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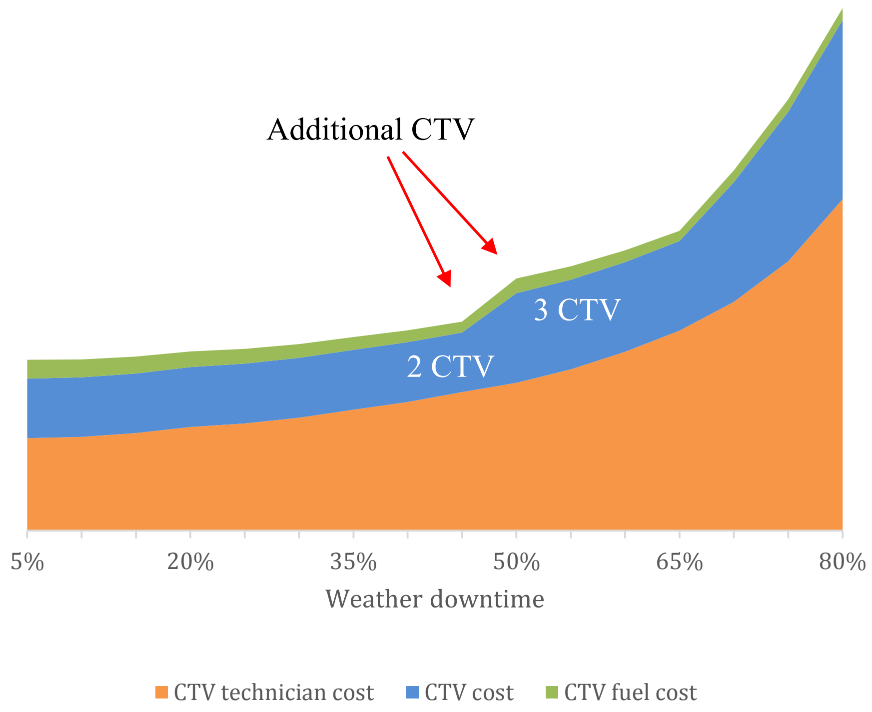

Maintenance Optimization of Offshore Wind Power

- Concept Development for Future Cost Reduction

Master of Science Thesis in Management and Economics of Innovation

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Göteborg, Sweden 2014

Report No. E2014:087

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Cover:
Impact of WDT on a CTV setup, see p.28

Chalmers Reproservice
Göteborg, Sweden 2014

Acknowledgement

The authors would like to express their gratitude to the people who have provided great support and valuable input during the process of writing this thesis. Without the support of our project team at *Siemens*, this study would not have been successful. With great enthusiasm and constructive feedback the project team guided our way forward through the project. We would also like to express warm thanks to everyone at *Siemens* who has contributed to this work, and especially the *Maritime and Aviation Solution* team. A special thanks to professor Mats Winroth for his excellent advices during the process of completing our thesis, his guidance and interest has made this a rewarding journey. In addition we would like to thank our families and friends encouragement.

Anton Gustavsson

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Chalmers University of Technology, Göteborg, 2014

Abstract

This study aims at increasing the knowledge within renewable energy, of which offshore wind power is believed to be one important technology. This technology is in an early stage of development and in order to be competitive against conventional energy sources, further cost reduction is needed. One potential area of cost reduction is offshore maintenance logistics. To explore this area, findings from expert interviews are combined with industry data and literature to create a cost model. This model is used to explore the impact of major cost drivers of offshore maintenance; *distance to shore, weather downtime, number of turbines,* and *number of service hours.* The results are presented graphically and used to explore two offshore-based concepts with site conditions of a future planned wind farm. The compared concepts are an accommodation platform and a vessel capable of hosting technicians offshore. An availability simulation is performed to compare the performance of the two service strategies. It reveals an equal performance level together with a positive availability impact of using helicopters for maintenance. The concepts are further elaborated on in order to explore their individual potential of cost reduction and the compounded effect is discussed. The results from the study show that the cost structure is impacted differently by the cost drivers depending on the logistical setup. Another important aspect of the service strategy is balancing asset capacity to service demand. The authors believes that knowledge of this study is vital for decision making in order to bring down the cost of offshore maintenance, thus the levelized cost of energy, making renewable energy competitive.

Keywords: offshore wind power, maintenance, service, cost drivers, O&M, cost reduction, service concept, strategic development, capacity utilization

Nomenclature

Abbreviations

CAPEX	Capital Expenditure
CTV	Crew Transfer Vessel
HHO	Helicopter Hoisting Operation
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
MLDT	Mean Logistical Delay Time
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
O&M	Operation & Maintenance
SOV	Service Operation Vessel
WDT	Weather Downtime
WF	Wind Farm
WFO	Wind Farm Operator
WTG	Wind Turbine Generator

Units

€	Euro
Hs	Significant wave height
kt	Knots (1.85 km/h)
MW	Megawatt
MWh	Megawatt hour
NM	Nautical Mile (1852 m)
Pax	Passengers

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1 Introduction

This chapter is to give a background within the field of offshore wind power, it describes the goals of Siemens, and challenges lying ahead for the industry. It further describes the assignment with two research questions that are to be answered to fulfil the aim and purpose of this study.

1.1 Background

The *European Commission* has directed a climate goal aiming to increase the use of renewable energy. The directive requires that 20 percent of the energy within the *European Union* should be produced from renewables in 2020 (European Commission, 2009). To reach this target, energy producers have to invest in new cost efficient technologies that produce energy from renewable sources. Offshore wind power is believed to be one important technology contributing to the EU's climate goal. This technology is however in an early stage of industrialisation and in order to make it competitive against conventional power generation it needs further cost reduction (Kost et al., 2012).

Siemens have promised their customers a 40 % cost reduction of offshore wind power by 2020 so as to bring the Levelized Cost Of Energy (LCOE) to less than €100 per MWh (Siemens, 2013). The two main cost are the cost of installation and the cost of service. A large part of the cost of service pertains to use of efficient logistical systems (Philips et al., 2013). The logistical setup is an important consideration due to challenges of remoteness, and often unpredictable weather conditions at offshore Wind Farms (WF). These challenges are expected to increase in the future, as wind power moves further from shore. These "farshore" WFs create a need for offshore based solutions such as a Service Operation Vessel (SOV) or an accommodation platform (Besnard, 2013, Philips et al., 2013).

In Great Britain alone, 3000 turbines are proposed to be built at farshore sites, with a distance to shore greater than 40 Nautical Miles (NM). Philips et al. (2013) explored the performance impact of distance to shore as a cost driver and concludes that it affects which setup is suitable. Halvorsen-Weare et al. (2013) and Besnard et al. (2013) reveals other important cost drivers such as weather conditions, number of turbines and turbine reliability, although no cost driver was subject to analysis. As such it is uncertain how service will be performed efficiently for future WFs.

With this study the authors want to increase the knowledge within maintenance in the renewable energy sector by performing a cost driver sensitivity analysis for farshore service solutions. This is novel within the field as neither the cost drivers of offshore wind power nor concept comparison between a platform and an SOV solution have been fully explored academically. It is also a critical field to examine, as wind power experiences a high cost pressure, and the cost of service will raise as service moves further from shore.

1.2 Assignment description

As the current market leader in the segment offshore wind power, *Siemens* predicts potential in new ways of organising offshore maintenance for future wind farms. This study aims at exploring this potential by studying the wind farm Hornsea, which is to host a large number of turbines. The service organisation serves to maintain the production capacity of the wind farm by conducting preventive and corrective maintenance. Large factors of the service organisation include: means of transportation, staff, location, sourcing strategies, service base and bundling possibilities. An optimised maintenance structure has potential to reduce the service cost.

Initially the assignment intends to take a “snapshot” of the present solutions. By gaining information from a broad spectrum, this study will provide basic understanding of cost drivers and key constraints related to offshore maintenance. The maintenance structure is to be mapped for offshore maintenance of wind farms. This knowledge will further be used to perform a sensitivity analysis of farshore solutions to reveal the impact of cost drivers. These results are used as a basis to develop concepts, which are then evaluated by simulated availability in order to measure their performance. The study is to show a cost efficient and high performing service solution for Hornsea. Conclusively the study will examine how service solutions would be affected by a future scenario with decreased number of service hours.

1.3 Aim & purpose

The aim of this study is to increase the knowledge within the field of renewable energy by examining future potential of cost reduction of offshore wind power. This knowledge is vital for the EU to reach its climate goals. The purpose of this study is to investigate how service of offshore wind power can be optimized through cost driver sensitivity analysis, thus contributing to cost reduction in the renewable energy sector.

1.5 Research questions

The major questions to be answered in this thesis are:

> *RQ 1, How do maintenance cost drivers of offshore wind power impact the cost structure and logistical setup for farshore service solutions?*
>
> *RQ 2, How can a service provider in the offshore wind power industry develop its service and offer a cost efficient service solution for future wind farms?*

1.6 Limitations

For offshore wind power the focus will be on the Operation and Maintenance (O&M) organisation, thus exploring the lifetime of a WF and disregarding commissioning and decommissioning. Further, the operational part of O&M is not regarded as affected in a major way depending on service solution and will thereby not be subject of this study. The scope will comprise only on the maintenance of the Wind Turbine Generator (WTG) disregarding substructure and all other equipment in the WF such as transformer stations, cables etc. In the maintenance organisation, focus will be at offshore logistics, excluding all technical aspects of WTGs except for the number of work hours.

Within logistics, considerations will be on transporting technicians to and from the turbine only, thus excluding the logistical aspect of stock management. The type of maintenance requiring a crane vessel, Jack-Up, will also be excluded. This part of service is performed with technicians and management tied to the Jack-Up and will thereby not affect other parts of the offshore logistics.

2 Methodology

This chapter presents methods used in this study. It describes the characteristics and the design of this particularly research followed by a description of the research process. It also describes the methods for data collection, and discusses the validity and reliability of the research.

2.1 Research characteristics

This study focuses on the cost driver impact on service solutions for future WFs and how concepts can be developed in order to provide customer value while reducing cost of service. To explore this, in-depth knowledge of the current situation is needed. Data collected will be compared with literature to test whether the current situation is aligned with theory giving the study deductive characteristics, meaning theory is driving the research process (Bryman and Bell, 2011).

Regarding the epistemological consideration: this study coheres with the concept of positivism, meaning that science should be conducted objectively. For the ontological consideration the research follows the concept of constructionism, which states that social phenomena are produced through social interactions and are in a constant state of revision (Bryman and Bell, 2011).

2.2 Research strategy

The research strategy has two general approaches, which can be of guidance when choosing methods of data collection and analysis; qualitative and quantitative. Qualitative research is the dominant method for conducting business research and can be used when data is hard to quantify, or when the sample size is small (Bryman and Bell, 2011). Quantitative research is suitable when large sample sizes of quantifiable data are desirable, the approach may also be suitable to test and validate theory. The scope of this study entailed the use of both research approaches.

In a relatively young industry there is a limited number of experts in the field, this calls for the use of qualitative methods to incorporate knowledge. Other measures regarding offshore maintenance are on the contrary well suited for quantitative research. An example of an area suitable for quantitative research is historical weather data, which can be used to estimate the accessibility and energy production of wind turbines.

2.3 Research design

The research design intends to guide the choice of research method used in a study. Since this research is based on an in depth investigation of a unique case connected to a single actor within the industry, a case study research design has been chosen. According to Bryman and Bell (2011) a case study design has the possibility to grasp the complexity and particularities of a unique case. This design is also widely used within business and management research (Bryman and Bell, 2011). Hence the design is deemed appropriate for the frame of questions in this study.

2.4 Research process

During this study, information was continuously collected and documented. The process is built up of five phases and results from earlier phases were used as a foundation for later stages in a linear process. This enabled a funnel structure with a wide scope of learning early in the process and a continuously narrowed focus towards significant areas in later stages. Iterations were however applied when gaps of knowledge were identified and a broader perspective needed. During the study continuous meetings were held with the supervisor at *Chalmers University of Technology* and the project steering group at *Siemens* to adjust the development and affirm the goals of the research.

In the first phase a pre-study was conducted to gain knowledge and to form a basic understanding of maintenance of offshore wind power. Information from the pre-study was collected from internal company reports, web-based search, and a few qualitative interviews with people from the industry and academia. By using both written sources and qualitative interviews, this pre-study provided both preliminary and secondary data.

