CHAPTER 5

ECONOMICS OF OFFSHORE WIND FARMS

5.1 Introduction

Twenty-two years have passed since the world’s first offshore wind farm, Vindeby (5MW) was built in Denmark [1]. Today, the world offshore wind power has an installed capacity of 4,620 MW, representing about 2% of total wind power installed capacity. More than 90% are installed off northern Europe, in the North, Baltic and Irish Seas, and the English Channel [2]. Most of the remaining offshore wind farms are located in two demonstration projects off China’s east coast. However, there were also great expectations placed for major deployment elsewhere; governments and companies in Japan, Korea, the United States, Canada, Taiwan and even India have shown enthusiasm for developing offshore wind farms in their waters. However the best-selling wind turbines in 2002, were those with rated capacities of 750 to 1500 kW with a market share of more than 50% and capacities above 1,500 kW were 30
percent. According to the future projections worldwide, a total of 80 GW offshore wind turbines could be installed by 2020 with three quarters from Europe.

Offshore wind has a number of advantages, such as higher wind speeds and less turbulence than on land and fewer environmental constraints [3]. Large scale wind farms would be employed for harvesting offshore wind energy. Operation and Maintenance aspects play an important role in the cost of electricity harnessed offshore, adding up to 30% of the costs of a kWh. Thus it is relevant to find ways to reduce the part of operating and maintenance cost of offshore wind farms. Offshore wind farms are particularly suitable for large scale development near the major port cities in the world to avoid long transmission lines. Offshore wind farms relatively a new technology with significant opportunities for cost reduction, technical innovations, revolutionary developments and generating employment, changing the face of renewable energy across the world.

Europe leading the way with a total capacity of 4,336 MW, consisting of 1,503 offshore wind turbines connected fully to the grid by 56 wind farms across ten European countries[4]. The UK and Denmark remain the two biggest markets for offshore wind in Europe, followed by Belgium, the Netherlands, Germany, Sweden, Finland and Ireland. Norway and Portugal each have a full-scale floating turbine. Currently, offshore wind capacity of 6GW is under construction in Europe with further plans of 114 GW in near future. The UK alone is expected to contribute 40 GW of offshore wind capacity by 2020 according to the Renewable Energy Roadmap published by the United Kingdom government. China’s present installed offshore capacity is 258.4 MW and it is ranked number three globally. The Shanghai Donghai Bridge project, totalling 102MW installed in 2010 is China’s first commercial offshore project.

5.1.1 Trends in offshore wind farms

The selection for an offshore wind farm site is important for determining the total energy cost and the economic viability [5]. The objective is to evaluate the capital investment cost [6] for an offshore wind farm to access the cost of energy. Operation and maintenance (O&M) costs constitute a sizeable share of the total annual costs of a wind turbine. The operating and maintenance costs are attracting greater attention and manufacturers are trying to lower these
costs significantly. The developments of new type of modern turbines are built to minimize the service visits and lower the downtime. The installed capacity of offshore wind power has been increasing rapidly despite increased capital cost, operation and maintenance costs. The reason for the growth in offshore wind farms capacity are high wind resources, availability of space, low visual and noise impact, better understanding of the economic risks and high financial incentives.

The challenges for current offshore wind turbines must withstand the harsh marine environment [7]. The introduction of the stringent regulation in marine environment has resulted in the reduction of reliability levels for the offshore wind turbines. The maintenance of growing number of offshore wind turbines figure 5.1 compared to onshore wind turbines represents a major challenge in reliability, yet cost effective source of electricity. The current practices used by the offshore wind farm operators for maintenance is reactive response maintenance. This means wind turbine repairs are taken at the first opportunity or as soon as a failure is detected. This Operation and Maintenance (O&M) strategy is based on excess maintenance practice leading to high cost per unit of energy produced. The current strategy is not economical for an existing offshore wind farm due to lower number of wind turbines were in operation. Most of the present wind farms are located close to shore at shallow waters. The future offshore wind farms were planned far from shore in remote locations due to the strong winds present there. This can lead to an expensive maintenance strategy since large resources were to be acquired to meet the technical challenges.

Computers were used for a planned intervention maintenance strategy for offshore wind farms. It was also to investigate its technical and financial benefits, when compared against the current practice. Considering a planned intervention maintenance policy, the repairs and maintenance of offshore wind turbines were undertaken at predefined intervals during the operational year. The parameters collected and computerized periodically were: wind farm capacity factors, time to failure, time to repair, transportation means and distance to shore, technical and economic feasibility, failures and maintenance related cost. As the wind farms move further offshore, the other emissions. The research and investigation in operating maintenance of each wind turbine necessitates the use of ships and helicopters which emit carbon dioxide and maintenance strategy for existing offshore wind [8] has proved more failure rates especially in the electrical and electronic systems.
Figure 5.1 Wind turbine installation growths for the period 2002 to 2010
The wind generator and gearbox failure were less common and requires long repair periods. Sophisticated instrumentations were being used to monitor the performance of turbine components in order to provide early warnings, such as gearbox oil temperature or vibration levels. The timely action or additional inspections might save downtime and reduce the costly failures. This is a good example of condition monitoring as applied to rotor blades, main bearings and pitch-control mechanism. Many turbine manufacturers now offer in-built condition monitoring equipment with a number of specialized instrumentation and software. This will assist in optimizing the spare parts components stock levels at regular intervals. The most important decision is to schedule the repairs during windy seasons or it could be delayed.

The cost of electricity from wind has two components, the capital cost repayments along with interest and the other component is operation costs and maintenance[2]. The latter component accounts for roughly 20% of the onshore wind generation cost and 15% of the offshore generation cost. The term "operation and maintenance" covers a wide range of cost such as land or seabed rent, insurance, servicing, spare parts, electricity purchases from the grid and administration costs. The most important aspects are focus on the servicing, spare part components, scheduled and unscheduled maintenance. This was estimated to be anywhere from 25 percent to 40 percent of operating and maintenance cost. The estimated amounts were $40/kW/year for onshore wind and $74/kW/year for offshore wind. These costs were expected to fall around 30% for both onshore and offshore by 2030. The reasons for this fall are improved maintenance strategies, technological innovations [9] in component material and remote sensing components.

