A THESIS

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The Operation and Maintenance Model for Cost Estimation of an Offshore Wind Farm

Graduate School of Specialized Wind Energy

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Jae-Hee Park

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The Operation and Maintenance Model for Cost Estimation of an Offshore Wind Farm

Jae-Hee Park
(Supervised by Professor Kyung-Hyun Choi)

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The thesis has been examined and approved.

Thesis Director: Jong-Hwan Lim, Professor, Department of Mechatronics Engineering

Jong-Chul Huh, Professor, Department of Mechanical Engineering

Kyung-Hyun Choi, Professor, Department of Mechatronics Engineering

Date

Graduate School of Specialized Wind Energy
GRADUATE SCHOOL
JEJU NATIONAL UNIVERSITY

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Contents

Appendices

List of Tables

List of Figures

Abstract

Several European countries have defined targets to install and to operate offshore wind energy and according to these targets more than 40 GW offshore wind power is expected for the year 2020. Republic of Korea has also defined targets to install and operate offshore wind energy as part of its renewable energy goals. According to its targets, more than 2.5 GW offshore wind power is expected to be installed across Jeju island region and the west side of mainland by the year 2020. So the required effort for operation and maintenance of offshore wind farms will be enormous, also a thorough and appropriate plan of maintenance during the lifetime of these offshore wind turbines is essential for an economical exploitation.

The aim of this thesis is to develop operation and maintenance model for an offshore wind farm in Rep. of Korea considering regional marine situation. The model should include both preventive and corrective maintenance plans which needs basic concept of wind energy, wind turbine, and maintenance strategies. The model should be based on real time metrological data, geographic data, generic wind turbine data, equipment data, spare parts and repair data. A 10 minute time series of wind speed data in public water surfaces of Daejeong-eup and 1 hourly time series of Marado significant wave height data in 2010 are used for metrological data. Equipment data is based on vessels of the operating offshore wind farm in the North Sea. Spare parts are modeled from commercial wind turbine components contribution and costs. To define repair data, there are various categories and step to determine the sequence of maintenance phases, and the corresponding amount of work, required equipment and time to organize an each maintenance phase.

The operation and maintenance costs are estimated for one year in order to verify the model. A plan of operation and maintenance is set up for offshore wind farm in Jeju Island, Rep. of Korea. The results show that availability of Jeju wind farm is around 90 %. The sum of revenue losses and the total costs of repair is estimated to be approximately 27 % of generation cost which includes 11 % of the total generation cost due to limited equipment usage and 9 % of the total generation cost due to revenue losses for one year in the offshore wind farm. The proposed model can be used for the analysis of different aspects that include overall contributions and costs of operation and maintenance and to make an operation and maintenance support organization and plan for offshore wind farm in Rep. of Korea.

초록

현재 세계 해상풍력 시장은 영국을 중심으로 한 유럽시장이 주도하고 있으며 2020 년까지 40 GW 규모에 달하는 설치용량을 보유할 예정이다. 국내에서도 해상풍력단지 조성이 본격화되고 있고 서해안 일대와 제주도 인근 해안을 중심으로 2020 년까지 2.5 GW 에 해상풍력발전단지를 조성하기 위해 단지 조성이 가능한 지역에 대한 탐색작업을 진행 중이다. 이에 따라 빠른 기술 발전과 급성장하는 해상 풍력발전 시설의 용량에 대한 운영 및 유지보수(O&M: operation and maintenance)가 심각화되고 있고, 해상 풍력발전기의 평균 운영기간 동안 체계적이고 적절한 유비보수에 대한 경제적 개발이 필수적이다.

본 논문의 목적은 우리나라 해상 상황을 고려한 제주 해상 풍력단지의 운영 및 유지보수 모델을 제시하는 것이다. 예방 유지보수 모델과 교정 유지보수 모델을 제시하기 위해 기본적인 풍력 에너지와, 풍력 터빈, 유지보수 전략에 대한 내용과 함께 실측 기상 데이터와 지형 데이터, 유지보수 장비 데이터, 풍력 발전기 부품 데이터, 유지보수 절차에 관한 내용을 포함하고 있다. 기상 데이터는 제주도 대정읍 지역 공유 수면에서 10 분 단위로 측정한 1 년동안의 풍속 데이터와 마라도 해상의 1 시간 단위의 유의 파고 데이터를 사용하였으며 장비와 풍력 발전기 부품 등에 관한 데이터는 현재 상업적으로 사용되고 있거나 유럽 등지에서 운영 중인 데이터를 기초로 작성하였다. 유지보수 절차에 대해서는 유지보수 작업을 준비하는 시간, 각 단계별 순서, 그에 상응하는 작업시간, 필요한 장비와 전문 인력에 의해 정의하였다.

제안된 유지보수 모델에 관하여 검증하기 위해 1 년간의 유지보수 비용을 추정하였다. 결과에서 풍력 발전단지 설비 이용률은 약 91%이고, 총 발전 비용 중에 약 27 %의 발전 손실과 총 수리비용을 포함한 운영 및 유지보수 비용으로 추정되고 이중 유지보수 장비와 발전량 손실에 의해 각각 11%와 9 %로 가장 큰 지출을 보여 주었다. 제안된 모델의 해상 풍력단지 운영 및 유지보수의 결과에 대한 분석을 통해 향후 우리나라에 설치 예정인 해상 풍력단지의 유지보수 계획을 수립하는 데 활용될 수 있을 것이다.

1. Introduction

1.1 Background

Wind energy is one of the fastest growing renewable energy sources in last decade. Currently it generates less than 1% of the world's electricity today, however, the stable technological growth of wind power suggests that it could become an indispensable energy source for many nations in the next 10 years [1][2]. There are many high technologies introduced in wind energy industry but still it faces many challenges for the development and operation of wind farm. Main issue of wind farm is the limited land and resident's opposition. To get better condition, wind farm development has been expending to offshore region which allows large wind turbine and wind farm. Constructing a large scaled offshore wind farm with bigger turbines is advantageous, because it is free to constraints concerned with noise, sight, civil complains, etc and it also has a better wind condition. It also brings new views to worry about high cost for production, transportation, grid connection and operation and maintenance. Wind turbine designs which are related to wave, tidal current, salty and bigger size conditions, are not verified as enough commissioning periods have not yet elapsed and track records are very few.

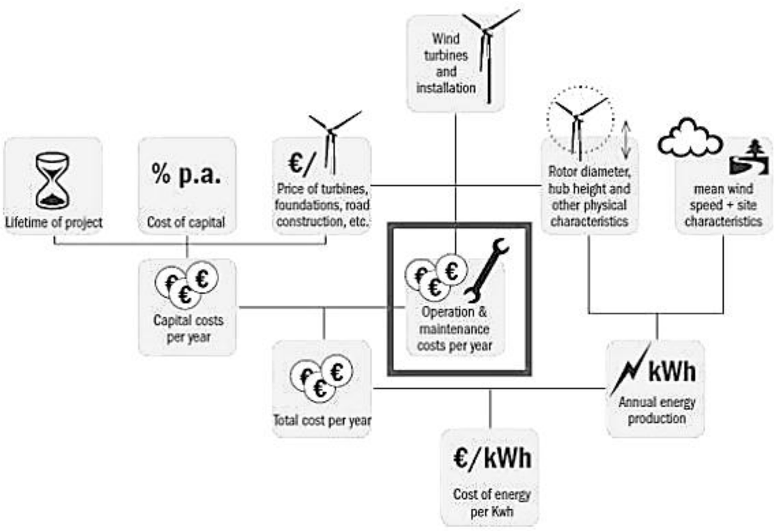

Figure 1 Overview of cost of wind energy and its relation to operation and maintenance [3].

The operation and maintenance costs are also increased for the offshore wind farm and contribute significantly to the energy generation costs. Reliable estimates of these costs are required during planning and operation of the wind farm at several parts.

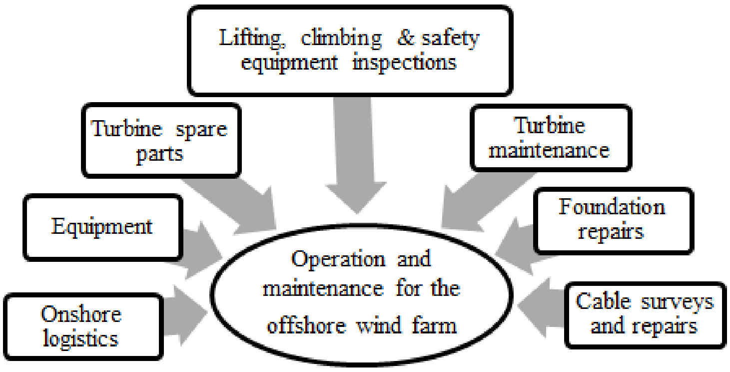

Figure 2 Key factors of operation and maintenance for the offshore operation.

1.2 Objective

The objectives of this thesis are to understand reliability, availability and maintenance strategies of offshore wind farms by reviewing the literature. This necessitates gaining knowledge on operation and maintenance modeling of offshore wind farms and identifying the limitations and technical challenges.

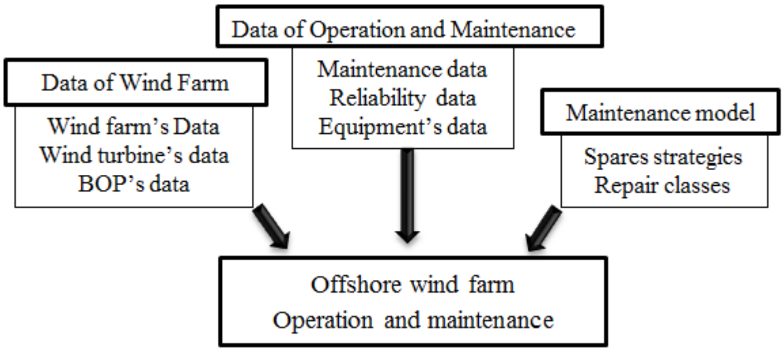

Figure 3 Different parts of the operation and maintenance model for the offshore wind farm.

This thesis also aims to propose possible model of offshore wind farms in Jeju Island considering Rep. of Korean offshore wind situation. In order to achieve the objective, the models have been developed based on integrations in information of wind farm and operation and maintenance data. For wind farm data, regional characteristics like electricity price, real time weather data, wind turbine data and balance of plant data are considered. For the operation and maintenance data, maintenance concepts, reliability of wind turbine and equipment are studied. For the maintenance model, spare parts of wind turbine and repair process are defined.

1.3 Outline of the thesis

This thesis is divided into 5 chapters:

Chapter 1 gives a background introduction and objective carried in this thesis. Chapter 2 provides theoretical background. This chapter deals with a literature review of the reliability, availability and maintenance issues of offshore wind turbines. Chapter 3 presents the classification of operation and maintenance as well as parameters of maintenance. Chapter 4 focuses on a detailed description of offshore wind farm model set up with the real-time metrological data, preventive and corrective maintenance strategies. And analysis of the operation and maintenance results on offshore wind farm model. General conclusion of the thesis and proposal for future work are presented in chapter 5.

1.4 Wind energy

Wind is simply a motion. It is caused by the uneven heating of the Earth's surface by radiant energy from the sun. Since the Earth's surface is made of very different types of land and water, it absorbs the sun's energy at different rates. Sailing boats and windmills are examples of prominent wind driven devices, which have contributed greatly to the development of our modern society. The discovery of the internal combustion engine and the development of electrical grids caused many windmills to disappear in the early part of this century. However, in recent years there has been a revival of interest in wind energy and attempts are underway all over the world to introduce cost-effective wind energy conversion systems for this renewable and environmentally benign energy source.

The actual energy in the wind is kinetic. Air has a density of 1.2 kg/m^3 (sea level and 15 degrees Celsius), and when this mass is set in motion it gets kinetic energy. The energy in wind depends on the cube of the wind speed, meaning that a doubling of the wind speed results in an eight-fold increase in energy.

The power in the wind is proportional to the cube of wind velocity. The general formula for wind power is:

$$\text{Power} = \frac{\text{density of air x swept area x velocity cubed}}{2} \quad (1.1)$$

$$P = \tfrac{1}{2}.\rho.A.v^3 \quad (1.2)$$

If the velocity (v) is in m/s, then at sea level (where the density of air is 1.2 kg/m^3) the power in the wind is:

$$\text{Power} = 0.6 \text{ x } v^3 \text{ Watts per } m^2 \text{ of rotor swept area} \quad (1.3)$$

Today most modern wind turbines have a rated power over 3 MW or more, even though there are a few really large wind turbines reaching up to 10 MW. A wind turbine produces rated power during wind speeds from approximately 12 m/s to 25 m/s. When the wind speed passes 25 m/s the wind turbine is shut down because of safety reasons. This is called the cut-out wind speed. The cut-in wind speed, when a wind turbine starts to produce electricity, is around 3-4 m/s. The power output is then lower than the rated output, but increases with higher wind speeds until the rated power of production is reached shown in figure 3. Wind speeds can fluctuate during short time periods, often to increase or decrease by 3-4 m/s in a few seconds of time.

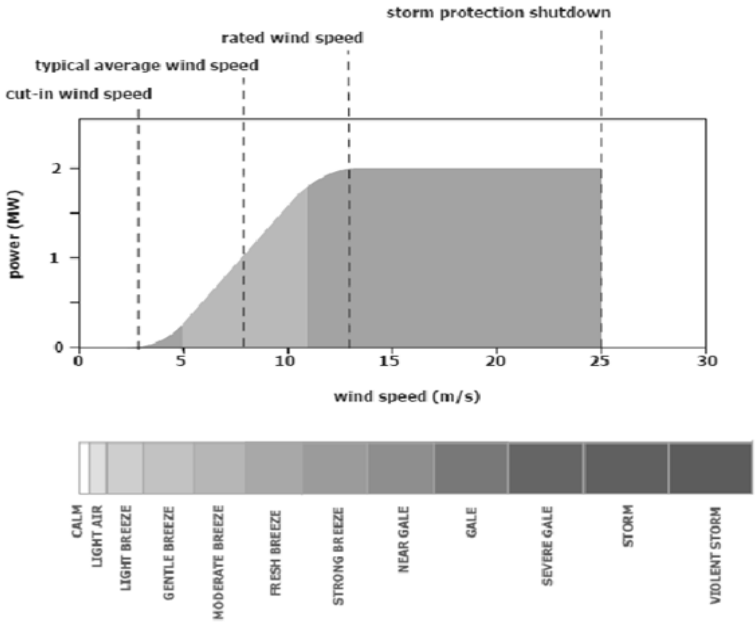

Figure 4 Typical wind turbine power output during different wind speeds [4].

To calculate the predicted power production over a year a power output curve for the specific wind turbine and a wind speed data for the wind turbine location is needed. When multiplying the two curves the result is the expected power production for a wind turbine over a year. This is the most proper way to calculate the predicted power output from a wind turbine. Using this way the wind turbine is assumed to be operational ready at all times. Since this seldom is the case, many wind turbine corporate developers and operators use the term capacity factor. The capacity factor is a measure of how much of the time a wind turbine is producing at its rated power. If the capacity factor is estimated, the yearly production can be done approximately.

$$\text{Capacity factor} = \frac{\text{Wind turbine yearly production (kWh)}}{\text{Wind turbine rated power (kW)*hours in a year}} \qquad (1.4)$$

1.5 Wind turbine

The wind turbine concept, with a vertical axis, is the most common for transforming wind energy into electric energy. A general wind turbine consists of three blades that are set in motion by the passing wind. This rotating motion is either transferred directly to a generator, or via a gearbox which increases the rotational speed into the generator. See the detailed in Appendix 1.

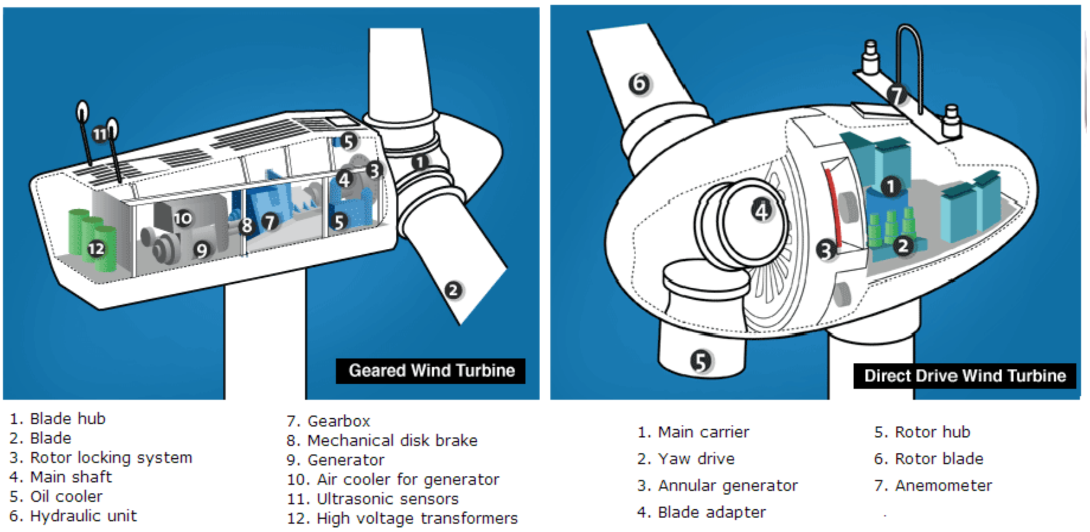

Figure 5 Geared type wind turbine and gearless type wind turbine [5].

Five major developments characterize modern wind turbine. The first development was considered for a while as a trade secret and involves the almost universal adoption of flexible or teetering rather than rigid hub structures, preventing catastrophic failure under gust wind conditions.

The second development involves the use of the economy of scale with larger capacity turbines reaching the 5~10 MW level, particularly for offshore sitting.

The third development is the use of variable speed wind turbines. Variable speed operation is a design feature that ensures that the turbine work at high efficiency compared with fixed speed wind turbines which only reach peak efficiency at a particular wind speed. While constant speed rotors must deflect high wind gust loads, the variable speed operation absorbs the loads from the wind gusts and converts them into electric power.

The fourth development is the adaption of gearless wind turbines eliminating the gear box as the weakest link in the chain in the design of the modern wind turbines: gearboxes last for an average of 5 years failing probably due to misalignment during operation over the 20 years design lifetime or to severe strain and shape changes under sudden wind gusts. In addition, it eliminates the need for oil cooling avoiding one cause of fires and environmental pollution in the case of the lubricant oil spillage.

The fifth trend is to use permanent magnets in the generator instead of electrical magnets. These use rare earths element such as Neodymium and reduce the standby power requirements of wind power converters [6].

1.6 Offshore wind farm

Offshore wind farm development has a short history of less than 30 years with the first offshore wind farm being built off the coast of Denmark in 1991 [7]. There are over 30 operational offshore wind farms in Europe shown in table 1. For the future, greater numbers of larger offshore wind farms having more powerful wind turbines are being planned [8]. In a time period of a couple of years wind power has gone from a minor energy source to a large scale industry. Wind energy has been the strongest growing renewable source of energy in the world this last decade, particularly in Europe where wind energy accounted for 6.3 % of the electricity generated, and 21.4 % of the generating capacity installed in 2011 [9].

Table 1 The operating offshore wind farms in Europe listed by the year of installation [7],[10]

Location	Country	Capacity in MW	No. of turbine	Turbine manufacturer	Year of installation
Vindeby	Denmark	5	11	Bouns	1991
Lely	Holland	2	4	NedWind	1994
Tuno Knob	Denmark	5	10	Vestas	1995
Irene Vorrin	Holland	17	28	Nordtank	1996
Bockstigen	Sweden	3	5	WindWorld	1998
Blyth	UK	4	2	Vestas	2000
Middelgruden	Denmark	40	20	Bouns	2000
Utgruden	Sweden	10.5	7	Enron wind	2000
Yttre strengung	Sweden	10	5	NEG Micon	2001
Horns Rev	Denmark	160	80	Vestas	2002
Arklow Bank	Ireland	25	7	GEWE	2003
North Hoyle	UK	60	30	Vestas	2003
Nysted	Denmark	158.4	72	Bouns	2003
Samso	Denmark	23	10	Bouns	2003
Scoby Sands	UK	60	30	Vestas	2004

Frederikshavan	Denmark	7.6	3	Various	2004
Kentish flats	UK	90	30	Vestas	2005
Ronland	Denmark	17.2	8	Bonus, Vestas	2006
Barrow	UK	90	30	Vestas	2006
Breitling	Germany	2.5	1	Nordex	2006
EMS-Enden	Germany	4.5	1	Enercon	2006
Beatrice	Uk	10	2	Pepower	2007
Egmond and Zee	Holland	108	36	Vestas	2007
Burbo Bank	UK	90	25	Simens	2007
Q7-PA	Holland	120	60	Vestas	2008
Thornton	Belgium	30	6	REpower	2008
Robin Rigg	UK	180	60	Vestas	2008
Lynn Dowsing	UK	194.4	54	Vestas	2009
Horns Rev 2	Denmark	209	91	Simens	2010
Gunfleet Sands	UK	172.8	48	Simens	2010
Rhyl Flats	UK	90	25	Simens	2010
Thanet	UK	300	100	Vestas	2010
Alpha Ventus	UK	60	12	REpower, Areva Wind	2012

In spite of the high capital cost and operation and maintenance costs, the installed capacity of offshore wind power has increased rapidly in Europe from 800 MW installed at the end of 2006 to 3.8 GW at the end of 2011 and many offshore wind farms are expected to be built in the near future, especially in Europe[8]. The reasons for this trend are high wind resources, the availability of space, low visual and noise impact, better understanding of the economic risks and high financial incentives [11]. The target of the European Wind Energy Association is to reach 230 GW of installed wind power in Europe by the end of 2020, of which 40 GW shall be generated by offshore wind farms [12].

