Engineering Insurance of Offshore Wind Turbines

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1. OFFSHORE WIND TURBINES .......................................................................................................................... 3
2. ERECTION PROCESS OF OFFSHORE WIND TURBINES .............................................................................. 3
3. CONSTRUCTING A MONOPILE FOUNDATION ............................................................................................ 3
4. SUPPORT STRUCTURE ......................................................................................................................................... 7
5. FOUNDATION GROUTING ............................................................................................................................. 10
6. TURBINE INSTALLATION .................................................................................................................................. 11
7. TRANSMISSION AND DISTRIBUTION ............................................................................................................ 12
8. SUBSTATION CONNECTION ............................................................................................................................. 13
9. SUBSTATION ........................................................................................................................................................ 14
10. GRID CONNECTION ........................................................................................................................................... 15
11. INSTALLATION OF SUBMARINE CABLES ..................................................................................................... 16
12. REPAIR OF SUBMARINE CABLES ................................................................................................................ 17
13. ECONOMICS .................................................................................................................................................... 18
14. DIFFERENCES BETWEEN ONSHORE AND OFFSHORE WIND TURBINES ................................................. 20
15. LOSSES .......................................................................................................................................................... 21
1. Offshore Wind Turbines

Offshore wind energy is a promising application of wind power, particularly in countries with high population density, and difficulties in finding suitable sites on land. Construction costs are higher at sea, but energy production is also higher.

The largest offshore wind farms in the world are Horns Rev and Nysted both in Denmark – 160 and 165.6 MW respectively. Tendering procedures for new offshore wind farms are ongoing in several countries including Germany, UK, the Netherlands etc.

2. Erection process of Offshore Wind Turbines

1. First, the foundation is placed. In case of a monopile foundation a cylindrical steel pipe with a diameter of about 4 metres is driven into the seabed. A pile driver placed on a barge, stabilized by legs, rams the pipe approximately 25 metres into the bed.

2. Then, the wind turbines are mounted by means of large vessels with submersible legs (jack up unit). A crane on the vessels lifts the turbines into place.

3. The wind turbines are connected via submersible cables to the offshore transformer substation which will collect the power.

4. Via a submarine cable, the substation is connected to the onshore power transmission grid.

3. Constructing a monopile foundation

The "monopile" concept is based on single piles that are driven into the seabed. Pile driving is a fast process, and piles are relatively inexpensive to produce.

Monopile foundations have been used for offshore turbines in Denmark, the Netherlands and Sweden. Similarly, the project’s meteorological tower rests on a monopile foundation.

The construction phases

A "mattress" of rock and stones is placed around the foundation to protect against erosion.
- Thickness: ~ 0.5 m.
- Stone diameter: 0.03-0.2 m.

The monopile is driven through the mattress to the planned depth - approximately 25 metres.

The transition piece - complete with pre-installed features such as boat landing arrangement, cathodic protection, cable ducts for submarine cables, turbine tower flange, etc. - is cast together with the monopile.
The transition piece makes it possible to raise the towers to a completely vertical position even if the foundation is not completely level.

The cable ducts for the submarine cables are closed. The concrete is left to cure.

The protective rock mattress is finished with an additional layer of rock and stones.
- Thickness: ~ 0.8 m.
- Stone diameter: 0.350-0.550 m.
Erection of the wind turbine and installation of cables to substation.

**Pile driving**
Specially designed barges with a heavy duty hammer are used to drive the monopile into the seabed.
A typical pile driving ram.

Buzzard, a pile driving vessel, at sea

Pile driving

The transition piece is attached to the monopile in a special concrete casting process. The top rim of the transition piece is a flange that accommodates bolting of the turbine tower.
4. Support Structure

So far, most offshore wind farms have been built using gravity base structures, when in very shallow waters (i.e. below about five metres depth) and monopiles, when in medium depth waters, (i.e. greater than 5 metres depth).

Gravity Base Structures (GBS)
Gravity base structures (GBS) have been used at the first three Danish offshore wind farms. The structure has a large flat base, to resist overturning forces imposed by the turbine rotor, the size of which will depend on the wave climate and the ground conditions. At the water surface level, an icebreaking cone is shown, as would be necessary in the less salty waters of the Baltic Sea. The water surface level must be at the level of the inclined surface of the cone at all tides, including storm surges, which also matches Baltic Sea conditions. Ice cones bring a benefit of reduced ice loading by causing the ice sheets to bend downwards and break-up as they make contact with the wind turbine however the greater structural size at the water surface also means that wave loads are increased and more difficult to predict.
Cost approximately € 600,000/ turbine.

