Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Masterthesis

Philipp Kruse

Two-bladed wind turbines: Reconsideration of a concept

Analysing potentials from an offshore O&M perspective combined with OEM background evaluation for the feasibility of a commercial pilot project

Fakultät Technik und Informatik
Department Maschinenbau und Produktion

Faculty of Engineering and Computer Science
Department of Mechanical Engineering and Production Management

Philipp Kruse

Two-bladed wind turbines: Reconsideration of a concept

Analysing potentials from an offshore O&M perspective combined with OEM background evaluation for the feasibility of a commercial pilot project

Masterarbeit eingereicht im Rahmen der Masterprüfung

im Studiengang Nachhaltige Energiesysteme im Maschinenbau
am Department Maschinenbau und Produktion
der Fakultät Technik und Informatik
der Hochschule für Angewandte Wissenschaften Hamburg

in Zusammenarbeit mit:
EnBW Energie Baden-Württemberg AG
Fischertwiete 1
20095 Hamburg

Erstprüferin: Prof. Dr.-Ing. Vera Schorbach
Zweitprüfer: Dipl.-Ing. Marcus A. Ihle

Abgabedatum: 19.10.2018

Zusammenfassung

Philipp Kruse

Two-bladed wind turbines: Reconsideration of a concept

Analysing potentials from an offshore O&M perspective combined with OEM background evaluation for the feasibility of a commercial pilot project

Keywords

wind energy, wind turbine, two-bladed, offshore, operations, maintenance, O&M, OEM, pilot project, wind farm, bankability, insurance, project development, expert interviews

Abstract

Innovation as a means to reduce the cost of energy is required for the offshore wind energy to be cost-competitive against onshore wind and conventional energy. This thesis is a practical contribution combining scientific analysis of innovative multi-megawatt two-bladed WTGs in operation with innovation processes as practiced by the offshore wind industry. Market entry with radical concepts has so far proven hard, typically hampered by factors like bankability and track record demands, real risks and risk perception. These factors above all explain why proven conventional wind technology is preferred, pushed by powerful established OEMs with the necessary financial background. Thus, topics like bankability and insurability need to be an essential part of the concept and development phase of a new technology. This process has to be taken up as early as possible to prevent a situation as it is the case with the two-bladed technology now. Namely that interesting concepts are developed but in the end, they fail not due to technical issues or a lack of cost reduction potential but rather because of the insufficient alignment to the target market and its peculiarities. The question of unique benefits and operation cost reduction potential seems to be answered insufficiently by two-bladed WTGs or the need for offshore wind energy cost reduction is not big enough yet to consider this technology.

Zweiblatt-Windenergieanlagen: Neubewertung eines Konzeptes

Offshore O&M Potenzialanalyse und OEM Bewertung für die Machbarkeitsprüfung eines kommerziellen Pilotprojektes

Stichworte

Windenergie, Windturbine, Zweiblatt, Offshore, Betrieb, Wartung, O&M, OEM, Pilotprojekt, Windpark, Bankability, Versicherung, Projektentwicklung, Experteninterviews

Kurzzusammenfassung

Innovationen zur Senkung der Kosten im Bereich Offshore Windenergie sind nötig, um gegenüber der Onshore Windenergie und konventioneller Energie wettbewerbsfähig zu sein. Diese Arbeit versteht sich als praktischer Beitrag, der die wissenschaftliche Analyse innovativer Offshore Zweiblatt-WEA im Betrieb mit Innovationsprozessen der Offshore Windindustrie kombiniert. Der Markteintritt radikaler Konzepte ist bisher schwierig und wird in der Regel durch Anforderungen an nachgewiesene Betriebsstunden sowie die „Bankability“, reale Risiken und Risikoperzeption behindert. Diese Faktoren erklären vor allem, warum bewährte Technologie bevorzugt wird, angetrieben von starken etablierten OEMs mit ausreichenden finanziellen Mitteln. Themen wie „Bankability“ und Versicherbarkeit müssen daher ein wesentlicher Bestandteil der Konzept- und Entwicklungsphase einer neuen Technologie sein, um eine Situation zu vermeiden, wie sie bei heutigen Zweiblatt-WEA der Fall ist. Gemeint ist die Entwicklung innovativer Konzepte, die letztlich nicht an technischen Problemen oder fehlenden Kostensenkungspotenzialen scheitern, sondern an der unzureichenden Ausrichtung auf den Zielmarkt und dessen Besonderheiten. Die Frage nach Vorteilen und Kostensenkungspotenzialen scheint von Zweiblatt-WEA unzureichend beantwortet, oder die Notwendigkeit von Kostensenkung ist derzeit nicht groß genug, um diese Technologie zu berücksichtigen.

Index

List of figures

List of tables

List of symbols

Abbreviation	Definition
2-B	Two-bladed
3-B	Three-bladed
AC	Alternate current
ACTV	Advanced crew transfer vessel
AEP	Annual energy production
BFOW	Bottom-fixed offshore wind
BMWi	Federal Ministry for Economic Affairs and Energy
BoP	Balance of plant
BSH	Federal Maritime and Hydrographic Agency
CAPEX	Capital expenditure
CCME	Central Command for Maritime Emergencies
CEO	Chief Execution Officer
COO	Chief Operating Officer
CPC	Collective pitch control
CTV	Crew transfer vessel
DC	Direct current
EEG	German Renewable Energy Act
EEZ	Exclusive Economic Zone
FID	Final investment decision
Fino	Research platform in North and Baltic Sea
FOU	Foundation
FOW	Floating offshore wind
GW	Gigawatt
GWh	Gigawatt hour
HSE	Health and safety
HVDC	High voltage direct current
IAG	Inner array grid

IMPL	Implentation
INS	Insurance
IPC	Individual pitch control
KPI	Key performance indicator
kV	Kilovolt
kWh	Kilowatt hour
LCoE	Levelized cost of electricity
LEG	London Engineering Group
LGS	Logistics
MTBF	Mean time between failures
MTTF	Mean time to failure
MTTR	Mean time to restore
MW	Megawatt
NPV	Net present value
O&M	Operations and maintenance
OEM	Original equipment manufacturer
OPEX	Operational expenditure
OSS	Offshore substation
OWF	Offshore wind farm
PM	Project management
QA	Quality assurance
SeeAnlV	Sea Facilities Act
SOV	Service operation vessel
WACC	Weighted average cost of capital
WindSeeG	Wind Energy At Sea Act
WTG	Wind turbine generator

Formula symbols	Definition	Unit
Arabic characters		
A	Area	[m²]
C	Capacity factor	[-]
c_p	Power coefficient	[-]
Db	Debt capital	[€]
E	Total annual produced electricity	[kWh/a]
Eq	Equity capital	[€]
h	Possibility of occurance	[%]
H	Height	[m]
I	Investment cost	[€]
i	Real calculated interest rate	[-]
n	Total operating time	[a]
P	Power	[kW]
t	Period of time / Tax rate	[s], [h], [a] / [-]
T	Total annual cost	[€/a]
Tc	Total capital	[€]
v	Wind speed	[m/s]
Greek characters		
λ	Tip speed ratio / Failure rate	[-]
ρ	Density	[kg/m³]

Index	Definition
0	Starting point
D	Debt
E	Equity
el	Electrical
i	Interval
R	Rotor
s	Significant
t	Per year
WTG	Wind turbine generator

1 Introduction

1.1 Initial situation and objectives

Politically the objectives for the turnaround of the energy sector in the European Union and particularly in Germany are clearly defined: Reduction of the greenhouse gases by 80 – 95 % until 2050 compared to the level of 1990 and simultaneous phasing out of nuclear energy until 2022. As a result, the demand for renewable energy grew significantly over the last decade and will still develop in the years to come. Due to the increasing ability to compete against conventional power plants, the market for renewable energy grew especially with the help of state funding. Offshore wind energy with its large potential is one of the cornerstones of the future renewable energy portfolio. Since 2009 German offshore wind farms (OWF) generate electricity and feed it into the grid. A closer look at the amount of electricity fed into the grid shows the enormous potential of wind energy in the North and Baltic Sea. The generated amount of energy increased from 176 GWh (2010) to 17,950 GWh (2017). An increase by a factor of one hundred in the span of seven years (Fraunhofer 2018). This represents around 3 % of the German gross electricity consumption in 2017. Until 2030 it is planned that the amount of offshore wind energy covers up to 7 – 14 % depending on three different growth scenarios. (WindEurope 2017a)

Wind turbines with a two-bladed rotor (two-bladed WTG) have been considered a valid design since the beginning of modern wind energy. However, their introduction lacks acceptance for onshore applications due to various factors such as unfavorable optical and acoustical behavior as well as design related high dynamic loads. As a result, the leading manufacturers of wind turbines consistently rely on three-bladed rotor design. (Hau 2016) On the one hand, innovation as a means to reduce cost of energy is required for the offshore wind sector to be competitive. On the other hand, conservative risk assessment and bankability are problems of innovative concepts. New concepts of established manufacturers are usually just an upscaling of existing three-bladed WTGs. The lack of diversity of innovation throughout the market is furthermore reinforced by the tendency for market adjustments through consolidation of previous competitors. (Jamieson 2011) Today the possible benefits of a two-bladed WTG for offshore use are reassessed, for example in the areas of transport, installation, operation and better resistance to extreme winds (Dalhoff et al. 2013).

Over the past few years, a number of new companies (OEMs) try to enter the market with updated concepts of two-bladed WTGs primarily designed for multi-megawatt offshore application. There is little information available about these companies when it comes to size and commercial background, partly because they are in the startup phase or even pure concept studies. They also consider different ways when it comes to solving challenges of two-bladed WTGs like high dynamic loads. Furthermore there is no such thing as a standard design (Dalhoff et al. 2013).