The maintenance cost is known to be an important part of the levelized cost of energy generated by wind farms. In the case of offshore, operation and maintenance contributes between 20-30 % of the cost of energy [13]. For example, Horns Rev offshore wind farm with capacity of 160 MW located 20 km off the coast of Esbjerg in Denmark, the maintenance was estimated to contribute to about 40 % of the life cycle cost because of early serial failures, as well as low investment costs compared to the current market.

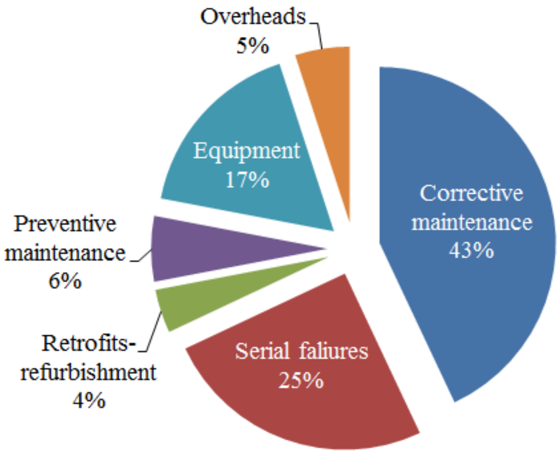

Figure 6 Estimation of operation and maintenance life cycle cost at Horns Rev wind farm using ECN O&M tool [13].

The main drivers of the maintenance costs were the major component replacements, major retrofits and the logistic as shown in Figure 6. Although the major retrofit can only be tackled by reliability improvements, the maintenance strategy of the major components has a major influence on the costs of replacement and refurbishment [13].

An important factor of offshore wind farms is the logistic that needs to be planned according to the distance from shore and weather conditions at site. The transportation of the technicians to the wind turbines is usually performed by small access vessel, which is imitated by the wave height and lead to poor accessibility resulting in long downtimes. The operating and maintenance support organization for offshore wind farms will become even more important for the new and undergoing projects being installed far from shore, in deeper water depth and harsher marine environment. The current offshore wind turbines were not designed to cope with the harsh conditions of the marine environment, as onshore wind turbines have been used [14]. The reliability of onshore wind turbines has been reported in several documents [15]-[18], but it is very hard to fine operating wind turbine data of offshore wind turbines. The availability of onshore wind turbines is typically in the range of 95-99% while for early offshore projects an availability as low as 60% has been observed at some wind farms due to serial failures and harsh weather conditions shown in Figure 7 [19], [20].

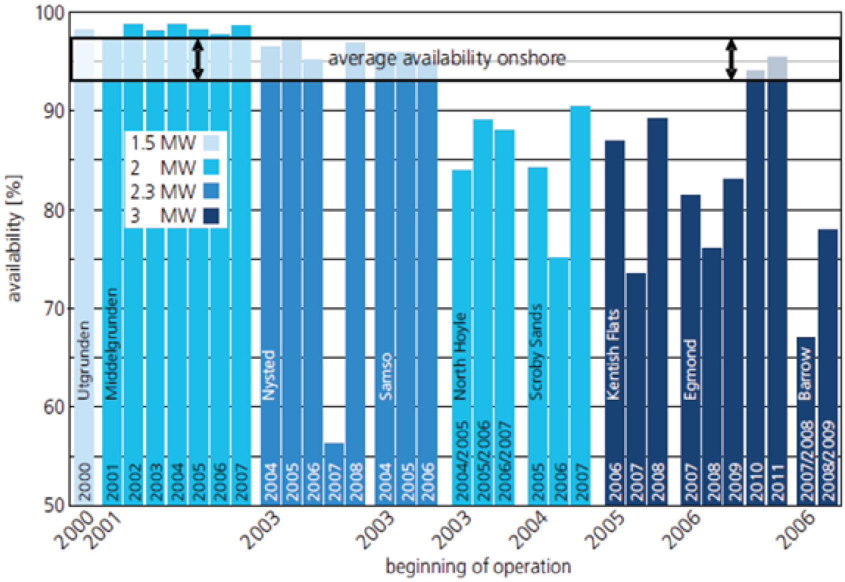

Figure 7 The per year availability of some offshore wind farms [19].

To improve availability and reduce costs of operating and maintenance of offshore wind farm, well-coordinated maintenance plans are needed. In this respect, the planning of the scheduled maintenance and corrective maintenance activities should be considered to increase the reliability and availability of wind farm theoretically and practically.

2. Theoretical background

2.1 Reliability of wind turbine

Offshore wind farm projects have been developed rapidly in the last decade. Wind turbine generators have reached a size of 5 MW on the market and wind turbines are planned at a size of up to 300 MW [21]. When wind farm is designed, the type of wind turbine resulting in the highest capacity factor was selected for the specified site. The drawback of the proposed method is the use of average output power as the desirable characteristics of a wind turbine type.

There are some problems occurred to use of capacity factor as the standard to choose of wind turbine type. If most of the extracted power corresponds to the times when there is no need of this power during early hours of the day and late hours of the night, there is an issue. Therefore, capacity factor is not the right criterion for evaluating the efficiency of different wind turbine types in a wind farm. Reliability indices have also been used in the assessment of different turbine types to be installed in a Wind farm [22]. In the condition of offshore wind farm operating and maintenance are closely related to reliability of wind turbine.

This part presents a reliability-based approach to select appropriate wind turbine types for a Jeju offshore wind farm. An analytic approach, based on previous research of various kinds of operation offshore wind farm, is utilized to analyze probabilistic model of a wind turbine system including a wind farm. The wind turbine model, however, may be extended to account for several wind turbines assigned farms in the system.

The proposed method in this paper forms the probability distribution of wind turbine components from different wind turbine data of different wind farm. The probability distribution of the each component result may be obtained using wind turbine characteristics and actual operating data. Considering probabilistic failure events of wind turbine, the probability distribution of the whole wind turbine may be evaluated. Afterward, the probabilistic model of wind turbine is convolved with the failure rate and downtime of the each system to obtain the probabilistic model of total system within one turbine.

2.1.1 Reliability theory

Reliability is defined as the probability that a product will perform its intended function under stated conditions for a specified period of time [23]. For a wind turbine, reliability is a probabilistic theory involving a turbine's planned use, its operating environment and time. Reliability assessments interface with all aspects of design, operation and maintenance requirements, limitations, and life cycle costs. Figure 8 shows the rate of failures of a batch of parts, their initial part has high level of failures due to manufacturing or material defect. After a while the number of failures will drop and hold steady at a low level until the parts reach the end of life. Then the failure rate will begin to climb again due to end of life failures. Usually many products are tested under stress conditions to weed out the bad parts.

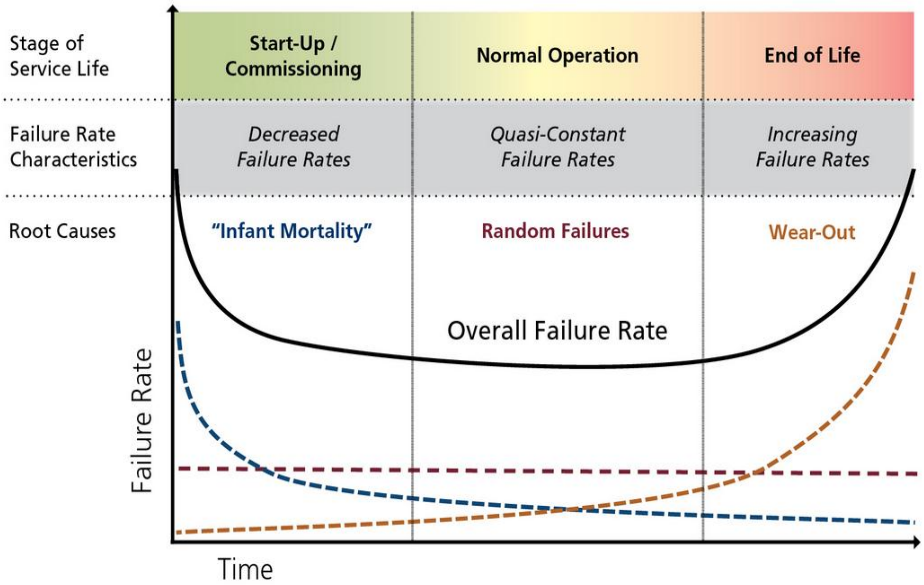

Figure 8 Bathtub curve showing product life cycle [24].

2.1.2 Reliability parameters

Reliability metrics are used in combination with each other. Occasionally, these parameters are stated together for the performance of a "RAMS Analysis", where Reliability, Availability, Maintainability, and Safety are all addressed together. Availability is most mainly related to energy production and revenues and is a key measure of system performance. The percentage of time that a wind power plant is not down for maintenance and is able to operate satisfactorily is called its availability. Because the wind does not always blow, the percentage of time that the machine is actually producing electricity will be lower than the availability. Maintainability is a design objective which provides for easy, accurate, safe, and economical performance of maintenance functions. Safety is the probability that the product will operate satisfactorily and without any occurrence of accidents, when under stated conditions.

A principle measure of the system performance is the mean time between failures (MTBF). It is the average time between failures of a component.

MTBF=Operational Time/ Number of failures (2.1)

Mean Time to Repair (MTTR) or Downtime defined as the average time taken to repair or replace a failed module.

MTTR=Total repair time/ Number of failures (2.2)

Mean Time to Failure (MTTF) is very similar to MTBF and is used when evaluating nonrepairable systems. MTBF assumes that a device is to experience multiple failures in a lifetime, and after each failure a repair occurs. For non-repairable systems, there is no repair. Therefore, in the lifetime of a non-repairable device, the device fails once and MTTF represents the average time until this failure occurrence. For the majority of systems, and particularly for electrical and digital systems, the failure distribution is exponential during its useful life. Such a rate implies that the occurrence of failures is random. Using some simple transformations, a distribution such as Weibull can be expressed as an exponential distribution. Furthermore, according to the method of stages, any distribution can be expressed as a combination of exponential distributions. Although this analysis is not realistic for all lifetime, it is a good approximation during the useful life time (the horizontal portion of the bathtub curve) of the component.

2.1.2 Reliability data

This thesis uses a quantity approach-based on statistical data from operating wind farm, as well as quality approach-based on article, internet resources. Several studies have been carried out with the purpose of generating generic information on the failure rates of wind turbines. A summary of the various sources is listed in the following table 2. See the detailed in Appendix 2.

Table 2 Summary of the various sources

Name of resources	Reliawind	wind stats Germany	wind stats Denmark	LWK	WMEP	Swedpower AB	VIT
Region	Europe	Germany	Denmark	schleswig-Holstein. Germany	germany	Sweden	Finland
Peroid	Jan 2004~ Sep 2008	1996~2008	Q4 1994~ 2003	1993~ 2006	1989~ 2006	1997~2004	1999 ~ 2009
Reporting interval	Event	Quarter	Month	Year	Turbine age(yrs)	Year	Year
Data source	Gamesa, Ecotecnia			Chamber of Agriculture		Elforsk	
Number of turbine	283	1803~4924	851~ 2345	158~643	1500	342~1050	63~118
Power[MW]	366	597~6349	328~593	11.5~ 45	~250(avg)	108~452	35~120
Average rating[kW]	1293	331~1289	385~253	73~70	167	316~430	556~1017
Turbine specification	Pitch = 850kW	>50kW	>50kW	>50kW	All	>50kW	>50kW
Reporting by ;	Event	Cause of stop	Type of stop	Make & model	Make & model, turbine age	Type / cause of stop	Cause of stop
Number of items in taxonomy	253(9 sub system)	14	18	16	56(12 groups)	13~55	16~30
Number of failures	Yes	Yes	Yes	Yes	Yes	No	Yes
Hours Lost	Yes	Yes	No	Yes	No	Yes	Yes

The data from various wind farms and turbines includes failure rates per wind turbine type, the relation between turbine size and its failure rate. The results are shown in figure 9. From these figures it can be seen that a clear relationship exists between turbine rating and the annual failure frequency, where figure increases with the size of the turbine.

Wind Turbine Types	Size of turbine [kW]	Failure Rate [failures turbine subassembly $^{-1}$ year^{-1}]
Vestas V27 [LWKSH]	255	1.05
Micon M530 [LWKSH]	250	1.1
Micon M1500[LWKSH]	1500	1.7
Micon M1500[WMEP]	1500	3.84
Nordtank 300 [LWKSH]	300	1.7
Enercon E40 [LWKSH]	500	2.39
Enercon E40 [WMEP, costal]	500	4.67
Enercon E40 [WMEP, all]	500	5.18
Vestas V39 [LWKSH]	500	1.82
Vestas V39 [WMEP, costal]	500	3.39
Vestas V39 [WMEP, all]	500	3.62
Tacke TW 600 [LWKSH]	600	2.15
Tacke TW 600[WMEP, costal]	600	3.15
Tacke TW 600[WMEP, all]	600	3.63
Vestas V44 [LWKSH]	600	1.21
Vestas V47 [LWKSH]	660	2.73
Nordex N52, N54 [LWKSH]	900	2.7
An-Bouns 1MW/54 [LWKSH]	1000	3.1
Tacke TW 1.5s [LWKSH]	1500	3.6
Enercon E66 [LWKSH]	1700	2.4

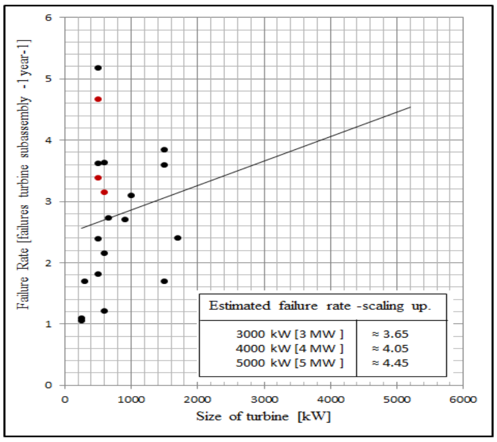

Figure 9 Relationship of turbine rating and the annual failure frequency.

The failure frequencies per wind turbine component are derived from the analysis of the data from various wind farms where the contribution of components to the overall failure rate is given in percentages.

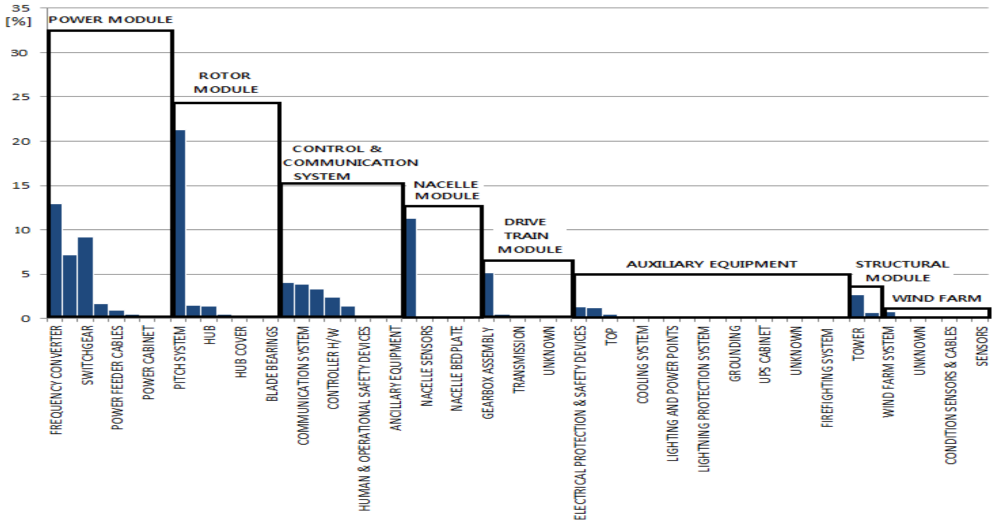

Figure 10 Contribution to total failure rate percentage [failures/turbine/year].

Figure 10 includes data of around 400 onshore wind turbines and is the most recent publicly available information on failure rates of large variable-speed, pitch-regulated wind turbines.

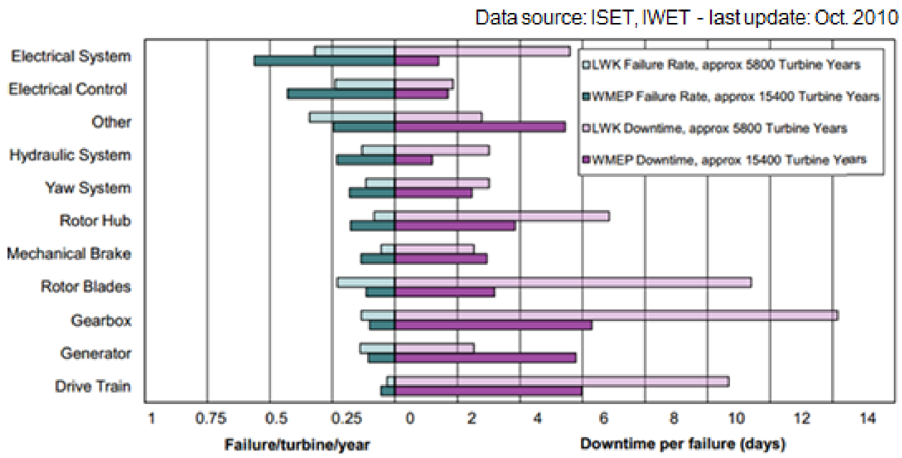

Figure 11 Yearly failure and downtime of European wind turbines (1993~2006).

Figure 11 illustrates that the results from the different databases showing similarities, but also showing some important differences. Most databases indicate that most failures occur in the power module (e.g. generator, inverter and transformer). These failures also account for the largest share of the total downtime (according to most databases). Second largest contributor to downtime is the drive train module (e.g. gearbox, shafts, brake), which according to most sources accounts for only a relatively small portion of the total amount of failures.

The relatively frequent occurrence of electric, gearbox(drive tr.), yaw and blade system failures are particularly critical since field service is expensive and time consuming, especially for offshore turbines where access is difficult and weather conditions may result in long delays. Indeed, the downtime of four components are reported to be responsible for up 80 % of all lost turbine downtime, with the majority of failures due to bearing wear and each failure resulting in an high downtime of several days even months.

2.2 Reference Designation System for Power Plants (RDS-PP)

The wind turbine breakdown is based on the guideline published by VGB for the application of RDS-PP (Reference Designation System for Power Plants) to wind power plants. RDS-PP taxonomy is based on basic and sector-specific IEC and ISO standards. The classification is made using the guideline for application of RDS-PP, which is published by VGB PowerTech [25].

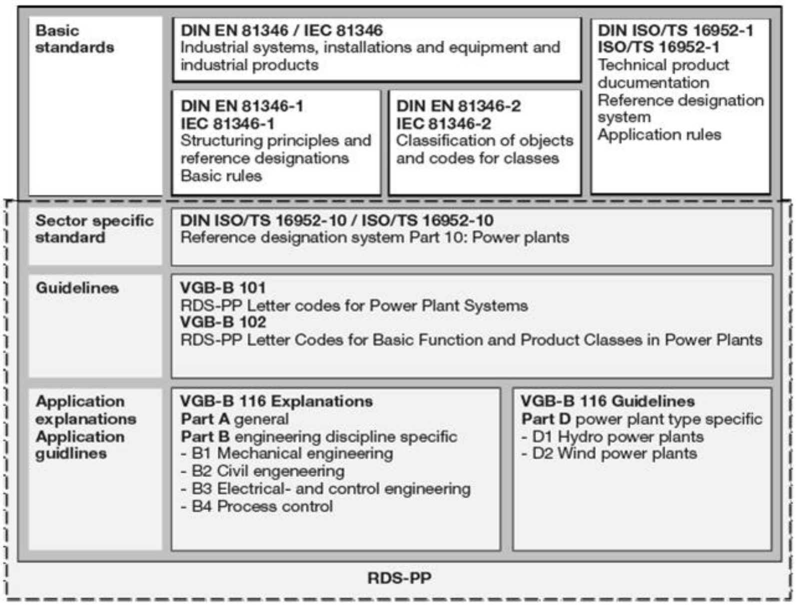

Figure 12 Relation between basic standard and applications [25].