Monopile
The current design philosophy for wind farms in water depths up to 20 m is based on the monopile with the installation methodology - driving, drilling or combination - depending on soil properties, water depth and contractors experience. Monopiles are a relatively compliant structure and hence are more difficult to design; uncertainties in ground conditions for example can result in a structure with a quite different structural frequency than designed for, with all the potential resulting problems of resonance induced dynamic oscillations. For this reason, the cost benefits of designing a less rigid support structure may not be considered worthwhile by the developer.
Cost approximately € 600,000/ turbine.
For deeper waters, tripod support structures are being considered but the optimum solution is not yet certain and may well be a concept currently being brought into the field by offshore and coastal engineering specialists. There has already actually been one offshore wind turbine constructed on a tripod, the first wind turbine built at Nogersund in Sweden; however this was a small turbine located in shallow water and hence unlike the structures to be built in the future. Cost approximately € 2,500,000/ turbine.

Floating
Potential for floating wind energy is going to depend whether the current cost disadvantages can be overcome by the development of innovative solutions to constructions and installation. Countries in North Europe are fortunate in that many have significant stretches of shallow water near to their shore and close to the demand centres and these will be the first to be developed. The USA and Canada also have suitable shallow regions however other regions, such as Japan, do not.
Bucket foundation
This type of foundation is thought to have much potential, as it makes manufacture, handling and erection less expensive and removal easier. This new kind of foundation (patent pending), formed in the shape of an up-turned bucket and sucked into the sea by means of a vacuum, has been developed by MBD Offshore Power A/S in close co-operation with Aalborg University.
5. Foundation grouting

Use of grouted foundation solutions results in flexibility and safety during the installation and throughout the life time of the wind turbines. Installation tolerances can easily be accommodated and compensated for within the grouted connections. The grouting process is simple and can be carried out above and below sea level using standard processing equipment. The grouting material is pumped through flexible hoses or hand pumping into the specimen to be grouted.
6. Turbine installation

The turbines are installed by means of specially built jack up vessels with submersible legs which lift the turbines into place on the foundations. The turbines are only connected to the transformer substation after the turbines are installed to avoid damaging the cables during installation.

By means of the two vessels Ocean Hanne and Ocean Addy it is possible to erect two turbines per day if weather conditions are optimal.
7. Transmission and distribution

A key strategic element in the successful penetration of wind power is its efficient integration into the electricity transmission and distribution network. The increase in the penetration of wind power production into the grid raises a number of issues.

• The output from a wind farm fluctuates from a certain degree according to the weather.

• Wind farms are often located at the end of the distribution networks. Most grids have been designed for large-scale electricity generation from a relatively small number of large plants, sending power outwards towards the periphery, rather than in the opposite direction.

• The technical characteristics of wind generation are different to those of conventional power stations, around which the existing systems have evolved. The requirement for grid network operators to handle an increasing proportion of such “distributed generation” is coming not only from wind energy. Environmental considerations and the liberalization of the electricity market have increased interest in smaller scale commercial generation; a shift in both the attitude of utilities, and grid operation, is required to accommodate this development. Intermittency issues require an understanding of variability and predictability. Wind prediction techniques are at an early stage of development, and improvements can help firm up wind power for system operators by reducing and specifying forecast error.
8. Substation connection

The wind turbines are connected via submarine cables to the offshore transformer substation by cables.

The cable consists of lead sheathed copper conductors for complete water resistance as well as a number of fibre optics for communication purposes.
9. Substation

The produced power is fed to a substation. After stepping up to approximately 150 kV, the power is conveyed to shore. The substation platform is normally designed as a tripod construction with a steel building. Among others, the platform accommodates the following technical installations:

- Switchgear
- Transformer
- Control and instrumentation system, and communication unit
- Emergency diesel generator, including fuel
- Sea water based fire extinguishing equipment
- Staff and service facilities
- Heli pad
- Crawler crane
- MOB boat (Man Over Board)

Cost approximately € 10 – 20 Mio.