In the second phase the maintenance structure at *Siemens* was mapped. This mapping was done by studying service and logistical data together with collecting additional data from interviews with logistical and operational experts at *Siemens*. These interviews had a semi-structured approach and explored identified cost drivers.

The third phase of this study was to develop a tool for cost calculation. This was done by developing a model which used 78 variable inputs to calculate cost. The inputs used for the model consisted of logistical costs provided by *Siemens*, data for the specific site Hornsea and turbine reliability. Historical weather data for the period 2001-2013 was used to simulate accessibility for different means of transportation. The model was validated against previous calculations of Hornsea service costs.

The fourth phase was to perform a cost driver sensitivity analysis of logistical setups using the model. This was done by changing parameters for each cost driver individually within intervals. This analysis provided results for how each cost driver impact the cost. This phase was to answer RQ 1.

The fifth phase used the results from previous phases to explore possible improvements of service concepts for Hornsea conditions. These concepts were measured on their performance through availability simulation using software provided by *Siemens*. Areas of potential improvement were explored using the cost calculation tool developed in phase three in order to answer RQ 2.

2.5 Methods for data collection and analysis

Several techniques were used for collecting data and performing analysis in this study. By describing the execution of each method with its scientific approach in detail, the authors hope to safeguard the quality and replicability of this study.

2.5.1 Data collection

During the investigation, data was collected from three repositories: it was firstly collected from easily available sources in the field using web and library search engines. This gave the authors of this paper a wide range of information during the pre-study phase.

Secondly, literature was provided from several departments at *Chalmers University of Technology: Department of Technology Management and Economics*, *Department of Energy and Environment*, and *Department of Shipping and Marine Technology*. The snowballing sampling was used which allows one to find new acquaintances of initial respondents through their guidance (Bryman and Bell, 2011). This provided a technical academic approach to the studied phenomena enabling a multitude of viewing angles.

Thirdly, literature and data was provided by *Siemens*. Literature provided included both general industry information, but also included in depth descriptions of operational challenges and trends. Specific information connected to service logistics and operational cost was also provided for cost calculations.

For all phases of this study, literature was continuously collected and documented from various sets of sources. This enabled additional relevant literature based on new information gained from each phase.

2.5.2 Qualitative interviews

In order to broaden the understanding of current services offered by *Siemens*, an exploratory approach was needed. According to Bryman and Bell (2011) a qualitative approach can help develop the initial research idea. Due to the novelty in the field, and unknown particularities of how offshore maintenance are offered by *Siemens* and semi-structured interviews were applied. Initially, 17 interviews were carried out with experts in the field within *Siemens*. The semi-structured interviews assured a coverage of relevant topics while allowing for respondents to spin off into relevant side-tracks as described by Bryman and Bell (2011).

2.5.3 Cost driver analysis model

To perform an analysis of different setups a tool for cost calculation was developed. The foundation for the tool was the scheduled and unscheduled service hours per turbine and the number of turbines. To calculate costs for different service solutions the workload was dedicated to different means of transport. In the model three head categories of transport means were specified; Service Operation Vessel (SOV), Crew Transfer Vessel (CTV), and Helicopter. These were possible to adjust further depending on the specifics of each transport means.

Each transport means effect how much time technicians can work at the turbine. This is mainly affected by the lost work time for each transport means, such as travel time and weather downtime (WDT), which is time where turbines cannot be reached due to weather conditions. The travel time is among several factors affected by transport speed, distance to shore and team size. This lost time is deducted from the technician's annual working hours, which affect the total number of technicians. The amount of technicians' impact the demand of transports means and consequently the total maintenance cost, see Figure 1.

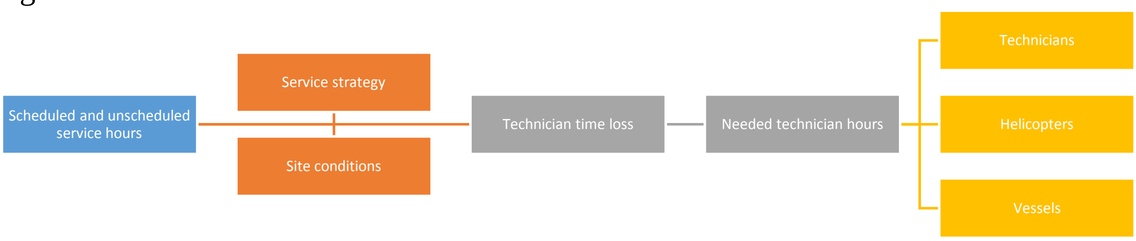

Figure 1 Schematic model of cost driver analysis tool

The output of model, graphically illustrates the effect of cost per turbine by different cost drivers and setups, e.g. distance to shore, number of turbines, and weather downtime. The costs were divided into several categories and displayed graphically for each asset type. For solutions that required offshore accommodation platform, the Capital Expenditures (CAPEX) of the platform and the maintenance cost per year were illustrated as one cost component.

2.6 Reflections on research quality

A large amount of information was collected from qualitative interviews. The approach of using semi-structured interviews entails the risk of anchoring, which is influence on the results depending on which questions are asked (Bryman and Bell, 2011). As such the respondents needed to have experience within the field as well as the study presented to them in order to gain accurate responses and ensure high construct validity allowing the study to measure what it was intended to (Bryman and Bell, 2011). For the reliability, the semi-structured interviews were held in private to eliminate outside influences. To ensure consistency of the results further, one researcher performed the interview, while the other took notes and asked clarifying questions.

Results and data were discussed with an expert group on a weekly basis in order to confirm the accuracy of conclusions and collected data. Any uncertainties were noted and followed up with additional interviews to enhance the internal validity. The external validity of this study can be perceived as low as the study focuses on one single case. This study did however analyse several correlations between different parameters, which is presented as a main result. These correlations can to a certain extent be generalized and applicable for other situations.

Although information largely came from qualitative industry interviews, information was also collected from scientific papers, together with quantitative industry data. Hence a triangulation of both source and method was applied in order to improve the quality of the research.

3 Theoretical framework

This chapter presents the theory behind this study. It starts by giving an introduction to service of offshore wind power and describes how maintenance may be structured together with turbine reliability and availability. Further, it addresses calculation of energy costs and asset utilization.

3.1 Maintenance organisation

Offshore WTGs face harsher environment and are more exposed to breakdowns compared to WTGs onshore. The offshore conditions have an impact on the cost of O&M, which amounts to 15 - 30 % of the total cost of energy (Besnard, 2013). Although facing harsh conditions and high service cost, there are some clear benefits of mounting wind turbines offshore. The wind speed is high and has low variability, providing a Wind Farm Operator (WFO) with a high and steady yield (Karyotakis, 2011).

The maintenance organisation is an important aspect of offshore wind power and impacts both cost and performance. It comprises of the resources required to perform maintenance such as staffing, sourcing strategies, and the challenge of offshore logistics. In order to expand the installed capacity of offshore wind power, the logistical challenges will be even greater as WFs need to be located further away from shore on deeper water with longer travel distances (Besnard et al., 2013).

Besnard et al. (2013) have identified several critical aspects for the maintenance organisation of offshore WFs that need to be considered. The location of a maintenance base is central for the service performance as it affects the travel distance. This location can be either at a harbour onshore or with technicians accommodated offshore at a platform or at a larger vessel. Another important aspect is which type of transportation is used. Vessels or helicopters differ in which type of maintenance they are suitable to perform, due to differences between scheduled and unscheduled service. The transport means also differs in limitations and specifications, such as operable wave height, wind speed, transport capacity, and speed. Location of maintenance base and type of transportation means will both affect the lead time to serve a wind farm through travel distance and transport speed (Besnard et al., 2013, Besnard, 2013).

3.2 Offshore assets

There are different types of assets serving as transport means and offshore accommodation for technicians. For transport of technicians, both vessels and helicopters can be used. The most common vessel is a CTV, which is used for crew and equipment transport. The CTV usually has a passenger capacity (pax) of 12 or 24 and is used for daily operations. To decrease transport time, and access the turbine at rough sea conditions, it is also possible to use a helicopter which hoist technicians directly to the nacelle at the top of the turbine. Although the fastest means of transport a helicopter is limited in transportation weight, and has less pax for service operations. There are also larger helicopter versions, which cannot be used for service but are suitable for crew transport to an offshore station (Philips et al., 2013, Navigant Consulting, 2013).

If the transport distance is too large from an onshore base, it is necessary to have offshore accommodation to decrease the time lost in transport (Philips et al., 2013). A platform serves as an offshore base, which has the possibility to host technicians close to a wind farm. From a platform, either CTVs or helicopters can be used to access the WTGs. The SOV is another option for offshore accommodation. It is a larger vessel used to host personnel and transfer technicians and equipment to the WTGs (Navigant Consulting, 2013).

3.3 Maintenance strategies

Maintenance refers to technical activities and connected administrative activities, with the aim of retaining or restoring the function of an item (Besnard, 2013). Tian et al. (2011) describe three types of maintenance strategies for offshore wind power; corrective-, preventive- and condition based maintenance. The condition based strategy refers to studying degradation of components in order to transfer corrective- into preventive maintenance (Besnard, 2013). Preventive maintenance is also referred to as *scheduled service*, while corrective is described as *unscheduled service* (Philips et al., 2013).

Scheduled service is planned maintenance with a predefined interval or criteria with the purpose on reducing the probability of failure. It can be either time or usage based. When time based, a probability distribution is assumed to determine service interval from e.g. the age of a component. For usage based maintenance the service interval is decided by the usage of a component. *Unscheduled service* is on the contrary unplanned maintenance carried out after failure in order to restore the function of a component or system. This is usually done when there is no efficient measure to predict failure. From a cost perspective it is preferable with scheduled service since the cost of the maintenance activities and production losses can be reduced (Besnard, 2013, Tian et al., 2011).

3.4 Cost drivers

Cost of offshore maintenance differs extensively depending on WFs site conditions. There is no one best solution and the logistical setup is designed with consideration to cost and performance. Cost can be calculated in cost per turbine for a setup and performance in turbine availability, which is connected to energy production (Besnard et al., 2013, Philips et al., 2013). The logistical setup has a number of main considerations, cost drivers, impacting the size, cost, and performance of the service organisation directly or indirectly (Halvorsen-Weare et al., 2013).

The cost drivers identified by Philips et al. (2013) are, distance from onshore facilities, substation design, average sea state; number, size, and reliability of turbine. The same authors identify the number and reliability of turbines as the most influential factor when deciding upon the most cost efficient service structure, followed by the distance from onshore facilities. Rademakers et al. (2003) also identify the importance of distance to shore, weather conditions, turbine reliability and number of turbines as parameters of maintenance cost, and further state water depth and service concept as cost drivers (Rademakers et al., 2003).

Number of turbines

The number of turbines, together with the service-need of each WTG, affect the total maintenance need of a WF. Every turbine has an amount of scheduled and unscheduled service hours that needs to be performed each year. These work hours multiply with the number of turbines into the total need of service hours. Consequently this affects the number of technicians and the asset need (Besnard, 2013).

Distance to shore

The distance, which technicians travel in order to access the wind farm, impacts the service structure. The travel distance between the service base and a WF lead to a time loss and reduce the time remaining for active work during a shift. When the working time is decreased, an increased number of technicians and vessels are needed to perform service. When the time lost in transit is too large, an offshore accommodation is needed (Besnard et al., 2013, Philips et al., 2013).

Weather conditions

Philips et al. (2013) state the difficulties of getting technicians on and off turbines. A major part of this pertains to the accessibility of a turbine. The accessibility refers to the ability to access a turbine using certain means of transport. It is a function of the limitations of the transport and the weather conditions. In order to execute maintenance a weather window is needed which covers the travel time and the time of the service operation (Halvorsen-Weare et al., 2013).

Accessibility of a transport is measured by limitations in significant wave height, wind and visibility. Significant wave height, Hs, is defined as the top third of a wave (Philips et al., 2013). It is claimed that an upper limits of vessels is about 2 m Hs and that it might be periods of 1 - 2 months during wintertime when accessing a turbine is impossible (Karyotakis, 2011).

Trends and setup

If the renewable targets for EUs energy consumption should be met, offshore wind power would have to increase in capacity. In order to do so, offshore wind power would have to expand further from shore. The maintenance cost will increase as WFs are built further offshore, in deeper waters and more challenging weather conditions. In order to keep the cost of energy down, it is important to keep the vessel fleet cost to a minimum, as it has a large impact on the maintenance cost (Halvorsen-Weare et al., 2013). If illustrated using the cost driver, distance to onshore base, the optimal setup of the vessel fleet will differ, see Figure 2.

