Offshore Wind Technology Catalogue

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Authors:	BLIX Consultancy: A. Alves da Silva , J. Godtschalk , T. Drummen
	Enersynt: P. van Leest
Checked:	I. Maassen van den Brink
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EXECUTIVE SUMMARY

BLIX Consultancy has the pleasure of presenting the Offshore Technology Catalogue. This catalogue will provide Elering/AST with the necessary information to get an insight in the current technologies that are on the market for offshore wind developments.

Overall, the outcome of compiling this catalogue is, that the nature of offshore wind technologies has evolved – and continues to evolve - at a rapid pace and that the offshore wind business has matured over the recent years. The catalogue goes into detail about the different types of foundations, wind turbine generators, substations and transmission cables. The grid connection system is the main focus of the catalogue and comparisons are made between AC and DC systems. BLIX has provided up-to-date market information on availability, reliability and – where possible - prices.

At the end a top level assessment is made of a specific connection for both technologies. In general it is stated that above 1GW and more than 100km the DC option would be preferred, as this should also consider the difference in losses during lifetime when corrected for the different power bins (wind profile) of the offshore wind farm.

Important to note in this document, is that assumptions had to be made on which the data had to be based. The assumptions are very general in nature and therefore should be considered as such. When using the catalogue, it is important that the user should always be aware of these restrictions and how they apply to the catalogue item.

Another important note to the use of this catalogue is, that during the compilation of the data, it became very clear during our research, that a lot of items and more specifically prices are site specific. This means that there are so many variables in designing, delivering or installing certain items that, without site specific detailed data, it is very difficult to obtain 100% accuracy. When compiling this catalogue, we used a lot of general available data which may lack detailed information.

Overall, we are confident that the quality of this catalogue will provide a very good, detailed, assessment of the main components for the development of an offshore wind farm in the Baltic Sea.

ACRONYM LIST

AC – Alternating current

ALU – Aluminium

BE - Belgium

BOP – balance of plant

CAPEX – Capital Expenditure

CTV – crew transfer vessel

DAS – Distributed Acoustic Sensing

DC – Direct current

DE - Germany

DK - Denmark

DOL – Depth of Burial

DTS – Distributed Temperature System

EMTP – Electro Magnetic Transient Program

EU – European union

EXC – Export cable

FAT – Factory Acceptance Test

FO - fibre optic

GB – Gravity base

GBS – Gravity base structure

HVAC – High voltage alternating current

HVDC - High Voltage Direct Current

IAC – inter array cable

IEC – International Electrotechnical Commission

LCoE – Levelised cost of energy

LFAC – Low Frequency Alternating Current

m – meter

MV - Mega Volt

MW – Megawatts

MVA – Mega Volt Ampere

NL - Netherlands

O&M – operations & maintenance

OEM – original equipment manufacturer

ONAF – Oil Natural Air Forced

ONAN – Oil Natural Air Natural

OPEX – Operational Expenditure

OSS – offshore substation

OWF – offshore wind farm

OWF – offshore windfarm

PSCAD – Type of SW package for EMTP simulations

PQ – Power Quality

RFQ – Request for Quotations

SAT – Site acceptance test

SCADA - Supervisory Control and Data Acquisition

SE - Sweden

SOV – service operation vessel

TIV – Transport installation vessel

TP – Transition piece

TRL – Technology readiness level

TSO – Transmission system operator

UK – United Kingdom

WTG – wind turbine generator

1 INTRODUCTION

BLIX Consultancy & partners were contracted by the Estonian and Latvian TSO's, Elering and AST, to create an offshore wind technology catalogue. This catalogue details all the technologies used in an offshore wind farm and grid connection system. General and technical details for each technology are explained, highlighting the various factors that dictate the design, cost and lifetime of a wind farm. Important factors include but are not limited to; wind farm capacity, distance to shore, water depth, seabed conditions and onshore grid connection.

Only technologies with a TRL greater than 5 have been considered. BLIX has provided costs for all the technologies however it should be noted that these costs are best estimates of the current market based on our experience and public literature. Prices will vary depending on site and project specifics.

The report is split into individual sections for each technology. Chapter 3 covers offshore substructures for both WTG's and platforms. It describes the various fixed bottom foundations used in water depths of up to 50m focussing on monopiles and jacket foundations.

Chapter 4 covers WTG's, looking at; the basics design, current and future outlook for size and capacity, considerations for wind farm density and end of life. Chapters 5-7 cover the grid connection system. It splits the technologies into two categories, AC and DC. Within each category the offshore platform, onshore land station and transmission cables are discussed. These sections go into detail about the various configurations, topologies and redundancies that are used in the market and their associated losses. For AC, there is a section detailing reactive power compensation considerations that are required for longer cable distances. In the cable sections the voltage, cross section, and conductive materials used are compared.

Chapter 8 briefly describes decommissioning of an offshore wind farm and grid connection system. Discussing the cost and considerations required to ensure marine users and the environment are not severely impacted by these activities. Chapter 9 provides a qualitative comparison of both AC and DC technology. For comparison purposes an example for a specific 1GW connection, 50km from shore is assessed using both technologies.

2 ASSUMPTIONS

Parameter	Assumed for catalogue	Comments
Water depth	< 50 meter	
Ice conditions	Considered	Ice conditions come in various forms. Per item it is explained what has been considered and what not.
Soil conditions	Sandy soils	A change in soil can have a major impact on the foundation design.
Seabed currents	Very low currents	Consequently, low seabed mobility (sand dunes) have been assumed. Seabed currents is an important parameter for scour protection and/or subsea cable design.
Earthquakes	Not assumed	If these need to be considered, a Seismic Hazard Analysis (SHA) will need to be performed in order to
Waves	Typical UK Sector North Sea conditions	Max wave heights (HMax) in the North Sea can go up to 10m (or more during a bad storm). Meaning a Significant wave height (Hs) of around 5-6m.
Tides	Small tides (<0.5m) have been assumed	
Other assumptions for foundation section	1. Total windfarm size: 1000MW 2. Water depth: 30m 3. Turbine: 10MW 4. Location: North Sea – UK Sector 5. Weight of foundation assumed 800 ton	

3 OFFSHORE SUBSTRUCTURES

3.1 WTG Foundations

3.1.1 Description

The primary function of a foundation of any structure is to transfer applied loads to the sub-bottom. The main loads that act on an offshore structure are wind, waves, currents and the 'self-weight' of the structure. Examples of other loads and actions that can occur in different offshore environments around the world are ice loads, earthquakes, typhoons and ship impact.

Offshore foundation types are particularly driven by:

- Water depth;
- Ground conditions;
- Loads (magnitude).

In offshore wind, a discrepancy is made between floating and bottom-fixed foundations. Only bottom-fixed foundations will be discussed here, considering the shallow water depths (up to ~50 m) in the area of interest.

In the table below the word "rock" is sometimes used when discussing the foundations. It should be noted that "rock" is geological term that is used to describe a naturally occurring solid mass of minerals. Rock can occur in various degrees of hardness, from very hard (granite) to weaker types (certain types of limestone or sandstone). For foundation design, encountering rock is generally not a good thing. When being hammered, rock will either resist the piling (so that drilling is required) or will break up, making it useless for foundation design, since the soil is unable to deal with the forces on the foundation. The General soil strength can be described as follows:

Type of Soil	Strength of Soil	Elastic Modulus, E (Mpa)
Fine sand	Loose	5-10
	Medium	10-25
	Dense	25-50
Silt	Soft	<10
	Stiff	10-20
	Hard	>20
Clay	Very soft	<3
	Soft	2-7
	Firm	5-12
	Stiff	10-25
	Very stiff	20-50
	Hard	40-80

Table 1 - Typical elasticity modulus (ES) values for different soil types[1]

[1] Handbook of Geotechnical Investigation and Design Tables - Burt G.Look (2007)

The following section considers the most common bottom-fixed foundation structures in the offshore wind industry. Other foundation types such as mono buckets, tripods (currently 126 operational, but ran out of fashion for larger turbines), twisted jackets have not been applied in commercial offshore wind farms and are therefore considered to be of less importance for this exercise.

Below tables also show installation options. It is noted here however, that no limitations have been assumed. For piling operations, noise mitigation measures might be required, such as bubble screens (single of double).

3.1.2 Technical Information

Foundation size (diameters/lengths) depends mainly on ground and loading conditions on the substructure.

An important parameter to keep in mind is steel quality. Especially for icy conditions, high grade steel might be required to deal with the low temperatures. Should there be permanent ice during winter, then the foundations need to be designed as such to be able to withstand the ice loadings. According to DNV rules DNVGL-OS-C101, ice loadings are depending on multiple factors:

- geometry and nature of the ice
- mechanical properties of the ice
- velocity and direction of the ice
- geometry and size of the ice and structure contact area
- ice failure mode as a function of the structure geometry
- environmental forces available to drive the ice

In order to make a proper assessment of the ice loadings, before the development stage of the project, as much as possible information should be collected on ice conditions. These conditions can be collected via a desktop study, via publicly available data bases or via meetings with knowledge institutes or other parties that have knowledge about ice and ice loadings.

Ultimately, the ice loadings can also be tested in a laboratory via simulations, for example in Hamburg (Germany)[2]

The ice loadings shall then be incorporated into the design of the foundation according to the applicable codes and standards.

So for the purpose of the catalogue, in these very early stages it’s very difficult to assess the exact impact of ice loadings on the substructure.

[2] https://www.hsva.de/expertise/safety/safety-in-cold-regions.html

3.1.2.1 Monopile Substructures

General	The monopile foundation consists of one circular open-ended steel pile that, after installation will be partly in the ground, partly in the water column and partly above water level. A transition piece will be installed afterwards, on which the WTG tower will be mounted.
Dimensions	- Diameter up to ~9 m - Length ~30 m to ~80 m - Wall thickness ~50 mm to ~120 mm - Diameter could go up to 12 m and more
Weight	- ~800 t to ~1900 t (in air) - Will increase with increasing diameters - Note: the latest monopile for Arcadis Ost 1 OWF in the Baltic was 2000t at 40m water depth
Applicable water depth	- < ~40 m - Could be stretched with increasing diameters
Applicable ground conditions	- Soft ground conditions (clay, sand and silt or alternations thereof) - Difficult to apply in rock
Fabrication methodology	Steel plates, rolled to circular elements that are welded together
Transport and installation methodology	- (Generally) transported in horizontal position on a transport installation vessel (TIV) or barge - Up-ended and lifted at WTG location and installed with a driving hammer - Transition piece (TP) is installed afterwards - Vibratory hammers are available, but not common yet - (Pre-)drilling is possible in hard ground conditions (but expensive) - TP-less monopiles are becoming more common
Pro's	- Well known and proven technology with a market share of about 75% in Europe - 'Simple' fabrication, welding can be done automatically - EU fabricators (e.g. SIF and EEW) are specialists and can produce ~4 to ~5 monopiles/week
Con's	- Driving hammer generates a lot of noise - Lean process does not create much local content (if applicable)

	- Decommissioning is currently considered to be difficult
Project examples:	Deutsche Bucht (DE), Arcadis Ost (DE), Borssele OWF Zone (NL), Hollandse Kust Zuid (NL), about any OWF in Europe
Applicability for Estonian/Latvian projects	- Very good, considering the shallow water depths - Not so good, considering hard ground (rock) conditions at some locations(1)
(1) Based on high level general geological maps	

3.1.2.2 Jacket Structures (3 or 4 Legged Substructures)

General	Jackets are braced steel structures that are commonly applied in the oil & gas industry. The braced structure will be present in the water column, and above water level. The WTG tower is directly connected (integrated TP). Loads are transferred to the ground with piles or suction buckets. Piles can be installed prior or after jacket installation. For WTG support jackets typically have 3 or 4 legs.
Dimensions	- Footprint at seafloor 25x25 m2 to 50x50 m^2 (depending on water depth) - Height 80 m to 120 m, but higher is possible - Oil & gas jackets up to 500 m
Weight	- 600 t to 2,000 t (in air), but larger is possible
Applicable water depth	- Between 60 m and 100 m, although larger depths are possible. - Jackets might be used in shallower water depths as well. However this might economically less viable.
Applicable ground conditions	- Depends on foundation system (piles or suction buckets) - Soft ground conditions (clay, sand and silt or alternations thereof) for piles - Soft ground conditions (clean clay or sand) for suction buckets - Difficult to apply in rock (impossible for suction buckets)
Fabrication methodology	Tubular braces welded together in a flat position and up-ended and connected together. Fabrication of piles and suction buckets (more or less) similar to monopiles
Transport and installation methodology	- (Generally) transported in vertical position on a TIV or barge - Lifted from vessel/barge to WTG location

	- Piles installed before or after jacket installation. Piles installed with driving hammer (or with vibratory hammer) - Suction bucket installation while lowering the jacket to the seafloor - Large jackets can be launched
Pro's	- Many (former oil & gas) construction yards can fabricate jackets - Proven technology - Applicable for high loads and large water depths - Labour intensive, which is favourable for local content - Suction bucket jackets can be fully decommissioned
Con's	- Labour intensive - Heavy structures require largest available installation vessels - Driving hammer for piles generates a lot of noise (can be mitigated by suction buckets)
Project examples:	Wikinger (DE), East Anglia (UK), Seagreen (UK)
Applicability for Estonian/Latvian projects	- Not so good, considering the shallow water depths. Cost/benefit decision
(1) Based on high level general geological maps	

3.1.2.3 Gravity Base Structure

General	Gravity base structures is a collective name for heavy foundations that transfer loads from the top structure to the sub-bottom, based on gravity. Commonly, they are concrete structures that are ballasted after set-down on the seafloor.
Dimensions	- Footprint at seafloor 25 to 35 m diameter for - Height up to 40 m, but higher is possible - Oil & gas jackets up to 350 m
Weight	- 2,000 t to 5,000 t (for up to 6 MW turbine) - Note that 6MW is the maximum known turbine size to date that is known to be installed on a gravity base.
Applicable water depth	Up to 30 m, although larger depths are possible
Applicable ground conditions	- Strong grounds, e.g. dense/very dense sands or rock - Not applicable on soft soil, e.g. clay
Fabrication methodology	Constructed with reinforced concrete in formwork

Transport and installation methodology	- Seabed needs to be levelized prior to GBS installation - GBS is towed to the site and ballasted in a controlled way to lower the structure to the seabed
Pro's	- Applicable for hard ground conditions - Can be towed to site, no need for large installation vessels - Possible to fabricate locally, since concrete is a common material for structures and infrastructure
Con's	- Structures require a lot of space - Difficult for serial production - No track record for larger turbines - Difficult (impossible?) to decommission - Concrete is not very environmental friendly
Project examples:	Thornton bank Phase 1 (BE), Avedfre Holme (DK), Kårehamn (SE), generally small turbines < 5MW
Applicability for Estonian/Latvian projects	- Potentially good, considering hard ground (rock) conditions at some locations(1)
(1) Based on high level general geological maps	

3.1.3 Costs

3.1.3.1 CAPEX

Main costs are driven by steel grade and weight. The standard EU steel grade is S355, but the steel grade that needs to be used, as mentioned, depends on the actual site conditions and loads. As with all commodities, steel prices may vary heavily over time, so may prove to be difficult to provide an accurate cost estimate per foundation type that might be valid over a long period of time. Also the steel will need to be rolled, processed and shaped in the required foundation (jacket, monopile). Consequently, we provide ball park figures and our assumptions are given below:

1. Total windfarm size: 1000MW
2. Water depth: 30m
3. Soil: sandy soils
4. Turbine: 10MW
5. Location: North Sea – UK Sector
6. Weight of foundation assumed 800 ton

Turbine foundation part	Cost (in Euro/MW)	Weaker soils	Stiffer soils (clay)
Foundation (monopile)	335.000	Diameter increase → price increase	Diameter decrease → price decrease
Transition piece	120.000	Diameter increase → price increase	Diameter decrease -> price decrease

Corrosion protection	24.000	Diameter increase → more protection → price increase	Diameter decrease –> price decrease
Scour protection	12.000	Higher chance of scour → price increase	Best case scour protection is not required.