Substation model

Asian Hercules at work  Substation in place
10. Grid connection

A trenched submarine cable connects the offshore wind farm to the onshore grid. Triple core cables with submarine armouring are normally used.

Works in shallow water involve certain problems and danger. A water depth is needed, that can accommodate heavy lift barges at any tidal stage. The tidal currents in shallow water may be very strong.

Costs:
- Lift barge approximately € 50,000 – 100,000 per day
- Cable approximately € 500,000 – 1,000,000 per kilometer
11. Installation of submarine cables

The installation of cables for power collection (array cables) and grid connection (main cable to land) is set against a contradictory background comprising critical elements such as cost, risk management, environmental constraints and geotechnical challenges.

The decision on the most appropriate cable-laying technique hinges mainly on the seabed conditions (hard or soft, topography). In addition, a cable-lay risk assessment is required to define the burial depth, taking into account factors such as shipping routes and potential damage by ships’ anchors. In some cases, burial depths of more than 3 metres may be necessary. It should be mentioned that even the anchors of smaller vessels are perfectly capable of penetrating the sea bed by up to 1.5 metres. Large anchors are known to penetrate some 5 metres into soft mud.

Prior to laying the cable, each cable route is surveyed to identify possible obstructions on the surface of the seabed. Divers assist in feeding the cable into J-tubes which are pulled into the turbine unit. A laying vessel, which is positioned and moved by anchors and winches, lays the cable as far as the next wind turbine location. The same technique is used to lay the main cable to land. Different techniques (plough or jetting) are available for burying the cable. For instance, a hydraulic jet-plough can be used, which travels along the cable lying on the sea bed and opens up a trench approximately 2 metres deep. The cable settles to the desired depth under its own weight and in accordance with the degree of jetting utilised. The natural movement of the sea is then sufficient to cover the cable.

It is recommended that a follow-up survey or even a real-time validation be performed to confirm that the cable is indeed in the desired position. Such a survey may indicate the need for additional mechanical protections such as mattress or rock dumping. The cable is especially exposed to damage by vessels operating in the vicinity at times when it is not adequately protected (e.g. in the course of jack-up operations where expandable legs are lowered to the ground).

Horizontal directional drilling or direct trenching may be required for landfall or in order to cross islands. In this case, a drilling rig is positioned behind the shoreline sand bank and drills a pilot hole followed by a larger hole through which the cable casing is passed. Once the cables that traverse the dunes have been connected up and tested, the casing is filled with bentonite.

The following problem areas have been encountered:

- Inexperience on the part of the team monitoring and supervising offshore cable installation (e.g. relating to the speeds and drag forces involved);
- Weather conditions, weather forecast;
- Lack of communication between manufacturer and installation contractor;
- Poor route selection and site survey;
- Unrealistic permit conditions;
- Inadequate design/contingency planning (water blockers/seals);
- Poor cable condition (e.g. armouring not sufficiently substantial)

Now that offshore wind farms are being developed at distances of, in some cases, 100 km offshore, the choice of the right laying technique is becoming even more crucial.
12. Repair of submarine cables

Submarine cables can be repaired by using special repair joints. In most cases, the cable is damaged by external aggressors such as anchors or fishing trawlers. The submarine cables have watertight filling compounds so that there is no water ingress along the cable even if cut. Then only a short length has to be replaced. A cable laying vessel is needed for the repair operation. Cost for the repair operation is very dependent of the type of damage, location, preparedness, availability of means, etc.
13. Economics

Offshore projects require initially higher investments than onshore due to turbine support structures and grid connection. The cost of grid connection to the shore is typically around 25% of the total cost, a much higher fraction than for connection of onshore projects. Other sources of additional cost include foundations - up to 30%, operation and maintenance - with expected lower availability - and marinisation of turbines, Figure 1 shows a possible distribution of the capital investment costs however the water depth and distance to shore can have a significant impact on redistributing the costs. Note that the O & M costs are excluded and these will probably typically amount to around a quarter of the Levelised Production Costs (LPC)\(^1\). The similar magnitudes of cost for several different components - wind turbine, support structure, power collection & transmission and O & M - emphasises the importance of an integrated approach to the design of the whole wind farm development.

Investment costs have been reduced from about 2,200 €/kW for the first Danish offshore wind farms to an estimated cost of 1,650 €/kW for Horns Rev (equivalent to 4.9 €c/kWh). This compares with typical figures for onshore sites of investment 700-1,000 €/kW and estimated energy cost of 3-8 €c/kWh for a mean wind speed of 5-10 m/s.