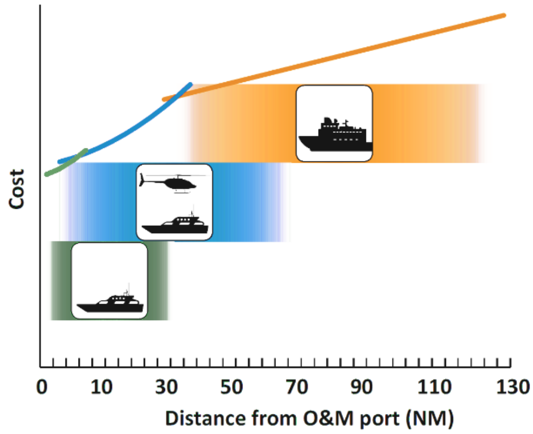

Figure 2 Case study of optimal vessel setup (Philips et al., 2013: 12)

When maintenance is performed further from shore, the overall cost and complexity of service will increase. In the case study of Figure 2, using a helicopter becomes cost efficient at a distance of 12 nautical miles from an onshore base. At 40 NM, the time lost in traveling is so great that an investment in an offshore base become cost beneficial. The effect of distance to shore as a cost driver will decrease as turbines will be built further from shore, and offshore concepts become more common in the business (Philips et al., 2013).

Cost reduction

As offshore wind power is in an early stage of development, large potential cost savings are expected as the industry develops. The potential cost savings come from many fields. Financially, the cost of capital is expected to decrease as more WFs are being built offshore, and the perceived investment risk decreases. Preventive and corrective maintenance, which are large parts of the O&M cost seen in Figure 3, are identified as areas of cost reduction following technical improvements. A large potential cost saving is due to economies of scale, both from an increased size of WFs, but also from an increased scale of WTGs (Hobohm et al., 2013).

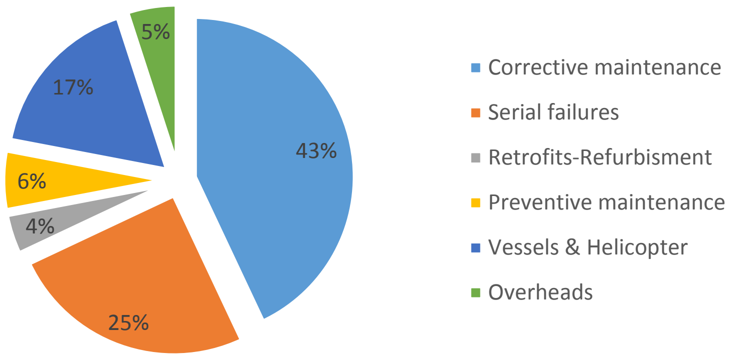

Figure 3 O&M costs of offshore wind power (Besnard, 2013: 2)

Asset optimization is expected to be an important area for cost reduction. One potential way of reducing asset cost is identified as synergies through sharing of resources. O&M is estimated to contribute with a cost saving of between five and eight percent of the LCOE, assuming an expected development of shared logistical assets between WFOs (Hobohm et al., 2013, Philips et al., 2013).

Availability is measured by the degree a system, subsystem or equipment is in an operable state, which for wind power is the state a WTG can produce energy. The WTGs availability is impacted by scheduled, unscheduled service, and the performance of O&M organisation. Each WTG's availability is measured individually to calculate an average for the WF. Availability can however be calculated by using different methods. There is a type of availability named *turbine availability* which Harman et al. (2008) describes to be misleading. It focuses on contractual warranty arrangements where several carve outs are included for each project, e.g. allowances for scheduled service or weather downtime risk (Harman et al., 2008, Philips et al., 2013). This type of availability causes two problems, firstly it can be misleading when comparing performance of WFs. Secondly, it does not reflect on the total down-time (Harman et al., 2008).

The availability described above is also misleading according to Conroy et al. (2011) since energy production from wind power is dependent on wind speed, which fluctuates. Conroy et al. (2011) argues that energy based (yield based) availability is a more appropriate method to provide accurate data. Energy based availability considers the non-linear relation between time and energy production due to different wind speeds, hence there are no losses for a temporary shutdown during a windless day (Conroy et al., 2011).

Another measurement for comparing setups in financial modelling is *system availability*, see Equation 1. This measures time where the turbine is in a functional state, against total time, disregarding wind data and reasons for downtime. This is the most simplistic measurement according to Harman et al. (2008).

$$System\ Availability\ = \frac{Time\ turbines\ are\ ready\ to\ operate}{Total\ time} \quad (1)$$

The system availability is usually 95 - 99 % for onshore WFs due to easy accessibility, while it has been significantly lower (e.g. Barrow WF in UK with 67 %) in early stages of offshore WFs due to remoteness, harsh weather conditions and serial failures (Feng et al., 2010).

Availability has impact on financial performance of the WF. The purpose of the maintenance organisation is to maintain the WTGs capability to produce energy and hence generate revenue. A general assumption is that a high performing organisation which deliver high availability also has higher direct cost of O&M compared to a low performing organisation (Harman et al., 2008). The cost impact of increasing the performance of the O&M organisation can be illustrated with an exponential curve, while lost revenues due to production losses can be illustrated as a linear cost curve correlating to availability. These two correlations can be mapped into a graph to illustrate the trade-off, where the sum of lost revenue and the direct O&M cost has a theoretical minimum, see orange curve in Figure 4 (Philips et al., 2013).

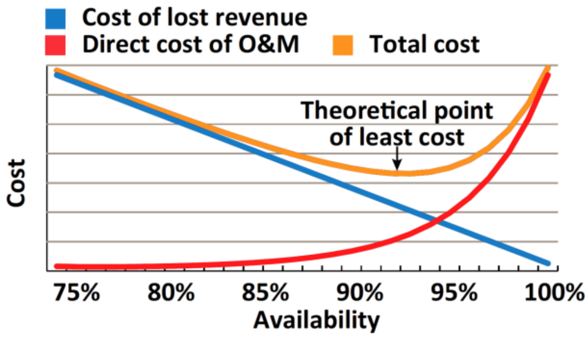

Figure 4 Illustration of lowest theoretical total cost (Philips et al., 2013: 9)

The main driver reducing availability for WTGs is the downtime that appears due to the *Mean Time To Repair* (MTTR), and the *Mean Logistic Delay Time* (MLDT). The sum of these two components and the *Mean time To Failure* (MTTF) gives the *Mean Time Between Failure* (MTBF), see Equation 2. These measurements can be used to calculate system availability, see Equation 3 (Mahadevan, 2010, Jin et al., 2012).

$$MTBF = MTTF + MITTR + MLDT \quad (2)$$

$$A = \frac{MTBF - MTTR}{MTBF} \quad (3)$$

3.5.1 Levelised Cost of Energy

The LCOE formula, see Equation 4, measures the average cost of energy over the lifetime of a power plant. By using this formula different types of energy sources can be compared from a cost perspective. LCOE is calculated as the present value of investment and operation cost during the lifetime of the plant divided by the value of generated energy during the corresponding period (Hobohm et al., 2013).

$$LCOE = \frac{l_o + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}} \quad (4)$$

LCOE	Levelised cost of energy in Euro/MWh
l_o	Capital expenditure in Euro
A_t	Annual operating costs in Euro in year t
M_{el}	Produced electricity in the corresponding year in MWh
i	Weighted average cost of capital in %
n	Operational lifetime
t	individual year of lifetime

3.5.2 Life Cycle Cost

Nilsson and Bertling (2007) used Life Cycle Cost (LCC) to calculate the total maintenance cost during the lifetime of a WF, LCC is calculated by Equation 5. The LCC contains cost for maintenance and the cost of production losses. Maintenance cost is the direct cost of maintenance, while production losses is the cost of lost revenue. The aim is to minimise the LCC, consequently reducing maintenance cost and/or increasing availability.

$$LCC = C_{Inv} + C_{CM} + C_{PM} + C_{PL} + C_{Rem} \quad (5)$$

C_{inv}	Cost of the investment
C_{CM}	Cost for corrective maintenance
C_{PM}	Cost for preventive maintenance
C_{PL}	Cost for production loss
C_{Rem}	Remainder value

3.6 Capacity balancing and waste

When capacity is increased, unit cost often reduces in what is referred to as economies of scale. Fixed cost do not usually increase to the proportion of changes in capacity need. When increasing capacity, fixed costs often increase stepwise following additional investments. The points of capacity increase is referred to as *fixed cost breaks* by Slack et al. (2013). In order to maintain an optimal cost level, it is important to match capacity with demand. If there is an overcapacity, the unit or production cost would be higher as fixed investments could have been shared over additional units. Should the demand be greater than the capacity there is a risk of additional cost such as overtime or increased maintenance cost of assets (Slack et al., 2013: 168).

When investing in additional capacity, it may be disadvantageous if the capacity steps are large. With a large increase in production capacity, there is a risk of low asset utilization following the fixed cost break. Thus, investing in several assets with lower capacity will enable a better match between capacity and demand curve. Slack et al. (2013) also identify other factors with potential of influencing unit cost including several types of waste of both asset and technician capacity. Waiting time and transportation are typical types of waste connected to work efficiency (Slack et al., 2013: 472).

3.7 Previous studies

A few previous studies have been found which examine the cost of offshore maintenance. Hofmann and Sperstad (2013) made a comparison between an SOV and a platform concept, which showed a higher availability for the SOV concept. In the study the SOV were however equipped with a crane, which decreased the lead time of waiting for a crane ship. Philips et al. (2013) studied the impact of the cost driver distance to shore and concluded that an offshore accommodation would be beneficial for a travel distance to WF exceeding 40 NM.

Besnard (2013) developed a tool for analysing the cost structure of a wind farm with 100 5MW turbines using the weather conditions of the WF Horns Rev, and a travel distance of 32 NM. The study took into account the availability of the WF as a factor, thus calculating the service cost from a WFO perspective. The study compared the cost of performing service from an onshore base or a platform, and concluded that a platform solution would be the most cost beneficial. For the logistical setup, the lowest total cost is achieved when servicing the WF using CTVs with a wave limitation of 2 m Hs. It also showed a connection between increasing failure rate, and the cost benefit of having a helicopter or platform (Besnard, 2013).

4 Empirical findings

In this chapter data collected through the assignment will be presented. Important maintenance factors such as work hours, logistical assets and cost drivers will be described.

4.1 Offshore maintenance

Although there is an IEC standard for what is regarded as corrective and preventive maintenance, *Siemens* has chosen its own definition, dividing maintenance into *scheduled* and *unscheduled service*. Scheduled service is planned and performed on an annual basis, while all other service is regarded as unscheduled service. For scheduled service *Siemens* deploy three technicians to the turbine, while unscheduled service generally is performed by service teams of two technicians. The division of annual working hours between scheduled and unscheduled service is comparable when considering the lifetime of a WTG.

4.1.1 Technician work hours

The annual working time and the technicians cost differs between regions, for this investigation *Siemens* UK conditions apply. The shift pattern is 12 hours per day for 7 or 14 days in a row. If service is performed from an onshore base, technicians will have a deduction in working time and get paid for fewer hours during WDT days.

Apart from WDT, there are other time losses for technicians. From *Siemens* experience, about two hours of the working day are lost in briefings and other activities. Time for transportation within and outside WF is added to that, limiting the time work can be conducted at turbines during a working day. These figures added together can be used to calculate the utilization of the work force, see Figure 5. A low utilization results in an increased number of technicians needed to perform required work hours, leading to an increased demand of logistical assets for transport.

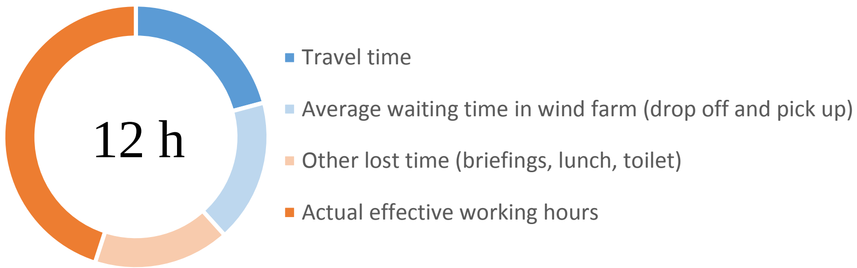

Figure 5 Example of technician time loss during a working day

4.1.2 Team size

The time loss differs with the type of transport used. For a CTV or helicopter the team size will also have an impact, since all teams in the vessel start and end at the same time. This implies that there is waiting time for several teams in the beginning and end of each shift.