The costs in offshore servicing for scheduled and unscheduled maintenance including replacement of parts were dropped substantially accordingly to a recent research in offshore wind farm project maintenance. The cost fell from $40/kW/year in 2008 to $25/kW/year in 2012. The average length of full-service contracts has increased from 4.5 years in 2008 to 6.9 years in 2012. The decreasing cost and increasing contract length suggest that turbine reliability is increasing. A further research shows that operating and maintenance costs increased on an average from $21/kW/year in 2008 to $31/kW/year in 2011.

5.1.2 Life cycle economics of wind farms
The lifecycle of a wind farm either onshore or offshore involves four main stages and the life cycle costs were calculated based on figure 5.2:

- Development: Including project design, environmental studies, legal agreements, project funding and planning permissions;
- Construction: Including preparing the site, manufacturing and installing the wind turbines and connecting to the grid;
- Operations and maintenance: Maintaining, operating the site and the turbines, typically over a 25 year period;
- Decommissioning and repowering: Replacement with new turbines at the end of their operational and maintenance period or removing turbines including site restoration towards the end;

Each of these stages could be broken down into a series of different tasks and activities, which may be undertaken by several different companies. In order to estimate the economic impact of onshore or offshore wind deployment [10], it is necessary to understand the type of activity that occurs within each stage and the extent to which this is or could be undertaken by the wind turbine manufacturing companies. This can be achieved through a series of consultations with wind turbine manufacturers engaged in the onshore and offshore supply chain. These consultations revealed that the supply chain for the wind sector were complex, involving a wide variety of manufacturers, professional services, civil engineers and electrical engineers. The impacts generated by the sector were those associated with transporting turbines, towers, other supplies to wind farm sites or those generated by construction workers who require accommodation and catering close to new wind farms especially during the construction phase.
Figure 5.2 Structure of life cycle cost analysis
A huge expenditure was required during the development, operations and maintenance phases. However, the involvements by the onshore wind sector expert were advantages for the emerging offshore renewable energy sector. The offshore wind farm installations were more difficult and expensive but also had a major impact on the accessibility for maintenance purposes. It might be that the complete wind farm would be inaccessible by boat or helicopter for a period of one or two months because of harsh weather conditions (wind and waves). And even if weather permits, the cost of offshore maintenance would be far higher than onshore wind farm.

When a cost or profit objective function was considered, a Life Cycle Cost was often used in order to calculate the value of money in time figure 5.3. A Life Cycle Cost model was the sum of the discounted capital and operational expenditures over the life time of a system. In the context of maintenance, the initial investment for the maintenance strategy[11] (equipment, monitoring system), the costs for corrective maintenance, preventive maintenance costs and production losses were calculated respectively. The costs for servicing, monitoring, analysis and administration rate were calculated for the number of years it was carried out. The expected lifetime of the system in years was calculated by using the discount rate as a function of the real interest after adjusting the inflation rate. The interest rate depends on the investment financed by a bank loan or on the expectation on the rate of return invested by the company’s own fund.

5.2 Maintenance costs, reliability and future challenges

The maintenance cost was known to be an important part for levelling the cost of energy produced by wind farms. In particular offshore operation and maintenance, contributes between 15-30% of the cost of energy. The estimated costs for the existing wind farms maintenance were found to be as 40% of the life cycle cost[12]. This was due to serial failures as well as low investment costs compared to the current market. The main drivers of the maintenance costs were replacing major
Figure 5.3 Estimation of O&M life cycle cost at Horns Rev offshore wind farm.
component, refurbishment of major components and logistic. The maintenance strategy of the major components had a major influence on the costs of replacement and refurbishment.

A challenging aspect of offshore wind farms was the logistic that needs to be pre-planned according to the distance from shore and the weather conditions at the site. The transportation of maintenance technicians to the wind turbines location were performed by workboats. They were restrained by the wave height and poor accessibility resulting in long downtimes, leading to employ helicopters escalating the capital investment. The logistic and maintenance support companies for offshore wind farms were more crucial for the new projects installed in deeper water. The planning of the scheduled maintenance activities will optimize the availability of offshore wind energy power generation.

5.3 Maintenance strategy concepts

Maintenance is defined as the combination of all technical and corresponding administrative actions, intended to retain a component or restore it to a state in which it can perform its required function. A common classification of maintenance strategies was based on the standard wind farm procedures[11]. Corrective maintenance (CM) was carried out after a failure has occurred and was intended to restore an item to a state, in which it could perform its required function. Preventive maintenance (PM) was carried out at predetermined intervals or corresponding to a prescribed criteria and was intended to reduce, the probability of failure or performance degradation of a component. There were two main approaches for preventive maintenance strategies:

Time Based Maintenance (TBM) was a preventive maintenance was carried out in accordance with established intervals of time but without previous conditional investigation. Time Based Maintenance was suitable for failures that were age-related and for which the probability of failure could be established.

Condition Based Maintenance (CBM) was a preventive maintenance based on performance and / or parameter monitoring. Condition Based Maintenance consists of all maintenance strategies involving inspections or permanently installed Condition Monitoring Systems (CMS) to decide on the maintenance actions. Inspection could involve the use of man
power, monitoring techniques or function tests. Condition Based Maintenance could be used for non-age related failures. This activity could be used if the ability to detect or diagnose the degradation in time, in a cost-effective manner.

The ability to detect the deterioration in time was linked to the concept of the P-F curve figure 5.4, represents a typical deterioration of the condition of a component in time. The point of time is represented by letter P, indicating a potential failure. The point of time is represented by letter F, indicating deterioration leading to a failure. A Condition Based Maintenance strategy figure 5.5 was effective, if it could identify the deterioration well in advance. This could ideally estimate the time to failure, in order to schedule a repair / replacement of a component before complete breakdown. This could minimize downtime cost and reduce further damage. If there were no chance for cost-effective maintenance strategy for critical components or failures then design / manufacturing improvement should be considered. This would increase the inherent reliability of the offshore wind farm components.