Source: Catapult Offshore Renewable Energy – BVG Associates[3]

In addition to steel prices, the costs of foundations are also driven by transport and installation costs. Since these are large structures transport costs can be serious. However, if they are produced locally, it might be more cost effective.

Item	**Cost (euro/MW)**
Foundation installation	100.000
Offshore transport	3.500

Source: Catapult Offshore Renewable Energy – BVG Associates

Although included already in the above foundation installation cost, it is worthwhile to mention that the day rate of a suitable installation vessel is approximately 300.000 euro a day.

For Gravity based structures, the cost estimate is very difficult to estimate. The first important factor is the levelness of the seabed. If the seabed is unsuitable to directly install a GB, there is the possibility that dredging work will need to be undertaking in order to prepare the seabed. Other factors are the same as per monopile or jacket foundations: soil, waves, ice loading, turbine size and seabed currents. Since the GB is standing "loose" on the seabed, a detailed study of the seabed currents is important. High currents potentially can lead to the seabed being "washed away" underneath the GBS, leading to instability of the WTG. Given the above, unfortunately, a price per MW is very difficult to provide.

3.1.3.2 OPEX

For all types of foundations, the OPEX are generally not very high. Making sure that the corrosion protection and the scour protection measures are still sufficient are the main OPEX drivers, together with the regular inspections of the substructures. The biggest cost driver here will be a service vessel that will need to go out and inspect foundations. Day rates for such vessels easily reach 100.000 euro per day (depending on the size & scope of the inspection). For small inspection work, cheaper vessels can be hired.

3.2 Offshore Substations Foundation

For foundations for the offshore substations, in principle the same applies as per the previous discussion of the WTG foundations. Note that for substations the monopile is not considered a viable option, since this is typically for WTG only.

[3] https://guidetoanoffshorewindfarm.com/wind-farm-costs

4 WIND TURBINES

4.1 Description

Wind turbine technology is constantly improving as OEM's battle for the title of who has the largest turbine. The race for who has the largest turbine has led to an offshore dominance of three manufactures; Siemens Gamesa, Vestas and GE.

The wind energy industry has seen a development unlike any other in the past 40 years. It has gone from 75kW machines with a tip height of 40m in the 1980's to recently announced turbines of 15MW that nearly rival the height of the Eiffel tower. The 15MW turbines are due for serial production by 2024 and in the future this could increase to 20MW by 2030.

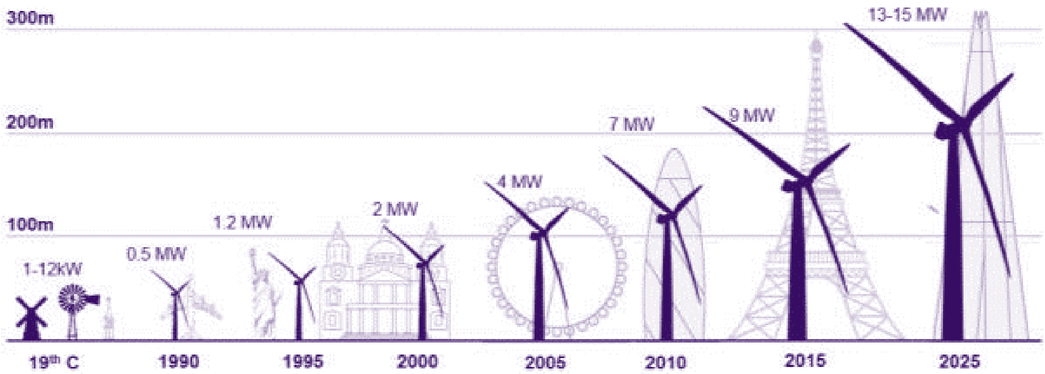

Figure 1 - Wind turbine power and size evolution over time[4]

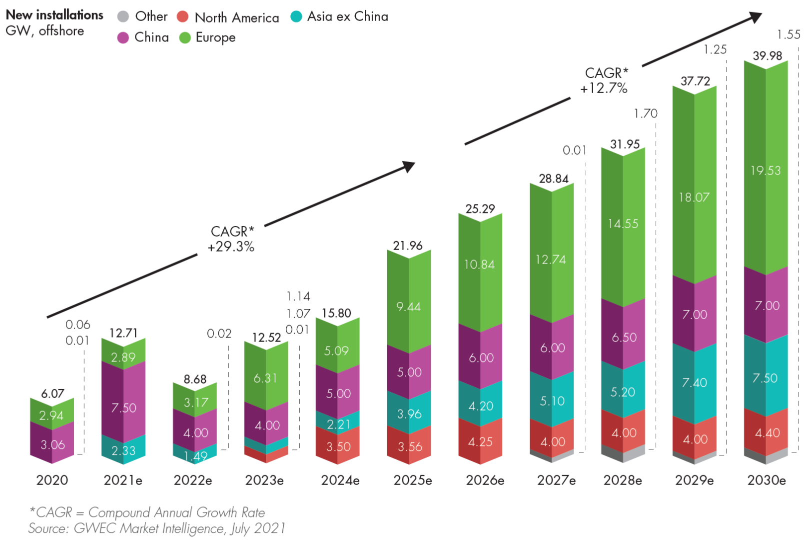

Figure 2 - Global offshore wind growth outlook to 2030[5]

[4] Pisanò, Federico. (2019). Input of advanced geotechnical modelling to the design of offshore wind turbine foundations

[5] https://gwec.net/global-offshore-wind-report-2021/

GWEC expects a total installed offshore wind capacity of 270 GW by 2030. It expects high compound annual growth rate of 30% towards 2025, with a slow down to 12.7 until the end of the decade. Promising outlook for offshore wind installation, because:

- Globally high ambition levels by governments
- LCoE keeps decreasing (competitive energy resource)
- Commercialisation and industrialisation of floating wind

4.2 Technical Information

Wind turbines extract energy by slowing down the wind. Albert Betz concluded that a wind turbine can only convert 59.3% of the kinetic energy from wind creating the Betz limit. For a turbine to be 100% efficient it would have to stop all the wind passing through it. In reality, this is not possible as a rotor needs the wind to pass over its blades to rotate. Modern turbines can convert 35-50% of wind energy, once you factor in mechanical and electrical losses this value reduces to 10-30% of wind power that is converted in usable electricity.

Offshore WTG consist of one tower section, nacelle, rotor and three blades. Inside the WTG there are electrical and mechanical equipment that are used to convert the wind energy. There are two types of drive train technologies that are used by all OEM's with horizonal axis machines; direct drive and gearbox machines. Below is a basic SLD for a wind turbine that shows the gearbox, generator, DC link converter, inductance to smoothen the waveform on the AC side and transformer. Not included in the image but equally important is the switchgear that receives the energy from the transformer before it reaches the grid.

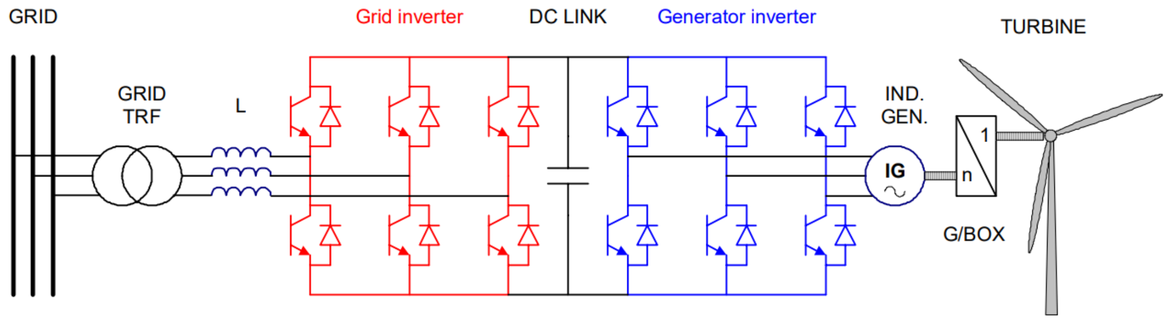

Figure 3 – Basic single line diagram of gearbox WTG showing IGBT converters

WTG's are designed and certified to operate in specific wind conditions. These wind conditions are defined by the IEC standard and correspond to high, medium and low wind speeds. Manufacturers have also designed WTG's that can withstand storms and typhoons for areas where this is an issue. If wind conditions are on the low end then manufacturers can increase the blade diameter and hub height to capture more energy as there will be less loads going through the turbines.

The WTG is controlled by various computers which monitor its condition and performance. They ensure that the WTG nacelle and blades are in the optimal position to capture the most wind. The SCADA system gathers and communicates the real time data so that asset owners can control and monitor the assets remotely. The power curve plots power vs wind speed which shows the cut in speed, partial and full load regions (see Figure 4). If the wind becomes too strong (typically above 25m/s) then the WTG will pitch the blades out of the wind and go into preservation mode to ensure that the WTG and substructures are not damaged.

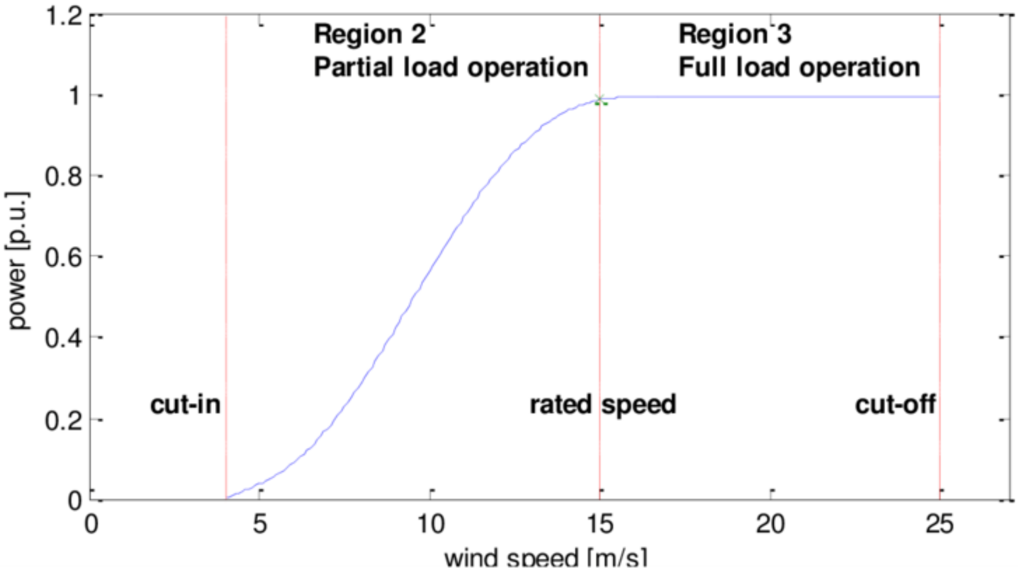

Figure 4 – WTG power curve[6]

4.2.1 Gearbox Wind Turbine Type

The gearbox wind turbine uses a multi-stage gearbox in between the low speed rotor and the higher speed electrical generator. The purpose of the gearbox is to increase the rotor speed before it is fed into the generator. The drive train consists of a main shaft, gearbox and electrical generator before the power is converted and sent to the grid.

4.2.2 Direct Drive Wind Turbine Type[7]

Direct drive wind turbines remove the need for a gearbox in the drive train, by connecting the rotor directly to the synchronous generator. A direct drive wind turbine's generator speed is equivalent to the rotor speed because they are directly connected. The power is transferred from the generator to the converter then the transformer and finally to the OSS through an inter-array cable.

Figure 5 shows the market share between OEM's of operating wind farms up to 2020. Senvion has since gone into administration and been bought by Siemens Gamesa. The Chinese manufacturer are not widely used outside of their own market and will not be discussed further. This market share should become more equal between three manufacturers (GE, Siemens Gamesa and Vestas) as they all start to deliver 10+MW turbines in the coming years. Figure 6 shows the announced capacity expected for 2020, which for the top three manufactures is greater than the total already installed.

[6] Source Wind energy conversion with a variable-ratio gearbox: Design and analysis

[7] https://www.engineering.com/story/the-future-of-wind-turbines-comparing-direct-drive-and-gearbox

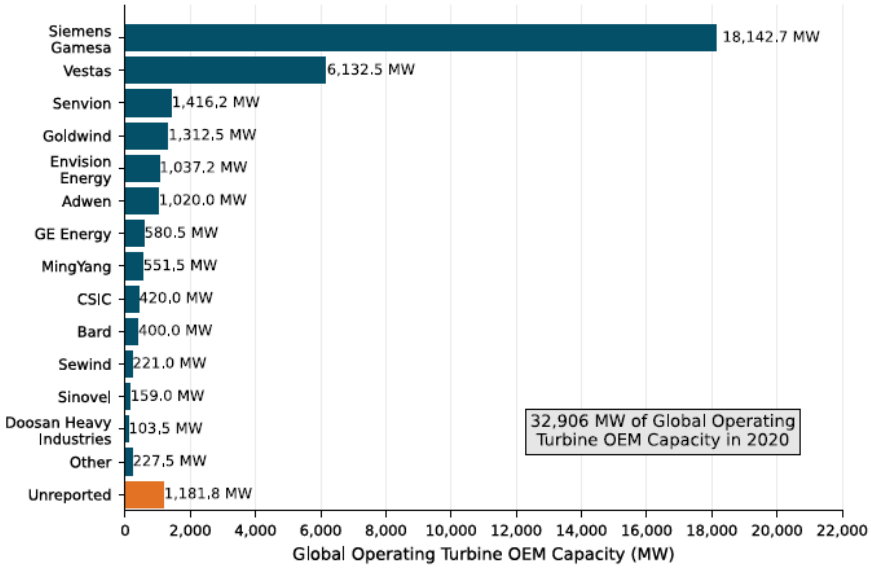

Figure 5 - Offshore wind turbine manufacturer market share in operating projects

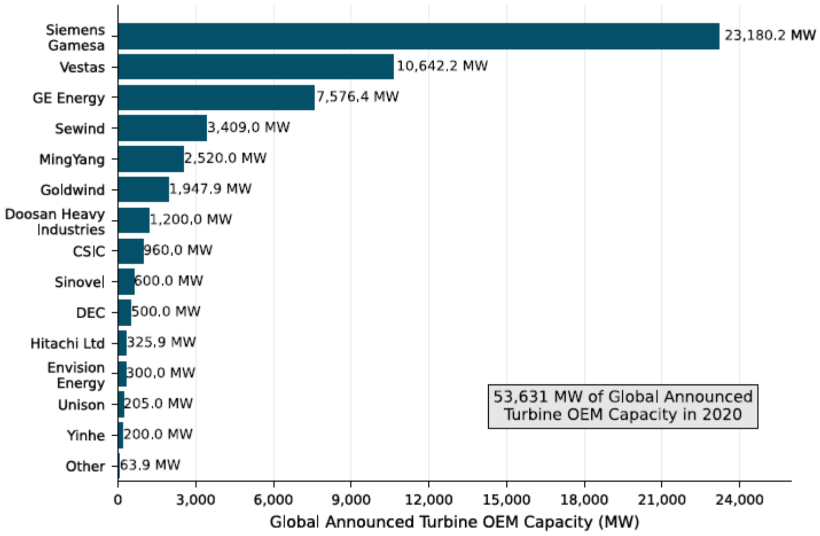

Figure 6 - Offshore wind turbine manufacturer market share for announced projects

4.3 Wind Farm Power Density

The optimal wind farm power density (MW/km^2) can vary depending various factors including, location, wind farm size, rotor power density and diameter, hub height, turbine capacity and spacing. Up to a certain level, a sparsely populated wind farm will have a lower LCoE than a dense wind farm due to lower wake effects. Over the last few years, the average power density of the Dutch offshore wind farms has increased from 5MW/km2 (Borssele) to 8MW/km2 (Hollandse Kust Noord) and will further increase to 10MW/km2. This trend has a negative impact on LCoE but is advantageous from an optimal use of space. The Energy Research Centre in the Netherlands commissioned a report that showed the optimal wind farm power density is 4.66 MW/km2 for a 10 MW wind turbine and 5.06 MW/km2 for a 15 MW wind turbine.[8][9]

4.4 Costs

4.4.1 CAPEX

Due to the size of wind turbines towers and blades they are constructed as separate components. Normally, fabrication yards are located near shore and are easily accessible for ships, so the components can be transported to the wind farms. The CAPEX below are assumed as a base case and consist of manufacture, transport, and installation. The further away a wind farm is from the assembly port the more expensive the project will be. In the short term turbine price will increase as there is a rise in raw materials prices (steel, copper, aluminium and fibres) combines with a sharp rise in logistic costs.