The time spent in transportation is affected by the amount of service teams, together with the number of technicians, which is consequently affected by team and vessel size. Figure 6 shows technician waiting time for different vessel and team sizes, assuming full vessel utilization. In the two bottom bars, the difference in time loss is displayed for 4 teams and

12 or 24 technicians being dropped off. In the two top bars, the difference in time loss is due to a change in team size only, having 4 or 8 teams being dropped off. From the figure it can be derived that the amount of teams have a larger impact for technician time loss than the amount of technicians. It can also be seen that it is possible to increase technician utilization by increasing team size. It is however uncertain whether or not this is beneficial for unscheduled service where the required team size is two. For scheduled service it is regarded as possible to increase team size from today's three to six technicians working at large WTGs.

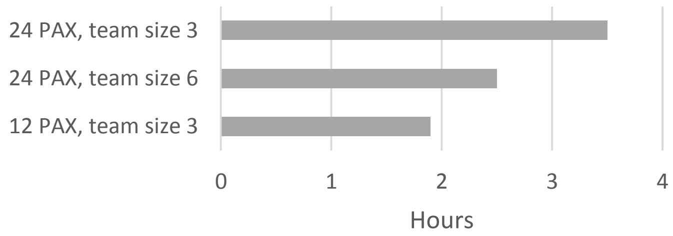

Figure 6 Illustration of working time following team size and vessel capacity

4.1.3 Staggered shift pattern

Staggered shift pattern is a model which implies that the working hours of technicians are spread out during the day and each shift start its working day with an offset of time period t to previous shift. By using this model, technician waiting time, which appears due to transportation, can be reduced. With this shift pattern it is possible to increase technician utilisation, especially if used with a vessel which is able to stay in the wind farm during the night (e.g. SOV). It could also be used for other transport means, which are able to return to a base or harbour to pick up new teams.

The purpose of the staggered shift pattern is to increase the technicians' time at the turbines by decreasing time wasted in transportation. This implies that the working day for the vessel is set by the working hours per shift plus, the compounded offset of additional shifts (e.g. 12 hours working day, 5 teams, 1 hour offset gives a 16 hours staggered shift). By increasing the number of technicians for each shift the same amount of work could be performed by less number of shifts, given that the technicians efficiency at the turbine is unaffected by team size.

The number of shifts and their working day can be illustrated as the left side of Figure 7, which illustrates eleven teams in a staggered shift pattern with one hour offset per shift. The theoretical optimum usage of an SOV under these conditions is illustrated in the left side of the figure. Each shift is dropped off during one hour and spends ten hours at the turbine before the shift is picked up during the last hour. The right side of the figure shows an example where the third shift is being picked up after two hours of work to continue work on another turbine (in this example it could be regarded as unscheduled work). This causes one hour delay for team 6, two hours delay for team 7 – 9 and two lost working days for team 10 and 11. This serial delay results in significantly larger time losses compared to not utilising shift 3 for the rest of the day.

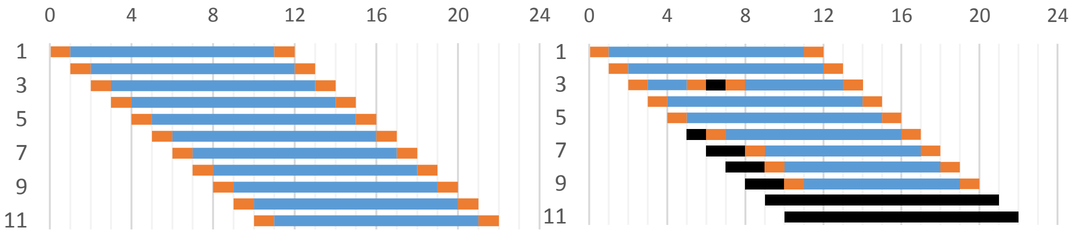

Figure 7 Staggered shift pattern

4.2 Offshore assets

The following chapter will describe the different assets suitable for offshore maintenance. It will further present technical specifications, limitations, and suitable usage.

4.2.1 CTV

The most common size for CTVs at *Siemens* is 12 pax, this due to larger time losses of using 24 pax vessels. Using a smaller CTVs also increases the possibility to match capacity with demand, the vessel cost per pax is however lower for a 24 pax compared to a 12 pax CTV.

The technicians spend a relatively large part of the day in the CTV, travelling to and within the wind farm. This causes seasickness for some of the technicians during rough weather conditions, which leads to time loss to recover for up to 30 minutes. An onshore CTV usually has large time losses during the transport between harbour and WF. The transit speed is 20 kt, but speed limitations may occur within the harbour. The transit time between harbour and wind farm is limited to 1.5 hours by *Siemens*. This means that a CTV with a transit speed of 20 kt is at maximum, able to serve a site 30 NM from harbour/base.

There are different types of CTVs that can be divided into three generations, where the first generation is a standard vessel used in the offshore oil and gas industry. The second generation is a catamaran vessel designed specifically for WF maintenance and is the type mainly used today. The second generation has better weather and loading capabilities than the first generations single hull design. There is currently a third generation under development, using jet engines for transportation at approx. 30 kt. This generation of vessel is a hovercraft type and can operate in harsher weather conditions due its design. A hovercraft vessel will however not be able to carry the same amount of tonnage and has a higher daily cost than its predecessor.

The CTVs are limited to how much cargo they can carry as well as by weather conditions. The main limitation for CTVs is the wave height, ranging from 1.5 to 1.75 m Hs for CTVs used today, but wind speed can also be critical. The direction of the step over at the WTG can be a limiting factor since vessel stability is influenced not only from the wave height and wind speed, but also by the direction of wave, wind and current.

4.2.2 Helicopter

There are two types of helicopters which *Siemens* consider to utilize for offshore maintenance; a small type suitable for Helicopter Hoisting Operation (HHO), and a larger type not allowed for HHO operations but suitable for transfer to offshore base.

A helicopter has the possibility to transfer technicians to turbines with a high transfer speed and hoisting a service team in about one minute. Although helicopters can transfer 4 technicians to a range exceeding 70 NM if offshore refuelling is possible, a shorter distance is preferable for operations. A helicopter used for hoisting operations has 5-7 pax, but is heavily restricted by weight limitations. The weight restriction is approximately 600 kilogram in total but differs with the transport distance. If the distance is short, less fuel is needed and more weight can be transported. Due to weight limitation, the helicopter is regarded more suitable for unscheduled service, as the scheduled service includes a heavy service package and would require multiple trips.

The helicopter has a relatively high accessibility with a weather downtime of approx. 15 %, with restrictions set by visibility and wind speeds exceeding 20 m/s. For nearshore operations a helicopter can fly teams out to WF directly. When using a helicopter for operations further offshore, there is a cost advantage of having a helipad for ranges exceeding 20 NM. This cost advantage is due to a regulatory limitation of hoisting to one WTG at a time. If there is a helipad in WF two teams can be carried out to different WTGs, with one service team being dropped off at helipad waiting to be hoisted.

4.2.3 SOV

The SOV is a vessel with accommodation capability suitable for service far from shore. The first SOV is currently under construction for *Siemens* and is to be launched in 2015. The main reason of introducing the SOV is to increase utilization of technicians, this is due to less WDT compared with other vessels and its capability to stay in WF for longer periods of time. The vessel has capacity for 40 pax, of which approximately 5 will be reserved for site management. It has the capacity to carry eight 20 ft containers of cargo, which enable it to host necessary equipment for service. In addition the SOV is equipped with a daughter craft, which can be used to transport service teams for unscheduled service during calm weather conditions.

The SOV is to operate in WFs for two weeks, returning to harbour only for refuelling and loading of supplies. The vessel is therefore suitable to service WF at farshore locations, where an onshore base is not an alternative. To utilize the technicians at the SOV efficiently, a staggered shift pattern will be used. The SOV is planned to perform mainly scheduled service for several WTGs within the same area of the WF simultaneously.

For service operations there are safety rules limiting the operational distance. There is a 30 minute rule for reaching technicians with first aid and a 60 minute rule for a more advanced level of medical assistance. All technicians have first aid training and if the team size is 3 or above, the 30 minute rule is regarded as fulfilled. The transfer time between two turbines is estimated at 60 minutes. The regulations make it hard to perform unscheduled service with the vessel since all teams must be deployed in the same area of the WF. The time limit is estimated to be covered within 5 turbines distance.

The currently developed SOV is limited to 2.3 m Hs, but can access the turbine from all directions due to its gangway access system. This means that wave and current direction is not as critical for the SOV as for smaller vessels. For the daughter craft the limitation in wave height is 1 m Hs, and accessing of the turbine is restricted to landing on the turbine. The transit speed of the SOV is 15 kt outside of WF. When moving in WF a dynamic positioning system needs to be used, limiting the transit speed to 5 kt. To exit the dynamic positioning system takes approx. 15 min, to turn it back on is however a procedure of about one hour. The positioning system is therefore not possible to exit if service teams are deployed in WF using the SOV only, due to the safety regulations of 30 and 60 minutes.

4.2.4 Platform

An offshore platform is an offshore base, which serves as accommodation for technicians. The platform is fixed to a location and by using an offshore base it is possible to reduce the transport time to a WF and thereby technician time loss. The platform has a helipad and possibility of docking vessels, e.g. CTV for technician transport. There are sites having offshore accommodation platform today, however it is rare due to a large initial investment estimated to around €70 million. Some platforms are used only during summer time for performing scheduled service.

4.3 Cost drivers of offshore logistics

When considering service of a WTG, it is possible to assess the amount of service which needs to be done in a WF on a yearly basis. These values are the starting point of calculating the logistical setup. When the effective working time is known, the number of technicians and fleet composition can be calculated for offshore maintenance. Depending on the chosen offshore assets, the amount of technicians will vary due to differences in time loss for accessing the turbine. The cost and efficiency of service is highly affected by the site conditions and the most suitable offshore setup of a WF will vary. The main conditions identified affecting the cost of service, hence referred to as cost drivers are:

1. Distance to shore
2. Weather downtime
3. Number of turbines
4. Service hours

In order to understand their impact on the service structure, they will be explored individually in depth and later used as a means of analysis.

4.3.1 Distance to shore

A key measurement for the location of a WF is distance to shore. This measurement is the shortest possible distance between a wind farm and a harbour. However, the distance to harbour is longer if the harbour is not situated on the exact nearest onshore spot to the WF. This means that the travel distance is usually longer than the distance between WF and shore. The travel distance could also be affected due to areas where it is not possible to travel e.g. islands or restricted zones.

There are also differences between transportation means, vessels travel by sea while helicopters travel airborne. This means that there is a need for two types of ports, one port for vessels and one for helicopters. These can be in the same location, where the helipad is situated in the harbour, or located separately e.g. by using an already existing airport. For this study the assumed distance to shore equals the travel distance to harbour and the same travel distance is assumed for vessels and helicopters.

The distance to shore and the average travel speed have direct correlation with the travel time to the WF. Due to travel time, each technician loses time waiting to be transported to the WF, which is deducted from the effective work hours the technician can perform. In order to cover the same amount of work hours, an increased number of technicians are needed. Consequently, the number of technicians impact the amount of transport means, which further impact flight hours and/or fuel cost.

Different assets are impacted differently by the cost driver distance to shore. Figure 8 shows a comparison of the cost between CTV generation 2 and the future generation 3. The 3rd generation of CTVs is more expensive, but has a higher traveling speed together with lower WDT. In Figure 8 the weather data of the Hornsea site is used, leading to a quite high WDT for a CTV strategy. When comparing the assets the 2nd generation vessel is cheaper up until it reaches *Siemens* breaking point of 1.5 hours travel time at these site conditions. The extended reach of the 3rd generation would not be applicable in this case due to an illustrated breaking point towards the cost of an offshore based strategy.