These applications intend to clarify the normative definitions by the inclusion of additional practical designation examples. The application specifications are divided into a general part for all fields of engineering, the parts with discipline specific scope and the parts for power plant type specific scope. Mostly main components are defined on a system level of wind turbine.

Table 3 Subsystems with grouped RDS-PP codes for wind turbine

INTERNAL GRID	A - Grid and equipotential bonding systems
	AAG10 - Medium-voltage switching system
EQUIPOTENTIAL BONDING SYSTEM	ABG - Lightning protection system
ELECTRICAL AUXILIARY POWER SUPPLY	BR - Uninterrupted power supply system UPS
WIND TURBINE SYSTEM	MD - Wind turbine system
ROTOR SYSTEM	MDA - Rotor system
HUB, ROTOR BLOCKING…	MDA30 - Rotor blocking
PITCH SYSTEM	MDC - Pitch system
	MDC10 - Pitch blade A-C total
	MDC10KF001 - Pitch control
DRIVE TRAIN,ROTOR SHAFT	MDK - Drive train
	MDK10 - Rotor shaft
GEAR	MDK20 - Gear
	MDK20TL001 - Main gear
BRAKE SYSTEM, CLUTCH/COUPLING	MDK31 - Hydraulic Brake system
	MDK40XN001 - Clutch between main gear and generator
AUXILIARY SYSTEM DRIVE TRAIN, MAIN GEAR OIL SYSTEM	MDK51 - Main gear oil system
	MDK51GP001 - Main gear oil pump(s)
YAW SYSTEM	MDL - Yaw system
	MDL10 - Yaw drive system
CONTROL AND PROTECTION EQUIPMENT	MDY - Control and protection equipment
	MDY10 - Electrical control system
	MDY10BG001 - Meteorology, wind direction
	MDY10BS001 - Meteorology, wind velocity
	MDY10BS002 - Vibration guard
	MDY10BU001 - Meteorology, wind measurement combined
	MDY10KF001 - Control unit top
	MDY10KF002 - Control unit bottom
HYDRAULIC SYSTEM	MDX - Hydraulic system
	MDX10 - Hydraulic system in nacelle
	MDX10GP001 - Hydraulic pump

	MDX10XL001 - Hydraulic rotating coupling
GENERATOR SYSTEM	MK - Generator system including cooling
	MKA - Generator system
	MKA10 - Generator
	MKA10WD001 - Generator slip ring arrangemenT
	MKF - Primary cooling system, water
CONTROL AND PROTECTION SYSTEM (POWER ELECTRONICS FOR GENERATOR)	MKY - Control and protection system(generator)
	MKY10 - Control including conversion
	MKY10TA001 - Converter
TRANSMISION OF ELECTRICAL ENERGY, TRANSFORMER	MSC - Generator circuit-breaker, and cooling
	MST - Generator transformer, and cooling
MACHINERY ENLOSURE, NACELLE, MAINFRAME	MUD - Nacelle enclosure
WIND TURBINE STRUCTURES, TOWER, FOUNDATION	UMD10 - Foundation
	UMD20 - Tower
ANCILLARY SYSTEMS, CRANES, VENTILATION, ELEVATOR, SAFETY SYSTEM	X - Ancillary systems
	XA - Ventilation and AC system
	XMA - Cranes
	XMA30 - Crane nacelle
	XN - Elevator system
	XS - Safety system
	XSD - Warning lights
	XSD10 - Naval lights
	XSD30 - Aviation lights
	XSF10 - Fog signal

2.3 Equipment

Four life cycle phases of an offshore wind farm can be identified, where physical presence of personnel and equipment at sea is required: Pre-Installation, Installation, Operation and Decommission.

Table 4 Life cycle phases of an offshore wind farm

Phase	Pre-Installation	Installation		Operation	Decommission
Tasks	Geotechnical & environmental surveys	Foundations	Turbines	O&M visits	Turbines
		Grid	Substation		Substation
Utilized vessels	Service vessels	Service and installation vessels		Service vessels	Service and installation vessels

The different tasks to be carried out during these phases require ports with certain properties and facilities as well as the utilization of a variety of vessels with certain abilities and features. During the operating phase of a wind farm there are two roles that have to be fulfilled which are utilized by the vessels for operation and maintenance. Small access vessels transfer technicians, tools and spare parts to wind farms in cases of minor repairs and technical problems which can be solved without heavy equipment.

In the early days fishing boats were deployed before the catamarans became more common place. The majority of the vessels used today have been designed according to general workboat or fishing vessel needs. To use fishing boat for offshore wind farm presents many challenges. The disembarkation is one of the biggest problems, causing dangerous situations for service technicians in rough weather. One of the problems of transferring from a vessel to a turbine foundation is that the structure is fixed to the seabed, resulting in considerable relative movement between the vessel and the foundation. The majority of transfers take place using what is known as the ‘bump and jump’ method which means that there should be little bumping and no jumping, whereby the vessel is pushed on bow first to the ‘j-tubes’ which run vertically on the outside of the access ladder.

Figure 13 Example of fishing boat in Jeju [26].

The risk for material damage is also evident, as boat landings suffer damages caused by both heavy displacement vessels with lower maneuverability and by faster, lighter vessels which are trying to stay put through continuous, intensive thrusting.

The turbine access ladder is set back from the j-tubes by 450 mm which provides a safety zone to prevent anyone on the ladder from being crushed should the vessel move during the transfer procedure. Large waves, especially if there is a strong current across the side of the vessel can, on occasion, cause the vessel to lose position. Small access vessel is also used to take small amounts of cargo out to sites, such as components and equipment for the operating and maintenance of the turbines. This means that accessible deck space is required with a load capacity ranging of 1 ton and over. In addition, vessels can have a dummy crane for lifting cargo from the harbor onto the deck but most lifting is done by the davit and internal nacelle crane on the turbine itself. Some vessels also provide refueling services where they carry fuel for the turbine generators offshore.

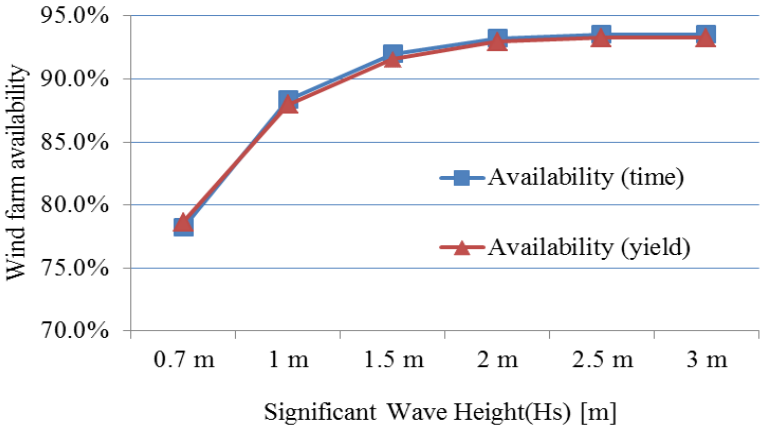

Figure 14 significant wave height limitation of wind farm availability.

Current Small access vessels are stable catamaran vessels of the order of 12-24 m length with a passenger capacity of approximately 12. They can typically work up to 2 m significant wave height. The cruising speed of the current fleet is in the range of 20 to 25 knots.

Figure15 Example of small access vessel [27].

The superior speed and stability of Small Waterplane-Area Twin Hull (SWATH) vessels and other novel designs may increase the range of Small access vessels only operation and maintenance strategies where regulatory or other factors limit the use of helicopter support.

Table 5 Aluminum Monohull working on near-shore wind farms in the North Sea

Name	MS Orkama	Bayard 1	MS Elisabeth M	Waterfall
Owner	KEM Offshore	Fred Olsen Windcarrier	KEM Offshore	Gardline Shipping
Operator	KEM Offshore	Fred Olsen Windcarrier	KEM Offshore	Gardline Environmental
Vessel Category	Wind Farm Service	Wind Farm Service	Wind Farm Service	Wind Farm Service
Vessel Description	Aluminum Monohull	Aluminum Catamaran	Aluminum Monohull	Aluminum Catamaran
Vessel Classification	Danish Maritime Authority	DNV ✠ 1A1 HSLC R2 Windfarm Service 1	Danish Maritime Authority	MCA Cat 2
Flag	Denmark	Denmark	Denmark	United Kingdom
Construction Country	Denmark	Norway	Denmark	GB
Construction Location	Granly Shipyard	Batservice Mandal AS	Granly Shipyard	Lyme Boats
Year Built	2008	2011	2006	2009
Date of Delivery	2008	2011	2007	2009
Length Overall (LOA)	21.83 m	20.9 m	20.83 m	16 m
Breadth	4.9 m	7 m	4.9 m	6.4 m
Minimum Draft	1.1 m			
Maximum Draft		2.1 m	1.1 m	1.6 m
Accommodation	12 passengers			14 persons
Transit Speed				24 knots
Maximum Speed	27 knots		27 knots	26 knots
Free Deck Space	15 m^2	51 m^2		
Max. Deck Load		2 t/m^2		
Max. Cargo Weigh		8 tons	5 tons	
IMO Number		9645803		
Call Sign	XPD8254	OZIX2	OXRF2	2CBT4
MMSI	219010982	219016577	219009397	235071392

Table 5 describes the recent reported information concerning small access vessels of near-shore wind farms in the North Sea. The detailed specification of different type vessels for purpose on operating and maintenance of near-shore wind farm is presented as well.

Offshore wind turbines are equipped with internal nacelle crane which can lift within 2~3 tons. For the replacement of large component(s) or system Jack-up vessel or Jack-up barge is needed. Jack-up vessel in service of the offshore wind industry is partly converted to match the required specifications, partly hired for only a short period of time. Jack-up vessel is combine the self-lifting and stabilization features of jack-up platforms with a self-propulsion system, making them independent from availability and limitations of towing vessels. This type vessel can lift itself above water level by lowering down a number of legs into the seabed providing good stability for crane operations under rough weather conditions. These vessels are slow and dependent on support ships' capabilities to tow it to its working area and position them for installation.

Figure 16 Jack-up vessel Sea Installer [28].

The detailed specification of Jack-up vessels for purpose on maintenance of near-shore wind farm in the North Sea is presented in table 6.

Table 6 Jack-up vessel & Jack-up barge working on near-shore wind farms

Name	MPI Resolution	MV Wind	SEA POWER	Seajacks Zaratan	SEA ENERGY (Ocean Ady)	Odin
Owner	MPI / Vroon	Danish Salvage & Towing Company DBB	A2SEA	Seajacks (Marubeni Corporation/INJC)	A2SEA	Hochtief Construction AG
Vessel Description	Jack-up vessel	Jack-up vessel	Jack-up vessel	Jack-up vessel	Jack-up vessel	Jack-up barge
Has Heli Deck?	No	No	No	Yes	No	No
Maximum Working Depth	35 m	25 m	24 m	55 m	24 m	45 m
Flag	Cyprus	Denmark	Denmark	Panama	Denmark	Germany
Length Overall	130 m	55 m	91.76 m	81 m	91.76 m	46.1 m
Breadth	38 m	18 m	21.6 m	41 m	21.6 m	30 m
Minimum Draft	3 m	2.4 m	4.25 m	5.3 m	4.25 m	3.25 m
Maximum Draft	4.3 m	2.4 m	4.25 m		4.25 m	5.5 m
Accommodation	70 persons		32 persons	90 persons		
Transit Speed	11 knots		7.8 knots			
Maximum Speed				9.1 knots	8.5 knots	
Free Deck Space	3200 m^2		1020 m^2	2000 m^2	1020 m^2	
Max. Deck Load	10 t/ m^2		2 t/ m^2	10 t/ m^2	2 t/ m^2	30 t/ m^2
Max. Cargo Weigh			2386 tons		2386 tons	1200 tons
Max Jacking Speed	0.5 m/min		0.7 m/min	0.4 m/min		
Num Legs	6	4	4	4	4	4
Leg Length	71.8 m	55.8 m	32 m	85 m	32 m	60 m
MMSI	246777000	220520000	219079000	373322000	219033000	211106900
First Crane Capacity	300 tons	1200 tons	210 tons	800 tons	450 tons	300 tons
First Crane Radius	25 m			24 m	20 m	15 m
First Crane Description		1200t @ 2.5m	Lift height to 100m. 22m radius with full load.	800t @24m main hoist. 600t@30m main hoist. 50t @ 22-90m / 20t @ 94m Aux hoist	Up to 83m above sea level. 110t at 20m outreach.	
Second Crane Capacity	50 tons		27 tons	13 tons	27 tons	
Second Crane Radius	35 m		19.5 m	30 m	19.5 m	
Second Crane Description	Kenz EHC 50/3500 O.S		Cargo Crane	Pedestal mounted at port and starboard sides	Cargo Crane	Optional Crawler Crane (Liebherr LR 1280)
Max. Lifting Capacity	600 tons		210 tons	800 tons	450 tons	900 tons

2.4 Spare parts

During the warranty period, it is normal for all spare parts to be sourced by the turbine supplier. However, once out-of-warranty, many wind farms have to find alternative suppliers for some of the more generic components and consumables, especially since turbine suppliers purchase in the majority of their components from sub-suppliers. The cost of lost revenue due to downtime means that a well-kept project should not suffer significant delays due to parts shortages. Large replacement components can often be taken off the turbine production line that the greatest source of delays when a replacement is needed is the lead time required getting a jack-up on site. All rapid turnover parts and consumables can be expected to be stored in a large warehouse requirement at onshore base.

2.4.1 Wind turbine components

A wind turbine consists of thousands of different items, which many are relatively cheap, such as screws, bolts and etc. Normally a wind power system would include foundation, electric cables and other equipment related to the operation of a number of wind turbines and expensive spare price. Many items in technical systems though, are sometimes repaired and sometimes discarded, depending on failure modes and other circumstances.

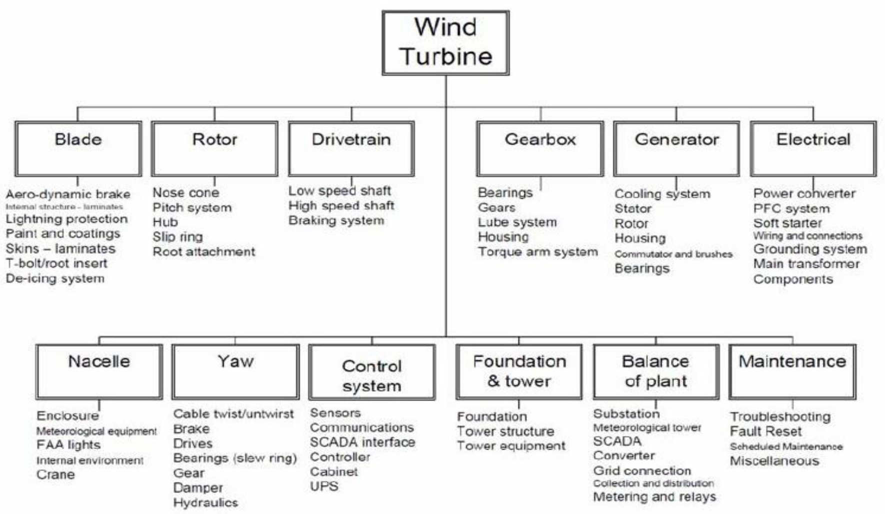

Figure 17 Wind turbine systems and subassemblies.

There are many wind turbine manufactures which have different wind turbine features. A typical wind turbine contains up to 8,000 different components. Figure 18 shows the main parts and their contribution in percentage terms to the overall turbine cost.

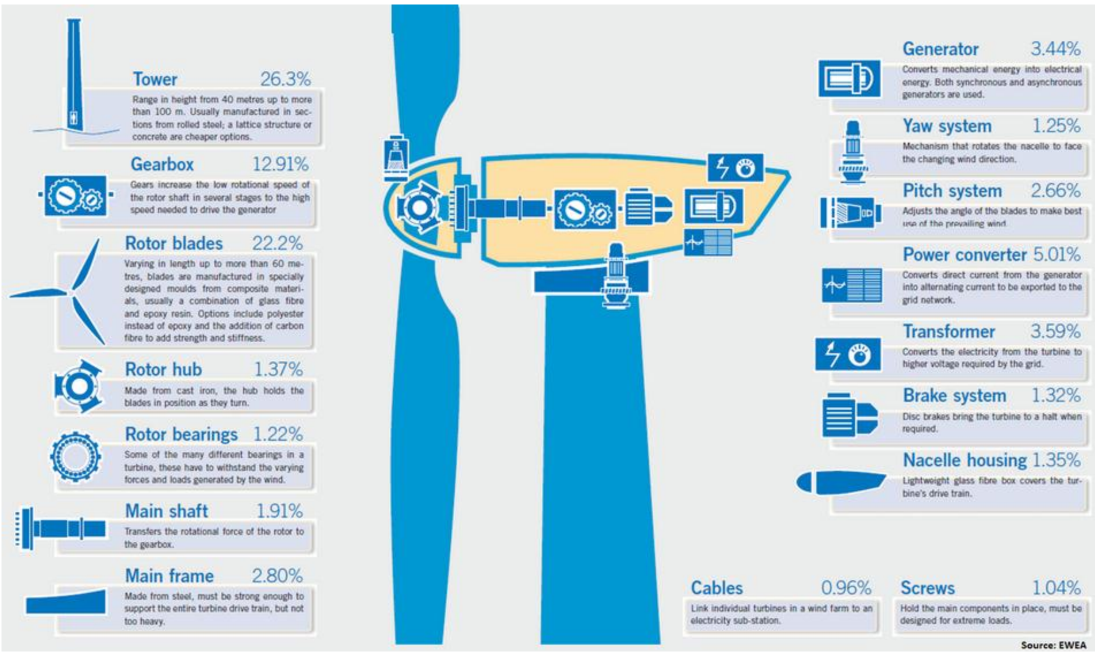

Figure 18 Wind turbine component cost contributions [29].

The detailed information of figure18 is based on a REpower MM92 turbine with 45.3 meter length blades and a 100 meter tower.

2.4.2. Spares of commercial modern wind turbines

First reviewed commercial modern wind turbine is Vastas 2.0MW wind turbine. Vestas have two different 2.0 MW wind turbines. The V80-2.0 has a rotor diameter on 80 m and the V90-2.0 has a rotor diameter on 90 m. The different blade lengths require a different setting of the gearbox between the models. This is the only major difference between the two types. The Vestas 2.0 MW series is inconsistent, with small changes and corrections made every year of production. Therefore two Vestas 2.0 MW models produced a couple years apart can have a complete different set of items used. Hereinafter Vestas V80-2.0 and V90-2.0 will be referred to as V80 and V90, or V80/90 in general. V80/90 have a hydraulic pitch system controlling the power output from the three bladed rotor, blades are pitched individually. The blades are manufactured by Vestas. The mechanical break is a hydraulic disc brake located at the high speed shaft exiting the gearbox. The generator at the end of the drive train is a 4-pole asynchronous generator operating with variable speed. V80/90 has a 3-stage planetary/helical gearbox, but the gear step up is a bit different between the V80 and the V90. Production is controlled by VCS (Vestas Converter System). A unique Vestas solution is that the transformer located in the nacelle of the V80/90, compared to other models where it is placed in the tower. From the nacelle the transformer can be hoist down if it has to be exchanged [30].

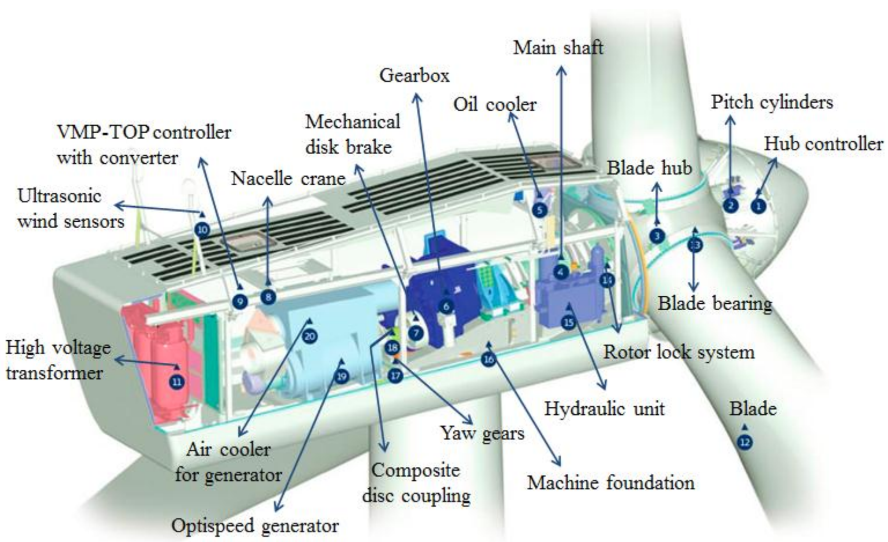

Figure19 Vestas V90 [30].