5.3.1  **Reliability centered maintenance**

Reliability Centered Maintenance was a qualitative approach to determine suitable maintenance strategies. This systematic risk-based method was used to optimize maintenance in order to preserve the functions of a system. This was further summarized as a systematic analysis of the way the system functions.
Figure 5.4 Deterioration observation curve concept.
Figure 5.5 Type of maintenance strategies
A comprehensive introduction to the reliability cantered maintenance method summarizes the key attributes to seven basic questions:

1. What are the functions and associated desired standards of performance of the asset in its present operating condition?
2. In what ways can it fail to fulfill its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What should be done to predict or prevent each failure?
7. What should be done if a suitable procedure cannot be found?

Reliability centered asset maintenance is an approach that brings together reliability centered maintenance with quantitative methods for reliability and maintenance optimization. It has been applied to distribution and transmission power systems including the most critical systems of wind turbines.

5.3.2 Quantitative maintenance optimization

Quantitative maintenance optimization was to find the optimal balance between the costs and the benefits of maintenance figure 5.6, while taking relevant constraints into account. The main purpose of quantitative maintenance optimization was to assist the management in decision making, by utilizing available data, in order to reduce the decision by experts. There were several inter-related maintenance decision areas as:

- Maintenance strategies related to the identification of suitable maintenance concept for the components of the system according to their failure behavior, probabilities and consequences. Failure at operation, fixed replacement strategies, inspection based or condition monitoring based maintenance.
Figure 5.6 Flow chart for an offshore wind farm for maintenance costs and the availability

- Maintenance support organization related to the optimization of the resources required to perform the maintenance such as size of the maintenance staff,
transportation strategy for the technicians and spare parts, purchase or lease of maintenance equipment and the spare part management.

5.4 Optimization of maintenance strategy

5.4.1 Reliability of wind turbines

The reliability of onshore wind turbines was typically in the range of 95-99% while for offshore projects it was as low as 60%[13]. This was due to serial failures and harsh weather conditions. There was downtime per component at the Horns Rev offshore wind farm project figure 5.7. This was in addition to the serial failures that occurred during the first year of operation. The yearly availability of power generation was 95-97%. The aggregate failure rate per wind turbines was around 5 failures per year. It has been observed that the main contributors to the failure rates are the power electronics, gearbox oil system, hydraulic and control systems. A similar result has been found for wind turbines at onshore sites.

The availability of the turbine for power generation could be improved by implementing redundancy. This was carried by a time based replacement of component, as it become old or by improving the maintenance support organization. The downtime resulted in layoff and this was due to delay in getting the spare parts and crane ship. The availability and maintenance costs for the major components could be minimized if condition monitoring systems were used. The reliability of the internal electrical grid and the transmission electrical system were critical too. The availability of the transmission electrical system was of high voltage direct current technology and in the range of 96 to 99 percent.
5.4.2 Current maintenance strategies and related research

Maintenance activities at wind power systems consist typically of corrective maintenance activities and preventive maintenance including scheduled service maintenance activities. Onshore wind turbines were generally serviced and inspected twice a year. However, due to higher transportation costs and production losses, wind turbines located offshore were often serviced only once a year during the month of April or August every year.
The yearly service maintenance takes generally 2-3 days per wind turbine and includes:

- Changes of lubrication systems and oil filters
- Check of brushes and slip ring of doubly fed induction generator
- Inspection with respect to leakage
- Test of safety systems and pad brake
- Strength testing and retightening bolts
- Oil sampling and analysis for the gearbox
- Visual inspection of the blades

The inspection performed as part of condition based maintenance were endoscopic inspection of the gearbox, ultrasonic or thermographs inspection of blades [14], thermographs inspection of the electrical components such as transformer, circuit breaker. For offshore wind farms, the inspection of the foundations especially corrosion was generally performed every two years. Vibration of the drive train and oil condition monitoring of wind turbine was common practice for offshore wind turbines. It could provide useful information on the deterioration condition of the different components of the drive train which could help scheduling and clustering major replacements. Recently, online condition monitoring system for blades has been proposed based on gauge strain or fiber optic strain or acoustic monitoring that could detect damages from cracks.

The analysis of the monitoring measurements for all type of condition monitoring system was generally performed by an expert, with the support of software in order to detect changes in conditions. The signal processing methods for detection and diagnosis based on condition monitoring systems has received much attention. Another approach to condition monitoring was to make use of existing measurements from the Supervisory Control And Data Acquisition (SCADA) system in order to detect and determine faults. The quantitative analyses of maintenance strategies for the wind turbine major components had been proposed such as:

- Cost-benefit analysis of condition monitoring for the drive train
- Time based replacement of major components
- Inspection of optimization based on delay time
- Physical based maintenance optimization
- Condition based maintenance optimization on fatigue for offshore foundations

### 5.4.3 Cost-benefit of condition monitoring systems

The failures of the major components of the drive train were expensive due to the high costs of spare parts, logistic, maintenance equipment causing energy production losses. Vibration and oil condition monitoring system were available for the components of the drive train. The condition monitoring system identifies failures well before requirement of a major maintenance. An inspection is performed as soon as a fault was suspected and either minor maintenance or replacement of the component was planned. The production losses and maintenance activities could be reduced if these costs were controlled. The economic benefit of this system depends on the probability of failure of the component in the drive train, the efficiency of the system and logistic. The proposed approach was to consider the cost and reliability of the drive train over the lifetime of the turbine.

### 5.4.4 Optimal condition based maintenance for blades

The wind turbine rotor usually consists of three blades, a critical component for the reliability, availability and profitability of wind turbines [15]. The sizes of the rotor blades for wind turbines have been increasing rapidly during the last decade and are subject to high stresses. Wind turbine blades were either inspected once a year during schedule service maintenance or if a lightning strike detected by lightning detectors. Condition monitoring could be used in order to detect cracks and de-lamination during inspection. The monitoring devices consist of infrared or ultrasound sensors installed [16] on an inspection robot that would scan and examine the inner material of the blade. On-line conditional monitoring system known as Structural Health Monitoring could be used for the tower, support structure and blades. This was
achieved by inserting fibre optical sensors. An operating and maintenance organization chart figure 5.8 was used for internal data transfer, to establish detailed information on administrative, technical and economics of offshore wind farms.