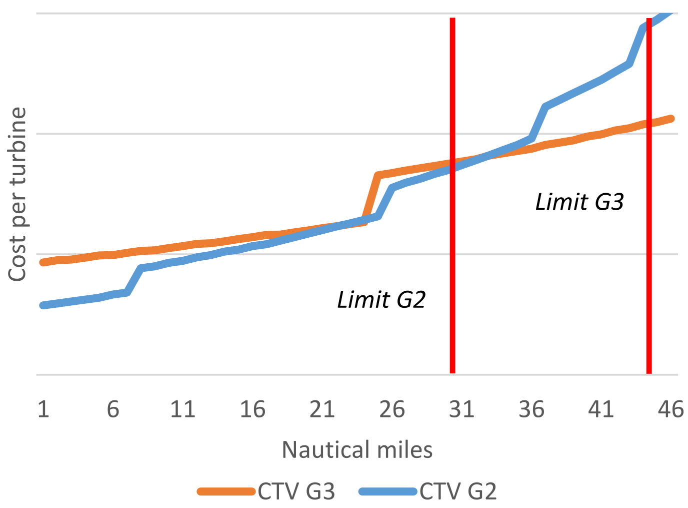

Figure 8 Cost impact of distance to shore

4.3.2 Weather downtime

Weather is a critical aspect when operating offshore, it is also identified as an important cost driver of offshore maintenance. Harsh weather often results in inaccessibility for the technicians to the turbines, meaning that resources are left unused. The reason for WDT is due to safety limitations in operable weather conditions for different vessels and helicopters. The two main components limiting the usage of vessels is significant wave height followed by wind, while helicopters are limited by wind and visibility. WDT is estimated by *Siemens* using a calculation tool, which plots the specifications of offshore assets towards historical weather data. Weather conditions differs during different periods of the year, where the wintertime is the most critical period of high winds and waves resulting in high inaccessibility for vessels. This implies that the technicians may not be able to perform work during several days or weeks, which affects the availability of the turbine and the energy production.

Weather downtime is affected by the transportation type used. A helicopter is unaffected by wave height and has the highest accessibility. A larger vessel will be able to withstand higher waves and has less time where turbines are unreachable, but at a higher cost. It is also possible to use a motion compensation system, which can be mounted on a vessel, to decrease WDT. The access systems used today needs to be mounted on a larger vessels, such as an SOV. There are tests regarding mounting access systems on CTVs, these systems are however not used by *Siemens* due to uncertainties regarding safety.

The weather downtime affects the size of the maintenance organization. With a higher WDT technicians have less working time left during a year and the amount of technicians needs to be increased. When the amount of technicians increases, so does the need for vessel capacity and in extension the number of vessels together with vessel cost. Figure 9 shows the cost structure of a CTV strategy, and how the amount of vessels is affected by increased WDT.

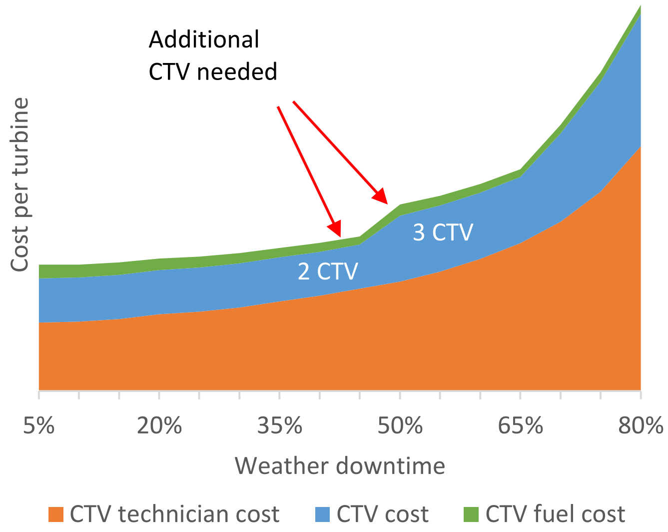

Figure 9 Impact of WDT on a CTV setup

When exploring the cost structure per turbine in Figure 9, the largest impact on the cost is the number of technicians. The cost of technicians increases exponentially as the available working time decreases. The amount of vessels also increases together with the vessel cost for a higher WDT, although not with the same incline as for the number of technicians.

4.3.3 Number of turbines

Number of turbines is a cost driver connected to the scalable effect of service for offshore wind power. The total amount of service hours is affected by the number of turbines. However, even if the demand of service hours correlates with number of turbines, the service cost will be shared across the turbines. This means that by changing the number of turbines the economies of scale within offshore maintenance can be explored.

Increased number of turbines leads to increased number of scheduled and unscheduled work hours for the wind farm. This means that there is a need for more technicians and further an increased number of logistical assets driving the total cost up. However, when measuring the cost per unit (in this case: cost per turbine), the cost can either increase or decrease within certain spans.

There is different scale effect for different logistical assets. Figure 10 illustrates the cost depending on number of turbines for two logistical assets. The blue area of Figure 10 represents the technician cost which is higher for the CTV than the SOV. This is due to the higher utilization of technicians on an SOV with a staggered shift pattern. The cost for technicians per turbine remains constant when increasing the number of turbines. The yellow and orange area illustrates the vessel cost which differ in cost per unit, where the SOV has a higher unit cost but also higher capacity to serve more turbines. This means that the SOV is more sensitive to number of turbines and need a higher number of turbines to be cost efficient. The grey part displays fuel consumption for both transport means. The cost increase in both graphs appears when an additional vessel is needed to carry the technicians. The graph is based on 12 pax CTVs and 33 pax SOVs.

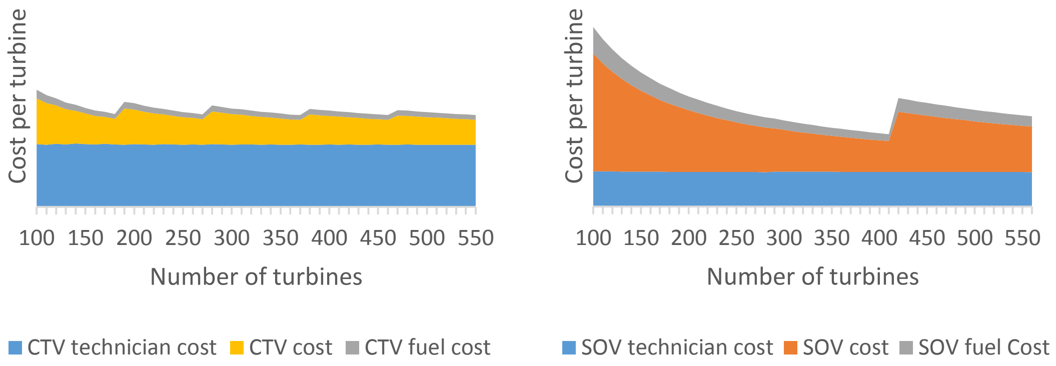

Figure 10 Scaling effect of CTV and SOV

4.3.4 Number of service hours

The scheduled service hours is based on the time it takes to perform the planned annual service. There are several ways which the scheduled service can be impacted. Changing the yearly service, or certain activities, to a wider time span can potentially reduce service hours. It is also possible that some service activities are eliminated in the future due to technical improvements or that learning effect reduces the time needed for service.

Service hours also consist of unscheduled hours, these are unplanned activities that appear due to failures of turbines. There are two components, MTBF and MTTR, which affect the annual hours of unscheduled service. These can be reduced by technical improvements or by increased knowledge of turbine maintenance leading to less repair time.

The main difference between scheduled and unscheduled service is the possibility to plan the scheduled service and perform it during certain spans of the year. Unscheduled service appears stochastically with an increased failure rate during periods of high wind. The impact on availability is higher for unscheduled compared to scheduled service. The main reason for the higher availability impact is that the mean downtime is higher for unscheduled service, where production losses appear from turbine failure until it is repaired. For scheduled service production losses only appear during the repair time and there is a possibility to restart the turbine between service days.

Number of service hours is the number of effective technician hours that is needed for service. Changing these will also change the number of technicians needed to perform service. This means that number of vessels or helicopters needed for transportation technicians is affected and thus fuel consumption and/or flight hours. Assets may be connected to a specific type of service. If so, the effect of service hours will differ depending on which type of service is changed, e.g. an SOV might perform only scheduled service. Hence, the cost structure will change differently with service hours depending on which type of asset is used, see Figure 11.

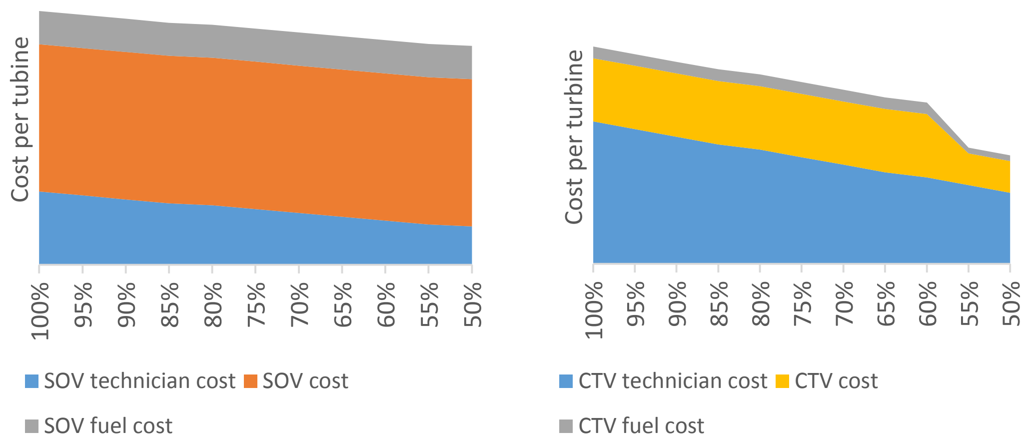

Figure 11 Impact of decreasing service hours for CTV and SOV

When reducing service for a CTV strategy, the number of vessels is decreased to match capacity. When an SOV is performing mainly scheduled service, the number of vessels cannot be decreased with number of service hours, and the main change would be in technicians needed. Thus, the largest cost factor, SOV cost, would be unaffected and the cost savings would be limited as it would lead to substantial overcapacity.

4.4 Hornsea - baseline

Hornsea is a planned WF located 66 nautical miles (122 kilometres) east of the UK in a large area containing several wind farms projects. The official name is Hornsea project one - Heron Wind and Njord, and will potentially consist of 166 6 MW WTGs provided by *Siemens* (4COffshore, 2013). For this study this assumption has been used.

The Hornsea project is situated far from shore in the North Sea. This does not only mean long transportation distances. It is also an area of high waves and harsh weather conditions. The vessel fleet must therefore be designed to operate in rough weather conditions in order to avoid inaccessibility. These factors could make the use of an SOV preferably, since it has the capability to operate during high waves and to stay in WF for long periods of time. Another alternative would be to construct a platform close to the WF as a service base, in order to decrease transport time.

To explore the future of offshore maintenance, *Siemens* has chosen to use the site conditions at Hornsea to develop a baseline. This baseline is calculated with 166 6 MW turbines and an SOV and helicopter concept performing all service which do not require a jack-up.

Figure 12 shows the Hornsea site and the closest land based port together with markings at the maximum travel distance from shore using a CTV strategy with 1.5 hour travel time each way.

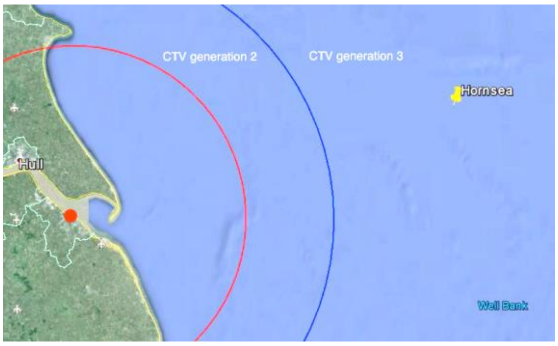

Figure 12 CTV travel distance and Hornsea site

4.5 Availability

The most common service contracts between Siemens and a WFO is to use turbine availability. Exceptions for weather downtime are usually included in these contracts, meaning that the WFO has the risk of production losses due to inaccessibility. This implies that the contractual agreement is not directly related to the financial performance of the WF. *Siemens* can however potentially raise customer satisfaction by increasing availability.

There is a trend in the industry where the risk of production losses due to weather downtime is moved from the WFO to the service company. Two example of this contracting are system based and energy based availability. This increases the incentives for the service companies to offer solutions which are less sensitive to WDT. For energy based availability there is also higher incentives to plan the scheduled service during times of the year where there is low production.

5 Analysis

The analysis will describe the impact of identified cost drivers for the farshore solutions SOV and platform when servicing a WF with Hornsea conditions.

5.1 Cost driver analysis

Besnard (2013) and Philips et al. (2013) described a trend in the industry where WFs are being built further away from shore, with greater logistical challenges. In *Siemens* case, this challenge will appear on several future sites and require a different service setup compared to what is used today, Hornsea is one of these sites.