At the moment OWF with state of the art offshore WTGs have higher levelized cost of electricity (LCoE) compared to onshore wind energy despite their higher average full-load hours of up to 4,500 hours per year. The causes for higher LCoE can be identified as increased costs for plant production and installation as well as operation and finance expenditures. (Kost et al. 2018)

A cost-reduction manifesto issued by DNV-GL in 2014 asserts that the following three strategies could collectively contribute to a reduction in the LCoE of up to 25 % (DNV GL 2014):

- Do it right – focus on reducing risk and preventing mistakes (7 % reduction)
- Do it better – improve the efficiency of existing processes (6 % reduction)
- Do it differently – implement alternative and innovative ways of doing things (12 % reduction)

Applying strategy number three on WTGs leads to alternative turbine designs such as a two-bladed WTG which is the central element of this study. An innovative design combined with the need to reduce the LCoE raises the following research questions from an operations and maintenance (O&M) point of view:

> *'Is it possible to significantly reduce offshore operating costs by* utilizing *two-bladed WTGs and can potential advantages be made concrete for further use in operational cost models? Even if the operating costs can be reduced, it remains unclear if and when the available concepts and their manufacturers are ready for a pilot project consistent with industrial project development requirements for bankability and further decision-making criteria.'*

The following Chapter 1.2 explains the methodology used to answer the above-mentioned research questions and the structure of the thesis is presented.

1.2 Methodology and structure of the thesis

This thesis is a practical contribution combining scientific analysis of two-bladed WTGs in operation with innovation processes as practiced by the offshore wind energy industry. First, technical and economic evaluation criteria are defined for an analysis of the currently available two-bladed WTGs. The analysis is utilized to compare the OEMs and their product/concept with regards to the feasibility of a pilot project and as a basis for further research of the thesis. A qualitative empirical study with expert interviews is conducted including internal and external specialists. The information gathered from the expert interviews is expanded upon through extensive use of professional literature to develop a basic understanding of two-bladed WTGs from an O&M perspective as well as to critically assess their technical and economic potential for further planning of OWFs.

The master thesis is structured as shown in Figure 1-1 and starts with an introduction in Chapter 1 which comprises information about the initial situation and background of two-bladed WTGs as well as a definition of the problem. Chapter 1 also gives a brief overview of the motivation for innovations in the offshore wind sector and defines objectives, methods and the structure of the thesis.

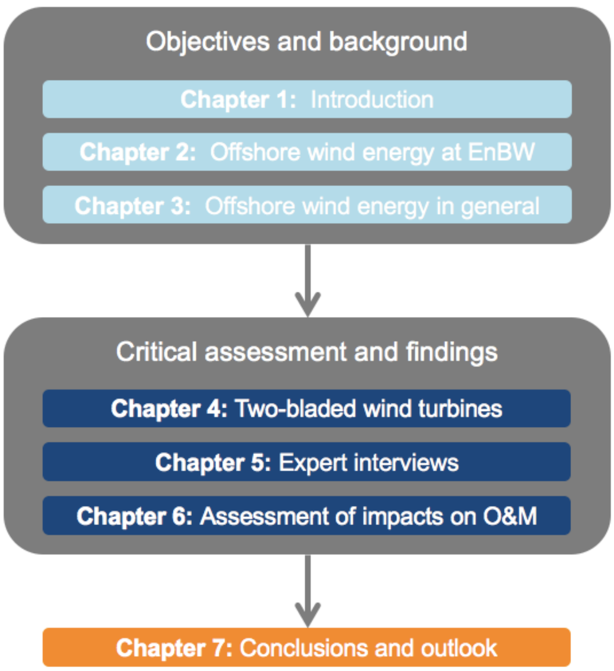


Figure 1-1: Structure of the thesis [Author's illustration]

Chapter 2 presents the economic environment and the status quo of EnBW's offshore portfolio. Another focus of this Chapter is on the topic of innovations at EnBW and practical projects are introduced. The basics of offshore wind energy and especially of the O&M phase of an OWF are explained in Chapter 3. Basics like the project life-cycle and financing of an OWF as well as the offshore wind LCoE are necessary for the understanding of this thesis and an evaluation of two-bladed WTGs from an O&M perspective. Chapter 4 describes the 'reconsideration' of the two-bladed WTG design for the offshore market. Former technical challenges, current concepts and solutions as well as their development state are reviewed. Additionally, the OEMs and the general investment cost reduction potentials are critically discussed. This Chapter and its conclusions about the two-bladed WTG for the offshore market combined with the basics of Chapter 3 represents the basis for the expert interviews in Chapter 5.

The expert interviews including a wide range of important decision-makers from the wind industry and research as well as the finance and insurance sector form Chapter 5 and are the central survey instrument of this thesis. In the course of Chapter 5 the participants with their field of expertise are mentioned and the interview and question buildup is explained in detail. An explanation of the transcription and evaluation methodology is followed by the presentation of the results in form of key statements.

Chapter 6 forms the second central part of this thesis and is concerned with the assessment of impacts of two-bladed WTGs on the O&M phase. It critically investigates different aspects such as reliability, maintainability and serviceability as well as typhoon proof operation, energy yield and other cost-effective impacts. Additionally, health and safety issues are highlighted at the end.

The master thesis ends with Chapter 7 and conclusions from the studies of Chapter 4, 5 and 6. Chapter 7 also gives an outlook on the possible development of two-bladed WTGs in the offshore market. Finally, it indicates possible further actions by EnBW regarding a pilot project and provides an overview of additional scientific investigation potential.

2 Offshore wind energy at EnBW

Chapter 2.1 includes an overview of the current economic situation of the major energy supply companies in Germany and their challenges due to the energy turnaround. Furthermore, the EnBW specific boundary conditions and the company's strategic focus by 2020 are explained. It continues with a closer look at the status quo of EnBW's offshore wind energy division and the offshore generation portfolio in Chapter 2.2. Chapter 2 concludes with the topic of innovation at EnBW (2.3).

2.1 Economic environment and 'Strategy EnBW 2020'

The expansion of renewable energies is politically fixed. By 2025, 40 – 45 % of the electricity shall come from renewable sources. By 2035 this value is set to be increased to between 55 and 60 %. The long-term goal for the year 2050 is at least 80 %. This development exacerbates the profitability problems of conventional power plants due to the 'Merit-Order-Effect'[1] and continuously shrink the market share of the Big 4 (RWE, E.ON, Vattenfall and EnBW). (Bontrup, Marquardt 2015) The EnBW Group assumed in 2014 that the contribution to earnings of conventional energy generation decline by 80 % until 2022 (EnBW 2016). In particular, the phase-out of nuclear energy by 2022 (Fraunhofer 2018) following the Fukushima nuclear disaster as well as stronger competition puts a strain on the economic situation of EnBW. Nuclear power production accounted for 51 % of the total generation portfolio in 2010. At 24 % in 2018, it is still the second largest item in EnBW's energy mix and has a corresponding impact on the group's economic situation. (EnBW 2018a)

Responding to these developments in the energy industry, EnBW published a press release in 2013 entitled 'Strategy EnBW 2020'. According to this strategy paper EnBW is aiming for a rapid restructuring of its generation portfolio by the year 2020. The 'Adjusted EBITDA'[2] of the renewables division is to be increased from the current 287.4 Mio€, which represents a share of 13.6 %, to 700 Mio€ in 2020, which corresponds to a share of 30 %. Compared to the base year 2012, this objective represents an ambitious 250 % increase, whereby wind energy, both onshore and offshore, is referred to as a key growth sector. The share of renewable energies in EnBW's installed capacity is to be doubled from 19 % (base year 2012) to more than 40 % by 2020. (EnBW 2013)

[1] The merit order effect describes the temporary displacement of power plants from the market by the entry of producers with very low marginal cost such as renewable energies (Graeber 2014)
[2] Adjusted EBITDA includes removal of one-time, irregular and non-recurring cost and earnings from the EBITDA (Earnings Before Interest Taxes, Depreciation and Amortization) (CFI 2018)

2.2 Status quo of EnBW's offshore portfolio

Since 2011 the first commercial German OWF EnBW 'Baltic 1' has fed the grid. The 21 WTGs of 'Baltic 1' have a total capacity of 48.3 MW. EnBW's second OWF 'Baltic 2' was put into operation in 2015. Compared to 'Baltic 1', the number and capacity of the installed WTGs increased to 80 turbines with a rated power of 3.6 MW/turbine which leads to a total installed capacity of 288 MW. The increase of the coastal distance and the water depth lead to higher planning and installation efforts. The water depth varies between 23 - 44 meters and depending on the local water depth the WTGs are mounted on monopiles in shallower water or steel truss structures called jackets in deeper water. (EnBW 2018b)

Figure 2-1 gives an overview of EnBW's actual OWFs and planned offshore wind projects (EnBW 2018b). Including EnBW's projects 'Hohe See' and 'Albatros' the total installed offshore capacity will be increased to 945 MW by 2020. 'Hohe See' and 'Albatros' will both be installed in the North Sea. Siemens will supply 87 WTGs of 7 MW rated power and foundations for depths of up to 40 m at a distance of 105 km from the shore. In 2017, EnBW's bid of 0.00 €$_{Cent}$/kWh in Germany's first offshore wind tender round[3] was accepted (EnBW 2017a).