Table 7 Vestas V80/90 spares part data

Spare Part	Price	Failure Rate	Type	MTTR
Description	EUR	per 10^{6} hours of operation	Repairable(LRU) /discardable(DU)	Hours
Blade	75000	0.55	DU	72
Proportional Valve	1800	5.48	DU	5
Hydraulic Cylinder	1800	1.73	LRU	5
Piston Accumulator	1800	5.48	DU	5
Rotating Union	3200	5.48	LRU	5
Encoder	600	1.73	DU	5
Gearbox	400000	5.48	LRU	144
Bearing Generator	1800	0.55	DU	72

Generator Fan 1	600	0.55	DU	5
Generator Fan 2	600	1.73	DU	5
Generator	120000	5.48	LRU	10
Encoder Rotor	200	17.32	DU	5
Slip Ring Fan	1800	5.48	DU	5
Fan	600	0.55	DU	5
Motor for Cooling System	600	5.48	DU	5
Yaw Gear (right)	1800	1.73	DU	10
Yaw Gear (left)	1800	1.73	DU	10
Yaw Motor	1800	0.55	DU	5
Mechanic Gear for Oil Pump	1800	1.73	DU	5
Electric Gear for Oil Pump	1800	17.32	LRU	5
Chopper Module	1800	1.73	DU	5
TRU card	600	1.73	DU	5
VCP card	1800	5.48	LRU	5
SKIIP 1	1800	17.32	DU	5
SKIIP 2	1800	1.73	DU	5
EMC Filter	1800	5.48	DU	5
Capacitors	200	71.32	DU	5
CT 3220 FFFF	600	1.73	DU	5
CT 316 VCMS	1800	0.55	DU	5
CT 3601	1800	0.55	DU	5
CT 3133	600	17.32	DU	5
CT 3220 FFFC	1800	1.73	DU	5
CT 3218	200	1.73	DU	5
CT 3614	600	1.73	DU	5
CT 3363	600	1.73	DU	5
CT 3153	600	5.48	DU	5
CT 279 VOG	200	5.48	DU	5
Ultra Sonic Anemometer	1800	17.32	LRU	5
Transformer	42000	1.73	DU	144
Phase Compensator Generator	600	17.32	DU	5
Q8 Main Switch	3600	17.32	DU	5
Q8 Electric Gear	1800	5.48	DU	5
Q8 EMC filter	200	17.32	DU	5

Note: Q8 is means part of the emergancy system

The other reviewed commercial modern wind turbine is Siemens 2.3MW wind turbine. As the acronym implies SWT-2.3-93 has a rated power of 2.3 MW and a rotor diameter of 93 m. There are similar models called SWT-2.3-82/101/107 where the major differences are the rotor diameter of 82 m, 101 m and 107 m. Hereinafter Siemens SWT-2.3-93 will be referred to as SWT- 2.3. The SWT-2.3 has a hydraulic pitch system controlling the power output from the three bladed rotors, with the blades pitched individually. The blades are produced by Siemens and are made of fibreglass-reinforced epoxy. SWT-2.3 is equipped with a three-stage planetary-helical gearbox produced by Winergy AG. The mechanical break is a hydraulic disc brake located at the high speed shaft exiting the gearbox. At the end of the drive train there is a generator. Production is controlled by a microprocessor-based industrial controller equipped switchgear and protection devices. Siemens have their own converter system, NetConverter® [31].

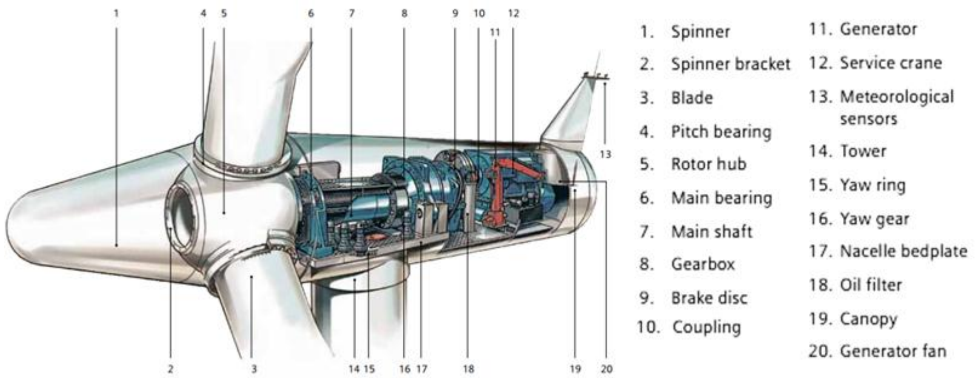

Figure 20 Siemens SWT-2.3 [31].

Table 8 Siemens SWT-2.3 Spare Part Data

Spare Part	Price	Failure Rate	Type	MTTR
Description	EUR	per 10^6 hours of operation	Repairable(LRU) /discardable(DU)	Hours
Blade	75000	0.55	DU	72
Proportional Valve	600	0.55	DU	5
Blade Block for Hydraulic Pitch	4000	5.48	LRU	10
Solenoid Valve	600	5.48	DU	5
Hydraulic Cylinder	1800	0.55	LRU	5
Rotating Union	600	5.48	LRU	5
Brake Disc	600	5.48	DU	10

Gearbox	400000	5.48	LRU	144
Bearing Generator	1500	0.55	DU	72
Yaw Motor	200	1.73	DU	10
Yaw Gear	600	5.48	DU	10
Piston Accumulator 6L	600	1.73	DU	5
Motor for Oil Pump	600	5.48	DU	5
Oil Pump	1800	1.73	LRU	5
Piston Accumulator 0,15L	200	5.48	DU	5
SMPS 1	600	17.32	DU	5
SMPS 2	600	5.48	DU	5
Delta Module (SKII Pack)	15000	5.48	LRU	10
Power Supply 240 V/24 V	200	5.48	DU	5
Wind Sensor	1800	17.32	LRU	5
Encoder	200	5.48	DU	5
I/O-Modul	600	0.55	DU	10
Motor 4kW	600	17.32	DU	5
Motor 1.8kW	600	5.48	DU	5
Generator	120000	5.48	LRU	10
Transformer	42050	1.73	DU	144

3. operation and maintenance of offshore wind farms

3.1 Classification on operation and maintenance

The objective of operation and maintenance are to make the best balance between spending cost and electricity output. Operation and maintenance occur throughout the life of the wind farm, which is commonly 20 years. In offshore wind industry, operation and maintenance are nearly similar to inspection, repairs and maintenance activity in the offshore gas and oil industry. As the name suggested, operation and maintenance comprises two distinct activities.

Operations refers to activities contributing to the high level management of the asset such as remote monitoring, electricity sales, environmental monitoring, marketing, administration and other office tasks. Operations present a small proportion of operation and maintenance expenses, the majority of which is accounted for directly by the wind farm or the supplier of the wind turbines. Maintenance accounts for the largest portion of operation and maintenance effort, cost and risk. Maintenance activity is the keeping and repair of the physical plant and systems.

Maintenance for the wind farm can be divided into operating period, wind turbine system condition and defects. In addition, depending on the purpose of maintenance there are mainly two types of maintenance that is preventive maintenance and corrective maintenance. Figure 21 shows the different types of maintenance.

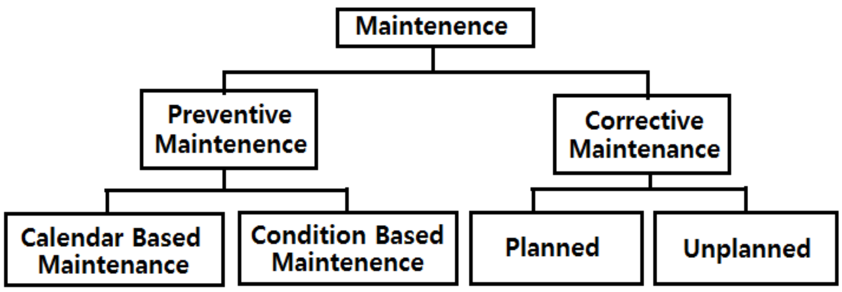

Figure 21 The different types of maintenance.

In case of preventive maintenance, actions performed on a time- or machine-run-based schedule that detect, preclude, or mitigate degradation of a component or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level.

In accordance with the operating period, calendar based maintenance is carried out regularly for all wind turbines and substation installed in farm and plan in advance to maintenance action in working places for a period of the time to check overall condition of the systems and repair or replacement in a timely manner. Condition based Maintenance is happed that detects the onset of system degradation (lower functional state), thereby allowing causal stressors to be eliminated or controlled prior to any significant deterioration in the component physical state. Results indicate current and future functional capability. It is also carried out a period time according to frequency of the use making a plan in advance to prevent of the degradation of the system. Planned corrective maintenance is that there is a sign of failure on system but doesn't have any operational issue it can be carried out during appropriate weather condition and wind farm situation for maintenance action.

Reactive maintenance is basically the "run it till it breaks" maintenance mode. No actions or efforts are taken to maintain the equipment as the designer originally intended to ensure design life is reached. Repair carried out soon after a turbine is down, or, alternatively, wait until a certain number of turbines are down.

Offshore wind operation and maintenance involve a various range of activities. However, there are a few essential concepts that reinforce the way that the key players are likely to approach operation and maintenance. Some of the most imperative factors in influencing operation and maintenance are availability, access and cost reduction.

Availability is the proportion of the time that a turbine is technically capable of producing electricity. Availability is therefore a measure of how little electricity is lost due to downtime of the wind turbine.

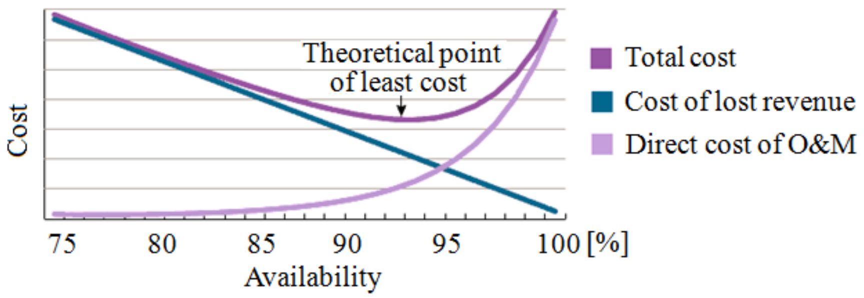

Figure 22 Balance between cost and lost revenue.

Although the cost of lost revenue declines towards zero as the turbines approach 100% availability, the cost of achieving it approaches exponential growth if 100% availability is required. The figure shows this theoretical optimum at the lowest point of the total cost curve, which of course will be slightly different for each wind turbine [27].

Access is one of the major difficulties to maintain offshore wind projects, which is getting technicians on and off the turbines and substations to carry out activity. There are two major factors that are transit time and Accessibility. Transit time is the time needed to transport a service crew from the operation and maintenance basement to the place of work. With limited transfer hours available, the time taken to transport crews to and from the wind turbine cuts into the amount of time actually working to maintain the turbines and other plant. Accessibility is the proportion of the time a turbine can be safely accessed from a vessel and is dependent on the sea conditions. Accessibility is especially serious for unplanned maintenance since the wind farm operator has not enough time to organize any production out for times of calmer sea conditions.

Reducing the cost of the energy produced by offshore wind projects is a major issue for the offshore wind industry. Finding ways to reduce the cost of operation and maintenance have essential roles to play as a significant contributor to the overall cost of energy. There are technical and non-technical areas for cost reduction. Technical areas are improved remote monitoring, control system, design and manufacturing developments. Non-technical ways to reduce the cost are greater synergies, sharing of resources or other logistics plant between neighboring projects and greater competition within the operation and maintenance supply chain for a range of contract packages.

3.2 Parameters of operation and maintenance on offshore wind farm

There is a wide range of possible techniques and equipment that can be used for offshore wind farm maintenance. When estimating the operation and maintenance costs of offshore wind farms then the effect of the following parameters on the cost of unit energy produced should be considered [32]:

• ***Weather and sea state.***

Compared to onshore wind farm, there are many difficulties of low accessibility, harsh climate, salinity, waves, and biological issues for operating and maintenance for the offshore wind farm. In critical weather conditions and sea condition, when wind turbines or even whole wind farms are susceptible of shutting down, wind power production forecast is important.

• ***The size and the reliability of the offshore wind turbines***.

There are many parameters that can be used to make a maintenance plan. The failure rate of components is needed constant over time. It is required a detailed information about size, weight, logistic time and cost of the system for repair parts.

• *Operation and maintenance strategy adopted for the project.*

There are the different types of maintenance which stated chapter 3.1. Each offshore wind project has different characteristics which determine the optimal strategy for operating and maintaining the wind farm.

• ***Distance to shore.***

Other than the number and reliability of wind turbines, the most important factor on the cost of offshore wind operation and maintenance is the distance of the turbines from onshore facilities (harbor). For this reason, the distance from shore is also the main consideration in determining the most cost effective approach to operation and maintenance. Depending on the distance to shore, all the logistic ways and equipment type can be defined.

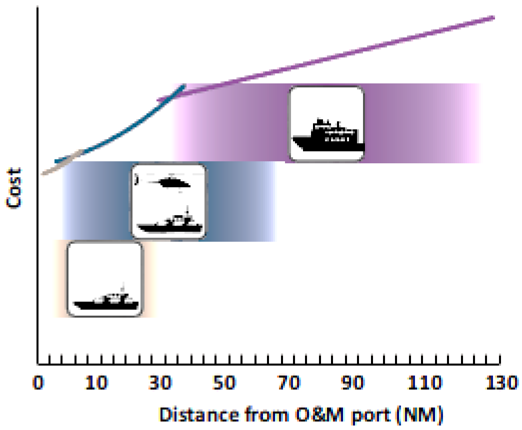

Figure 23 The lowest cost as a function of distance from operation and maintenance port [27].

Figure 23 shows simplified results for a generic offshore wind project at various distances from the nearest operation and maintenance harbor. Based on the relative costs and characteristics of each of these approaches to offshore wind operation and maintenance, it is expected that workboat-based strategies are likely to be the most economic option for supporting near-shore sites, while shore-based workboats will benefit from support by helicopters (heli-support) for sites further from shore. The transit times for port-based workboats to the very furthest sites are so long that some form of offshore-based can be only option which uses fixed or floating offshore accommodation [27].

• ***Accessibility and transportation means.***

The key point of offshore wind access logistics is to get people on and off turbine site as safely and quickly as possible. The main factors that influence the suitability of the offshore accessibility and transportation include safety regulation, personnel carrying capacity, time as a function of speed, weather and sea-state dependency and direct cost of retaining and using a service.

• ***Capacity factor.***

Capacity Factor is an indicator of how much energy a particular wind turbine makes in a particular place.

• ***Size and orientation (micro-sitting) of the wind farm.***

The sitting of an offshore wind farm is to find the most suitable location where the park can be located, considering a range of relevant factors such as wind potential, grid connection, bathymetry, water depth and distance from the shore. Table 9 shows the basic maintenance parameters which relevant for offshore wind farms.

Table 9 Parameters of operation and maintenance model for offshore wind farm

General	Price of energy	
	wind farm efficiency	
	Weather data	Wind speed & significant wave height
	Maintenance data	Working time
		control room type
		Maintenance periods
		Cost of technicians
Equipment	Type of equipment	Logistic data
		Equipment costs
Spare	Spare parameters	Logistic time
		Material costs
Repair	Mission phases	Remote reset
		Inspection
		Repair
		Replacement
Wind farm	Number of turbine	
	General turbine information	PV-curve, Rated power etc.
	Turbine system information	System failure rate
		Fault type
		Repair & spare type

4. Operation and maintenance plan of offshore Wind farm in Jeju Island, Rep. of Korea

4.1 Workflow of offshore wind farm model

Operation and maintenance an offshore wind farm is a promising work, but there are many challenges to make a model. Wind farm administrators selling power to wholesale electricity markets are looking for ways to maximize profits and reduce revenue uncertainty. To do so, operation and maintenance model is needed to manage offshore wind farm and make a future maintenance plan. For operation and maintenance modeling work, it is important to get a lot of information such as analyzing historical data, forecasting prices, and collecting real-time operation data.

Operation and maintenance of offshore wind farm have two key components: the amount of energy wind produces and the repair and energy losses for each available time frame. The workflow for operation and maintenance of offshore wind farm has three main data: wind farm data, operation and maintenance data and Criteria for spares and repair action. First, wind farm data sources for modeling work are price of electricity, time series of meteorological data, wind farm lay out, wind turbine and balance of plant design information. Second, operation and maintenance data include personnel data, preventive maintenance data, wind turbine reliability data and equipment data. Third, criteria of spears of wind turbine's components and repair categories are defied. Figure 24 shows workflow of the operation and maintenance model for the offshore wind farm.

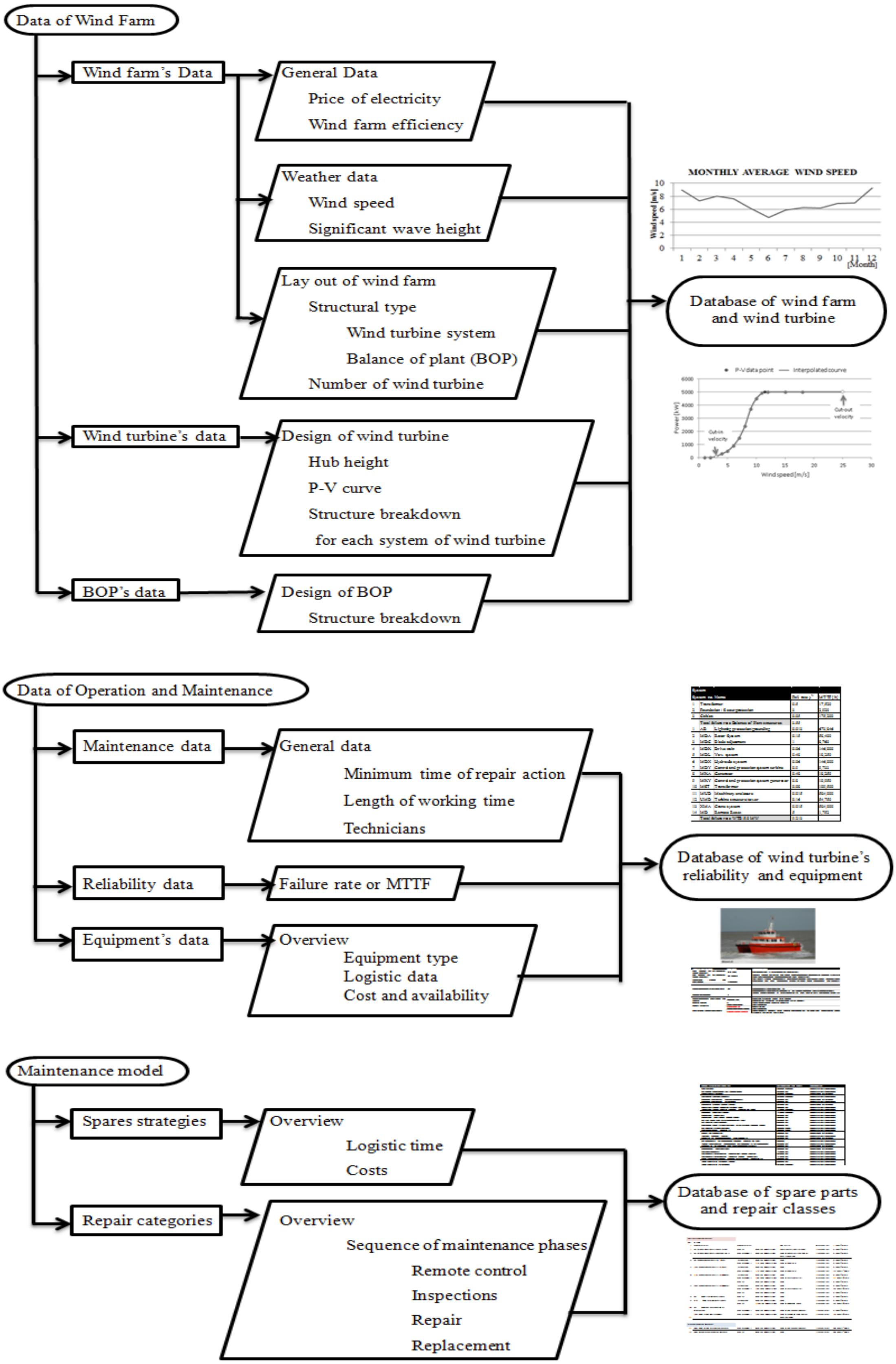

Figure 24 Workflow of different parts of the operation and maintenance model for the offshore wind farm.