1.0 – 1.2 M€/MW

4.4.2 OPEX

The price for OPEX can vary widely depending on the location, turbine type and O&M strategy. Distance to shore affects transfer time of technicians when using CTV vessels and logistics of components for replacement. Newer wind farms are moving more towards hiring SOV vessels for week shifts that provide better and safer access to the WTG.. Turbine repair costs increase with age as more parts begin to fail. This is usually factored into the O&M contract price being larger towards the end of life of a project as repairs of main components require the use of jack up vessels that are expensive.

35 – 53 k€/MW/year

4.5 Lifetime

The normal design life of a wind turbine is 20-25 years. During the development stages of a wind farm the end of life options should be considered. There are three options at the end of life;

1. Decommission – remove the wind turbines and their foundations. Costs for this activity should have been accounted for in the development stage (typically 2-3% of CAPEX).
2. Life extension – depending on environmental factors and maintenance quality there is the possibility to extend the life of the turbines. This would typically involve carrying out an assessment that would identify any parts that need to be exchanged. During the operation of a wind farm measuring the loads experienced by the turbine and foundations is important for the life extension assessment.
3. Repowering – The owner of the wind farm can look to take advantage of the existing infrastructure (foundations, cables and OSS), which tend to have longer design life, to repower the wind farm with larger wind turbines. An assessment will need to be carried out on the technical feasibility of such an option.

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[8] http://resolver.tudelft.nl/uuid:dfe0ce2f-04fb-4db2-80db-52bc02cfb515

[9] https://blixconsultancy.com/wp-content/uploads/2021/06/20210125_RAP_Pathways_to_potential_cost_reduction_offshore_wind_energy_F03.pdf

The end of life decision will consider the site conditions, regulatory situation, permits and leases, energy prices, subsidy schemes and compare it against the cost and value of decommissioning.

4.6 Availability

When evaluating the turbine availability (uptime) there are two methods that are used: Time based and Production based availability.

For time based availability, the O&M provider will guarantee a contractual availability between 95-96% for each year starting after all turbines are taken over from construction. Any downtime due to non-turbine related issue are excluded from the guarantee such as weather access, BOP and Grid availability. Time based availability is calculated based on the time that the turbines are available to produce regardless of wind speeds.

Production based availability was created to prioritise the importance of having the turbine available during high wind periods which means maintenance activities are carried out in low wind periods otherwise it penalises the service provider. The so-called capacity factor gives a good indication of the wind resource available at a site by showing how well a wind turbine's full capacity is used. Offshore windfarms have an average of 42.22% based on data available in the UK. As wind farms move further away from shore and in deeper water (floating foundations) there is scope for this to increase as seen at Hywind OWF which reached 57.1% during 2019/20.

Any form of maintenance whether schedule or unscheduled would count against the availability guarantee which incentivises an O&M provider to plan around high wind periods.

It is not possible to provide specific numbers for downtime due to regular maintenance as there is difference in types of technology and what O&M providers include in their scope of service. However looking at time based availability guarantee there are 8760 hours in a year, if the guarantee is for 96% then the wind farm would not be available for 350.4 hours (14.6 days) per year.

Seasonality affects the production, maintenance and access to site. O&M providers should concentrate maintenance during the low wind periods (spring and summer) leaving the turbines alone during high capacity seasons (autumn and winter). Non access days can affect the performance of an asset when there are failures. On average in the UK wind farms, 96 days a year access is restricted, meaning that vessels cannot access the turbines due to adverse sea and weather conditions. Use of SOV as opposed to CTV will further lower this average.[10]

[10] https://ore.catapult.org.uk/wp-content/uploads/2021/02/SPARTA-Review-2020.pdf

4.7 WTG Catalogue

Below is a list of the largest turbines currently in serial productions as well as the next generation prototypes that are either installed or close to being installed.

WTG supplier	Largest WTG in serial production (TRL 9)		Largest Planned WTG			
	Capacity (MW)	Rotor ø (m)	Capacity (MW)	Rotor ø (m)	Year of prod.	TRL
Siemens Gamesa (SGRE)	8.4	167	15	236	2024	7
Vestas	9.5	164	15	236	2024	6
General Electric (GE)	6	150	14	220	2024	7

Table 2 - Offshore WTG specifications

5 OFFSHORE GRID CONNECTION SYSTEMS

The first offshore wind farm was constructed in 1991 off the coast of Denmark near a town called Vindeby where it also got its name. The market took a long time to mature however now due to various factors (government policies and incentives, cost reductions, land restrictions etc) there is more deployment of offshore wind.

Electricity transmission is divided into two main grid technologies, Alternating Current (AC) and Direct Current (DC), both with their own variations as LFAC, intermediate compensation (AC), different DC technologies/setups etc. During the next sections the technical concepts for each technology will be further assessed. The main factors like wind farm size and location offshore (transmission distance) dictate the connection type that is best. Most current offshore wind farms are relatively close to shore and have been connected using AC.

The DC alternative becomes competitive for combined CAPEX and OPEX with increasing power ratings and transmission distance. Although AC substations are cheaper, DC has lower cable costs and is able to carry more MW per cross section. In general there is a tipping point of CAPEX (DC-stations versus AC, more cables versus less for same MW, transmission distance) and OPEX (losses of stations, losses of cables, maintenance costs) together which favors one of both options.

6 AC TECHNOLOGY

6.1 HVAC Offshore Substation

6.1.1 Description

The AC offshore substation (OSS) collects the energy generated by the wind turbines and steps up the voltage to decrease the losses during transmission. This uses a radial system where the turbine are connected in strings and those strings then feed into the OSS. The design concept widely used currently is that one offshore wind farm would feed into a corresponding OSS and the power is then transported to onshore substation through an export cable (EXC) where it is connected to the grid.

This design is now being improved as countries and energy producers look to reduce costs and share energy between multiple markets. One option is to develop hub systems that can collect energy from multiple wind farms. The higher substation costs required is offset by requiring fewer EXC and increasing the wind turbine capacity factors through less curtailments. This option could be expanded to include interconnectors that connect various offshore hubs with multiple countries. A good example is the Kriegers Flak and Baltic wind farms that connect two separate markets, Denmark and Germany (although the two markets are non-synchronized leading to an additional HVDC back-to-back converter station).

At this moment AC platforms of a size larger than 1400MW are not very common, it is even considered to have multiple smaller platforms (350-450MW, for instance like the Siemens OTM which could even be regarded as a ‘standardized’ setup) as the length of the inter array cable (IAC) will increase dramatically (as the area to be built will be larger with higher power, but all need to be connected to one large OSS). Therefore the rated powers will be limited to 350, 500, 700, 1000 and 1400MW for a HVAC OSS.

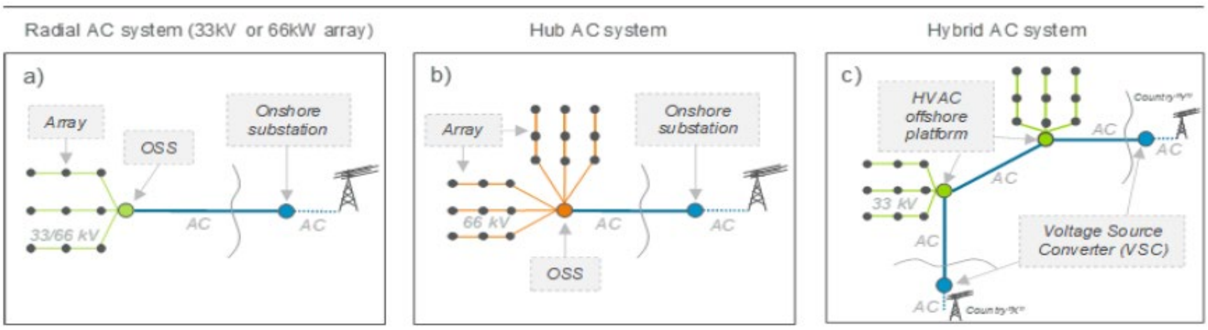

Figure 7 - AC offshore grid connection layouts[11]

6.1.2 Technical information

When an AC-connection is considered, there are some options that impact the high-level decisions:

- length of EXC, as a longer length leads to higher capacitance / higher reactive power losses / less available MW-transmission (this can be partly reduced by symmetrical compensation and/or an intermediate compensation)

[11] https://guidehouse.com/-/media/www/site/downloads/energy/2019/2019-navigant-comparison-offshore-grid-development.pdf

- voltage of EXC, as a higher voltage leads to a higher MVA-transmission but also higher reactive power losses lowering MW-transmission
- on top of this, the redundancy should be considered
    - is there a need for redundancy on the OSS (maybe based on TSO requirements and compensation schemes)?
    - is there a need for redundancy for the EXC

The redundancy is not further considered. It is of course clear that any OSS with at least two EXC and/or two transformers can provide partial redundancy:

- design the transformers for ONAN in normal operating conditions and use ONAF when one transformer fails
- design the EXC for normal operating conditions and use a DTS system (monitoring the complete length of the cable) when one EXC fails
- design of the system so if the compensation reactor is out-of-service the turbines can partially take over the compensation functionality
- connect to a neighboring OSS (IAC or EXC level) to have partial redundancy or only AUX power for turbines

Based on the average ampacity/capacitance of EXC with large cross sections, the following general rules can be applied for average distances (40km – 70km):

- the maximum power to be transmitted by 220kV equals to 400MW
- the maximum power to be transmitted by 275kV equals to 500MW
- offshore transformers larger than 500MW (550MVA) are not preferred as less standard
- having the amount of EXC equal to the amount of transformers leads to an ‘optimized’ balance between the two types of equipment

These statements are very general and based on experience / calculations of different setups and of course deviations can always be found.

Based on the above the following is expected as optimal technical-economical choices:

Power [MW]	Main TR [#]	Voltage [kV]	EXC [#]
350	1	220	1
500	1	275	1
700	2	220	2
1050	2	275	2
1400	3	220	3

Table 3 - General setups for different transport powers

The exact distance from shore is no real parameter here except for the cable losses and the size of the compensation reactor. For very large distances, intermediate compensation platforms may need to be considered.

The standards / brochures that are related to OSS are in general the DVN-GL ST-0145 which refers to many other standards based on the equipment installed on the OSS.

6.1.3 SLD

- compensation reactors are consider to be connected via a DC/ES to the EXC
- an average of around 80MW/string is considered
- transformers are assessed as 2 winding each winding having a MV earthing/AUX transformer and associated bay

Figure 8 shows the resulting high level SLD (additional ES/DC are omitted) where the colors denote the amount of offshore transformers/EXC/compensation reactors (black = 1, red = 2, green = 3):

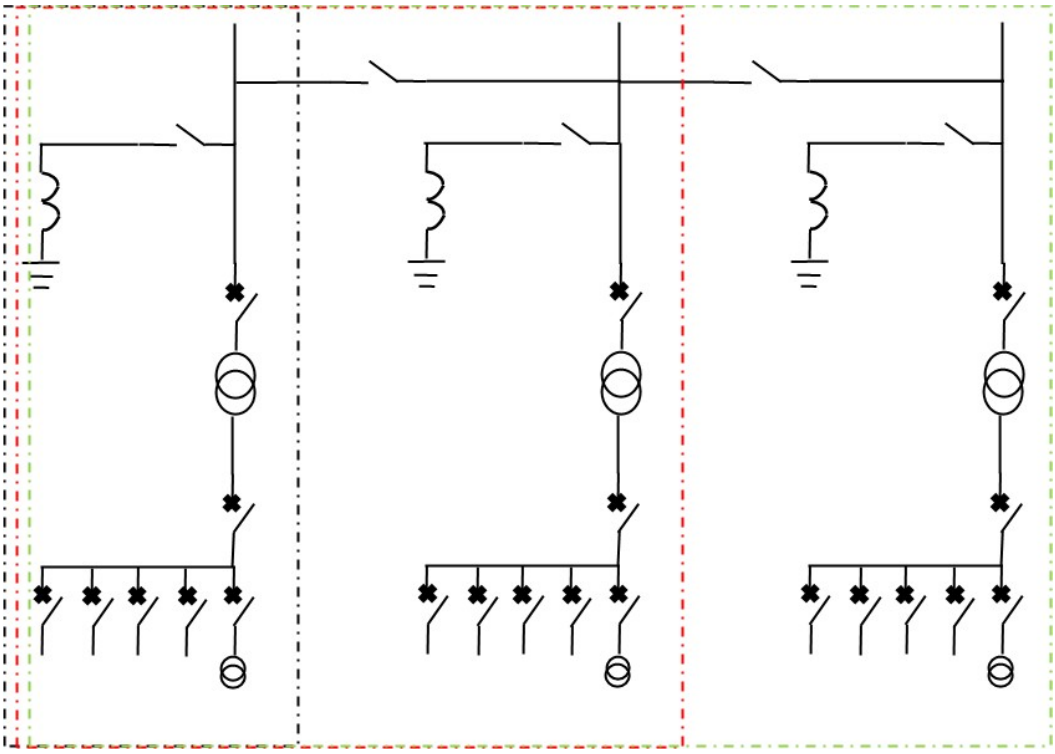

Figure 8 - High level SLD's in relation to # transformers

6.1.4 Costs

6.1.4.1 CAPEX

The CAPEX of the chosen system design is highly impacted by design choices and the prices in the OEM market for electrical components and metals. It has been observed that RFQ for main components sometimes even resulted in a spread of 100% on the received offers. For the CAPEX estimation below a range of ±20% is assumed.

The following overview is based on a minimal approach:

- amount of transformers and reactors as per previous table / SLD
- reactors connected with DC/ES
- if more than one EXC, a DC/ES between the both
- transformers and reactors housed outside
- LV and HVAC redundant
- no large crane or diesel generator
- unmanned

The CAPEX can be raised considerably based on the following decisions:

- making it a manned OSS with all additional HSSE requirements
- housing the transformers and reactors inside (even with HVAC, this should get an increased capacity then)
- gensets (for OSS and turbines) and IAC-compensation reactors for during grid outage
- large cranes (they tend to fail at the moment you need them, better come with an equipped vessel)
- a helideck (roughly 3M€)

Power [MW]	CAPEX [M€]	€/MW [k€]	HVMV [%]	LV-AUX [%]	Structural [%]	PM, Install & Comm [%]
350	71	204.1	22%	17%	29%	32%
500	86	171.9	23%	14%	35%	28%
700	121	173.0	23%	12%	37%	27%
1050	155	148.0	23%	11%	39%	26%
1400	179	127.6	24%	11%	40%	25%

Table 4 - Overview of CAPEX HVAC OSS for different transport powers

6.1.4.2 OPEX

OPEX is typically expressed as a percentage of CAPEX. BLIX through previous projects and confirmation from various sources finds that 1.5% is a reasonable value to apply. This is further confirmed through various research papers that arrive at similar values of 1%[12] and 0.9 – 1.45%[13].

The activities for preventive maintenance include:

- maintenance HVMV equipment (inspections & functional specs)
- maintenance LV equipment ((inspections & functional specs)
- maintenance AUX equipment ((inspections & functional specs)
- coating repair
- C&P: rolling testing in time of all relays by injection
- cleaning: removing of guano

Corrective maintenance is expected mainly on AUX-systems and could we require 12-24 interventions/year.

6.1.5 Lifetime

The lifetime of a platform is considered to be a minimum of 25 years, where the most wear and tear can be expected from rotating components and the components that stress by continuously heating up and cooling down (transformers) and being in full power continuously (reactors). Next to having correct preventive maintenance on these components (preferably with an online gas-measuring unit

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12 Brard, B. (2017). The regulation of radial grid connection systems for offshore windfarms. Delft University of Technology.