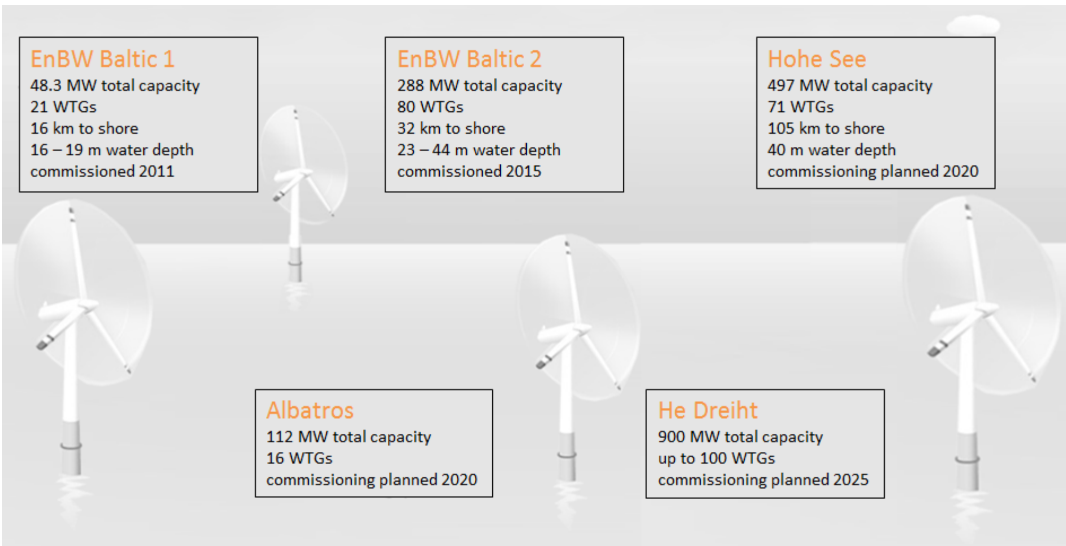


Figure 2-1: Overview of EnBW's actual offshore wind farms and project pipeline [Author's illustration based on (EnBW 2018b)]

The new North Sea project is called 'He-Dreiht' and with an installed capacity of 900 MW it is the largest single project of this tender round. Due to a combination of

[3] The effects of the new German offshore wind tender procedure are discussed under Chapter 3.1 in detail.

several factors, 'He Dreiht' offers the possibility to be highly cost effective. With a planned commissioning in 2025, the OWF will profit from the rapidly advancing technology development and further professionalization in the wind energy sector. Technology development means especially that WTGs with a rated power of 9 MW or more will be installed (EnBW 2017a). MHI Vestas already offers a turbine with 9.5 MW rated power which result in higher energy yields compared to smaller turbines (MHI Vestas 2018). Significant synergies and thus cost-cutting effects also result from the proximity to the two other EnBW OWFs in the North Sea. Overall, around 1,500 MW can be realized and operated in the direct vicinity of 'Hohe See', 'Albatros' and 'He Dreiht' (EnBW 2017a). The combination of these factors provides a forecast of declining LCoE and 'He Dreiht' can be realized and operated without subsidies (EnBW 2017a) despite the estimation that the trend to larger equipment (Fraunhofer 2018) will lead to increased capital expenditure (CAPEX) (Rodrigues et al. 2015).

In addition to the German market, the focus lies also on markets in Asia and the USA. In 2018, EnBW confirmed a participation in three projects off the Taiwanese coast with a total volume of about 2,000 MW. Taiwan holds strong potential for renewable energies after deciding to phase out of nuclear power by 2025. They aim to make up for the resulting shortfall of some 20 % by expanding renewable energies and most of all offshore wind power. Taiwan has set ambitious targets in this regard and plans 5.5 GW of offshore wind power to be ready by 2025. Allocation of the necessary grid connection capacity is planned for the first half of 2018. (EnBW 2018c)

2.3 Innovations and projects in practice

Innovation is of strategic importance not only for EnBW but for the entire energy sector. The already mentioned political and economic goals strengthen the need for further innovations to provide cost effective and reliable green energy as well as smart solutions to implement them in the daily life. Wind and water, sun and bioenergy are the main resources that pave the way for an energy system without carbon-containing fuels. There are still open questions on how to use renewable resources more efficiently and if other natural resources can be used to generate energy. Besides energy production, EnBW is intensively involved in the development of various technologies such as electro mobility including public and home charging solutions or hydrogen as a fuel substitute. Smart grid and smart home technologies are other key components to solve the future energy distribution challenges resulting from fluctuating green energy production. (EnBW 2018d)

In the field of wind energy, EnBW is currently engaged in a research project on electricity generation from high-altitude winds. As a joint project partnership SkySails Power GmbH, EnBW AG, EWE Offshore Service & Solutions GmbH and Leibniz University Hannover are developing and testing a fully automated onshore airborne wind energy system with an output of 100 kW by 2020. Airborne wind energy systems have the advantage that they are able to operate in higher air layers with stable high-energy wind speeds. Gradually, the technology is further developed for multi-megawatt offshore operation in the future (see Figure 2-2). (EnBW 2018e)

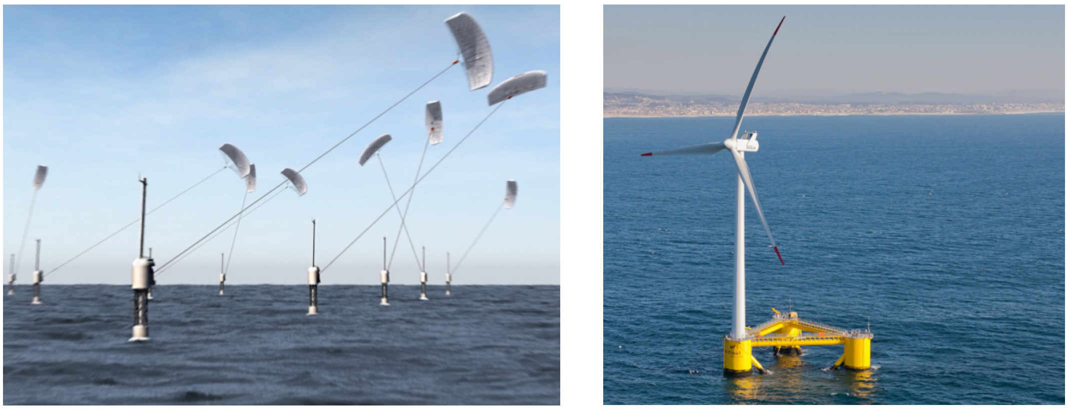


Figure 2-2: Offshore airborne wind energy system (left) (EnBW 2018e) and a floating offshore WTG off the Portuguese coast (right) (EnBW 2017b)

Another field of research and project development is the offshore foundation sector. EnBW is having a detailed look at several innovative foundation solutions. Suction buckets have been considered but were dismissed due to commercial and technical issues. In 2018, EnBW North America and Trident Winds Inc., based in Seattle, Washington, have formed a joint venture to advance the 650 - 1,000 MW 'Morro Bay' offshore wind project off the central coast of California with a grid connection in Morro Bay. Together, both companies will work on the development of the first large-scale floating offshore wind project in the region. EnBW sees maturity of the floating foundations (see Figure 2-2) as representative of the future of offshore wind. Several other projects and floating technology solutions are evaluated at the moment. Floating offshore wind opens up new areas with greater water depth as well as better wind conditions and thus offers the possibility to advance in new offshore wind markets. (EnBW 2018f)

3 Offshore wind energy in general

In order to assess the cost reduction potential of two-bladed WTGs from an offshore O&M point of view, a general understanding of the offshore wind energy boundary conditions as well as detailed knowledge of the O&M phase is essential. Chapter 3.1 summarizes the current situation of the offshore wind energy sector and gives an outlook on the future development followed by Chapter 3.2 about the wind turbine technology. Chapter 3.3 is on OWF backgrounds and Chapter 3.4 looks at offshore environmental conditions. Subsequently, a general overview of the project life cycle of an OWF is given in Chapter 3.5. Chapter 3.6 outlines the financing basics and the financial model including capital (CAPEX) and operational (OPEX) expenditure. The following Chapter 3.7 describes the approach of the LCoE to compare the cost of different power production technologies. Challenges of the operating phase of an OWF and the tasks of the O&M phase arising from these challenges are explained in Chapter 3.8.

3.1 Current situation and future prospects

The 2016 Fraunhofer wind energy report shows an expansion of 818 MW installed offshore capacity in Germany. In 2015, almost 2,300 MW were newly connected to the grid. This exceptionally high value is justified by the completion overhang. That means already installed systems which could not be connected to the grid due to a lack of capacities finally were plugged in. At the end of 2016, a cumulative capacity of 4,089 MW of offshore wind power is already in operation in German waters. (Fraunhofer 2017) According to the Federal Ministry of Economics and Energy (BMWi), the offshore wind energy sector already exceeded the threshold for industrialization in 2015 (BMWi 2015).

The expansion plans of the BMWi comprise three phases. An installed capacity of 6,500 MW is the expansion target of the first phase and should be achieved by 2020. The upper limit is set at 7,700 MW. The second and third phase of expansion from 2021 to 2030 implies an average annual installed capacity of 800 MW. According to this scenario, an installed capacity of 15,000 MW will be reached at the end of the third expansion phase. (BMWi 2015) Looking at the total installed capacity of 818 MW in 2016 and the annual installed capacity planned between 2021 and 2030, it is noticeable that no increase in installed capacity is planned for the coming years. This is considered a negative sign for the offshore wind energy industry. A commitment to expanded installation targets rather gives the industry a clear signal for further investments and innovations.

The big energy companies, project developers, investors and manufacturers are also geared towards foreign markets due to the large potential and partly due to the moderate expansion targets in Germany and the entire EU. In this context, the emerging markets in Asia (e.g. Japan, Taiwan) and the USA (e.g. Hawaii, California) have to be named (EnBW 2017b, 2018f). Especially the typhoon areas in Asian markets are of interest to two-bladed WTG concepts and this thesis.