The reasons for maintenance were:

- To compare the expected maintenance costs for visual inspection, inspection using condition monitoring technique
- To optimize the inspection interval for the inspection strategies.

An overview of cost comparison of onshore with offshore wind farms:

**Onshore**

- Investment was anywhere between 700 and 1000 €/kW
- Cost was between 3 and 8 € cents/kWh
- Operating and Maintenance cost was between 1 and 3 percent of installed cost
- Could be built in smaller units
- Might need to run less optimally (e.g. noise considerations)
Figure 5.8 Offshore wind farm operating and maintenance organization chart

Offshore

- Investment amount was around 1650 €/kW (site dependent)
- Cost was between 5 and 10 € cents/kWh
- High initial investment (foundations/grid connections)
- Higher operating and maintenance cost at 30 €/kW plus 0.5 € cents/kWh variable
- Large turbines
- Large farms (reduces unit cost)
5.5 Cost Estimation for operating and maintenance

The operating and maintenance costs were related to a limited number of components costs:

- Insurance
- Regular maintenance
- Repair
- Spare parts
- Administration

The insurance and regular maintenance costs were obtained from standard contract data covering the total lifetime of the wind turbines. The costs for repair and spare parts were more difficult to predict and estimate. The cost components of all parts tend to increase gradually as the turbine gets older. The cost for repair and spare parts were particularly influenced by turbine age. Since only few turbines reach the life expectancy of twenty years, the wind industries has not fully established and were still involved in the research process. Moreover, these turbines were much smaller than the current available turbines in the market. The estimates of Operation and maintenance costs were still highly unpredictable, especially towards the end of a turbine’s lifetime. A certain amount of experience and data collected from various operating wind farm projects could be utilized for corrective action and implement in the future new projects.

The experiences based in Germany, Spain, the UK and Denmark [9] has shown that the operation and maintenance costs, over the lifetime of a turbine were generally estimated to be around 1.2 to 1.5 eurocents per kWh of wind power produced. The Spanish data indicates that less than 60 per cent of this amount goes strictly to the operating and maintenance of the turbine installations, labor costs and spare parts. The remaining 40 per cent was split equally between insurance, land rental and overheads. The total operating and maintenance costs from a German wind farm from the years 1997 to 2001 were split into six different categories. The expenses pertaining to buying power and land rental were included in the operation and maintenance costs. For the first two years of its turbine’s lifetime as a standard, manufacturer’s warranty was covered. Whereas, Germany’s wind farm data for operation and maintenance costs was a small percentage of 2 to 3 per cent of total investment costs. This was for the first two years and was
corresponding to 0.3-0.4 c € /kWh. The total operation and maintenance costs were found to be increasing gradually to 5 per cent of the total investment costs and found to be around 0.6-0.7 c €/kWh. These operating and maintenance costs were compared to the newly installed Danish turbines and were found to be similar figure 5.9.

The total Operating and maintenance costs figure 5.10 resulting from a Danish study on a three year old 600 kW machine were distributed among various categories. In general, the study revealed that expenses for insurance, regular servicing and administration were stable over a period of time, while the costs for repairs and spare parts were fluctuating considerably. The Operating and maintenance cost were found increasing corresponding to the age of the turbine. If there is a decline in investment cost per kW, accordingly an increase was found in the turbine capacity. The same economies were found for an operating and maintenance costs. This means that a decrease in Operating and maintenance costs correspond to a turbine scaling. The new and large turbines were better than older models with advantages of lower operating and maintenance requirements throughout the life time of a turbine. However, this may also have the adverse effect that new turbines will not withstand as effectively as old, until the running-in operation was successful.
Figure 5.9 Operating and maintenance costs for types and ages of turbines
The Foundation and grid connection costs were substantially more expensive compared with onshore wind energy. The onshore foundations were found to be less than one third the costs, whilst grid connection costs were found even lower than half the offshore wind farm. The costs control exercises required for an offshore wind farm were:

- The need for expensive foundations, cost increases corresponding with water depth and this accounts for 30 percent of the total cost
• Increased operation and maintenance costs with risks of lower availability. This is due to reduced access to the wind turbines during bad weather

• The need to protect the wind turbines from the corrosive influence of salt spray may add up to 20% of the turbine costs.

To determine the costs and availability of an offshore wind farm [17], the necessary input and results of the corrective maintenance of offshore wind farm are implemented covering various data table 5.1 in a suitable format for better understanding. The following analyzed information could be used would be useful as a corrective measurement tool for future offshore projects:

• The failure behaviour of the turbine

• The tools, equipments, access systems and repair procedures necessary to carry out the repair actions and their costs

• The climate data, especially wave and wind data operational windows

• The calculated costs and availability
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<th>Operational Phase Wind Farm: O&amp;M Cost Estimator</th>
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<td>• Based on ‘design’ data</td>
<td>Wind Farm data and experience included</td>
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Table 5.1 Operating and maintenance cost estimate data format
The costs and availability related to preventive maintenance of the turbines for optimizing the initial maintenance strategy by:

- Adjusting the preventive maintenance plan
- Improving the reliability of the turbine to lower the failure rate or the consequences of a failure
- Selecting more adequate access and appropriate lifting equipment that can work up to higher wave heights and wind speeds.

It is observed from various offshore wind farms the costs for maintaining the electrical infrastructure and the civil works were minor as compared to the costs needed for maintaining the turbines. The same holds for the contribution to the unavailability of a wind farm. The cost of maintaining this cable and the unavailability of the wind farm due to failure of this cable were calculated in the same way. The optimization of the maintenance procedure would be started only after incorporating the uncertainties in the input values, variations in reliability and accessibility.