13 Ritzau, M., Macharey, U., Svoboda, P., & Wilms, J. (2017). Determination of an operating cost lump sum for offshore plants. Decision BK4-17-0002 of the Federal Network Agency

for transformer/reactor), fans (rotating) or diesel generators (needing filtered diesel by pumps) should be avoided to increase lifetime and limit maintenance.

6.1.6 Availability

The availability is assessed in respect to preventive and corrective maintenance.

Preventive maintenance is foreseen for 24 interventions per year of 4 days without the need for production loss as all (impacting) maintenance is foreseen to be planned during low/no wind.

Corrective maintenance is difficult to assess as this is determined by the design of the system:

- each supporting system which is critical to the main functionality, should be constructed 100% redundant. Examples:
    - HVAC system
    - LV-system
- the HV-setup determines to which level partial redundancy can be derived
    - when only one healthy transformer is available this can be boosted with later attached fans

A RAMS assessment of an OSS-design will lead to the theoretical power lost availability figure which normally is higher than 99.5% (taking into account the specific power loss depending on the failure).

6.1.7 Losses

Losses can be easily derived from the losses of the main components and the own consumption of the OSS. On top of that the wind profile/powercurve should be assessed (power bins) to come to the percentage of energy produced that is considered as consumed/lost on the OSS (and include the load-losses of transformers). This is normally in the range of 0.3%-0.4%.

6.2 AC cables

6.2.1 Description

For offshore multiple submarine cables (voltages, cross sections) are available (Prysmian catalogue):

Voltage class [kV]	Cross section [mm2]
66	240 - 2000
110	400 - 2500
132	400 - 2500
150	400 - 2500
220	630 - 2500
275	630 - 2500
345	800 - 2500
400	800 - 2500
500	1600 - 2500

Table 5 – General overview of available submarine cable cross sections per voltage class

For each OWF (Offshore Windfarm) several types of cables/accessories are needed, assuming the land station is located not too far from the coastline.

- Inter Array Cables (IAC) to connect the offshore turbines with strings towards the OSS
- Export Cables (EXC) to connect the OSS to the land station. In most cases they consist of:
    - a 3-core submarine cable
    - a transition joint (normally) on land to switch from the 3-core submarine cable to single land-core cables
    - single land-core cables to connect to the land station
- Grid cables: cables to connect the land station to the TSO-grid

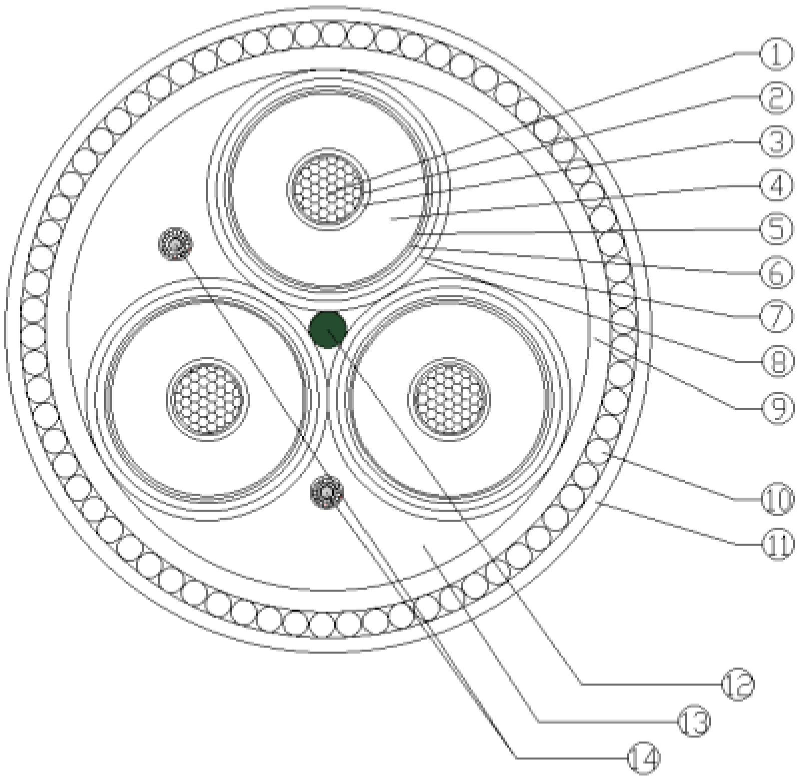
This chapter will concentrate on the submarine cables (IAC and EXC).

6.2.2 Export cables

6.2.2.1 Technical information

To lower the losses of the transport system, the voltage of the IAC is raised by transformers to the EXC level. At this moment the main used voltage level used is 220kV and sometimes 155kV (to connect lower power, mainly used to connect to offshore DC-stations of TenneT Germany) and 275kV.

These cables are normally made with a XLPE-insulation while having led both a radial-water-blocking element and return path for the single-phase short circuit current [7]. See below picture as a general setup:



1 Stranded wires

2 Semiconducting tapes

3 Conductor extruded screen

4 XLPE

5 Extruded screen

6 Semicon tapes for LWB

7 Lead

8 Semicon PE

9 Yarns

10 Armour (GS/HDPE)

11 Yarns

12/13 Filler / extruded filler

14 FO

Figure 9 – Export cable example

The cable also contains FO (communication and temperature measurement system), armouring (protection), fillers (strength) etc.

As the cable can be considered as a large capacitance, capacitive current and hence power loss will be imminent. As the Mvar raises with the square of the voltage, this is considered having a high impact and is used in discussion what the tripping point is to move from AC-technology to DC-technology. Of course the cable is available in different cross sections (range depending on voltage level, see table) in both ALU (stranded or solid) or Cu. Milliken types are normally not used due to expenses.

Five types of information are normally available for EXC:

1. mechanical properties / cable handling
2. geometrical properties (how is the cable built up, layers, materials)
3. electrical properties
4. ampacities
5. FO-properties

Item 1 is required to have sufficient comfort that the cable handling by the installation contractor will be withing the cable handling limits. This is both for spooling of cables between different locations, installation on the seabed, burying the cable and installation of cables into the OSS until termination.

Item 2 is required if specific frequency sensitive simulations need to be executed as transient analysis or harmonics distortion calculations. Normally these parameters are translated by simulations packages as PSCAD or EMTP to frequency dependent electrical parameters which are then used in follow-up simulations.

Item 5 refers to the fiber optic properties, normally the capabilities are well within the required boundaries.

For item 3 and 4 the following can be assessed as some general cable characteristics for a small and large cross section of ALU and Cu.

Cable characteristic	Unit	ALU 800m2	ALU 1600mm2	Cu 1200mm2	Cu1400mm2	Cu 2200mm2
Nominal voltage between phases U_N	kV	220	220	220	275	275
Maximum voltage between phases U_M	kV	245	245	245	325	325
Maximum electrical stress at U_N @conductor surface	kV/mm	8.3	7.8		10	9.7
DC-resistance conductor 20 degrees	Ohm/km	0.0367	0.0186	0.0151	0.0129	0.0082
AC-resistance conductor 90 degrees @50Hz	Ohm/km	0.0497	0.0287	0.026		
Positive sequence impedance @50Hz	Ohm/km	0.071 + 0.129j	0.047 + 0.114j		0.0272 + 0.1154j	0.024 + 107j
Inductance of conductor	mH/km	0.412	0.361	0.37		
Capacitance per phase	µF/km	0.154	0.2	0.195	0.207	0.25
Total losses @ampacity	W/m	146.6	167			
Conductor losses	W/m	3x33.8	3x33			
Dielectric losses	W/m	3x0.8	3x1.0			
Metallic screen losses	W/m	3x5.5	3x9.2			
Armour losses	W/m	26.5	37.3			
Maximum short circuit current conductor (1s)	kA	76	151	172		
Maximum short circuit current metallic screen (0.6s)	kA	21.2	21.7	22		
Armour material		GS	GS	SS	50%GS/50%HDPE	50%GS/50%HDPE
Ampacity (DoB 1.5m / soil 10 degrees / soil 0.6Km/W)	A	824	1073			
Ampacity (DoB 1.5m / soil 15 degrees / soil 0.7Km/W)	A				1180	
Ampacity in HDD	A			1000		1180

Table 6 – Electrical characteristics of HVAC cables

These values are available from several cable suppliers which cannot be referred to due to confidentiality. Main suppliers at this moment are:

- NKT, Germany
- LS, South Korea
- Prysmian, Italy
- Hellenic, Greece
- Nexans, Sweden
- Chinese suppliers upcoming

Next to the cables several related accessories are important:

- factory joint: to be able to make long lengths in the factory, suppliers will 'connect' single cores with factory joints for their laying-up machine. The FJ are most times also capable of switching in cross section and sometimes even to switch in conductor material
- repair joints or offshore joints: joints to connect (or repair) offshore cables, normally consisting of 3 'normal' joints in a metal casing
- transition joint: joint onshore to connect the 3-core submarine cable to single land-cable cores, normally consisting of 3 'normal' joints
- terminations: mostly Pfisterer size 6 terminations which are used to connect to an inline joint or a HV-GIS
- inline joint: several types exist, but the most common is a SF6 filed system which connects to male terminations (example: Pfisterer 6 size)

The standards / brochures that are related to these type of cables are mainly IEC 62067, TB490 and TB623 (and referred standards therein). These documents refer to construction, pre-qualification tests (PQ), type tests (TT), routine tests (last test as FAT), sample tests and SAT, both for cables and their accessories.

6.2.2.2 Installation

The installation of EXC is normally executed from a cable laying vessel that contains large baskets on turntables that are filled at the quay side. Figure 10 shows the design of this equipment to be placed on a cable laying vessel:

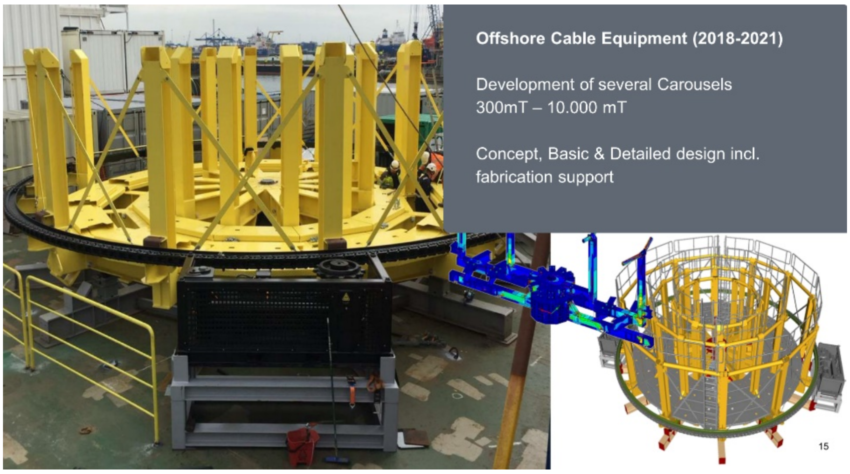


Figure 10 – Design of turntable on a cable laying vessel[14]

The cable is 'laid down' with a special system (checking all mechanical stress parameters on the 3-core cable) on the seabed. Afterwards normally a ROV is used to bury the cable by liquifying the seabed which allows the cable to sink easily to the required depth.

At the OSS the cables are guided through a Cable Protection System (if applied, also only scour is used) and the J-tubes. Then they are stripped on the cable deck of the OSS (3-core cable will be fixated by hang-off) and the single cores are guided to the HV-GIS and terminations are installed and connected. Sometimes an inline joint is used to connect the EXC and pre-installed platform cables.

Of course, many more requirements and activities need to be fulfilled/executed during this installation process, only the high-level activities are mentioned.

6.2.2.3 Costs

6.2.2.3.1 CAPEX

The following table shows some costs that can be expected for different types of EXC. When this information is used, the next points should be considered carefully which requires to use the prices with a large margin:

- it should be noted that the cable prices have been very volatile in 2020/2021 due to COVID and the price of metal
- the tender prices that have been used are the variable prices per meter
- the tender prices are also highly depending highly on the cable-volume of the project (LOW < 50km, MEDIUM, HIGH: > 150km)

[14] Enersea presentation of activities. www.enersea.nl

- suppliers tend to also assess the risk of a project in their price, this is not further detailed
- based on the above a margin of at least 25% should be applied

Voltage class [kV]	Cross section [mm2]	Conductor material [ALU/Cu]	Armour material [GS/SS/HDPE]	Volume	Costs [€/m]
220	630	ALU	GS	LOW	480
220	800	ALU	GS	HIGH	410
220	800	ALU	SS	HIGH	480
220	1000	ALU	GS	HIGH	430
220	1000	ALU	SS	HIGH	510
220	1000	Cu	SS/HDPE	HIGH	750
220	1200	ALU	GS	HIGH	450
220	1200	ALU	SS	HIGH	505
220	1200	ALU	SS/HDPE	HIGH	530
220	1600	ALU	SS	MEDIUM	770
275	1400	Cu	GS/HDPE	MEDIUM	1200
275	2000	Cu	SS	MEDIUM	1500

Table 7 – Cost per meter of several HVAC cables

The above prices do not include:

- engineering and if needed additional type test or PQ tests
- fixed (starting) costs for supply
- installation of offshore joints / transition joints (high costs due to vessel availability)
- termination and testing (T&T)
    - termination is normally not the highest portion of costs but does pose a risk (check: availability)
    - testing can be quite expensive if a resonance test (from onshore) is conducted

In recent projects calculations for EXC are done based on dynamic rating (per IEC 60853-2) instead of continuous rating (per IEC 60287) as it has been shown that the cables are over-dimensioned and never reach their maximum temperature. This lowering of cross sections of course does add to higher losses during normal operation and less margin during n-1 situations.

The installation costs of all cables are roughly the same (if the cable is larger/heavier the vessel needs to make more trips / more offshore joints are needed) and can be assessed for €200/m for the variable part with a margin of 20%. The mobilization and demobilization costs should be added including weather delay provisions which are very project specific.

6.2.2.3.2 OPEX

OPEX is very depending on the project specific situation (how is it buried, rocks, sand, mattresses (for crossings), clay, ..) leading to a wide spectrum of inspection techniques and cannot easily be given.

The OPEX can be ‘minimized’ by use of DTS (Distributed Temperature Systems) and/or DAS (Distributed Acoustic Sensing) which monitors the temperature (and if installed correctly, the DoL (Depth of Laying)) next to free hangs or other mechanical stress adding activities.

In a ‘normal’ situation the following activities are covered as preventive maintenance:

1. a 1-5 yearly survey is needed to check the exact laying configuration of the cable (based on the magnetization of the armour during load-out)
2. a Remote Operated Vehicle (ROV) with camera’s to inspect CPS (Cable Protection Systems) entering the J-tubes and crossings done with mattresses
3. re-execution of LIRA/TDR tests to assess impact on insulation

6.2.2.4 Lifetime

Lifetime of type tested cables (all cables are assumed to be a dry design) are considered to be 25-40 year. Formally the IEC-standards do not mention this and the first installed submarine cables have barely reached this lifetime

6.2.2.5 Availability

The availability of EXC is depending on 4 major items:

1. The electrical quality of the cable: normally if this is correctly tested (PQ, routine, FAT, SAT) there is a low expectation on failure
2. The mechanical quality of the cable: normally if this is correctly tested (PQ, SAT) and the installation conditions have been monitored and kept all beneath the allowed limits, there is a low expectation on failure
3. Man-made additions as repair joints and terminations: this can be a source of failure
4. Mechanical damages due to free-hanging (stress), anchors, fishing nets etc.: this is a major source of failures and is heavily depending on the offshore location

Item 3 is partly covered by the SAT (Site Acceptance Test) which stresses the cable according to IEC 62067 including the accessories. This is normally a resonance test until $1.7U_0$ per phase in the range of 20Hz - 300Hz (or a bit lower as per table 10 of IEC 62067). If a choice is made for a 24hr soaktest, this is not applicable and not ‘tested’. The failure rate of the EXC is normally expressed as an electrical failure rate per km (λ) and added on top that the failure rate per joint/termination (which usually derived from land-based failure rates).