Offshore wind energy continues to be an expensive technology despite the industrialization mentioned earlier. The technical and financial expenditure for the planning, construction, operation and dismantling of OWFs is significantly higher than for onshore projects. Higher energy yields, large wind farm units and clusters, large plant capacities and the previous funding regulation according to the German Renewable Energy Act (EEG) help to make profitable use of offshore wind energy. (Fraunhofer 2018) Despite average full load hours of up to 4,500 hours per year the resulting LCoE for current offshore projects vary from 7.50 to 13.80 $€_{Cent}$/kWh. Onshore wind turbines generate LCoE in the range from 4.00 to 8.20 $€_{Cent}$/kWh. (Kost et al. 2018)

To ensure cost-competitiveness of offshore wind energy it is a major task for the whole industry sector to constantly identify cost reduction potential throughout the life-cycle of an OWF and actually achieve a reduction of the LCoE. The greatest cost reduction potentials are certainly in plant production, logistics, installation and financing but also in the O&M phase. (Böttcher 2013) Additional challenges and higher CAPEX potential arise by future sites located further from shore and in harsher conditions (Rodrigues et al. 2015). A trend to larger WTGs and projects (WindEurope 2017b) also means larger equipment and new logistics as well as O&M requirements (Fraunhofer 2018). Further Gonzalez-Rodriguez also assume that CAPEX will not decline (Gonzalez-Rodriguez 2017). Schwanitz and Wierling even doubt the profitability of investments in OWFs (Schwanitz, Wierling 2016). Additionally, the actual legal framework in Germany puts pressure on cost reduction due to a new remuneration model for offshore wind energy and the resulting competition between OWF project companies. The amount of the market premium is now determined through tenders and is no longer guaranteed in accordance with the EEG. (Fraunhofer 2018) In 2017 the first tender round finished with the lowest accepted bid of 0.00 $€_{Cent}$/kWh and the highest of 6.00 $€_{Cent}$/kWh. This means in fact no funding of the 'zero cent bids' according to the EEG for the first time. Overall the tender round included a total capacity of 1,550 MW of which 1,490 MW were awarded to four bids. The average accepted bid of 0.44 $€_{Cent}$/kWh was unexpected low according to the president of the German Federal Grid Agency, Jochen Homann (Bundesnetzagentur 2017). Also in the second tender round in 2018, 'zero cent bids' were awarded but the average accepted bid of 4,66 $€_{Cent}$/kWh is around ten times higher which is a result of the fact that at least 500 MW of Baltic Sea projects had to be awarded. Thomas Bareiß, secretary of state (BMWi) construes the tender results as proof that the offshore wind energy sector is on the way to cost-effectiveness. (BMWi 2018) Not all offshore wind experts interpret the results solely positive. "At current market conditions, the projects can't be realized. Behind the 'zero cent bids' is the assumption that prices for technical equipment fall, the interest rate environment remains favorable and electricity prices rise. The risk that individual projects will not be realized at the end can therefore not be dismissed", says Klaus Meier, who is chairman of the board of wind farm developer wpd from Bremen (Handelsblatt 2018).

Despite that, a significant cost reduction potential is generally assumed, as already mentioned in Chapter 1. The BMWi estimates the savings to be in the magnitude of 20 – 40 % by 2020 (BMWi 2015) and thus in the 'best case' even higher than the cost-reduction manifesto of DNV-GL with 25 % (DNV GL 2014). A study compiled by the Prognos AG and Fichtner Group in 2013 assumes a cost reduction potential of between 32 - 39 % (Prognos AG 2013). Fraunhofer Institute's LCoE forecast of 3.50 - 10.10 $€_{Cents}$/kWh by 2035 confirms this assessment (Kost et al. 2018). The summary of the offshore wind sector cost situation and its interpretation shows that the experts are divided over the future prospects. To state an accurate number is only possible when the corresponding projects have been realized and evaluated.

A closer look at the topic and speaker selection of a separate own desktop study research on upcoming offshore wind exhibitions and conferences in 2018 clearly shows that floating foundations are currently strongly represented in the area of innovation at all events. As described in Chapter 2.3, EnBW also focuses on the potential of floating foundations for new markets and applications further away from the coast, in deeper waters and with better wind conditions. The subject two-bladed WTGs is not focused on, which is not only reflected in the selection of topics and speakers for conferences, but also in the lack of presence of two-bladed WTG OEMs/concepts at exhibitions. Nevertheless, this technology is also expected by its OEMs and various experts to have potential for reducing the costs of OWFs, which is critically considered in this thesis.

3.2 Wind turbines and support structures

Independent of the construction or application of a WTG its purpose is to convert the kinetic energy of the wind into mechanic rotation energy. Therefore, they belong to the superior group of energy converters and can be used for:

- Direct mechanic deployment: Propulsion for machines
- Conversion into hydraulic energy: Water pumps
- Conversion into thermal energy: Heater, cooler
- Conversion into electrical energy: Grid feed, island operation

Most of the modern WTGs are used for generating electrical power. They can be divided by two different aerodynamic principles, the buoyancy force or resistance (see Figure 3-1).

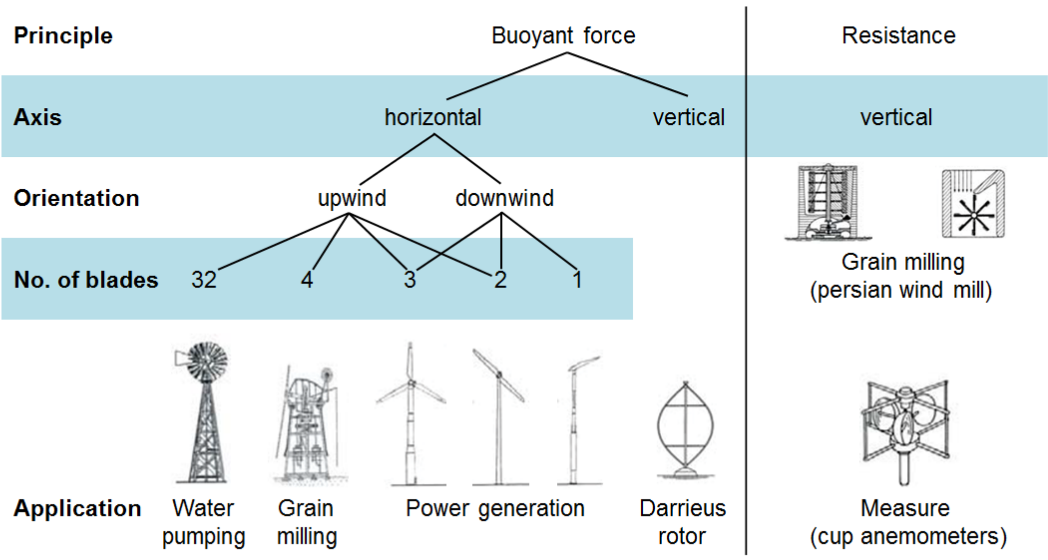


Figure 3-1: WTG overview [Author's illustration based on (Gasch, Twele 2016)]

In theory, up to 16/27 (ca. 59 %) of the existing wind energy can be converted. This theoretical value assumes no power losses. In practice only values of 50 % are achievable. Further power is lost due to aerodynamic, mechanical and electrical losses and modern WTGs reach an efficiency of approximately 45 % (Gasch, Twele 2016).

MECHANICAL CONSTRUCTION

The mechanical construction of a WTG can be divided into two main components:

- Support structure
- Turbine

All structural components between seabed and the turbine can be summarized as support structure. This includes the tower, the transition piece and the foundation. The turbine itself consists of the nacelle and usually a hub with a three or two bladed rotor. (BSH 2007)

Figure 3-2 shows the different offshore foundation concepts. In general, they can be divided into floating offshore wind (FOW) and bottom-fixed offshore wind (BFOW). Over the past few years the monopile foundation (BFOW) concept has developed as the most widely used foundation variant. In 2016, around 76 % of the newly built offshore WTGs were built on monopiles. About 9 % of the new installations were founded on gravity foundations. The remaining 15 % are split between: Jacket (6 %), tripod (3 %), high-rise pile cap (3 %), tripiles (2 %) and others (1 %). (Fraunhofer 2018) FOW foundations are being tested in a commercial scale in several projects such as Hywind, Scotland or WindFloat Atlantic, Portugal. 80 % of all offshore wind resource is located in waters 60 m and deeper in European seas, where traditional BFOW is not economically attractive. (WindEurope 2017c)

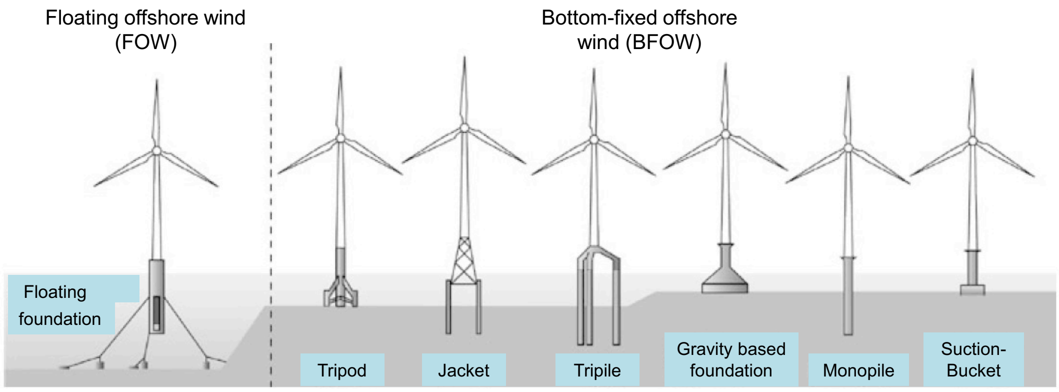


Figure 3-2: Types of offshore wind foundations [Author's illustration based on (Kaltschmitt et al. 2014)]

Transition piece and foundation are connected via grout (grouted joint). This ensures that installation tolerances between the two components can be compensated which allows an exact alignment of the transition piece. One part of the transition piece is the ladder for service technicians to enter the WTG via vessel (see Figure 3-3). A crane on the platform can be used to lift up heavy equipment. The turbine can be reached by technicians with smaller parts or equipment via elevator inside the tower. Personnel and equipment can also be transferred to the WTG with a helicopter by a winch. For this purpose the WTG has a separate winch operating area on top of the nacelle. (Hau 2016) Nacelle cranes usually have a lifting capacity of up to 15 t (Palfinger 2018). Equipment extending the capacity of the nacelle crane requires an external crane in form of a jack up repair vessel with an onboard crane. (Kaltschmitt et al. 2014)