4.2 Offshore wind farm model

The development of wind power industry has been steady for decades worldwide and has mainly taken place in Europe. There is no offshore wind farm in Rep. of Korea so far, several offshore wind farm projects are under planning and project execution with a target of about 2,500 MW by 2020. In this respect, the importance of the installation as well as the operation and maintenance of offshore wind farm have been proposed. An operation and maintenance scenario is set up for a hypothetical offshore wind farm which represents a near offshore wind farm in Jeju Island. It is assumed that this wind farm is located within 10 km off the Coast of the south-west side of Jeju Island. The wind farm consists of 16 wind turbines with an installed capacity of 80 MW. Based on generic data representative for an offshore wind farm and operating and maintenance modeling, a maintenance strategy is worked out and a model is set up where both preventive and corrective maintenance are considered. Because Balance of Plant failures may significantly affect costs and downtime, both wind turbine failures and balance of plant failures are considered.

4.2.1 Wind farm and wind turbine layout

4.2.1.1 General

The Korean government apply variable weights to renewable energy certificate (REC) for offshore wind power which require huge amount of investments in early stages, to achieve the target of mandatory generation and help companies mitigate burden of up-front investments. Namely, the government helps offshore wind power companies to recover their investments early by raising the weight to 3.0 for the first 5 years of operation and lower the weight to 2.0 for 15 years thereafter.

With REC (Renewable Energy Certification or Renewable Energy Verficate), a fixed price of ₩ 380 (0.25 €)/ kWh is assumed as the kWh price is used to calculate the revenue losses.

Revenue = Power generation x (SMP: System Marginal Price+ REC +weight) (4.1)

4.2.1.2 Wind farm location and climate data

A fictitious 80 MW wind farm consisting of 16 wind turbines is analyzed. The wind farm is located within 10 km from the nearest harbor which is accessible for jack-up vessels. The water depth in the wind farm is around 30 m. The wind farm is connected to the grid via one transformer connected to 16 turbines. Total losses in production due to wake effects, electrical losses, etc. are 10 % on average. For the analysis of downtime and revenue losses, time series of meteorological data have been used. Jeju National University Fluid Laboratory furnished 10 minute time series of wind speed data in public water surfaces of Daejeong-eup of 2010. 1 hourly time series of Marado significant wave height data was provided from Korea Meteorological Administration (KMA) of 2010.

Figure 24 Location for Jeju offshore wind farm.

Offshore wind and wave conditions are modeled for south-west of Jeju Island. Water depth at the model point is estimated to be 30 m. The sustained wind speeds (V_w) in the data are measured at 60 m above the sea.

4.2.1.3 Wind turbine and Balance of Plant structures

A generic 5 MW direct-drive wind turbine is considered. This theoretical turbine is representative of typical utility-scale, multi-megawatt turbine. The turbine is controlled via a variable-speed, collective-pitch control system connected through a high-speed drive train, using a gearless design. The main turbine specifications are given in Table 10. The turbine's power curve is depicted in Figure 26. The turbine and power curve are modeled based on assumptions. To assume the generic 5 MW wind turbine for Jeju offshore wind farm, we obtained some design information from the published documents of turbine manufacturers and analysis of wind farm operating reports. And then make a composite from these data, extracting the best available and most representative specifications.

Table 10 Turbine Specifications

5 MW Direct Drive turbine	
Parameter	**Value**
Rotor diameter	126 m
Hub height	90 m
Rated power	5 MW
Power regulation	Pitch control
Operational wind speed limits	3 m/s cut-in , 25 m/s cut-out
Pitch regulation	Electrical
Generator	Permanent Magnet

The turbine is equipped with a nacelle internal crane that is able to hoist small components like pitch motors and yaw drives (weight < 2000 kg). Hoisting can be done outside the tower using the nacelle internal crane. The hoisted components can be put on a platform at the bottom of the tower during the replacement actions. On this platform a davit crane is mounted that hoists the components to and from the deck of a small access vessel.

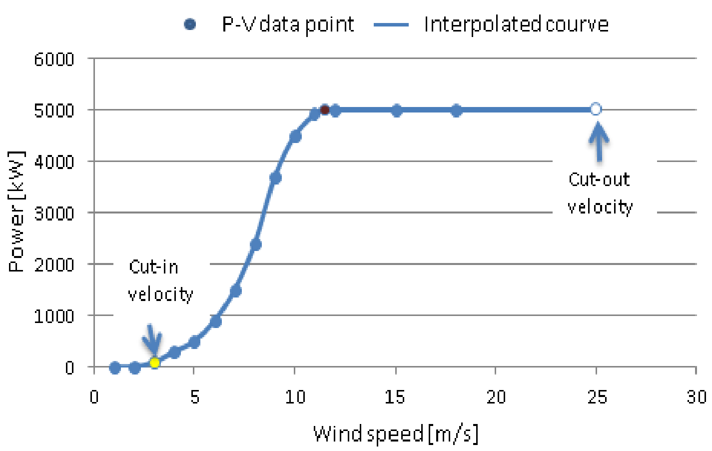

Figure 26 Power curve data and plot of generic 5MW wind turbine.

In the thesis, the Reference Designation System for Power Plants (RDS-PP) is used. It results from further development of the successful KKS Identification System for Power Plants [29]. This classification system is rather new, and provides standardization of power plants, including newer technologies such as wind power plants. For this reason, it was decided to use this classification system for the failure analyses in this report. Table 11 shows the relevant RDS-PP codes for the correspondent components of a wind power plant. Mostly main components are defined on a system level.

Table 11 Breakdown of main system for 5MW Direct Drive turbine

System no.	RDS-PP Code	Name
1	AB	Lightning protection/grounding
2	MDA	Rotor System
3	MDC	Blade adjustment
4	MDK	Drive Train
5	MDX	Hydraulic systems
6	MDL	Yaw system
7	MDY	Control & protection systems
8	MKA	Generator system
9	MKY	Control and protection system generator
10	MST	Generator transformer, and cooling
11	MUD	Machinery enclosure
12	UMD	WTG structures
13	XMA	Cranes system
14	MD	Wind Turbine

The one transformer and cables located at the offshore wind farm are modeled as Balance of Plant systems. The Balance of Plant breakdown in main systems is shown in Table 12. Both the wind turbine and Balance of Plant breakdowns on system level are required to assign maintenance and reliability data (Meantime to failure or failure rates) to the individual systems. The reliability and maintenance data will be further discussed in the following sections.

Table 12 Breakdown of main systems for Balance of Plant of 80MW wind farm

System no.	Name
1	Transformer
2	Foundation / Scour protection
3	Cables

4.2.2. Model for reliability and maintenance

Maintenance is defined as the combination of all technical and corresponding administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function [33].

Corrective maintenance is carried out after a failure has occurred and is intended to restore an item to a state in which it can perform its required function. It is typically performed when there are no cost-effective means to detect or prevent a failure.

Preventive maintenance is carried out at predetermined intervals or corresponding to prescribed criteria, and intended to reduce the probability of failure or the performance degradation of an item. It also carried out in accordance with established intervals of time or number of units of use but without previous condition investigation. This type of maintenance is suitable for failures that are age-related and for which the probability distribution of failure can be established.

4.2.2.1 General maintenance data and cost of technicians

Personnel will work only in a single shift during daylight periods for all possible maintenance. On average they work from 7:00 h to 19:00 h, which means that the total workday length is set at 12 hours on average. Maintenance will be initiated if the technicians can spend a minimum of 2 hours to the repair onsite.

The wind farm has a control room which is 24/7 occupied to monitor the status of the wind turbines and wind farm structures. Maintenance is initiated from the control room.

An estimate for the number of required technicians is based on having concrete technicians required to man one small access vessel, which requires up to 12 technicians. In Jeju offshore wind farm a total number of 6 technicians for the one crew are assumed to be employed on a fixed contract basis and are estimated to cost ₩ 130,000,000 (87,000.00 €) per person per year leading to a total fixed cost ₩ 780,000,000 (522,000.00 €) per year.

Additional crew or technicians to perform maintenance is hired for periods when this type of maintenance is performed. This crew or technicians is assumed to be paid with a rate of ₩ 100,000 (67.00 €) per hour.

4.2.2.2 Preventive maintenance

All wind turbines in the wind farm will have scheduled preventive maintenance once per year with 2 technicians. The repair time of yearly maintenance is on average 40 hours. The material costs per turbine are on average ₩ 18,000,000 (12,000.00 €).

An underwater inspection of the transformer platform is required yearly. A small access vessel with divers and diving equipment comes from the harbor. Each year 90 hours of BOP (Balance of Plant) preventive maintenance has to be carried out. The preventive maintenance for the wind turbines and BOP structures is scheduled for the period of May – June each year. No additional equipment will be reserved specifically for preventive maintenance.

4.2.2.3 Random failures

Generic reliability data is used to model the maintenance effort for the 80 MW offshore wind farm. The failure frequencies per wind turbine component are derived from the results of the reliability study in chapter 3. Based on analysis of several wind farms, the average annual failure rate for a wind turbine lies between 3 and 6, therefore a failure rate of λ_{wtg}=4 ~ 5 $year^{-1}$ is assumed.

BOP (Balance of Plant) failure rate are assumed $\lambda_{BoP}=3.55\ year^{-1}$ for all BOP systems which are transformer stations, foundations and scour protection. Table 13 shows the failure rates for both the 5MW wind turbine and the BOP structures.

Table 13 Failure rates per system of 5MW turbine and BOP structures

System System no.	Name		Fail. rate y^{-1}	MTTF [h]
1	Transformer		0.50	17,520
2	Foundation / Scour protection		3.00	2,920
3	Cables		0.05	175,200
	Total failure rate Balance of Plant structures		3.55	
1	AB	Lightning protection/grounding	0.013	673,846
2	MDA	Rotor System	0.150	58,400
3	MDC	Blade adjustment	1.000	8,760

4	MDK	Drive train	0.060	146,000
5	MDL	Yaw system	0.480	18,250
6	MDX	Hydraulic system	0.060	146,000
7	MDY	Control and protection system turbine	0.900	9,733
8	MKA	Generator	0.480	18,250
9	MKY	Control and protection system generator	0.800	10,950
10	MST	Transformer	0.080	109,500
11	MUD	Machinery enclosure	0.015	584,000
12	UMD	Turbine structure/tower	0.160	54,750
13	XMA	Crane system	0.015	584,000
14	MD	Remote Reset	5.000	1,752
	Total failure rate WTB 5.0 MW		9.213	

4.2.2.4 Description of maintenance scenario

In the operational phase of the wind farm, a small access vessel is launched from the proximity of the harbor to perform corrective and preventive maintenance. The travel time to a turbine in the farm is on average 1 hour, including the transfer of personnel from a small access vessel to the turbine and other turbines.

The small access vessel is also able to transfer spare parts and small parts (up to 2000 kg) to the turbines. Such small parts are picked up from the vessel with the crane placed on the platform at the transition piece of the turbines. Subsequently, the components are lifted into the nacelle using the internal nacelle crane.

For the replacement of large component(s) (weights in excess of 2000 kg) additional equipment - a jack-up vessel is required. This vessel will also transfer the spare part to the wind farm. For the replacement of the large component(s), access of technicians is performed with a small access vessel. Large component(s) will be directly ordered from the manufacture and transferred to the harbor to be picked up by the jack-up vessel.

Access to the transformer stations for small repairs is also done with a small access vessel. To repair power cables inside the wind farm and for preventive maintenance of the cables and foundations, a small access vessel is used with diving equipment or remotely operated vehicle (ROV).

4.2.3 Equipment model

The proposed offshore wind farm is located near shore within 10 km distance from the nearest harbor; therefore, it is chosen to assess the wind turbine only by boat similar to other operating near shore wind farms. As a consequence crew and technicians have to be brought at site with a small access vessel and transfer from the vessel to the turbine. To maintain the offshore wind farm, the following equipment is used for the transfer of personnel and spare parts, and for hoisting component(s) [35]:

- The small access vessel is used for the transfer of technicians and transporting small components in the wind farm. When additional small access vessels are required, they are chartered to perform condition based maintenance. One small access vessel is permanently leased on a fixed contract.
- The jack-up vessel is used for transportation and hoisting of large component(s). One jack-up vessel is chartered on the spot market when required.
- Each turbine in the wind farm is equipped with an internal crane at the nacelle capable of hoisting small components to and from the nacelle and a davit crane on the platform capable of hoisting small components to and from the small access vessel.
- For underwater repairs a ROV is chartered on the spot market when required for maintenance.

4.2.3.1 Small access vessel

In order to help in reducing the maintenance cost, the operators need to develop technologies that allow access and repairs to the wind turbines in worse weather conditions. Typical dimensions are an overall length of about 15~25 meters width 6 meters, transporting capacity up to 12 persons and a speed up to 30 knots. For all these vessels the significant wave height limitation of the suitable weather window are about 1.5~2.0 meters.

Figure 27 Example of a small access vessel (Waterfall) [36].

For the transfer of personnel and small spare parts a small access vessel type is used shown in Figure 27. As an example, waterfall vessel is used on London Array Phase 1 offshore wind farm for carrying out survey work, including the export cable rout and Thanet offshore wind farm for providing crew transfer services. The specifications used for the cost modeling are given in Table 14.

Table 14 Specifications of the small access vessel

Specification	Value	Remarks
Hs max at transfer and travel	1.5 m	Between 1.5 and 2.0 meters.
V max at transfer and travel	12 m/s	This limit refers to the maximum allowed wind speed for personnel working in the nacelle.
Travel time to turbine (or speed)	1 hour	Travel time includes transferring technicians from the harbor to the turbine and from the turbine to other turbines.
Maximum crew size	14	Accommodation : 14 persons Number of Crew : 2 Number of Passengers: 12 (Including Technicians.)
Availability	1	The workboat is stationed at the nearest harbor and is therefore always available. Chartered vessels for preventive maintenance.
Maximum weight of load	2000 kg	Deck crane capacity is 2 tons. Nacelle crane capacity is 2 tons.
Day rate	-	Included in fixed costs

Fuel costs	₩ 105,000 (70.00 €)	Estimate Per trip
Yearly fixed costs	₩ 300,000,000 (200,000.00 €)	Estimate Includes costs for part delivery, crew to operate the small assess vessel.

4.2.3.2 Jack-up vessel

The transportation and hoisting of large components will be done with a jack-up vessel as shown for example in Figure 28. The SEA POWER jack–up vessel is used on various offshore wind farms for the replacement turbine of generator, transportation, installation of offshore wind turbines and supplied the jack-up vessel for maintenance purposes. The MV Wind jack–up vessel has used on various offshore wind farms for preventative and condition based maintenance by replacing the pitch bearings on the turbines.

Figure 28 Jack-up vessel (Left: SEA POWER, Right: MV wind) [36].

During the gearbox and generator replacement activities and the large repairs, the use of jack-up barge and floating cranes are necessary. The jack-up vessel must have jack-up legs, the barges stand firmly on the seabed to create a stable working platform rising around 10 meters above sea level at the offshore site in order to lift heavy components and install them with high level precision without being affected by the waves, wind and current.

Table 15 Specifications of the jack-up vessel

Specification	Value	Remarks
Hs max	2 m	Equipment survival limit when jacked-up is higher.
V max	10 m/s	Travel limit applies to daylight and night breaks.
Time for positioning	2 hours	
Travel time (one way)	2 hour	Assumed speed of 5 ~ 10 knots per hour. Maximum Speed of SEA POWER : 8.5 knots
Mobilization time	360 hours	Estimate Dependent on market conditions
Demobilization time	24 hours	Estimate Vessel modifications are removed and vessel returns to market
Availability	Limited	Chartered when necessary
Maximum height of crane	100 m	Crane of SEA POWER upgraded in March 2012 increasing lift height to 100m. 22m radius with full load.
Maximum weight of load	> 100 MT	Max. Cargo weigh of SEA POWER is 2386 tons. Max. Lifting Capacity of SEA POWER is 210 tons.
Day rate	₩ 150,000,000 /day (100,400.00 € /day) (75% during waiting)	Estimate Included fuel cost for travel
Mob + demob costs	₩ 300,000,000 /mob (200,000.00 € /mob)	Estimate
Cost during travel	-	
Positioning	four Legs	

4.2.3.3 Turbine cranes

To hoist small components up to 2000 kg to the nacelle for repairs and small replacements, the davit and internal cranes in nacelle on the wind turbine are used. The davit crane on the platform is used to hoist small components from a vessel to and from the platform, after which the nacelle crane is used to lift those up to the nacelle. The nacelle crane can lift small components from the platform of the wind turbine up to the nacelle at subject to operational available wind speed limits.

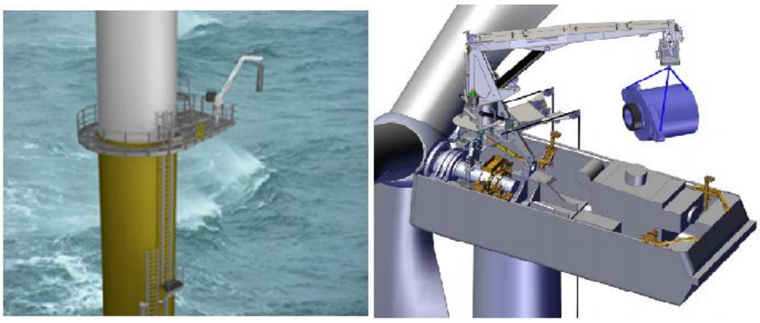

Figure 29 Example nacelle internal crane and davit crane [37][38].

Table 16 Specifications of the davit crane

Davit crane		
Specification	**Value**	**Remarks**
Hs max at transfer	Hoisting 1.5 m	Estimate Assumed the same as the small access vessel limits
V max at transfer	Hoisting 12 m/s	Estimate Assumed the same as the small access vessel limits
Availability	One crane available for each wind turbine.	16 Cranes in total
Maximum weight of load	2 tons	Estimate
Costs	-	Not applicable The fixed costs for the crane are already included in the wind turbine investment cost. The crane will receive preventive maintenance at regular intervals.

Table 17 Specifications of the nacelle crane

Nacelle crane		
Specification	**Value**	**Remarks**
Hs max at transfer	Hoisting -	No wave height limit for hoisting components from the wind turbine base
V max at transfer	Hoisting 12 m/s	Estimate
Availability	One crane available for each wind turbine.	16 Cranes in total
Maximum weight of load	2 tons	
Costs	-	Not applicable The fixed costs for the crane are already included in the wind turbine investment cost. The crane will receive preventive maintenance at regular intervals.

4.2.3.4 Additional equipment

For underwater repairs within the wind farm a Remotely Operated Vehicle (ROV) is used. The small access vessel is used for transportation of ROV. The purpose of this equipment is to dig up and remove the failed cable, lay the new cable and bury it.

Table 18 Specifications of the Remotely Operated Vehicle(ROV)

Specification	Value	Remarks
Hs max at transfer	1.5 m	Estimate Assumed the same as the small access vessel limits
V max at transfer	12 m/s	Estimate Assumed the same as the small access vessel limits
Availability	Limited	Chartered when necessary
Yearly fixed costs	₩ 6,000,000 (4,000.00 €)	Estimate

4.2.4 Criteria for spare parts and repair categories

The repair process and costs of each failure have different characteristics; therefore, it is hard to define maintenance strategies which apply to Jeju offshore wind farm. In this section, the spare control model, repair category and failure model are determined. It depends on the type of failure and its severity. Previously, type of systems and reliability are estimated and repair strategy, and a spare control strategy can be classified from literature review and generic data.

4.2.4.1 Spares

The preventive maintenance of the Jeju wind farm is done once a year, during the summer when the average wind speed and significant wave height are lower. In our model, it has included spare parts for corrective and preventive maintenance service. In preventive maintenance, shifted items are mostly inexpensive spares. But corrective maintenance leads to, high downtime, unavailability and expensive parts for the wind farm. In this part, the price of spare parts is defined for wind turbine system according to the previous chapter 2. There is Conversion of taxonomy used for data collection in Jeju wind farm to RDS-PP taxonomy in table 19.

Table 19 Wind turbine system and subassemblies

System (RDS-PP Code)	Sub system or assembly
AB- Lightning protection/grounding	Lightning protection + grounding
MDA- Rotor System	Blades + hub + hub cover
MDC- Blade adjustment	Pitch system + slip rings + blade bearing
MDK- Drive Train	Drive Train module
MDX- Hydraulic systems	Hydraulic systems
MDL- Yaw system	Yaw system
MDY- Control & protection systems turbine	Control system + nacelle sensors + CMS + auxiliary
MKA- Generator system	Generator assembly
MKY- Control and protection system generator	Power cabinet + protection cabinet + frequency converter
MST- Transformer	Transformer
MUD- Machinery enclosure	Nacelle cover + bedplate + lighting point + beacon
UMD- WTG structures	Structural module
XM- Cranes system	Service crane

The information required when modeling spare parts logistics are item failure rates, prices, types(discardable or repairable), lead time. There are a number of spares in the turbine and substructure system. It is necessary to limit the study by looking at approximately 30 items. One important criterion for sorting out items was to create a diversity of prices. The items are also selected to represent all wind turbine subsystems. It is very important to know that each wind turbine type has different spares according to the wind turbine manufacturers. Because of the fact that failure rates and other data, such as item prices, are estimates and differ between different wind turbine sites and models, it is classified as the items under the price of general and common system. The collecting item data for Jeju wind farm is present table 20.