The distance to shore for Hornsea is 66 NM, hence above the 40 NM Philips et al. (2013) described as the limit for onshore solutions. Due to the remote conditions of Hornsea, a farshore solution is necessary to perform service. As described by Besnard (2013) and Philips et al. (2013) there are two offshore based strategies, an SOV strategy or a platform strategy. The SOV can perform scheduled service during harsh weather conditions. However, since the SOV is unable to perform all required unscheduled service at Hornsea, it would have to be complemented. Helicopter are the only complement which can be used without having to invest in an additional offshore base, however investment in a helipad with refuelling capacity is needed. The other option is using a platform concept together with CTV and possibly helicopter.

The empirical study of Hornsea showed that a 33 pax SOV has a capacity to serve 400 turbines when used for scheduled service only. This means that the SOV has an overcapacity for scheduled service at Hornseas 166 WTGs. By analysing the sensitivity of staggered shift pattern together with input from expert interviews, the authors' estimates that it will be possible to perform 20% of the unscheduled service from the SOV. The remaining 80% of the unscheduled service is assumed to be performed by helicopter. Due to safety regulations, the helicopter technicians for SOV concept are assumed to be accommodated onshore due to uncertainties with restrictions of helicopter hoisting from SOV in WF.

For the platform concept the same division and utilization of helicopters is made although CTVs could perform all service at Hornsea. The introduction of helicopters is founded in the high weather downtime for CTVs at Hornsea, which would have a negative impact on energy production due to high inaccessibility. The platform is situated outside the wind farm which means that it is not affected by hoisting regulations for helicopters, hence it is possible to station helicopter technicians offshore.

5.1.1 Distance to shore

Distance to shore is seen as a major cost driver, something pointed out by Philips et al. (2013). Due to the remoteness of the Hornsea site, both concepts have to be offshore based. These solutions are not as cost sensitive regarding the distance to shore as onshore based solutions due to decreased transport time for the technicians.

SOV

The concept with SOV, where the helicopter technicians are hosted onshore, showed a cost increase mainly due to increased number of flight hours. This results in a need for an additional helicopter after 45 NM, see Figure 13. All cost components except the SOV cost increases with distance to shore. However the increase of fuel is only slightly affected since the vessel seldom returns to harbour, and the differences in fuel consumption is minor between operating within WF compared to transit. Using an SOV concept 60 NM from shore is 19% more costly than using the same concept for nearshore operations at a distance of 0 NM from shore.

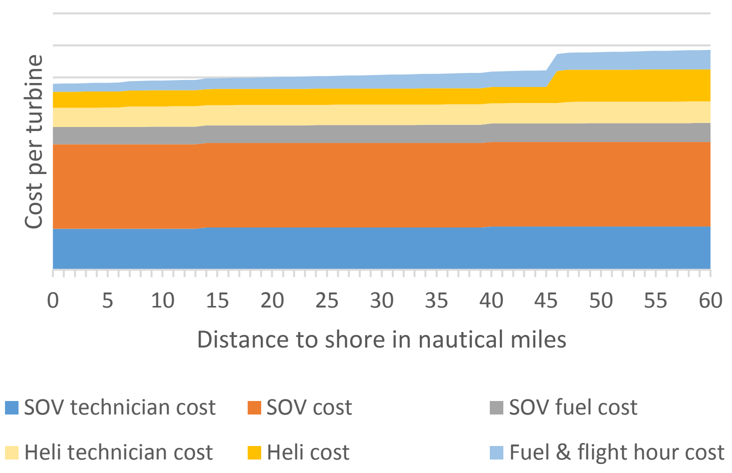

Figure 13 Impact of distance to shore on SOV concept

Platform

The cost factors of the platform concept, is slightly affected by the cost increase. In the platform concept, technicians performing service by helicopter are assumed to be accommodated on the platform. This means that the needed number of helicopters is constant within the interval 0-60 NM, hence it is a less sensitive concept than the SOV concept. The cost of a large helicopter for technician exchange is assumed as a cost per transport, hence it is not affected by the distance.

Comparison

Both farshore concepts are robust to the cost driver distance to shore. This is in line with the prediction of Philips et al. (2013), stating that farshore concepts are developed to be insensitive by distance to shore. Although, the impact of distance to shore is relatively small for the setup and cost of both concepts, there could be other limiting factors. The possible operable range of a hoisting helicopter from shore is calculated to be over 70 NM, still the limit of such strategy is near the distance of Hornsea. Conclusively, there is no large cost difference due to distance to shore apart from the helicopter cost, which is affected by the strategy to have the technicians onshore or offshore.

5.1.2 Weather downtime

Weather downtime is identified as an important cost driver by *Siemens*, and in literature by Philips et al. (2013) and Halvorsen-Weare et al. (2013). When examining WDT the helicopter is kept constant due to its superior accessibility and insensitivity to wave height.

SOV

The SOV is designed to withstand rough weather conditions. The ship is both large and has a motion compensation system for additional accessibility, making it possible to access turbines in up to 2.3 m Hs. The highest average WDT for a SOV at Hornsea is estimated during January with an average of 42%, while June and July have the lowest WDT of 6%. Hornsea conditions can be regarded as harsh due to the sites remote location, still the WDT of the SOV is quite low. Hence, looking at a changing WDT in the same interval as for CTV would not be reasonable. The capacity for a SOV serving Hornsea is 33 pax of which an average of 15 is in use. This would allow for double the amount of technicians before reaching its capacity limit due to WDT. The SOV can thereby be regarded as robust to WDT for Hornsea conditions.

Platform

CTVs of the second generation have a limit of 1.75 m Hs, with Hornsea conditions this implies an average WDT of 44 %. The number of CTV technicians' increases by 80% as the WDT increases from 5 – 45 %. The cost increase is exponential and the large incline starts when an additional vessel is needed after 45 %, see Figure 14, this happens when technicians at site exceeds the capacity of 2 CTVs. At 45 % the cost increase is 10 % compared to the starting value of 5 % WDT, at 50 % WDT the same increase is doubled at 21 % due to the need of an additional CTV.

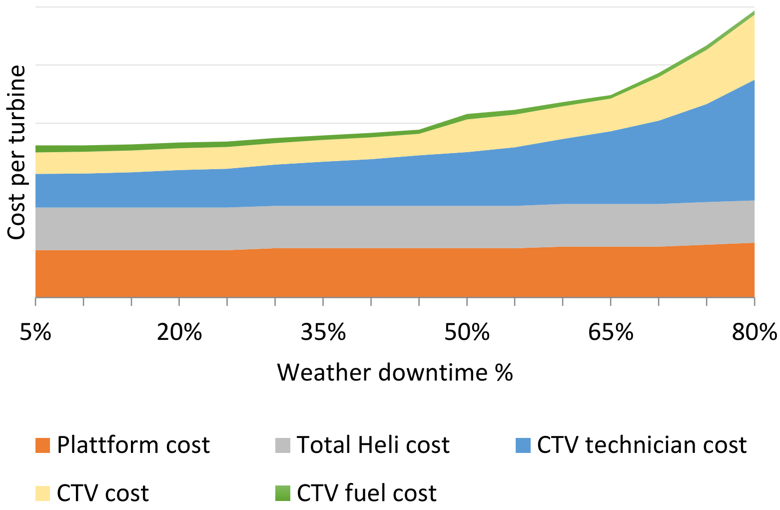

Figure 14 Impact of WDT on platform concept

Comparison

A conclusion can be drawn that WDT has its major percentual change when additional transportation capacity is needed. This will happen for the CTV at an increasing rate as technicians' working days decrease, while an SOV would be robust due to overcapacity in number of pax. These fixed cost breaks are slightly different compared to the cost breaks described by Slack et al. (2013), since the scale of operation remains constant even though the needed capacity increases. Still, the utilization of an additional vessel would be lower immediately after adding additional capacity.

Comparing the concepts while keeping the WDT of the SOV constant, the total cost of service reaches the same cost level when the CTV has 60 % WDT. Karyotakis (2011) stated that a WF might have a long period in the winter where turbines are inaccessible, this has seen to be true in this study as the maximum WDT for CTVs during a single month exceeded 93 %. When considering both technician time loss and turbine availability impact, the usage of helicopters at Hornsea could be regarded as beneficial. As the helicopter is included in both cases, this will have the positive upside for service.

5.1.3 Number of turbines

The cost driver number of turbines has the highest impact on cost within the studied intervals, this is due to the large fixed costs of offshore based strategies, and the possibility of sharing these costs. This cost driver is identified both by *Siemens* and theoretically (Philips et al., 2013, Halvorsen-Weare et al., 2013).

SOV

For the SOV concept the helicopter cost remains virtually the same in cost per turbine, even though the number of helicopters rises from two to three in the interval. For the SOV cost there is a clear benefit of sharing the annual cost over more turbines and a substantial cost decline can be seen. The breaking point of 375 WTGs is calculated with the SOV reaching its capacity limit for 100 % scheduled service, which can provide high technician utilization, and 20 % unscheduled service.

Platform

For the platform the large cost decrease, following an increased number of turbines, is the sharing of the platform cost. When serving 100 WTGs the platform cost is the largest cost factor but it decreases with the size of the WF. For the Hornsea site of 166 turbines, the CTV technician cost is equally large as the platform cost. If the number of turbines is increased further the technician cost becomes the largest cost factor. Within the interval of Figure 15, the number of technicians required for service in the platform concept may however exceed the capacity of the DanTysk platform, as the number of turbines is increased (Dantysk, 2013). The vessel setup for 100 turbines consists of 2 CTVs and 1 helicopter, increasing up to 4 CTVs and 2 helicopters for 300 turbines. As the platform cost decreases, fixed cost breaks appears where an additional CTV or helicopter is needed to perform the service. As described by Slack et al. (2013), additional asset cost gives irregularity to the cost decrease due to economies of scale, this can be seen for the platform concept.

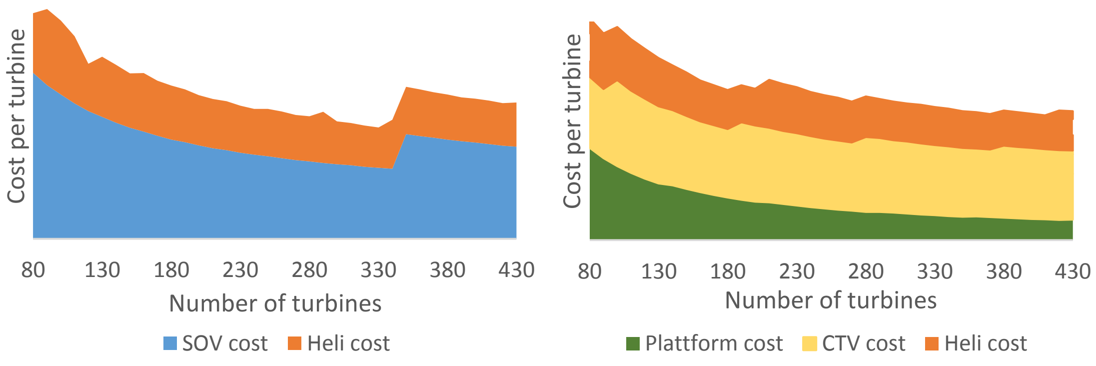

Figure 15 Impact of number of turbines on SOV and Platform concept

Comparison

When exploring the cost impact from the number of WTGs served, the main savings for both concepts are due to sharing of the large fixed costs of the concepts, see Figure 15. This is in line with the cost reduction due to economies of scale, as described by Slack et al. (2013). For the SOV, the cost of service starts at index 100 and is reduced by 46 % to 54, in the span of 100 - 300 turbines. For the platform concept the initial cost is lower, starting at index 85 but it does not have the same percentual cost saving as the SOV concept and is reduced by 35 % to index 56. The SOV strategy is thereby a cheaper solution for a WF of approximately 300 turbines.

5.1.4 Number of service hours

The amount of work hours is described by Philips et al. (2013) as an important cost driver. *Siemens* identifies improvement potential and a possible reduction in the amount of service hours as the technology of WTGs develop.

SOV

Looking at a decreased number of service hours performed at Hornsea, the large vessel cost remains constant. Since the SOV has a high capacity, and the fixed cost cannot be adapted to a decreasing demand, the only SOV cost saving in the interval of Figure 16 is due to a decreased number of technicians. In this calculation the SOV is staying offshore the whole year with a fixed fuel cost for time spent in WF. For the unscheduled service the total helicopter cost is adaptable, since the number of helicopters can be decreased if reducing the amount of work hours, see Figure 16. The total cost decrease of 23 % in the interval would be lower in a case where the number of logistical assets is constant. This is the case if only the amount of scheduled service performed by the SOV, decreases.