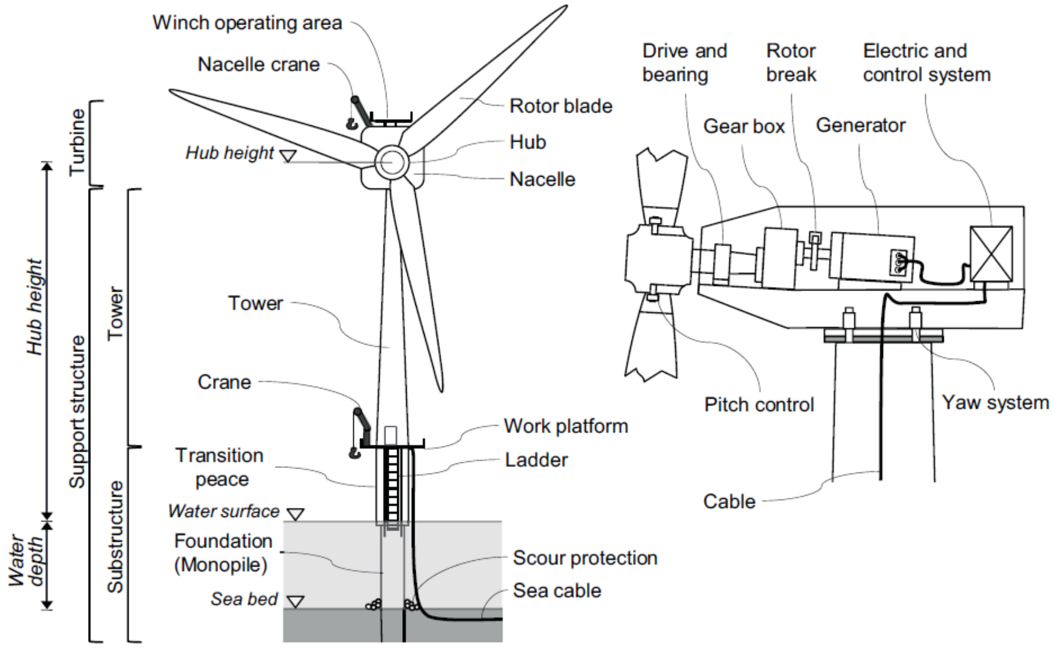


Figure 3-3: Example construction of an offshore WTG and a nacelle in detail (Kaltschmitt et al. 2014)

Composite fiber material is state of the art when it comes to rotor blades which are connected to the drive train through the hub. The hub includes the pitch-system to regulate the speed of the rotor and the power output of the generator by rotating the blades across its longitudinal axis. The turbine is mounted to the tower and can be rotated with the help of azimuth drives and bearings. Figure 3-3 shows a detail of the nacelle including the drive train, electrical and control systems as well as the yaw-system (azimuth). The drive train in this example is a classical design with a transmission gear located between the rotor and generator. Other alternative concepts are based on a so-called direct dive and need no gearbox. The dissolved design type has a separate bearing and the integrated type's bearing is part of the gearbox. (Hau 2016)

OPERATION

WTG operational management is mostly automated and manual operation procedures are only exceptions. The control system is managed by the operational system and enables the fully automated operation according to external parameters, like wind speed and wind direction. The different operation states of a WTG are described in Table 3-1. Only idleness and load operation are steady states. Other states are only transition states in between the steady states. The control system aims to minimize mechanical load to avoid wear and tear as well as to maximize efficiency for each state of operation. (Hau 2016)

Table 3-1: WTG states of operation [Author's illustration based on (Hau 2016)]

State of operation	**Description**
Idleness	*The plant is ready to operate, but not in operation*
System inspection	*The operation cycle starts with the inspection of the most important systems*
Yaw control	*The rotor is moved into the wind after successful inspection*
Comissioning	*For the commissioning the breaks are released, the rotor blades are pitched and the rotor starts rotating*
Start-up	*The revolutions per minute are increased until 90% of the rated revolutions per minute*
Load operation	*Electrical power is generated and fed into the grid. Depending on the wind speed it is distinguished between full load or partial load operation*
Overload operation	*Before the revolutions per minute exceed the rated revolutions per minute the rotor blades are usually pitched to decrease the speed below the rated limit*
Shut down	*If the wind speed is lower than the minimum operational speed, the WTG is shut down by pitching the rotor blades and disconnecting the generator from the grid. This also happens in case of too high wind speeds*
Standby	*The number of revolutions per minute is reduced to zero and the WTG is in idle mode. The total stop of the WTG is reached by applying the mechanical brakes*

SAFETY SYSTEM

The safety system of a WTG is an essential part and has to make sure that in case of an emergency the system is shut down instantly. It has to be independent from the operational and control system and is always redundant. A great variety of relevant safety data is needed. This data covers the state of operation as well as the condition of different components:

- Generator power, respectively torque
- Temperature of critical components
- Unusual vibration of certain components

- Revolutions per minute
- Electrical parameters in connection to the grid feeding
- Malfunction of speed and power control
- Inadmissible cable torsion

In case of a failure the safety system activates primarily the brake system to stop the rotor and the WTG is disconnected from the grid. The rotor brake and stop of larger WTGs is initialized by aerodynamic measures at the rotor blades. (Hau 2016) (Gasch, Twele 2016)

OPERATING CHARACTERISTICS

The power output P_{el} of a WTG depends on the wind speed *v*, the power coefficient c_p[4], the air density *ρ* and the rotor swept area A_R according to Equation (3-1).

$$P_{el} = c_p \cdot \frac{\rho}{2} \cdot A_R \cdot v^3 \qquad (3\text{-}1)$$

A typical power and c_p-curve is shown in Figure 3-4. The c_p-curve of a WTG is dependent on the tip speed ratio λ[5].

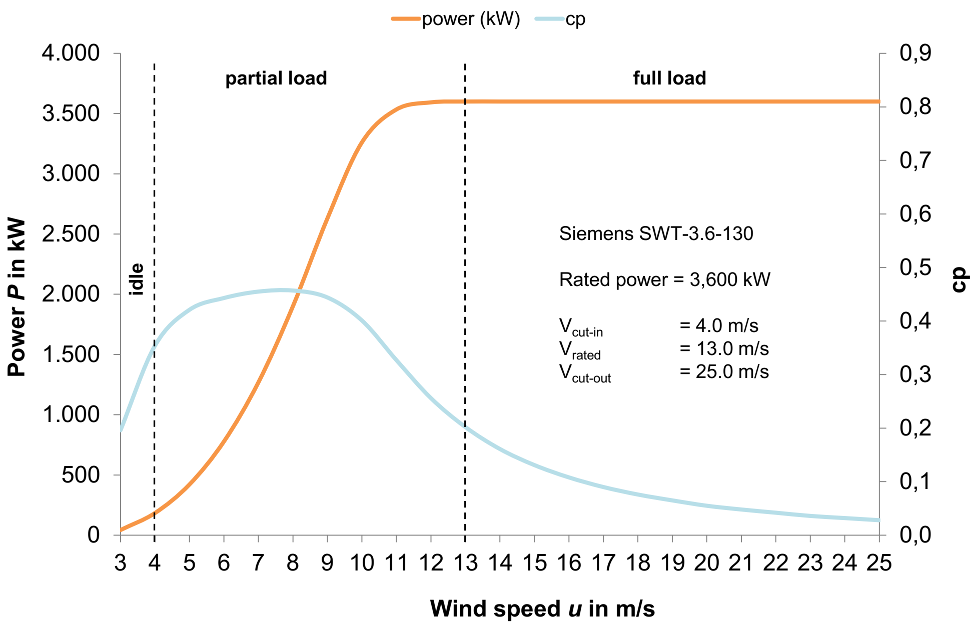


Figure 3-4: Example power/c_p-curve of the Siemens SWT-3.6-130 [Author's illustration based on (WTM 2018)]

It can be divided in three areas: Idle, partial load and full load. Below the WTG's system-specific cut in speed the rotor stands still or is trundling. In this state the

[4] Coefficient c_p is the quotient of the extracted wind power and the winds total power. (Hau 2016)
[5] The tip speed ratio λ indicates the ratio of the blade tip speed to the wind speed. (Hau 2016)

system is in idle mode without generating power, respectively feeding the grid. A WTG starts generating power in partial load at wind speeds above cut-in speed. At wind speeds above the rated wind speed the WTG is under full load and generates rated power. The generated power is limited to rated power over the entire full load operation by pitch-control, which reduces the revolutions per minute if necessary. Above cut-out speed the WTG system shuts down to prevent over-loading and possible damages. Blades are brought into feathered position and the system is disconnected from the grid. (Gasch, Twele 2016)

ENERGY YIELD

The total potential energy yield E_{WTG} of a WTG can be calculated according to Equation (3-2) by using the wind speed distribution at the specific site and the WTG's power curve. h_i *is* the probability of occurrence of the wind speed in a defined interval *i* during a period *t*. Dedicated to the defined interval *i*, $P_{el,i}$ describes the electrical power corresponding to the power curve. The total potential energy yield is determined by the addition of each interval specific product.

$$E_{WTG} = \sum_{i=1}^{n} h_i \cdot P_{el} \cdot t \tag{3-2}$$

The energy production is proportional to the third power of the wind speed. Better wind conditions of 10 % accordingly mean an increase of the annual energy production by more than 30 %. Figure 3-5 shows the cohesion between wind speed and energy yield. (Kaltschmitt et al. 2014)

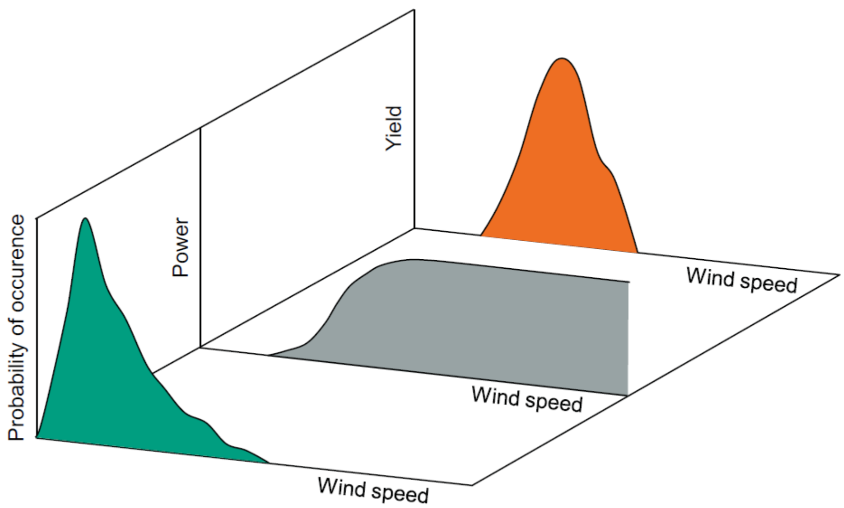


Figure 3-5: Energy yield of a WTG (Kaltschmitt et al. 2014)

A specific parameter to describe the energy yield is the capacity factor *C*. It is defined as the percentage of the annual energy production AEP over the product of the rated power output P and the hours in one year according to Equation (3-3):

$$C = \frac{AEP}{P \cdot 8760} \tag{3-3}$$

Another characteristic parameter is the number of full load hours. It describes the number of hours that is needed to generate the overall energy yield of a WTG under full load (i.e. at rated power). The full load hours can be derived by multiplying the capacity factor *C* with the length of the observed period. (Kaltschmitt et al. 2014)

3.3 Offshore wind farms

The availability of space in combination with good wind resources is the main reason to build OWFs. (Perveen et al. 2013) Implementing offshore projects in Germany and thus the construction of WTGs at sea has to overcome specific challenges. According to the EEG, a wind farm is called OWF if it is located with a distance to shore of at least three nautical miles (BMWi 2014). An OWF is the spatial and organizational set of WTGs at sea (Hau 2016).