5.6 Maintenance cost

5.6.1 Scope

The costs for maintaining an offshore wind farm were determined by both corrective and preventive maintenance. In figure 5.11, the costs over the lifetime of the wind turbines were presented schematically. The comparison of costs for onshore and offshore wind farms are given in figure 5.12. Two major phases were identified while reviewing offshore wind farms operating and maintenance costs:
Figure 5.11 Schematic overview of the maintenance effort over the lifetime of a turbine
Figure 5.12 components cost used in onshore and offshore wind farm
Phase 1: The first five years from the commissioning period

During the commissioning period, the running-in operations usually requires additional maintenance leading to additional costs. Time should be spent on finding the right computer software with detailed inputs. The turbine manufacturers usually provide a contract to the customer with a fixed price covering the first five operational years. The contracts include commissioning, preventive and corrective maintenance, warranties and machine damage.

Phase 2: The last fifteen years with one or more major overhauls between the 7th and 13th year.

After about 10 years of operation, it is very likely that some of the main systems of the turbines should be revised such as pitch motors, hydraulic pumps and lubrication systems. There was not much experience available up to now regarding the period of major overhaul should be carried in an offshore wind farm turbine. The major overhaul in fact, was considered to be “condition based maintenance”. There could be more likely that more corrective maintenance would be required towards the end of the lifetime than at the beginning. It was still unclear, the quantum of further maintenance required during the lifetime of the turbines. The offshore wind farm maintenance project team has proposed to implement the preventive maintenance and corrective maintenance by observing the level of constant failure rate.

5.6.2 MAINTENANCE CATEGORIES AND REPAIR STRATEGIES

The Maintenance strategies were divided into four main categories and the equipments figure 5.13 deployed during the maintenance were:

Category 1: Heavy component; external crane

This category contains all types of maintenance required to lift heavy / large components that could not be lifted by the internal cranes. Such heavy components were lifted from the wind turbine directly to the vessel. This maintenance was supported by limited number of vessels due to rare occurrences.
Support equipment

Figure 5.13 Support equipment for offshore wind farms installation
A special team was designated to handle this maintenance as a separate project. This project was not included in the day to day operating and maintenance routine and the effective repair time was one week. However the major problem was the mobilization time of the crane vessel, as she was occupied in other parts of the world. The non-availability of spare parts significantly increases the downtime of the wind turbine generator.

**Category 2: Heavy component; build up internal crane.**

This category contains all types of maintenance requiring the lift of heavy/large components that were lifted by the build-up internal crane because they could not be lifted by the permanent internal crane and were not necessarily to be lifted by an external crane. This includes components like the gearbox, generator and one single rotor blade. The maintenance requires a crew of six fitters and one foreman. They work ten hours a day in one shift. If for example a generator, gearbox or single blade has to be replaced, the 50 MT internal cranes were necessary. The operating access system was not large enough to handle, the large components and a vessel with a 50 MT crane with compensation for heaving was needed. The weather conditions should be good with wind speeds less than 6 m/s for hoisting and 10 m/s to work in open nacelle.

**Category 3: Small parts, permanent internal crane**

This category contains all types of maintenance requiring lifting the components that could not be man carried and thus requires the permanent internal crane. This includes a pitch motor in the hub or a yaw motor. The maximum weight of such components would be 950kg. The maintenance requires a crew of four fitters. They work ten hours a day in one shift. The Smaller spare parts like a pitch motor or a yaw motor were lowered onto the platform and hoisted into the nacelle by one ton internal crane. The spare parts on the platform could be placed either by a crane or through the gangway. The retrofit arrangements were currently being redesigned to suit the weather condition for transferring parts smaller than 1000 kg from the supplier to the turbine. Furthermore, few of the most common spare parts up to 1000 kg were stocked at the substation.

**Category 4: Small / no parts, 24 hours repair time**
This category contains all other types of corrective maintenance. All components and equipment were able to hand carried by man. The maintenance requires two fitters for corrective maintenance. They effectively work one eight hour shift.

**Category 4A: Inspection and repair (inside)**

At least two technicians were required to be transported to the turbine in order to carry out the repair. No additional equipment needed and only tools that fit into a tool box were sufficient. The transportation of personnel were done up to wind speed 10 m/s and to a significant wave heights of 0.5 to 1.0 m. For a base line calculation wave height was set to 0.5 m. The use of a helicopter was not realistic, since the turbines were not equipped with a hoisting platform.

**Category 4B: Inspection and repair (external)**

This category includes for instance cleaning of the blades or inspection [18] of the tower or repairing the gel coat of the blades. The research shows lightning, damage to the surface and the receptors happen despite the lightning protection works satisfactory. The insurance company insists on the annual inspection of rotor blades and the wind farm owner was happy to oblige. Two technicians were transported to the turbine in order to carry out an inspection or repair to the external of the turbine. An external special hoist was used to hoist technicians from the hub along the blade. The repairs were done with the wind speeds up to a maximum 6 m/s. The inspections of all blades could take 4 to 8 hours.
When redefining the four maintenance categories, the following points were observed:

1. A supply boat with at least eight maintenance technicians would be present within the wind farm. This means that the travel time was limited to approximately thirty minutes.

2. A helicopter platform was available at the transformer station. This offered and responded very quickly to failures in the transformer station. Such failures usually lead to turbine downtime along with a cluster of turbines.

3. Turbines was equipped with mobile cranes for hoisting large components.

4. The turbine was permanently equipped with a crane for hoisting the small spare parts with a max capacity of 950 kg outside the turbine.

5. The turbine was equipped with a platform outside the mast, at a height of twelve metres on which spare parts were laid down during replacement. The platform was large enough to accommodate the two mobile cranes, the failed parts and the spare parts. This means that two blades (old and new one) can be stored on the platform.

6. An external crane was needed to replace entire rotor and nacelle and this was a jack-up platform.

7. The possible means for transportation used were offshore access system (OAS), helicopter in case of repairs with very high priority during bad weather conditions and supplier with man over board boat (MOB-Inflatable boat).