Platform

With a platform concept using CTV and helicopter for transport, the amount of technicians' decreases by 50%, for the reduction of service hours seen in Figure 16. The large cost decrease is where the capacity need is reduced and the number of CTVs is reduced from 2 to 1. With a setup of one CTV and one helicopter there is no further fixed cost breaks from reduction of transport means. The total cost reduction in the interval is 30%.

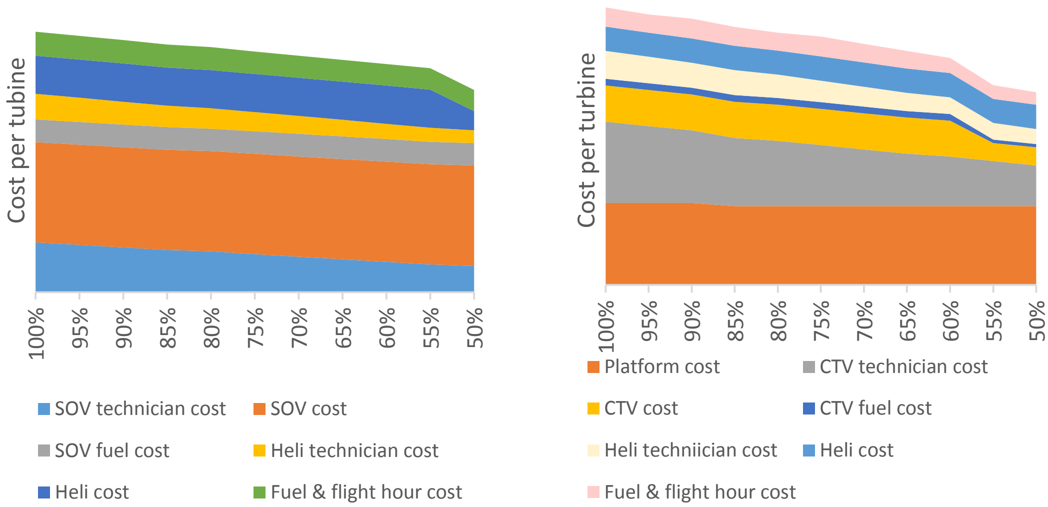

Figure 16 Impact of service hours on SOV and Platform concept

Comparison

When looking at a decreasing number of work hours, the SOV has a 23 % reduction from index 100 down to 77. The cost savings for the same change of work hours with a CTV is 30 %, starting at 83 and decreasing down to 58. The platform is initially 17 % cheaper, this figure increases to 25 % with a service hour reduction of 50 %. When reducing the amount of work hours, the CTV technician cost reduces in a higher extent than the technicians using the SOV due to shorter effective working hours for CTV technicians.

5.2 Availability

As stated by Harman et al. (2008) and Conroy et al. (2011), there are several ways to measure availability. The empirical study showed that these are used by *Siemens* and WFOs. For financial performance system availability is a key performance indicator for the WFs and is used for analysis in this study.

Different logistical setups will result in different availability and could therefore be measured against the logistical cost to give a production-cost optimum, see Figure 17 (Philips et al., 2013). The logistical cost affects the annual operating cost used for calculation of LCOE, and the availability has direct consequences for the energy production. Hence, these two quantitative measurements are important for analysis of LCOE.

Figure 17 Production-cost optimum of maintenance

In order to investigate the availability, a simulation was performed using the different setups for Hornsea. The main finding from the availability simulation is that both SOV and platform concepts provided quite similar availability performance. This is mainly due to the use of a helicopter for unscheduled service in both concepts. Unscheduled service has previously been described as the service type which has the main impact on availability. The simulations also showed that use of helicopters at site will increase the availability compared to only using CTVs for all service. This can be explained by the lower weather downtime for helicopters which results in less downtime for the turbines. The simulation showed that increasing the amount of helicopters gave higher availability. How big the impact is could not be concluded, but the simulation gave an indication of 0-2 % increased availability when using 4 helicopters instead of 2.

Results from availability simulation are illustrated in Figure 18, which shows availability for 166 WTGs located at Hornsea. The gain of increased availability for this wind farm is calculated using the Equation 5, described by Nilsson and Bertling (2007). Inputs for calculation of lost revenue used were; average wind speed, turbine power curve, wake losses, and electricity price. The calculation revealed that the revenue increase from one percent of availability is comparable with the cost of two additional helicopters.

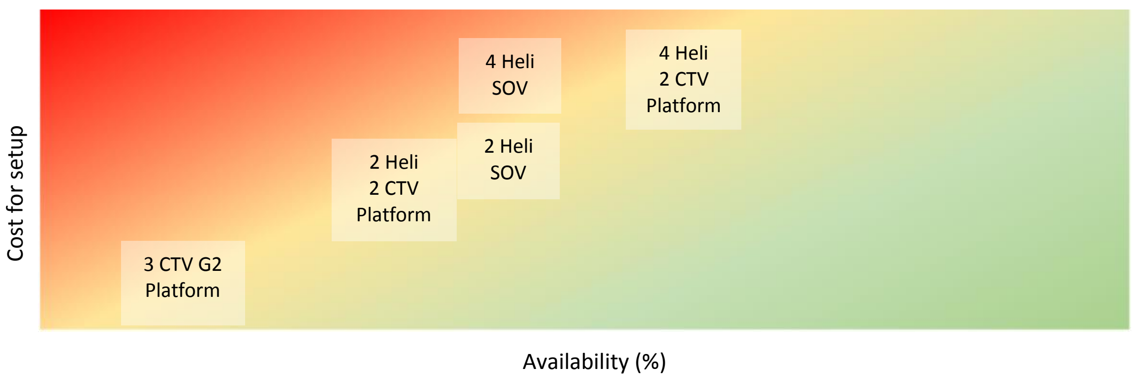

Figure 18 Cost and availability simulation of service concepts

5.3 Service optimization

In order to further explore the farshore concepts, areas of importance for the cost structure of service is followed up in this chapter. The analysis is performed for the concepts individually and presented below.

5.3.1 The platform concept

For the platform combined with CTV and helicopter, the importance of capacity utilization will be lifted, this is pointed out by Slack et al. (2013) as significant for the cost. In order to balance utilization of resources used for service, work division should be subject to consideration. In Figure 19, the helicopter usage is investigated on the amount of unscheduled service performed in the WF. The helicopter usage can balance the resource utilization of the CTV. When reaching an optimum balance, the amount of assets could potentially be reduced. The total cost span between the worst and optimal usage is 10.5 %. From the initial assumption in the cost driver analysis, with the helicopter performing 80 % of the unscheduled service, the number of assets is already at a minimum. Increasing the service performed by helicopter up to 95 % would lead to a potential cost saving of 1.4 %.

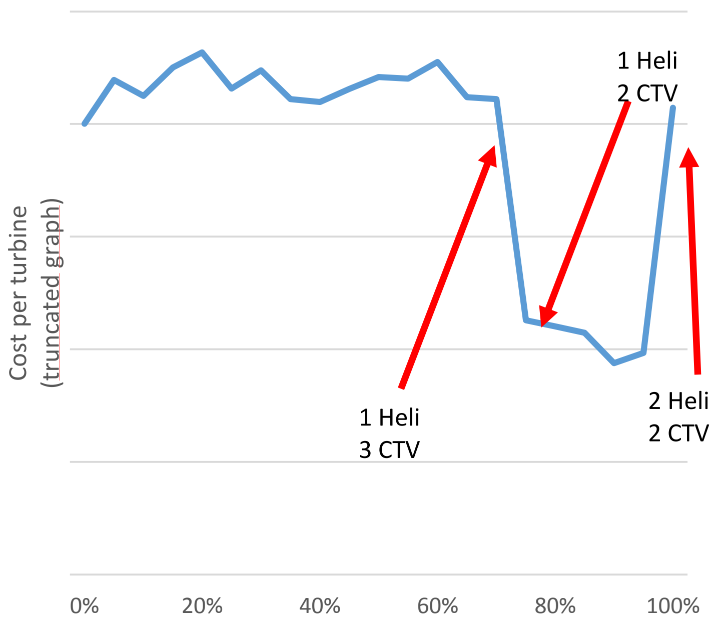

Figure 19 Optimal utilization of assets

Another observation connected to utilization of technicians is the impact of team size for CTV usage. Due to the waiting time between drop offs from a CTV, there is a time waste between the first team being dropped off, and the last. When exploring the possibility of increasing the team size of scheduled service, from today’s three to six technicians, a cost reduction can be seen. If reducing the waiting time by an increased team size, the needed number of technicians is reduced. The total cost savings of doubling the team size for scheduled service would amount to 1.8 %.

5.3.2 The SOV concept

For the SOV, one area of improvement is the helicopter utilization. In the initial SOV concept calculations technicians are stationed onshore. When regarding the utilization of the SOV, it has the capacity of deploying 11 service teams using a staggered shift pattern. When stationed full time at Hornsea it is utilized for 5 teams. The average travel time to a substation equipped with a helicopter pad would be the same time as deploying 3 teams. Thus, there would be time remaining during a working day for dropping off helicopter technicians at a substation for hoisting operations. This could reduce the number of rounds a helicopter would have to fly out to the wind farm each day of operation. Having technicians hosted on the SOV would also reduce technician waiting time each day. Together these factors would provide a cost saving of 12%.

The largest potential gain is however the scaling effect. A larger scale of operation, and operating close to the capacity limit is, as described by Slack et al. (2013), a possible way of cost reduction. Scale and sharing of resources is also identified by Hobohm et al. (2013) and Philips et al. (2013) as important for cost reduction within offshore maintenance.

When exploring the scale of operations for displayed farshore concepts, the utilization of assets shows potential for reducing the service cost per unit. This is especially true for the SOV concept, as it display the highest cost reduction potential of the compared concepts. If exploring in depth, the overcapacity of the SOV is eminent for a site the size of Hornsea. Should the SOV be used at full capacity and perform only scheduled service, it would only require 150 days to complete the annual service need.

There are two possibilities for sharing the SOV capacity in order to achieve cost savings through scaling effects. It could either serve a larger WF or be shared with other WFs. These factors would however require influence by WFOs and not directly affected by the service provider. A different approach would be to develop a smaller service vessel, an SOV-light concept. On the backdrop of this an additional investigation was made, using the pricing, size and weather restrictions of a smaller 25 pax vessel restricted to 2 m Hs. The study showed that the small vessel has the capacity to perform the full scheduled service at Hornsea in 350 days, thus providing a good capacity match between the vessel and the WF size.

6. Discussion

In this chapter the results of this study are discussed together with implications following a combined cost saving within offshore maintenance.

The cost drivers analysed in this investigation were studied individually. There may however be correlations between them. Distance to shore and WDT have to a certain extent positive correlation. This means that large distance to shore implies large WDT due to the harsher weather conditions which appear further from shore. It can be useful to study how large this correlation is for seas where an expansion of WFs is planned.

The presented cost drivers had different effect on the cost structure. It is hard to determine which of the cost drivers have the largest impact on cost. This is such as the cost impact differs depending on the studied interval. When exploring the cost drivers, there are however several arguments that can be lifted to elaborate on which cost driver is the most important.

The cost driver *number of turbines* has a strong trend of decreased cost per turbine as the number of turbines increases. It is arguable that the studied interval is realistic based on industry development, hence this can be seen as the most influential cost driver. Since its cost reduction is mainly through sharing of fixed costs required for farshore solutions, this cost reduction will not be as significant for onshore based solutions.

The *weather downtime*, which appears due to the transport means limitations and weather state on site, has an exponential cost increase. This means that the slope of the cost increases as the weather downtime increases. Thus, the impact of this cost driver is heavily affected by the studied interval. When considering WDT for unscheduled service, the availability impact should be considered. There is a negative correlation between weather downtime and availability. This means, that when studying the impact of WDT, the availability should be included to analyse the total cost. For this study, a large share of the unscheduled work is dedicated to helicopters which are not affected by the sea state, hence the concepts are not heavily affected by WDT.

The *service hours* comprises of two categories; scheduled and unscheduled service. Reducing the scheduled service hours will mainly shorten the days of work per turbine. The amount of unscheduled service hours is however more complex as it is affected by both the failure rate and the repair time. These two parts can be analysed individually for increased knowledge of the cost impact from unscheduled service.