Item 4 is a practical assessment which needs to be made by the OWF and differs all over the world. A value derived from available sources shows an average of 0.003 failures/km/year[15].

6.2.2.6 Losses

It should be clear that for losses calculations 3 options can be used:

- W/m as given for the 220kV cable (see overview)
- metallic screen losses can also be referred to as λ_1 being the ratio between conductor losses and metallic screen losses and armour losses can be referred to as λ_2 being the ratio between conductor losses and the armour losses
- use of positive sequence resistance which incorporates all these 3 losses (but missing the dielectric losses which are considered small)

As stated before, the losses and Mvar of the cable do impact the tripping point where an AC connection is becoming less attractive. A qualitative approach is shown in the compensation chapter.

[15] Failure Rates of Offshore Wind Transmission Systems. energies-12-02682

To lower/eliminate the armour losses, suppliers can replace the galvanised steel wires by stainless steel wires or HDPE (if the impact amount of pulling force is allowed) or a mix of these types.

6.2.3 Inter array cables

6.2.3.1 Technical information

To connect the turbines to the OSS, the inter array cables (IAC) are used. They will operate on the voltage level of the turbines on the HV-side of the transformer. Until a few years ago this voltage level for offshore was 33kV, this has been changed now to 66kV, amongst others by projects initiated by the Carbon Trust. Further the next step, also initiated by the Carbon Trust, is to increase this level to 132kV, however cable characteristics are still unknown. This level is ‘agreed’ between cable suppliers and turbine suppliers will follow. This also has to do with the amount of power each turbine is able to produce which has raised very fast from 4MW (Gemini, 2010), 9.5MW (Blauwwind, 2018) to 15MW (expected in 2024/25). Further the higher voltage will give reduced losses, longer distances and a more acceptable voltage profile along the string.

These cables are normally made with a XLPE-insulation or EPR-insulation (Prysmian), the last one having more flexibility then XLPE-cables (and also claimed better ampacity). The radial water blocking functionality can be present (overlapping, glued foils or ALU welded sheath) or constructed as a (semi)wet design which allows the cores (screen wires, outside semicon) to come in contact with the seawater. See below picture as a general setup for a dry design:

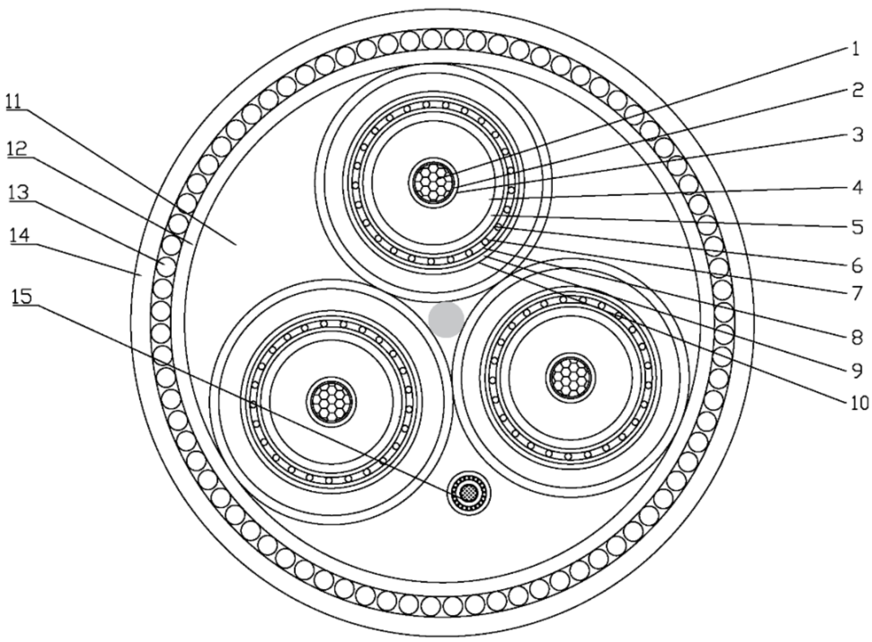


Figure 11 – Inter array cable example

1 Stranded wires
2 Semiconducting tapes
3 Conductor extruded screen
4 XLPE
5 Extruded screen
6 Semicon tapes for LWB
7 Copper wires
8 Semiconducting tapes
9 RWB tapes
10 HDPE sheath
11 Extruded fillers
12/14 Yarns
13 Armour GS
15 FO

The cable also contains FO (communication and temperature measurement system), armoring (protection), fillers (strength) etc. The information types of IAC are identical as for EXC.

Cable characteristic	Unit	ALU 800m2	ALU 1200mm2
Nominal voltage betwen phases U_N	kV	66	66
Maximum voltage between phases U_M	kV	72.5	72.5
Maximum electrical stress at U_N @conductor surface	kV/mm	6.5	6.3
DC-resistance conductor 20 degrees	Ohm/km	0.0367	0.0247
AC-resistance conductor 90 degrees @50Hz	Ohm/km	0.0508	0.0371
Positive sequence impedance @50Hz	Ohm/km	0.061 + 0.096j	0.048 + 0.092j
Inductance of conductor	mH/km	0.305	0.292
Capacitance per phase	µF/km	0.384	0.4621
Total losses @ampacity	W/m	108.1	115.3
Conductor losses	W/m	3x29.2	3x28.8
Dielectric losses	W/m	3x0.1	3x0.1
Metallic screen losses	W/m	3x2.0	3x3.0
Armour losses	W/m	14.3	19.6
Maximum short circuit current conductor (1s)	kA	75.6	113.5
Maximum short circuit current metallic screen (1s)	kA	3.4	3.9
Ampacity (DoB 2m / soil 15 degrees / soil 0.7Km/W)	A	757	881

Table 8 – Electrical characteristics of IAC AC cables

These values are available from several cable suppliers which cannot be referred to due to confidentiality. Main suppliers at this moment are (known for 66kV):

- NKT, Germany
- LS, South Korea
- Prysmian, Italy
- Hellenic, Greece
- JDR, UK
- TKF, Netherlands
- Chinese suppliers upcoming

Next to the cables several related accessories are important which are sort of identical to EXC. The use of FJ is normally not needed and allowed (by clients) as the single lengths of cables are, with an exception, not so long that this is needed.

The standards / brochures that are related to these type of cables are mainly IEC 63026, TB623 and TB722 (and referred standards therein). These documents refer to construction, pre-qualification tests (PQ, only if a certain stress-level is passed), type tests (TT), routine tests (last test as FAT), sample tests and SAT, both for cables and their accessories.

6.2.3.2 Installation

The installation of IAC can be assessed as like the EXC except for lighter, smaller cables, shorter lengths and more pull-ins, stripping and terminations.

The installation on the OSS is nowadays more often with an inline joint already pre-installed at the cable deck.

6.2.3.3 Costs

6.2.3.3.1 CAPEX

The following table shows some costs that can be expected for different types of IAC. It should be mentioned that many 33kV-producing factories have reacted to 66kV as a small additional step (and therefore small price increase) which showed to be incorrect at the end. Therefore prices have, next to market prices, relatively grown. When this information is used, a large margin should be used for the same reasons as for the EXC (25%).

Prices for 132kV cables are not readably available as not in use at the moment. An estimate has been added based on prices for 66kV and 220kV cables. This should be confirmed later once it becomes more widely used as the product matures.

Voltage class [kV]	Cross section [mm2]	Conductor material [ALU/Cu]	Armour material [GS/SS/HDPE]	Volume	Costs [€/m]
66	300	ALU	GS	MEDIUM	150
66	400	ALU	GS	HIGH	140
66	800	ALU	GS	HIGH	190
66	800	Cu	GS	HIGH	420
66	1200	Cu	GS	LOW	710
132	800	ALU	GS	MEDIUM	310
132	1200	Cu	GS	MEDIUM	750

Table 9 – Cost per meter of several IAC cables

The above prices do not include:

- engineering and if needed additional typetest or PQ_tests
- termination and testing (T&T)
    - termination can be quite a portion of all costs and do pose a risk (check: availability)
    - testing can be quite expensive if a resonance test offshore is conducted

The installation costs of all cables are roughly the same (if the cable is larger/heavier the vessel needs to make more trips) and can be assessed for €200/m for the variable part with a margin of 20%. The mobilization and demobilization costs should be added including weather delay provisions which are very project specific. Further the Installation of IAC on the turbines/OSS require relatively an additional high additional CAPEX part compared to the EXC as the lengths of section are quite small (1.5km – 2.5km), on the other hand in general offshore joints are not considered for IAC.

6.2.3.3.2 OPEX

Reference is made to EXC.

6.2.3.4 Lifetime

Lifetime of type tested cables (especially the dry design) are considered to be 25-40 year. Formally the IEC-standards do not mention this and the first installed submarine cables have barely reached this lifetime.

6.2.3.5 Availability

The availability of IAC is depending on these same 4 major items as the EXC except one item is much more prominent: as the IAC normally have a 2 terminations per 2km (distance between 2 turbines), the EXC have a joint/termination per 40km. This makes the sensitivity for man-made terminations per km cable much higher.

This is partly covered by the SAT (Site Acceptance Test) which stresses the cable according to IEC 63026 including the accessories. This is formally a resonance test until $3U_0$ per phase in the range of 10Hz - 500Hz, but this test, which is standard onshore, has only recently been developed. Oher options are VLF (Very Low Frequency) tests, normally on 0.1Hz, sinusoidal, square waved or a damped AC test. The reader should be aware that the VLF and AC-damped tests do not conform to standards. Another test is the 24hr soak test, although this is not assessed as 'tested'. A practical solution could be to agree with a supplier a VLF or damped AC test and use the soak test as the formal contractual milestone.

The above is not valid for the 132kV version of the IAC as the IEC 63026 'ends' at 72.5kV. For that voltage level the IEC 60840 needs to be used. This would mean a resonance test between 20-300Hz of U_N per phase or a soak test.

In reference 16 a value derived from there shows an average of 0.0045 failures/km/year.

6.2.3.6 Losses

Reference is made to EXC.

[16] Failure Rates of Offshore Wind Transmission Systems. energies-12-02682

6.3 Reactive Compensation

6.3.1 Technical information

The main aspect of the EXC (and the discussion of DC) is related to the reactive power that is induced by the power frequency with long cables.

Compensation of the reactive current can be applied in 3 ways, each resulting in a different reactive current profile (with an assumed EXC capacitance):

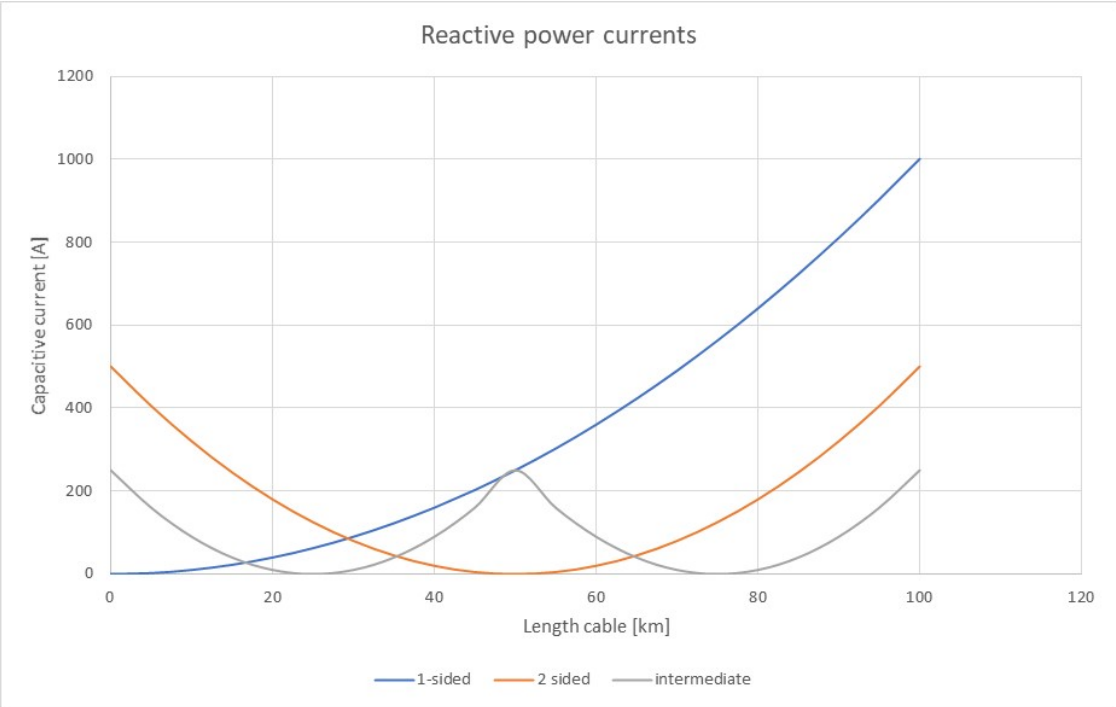


Figure 12 - Capacitive current AC EXC versus distance

- with one-sided compensation, at the onshore station, the Mvar current is high when reaching the beach (sometimes via a HDD). The effective current is the highest, resulting in the highest losses
- with symmetrical compensation it can be observed the Mvar current has been lowered to 50% on both ends
- with intermediate compensation this can even be further reduced

A practical calculation can show the difference:

Voltage	220	kV		
Capacitance	0.2	µF/km		
Ampacity cable	1000	A		
	Length [km]	1-sided [A]	2-sided [A]	Intermed. [A]
Capacitive current	50	399	200	100
Available MW current	50	917	980	995
Capacitive current	100	798	399	200
Available MW current	100	603	917	980
Capacitive current	200	1596	798	399
Available MW current	200	NA	603	917

Table 10 - Example of available ampacity ([A] versus compensation)

The project Gemini in the Netherlands was built with a 110km long export cable on 220kV and a 2-sided symmetrical compensation. Of course, long AC-connections will also give other PQ-challenges to check / mitigate.

In practice the EXC can have smaller cross sections on locations where the overall current is the lowest. Which in return also lowers the capacitance hence the reactive current.

6.3.2 Costs

The CAPEX for reactors is assumed as follows (margin 20%):

Voltage class [kV]	Reactive power [Mvar]	Costs [k€]
220	76	1500
275	137	2500

Table 11 - CAPEX of compensation reactors

These values are based on a 50km EXC. The differences are based on the EXC voltage and the assumed capacitance per kilometer for the cable.

Of course intermediate compensation requires a complete additional offshore platform.

6.3.3 Losses AC versus DC

First it should be assessed that based on the required power, both the AC and DC options are technically feasible. When comparing the two options, the following items should be compared:

- the CAPEX of the AC and DC solution should be made available including the cables
- the OPEX should be made available of both solutions
- the losses during lifetime should be calculated and made actual by means of a NPV calculation. This means the wind profile (and resulting EXC currents) should be made available, the interest rate and the future electricity price (or even lower subsidies)

It is not difficult to assess that the CAPEX and OPEX of the DC-option is normally substantially higher. So the gain will come from less losses.

6.4 Onshore HVAC Land Stations

The AC-landstations function as the intermediate for the EXC arriving and the connection to the onshore TSO-grid. On this connection point the grid code of the TSO will apply. The function of this landstation is therefore:

- bring the voltage to the required grid voltage
    - a transformer could even be considered as to be able to cope with voltage variations leading to higher losses in the EXC
- connect compensation reactors (compensation of EXC)
- have equipment installed to show grid compliance in respect to reactive power:
    - add a reactor with OLTC
    - add reactor and capacitor banks to be switched
    - add a STATCOM in case fast voltage support is needed which cannot be supplied by the turbines
- have equipment installed to show grid compliance in respect to PQ (power quality):
    - add a filter to limit the harmonic distortion to the allowed limits
    - add a filter to take care of TOV in case of energization or load rejections
    - take care of stable operation of the wind turbines, which is highly impacted by the minimum short-circuit-ratio (MW-OWF/MVA-grid). It is considered this value should at least be 3 to be able to have a stable operational connection without the probable need for this additional equipment

The design of such a station is very depending on all functions that are required but a ball park figure for a 1000MW AC station including the above amounts up to 80M€ - 90M€. Depending on the size, the STATCOM (including transformer, bays, C&P) represents 30% of this CAPEX figure.