5.7 Cost and downtime estimation

The major results of the costs per year and the downtime was based on a single turbine model of capacity 6000 kW were expressed in €cents per kWh
The annual unavailability of a turbine was estimated to be around 8.4 percent with a capacity factor of 43 percent, the cost was 8 €cents per kWh. This corresponds to a financial loss of 151.145 € per turbine due to revenue losses. If the entire wind farm consists of 80 turbines, then the revenue losses would be 12.1 M€. The downtime was split up into logistic downtime, waiting time, travel time and repair time.

The total maintenance cost per turbine was the direct costs without any revenue losses. This consists of material costs, labour costs and equipment costs amounting to 124 566 € per turbine or 10.0 M€ for the entire wind farm. The revenue loss contribution amounted to 55 % of the total wind farm cost. The annual energy thus generated has been calculated as the product of the rated power, the capacity factor, the availability and the number of hours per year. Then annual energy generated would be 6000 kW x 0.43 x 0.916 x 8760 = 20 626MWh/yr. The total costs were divided by the annual energy production that gives cost of energy price as 1.34 €cents /kWh.

The suggestion for improvements in the design or in the selection of cranes and supply vessels were based on the cost drivers. This was done by analyzing the intermediate results in detail. Figure 5.14 gives an overview of the costs and downtime for the individual

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**Summary: long term yearly repair costs of 1 wind turbine (6000kW)**

<table>
<thead>
<tr>
<th></th>
<th>Turbine</th>
<th>Inspection</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year 43%</td>
<td>Year 43%</td>
<td>Year 43%</td>
</tr>
<tr>
<td>------------------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td><strong>Downtime</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logistics</td>
<td>49.5</td>
<td>3.6</td>
<td>53.1</td>
</tr>
<tr>
<td>Waiting</td>
<td>656.6</td>
<td>0.9</td>
<td>657.5</td>
</tr>
<tr>
<td>Travel</td>
<td>2.4</td>
<td>0.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Repair</td>
<td>19.5</td>
<td>1.8</td>
<td>21.3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>728.0</td>
<td>7.0</td>
<td>735.0</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td><strong>91.7%</strong></td>
<td><strong>99.9%</strong></td>
<td><strong>91.6%</strong></td>
</tr>
<tr>
<td><strong>Mean capacity factor</strong></td>
<td>Year 43%</td>
<td>Year 43%</td>
<td>Year 43%</td>
</tr>
<tr>
<td>Loss of production</td>
<td>1871350</td>
<td>17,957</td>
<td>1,889,307</td>
</tr>
<tr>
<td>Energy production</td>
<td>20646682</td>
<td>22,500,061</td>
<td>20,628,711</td>
</tr>
<tr>
<td>kWh price</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Revenue losses</td>
<td>149,708</td>
<td>1,437</td>
<td>151,145</td>
</tr>
<tr>
<td>Material costs</td>
<td>58,498</td>
<td>0</td>
<td>58,498</td>
</tr>
<tr>
<td><strong>Labour costs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wages</td>
<td>2,644</td>
<td>255</td>
<td>2,899</td>
</tr>
<tr>
<td>Daily allowance</td>
<td>529</td>
<td>51</td>
<td>580</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>3,173</td>
<td>306</td>
<td>3,479</td>
</tr>
<tr>
<td><strong>Costs equipment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOB/DEMOB</td>
<td>19,432</td>
<td>0</td>
<td>19,432</td>
</tr>
<tr>
<td>Waiting</td>
<td>24,592</td>
<td>1,008</td>
<td>25,601</td>
</tr>
<tr>
<td>Repair</td>
<td>15,554</td>
<td>2,003</td>
<td>17,557</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>59,578</td>
<td>3,011</td>
<td>62,589</td>
</tr>
<tr>
<td><strong>Total costs in season</strong></td>
<td>Year 270,957</td>
<td>Year 4,754</td>
<td>Year 275,711</td>
</tr>
<tr>
<td><strong>Total Costs per kWh</strong></td>
<td>1.31</td>
<td>0.02</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table 5.2 Costs and downtime per year summary of a single turbine
maintenance categories and detailed results were given in figure 5.15. The maintenance of large components was the reason for figure 5.16 most of the downtime and thus the cost increases. It was concluded that the downtime mostly dominated by the waiting time such as lifting the two
internal cranes during good weather. The blade failures, generator failures, and gearbox failures together contribute over seventy five percent driving the costs and the downtime.

The analyses from the ongoing offshore wind farm operation and maintenance data for a single turbine give insight the number of times per year, certain major equipments were needed:

- Supplier with operating access system requires 124 times per year.
- Jumping jack requires one time.
- Crane ship requires nine times.
- Internal crane, hoisting out capacity of one metric ton required twenty nine times.
- Internal crane, hoisting outside of capacity 50 metric tonnes required nine times.

5.8 Economic impact job opportunities

The offshore and onshore wind industry started operation in many countries over a decade. The investment by public, private and governments had invested heavily in wind power. The current energy policies around the world imply that there was a lot of untapped potential investment yet to come. Most existing wind farms has been built onshore but some countries have also started more investment in offshore wind, the United Kingdom in particular had aspirations for offshore wind farms a decade ago, to make up nearly one-third of its generating capacity by the year 2020. Higher and steadier offshore winds make offshore wind farms more productive.
Figure 5.15  Above Maintenance categories to the costs and downtime  
Below: The cost and downtime items to the total values for maintenance
Figure 5.16 Relative contributions of the components to the costs and downtime
The costs of building offshore wind farms require huge investments and with complicated supply chain management. This is due to the relatively limited number of installation vessels and the long queues in suppliers’ order books. The production volumes of equipment and spare parts are limited. Most of the countries onshore and offshore wind farms have been delayed or blocked by difficulties in getting government’s permission and requirement of investments. The offshore wind farms offer the flexibility to locate closer.