Figure 1: Typical Distribution of Costs for Offshore Wind farm

The distribution of the investment costs for an onshore wind farm show a much heavier focus on the wind turbine as illustrated by a typical example in Figure 2.

Figure 2: Typical Distribution of Costs for Onshore Wind farm

\(^1\) The LPC is the cost of one production (kWh) averaged over the wind power station’s entire expected lifetime, expressed in €/kWh.
Financing
From the current developments of demonstration offshore projects of various sizes, it would appear that sufficient equity capital is available for financing offshore wind farm projects. Some major oil & gas companies and utilities have announced projects, which could be financed by company equity. However it still remains to be determined under which conditions (due diligence, certification, insurance etc) bank loans will be granted for offshore wind farm projects. Only test and demonstration projects will provide information to allow an answer to this question. At least they will reduce the present uncertainties related to the cost of energy generated. Important support comes from a variety of national incentive mechanisms, such as investment subsidies, tax exemptions, fixed tariffs and green certificate schemes.

Overall cost of wind power
When all cost elements are considered together, the cost of wind power ranges from approximately 4- 5 c€/kWh at sites with good wind speeds to 6- 8 c€/kWh at sites with low wind speeds (2003). This calculation assumes a medium-sized turbine of 850- 1,500 kW capacity, investment cost ranging from 900- 1,100 €/kW, O&M cost averaging 1.2 c€/kWh over a lifetime of 20 years, and a discount rate of 7.5% per annum.

The cost of capital (discount or interest rate) is a particularly important factor. Like hydropower, wind power is a very capital intensive technology with about 75% of total costs as capital up front (for a natural gas plant the share is typically 40- 60%). Therefore, the economic performance of a wind power project is highly dependent on the level of interest rates.

External cost
If the entire fuel cycle is assessed, from fuel extraction, through processing, transformation, and construction, to operation and waste disposal, it becomes very clear that the economic damage attributable to conventional fuels towers over that of wind. The most detailed analysis of externalities to date is the European Commission’s ExternE project. This was conducted over a period of more than ten years and still continues. It values the external cost of wind energy less than 0.26 c€/kWh whilst those for coal-fired generation range from 2 to 15 c€/kWh.
14. Differences between onshore and offshore wind turbines

The main differences of offshore turbines compared to onshore installations of the same type and with identical performance can be concluded as follows:

- Extended measures for corrosion protection of mechanical and electrical equipment and special facilities for dehumidification
- Metal cladding and special design of the machine housing
- Different location of the transformer and the frequency converter offshore wind turbines in the nacelle and onshore wind turbines in the foot of the tower
- Redundant and automatic cooling system
- Special facilities for service at sea (i.e. crane)
- Facilities for extended condition monitoring which allow extension of periods between maintenance works.

As a result of such special features the weight of offshore turbines becomes higher than the weight of onshore machines. This means an extended effort during erection by use of specific erection equipment. Obviously manufacturers try to compensate the increased weight by changes in the construction of components where possible.

As an example, the weight of the gearbox of a 2.5 MW turbine of a specific type is in the onshore version 500 kg less than in the offshore version.

The future will probably show turbines with extended performances. The tendency towards higher turbine performance is very much forced by offshore installations to reduce the specific investment costs per MVA. In a first step the performance of turbines will increase to 3.6 MVA and later on to 5 MVA. Turbines reaching this performance classes are under development already. It will be interesting to see how this upscale will influence reliability and operating stability of the machines and their components especially as far as gear boxes and bearings are concerned. The -not always satisfying- experiences with upscale steps in the past may give a hint of what has to be expected.
15. Losses

An example of a loss incurred during erection of offshore wind farm:

Some characteristics of the project:

- The wind farm consists of 80 2 MW wind turbines
- The wind park is located 14-20 Km off the coast at a water depth of 6-12 metres
- In winter, weather conditions are often severe, with strong winds and waves of up to 14 metres
- The distance between the wind turbines is just over 500 metres
- The time of erection was estimated at two years with limited activities during the winter period

The project was not completed on time, and the erection all risks insurance cover was extended several times.

During the period of erection, eight recoverable claims were reported, of which six related to the erection phase, one resulted from a stroke of lightning, and one from storm damage.