Table 20 Spare parts cost data for Jeju wind farm

Description	PRICE (€)	Type
Blade	500000	Discardable
Proportional Valve	2500	Discardable
Generator	250000	Repairable

Transformer	250000	Discardable
Hydraulic Cylinder	3000	Repairable
Hydraulic cable	6000	Discardable
Rotating Union	3000	Repairable
Bearing Generator	5000	Discardable
Slewing bearing of blade	120000	Discardable
Hub bearing	120000	Discardable
Yaw Gear	2500	Discardable
Yaw drive motor	5000	Discardable
Piston Accumulator	2500	Discardable
Pitch motor	6000	Discardable
Control system circuit boards	6000	Discardable
Pitch system	50000	Discardable
Cooling parts	50000	Discardable
Oil Pump	2000	Repairable
Delta Module (SKII)	2500	Repairable
Power Supply 240 V/24 V	200	Discardable
Switched Mode Power Supply	2500	Discardable
Ultra Sonic Anemometer	2000	Repairable
Wind Sensor	2000	Repairable
Encoder	1000	Discardable
Emergancy Main Switch	3600	Discardable
Emergancy Electric Gear	1800	Discardable
Foundation protection rocks	6000	Discardable
Subsea coating	6000	Discardable
Subsea cable	350000	Discardable

4.2.4.2 Repair categories

Different repair categories are modeled as Repair Classes (RC's). The RC's in fact determine the sequence of maintenance phases, and the corresponding amount of work, required equipment and time to organize for each maintenance phase.

Corrective maintenance

(1) RC 1: Remote reset

The wind turbine is shut down because of warnings from a turbine. For the remote reset, the process is as follows:

① The turbine is shut down due to a warning.

② The monitoring team has an investigation what causes the alarm (~ 2 hours).

③ If there is a minor problem or nothing, the turbine restarted.

The access to turbine is not necessary; therefore, it requires no equipment, spare parts and technicians onsite.

(2) RC 2: 4h Inspection/ small repair inside

An inspection and/or small repair inside the wind turbine, is carried out by 2 technicians, and requires a small access vessel to access the turbine. The operator has an organizational period to analyze the current situation and prepare the necessary arrangements on equipment and technicians etc. This organizational period takes about 6 hours.

An inspection is carried out as follows:

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine, or to the harbor.

② 2 technicians carry out the inspection and/or small repair (~4 hours).

③ The turbine is commissioned and technicians leave the turbine and are transferred to other turbines by the small access vessel.

Transfer of personnel is determined by the capabilities of the small access vessel. In this case, the maximum number of personnel for transportation is 2 crew and 12 passengers including technicians per a small access vessel. Transportation of technicians in the wind farm and transfer to and from the turbine takes about 1 hour. This action can be split up over multiple available weather windows on more days. The repair is modeled with the small access vessel as access equipment and has a work period of 4 hours with 2 technicians.

(3) RC 3: 9h Inspection/small repair outside

An inspection and/or small repair outside the wind turbine, is carried out by 2 technicians, and requires a small access vessel to access the turbine. The operator has an organizational period to analyze the current situation and prepares the necessary arrangements on equipment and technicians etc. This organizational period takes about 6 hours.

Generally, inspection is conducted before full-scale replacement to get information is about fault condition of the component(s). The organizational period for the operator to analyze the situation and prepare the necessary arrangements on equipment, technicians and etc. for the inspection is about 6 hours.

An inspection is carried out as follows:

① The small access vessel picks up technicians and hoisting equipment from the harbor and travels to the faulted turbine.

② The technician hoisting equipment is hoisted on the platform with the davit crane and hoisted with the nacelle crane into the nacelle or hub, and the equipment for lowering technicians is installed (~2 hours).

③ Technician is hoisted from hub along blade 1 and blade 1 is inspected. After inspection, the technician is hoisted back into the hub (~2 hours).

④ Rotor is rotated through 120 degrees and step 3 is repeated (~2 hours).

⑤ Step 4 is repeated for 3rd blade (~2 hours).

⑥ Hoisting equipment is demounted and hoisted to platform by nacelle crane from where it is hoisted to a small access vessel with the davit crane (~1 hour).

⑦ The turbine is commissioned and technicians leave the turbine and are transferred to the harbor or other turbine by the small access vessel.

The transfer and installation of the hoisting equipment and the subsequent outside inspections take approximately 9 hours. Transfer of personnel and equipment are determined by the capabilities of the small access vessel. Hoisting by the nacelle crane can be done up to the crane wind limit of wind speeds 10 m/s. Transportation of technicians and transfer to and from the turbine takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day.

(4) RC 4: 9h Replacement parts (< 2MT)

Smaller spare parts like e.g. a pitch motor, or parts of a hydraulic system need to be transported to the turbine, put on the platform and subsequently hoisted into the nacelle with the internal crane. Smaller spare parts can be transferred and hoisted by the small access vessel and nacelle crane within operational limits. The organizational period for the inspection is 6 hours.

Inspection

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the inspection. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines (~4 hours).

③ Technicians leave turbine and are transferred to the harbor or other turbine by the small access vessel.

Once the inspection is completed, the technicians report their findings to the operator, who then will order spare parts, equipment and technicians for the replacement phase. This organizational period takes about 12 hours. When the spares, equipment and technicians are all available, the replacement starts.

Replacement

① The small access vessel picks up 2 technicians and the spare part from the harbor and travels to the faulted turbine.

② The spare part is hoisted to the platform with the davit crane (~1 hour).

③ The failed component is dismounted (~1 hour).

④ The failed component is hoisted to the turbine platform with the nacelle crane (~2 hours).

⑤ The spare part is hoisted from the turbine platform with the nacelle crane (~2 hours).

⑥ The spare part is mounted (~2 hours).

⑦ The failed component is hoisted to the small access vessel with the davit crane (~1 hour).

⑧ The turbine is commissioned and technicians leave the turbine and are transferred to other turbine by the small access vessel.

The replacement takes 9 hours in this action. Transfer of personnel and small parts to the platform is determined by the capabilities of the small access vessel. Hoisting of equipment from the platform with the nacelle crane is possible up to wind of speeds 10 m/s. Transportation of technicians in the wind farm and transfer to and from the turbine takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day.

This replacement is modeled with the small access vessel as access equipment, and has a work period of 9 hours with 2 technicians at all times. Step 2 to 3 in the description above are modeled as a preparation of 2 hours, steps 4 to 5 are modeled as a hoisting phase of 4 hours for which the nacelle crane is applied as the 2nd equipment and steps 6-7 are modeled as a finalization phases of 3 hours.

(5) RC 5: 18h Replacement parts (< 2MT)

Smaller spare parts need to be transported to the turbine, put on the platform and subsequently hoisted into the nacelle with the help of the internal crane. Smaller spare parts can be transferred and hoisted by the small access vessel and nacelle crane within operational limits. The organizational period for the inspection is 6 hours.

Inspection

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the inspection. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines (~4 hours).

③ Technicians leave turbine and are transferred to the harbor or other turbine by the small access vessel.

Once the inspection is completed, the technicians report their findings to the operator, who then will order spare parts, equipment and technicians for the replacement phase. This organizational period takes about 12 hours. When the spares, equipment and technicians are all available, the replacement phase starts.

Replacement

① The small access vessel picks up 2 technicians and the spare part from the harbor and travels to the faulted turbine.

② The spare part is hoisted to the platform with the davit crane (~1 hour).

③ The failed component is dismounted (~6 hours).

④ The failed component is hoisted to the turbine platform with the nacelle crane (~2 hours).

⑤ The spare part is hoisted from the turbine platform with the nacelle crane (~2 hours).

⑥ The spare part is mounted (~6 hours).

⑦ The failed component is hoisted to the small access vessel with the davit crane (~1 hour).

⑧ The turbine is commissioned and technicians leave the turbine and are transferred to other turbine by the small access vessel.

The replacement takes 18 hours in this action. Transfer of personnel and small parts to the platform is determined by the capabilities of the small access vessel. Hoisting of equipment from the platform with the nacelle crane is possible up to wind speeds 10 m/s. Transportation of technicians in the wind farm and transfer to and from the turbine takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day.

(6) RC 6: 21h Replacement parts (<100 MT)

A jack-up vessel is required to hoist large and/or heavy component(s). There are four process of maintenance action for large replacements which are an inspection, the actual replacement of the component(s), a repair phase and commission of the wind turbine. The organizational period for the operator to analyze the situation and arrange equipment and technicians for the inspection is about 6 hours.

Inspection

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the inspection. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines. (~4 hours).

③ Technicians leave turbine and are transferred to the harbor or other turbine by the small access vessel.

Once the inspection is completed, the technicians report their findings to the operator, who then will order necessary spare parts, equipment and technicians for the replacement phase. This organizational period takes about 16 hours. When the spares, equipment and technicians are ready, the replacement phase starts.

Replacement

① The spare part is transported from the harbor to the wind farm by the jack-up vessel. This vessel then travels to the wind farm (~ 1 hour).

② The small access vessel picks up technicians from the harbor and travels to the faulted turbine, where 4 technicians are transferred to the turbine.

③ The failed component is dismounted (~3 hours).

④ The jack-up barge positions itself next to the failed wind turbine (~2 hours)

⑤ The failed component is hoisted by the jack-up vessel to its base (~3 hours).

⑥ The spare part is hoisted from the jack-up vessel to the nacelle (~3 hours).

⑦ The spare is mounted crudely (~2 hours).

⑧ Mounting new part is finalized (~8 hours).

⑨ Technicians leave turbine and are transferred to harbor or other turbine by the small access vessel.

The total duration of the replacement is about 21 hours. Transfer of personnel to the platform is determined by the capabilities of the small access vessel. The positioning and hoisting of components with the jack-up vessel is determined by the capabilities of the jack-up vessel. Transportation of technicians in the wind farm and transfer to and from the turbine takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day while the jack-up vessel remains positioned at the wind turbine during the night.

Once the replacement is completed, a final repair phase is initiated by the operator to assess the status of the repairs made and to commission the turbine. The organizational period for the operator to arrange equipment and technicians for the final inspection/repair is about 6 hours.

Repair

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the inspection and make adjustments where needed. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines. (~9 hours).

③ The turbine is commissioned and technicians leave the turbine and are transferred to the harbor or other turbine by the small access vessel.

After the replacement phase, a repair phase is concluded. The inspection can be split up over multiple available weather windows on more days, with the small access vessel as access equipment, and has a work period of 4 hours with 2 technicians.

The following replacement is modeled with the small access vessel as access equipment with 4 technicians in all steps. The repair can also be split up over multiple available weather windows on more days, is modeled with the small access vessel as access equipment, and has a work period of 9 hours with 2 technicians.

(7) RC 7: 36h Replacement parts (<100 MT)

A jack-up vessel is required to hoist large and/or heavy component(s). There are four maintenance actions for large replacements which are an inspection, the actual replacement of the component(s), a repair phase and commissioning of the wind turbine. The organizational period for the operator to analyze the situation and arrange equipment and technicians for the inspection is about 6 hours.

Inspection

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the inspection. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines. (~4 hours).

③ Technicians leave turbine and are transferred to the harbor or other turbine by the small access vessel.

Once the inspection is completed, the technicians report their findings to the operator, who then will order required spare parts, equipment and technicians for the replacement phase. This organizational period takes about 16 hours. When the spares, equipment and technicians are ready, the replacement phase starts.

Replacement

① The spare part is transported from the harbor to the wind farm by the jack-up vessel. This vessel then travels to the wind farm (~ 1 hour).

② The small access vessel picks up technicians from the harbor and travels to the faulted turbine, where 4 technicians are transferred to the turbine.

③ The failed component is dismounted (~8 hours).

④ The jack-up barge positions itself next to the failed wind turbine (~2 hours)

⑤ The failed component is hoisted by the jack-up vessel to its base (~3 hours).

⑥ The spare part is hoisted from the jack-up vessel to the nacelle (~3 hours).

⑦ The spare is mounted crudely (~2 hours).

⑧ Mounting new part is finalized (~ 18 hours).

⑨ Technicians leave turbine and are transferred to harbor or other turbine by the small access vessel.

The total duration of the replacement is about 36 hours. Transfer of personnel to the platform is determined by the capabilities of the small access vessel. The positioning and hoisting of components with the jack-up vessel is determined by the capabilities of the jack-up vessel. Transportation of technicians in the wind farm and transfer to and from the turbine takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day while the jack-up vessel remains positioned at the wind turbine during the night.

Once the replacement is completed, a final repair phase is initiated by the operator to assess the quality of the repairs made and to commission turbine. The organizational period for the operator to arrange equipment and technicians for the final inspection/repair is about 6 hours.

Repair

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the inspection and make adjustments where needed. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines. (~ 9 hours).

③ The turbine is commissioned and technicians leave the turbine and are transferred to the harbor or other turbine by the small access vessel.

After the replacement phase, a repair phase is concluded. The inspection can be split up over multiple available weather windows on more days, with the small access vessel as access equipment, and has a work period of 4 hours with 2 technicians.

The following replacement is modeled with the small access vessel as access equipment with 4 technicians in all steps. The repair can also be split up over multiple available weather windows on more days, is modeled with the small access vessel as access equipment, and has a work period of 9 hours with 2 technicians.

(8) RC 8: 9h BOP transformer repair

To repair the Balance of Plant transformer station in small parts, it requires 2 technicians with a small access vessel to transfer and carry out the inspection and/or repair action.

Before an inspection and/or small repair can start the operator has to analyze the current situation and then make a plan and arrangements to prepare equipment, technicians and spare parts. This organizational period takes about 6 hours.

The typical inspection or repair is as follows:

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted transformer station.

② 2 technicians carry out the inspection and/or small repair. (~9 hours)

③ The transformer and connected turbines are commissioned and technicians leave the platform and are transferred to the harbor or other turbine by the small access vessel.

Transfer of personnel and equipment are determined by the capabilities of the small access vessel. Transportation of technicians in the wind farm and transfer to and from the transformer platform takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day.

This RC can be split up over multiple available weather windows on more days. The repair is modeled with the small access vessel as access equipment and has a work period of 9 hours with 2 technicians.

(9) RC 9: 42h BOP transformer repair

An inspection is conducted before a large repair on the transformer to get information about fault conditions. The organizational period for the operator to analyze the situation and arrange equipment and technicians for the inspection is about 6 hours.

Inspection

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the inspection. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines. (~4 hours).

③ Technicians leave turbine and are transferred to the harbor or other turbine by the small access vessel.

After the inspection, the technicians make a report on their findings to the operator, and then spare parts, equipment and technicians will be assigned and ordered for the repair phase. This organizational period takes about 12 hours. Once the spares, equipment and technicians are ready, the repair phase starts.

Repair

For a large repair at the transformer station on average 2 specialized technicians are required to carry out the repair. Before the repair can start the operator makes the necessary arrangements to organize equipment, technicians, and spare parts. This organizational period takes about 12 hours.

The typical inspection or repair is modeled as follows:

① 2 technicians are transported by a small access vessel from the harbor to transformer station (~1 hour).

② The failed components are dismounted and hoisted. Hereafter, the spare parts are hoisted to the transformer platform (~8 hours).

③ Technicians carry out the repair on the transformer (~27 hours).

④ The transformer and connected turbines are commissioned and the technicians are transported back to harbor by a small access vessel (~2 hours).

The total duration of the repairs is about 42 hours. Transfer of personnel and hoisting of spare parts to the platform is determined by the capabilities of the dummy crane. Transportation of technicians in the wind farm and transfer to and from the transformer platform takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day.

(10) RC 10: 9h BOP (Balance of Plant) foundation/scour protection

The BOP (Balance of Plant) foundation/scour protection is worked underwater which required diving crew. Before the repair can start the operator makes the necessary arrangements to organize the required diving equipment including diving technicians and spare parts. This organizational period takes about 6 hours.

A typical under water repair to the foundation or scour protection looks as follows:

① The small access vessel picks up the spare parts from the harbor and travels to the location where the fault occurred.

② The vessel is positioned near the fault and the diving crew enters the water (~1 hour).

③ The divers carry out the repair (~8 hours).

④ The divers return to the small access vessel and travels back to the harbor.

The repair can be carried out in about 9 hours. Transfer of personnel and equipment are determined by the capabilities of the small access vessel. For this RC it is assumed that the diving operations need to be finished in a period with good weather.

(11) RC 11: 26h BOP (Balance of Plant) cable replacement

This requires a small access vessel to transfer for technicians and spare parts. The organizational period for the operator to analyze the situation and arrange the required equipment, technicians, and spare parts for the replacement is about 24 hours.

Once the spares and equipment are ready, the replacement phase starts.

① The small access vessel picks up the spare parts from the harbor and travels to the location of the faulted cable.

② Technicians use a Remotely Operated Vehicle (ROV) to detach the faulted cable from affected structures (~6 hours).

③ The small access vessel is positioned above the broken cable (~4 hours).

④ The small access vessel hoists the broken cable from the sea surface (~4 hours).

⑤ The small access vessel lays the new cable (~6 hours).

⑥ Technicians use an ROV to attach the new cable to the affected structures (~6 hours).

⑦ The transformer/wind turbines affected are commissioned and the small access vessel travels back to the harbor.

The replacement can be carried out in about 26 hours. Transportation of the small access vessel to the wind farm takes about 1 hour. In case the work is spread over more days, the operations take place every day. This RC is assumed that the cable laying operations need to be finished in a continuous period with good weather.

Preventive maintenance

Preventive maintenance is performed on all wind turbines and underwater inspection of BOP (Balance of Plant) once per year.

(12) RC 12: 90h BOP (Balance of Plant) preventive maintenance

An underwater inspection of the transformer platform is required as part of preventive maintenance annually. A small access vessel with divers and diving equipment comes from the harbor. 90 hours of BOP (Balance of Plant) preventive maintenance has to be carried out every year. Only small parts are required.

The maintenance is scheduled to be performed each year in the period of May – June. The equipment, technicians and spare parts to perform the maintenance are arranged by the operator to be available at the 1st of May to perform this maintenance.

① The small access vessel picks up the spare parts from the harbor and travels to the wind farm.

② The divers carry out inspections and make repairs where applicable for the BOP (Balance of Plant) systems (~90 hours).

③ The divers return to the small access vessel and the vessel travels back to the harbor.

The work is spread over more days, the divers will work every day. Diving operations are limited to the capabilities of the small access vessel. This RC is assumed that the diving operations need to be finished in a replacement with a continuous period with good weather.

(13) RC 13: 40h WT (Wind turbine) preventive maintenance

Preventive maintenance is defined for yearly maintenance on the wind turbines, which requires 2 technicians who are transported to the turbine with a small access vessel in order to carry out the inspections and repairs. Only small parts are required.

The operation has to have preventive maintenance on 16 wind turbines with the small access vessel which is also applied for unplanned corrective maintenance. The maintenance is scheduled to be performed each year in the period of May –June. The equipment, technicians and spare parts to perform the maintenance are arranged by the operator be available at the 1st of May to perform this maintenance. The turbine is only shut down each day maintenance is performed.

① The small access vessel picks up technicians from the harbor or from another wind turbine and travels to the faulted turbine.

② 2 technicians carry out the preventive maintenance. The small access vessel stays in the wind farm and is possibly used to transfer technicians to or from other turbines (~40 hours).

③ The technicians leave the turbine and are transferred to the harbor or other turbine by the small access vessel.

Transfer of personnel is determined by the capabilities of the small access vessel. Transportation of technicians in the wind farm and transfer to and from the turbine takes about 1 hour. In case the work is spread over more days, the transfer of technicians is done every day and the wind turbines are shut down only when the work is being performed.

This RC can be split up over multiple available weather windows on more days. The repair is modeled with the small access vessel as access equipment and has a work period of 40 hours with 2 technicians.

4.2.4.3 Fault type classes

There are many components in each turbine and they have different fault characteristics in their operation. It is difficult to make and define simple models for fault type. Although many surveys have been done on wind turbines, it is still clear that the statistical data on the failures of its subassemblies is difficult to obtain. There are several reasons that the majority of manufactures refused to reveal their data, e.g. no such data was collected for the wind farm or the available data was not comparable subject of the time and design details. However, provides a detailed and comparable statistics of these failures and it has been taken as our reference data.