In the prevailing direction of the wind the usual distance between the WTGs is six to eight times the diameter of the rotor. Vertically to the main wind direction a distance of four to six times is usually chosen. The distance between the WTGs is needed to reduce wake losses to acceptable levels. OWFs can be characterized by the ensuing parameters (Gasch, Twele 2016):

- Number, type (capacity) and reliability of WTGs
- Type of grid connection (alternate current (AC) or direct current (DC))
- Distance to base station (onshore)
- Environmental conditions

ELECTRICAL POWER TRANSMISSION

In Germany, the energy is transported from offshore to land via high voltage direct current (HVDC) due to less transmission losses for distances between 60 and 100 km and thus more cost-efficiency compared to high voltage three-phase AC cables. (Hau 2016) The generated power of each WTG is conducted via the inner park cable to the substation where it is transformed to high voltage level (150 kV). In order to use HVDC the power of multiple OWFs is conducted to the offshore converter platform where it is converted from AC to DC. The converter platform is installed and operated by the transmission system operator. A 900 MW converter platform dimensions are about 65 m by 105 m. (BSH 2015) The converter station is connected to the onshore grid through a submarine cable. Onshore, the DC is converted back to AC power and fed into the high or very high voltage grid. (Hau 2016)

GEOGRAPHICAL CLASSIFICATION

Most OWFs are located at great distances to the coast, mostly in the area of the Exclusive Economic Zone (EEZ) in the North Sea behind the 12-nautical mile zone due to concerns regarding preservation of nature and landscape like the Wadden Sea nature reserve. The EEZ is extending seaward to a distance of no more than 200 nautical miles (about 370 km) out from the coastal baseline (Rodrigues et al. 2015). In the North Sea, it covers an area of about 28,600 km. Figure 3-6 shows an overview of the German EEZ including the clustered areas for OWFs (orange, red, green). (BMWi 2015)

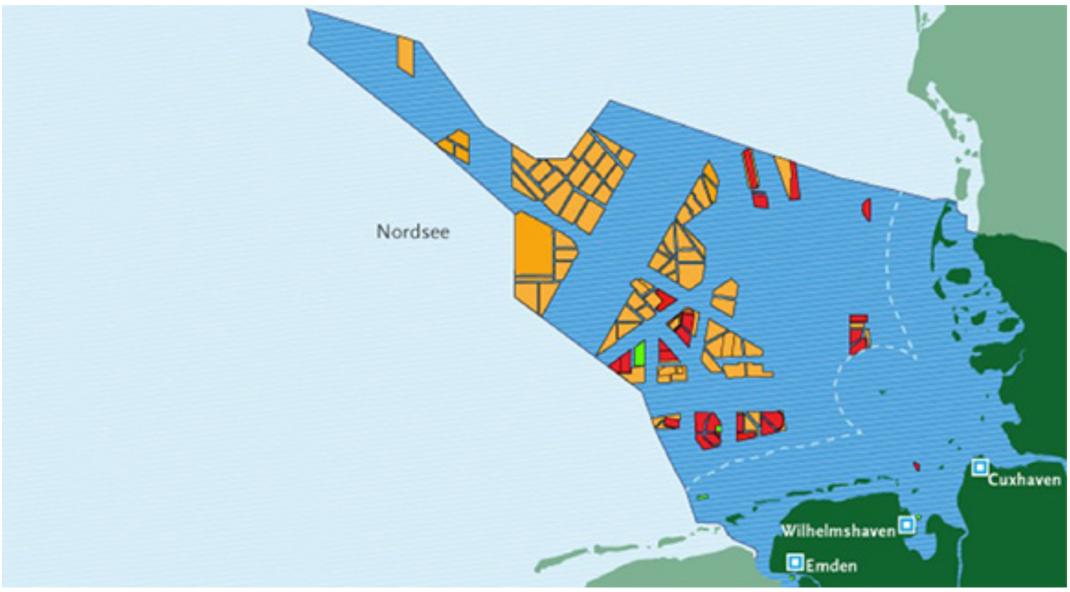


Figure 3-6: Overview of the German EEZ (BMWi 2015)

For the German EEZ (dark blue area) the spatial planning of all offshore activities is done by the Federal Maritime and Hydrographic Agency (BSH). The spatial planning ensures safety and ease of maritime navigation and the protection of the marine environment (BSH 2015). The area of an OWF has to comply with various boundary conditions which are both nature and human-base. Among others, following criteria are important for the choice of an OWF location (Rodrigues et al. 2015):

- Military operation or exercise zones
- Environmental protected areas

- Oil & gas lease or concession areas
- Minimum suitable available space
- Minimum distance to the high voltage grid
- Distance to nearest port with sufficient capacity
- Vessel traffic routes, separation and precautionary zones
- Fishing areas
- Extraction, dredging and dumping sites
- Existing OWFs
- No anchoring areas
- Suitable export corridor area
- Seabed characteristics
- Environmental impact
- Water depth
- Suitable wind resources

Especially the last four points are considered in the following Chapter 3.4 environmental conditions for offshore wind energy.

3.4 Environmental conditions

The northern European seas have a seabed with relatively low water depths but still good wind resources. These conditions have allowed adjacent countries to make initial offshore progress and to take a leading role in the offshore wind industry. (Rodrigues et al. 2015)

Metocean data is used to characterize the environmental conditions. The data consists of meteorological (including wind, air pressure, temperature) and oceanographic data (e.g. waves, currents, salinity, ice). (Hau 2016) Due to the harsh environmental conditions the installation and maintenance of OWFs is much more complex than onshore and therefore needs special equipment and good weather conditions. Higher wind speeds may lead to storms as well as big waves, and salty water causes corrosion to the foundations. (Perveen et al. 2013) Wind and waves are the major relevant and limiting parameters when it comes to accessibility and availability of offshore WTGs. Especially for the use of jack-up (repair) vessels, the water depth is of importance. Ice drift can be another design and maintenance factor but for the North Sea, tidal range and salinity are more import. (Thomsen 2014)

The potential of an offshore site can be characterized by the mean annual wind speed, which is used to forecast the energy output of an OWF. As an example, Figure 3-7 shows the mean wind speed of the past years at a height of 90 m in the North Sea (Fino[6] 1 and 3) and 92 m in the Baltic Sea (Fino 2). Fino 3 measured the highest average annual wind speed of 9.7 m/s. Fino 2 in the Baltic Sea measured a slightly higher average annual wind speed of 9.4 m/s compared to Fino 1 with 9.1 m/s (North Sea). This can be explained by the OWF Alpha Ventus with its nearest WTG only 400 m from Fino 1 and therefore winds from the east affect the measurements. Shading effects due to an increasing number of OWFs near the research platforms will eventually lead to higher measuring failures in the future. (Fraunhofer 2018)

The wind speed distribution can be described by the Weibull distribution (Hau 2016). Over a year's period the wind speed shows significant differences. In the winter months the wind speed is usually higher than during the summer period (Gasch, Twele 2016).

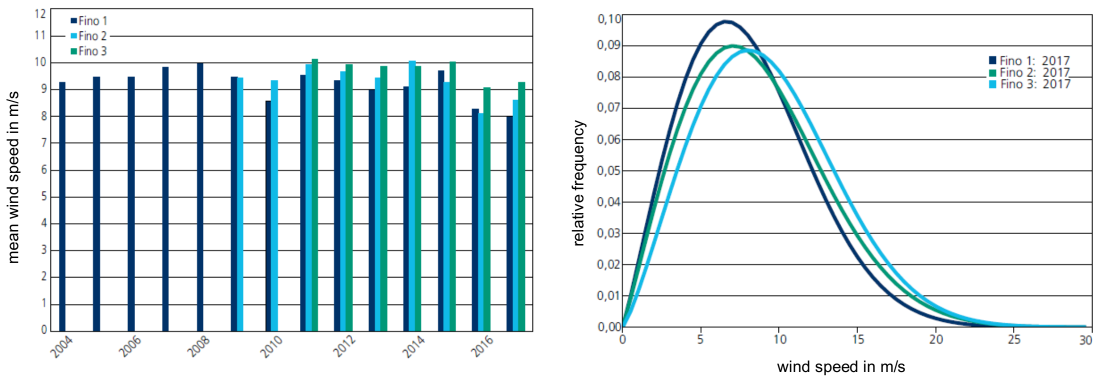


Figure 3-7: Mean annual wind speed 2004 - 2016 (left) and frequency distribution of measured wind speeds in 2016 (right) from Fino 1, 2 and 3 (Fraunhofer 2018)

Increasing height above the ground results in higher wind speed depending on the surface profile. This effect has a stronger impact at sea than on land. Thus, offshore wind is stronger and steadier. Operating OWFs have shown that with up to 4,500 h the number of full load hours is significantly higher compared to onshore wind farms. (Fraunhofer 2018)

Accessibility to an offshore WTG by ship is essentially determined by the wave height. In general, weather situations with a significant wave height (H_s) of more than 1.5 m are referred to as 'weather days' (Fraunhofer 2018). Even with special access systems which can compensate for the movements of the vessel, the transfer of service personnel to the ascent ladder of the WTG is too risky. (Thomsen 2014)

[6] Fino 1, 2 and 3 are research platforms.

