to be supplied. The two cable suppliers ensured the availability of the production for the project.

HOW02

After Hornsea windfarm One, the Hornsea windfarm project Two furtherly increases the Hornsea windfarms reputations as the biggest wind farm in the world. The ensuing true scale of the Hornsea windfarm confirms the fact that it is the world's largest offshore windfarm by a considerable margin and additionally aided the goals of both Ørsted and the UK government for a greener home planet. The sheer scope of the project warranted some new thinking regarding array cables.

In HOW02, contrary to conventional practice, as for example in HOW01 which utilized 36 kV array cables, the 66 kV array cables where carefully chosen. The increase in voltage would ultimately allow for longer cables and would ultimately decrease the amount of wind turbine strings and the consequent losses. The increase in voltage for the cables increased the complexity in the electrical components utilized for the project, as their revision also had to be considered to also comply with the increase in voltage.

Similar, as in the Hornsea One Project, two array cable suppliers were carefully chosen. Here with Prysmian as a newcomer to the conventional framework agreements and JDR having supplied to two projects already, were chosen. The cable designs of the suppliers were somewhat different, JDR supplied the conventional XLPE semi dry cable designs and Prysmian supplied the wet design EPR cable.

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GLOSSARY

DTS: Distributed temperature sensing
FOC: Fibre Optic Cable
GIS: Gas Insulated Switchgear
HDD: Horizontal directional Drill
HIRA: Hazard Identification and Risk Analysis
NG: National Grid
OnSS: Onshore Substation
OTDR: Optical Time Domain Reflectometry
scPE: semi-conductive polyethylene
SVL: Sheath Voltage Limiter
TDR: Time Domain Reflectometry
TJB: Transition joint Bay
XLPE: Cross-linked polyethylene