In this part, Fault Type Classes (FTC) is defined to apply for generic 5 MW wind turbine. Quantification of failure rates and repair time are aimed at a component and sub system level but also consider the four overall wind turbine system repair actions: manual restart, minor repair, major repair and major replacement. The detail of main system on wind turbine is noted 5.1.2. All the fault types are based on the overall downtime and assumption.

Table 21 Wind farm structure, failure rates, and fault type classes

Sys. no.	Name Unit:	MTTF h	BoP %	FTC no. -	FTC name -	Freq. %	RC -	SCS -	PL -
1	Transformer	17,520	100						
				1	FTC1	90	8	1	3
				2	FTC2	10	2	2	3
2	Foundation/Scour protection	2,920	0						
				1	FTC3	100	10	9	3
3	Cable	175,200	15						
				1	FTC4	100	11	10	3
1	AB Lightning protection/ grounding	673,846							
				1	FTC2	100	2	2	3
2	MD Wind Turbine	1,752							
				1	FTC1	100	1	1	3
3	MDA Rotor system	58,400							
				1	FTC2	50	2	2	3
				2	FTC3	8	3	2	3
				3	FTC4	15	3	3	3
				4	FTC6	14	5	4	3
				5	FTC12	5	7	6	3
				6	FTC13	8	7	7	3
4	MDC Blade system	8,760							
				1	FTC2	65	2	2	3
				2	FTC6	10	5	4	3
				3	FTC10	25	6	6	3
5	MDK Drive train	146,000							
				1	FTC2	45	2	2	3
				2	FTC4	20	3	3	3
				3	FTC6	22	5	4	3
				4	FTC11	13	6	6	3
6	MDL Yaw system	18,250							
				1	FTC2	50	2	2	3
				2	FTC13	50	7	6	3
7	MDX Hydraulic system	146,000							
				1	FTC2	60	2	2	3
				2	FTC4	40	3	3	3
8	MDY Control and protection system turbine	9,733							
				1	FTC2	55	2	2	3
				2	FTC4	45	3	3	3
9	MKA Generator	18,250							
				1	FTC2	55	2	2	3
				2	FTC6	35	5	4	3
				3	FTC7	8	6	5	3
				4	FTC13	2	7	7	3
10	MKY Control and protection system generator	10,950							
				1	FTC2	35	2	2	3
				2	FTC5	35	4	3	3
				3	FTC6	20	4	4	3
				4	FTC8	10	7	5	3
11	MST Transformer	109,500							
				1	FTC2	60	2	2	3
				2	FTC5	30	4	3	3
				3	FTC6	5	5	4	3
				4	FTC7	5	6	5	3
12	MUD Machinery enclosure	584,000							
				1	FTC2	40	2	2	3
				2	FTC4	60	3	3	3
13	UMD Turbine structure/tower	54,750							
				1	FTC2	50	2	2	3
				2	FTC4	30	3	3	3
				3	FTC6	10	5	4	3
				4	FTC7	8	6	5	3
				5	FTC13	2	7	7	3
14	XM Crane system	584,000							
				1	FTC2	100	2	2	3
1	BOP_Preventive					100	14	13	3
2	WT_Preventive					100	15	14	3

4.3 Modeling results

There are several technical challenges which are corrosion, personnel access, shelter and safety, typhoon, ice loading, grids and submarine electrical infrastructure, decommissioning and environmental impacts on offshore situation in Rep. of Korea. Operations and maintenance costs vary significantly by project conditions such as depth, distance to shore, prevailing sea and weather conditions. There are many uncertainties with operation, maintenance, logistics, and replacements. Therefore, offshore operation and maintenance costs are difficult to estimate and are higher than expected. Over 20 % of life cycle costs of an offshore wind project are driven by frequent minor repairs or faults that are unknown.

Generally, near shore wind farm like Jeju offshore wind farm, which have fixed bottom shallow water depth of about 0 ~ 30 m, 2~5 MW upwind rotor configurations, over 70 meter tower height, reliability problems have discouraged early boom in development. Lower availability in offshore projects has been an issue due to vessel deployment cost and logistics, accessibility, weather windows, safe personnel access and reliability of the wind turbine designs. So it is very important to achieve and sustain high availability of offshore wind farms.

For the estimation of operation and maintenance on the Jeju offshore wind farm, OMCE-Calculator (Operation and Maintenance Cost Estimator) is used by ECN (Energy research Centre of the Netherlands). The OMCE Calculator has been developed to estimate the future operation and maintenance costs of an operating offshore wind farm. The OMCE Calculator in fact is the tool to calculate the O&M aspects which are downtime, costs, and revenue losses. The OMCE Calculator uses actual wind farm data as input and is able to estimate the future O&M costs for a period that is typically 1 to 5 years [40].

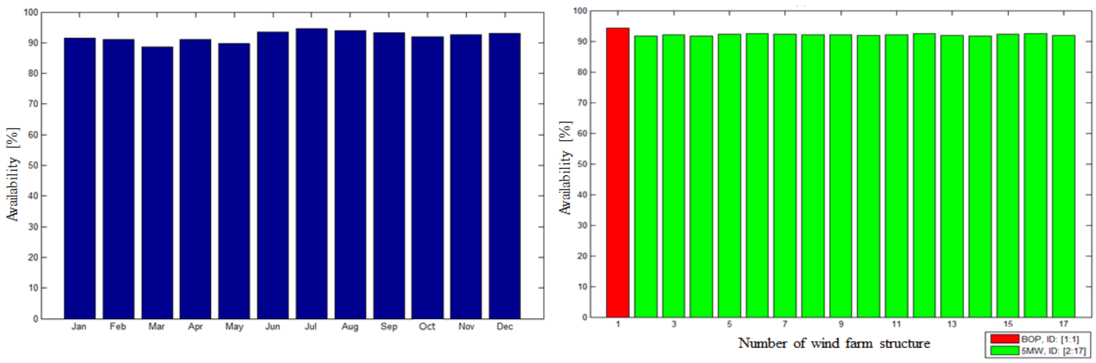

Figure 30 Average wind farm availability per month (Left), availability per structure in wind farm (Right).

Figure 30 shows average wind farm availability per month and per structure in Jeju offshore wind farm. There are 'Seasonal' variations that are done through visiting a wind turbine either for preventive maintenance or for repair actions. Since wind farm preventive maintenance is done from May to June, availability has always been below than other seasons. In addition, site accessibility always has a level below 100% for ocean conditions and it is important to emphasis first on the decrease of the failure frequency of an offshore wind turbine system.

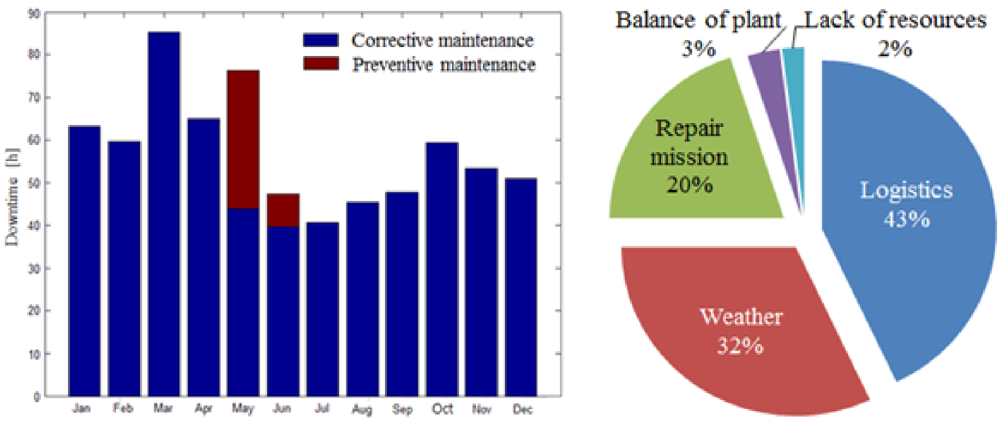

Figure 31 Average downtime per month (Lift), breakdown average downtime wind farm (Right).

Main attribution of downtime is logistics and weather. There are two types of logistics in offshore wind farm which are onshore based logistics and offshore based logistics. Onshore based logistics is harbor-side activity, warehousing and on-site office spaces. In the case of offshore based logistics, it leads to heavy downtime which is equipment, resources to move technicians and system components at sea including small access vessels, offshore bases, and jack-up vessels. Due to logistics, 43 % of downtime is occurred.

Equipment is subject to strictly defined weather restrictions. Local weather characteristics have great impact on the maintenance duration. The influence of weather on a process depends on three general parameters, the restriction of the operation with respect several weather parameters, the required time for operation execution which the length of the required weather window, and the seasonal point in time the activities are to be performed.

In terms of accessibility, 30-50 % downtime is due to poor weather and it varies from site to site and year to year. Accessibility is dependent on weather conditions, sea state is a driving factor and stepping off a boat to a landing point is only safe in calm waters. The weather windows can be widened with better access and construction methods, smaller boats, temporary bridges, and improve forecasting integrated into maintenance strategy. Because of the weather, 32 % downtime occurred in Jeju offshore wind farm.

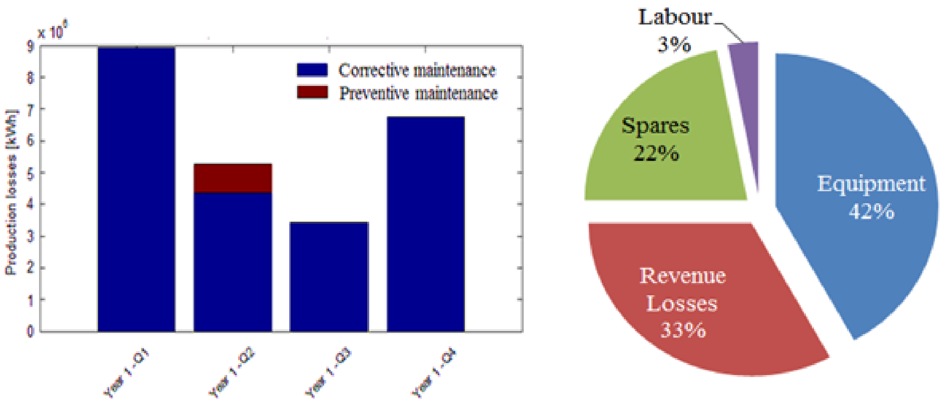

Figure 32 Average production losses of wind farm per season (Lift), breakdown average the operation and maintenance costs wind farm (Right).

In case of equipment deployment costs and logistics, day rates are very expensive and equipment is scarce and may not be available when needed. To minimize the operation and maintenance costs, the maintenance actions which require the usage of external crane or jack up vessel should be limited and turbine designs should also be considered to avoid large vessel dependence. In Jeju offshore wind farm, equipment costs contribution the maximum of the overall operation and maintenance costs which is 42 %.

Production losses are also the main component of operation and maintenance costs. Due to the expensive electricity price, the costs of production losses are also high.

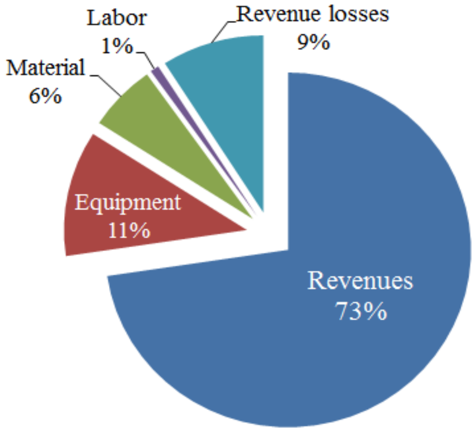

Figure 32 Total cost distribution of Jeju offshore wind farm.

The operation and maintenance cover both preventive maintenance and corrective maintenance based on Jeju regional meteorology data for 1 year. The average total operation and maintenance cost is estimated to be 67,138 k€. 11 % of the total generation cost is due to limited equipment usage. As previously mentioned, high electricity price leads to high revenue losses which are up to 9 % of the total generation cost. The sum of revenue losses and costs of repair is estimated to be 18,360 k€. It is approximately 27 % of total generation cost for one year in the offshore wind farm.

The electricity generated from Jeju offshore wind farm has high price which estimate a fixed price of 380 ₩ (0.25 €)/ kWh. There is a high renewable energy certificate (REC) for offshore wind power which weight to 3.0 for the first 5 years of operation and its weight get lower to 2.0 for 15 years supported by Korean government. The high electricity price make offshore wind farm a viable source of power generation in Rep. of Korea.

5. Conclusions

This chapter summarizes the main results from the thesis and presents ideas for future work.

5.1 Conclusions

This thesis presents basic information of offshore wind energy and operation and maintenance of offshore wind farms. First, background information and objective of the thesis is provided. This part covers general knowledge of wind energy, wind turbine and offshore wind farm. Second, theoretical background is discussed. This part deals with a literature review of the reliability, availability and maintenance issues of offshore wind turbines. Reliability of wind turbine is one of the important factors to make operation and maintenance plan for offshore wind farm. Reliability is related to all aspects of design, operation and maintenance requirements and limitations, and life cycle costs. For the classification of wind turbine system RDS-PP (Reference Designation System for Power Plants) taxonomy was used. Commercial wind turbine components costs and distributions are studied for the Spare parts information. Third, the classification of operation and maintenance and parameters of maintenance for the offshore wind farm are mentioned. Lastly, Study manly focus on the operation and maintenance modeling work of Jeju Island, Rep. of Korea.

The operation and maintenance cover both the preventive maintenance and the corrective maintenance based on Jeju regional meteorology data for 1 year. The location of 80MW offshore wind farm is defined and then selects a 5 MW wind turbine and a fixed price of ₩ 380 (0.25 €)/ kWh is assumed as the kWh price. Wind speed data in public water surfaces of Daejeong-eup and Marado significant wave height data in 2010 are used for metrological data. The number of technician for Jeju offshore wind farm is 6. Access vessel and Jack-up vessel, turbine cranes and remotely operated vehicle are addressed. There are 30 items for spare parts and 13 categories for repair processes.

The results of operation and maintenance model shows that the major contributions of operation and maintenance costs are revenue loss from the downtime of wind turbines, equipment and component parts. The main attributions of downtime are logistics, weather, and repair mission. 11 % of the total cost is due to limited equipment usage. The high electricity price leads to high revenue losses which are up to 9 % of the total generation cost. The sum of revenue losses and costs of repair is estimated to be approximately 27 % of the total generation cost for one year in the offshore wind farm. Availability of wind farm is around 92 %.

5.2 Future work

During this thesis a lot of factors concerning operation and maintenance model have been addressed. One of the most troubling aspects is the fact that there is no study on wind turbine and wind farm in Rep. of Korea. This should be of primarily interest for further research to contain Korean offshore situation. Emerging technologies such as large wind turbine, advanced service vessels, introduced condition based maintenance etc, could become possible candidates for the application of planning of intervention maintenance model, which can be an intriguing area for further research.

This thesis developed an operation and maintenance model of offshore wind farm for 1 year, but generally modern wind turbines can carry on generation of electricity for 20-24 years. It would be also interesting to develop a long-term extended operation and maintenance plan.

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Appendices

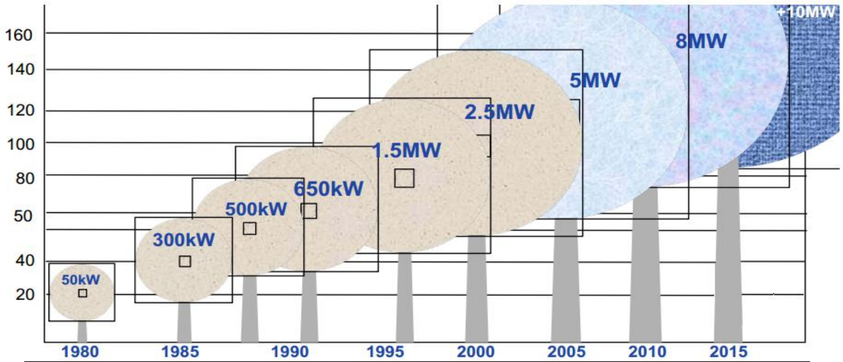
Appendix A: Geared and gearless (direct-drive) generator systems of wind turbine

Appendix B: Reliability of wind turbine

Appendix C: List of input parameters of operation and maintenance model

Appendix A

Geared and gearless (direct-drive) generator systems of wind turbine



Drive Train	Induction	DFIG	DFIG	DFIG	Full Conv.	PM	HTS
Tower Height (m)	60	70	75	80	100	120	140
Torque Produced (ft-lb)	19k	124K	218K	754K	353K	2932K	5118K
Top Weight (Metric Tons)	50	100		200		400	450

Figure 1 The Growth in Turbine Size [1].

According to the comparison of different geared and gearless (direct-drive) generator systems discussed in many literatures, the features of the systems can be summarized as the following [2].

1. Considering the energy yield and reliability, the direct-drive generator systems seem to be more powerful compared to geared drive systems, especially for offshore.
2. The permanent magnet synchronous generator with one stage gearbox has the highest ratio of the annual energy yield to cost.
3. The direct-drive permanent magnet synchronous generator system (PMSG DD) is more superior compared to other systems in terms of losses and energy yield.
4. The doubly-fed induction generator system with three stage gearbox (DFIG 3G) seems lightweight and low cost solution.
5. Different generator systems can be arranged in the order of high cost as

    Direct-drive electrically excited synchronous generator

    Direct-drive permanent magnet synchronous generator

    Permanent magnet synchronous generator with one stage gearbox

    Doubly-fed induction generator system with three stage gearbox

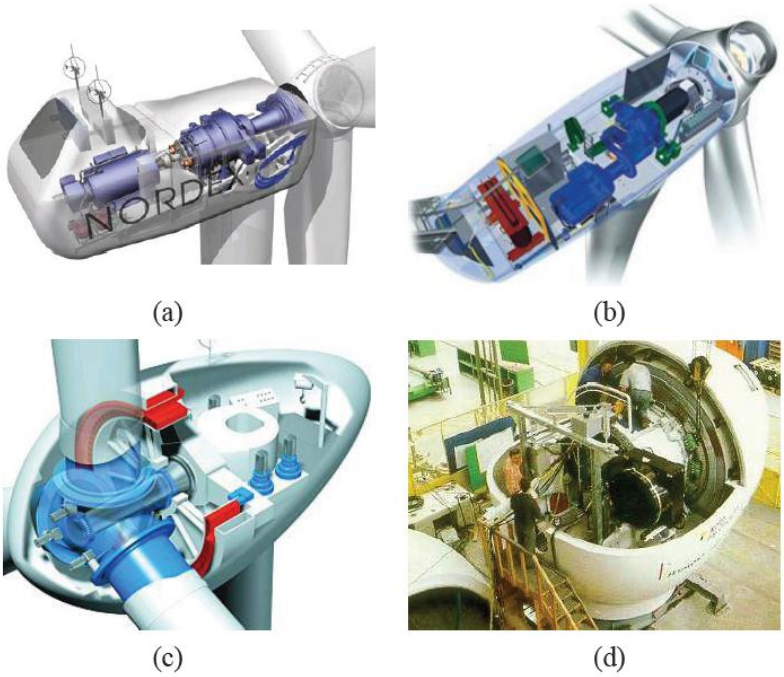


Figure 2 Generator topologies: (a) Induction generator [© Nordex], (b) Doubly-fed induction generator [© NEG Micon], (c)Synchronous generator [© Enercon], (d) Permanent magnet synchronousgenerator [© Jeumont Industrie].

The necessity of new wind power system comes from recent studies which have shown that gearboxes are responsible for the greatest percentage of outage time [2]. In conventional wind turbines, the gearbox increases the speed of the wind-driven rotor several hundred fold, which radically reduces the size of the generator required.

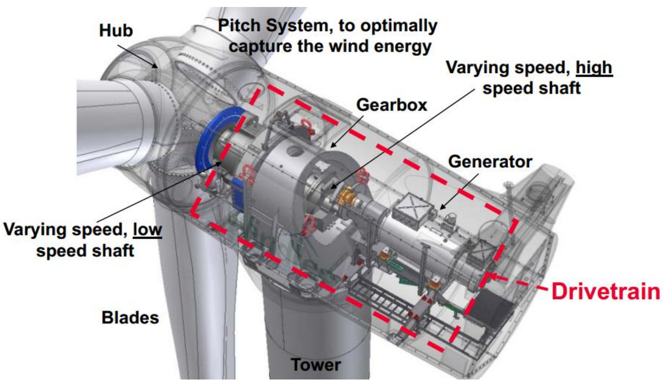


Figure 3 Conventional wind turbines with gearbox [1].