OPEX activities in general are the same as for OSS except the coating repairs. Be aware of the preventive cleaning of insulators in (marine) environments if the land station is located nearby the coast.

7 DC TECHNOLOGY

7.1 Basic Components of DC Connections

The DC-technology is conceived as the next generation of connectors for longer distances / higher powers of OWF. A DC-link has already been in operation since 1954 by means of Line Commutated Converters (LCC-HVDC). As such this is a very mature technology used to transmit high power over long distances using grids overhead lines, submarine cables, back-to-back). Some specifics are:

- based on thyristor technology (thyristors only conduct current in one direction after gate signal, the current is transferred from one phase to another between thyristor valves). Thyristors can now even conduct 5000A as 8kV devices
- need for strong network connections (SCR > 3) or supporting systems
- need to filter both on the AC and DC-side
- absorption of reactive power (both as rectifier or inverter)
- direction of power flow not easily changed and if so, the polarity of the cable conductor changes
- large footprint due to filters
- losses: 0.6% - 0.8% per converter

Short Circuit Ratio (SCR) is here considered to be the MVA (LCC inverter) / MVA (Grid).

To have a smaller footprint (OSS platform) and to be able to connect to weak grids (OWF with wind turbines) the converter type used for the connection of OWF is the MM-VSC (Modular Multilevel Voltage Source Converters or MMC, Modular Multilevel Converters). Key specifics are::

- based on IGBT technology (based on modules, half bridge or full bridge that are put in series and can already include some ‘redundancy’)
- able to connect to weak grids (self-commutating)
- the need for a filter to have the correct power quality to feed the grid will be minimal
- able to control reactive power on each side of the connection
- power flow easily changed (other direction current)
- smaller footprint (30% - 50% reduction compared to LCC)
- higher losses than LCC-HVDC: 1.0% per converter station

The key element of VSC is the use of power capacitors integrated with the converter modules. They function as an intermediate storage which realizes the balance between constant DC power flow and oscillating AC power flow. Values that are common are 3.3kV IGBT’s with 10mF capacitors. To arrive at for instance 320kV this would lead to more than 400 modules if 5 - 10% redundancy is included. Nowadays IGBT’s (ABB types, Mitsubishi types) conduct to around 2200A.

Examples of such a module is shown below where the half bridge is only capable of providing half the output voltage compared to the full bridge.

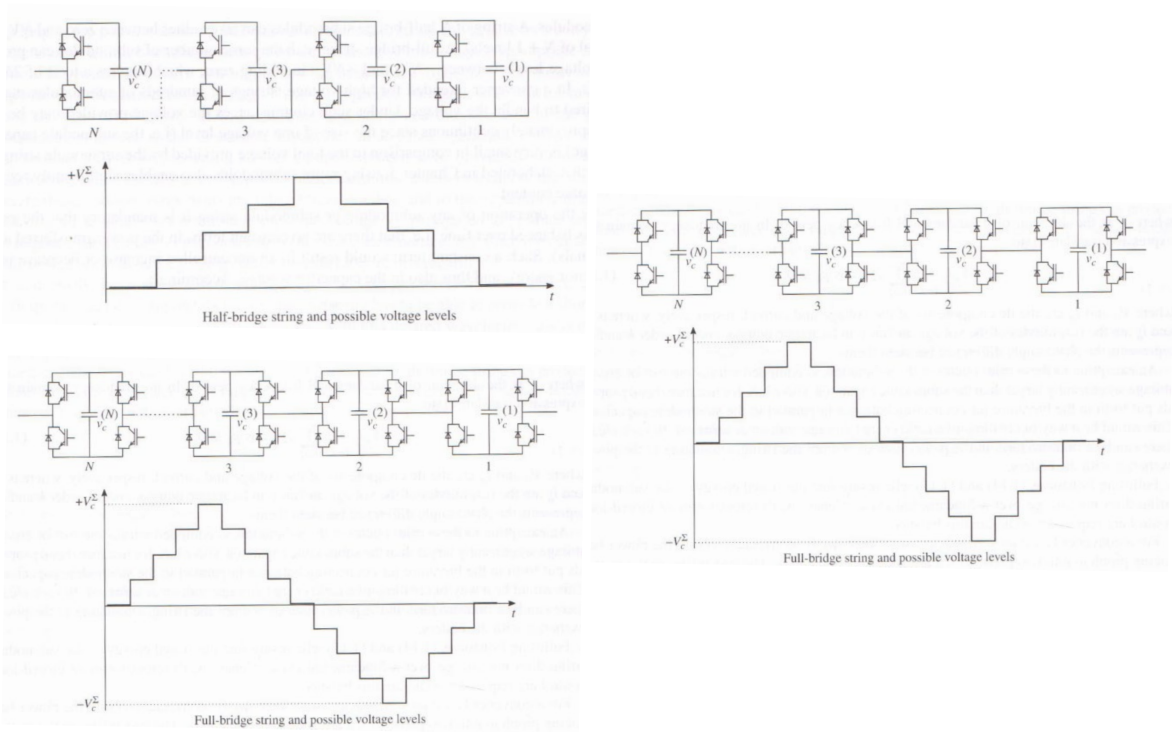


Figure 13 – Output voltage levels depending on type of bridge

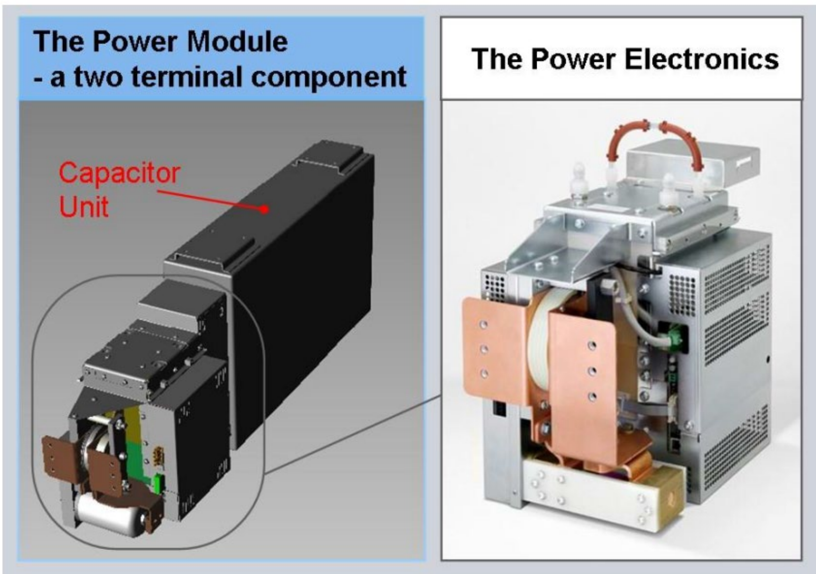


Figure 14 - Siemens HVDC Plus module

The overall system should be made robust for faults such as:

- internal faults as submodule faults, modulation & control faults and phase reactor fault
- external faults as AC network faults at PCC, AC faults inside the converter station and DC-faults, pole-to-pole and pole-to-ground.

The components and systems to mitigate these faults are rapidly developing and are considered differently by each of the 3 main suppliers:

- discharging cable system
- onshore DC choppers/dynamic breakers
- inrush current limiting resistors
- series pole reactor to limit peak/rise of currents and smoothen ripple/harmonics
- phase reactor to suppress circulating currents due to imbalances in the converters and ability to control active and reactive power flow
- DC-breakers

Special attention should be given to the DC-breakers. There are available in the market and to a certain theoretical extent work (in all kind of hybrid solutions) but the missing current-zero moment (as with AC) hinders an easy extinguishing of the arc-flash. Also several suppliers as ABB and Mitsubishi are (further) developing the hybrid solution which uses mechanical switches, full electronic bridges and artificial current-zero moments by injection.

Until now the faults of a point-to-point DC-connection with VSC is cleared by opening AC-breakers. To have selective fault detection and clearing for meshed DC-grids, there is no real proven affordable solution yet available which hinders the meshed grid development.

7.1.1 SLD

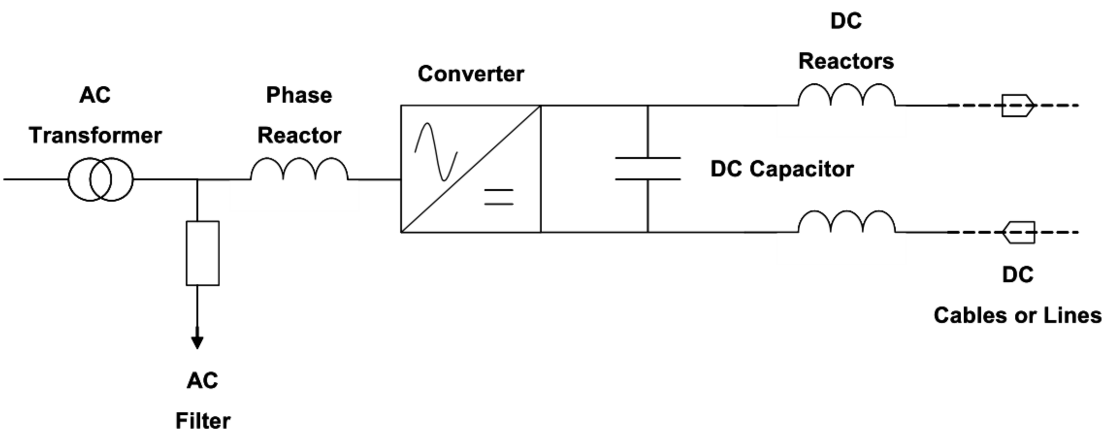


Figure 15 - Simple HVDC single line diagram

7.2 HVDC Offshore Substation

7.2.1 Description

The first large group of VSC OWF-connections has been pursued by Germany after the decisions to close all nuclear power plants. These connections, consisting of 8 platforms in total have power ranges of 576MW to 900MW, link voltages of 250kV – 320kV and have been provided by the 3 large suppliers (ABB, Siemens and GE/Alstom). It has been experienced that the commissioning and reliability of these 'new' technologies in the harsh marine environment including a constant 'vibration' as standing on a jacket is/was very challenging.

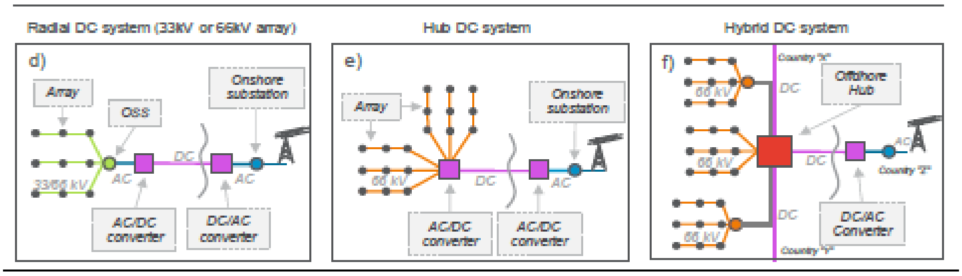


Figure 16 - DC offshore grid connection layouts[17]

The 3 main different setups can be derived from the figure:

1. Connection of an OSS platform (or more) to the DC-platform. This is the standard way of connections of the German OWF by TenneT Germany
2. Connection of the IAC directly to the DC-platform, of 1 OWF or more. This is making the OSS of the OWF superfluous. This is the new way of TenneT Holland to connect to IJmuiden Ver
3. Connection of IAC of more OWF to an offshore hub, which can be connected to multiple countries/markets

7.2.2 Technical information

The 5 main topologies that are used/proposed to build DC-connections with VSC are (also applicable to land connections):

1. Symmetrical monopole (figure a), this one is used in the TenneT Germany DC-platforms
2. Asymmetrical monopole: only 1 pole with a high voltage (positive or negative) with a metallic return (figure b)
3. Asymmetrical monopole: only 1 pole with a high voltage (positive or negative) with no metallic return (figure c) so making use of the ground electrode return, normally not allowed by the permit

[17] https://guidehouse.com/-/media/www/site/downloads/energy/2019/2019-navigant-comparison-offshore-grid-development.pdf

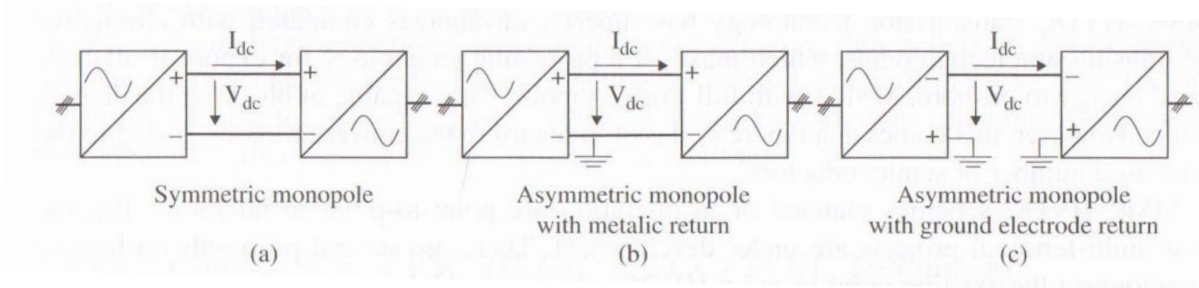


Figure 17 – Different topologies for monopoles

4. bipolar with a metallic return, this one will be chosen by TenneT Holland for 2GW
5. rigid bipole: no metallic return or ground electrode return, mostly not allowed by permit but the current should be minimal if balanced poles

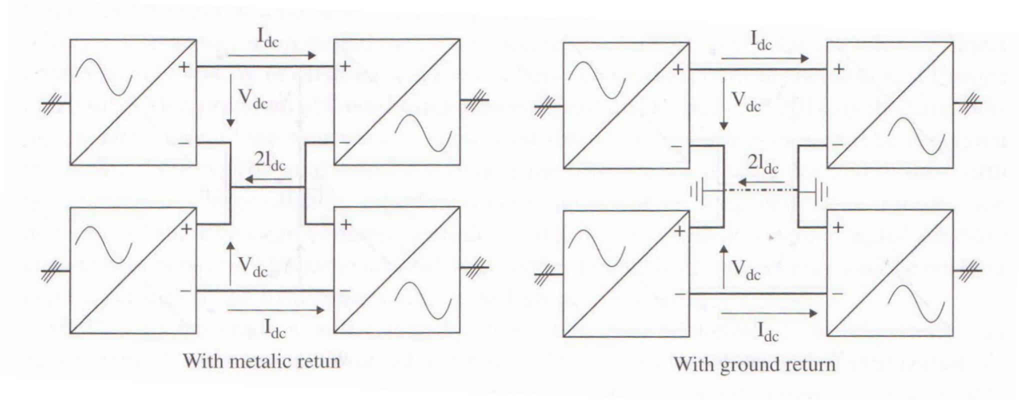


Figure 18 – Different topologies for bipoles

As alternatives also homopolar schemes are possible (so twice a negative or positive voltage).

In addition it can be reported there has been 1 project executed which has connected a LCC-converter station with a VSC-converter station.

The choices of which system would be the most appropriate is depending on the following:

- what is the amount of power that needs to be transported
- what is the good balance between voltage (investment in converters) and cables (investment in metal and insulation material)
- what is the required availability: in case a bipolar system is chosen, the failure of 1 converter will only lead to 50% power reduction (in case of a not allowed ground return, the cable of the faulty converter can be re-arranged as the metallic return)
- how are the losses calculated (power curve, wind-data) and evaluated (NPV, future electricity prices, interest rate etc.)

A general overview based on some high level calculations:

Power [MW]	Topology [#]	Voltage [kV]	Current [A]	Cable Cu [mm2]
700	2	320	2188	2000
1000	1	320	1563	1000
1400	1	400	1750	1500
1750	4	400	2188	2000
2000	4	525	1905	1500
2100	4	525	2000	2000

Table 12 – Practical relation between power, voltage and cable type

It should be noted that this overview can change due to:

- other cable cross sections needed due to unfavorable installation circumstances
- overall loss calculation shows the voltage level should be raised (lowering current and usage of other type of DC-cable) as stated before

7.2.3 SLD

The SLD which is used by the German project is shown below.