Below Cost and downtime items to the total values for maintenance to major ports with a little distance to shore, reducing transmission losses and avoid congestion. The physical space available for onshore turbines in most countries is either limited or expensive, but building offshore wind farms allows a significant increase in the total potential contribution. In addition the wind energy sectors provide employment and generates the growth of the wind energy directly especially in the supply chain. The onshore and offshore wind sector supports a range of wider economic impacts and the following were included:

- Local and regional supply chain development: The onshore and offshore wind sector has and continues to create opportunities for a wide range of businesses across the globe that are engaged in the supply chain;

- Income effects: Spending by employees in the onshore and offshore wind sector;

- Impacts on land owners: Wind farms have been used by farmers and other land owners to generate additional revenue and diversify income streams in order to support the continued viability of their businesses;

- Community ownership: The development of community owned wind farms generates income for community shareholders and can help to improve the community unity and invest in further community economic and social development;
• Community benefit funds: These support community projects close to wind farms. The size of these funds varies from project to project; Business and tourism effects: Spending by employees in local businesses, for example on food and accommodation;

• Other tourism economy effects including the provision of visitor facilities and the role of wind farms in improving access to the countryside; Wildlife and habitat management: Wind farm developers often contribute to ecological projects which could help to enhance the local area and support further employment; investment in local infrastructure. Wind farm developers often develop or improve local infrastructure such as access roads, which brings wider benefits to the local economy and community. This could create short-term construction jobs and longer-term benefits as a result of the improvements to infrastructure.

The costs for offshore wind generation had indeed been significantly higher throughout than for onshore wind farms. This was despite recent technological improvements in the size and design of turbine technology. In recent years, offshore wind turbine costs had risen rather than falling. This was driven partly by increasing material prices like steel and partly by a rapidly increasing demand relative to supply chain capacity. The slow growth rates by new investment over the period 2001 to 2004 and with a sudden surge in market growth later by an average 35% per annum. This had caused the capacity shortages, long order books for manufacturers and thus resulting to a price surge. These factors were likely to remain relevant in future and the costs predicted were between €2,707/kW and €4591/kW in 2015 figure 5.17. There is severe shortage of investment in onshore wind and the offshore supply chain developments around the world.

European Wind energy association had developed cost estimation for the capacity of offshore and onshore wind installations for up to 2030 depending upon demand and supply of turbines. According to these figures, the average capital cost
Figure 5.17 The calculated production cost for different offshore wind farms
for a kW of offshore wind to be installed in 2009 was in the region of €2,300 compared to €1,300/kW for onshore capacity. These figures were comparable to the estimates presented in the year 2010 ranging between €1,571/kW and €1,977/kW for onshore but the offshore was higher between €2,732-€3,943/kW in the same year. Of course, the level of capital costs would be affected by geographical factors and hence variations by location were expected.

There were many offers with a comprehensive survey of the factors that influence the cost estimates for onshore and offshore wind turbines. This was a sample from wind energy manufacturers to estimate an average generation costs for onshore and offshore farms. Although the investment costs for onshore wind were expected to fall over time, the price of offshore capacity is expected to fall faster. This is due to scale-economies achieved by manufacturers and easing complication in the supply chain. In addition, manufacturers have introduced newer, larger turbines with high efficiency for offshore farms. The predicted costs for onshore and offshore wind farm up to the year 2030 are furnished in figure 5.18.

These cost differences for offshore and onshore wind stations were often attributed to factors associated with the design, building and transmission of offshore stations. For instance, laying foundations for an offshore or near shore wind station could be 50% more expensive or more than for a conventional land-based turbine. The exact level of the cost premium depends on factors including water depth and distance from shore. Recent cost data collected from the two largest offshore wind farms (the Horns Rev project and the Nysted offshore wind farm-Reference Chapter 3) suggests that foundations for offshore wind turbines can claim as much as 21 percent of total cost expenditure as against 5 to 9 percent for onshore turbines.
Figure 5.18
Past and predicted cost of onshore and offshore wind farms
The costs increase significantly with distance from shore and water depth table 5.3. The table shows the adjustment factor by which investment and installation costs based on a turbine closer to shore in shallow waters should be multiplied for deeper water and greater distances. This relationship between water depth and costs has discouraged the development of deep water turbines. This is despite the additional energy production benefits due to higher wind speeds that were often generated at a short distance from shore. The present operating wind farms tend to be located not further than 20 km from shore and in water depths of not more than 20 meters. Future developments would involve greater distances about 200 km from shore and with a maximum depth of 63 meters. The costs of building and maintaining wind turbines in these locations would be significantly higher than those near shores due to the transmission to the main electricity system ashore.

5.9 Offshore wind farm foundation Costs

The water depths in the range of 2 metres to 30 metres have been considered relevant for off shore wind farms. The depths below 2 metres were created accessibility problems by boat. A specially designed vehicle might be an alternative for transportation of the equipments to the site. The foundation for over 30 meters had so far not been used by the offshore industry and was considered expensive. The floating wind turbine generators are considered for deep water depths and were of large capacity turbine for economical reasons. Three types of foundations were normally considered as alternatives:

- Gravity (2 to 20 metres)
- Monopole (5 to 30 metres)
- Jacket (15 to 30 metres)
Table 5.3 Offshore wind farm cost escalation with respect to depth and distance

<table>
<thead>
<tr>
<th>Water depth (m)</th>
<th>Distance from shore (km)</th>
<th>0-10</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
<th>40-50</th>
<th>50-100</th>
<th>100-200</th>
<th>&gt;200</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-20</td>
<td></td>
<td>1</td>
<td>1.02</td>
<td>1.04</td>
<td>1.07</td>
<td>1.09</td>
<td>1.18</td>
<td>1.41</td>
<td>1.60</td>
</tr>
<tr>
<td>20-30</td>
<td></td>
<td>1.07</td>
<td>1.09</td>
<td>1.11</td>
<td>1.14</td>
<td>1.16</td>
<td>1.26</td>
<td>1.50</td>
<td>1.71</td>
</tr>
<tr>
<td>30-40</td>
<td></td>
<td>1.24</td>
<td>1.26</td>
<td>1.29</td>
<td>1.32</td>
<td>1.34</td>
<td>1.46</td>
<td>1.74</td>
<td>1.98</td>
</tr>
<tr>
<td>40-50</td>
<td></td>
<td>1.40</td>
<td>1.43</td>
<td>1.46</td>
<td>1.49</td>
<td>1.52</td>
<td>1.65</td>
<td>1.97</td>
<td>2.23</td>
</tr>
</tbody>
</table>
The basis price for an 8 metres water depth foundation based on Denmark offshore calculation was 250-300 €/kW including installation. The traditional foundation cost on land were 40 to 50 €/kW and thus the increase was found to be a factor of 7. If an increase in water depth per metre additionally would increase 2 percent roughly. The cost of foundations figure 5.19 represent 20-25% of the total project cost and vary with seabed conditions and weather conditions. The high waves and tidal or icing condition changes depending upon the region. The price of the type of foundation in general does not fluctuate much but depends on finding a suitable solution for the specific conditions.