On the left, Figure 3-8 presents the measured mean significant wave height per month (2016) and over a period from 2013 to 2015 compared for North Sea (Fino 1) and Baltic Sea (Fino 2). Also, the frequency distribution of measured significant wave heights over different periods (right) from Fino 1, 2 and 3 are shown. Missing data can assume a defect of the measuring equipment. The North Sea shows higher significant wave heights over the complete period of 2016 as well as over the long-term average and thus a limited accessibility. In terms of installation, commissioning and service, accessibility plays an important role. At both locations, the relatively lower significant wave heights can be recognized in summer. Combined with lower wind speeds in summer and better lighting conditions, most operators plan their regular scheduled maintenance activities for those months. (Fraunhofer 2018)

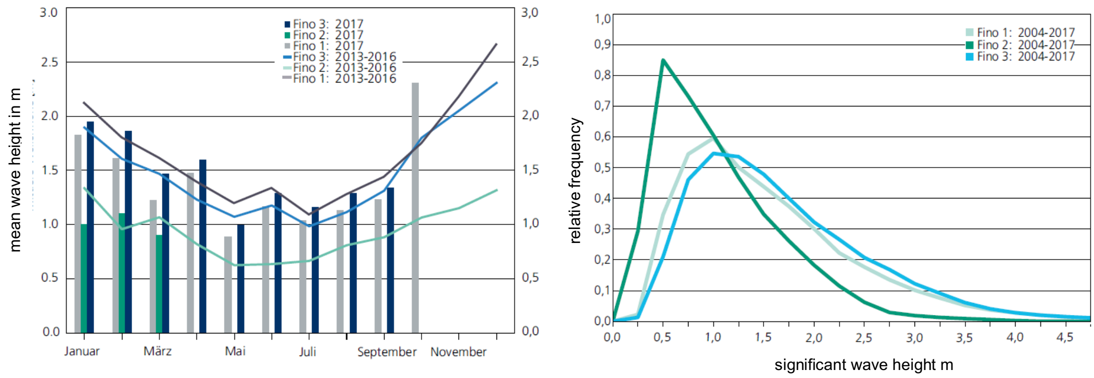


Figure 3-8: Mean significant wave height per month in 2016 and on average 2013 – 2015 (left) and frequency distribution of measured significant wave heights over different periods (right) from Fino 1, 2 and 3 (Fraunhofer 2018)

3.5 Project life-cycle of offshore wind farms

Chapter 3.5 describes the project life-cycle of an OWF. Following the project idea, biological and technical studies will be carried out in a multi-year project development phase to obtain approval for the construction of the OWF. The plan approval decision in accordance with § 2 Sea Facilities Act (SeeAnlV) issued by the BSH takes into account different topics such as safety and ease of traffic as well as the protection of the environment (§ 5 para. 6 SeeAnlV). The complicated and protracted plan approval process and decision is a major investment obstacle according to a survey by Norton Rose and Deloitte which includes representatives of energy companies, institutional funds, credit institutions and insurances (Deloitte / Norton Rose 2013). Followed by financing negotiations and their conclusion the construction of the OWF begins with the final investment decision (FID). Past the commissioning of the wind farm the operating phase of 20 to now commonly 25 years begins and is followed by the decommissioning or repowering of the OWF, which has to be planned timely before the end of the operating phase according to the BSH. (BSH 2015)

Figure 3-9 shows the average timeline of an OWF project generated by a survey of Prognos AG and Fichtner Group (2013).

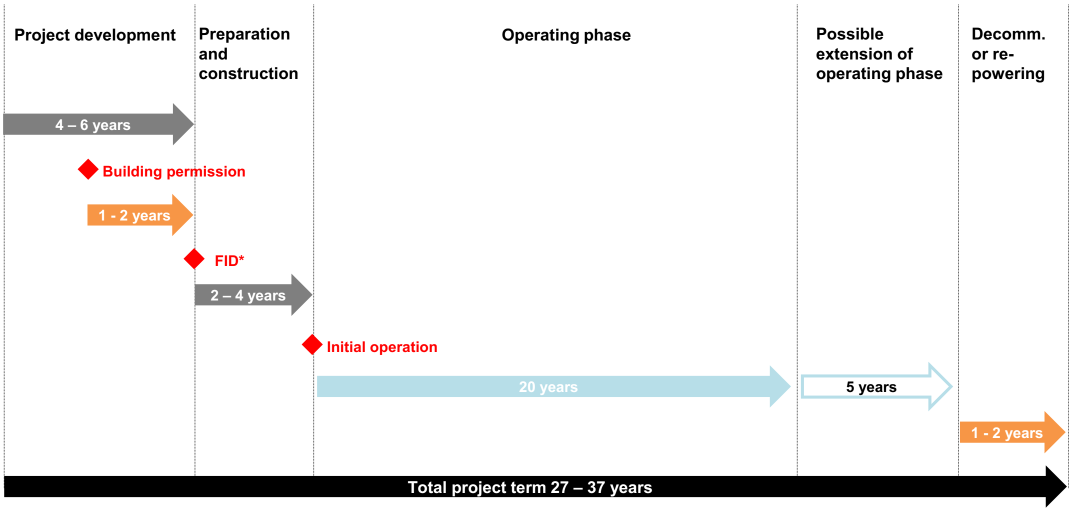


Figure 3-9: Average timeline of an OWF project [Author's illustration based on (Prognos AG 2013)], *FID = final investment decision*

3.6 Financing basics and the financial model

The financing of OWFs is one of the biggest challenges in the expansion of offshore wind energy. The investment volume is substantial and risks have to be carefully assessed. The investment volume of an OWF in the German North Sea with 80 WTGs and a rated power of each 7 MW amounts to 1.7 to 2.6 billion Euros (Kost et al. 2018).

Regardless of whether onshore or offshore projects are considered, the question arises as to which financing methodology will be used for the implementation of the project. Possible options are corporate financing or project financing and both approaches are briefly described in Chapter 3.6.1. Major power producers can use corporate financing due to their huge capital resources. Other market participants use project financing which is the most common financing methodology to date. (Böttcher 2013)

Figure 3-10 shows the on- and offshore capacity distribution of major equity investors in 2016. The equity mix continues to bring in more corporate, financial and in particular for offshore wind, overseas investors. However, power producers still account for most of the equity, especially through the development phase. (WindEurope 2016)

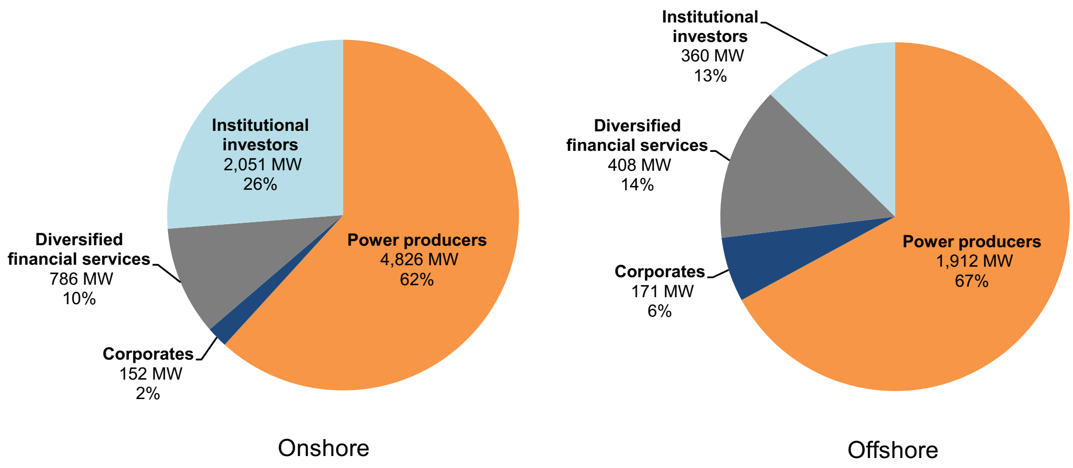


Figure 3-10: Major equity investors in 2016 [Author's illustration based on (WindEurope 2016)]

In Chapter 3.6.2, the financial model, the CAPEX model as well as the OPEX model is presented and influencing factors on the OPEX model are discussed.

3.6.1 Financing offshore wind projects

The difference between corporate and project financing is outlined in Figure 3-11.

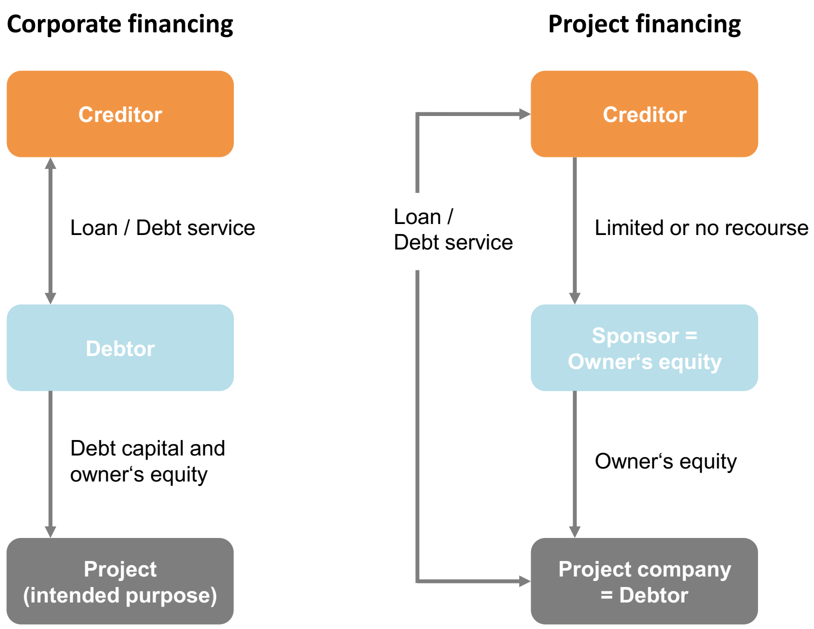


Figure 3-11: Comparison of corporate and project financing [Author's illustration based on (Böttcher 2013)]

If corporate financing is used, the investment project is seen as part of the corporation (debtor) and the creditor's valuation is based on the creditworthiness of the debtor instead of the expected project cash flow[7]. However, if a project financing is used, the creditor's valuation aims only at the capability of the project (debtor) to generate an own adequate cash flow. In case of a project financing, the corporation (sponsor) refuses unlimited liability for the debt service and the foundation of an independent project company by the sponsors as shareholders is necessary. Sole business purpose of the project company is the implementation, thus the construction and operation of the project. The project company borrows the loan and assumes unlimited liability with its assets. A reimbursement depends only on the cash flow of the project. Therefore, there are only assets and cash flow as securities for the creditor. As the cash flow is the only source for debt service and return on owner's equity, the requirements for stability and reliability are accordingly high. (Böttcher 2013) Thus, the creditor carries out a detailed technical and economic valuation of the project and therefore has an influence on the investment decision. Financial institutes require a minimum amount of equity capital to reduce their own financial risk. The usual debt to equity capital ratio is 70/30 (Kost et al. 2018). A participation of less risk-averse venture capital companies is also possible. (Hau 2016)

3.6.2 The financial model

Major offshore wind projects are divided into two phases, the project phase and the operating phase. The key components of the economic project valuation construct are the financial model as well as the CAPEX model for the project phase and the OPEX model for the operating phase. The CAPEX model is used only during the project phase to calculate all expenses and investment costs whereas the OPEX model is developed at the beginning of the project but is used over the entire project life-cycle of an OWF (see Figure 3-12).