As stated, the next generation to be constructed by TenneT NL is including the OWF platform functionality on the converter station platform.

Main thing will be that the transformation of IAC voltage to converter voltage is done in 1 step. Of course the requirements to these transformers, as being stressed both by AC as DC voltages, is more stringent than for the OWF main transformer.

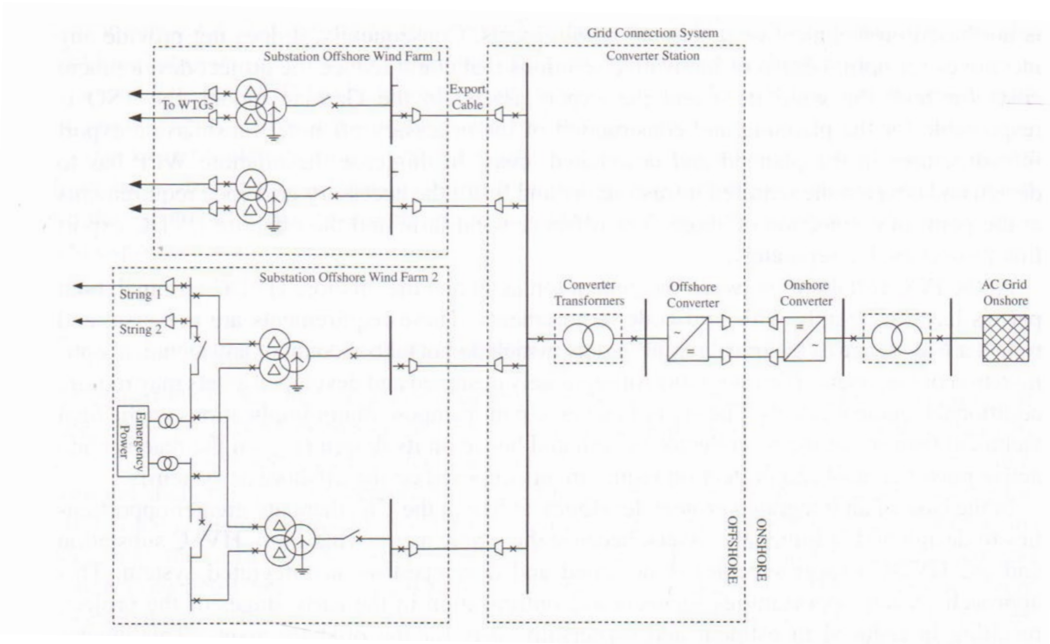


Figure 19 – Standard setup for DC-connection for OWF

7.2.4 Costs

7.2.4.1 CAPEX

Based on several sources (publicly available reports, project data) the following overview can be derived. It should be noted that these kind of prices are depending heavily on the pipeline (amount of projects) of the main HVDC suppliers, HV suppliers and the metal prices (OSS and jacket). It should be mentioned the HVDC market is a sellers market due to a limited amount of suppliers. Further the suppliers / buyers of the several existing projects are not open to disclose information in respect of costs.

The first table shows the estimates (±25%) for a DC-platform (as per TenneT Germany) with separate OWF-platforms and the second table shows the estimation if the functionality is combined (as per TenneT NL). In both table the HV-related components are priced separately.

Power [MW]	HV Offshore [M€]	ACDC Platform [M€]	Total [M€]	k€/MW
700	70	450	520	743
1000	150	490	640	640
1400	200	570	770	550
1750	250	650	900	514
2000	300	730	1030	515
2100	315	750	1065	507

Table 13 - CAPEX of HVDC OSS

Where the data was not available, intelligent extrapolation has been made between the different power sections. A bipole HVDC equipment is considered 35% more expensive than a monopole (700MW). As the system grows in power, the related platform size grows as the weight and amount of steel.

7.2.4.2 OPEX

The OPEX of DC-stations is considered to be roughly based on a percentage of the CAPEX.

Power [MW]	Total ACDC [M€]	OPEX [%]	Total [M€]	k€/MW/ year
700	520	1.5	7.8	11.1
1000	640	1.5	9.6	9.6
1400	770	1.5	11.6	8.3
1750	900	1.5	13.5	7.7
2000	1030	1.5	15.5	7.7
2100	1065	1.5	16.0	7.6

Table 14 - OPEX of DC-platforms

Activities are based as for the AC-substations and include:

- maintenance HVMV equipment (inspections & functional specs)
- maintenance LV equipment ((inspections & functional specs)
- maintenance AUX equipment ((inspections & functional specs)
- coating repair
- C&P: rolling testing in time of all relays by injection
- cleaning: removing of guano

Corrective maintenance is expected on AUX-systems (more complex than AC OSS, for instance water cooled systems) but also on converter systems (IGBT's, although they have some built-in redundancy) and could we require 24-36 interventions/year.

7.2.5 Lifetime

The expected lifetime of the system is 25 years and it should be capable of 'surviving' the OWF/turbines that are connected to the OSS. This can vary depending on each countries regulatory and legal frameworks as well as the wind farm lease lengths. However an extension to wind farm operating life can be requested as long as proper/expensive preventive maintenance and lifetime extension analysis is carried out. TenneT is designing platforms with an expected life of 30 years. HVDC offshore platforms have only been installed recently (since 2015) so there is much to learn about the reliability of the technology in harsh marine conditions.

7.2.6 Availability

As already stated before, the availability of the system can be improved in several ways:

- have a metallic return for a bipole such that if one pole is malfunctioning / in maintenance there is still 50% power flow possible
- add a certain percentage additional modules in the converters arms. The system is setup such, that if one fails, a short circuit is made and the other available IGBT-modules can take over
- have spare IGBT-modules available, in case of failure they can be replaced in 2-4hrs (depending on access on the topside).

Numbers are not yet available based on a large database, CIGRE TB713 did a simulation based on a fictitious grid and came up with a forced outage of 2.2% for a bipole converter (including 200km cable).

The input consisted of:

- symmetrical monopole: λ = 0.0153 failures / year MTTR: 1664h
- bipoles: λ = 0.0153 failures / year /pole MTTR: 1664h

MTTF (Mean Time To Failure) = 8760/ λ

Which results in a technical availability of A = MTTF / (MTTF + MTTR)

- symmetrical monopole: MTTF = 572549 A = 99.71%
- bipoles (per pole): MTTF = 572549 A = 99.71%

Downtime due to preventive maintenance should be minimal for bipoles if this can be done in low wind periods (as then the system can be operated for 50% of transport power. Loss of availability due to monopole maintenance is not available.

7.2.7 Losses

Losses are derived from the general data which should be evaluated for different currents.

Let us assume:

- 1000MW bipolar system
- ±320kV
- 100km 1400mm^2 ALU cable (Rdc_{20} = 0.0129Ohm/km, Rdc_{70} = 0.0154Ohm/km):
- no-load losses passive components and IGBT (switching losses): 0.05% * P_{nmon}
- load losses IGBT (conducting losses, related to I^2): 0.62% * P_{nmon}
- average losses passive components: 0.33 * P_{nmon}

Power [MW]	Current [A]	Rdc [Ohm]	Losses 2xHVDC [kW]	Losses Cable [kW]	Total Losses [kW]	Total Losses [%]
0	0	1.29	7600	0	7600	0.8%
250	391	1.34	8375	409	8784	0.9%
500	781	1.39	10700	1697	12397	1.2%
750	1172	1.48	14575	4065	18640	1.9%
1000	1563	1.54	20000	7520	27520	2.8%

Table 15 - Losses of 1000MW DC system

7.2.8 DC Offshore Substation in Meshed Grids

As already stated in 7.1 the meshed grids, more specific the multi-terminal DC (MTDC), are seen as the way forward but are not executed on a large scale yet, partly due to the absence of proper protection schemes to have more selective mitigations.

The simplest version if the parallel set-up, where all HVDC converters are connected to the same DC-cables and 'do their thing', either consuming or generating power. The most complex is the meshed grid where units are set in series (so adding up in voltage) and set in parallel (same voltage).

Special grid control strategies as LF-control, master voltage control, current-voltage control, voltage-power control etc. should be derived to operate in combination with sophisticated fault detections.

In theory the values as given for DC OSS are applicable but need to be increased with:

- double connection of DC cables
- installation of DC-breakers
- more complex control of power, voltage and current
- fault detection and protection measures

The fault detection will consist of direct measurements (as distance, differential and over current) and signal processing methods (travelling wave, voltage derivative, frequency based) which will activate the needed fault-mitigation.

ABB has provided a general overview of protection systems for their HVDC-Light:

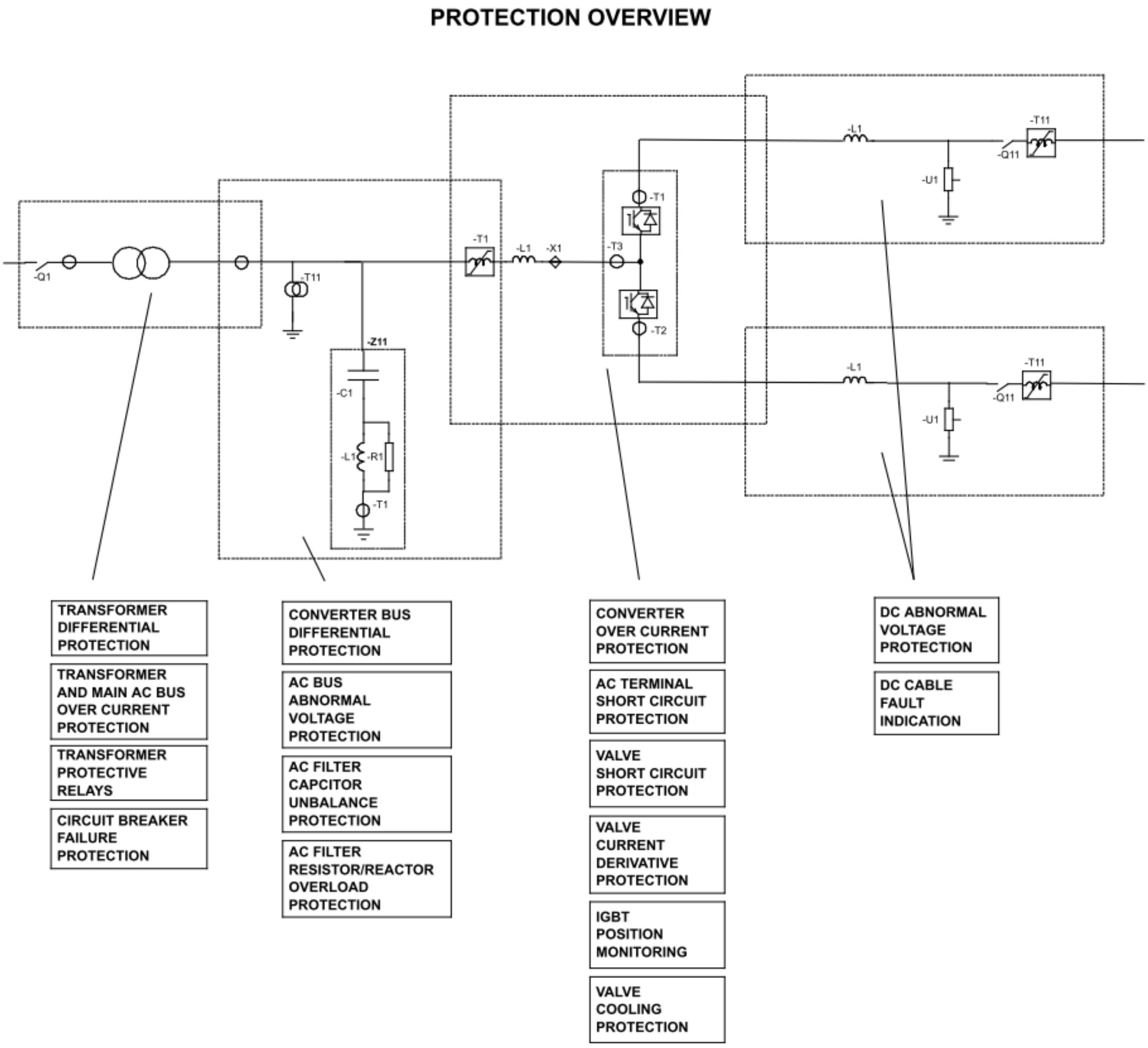


Figure 20 – Different protection systems as proposed by ABB for HVDC-Light

7.3 HVDC Land Station

7.3.1 Description

The DC-land station in principle mirrors the OSS HVDC setup (only from DC to AC) except the connection to the onshore grid should be done at the correct local voltage level and quality.

The AC-switch yard is considered to be a standard setup (AIS, GIS) and filters are considered to be minimal with VSC due to the multi-level system.

The type of grid transformers should be assessed based on the power. For large powers (>1500MW) single phase units are considered more realistic.

7.3.2 Costs

7.3.2.1 CAPEX

The CAPEX is based on the HVMV component prices of the offshore substations but a bit lower for due to easier access and building freedom. Added to that are the civil works that include also all other supporting systems (LV, HVAC, building-systems etc.). Margin is expected to be 20%.

Power [MW]	ACDC Onshore [M€]	Civil [M€]	Total [M€]	k€/MW
700	50	20	70	100
1000	120	30	150	150
1400	160	35	195	139
1750	205	40	245	140
2000	250	45	295	148
2100	262.5	45	308	146

Table 16 - CAPEX of HVDC land station

7.3.2.2 OPEX

Power [MW]	Total ACDC [M€]	OPEX [%]	Total [M€]	k€/MW/ year
700	70	1.5	1.1	1.5
1000	150	1.5	2.3	2.3
1400	195	1.5	2.9	2.1
1750	245	1.5	3.7	2.1
2000	295	1.5	4.4	2.2
2100	307.5	1.5	4.6	2.2

Table 17 - OPEX of HVDC land station

7.3.3 Lifetime

Reference is made to offshore although the land conditions shall be favorable in relation to the marine conditions so preservation shall be longer.

7.3.4 Availability

Reference is made to offshore.

OPEX activities in general are the same as for OSS except the coating repairs. Be aware of the preventive cleaning of insulators in (marine) environments if the land station is located nearby the coast.

7.4 HVDC Cables

7.4.1 Description

To connect DC-stations, DC cables are required. In general there are 2 types:

7.4.1.1 Mass impregnated cables (MI)

Mass impregnated insulation consists of layers of Kraft paper which are heated, subjected to vacuum and impregnated with high viscosity oil over several weeks. The technology is very mature and has been employed since the 1950s for HVDC applications. A survey conducted by Cigré Working group B1.21 revealed over 15,000km of HVDC Mass Impregnated cable cumulatively installed amongst its respondents prior to 2005. Mass impregnated paper is not used for HVAC applications due to problems with partial discharge. This is not an issue for HVDC cables due to the lack of rapid polarity reversal.

7.4.1.2 Extruded XLPE cable (XLPE)

The first real utility scale HVDC cable to be installed using extruded XLPE as an insulation medium was the Cross Sound Cable installed in 2002 between Connecticut and Long Island in the northeast USA, operating at ±150kV and capable of transporting 330MW.

XLPE cables have several advantages over Mass Impregnated which is the reason why they are dominating the market now for VSC types of converters. In the case of land applications, XLPE cables are lighter which allows longer transportation lengths and therewith longer distances between joints. XLPE land cables are also quicker to manufacture. In essence they are like HVAC cables (see other chapter on build-up of these cables) with the following other process steps:

- higher XLPE base material cleanliness
- a longer degassing period on less high temperatures

For long distance submarine cable, factory joints are necessary. Here the distance between joints would be longer than for Mass Impregnated cables. XLPE is generally more mechanically robust and they may operate at higher temperatures (70^0) than Mass Impregnated cables allowing them to carry more current for a given conductor cross section. For this last reason XLPE cables are often used with aluminium conductors to reduce the weight and cost of the cables (although copper conductor is still common for submarine applications). For land applications, pre-moulded joints are available, reducing the time required for cable jointing, making this technology attractive.