The offshore wind farm project at Horns Rev, Denmark has used a mono pillar foundation that added 9 metres height above sea level. This decreases the need for tower height but on the other hand, the natural frequencies of the foundation demand that the tower construction has to withstand a maximum weight 150 tonnes. This problem was solved by restricting the weight to 110 tonnes for this tower height. The prices of course fluctuate, due to the technical changes during the project implementation. There were many factors that influence the costs and the foundation types but the sea bottom conditions could change the costs radically. There were cheaper solutions for on bedrock seafloor based on drilling holes in the rock for mono pillar implementation. The break-up of the costs of various composition used in a gravity foundation for a 8 metres water depth shown in figure 5.20. The cones and the overall dimensions were affected due to a risk of thick ice in the northern region. The major cost involved were the weight fill, but it was considered in the calculations that special heavy weight fill were cheaper than increasing the dimensions of the gravity foundation.

5.10 Costs of offshore wind grid

All new generators would need a connection to the electricity network and particularly a challenge for offshore wind farms. The subsea cables were expensive than overhead transmission lines and some of these cables had to travel
Figure 5.19
Offshore wind farm foundation cost with reference to depth and capacity.
Figure 5.20 Offshore wind farm gravity foundation costs breakdown
long distances to the transmission system. A cable connecting to a particular generator could be used when that generator alone was actually generating current. This could increase the average cost per MWh generated due to low load factor of the wind station. The economies claim, the wind farm capacity should be slightly larger than the capacity of the cable. But the cables come in fixed capacities that were many times larger than a typical wind turbine since wind farms rarely generate full capacity. The optimal balance was between the reduction of the connection cost per generator and increasing the amount of electricity instead of bypassing. This was done when the wind farm generation does exceed the cable capacity of 112% of its connection capacity. The estimated cost of connecting 19 GW of offshore wind farms were between €7.08 billion and €11.8 billion depending upon the distance from shore figure 5.21.

This makes it particularly important to minimize the cost of connecting offshore wind farms to the grid. If many different connections were designed in small portions, the cost of each portion varies at a later stage, making more expensive and hence affects the capital cost of the project. A monopoly developer would be under less pressure to keep costs down than a group of competing companies. There should be an overall development plan taking account of the interactions between projects and the existing onshore grid. This should be prepared in close collaboration with the onshore expert transmission operator and should not automatically be allowed to develop the individual connections of the development plan.

The individual wind farm developers were responsible for connecting their station to shore. The developer had a strong financial incentive in obtaining a cost-effective connection. The high costs or low availability would directly affect its profits from the offshore wind farm station. But most of the government policies would require a high degree of separation between generation and transmission activities. In future, the regulator would run tenders to appoint the Offshore Transmission Owner (OFTO), to build, own and operate the connection assets for
Figure 5.21 Change in energy production with change in distance from coastline
each wind development zone. This would allow coordination between the developer and the zone offshore transmission owner. The generator will pay for their use through the main system of regulated transmission tariffs used in Great Britain. Generators pay a charge per kW of capacity, based on the impact of their output on peak flows through the grid. Charges were calculated based on the number of MW-km of extra capacity required to accommodate the output from stations located in different zones on the network.

The same principle would be used in future, but new zones would be set up so that each offshore generator pays its own specific charge. The length of the line between the offshore zone and the rest of the transmission system would be calibrated to ensure that the OFTO for that zone recovers an amount of revenue dependent on its tender bid. This would be equivalent to the offshore generator paying a connection charge to the OFTO, based on the cost of connecting it to the main onshore grid and also paying the onshore transmission companies. The future wind farms being planned are much larger and will need several cables to bring their power to shore. A saving in capacity if two farms expected to have different generation patterns shared their connections. The optimal capacity for the two stations together would be less than the sum of their individual needs. One of the offshore grid in Great Britain transfers power between the countries on two sides of the sea. This would make sense for wind farms, which are nearly halfway between two countries. It would give the wind generator the option of exporting its power in either direction depending upon the higher market price. When the wind farm was not generating or not generating to the cable’s capacity, power could be transmitted from one country to the other. They would also tend to reduce short-term fluctuations in electricity prices.

Most of the offshore wind farms production output losses were found to be around 9 to 36 percent maximum and this could be adjusted if the sharing option was accepted. If the wind farm had a load factor of just over 40% and a slightly greater capacity than the cable, then less than 60% of the cable’s capacity would be available for trade as an average. If the wind farm was nearly midway between the countries, this 60% of capacity might be obtained for roughly 50% of the cable costs. The additional costs of an excess connection had a value of 6% interest rate in 2010. The cost of the cable connection to shore forms a significant proportion of offshore wind farm costs, typically in the range 17-34%. At Vindeby (5 MW), the first Danish offshore farm
and at Laeso (117 MW) was around €250/kW table 5.4, which could be taken for guidance. Exact levels will be site-specific, dependent on the cable length and burying method.
Table 5.4 Example of estimated cost for a 240 MW offshore win ports with
REFERENCE


[6] Initial capital cost of wind farm and energy generation cost per kilowatt-S. A. Herman ‘Offshore wind farms’ Analysis of Transport and Installation Costs – February 2002