Regarding *distance to shore*, there are certain cost differences between an onshore based strategy and an offshore based one. The study showed that the developed concepts were robust against distance to shore. However, as mentioned in this chapter, an analysis including the correlation between distance to shore and weather downtime might show higher sensitivity for these concepts.

If attempting to see further ahead, both WTGs and WFs have increased in size and this trend is expected to continue. This provides profitability benefits due to economies of scale. For the WF Hornsea, the turbine type and the size of the WF are larger than what is customary within the industry today. There are however other areas which have been explored in this study, such as the amount of service hours. It is assumed that, as the technology develops, the number of service hours will decrease. If considering a combined effect of this, together with other areas of cost reduction, it could reveal future potential of a service concept.

For elaboration on this, concept specific improvement areas from the study can be combined with reduction of service hours. For scheduled service, an optimistic assumption would be to reduce service hours by 80%. This could be assumed as having the same amount of service performed every five years. Reducing the unscheduled service by 50 % can also be regarded as an optimistic assumption.

Locating the helicopter technicians offshore showed great potential of cost reduction. If this is done, and there is a helipad with refuelling capabilities by the WF, the helicopter only needs to fly back and forth to the WF once a day. It is possible time wise for an SOV to drop off helicopter technicians at a helipad located at Hornsea. As shown in the analysis, there were clear benefits of using an SOV light concept for additional cost reduction. This would provide a close match between the service capacity and the required service at Hornsea. If the scheduled service hours are reduced to a fifth, and the unscheduled service to half of todays level, the compounded effect of this scenario would have a cost reduction of 44 %, see Figure 20.

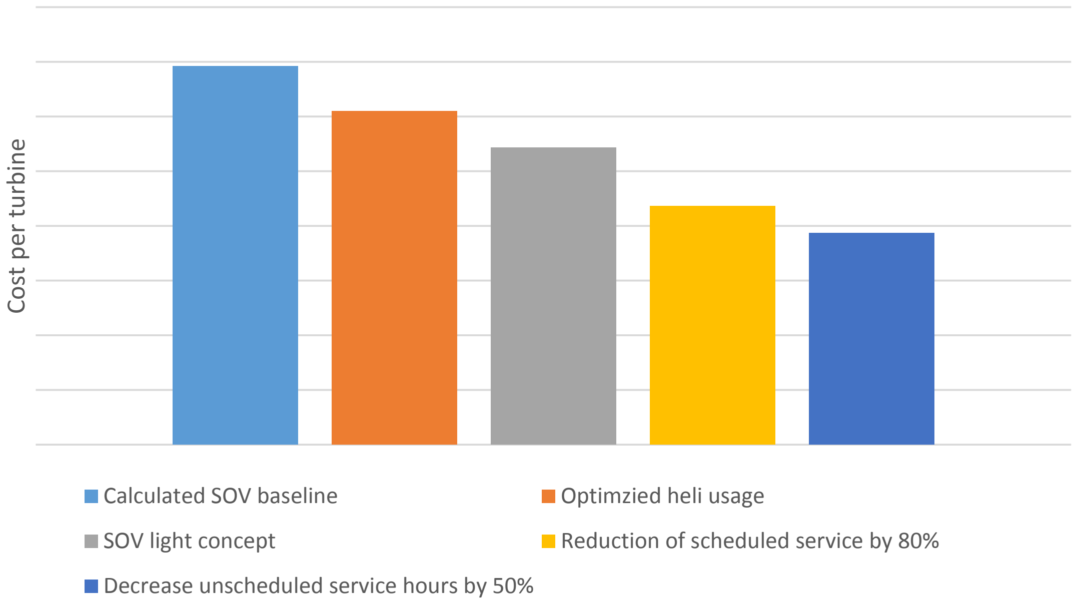

Figure 20 Potential cost reduction of SOV concept

For the platform concept, the cost reduction of an increased team size can be included, see Figure 21. This illustrates the effect of an increased team size for scheduled service. As the turbine size increases, more technicians are assumed to be able to work at a WTG simultaneously. The team size might be able to increase further than 6 technicians, there are however risks that technician waiting time will be sub-optimized due to ineffective maintenance at turbines. If the scheduled service hours are reduced to a fifth, and the unscheduled service reduced by half, there are further potential cost savings. Additionally, the effect of having a platform over a longer time span, assuming that a new WF is built in the same place after the first one has been decommissioned, could potentially decrease costs additionally. In total, this scenario of compounded effects would have a cost reduction of 48 %.

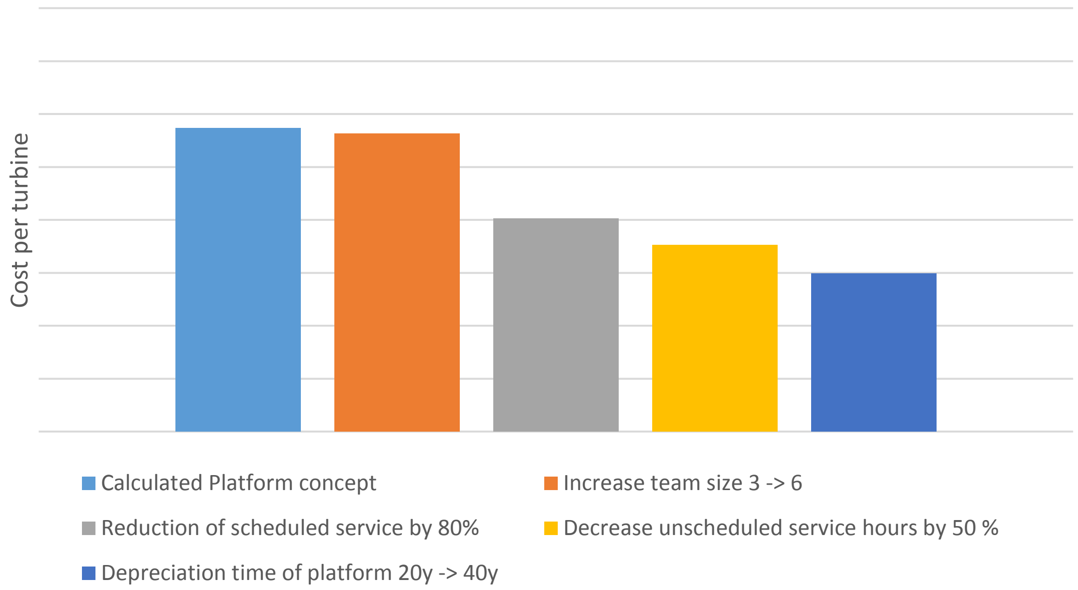

Figure 21 Potential cost reduction of platform concept

From these scenarios, the platform concept shows a slightly higher cost reduction potential compared to the SOV concept. For Hornsea conditions, the initial platform concept is calculated to have a lower cost level, this would also apply for an optimistic scenario of compounded cost reduction potentials. However, if disregarding a reduction in service hours, the SOV light concept would be the most cost beneficial.

As there are several uncertainties regarding potential cost reduction, based on which factors are adjusted, the most favourable solution for offshore maintenance will vary. The authors of this paper argues that cost drivers have a profound impact when deciding on a suitable service solution, and the combined effect should be considered, together with turbine availability, for decision making. It is further argued that, if disregarding the uncertainty of a reduced number of service hours, a SOV light concept with a close capacity match to the service need of a WF is the favourable solution within a foreseeable timespan.

7. Conclusion

This chapter is to conclude the results from the study by summarizing the analysis and answering the two research questions. The research questions are answered with the concept of positivism where the results are objective.

This study aimed at increasing the knowledge within renewable energy sector. This was done by examining the cost structure of service for offshore wind power. Literature and empirical findings were combined to create a tool for analysing different parameters, in this study referred to as cost drivers. The conclusion from the study is based on analysis using the developed tool and presented by answering the two research questions.

> *RQ 1, How do maintenance cost drivers of offshore wind power impact the cost structure and logistical setup for farshore service solutions?*

This study shows the strategic impact on service solutions from four major cost drivers; *distance to shore*, *weather downtime*, *number of turbines*, and *service hours*. Depending on the cost drivers, the preferred setup of logistical assets will vary. This is so since assets are affected by cost drivers differently. One major strategic consideration is the use of an onshore or offshore base for maintenance activities. The use of an offshore base is beneficial for WFs located farshore, such as the site Hornsea. Analysis has been made using two service concepts; an SOV supported by helicopter and a platform concept including CTV and helicopter.

Due to the use of an offshore base, farshore solutions were shown to have low sensitivity towards *distance to shore*. The impact of the cost driver was similar for both farshore concepts, and mainly affected the helicopter usage.

For the cost driver *weather downtime*, a large cost impact was identified for the platform. WDT led to additional need of technicians and vessels resulting in an exponential cost increase. The SOV was less cost sensitive and the concept showed robustness against WDT.

The cost driver *number of turbines* showed cost reduction through economies of scale for both farshore concepts as fixed costs were shared across WTGs. It revealed cost reduction potential of asset-sharing, together with the advantage of the higher accessibility limit of the SOV. While the SOV is the service concept with the highest annual cost, it also allows for a better asset utilization with its lower WDT. This allows the SOV to reap larger advantages from economies of scale than the platform, consequently making it the cheapest concept for large scale operations.

The cost impact of a decreased amount of *service hours* was countered by the large fixed investments of an offshore base. The platform displayed a larger cost reduction than the SOV. This is so as the CTV has less capacity than the SOV and consequently lower fixed cost breaks, thus better possibility of matching demand.

> *RQ 2, How can a service provider in the offshore wind power industry develop its service and offer a cost efficient service solution for future wind farms?*

This study showed that a service provider within offshore wind power can develop its solutions to become more cost efficient through strategic decisions and optimization. A large share of cost savings was to use logistical setups customized to the service need. A cost efficient offering should have a low maintenance cost and deliver high availability.

The availability simulation showed that there are benefits of using helicopters for unscheduled service since it increases the availability. Maintaining high availability can be a competitive advantage for the service provider. To decrease the cost of helicopter usage there are benefits of locating helicopter technicians offshore in order to reduce flight hours and transport time.

There were two concepts presented in this study as farshore solutions. These had several fixed costs, where the vessel cost for the SOV and the platform cost were large shares of the total maintenance cost. Both concepts showed cost reduction per turbine as the number of turbines increased. Hence, it is beneficial for the service provider to contract large WFs, or if possible, bundle services between WFs.

The cost for the platform concept can be reduced by optimizing the needed number of logistical assets. This can be done by utilising each transport means at a maximum regarding the division of scheduled and unscheduled service. The cost of service can further be reduced by increased utilization of technicians. This can be done by increasing the team size, which will reduce the transport time within the wind farm.

A conclusion that can be drawn from this study is that a 33 pax SOV has overcapacity for Hornsea. Hence, it could be advantageous to use a smaller SOV to perform the service as it is less expensive and matches the demand of service. This can reduce the cost of service while providing same value to the customer. This solution was calculated to be most cost efficient for service of 166 WTGs at Hornsea.

8. Further research

This chapter presents the authors suggestions on further research within the studied field. This research may be important to further bring down the cost within renewable energy and wind power. The presented suggestions of research are also subject of analysis to further validate the results of this investigation.

As the usage of an SOV has not been fully explored in practice, the authors suggest that this study is validated through a case study of the operational performance of an SOV. This to conclude its actual capacity regarding number of turbines and the impact of performing unscheduled service. It is concluded that the SOV has an over capacity for Hornsea and that a smaller SOV has a potential to provide a better match between capacity and service demand. Hence is a suggestion to further research cost and performance of a smaller SOV.

For the platform concepts, calculations have been made for one WF. Since the cost of a platform is a large part of the service cost, it could be advantageous to share a platform between WFs in order to decrease the overall service cost. If a platform is shared between WFs, it may however impact the utilisation of technicians and assets. By investigating this subject further, advantages and disadvantages of bundling service could be explored.

This investigation assumed that helicopters were able to perform 100 % of the unscheduled service, there are however uncertainties. This assumption was based on expert interviews, but it need a further in-depth investigation of operations to reveal the actual impact of using helicopters instead of vessels. In addition to this investigation the authors recommend a study of using helicopters to perform scheduled service in order to conclude the impact on maintenance.

In conclusion, the authors identifies several topics that could be further explored within renewable energy and more specified the field of maintenance for offshore wind power. By exploring these topics, new knowledge could be created within cost reduction of offshore wind power, thus potentially supporting the EU to reach its climate goals.

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