In the direct-drive generator for wind turbine, the rotor is directly connected to the rotor hub. Direct-drive generators operate at the same speed as the turbine's blades and must therefore be much bigger. Even for a large direct-drive generator, with a diameter of several meters, the air-gap should not exceed a few millimeters, to avoid excessive magnetization requirements. This means that the mechanical construction has to be very rigid, in order to maintain the air-gap against the powerful force of attraction between the rotor and the stator. This stiffness requirement applies to the load path through the rotor, the shaft, the bearings and the stator. Thus the stiffness places a practical and economical limit on the diameter of a conventionally built generator.

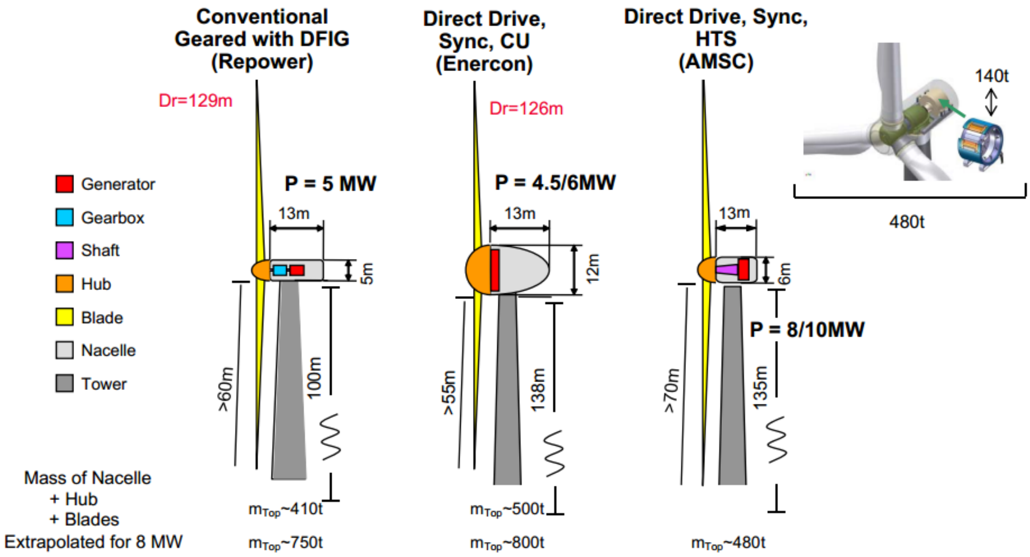


Figure 4 Wind turbine size comparisons [1].

A typical 10 MW superconductor generator will have a nacelle 10 meters long by six meters high, with a combined nacelle and rotor weight that is about 420 tons. For comparison, a conventional direct drive machine, scaled up to the same nameplate capacity, may require a nacelle 13 meters long and 12 meters high, weighing some 800-900 tons. A geared turbine, meanwhile, would likely be topped with a nacelle 13-15 meters long and five meters high, weighing 750-850 tons.

A new generation of low cost HTS wires, based on coated conductor technology is currently under development, including early commercial availability, by several HTS wire manufactures around the world.

Direct-drive generator has a larger diameter to produce higher torque because the torque is proportional to the air gap diameter squared. Thus higher torque demands large air gap diameter of the generator and high tangential force. This results in the increase of materials to maintain the air gap in proper deflection against the normal stress between the rotor and stator. Therefore the concept of direct-drive generator is operated in low speed and has the disadvantages such as high large diameter, heavy mass, torque rating and high cost compared to the concept of geared generator. That is why the concept of direct-drive generator is designed with a large diameter and small pole pitch to increase the efficiency, to reduce the active material and to keep the end winding losses small.

Direct-drive permanent magnet machines have several advantages compared to the electrically excited machines.

1. Higher power to weight ratio
2. Improvement in the efficiency
3. High energy yield and light weight
4. No additional power supply for the field excitation, higher reliability without slip rings

Because of those advantages permanent magnet machines are considered as the promising electromagnetic structure for direct-drive generator.

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Appendix B

Reliability of wind turbine

Case 1 Data of different wind farms [1]

• MWEP downtime data exists but is not available.							
• Number of failure is reported until 1999 but is not included in this study due to the length of this period.							
	Reliawind	wind stats Germany	wind stats Denmark	LWK	WMEP		VIT
Region	Europe	Germany	Denmark	schleswig-Holstein. Germany	Germany	Sweden	Finland
Period	Jan 2004~ Sep 2008	1996~2008	Q4 1994~ 2003	1993~ 2006	1989~ 2006	1997~2004	1999 ~ 2009
Reporting interval	Event	Quarter	Month	Year	Turbine age(yrs)	Year	Year
Data source	Gamesa, Ecotecnia			Chamber of Agriculture		Elforsk	
Number of turbine	283	1803~4924	851~ 2345	158~643	1500	342~1050	63~118
Power[MW]	366	597~6349	328~593	11.5~ 45	~250(avg)	108~452	35~120
Average rating[kW]	1293	331~1289	385~253	73~70	167	316~430	556~1017
Turbine specification	Pitch = 850kW	>50kW	>50kW	>50kW	All	>50kW	>50kW
Reporting by ;	Event	Cause of stop	Type of stop	Make & model	Make & model, turbine age	Type / cause of stop	Cause of stop
Number of items in taxonomy	253(9 sub system)	14	18	16	56(12 groups0	13~55	16~30
Number of failures	Yes	Yes	Yes	Yes	Yes	No	Yes
Hours Lost	Yes	Yes	No	Yes	No	Yes	Yes

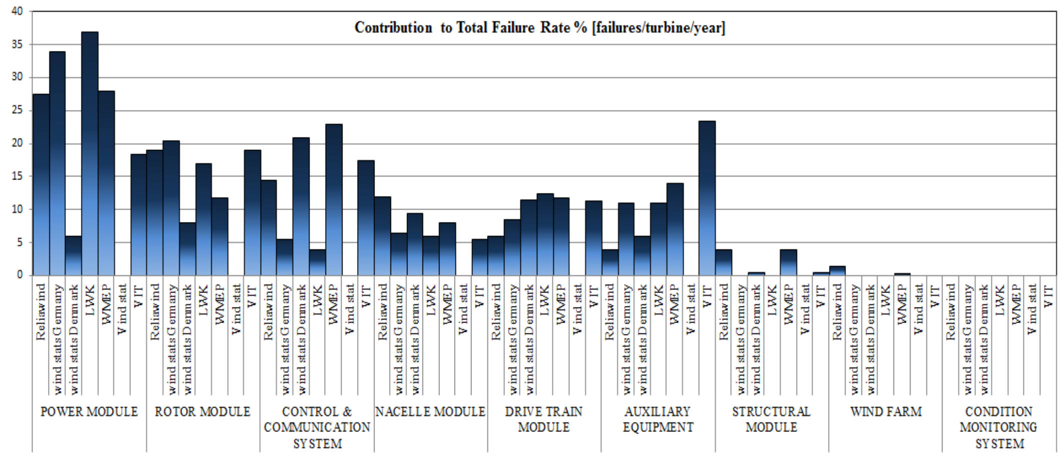


Figure 1 Annual failure rates of different wind farm.

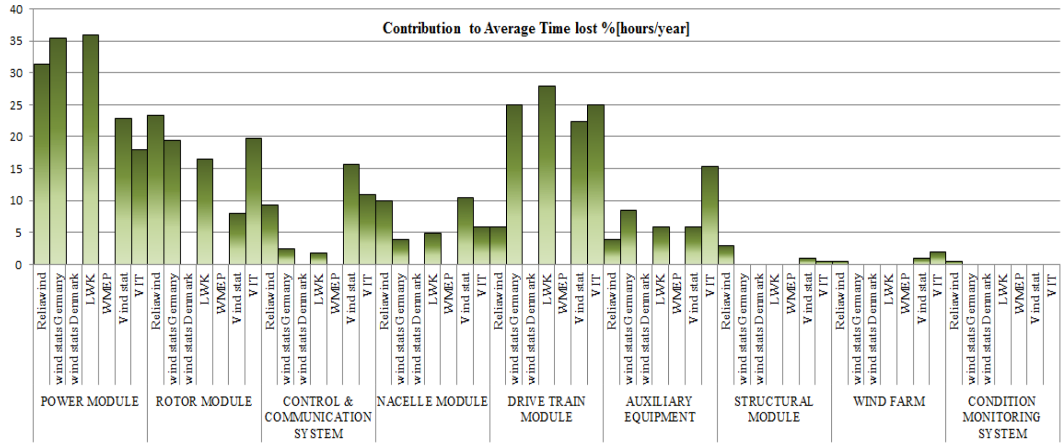
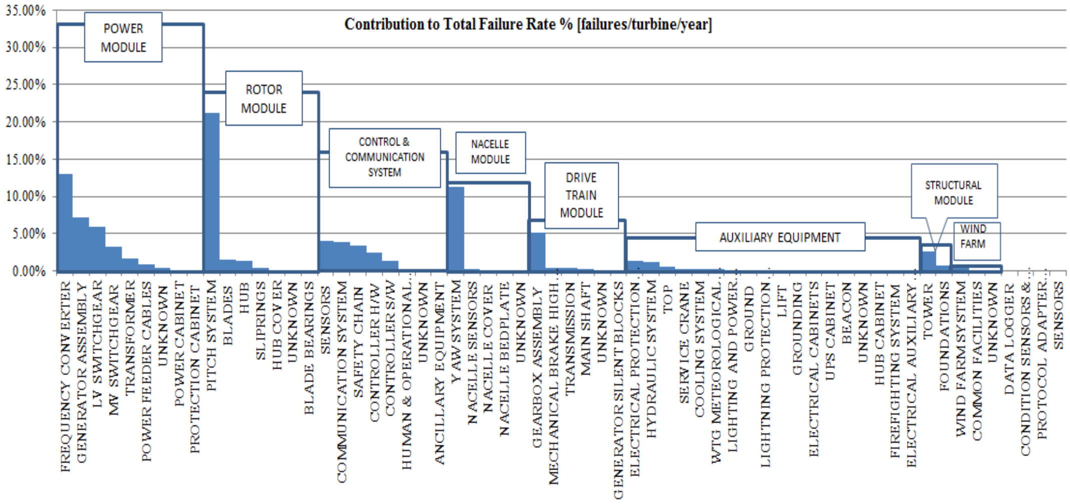


Figure 2 Average time lost (%) of Different Wind Power Plants.

Case 2 Data of Reliawind-Europe [2]

Reliawind-Europe-Jan 2004 ~ Sep 2008	
Reporting Interval	Event
Data Source	Gamesa, Ecotecnia
Number of Turbines	283
Power[MW]	366
Average Rating[kW]	1,293
Number of Items in Taxonomy	253(9 Sub system)



Failure 3 Failure rates of Reliawind Data.

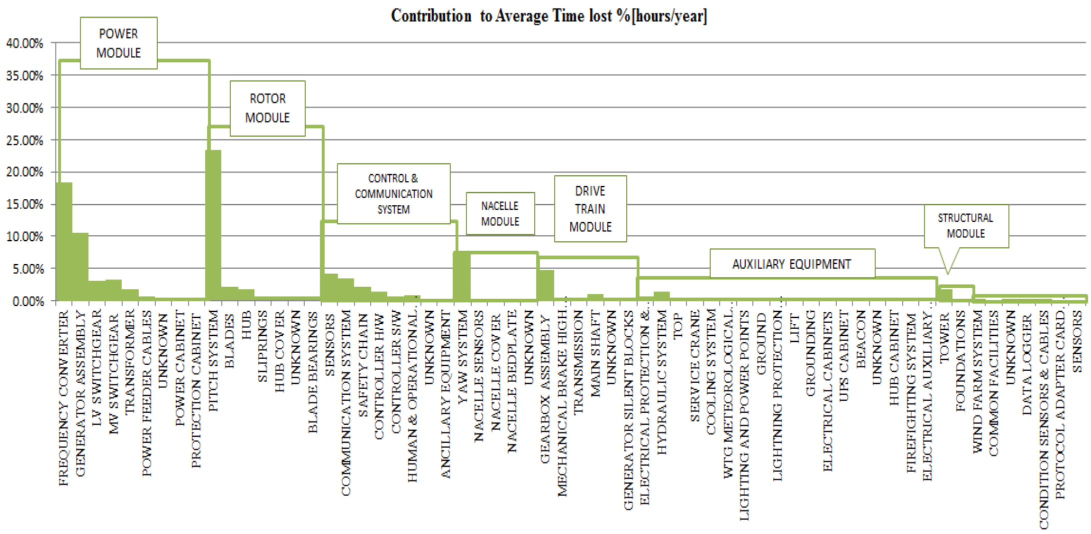


Figure 4 Average time lost (%) of Reliawind Data.

Case 3. Failure rate vs. Technical concept [3]

Characteristic features of the different concepts				
	Simple Danish Concept	Advanced Danish Concept	Standard variable-speed	Direct-drive
Exemplary turbine groups(WMEP)	AN Bonus 100/150, Vestas V 17/20	Vestas V 25/27/29, Ventis 20-100	Vestas V 63/66, Enercon E32/33	Enercon E 40, Enercon E 66
Control	Stall	Pitch		
Speed Characteristic	Constant		Variable	
Gearbox	Gearbox			Direct-drive

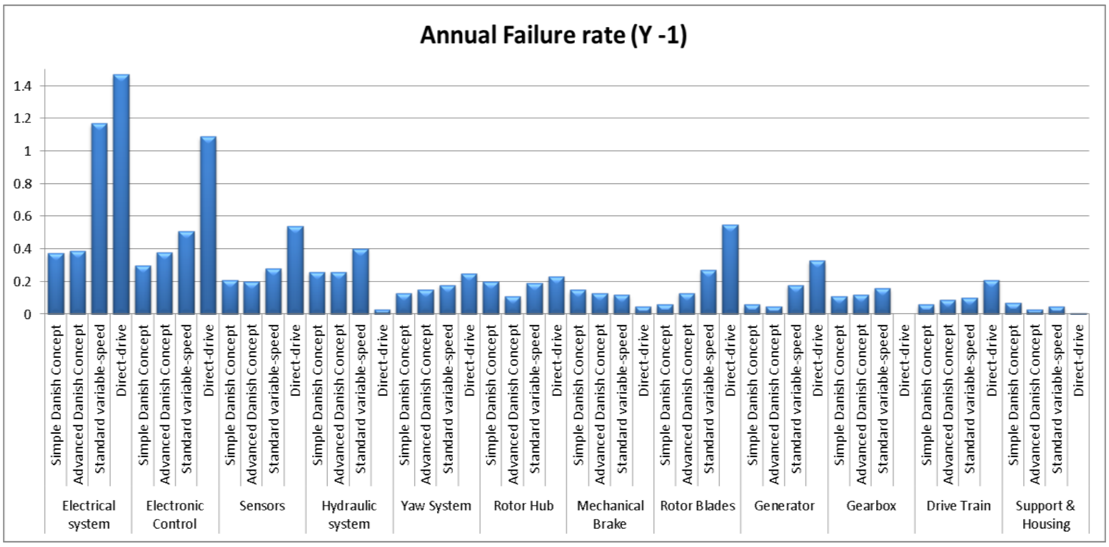


Figure 5 Failure rate of different wind turbine concept.

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Appendix C

List of input parameters of Jeju offshore wind farm operation and maintenance model

Table 1 General Jeju offshore wind farm and maintenance data

Project:	Jeju offshore wind farm model	Unit	Input
Wind farm data			
	Price of energy	€/kWh	0.250
	Wind farm efficiency	%	90
Meteo			
	Reference height weather data	m	60
	Power law exponent	-	0.23
Maintenance data			
	Minimum length of repair period	h	2
	Clock time start of working day	h	7
	Clock time end of working day	h	19
	Control room type	-	24/7 operational
Cost of technicians			
	Maintenance	€/y	522,000
Maintenance periods			Period (relative to sim. period)
	Preventive maintenance	dd-mm	01-May to 30-Jun

Table 2 spare input data of Jeju offshore wind farm

Corrective	SCS no.	Name	Logistic time [h]	Material costs
	1	No cost	0	0
	2	Consumables	0	400
	3	Small parts-6	24	6,000
	4	Small parts-240	24	240,000
	5	Large parts-140	150	140,000
	6	Large parts-200	300	200,000
	7	Large parts-600	300	600,000
	8	Large parts transformer	1080	280,000
	9	Small parts foundation/ scour protection	48	6,000
	10	Cable	240	200,000
Preventive	**13**	BOP	0	60,000
	14	WT	0	12,000

Table 3 Equipment input data of Jeju offshore wind farm

	Type Logistics & availabili	Name Unit	Input	Weather limits		Unit	Input	Cost	Unit	
1	Access vessel	Small access vessel								
	Travel time	h	1	Wave height	Travel	m	1.5	Fixed	/year	200,000
	Max. technicians	-	6		Transfer	m	1.5	yearly		
	Transfer category	-	multiple cre	Wind speed	Travel	m/s	12			
	Travel category	-	daily		Transfer	m/s	12			
2	Vessel for replacement	Jack-up vessel								
	Mobilisation time	h	360	Wave height	Travel	m	2	Work	/day	100,400
	Demobilisation time	h	24		Transfer	m	2	Wait	/day	75,300
	Travel time	h	2		Positioning	m	2	Mob/	/mob	200,000
	Transfer category	-	single crew		Hoisting	m	2	Demob		
	Travel category	-	stay	Wind speed	Travel	m/s	10			
	no. of eqp corrective	-	1		Transfer	m/s	10			
					Positioning	m/s	10			
					Hoisting	m/s	10			
3	Support vessel	ROV								
	Travel time	h	1	Wave height	Travel	m	2	Fixed	/year	4,000
	Max. technicians	-	0		Transfer	m	2	yearly		
	Transfer category	-	single crew		Positioning	m	2			
	Travel category	-	daily		Hoisting	m	2			
	no. of eqp corrective	-	1	Wind speed	Travel	m/s	12			
					Transfer	m/s	12			
					Positioning	m/s	12			
					Hoisting	m/s	12			
4	Support vessel	Diving E.								
	Travel time	h	1	Wave height	Travel	m	1.5	Fixed	/year	4,000
	Max. technicians	-	2		Transfer	m	1.5	yearly		
	Transfer category	-	single crew		Positioning	m	1.5			
	Travel category	-	daily		Hoisting	m	1.5			
	no. of eqp corrective	-	1	Wind speed	Travel	m/s	12			
					Transfer	m/s	12			
					Positioning	m/s	12			
					Hoisting	m/s	12			
5	Internal crane	Nacelle crane								
	Transfer category	-	single crew							
	Travel category	-	daily							
6	Internal crane	Davit crane								
	Transfer category	-	single crew	Wave height	Hoisting	m	1.8			
	Travel category	-	daily	Wind speed	Hoisting	m/s	12			

Table 4 Repair classes input data of Jeju offshore wind farm

RC no.	Name	Unit Mission	T_{org} [h]	Eq1	Eq2	Eq3	T_{work} [h]	N_{tech}
1	Remote reset							
		Remote reset	-	-	-	-	2	-
2	4h Inspection/small repair inside							
		Repair	6	1	-	-	4	2
3	9h Inspection/small repair outside							
		Replacement	6					
		Preparation	-	1		5	2	2
		Hoisting	-	1	5	-	6	2
		Finalisation	-	1	5	-	1	2
4	9h Replacement parts(<2)							
		Inspection	6	1	-	-	4	2
		Replacement	12					
		Preparation	-	1		-	2	2
		Hoisting	-	1	5	-	4	2
		Finalisation	-	1	-	-	3	2
5	18h Replacement parts(<2)							
		Inspection	6	1	-	-	4	2
		Replacement	12					
		Preparation	-	1		-	7	2
		Hoisting	-	1	3	-	4	2
		Finalisation	-	1	-	-	7	2
6	21h Replacement parts(<100)							
		Inspection	6	1	-	-	4	2
		Replacement	16					
		Preparation	-	1	-	-	5	4
		Positioning	-	1	2	-	3	4
		Hoisting	-	1	2	-	5	4
		Finalisation	-	1	-	-	8	4
		Repair	6	1	-	-	9	2
7	36h Replacement parts(<100)							
		Inspection	6	1	-	-	4	2
		Replacement	16					
		Preparation	-	1	-	-	10	4
		Positioning	-	1	2	-	3	4
		Hoisting	-	1	2	-	5	4
		Finalisation	-	1	-	-	8	4
		Repair	6	1	-	-	9	2
8	9h BOP transformer repair							
		Repair	6	1	-	-	9	2
9	42h BOP transformer repair							
		Inspection	6	1	-	-	4	2
		Repair	12	1	-	-	38	2
10	9h BOP foundation/scour protection							
		Replacement	6					
		Hoisting	-	1	6	7	9	2
11	26h BOP cable replacement							
		Replacement	26					
		Preparation	-	1	6	3	6	2
		Positioning	-	1	6	3	4	2
		Hoisting	-	1	6	3	10	2
		Finalisation	-	1	6	3	6	2
14	BOP (preventive)							
		Repair	-	1			90	2
15	WT (preventive)							
		Repair	-	1			40	2