Of the erection claims, one claim was for damage to the sea cable to the wind turbine, by far the largest individual claim to have occurred during the erection of the wind farm.

Total claims incurred amounted to approx. € 2.5m, of which the storm and lightning claims accounted for approx. 3.5%.

Total claims incurred:

- Repair costs – direct payroll costs and costs for new component or repair of damaged property
  12 %
- Costs incurred in connection with the disassembly and reassembly of damaged parts
  3 %
- Costs incurred in connection with mobilisation and demobilisation of contractor ships
  31 %
- Costs incurred in connection with the hiring of contractor ship with crew
  54 %

These costs are representative of the wind farm mentioned above, however, wind farms get bigger and bigger and are erected in different locations. The price of a wind turbine has increased considerably within the past year. All of these factors contribute towards another claims picture.

Some of the erection claims could have been avoided if due care had been exercised in the work. Most of the erection claims were a result of human error or miscalculation.

As contractors gain more experience in the field of offshore wind turbine erection, the risk will decrease. However, it seems that wind farms are erected far from the coast line and at water depths of up to 30 metres. This represents a bigger challenge for contractors and their equipment.

Contractors’ equipment for erecting offshore wind turbines has also improved and is now more than previously designed specifically for this purpose.

Wind turbines are getting bigger and bigger, also offshore turbines. This places great demands on the quality control, design, manufacturing and erection.

It is important to keep in mind that the design life is 20 years!

Know-how, wind conditions and insight continue to be key words in relation to offshore wind turbines.

Based on experience gained so far from the erection of several offshore wind farms, the risk of damage to sea cables seems to be the greatest by far. Such cables are damaged very easily, and repair costs may amount to as much as € 4m.
The costs involved in the repair of damage to offshore wind turbines are considerable. Such repair is troublesome and costly and may take several weeks due to unfavourable weather conditions.

Nowadays, components must be designed for usage at sea, which also places great demands on protection against corrosion.

Quality control acquires a whole new meaning when taking into account the fact that changing a minor defective component in an offshore wind turbine may easily amount to € 100,000 or more.

To some extent, the risk of damage depends on where (proximity to ship routes) and when (weather conditions) the wind farm is erected. Furthermore, the size (number of units) of the farm and the size of the wind turbines (installed effect) also impact the risk picture, not to mention the risk of damage to the transformer located on the sea floor.

In general, claims will be larger and perhaps also more frequent as newer and larger types of wind turbines are introduced on the offshore wind turbine market.

In future, we will also be seeing claims which we previously thought unlikely, such as:

- weather conditions
- series of claims
- mislocation of a wind turbine or wind farm
- serious lack of critical components
- collision with transformer
- fire in offshore transformer or wind turbine

just to mention a few causes of claims. The worst case scenarios are endless.

Insuring offshore wind turbines, whether during erection or operation, will continue to pose a significant challenge to the insurance industry.

The industry must invest a large amount of engineering hours in this technology in order to be able to meet the challenges posed by offshore wind turbines in future.

Attached is a list of relevant issues which should be addressed in offshore wind turbines project in order to avoid or mitigate the risks. The list is by no means exhaustive:

- Decision log: Who can authorise changes in installation method during erection? Is a substitute available?
- Emergency plan: Appointed decision makers, plans for possible emergency situations should be rehearsed
- Geological survey: Is a geologist on site during installation?
- Obstacles in the sea bed e.g. wrecks, existing pipes and cables
- Environmental conditions and permits
- Navigation risk
- Proven track record of suppliers and sub-suppliers: Assurance of certified and qualified staff
- Handling of authorities, legal claims
- Contractor information and updating of plans to avoid delay
- Examine contractors planning
- Boundaries between contractors: Examine the interface documentation
Some losses (mainly onshore)
Fire/lightning loss

Over speed

Hail (ice cube 1.6 kg)
Windstorm
Design/ Mat (27%)
Lightning (24%)
Storm (20%)
Short circuit (8%)
Fire (7%)
Others (14%)

Tower (18%)
Blades (17%)
Gearbox (16%)
Generator (13%)
Transformer (10%)
Nacelle (8%)
Control eq. (5%)
Others (13%)

In number of losses

Based on 3,200 claims from various sources\(^2\)
(mainly onshore)

\(^2\) Mainly based on discussions with Swiss Re, Allianz and Munich Re