XLPE cables cannot presently be used with current source converters (CSC); the reason for this is outlined below. XLPE cables suffer from a space charge phenomenon (which can be triggered also with higher temperatures, hence a HVDC-XLPE conductor may rise to 70⁰ as opposed to HVAC-XLPE to 90⁰). After being subjected to a constant electric field for a protracted period of time, as in HVDC applications, the insulation becomes polarized and this can lead to breakdown and failure should the polarity of the field be reversed. This renders currently available XLPE cables unsuitable for use in current source HVDC installations where in order to reverse the direction of power flow the polarity must be reversed. Hence XLPE cables can presently only be used in voltage source installations (or 'oversized' cables can be used on a lower voltage).

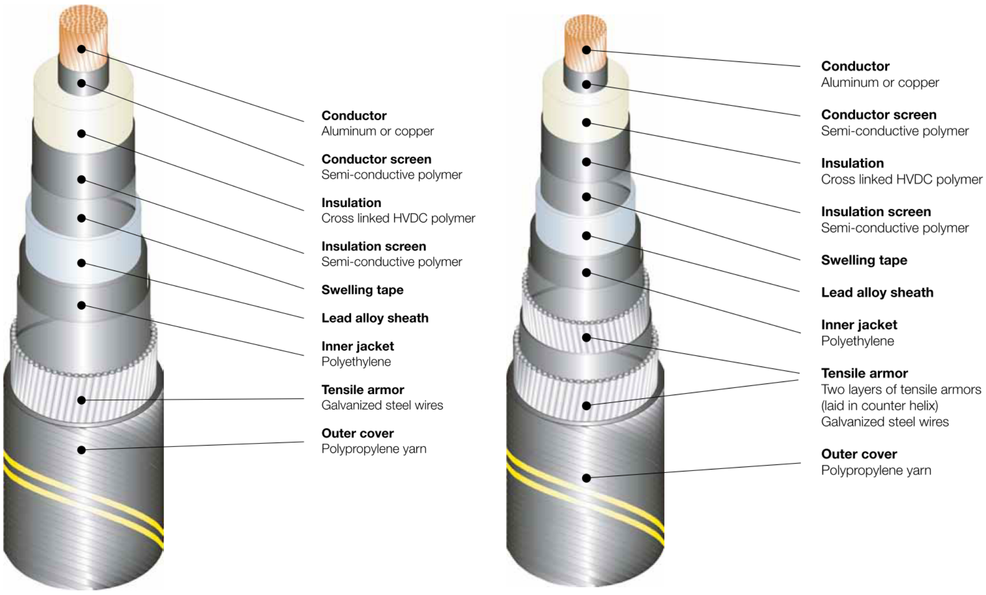


Figure 21 – Typical setup HVDC cables[18]

Figure 21 shows the drawing of an XLPE submarine HVDC cable and a deep sea HVDC cable. The last one having 2 armor layers.

On HVDC cables a next generation is being developed, namely the cable based on Polypropylene (PP). This cable type does not require cross-linking like XLPE hence referred to as much more environment friendly (as it can be recycled and used for other applications), although on XLPE recycling is mentioned through pyrolyse (TKF).

Prysmian claims to be able to supply an improved solution (P-Laser type) of this High Performance Thermoplastic Elastomer (HPTE) which is allowing the conductor to heat until 90⁰ and allows voltage reversal. It can also make used of the existing XLPE-accessories and does not need degassing. In essence they have further improved the PP-base material (by very fine filtration just before the extrusion heads) to avoid by-products.

[18] As per most HVDC cable suppliers

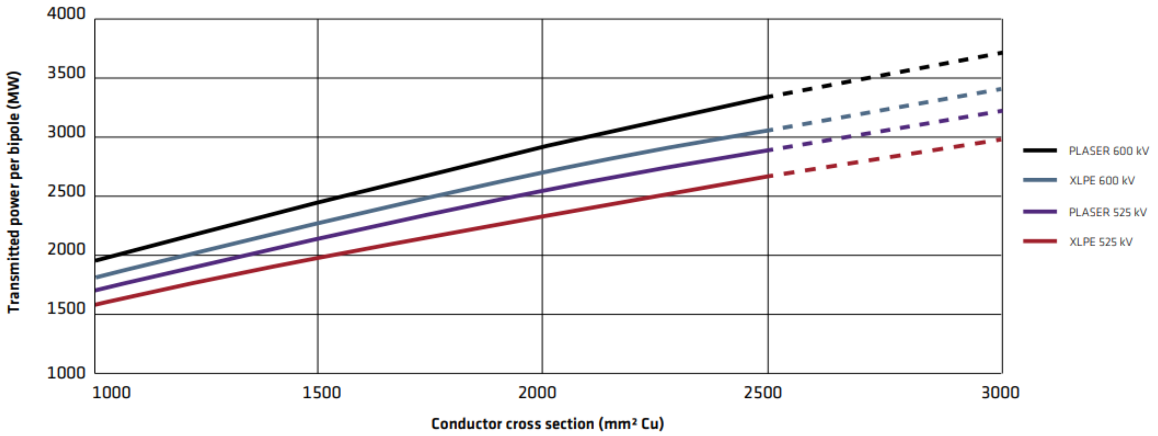


Figure 22 - Prysmian overview of PP cable capabilities versus XLPE

7.4.2 Technical Information

The XLPE HVDC cables can be found/made in all voltage classes, from 150kV until nowadays 525kV.

As per the positive aspects of the XLPE cable as described before (see 7.4.1) this cable type is expected to support whichever future HVDC application levels are required. As such all information is only considering XLPE-extruded cable types.

As DC-systems are missing the capacitive current and the skin effect, the ampacity of transported energy is much higher than with long HVAC cables.

General data for a Cu 2500mm^2 cable as reference:

- $R_{conductor}$ = 0.0073Ohm/km, this can be used for losses calculations (conductor temperature is allowed to rise until 70^o)
- R_{sheath} = 0.23Ohm/km, R_{jacket} = 0.1Ohm/km
    - these values are important for the 1 phase short circuit
    - the cable needs to be grounded every 5km - 10km (sheath and jacket connected) as to limit the voltage on the sheath
    - submarine cables will have an interconnection between armour and sheath each 5km made in the factory

Further technical cable data:

Cable characteristic	Unit	ALU 800m2	ALU 1400mm2	ALU 1200m2	ALU 2500mm2	Cu 2500mm2
Nominal voltage	kV	±200	±200	±320	±320	±400
DC-resistance conductor 20 degrees	Ohm/km	0.0221	0.0129	0.0151	0.0073	
DC-resistance conductor 70 degrees	Ohm/km	0.0264	0.0154	0.0181	0.0087	0.0073
Maximum short circuit current conductor (1s)	kA	92	161	138	287	
Maximum short circuit current metallic screen (1s)	kA	16.6	22	29.9	40	
Ampacity (DoB 2m / soil 15 degrees / soil 0.7Km/W)	A	1105	1505	1336	2030	

Table 18 - Electrical specifications of some HVDC cables

Main suppliers at this moment are:

- NKT, Germany
- LS, South Korea
- Prysmian, Italy
- Hellenic, Greece

- Nexans, Sweden
- Chinese suppliers upcoming (ZZT)

7.4.3 Installation

The installation of HVDC cables can be done in several ways if the known topology has been chosen.

	Two-core cable or two single-core cables bundled
	Two separate single-core cables
	Single-core cable with metallic return
	Two separate single-core cables with metallic return
	Concentric cable (integrated return)

Table 19 - Installation configurations of HVDC cables

Some considerations:

- to have the two current conducting paths bundled, will give the lowest ecological footprint (spatial, magnetic field) but is impacting negatively the ampacity as the cables heat up (each other)
- bundles of 2 cables is not 'round' and less easy to process, so adding the (single) metallic return is beneficial
- split laying of 2 HVDC cores (including a metallic return path per core) is giving the highest availability and possibility to repair when the second circuit is still functioning

Further reference is made to the installation of HVAC cables.

7.4.4 Costs

7.4.4.1 CAPEX

As the market is reluctant to supply information (except for projects), the data available is minimal. Table 19 shows the variable price per meter with a very large margin (-10% - +30%):

Voltage class [kV]	Cross section [mm2]	Conductor material [ALU/Cu]	Armour	Volume	Costs [€/m]
320	1800	Cu	GS/Single	MEDIUM	395
400	1600	Cu	GS/Single	MEDIUM	375
400	2500	Cu	GS/Single	MEDIUM	615

Table 20 - Costs for several HVDC cables

The prices in Table 19 do not include:

- engineering and if needed additional type test or PQ tests
- fixed (starting) costs for supply
- installation of offshore joints / transition joints (high costs due to vessel availability)
- termination and testing (T&T)

Further reference is made to HVAC EXC.

7.4.4.2 OPEX

Reference is made to EXC.

7.4.5 Lifetime

Just as HVAC cables, the PQ-testing of HVDC cables according to the TB852 (and included references) should be the guarantee for a long lifetime of XLPE HVDC cables. The fault conditions and heating cycles should reflect a lifetime of 30 years.

7.4.6 Availability

Numbers are not yet available based on a large database, CIGRE TB713 did a simulation based on a fictitious grid and came up with a forced outage of 2.2% for a bipole converter (including 200km cable).

The input consisted of:

- cable ±200kV or ±400kV: λ = 0.0007 failures / year / km MTTR: 1440h

MTTF (Mean Time To Failure) = 8760/ λ

Which results in a technical availability of A = MTTF / (MTTF + MTTR)

- cable ±200kV or ±400kV: MTTF = 62571 A = 97.75%

7.4.7 Losses

Losses of cables is easy to derive from the DC-resistance calculation. One could assume different DC-resistances with different power flows (between 20^o and 70^o). Be aware that 2 cables are carrying current. See further 7.2.7.

On top of this additional losses can be expected caused by the ripple current (resulting in induced current in the sheath) and ripple voltage (resulting in a charging current from core to sheath). This will require a correct sheath bonding scheme as per 7.4.2 to be minimised.

8 DECOMMISSIONING

During the project development stage of an offshore wind farm the plan for how to decommission a wind farm is usually required as part of the permit application. Depending on the technology used there are various options and marine users, environment, pollution, and costs should all be considered. Most of the structures that are not buried can be easily removed by dismantling or cutting just below the seabed mudline. Once removed they are transported to shore and can be processed and recycled accordingly. The parts of the foundations that are below the seabed cannot be removed without disturbing the seabed and surrounding environment. This process can become expensive and risky depending on how far below the mudline you want to go. If it does not pose an environmental or pollution risk, it is usually left.

Cables will be partially or fully removed but this depends whether the cable is buried on not. Buried cables do not pose a risk to marine users and have limited environmental or pollution impacts although this can depend on the cable technology adopted. The complete removal is considered to cause substantial damage and disruption to the seabed given the extensive length of the cables. There would be need for excavation to pull them out of the trench, and then cutting, which involve high costs. Leaving the cables in situ and well buried is therefore the best option suggested till date.[19]

[19] https://www.researchgate.net/publication/309654822_Sustainable_Decommissioning_of_an_Offshore_Wind_Farm

9 EXAMPLE GRID CONNECTION

In this section we compare each high voltage technology to get a better understanding of their strengths and weaknesses. For comparison purposes a specific connection will be assessed for both technologies. This will be a top-level comparison using the information already discussed as well as making some assumptions.

To have an overview of both presented technologies (AC and DC), Table 20 shows a list of the high-level pro's and con's.

	AC-technology	DC-technology (VSC)
Pro's	- many vendors of equipment / many engineering firms - very mature technology (lifetime phase: lowering costs) - experience on onshore grids available with TSO's - intermediate compensation can extend distances - all phenomena and their mitigations are known - high robustness / availability	- low(er) losses above a certain transport level and distance - high level of grid supporting reactive power - availability can be improved by redundant IGBT set-up or chosen topology - very modular so transport power can increase with same technology
Con's	- over long distances less available ampacity / high losses due to capacitive currents - skin effect having low gain in higher cross sections of cables	- only 3 major vendors of equipment - in general high(er) costs/MW (CAPEX) - technology still improving (lifetime phase: higher robustness/ improving components) - due to sensitive devices (IGBT) lower robustness / lower availability (higher OPEX)

Table 21 – Pro's and Con's of AC and DC

For comparison purposes a specific connection will be assessed for both technologies.

General information:

- transport power: 1000MW (P_{MAX})
- distance from onshore land station: 50km
- seabed temperature: 10^{o}C
- depth of burial (DoB) of EXC: 2m
- frequency: 50Hz
- IAC not considered as equal for both
- Mvar requirement: cos phi = 0.95 (Q = 0.33pu P_{max}), can be supplied by onshore components or turbines (not considered in losses or ampacity calculations)

AC:

- 220kV
- 1000MW leading to 2624A
- symmetrical compensation (assuming cable capacitance is 0.2µF/km): 400A/cable and 152Mvar (76Mvar reactor on each side)
- total 962A leading to 3 HVAC cables of 1200ALU SS (50%) and 1200 ALU GS (50%)
- 3 separate small OSS with one transformer per OSS (no redundancy)
- land station without STATCOM

DC

- bipole arrangement
- ±320kV
- 1000MW / 320kV / 2 = 1562A, leading to 2 HVDC 1400mm^2 Cu XLPE cables

- for comparison the AC collection system is included in the OSS

Below a comparison of the two options where it must be noted the losses are quite high and include cables and both onshore and offshore substations:

	OSS [M€]	EXC proc. [M€]	EXC inst. [M€]	ONSS [M€]	Total [M€]	OPEX/y [k€]	Losses 100% P [%]
AC	214	71.6	35	60	381	2744	3.1
DC	640	39.5	25	150	855	7900	2.8

Table 22 – Comparison of several parameters for AC and DC of 1000MW

In general it is stated that above 1GW and more than 100km the DC option would be preferred, as this should also consider the difference in losses during lifetime when corrected for the different power bins (wind profile) of the OWF. This business case can although be challenged with intermediate compensation platforms and hence a project specific assessment should always be carried out each time.

Table 22 shows the TRL's for the HV technology described in this report. AC technology up to now has been widely adopted in the offshore wind market and is therefore a mature technology scoring nine in all cases. DC technology for offshore wind farms exists but it is still a maturing market. As more wind farms are built further away from shore and interconnectors become more common, so will the technology mature and price decrease.

Equipment	Solution	TRL
Offshore substation	HVAC	9
	DC – VSC (all poles)	8
	Meshed DC – VSC (all poles)	6
Land station	HVAC	9
	DC – LCC	9
	DC – VSC (all poles)	8
Export cables	AC - XLPE	9
	DC – Mass impregnated	9
	DC – XLPE	9
	DC – PP	6

Table 23 - Different TRL of related solutions

10 ANNEXES

10.1 Technology Readiness Level

Table 23 describes the technology readiness level scale. This catalogue has focussed on technology with a level of 5 or greater.

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Table 24 - Different Technology Readiness Levels[20]

10.2 Raw Material Costs

In this section we will briefly state the main raw materials that are used in the construction of an offshore wind farm. Prices for these material can heavily influence the final price of certain products. Typically suppliers will include clauses in the procurement contract that allow the final price to be subjective to current raw material prices.

Steel

The substation, foundations, WTG tower section and cables all use steel as a primary material. Steel prices have seen a sharp increase over the last year, seeing 5 year highs in May and close again in October 2021. As an example the Hollandse Kust Noord (759MW) platform jacket foundation weighs 2100 tonnes. On a platform a 400MW transformer can weigh 92 tonnes (tank, radiator & pipes). These examples give a good indication of the amount of steel that is required during an offshore wind project.

Copper

All electrical components will use copper due to its conductive properties. The WTG generator especially direct drive types, platform transformers (42t for 400MW) and inter array and export cables all rely heavily on the material. Export cable lengths can go from near shore 5km up to hundreds of km's in distance for interconnectors between different platforms and countries. Copper saw the same sharp increases as steel and continues high.

[20] HORIZON 2020 – WORK PROGRAMME 2014-2015