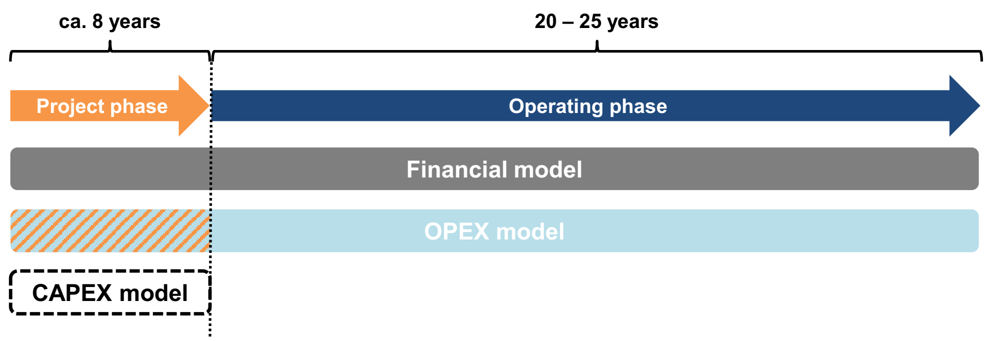


Figure 3-12: Project assessment phases [Author's illustration based on (EnBW Interviews 2018)]

[7] Cash flow = Difference between income and operating expenses including interest payments. It is the operating result before depreciation, debt service, taxes as well as profit and thus, the cash available for these payments. The expected cash flow is part of the financial model output. (Ernst et al. 2017)

Figure 3-13 provides a rough overview of the input, calculation and output of the OPEX / CAPEX model as well as the context in which they stand with the financial model.

The financial model can be seen as an aggregating tool and central element of the investment decision of investor and operator. CAPEX and OPEX data converge in the financial model and are processed into a plan balance sheet, income statement and cash flow statement by adding legal framework conditions and price criteria.

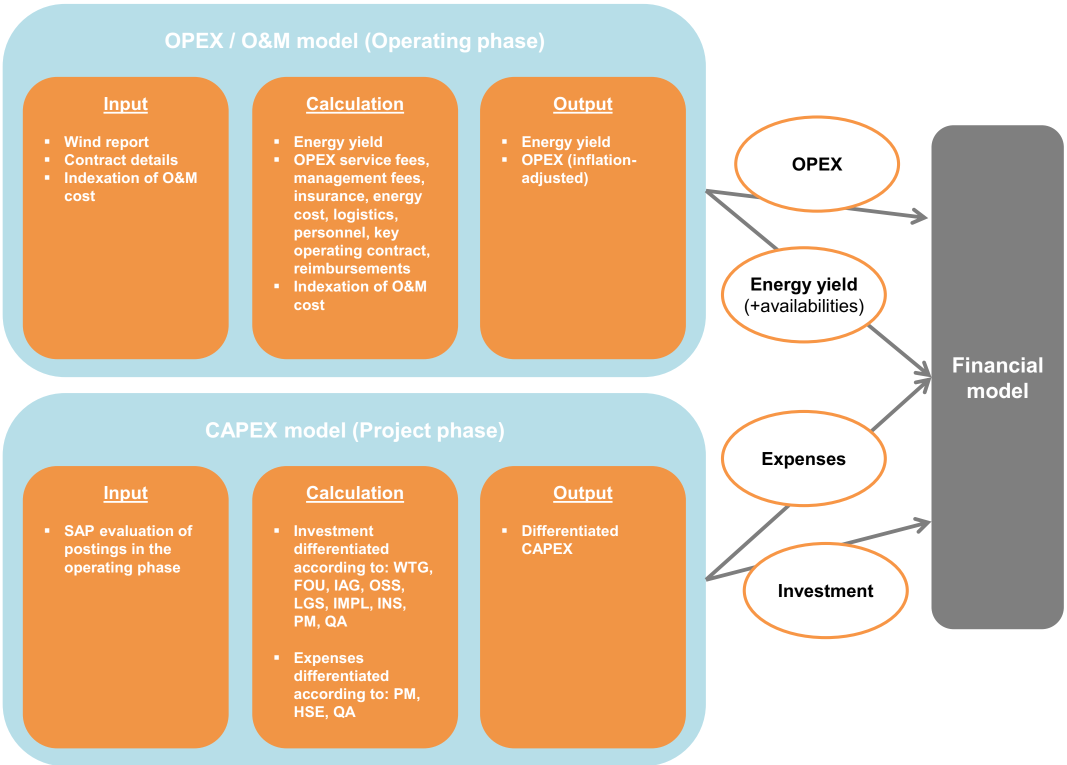


Figure 3-13: Context of OPEX, CAPEX and financial model [Author's illustration based on (EnBW Interviews 2018)]

The fundamental purpose of the OPEX model is the detailed modeling of the expected AEP, the availability and the costs of the operating phase. The significantly longer operating phase is static in nature. This is particularly noticeable in the OPEX model as most calculations of the project phase are no longer relevant in the operating phase and sizes like the energy yield remain unaffected in this phase, unless the planning and actual state differ from each other for a longer period.

The following main factors and variables are influencing the output of the OPEX model. The CAPEX model is not specified in greater detail as the main focus of this thesis is on the operating phase. (EnBW Interviews 2018)

ENERGY YIELD

Values concerning the annual energy yield (Böttcher 2013):

- Annual energy yield as P50 value
- Wake effects
- Inner array grid (IAG) and offshore substation (OSS) electrical losses
- Technical availability of the OWF

Within the first five years of operation the OEM usually carries out all maintenance measures as part of a full-service contract. A minimum availability of the OWF is guaranteed for this period which needs to be included in the annual energy yield calculation. Independent wind experts can be assigned to prove the impartiality of the energy yield forecast to future project partners. The forecast is routinely provided in the form of a so-called P50 value, which is the value that is exceeded with a probability of 50 percent. Particularly risk-averse investors often demand a P90 value which is not undercut with a probability of 90 percent. (Gasch, Twele 2016) Internal wake effects reduce the OWF's efficiency, since the WTGs alternately take wind of each other. Wake effects by neighboring OWFs have to be considered as well. (Prognos AG 2013) Electrical losses inevitably result from the need to overcome the resistivity of the conductor when transmitting the current through the park or the OSS. It can quickly reach a relevant level depending on the cable design and length. The technical availability of the OWF refers to technical downtimes. These scheduled or unscheduled shutdowns of the WTGs represent the largest energy losses of an OWF. (Gasch, Twele 2016)

OPERATING COSTS

Main operating cost blocks of German OWFs (Böttcher 2013):

- Material costs for maintenance
- Personnel costs including equipment and training
- Offshore logistics costs
- Internal electrical consumption of WTGs and OSS
- External services like port logistics or bio monitoring
- Insurance
- General costs for management and remote maintenance

The operating cost blocks are contractually agreed and the most important contract of the operating phase is the service contract. Most commonly the contract period with the OEM is five years. Its scope depends on the operators demands. If operators intend to minimize their own risks, all maintenance measures and offshore logistics such as provision of vessels are included. Billing is than based on fixed lump-sum remuneration. On the other hand, the offshore logistics can be managed by the operator or a third party if the operator pursues to keep significant parts of the maintenance measures in their own hands and take over all activities after the contract period ends. In this case the service contract contains technical training of the operator's personnel. The five-year service contract with the OEM is followed by new contracts for the remaining lifetime. This service contract structure is custom and complex due to the use of different third parties. It is quite common that the owner of the OWF does the operating management if this is a major energy supplier. In this case, a management contract between the OWF project company and the energy supplier or a subsidiary is concluded.

PERFORMANCE DEGRESSION

Another significant assumption for OWFs due to the very long-life time is a performance degression of the WTGs which results from a gradual deformation of the rotor blades. The aerodynamically optimal profile of the rotor blades cannot be considered as constant over the entire lifetime and this will result in a loss of net annual energy yield. (Gasch, Twele 2016) The performance degression can be included in the OPEX model as part of the energy losses. (EnBW Interviews 2018)

BATH-TUB CURVE

The bath-tub curve of maintenance costs: Eventually, failure rates of the components necessitate service efforts and are crucial for a long time forecast of the operating costs. The distribution of the failure rates can be usually described by the bath-tub curve. It results from the overlay of three failure rate distributions. On the one hand, there are high failure rates at the beginning of the operating phase due to problems during commissioning and faulty components, which are decreasing during the life cycle. On the other hand, the number of maintenance measures is increasing at the end of the lifetime caused by failures due to the wear out period. In addition, unscheduled maintenance measures with no wear and tear background have to be performed over the entire life cycle. In general, the wear-induced increase in failures of moving parts should not be ignored. (EnBW Interviews 2018) The bath-tub curve is further discussed in Chapter 3.8.1.

3.7 Levelized cost of electricity

To calculate the total cost of electricity generation, respectively the LCoE, the sum of all costs over the complete project life-cycle is set in relation to the total energy production of the power plant (see Figure 3-14). (Fraunhofer 2018)

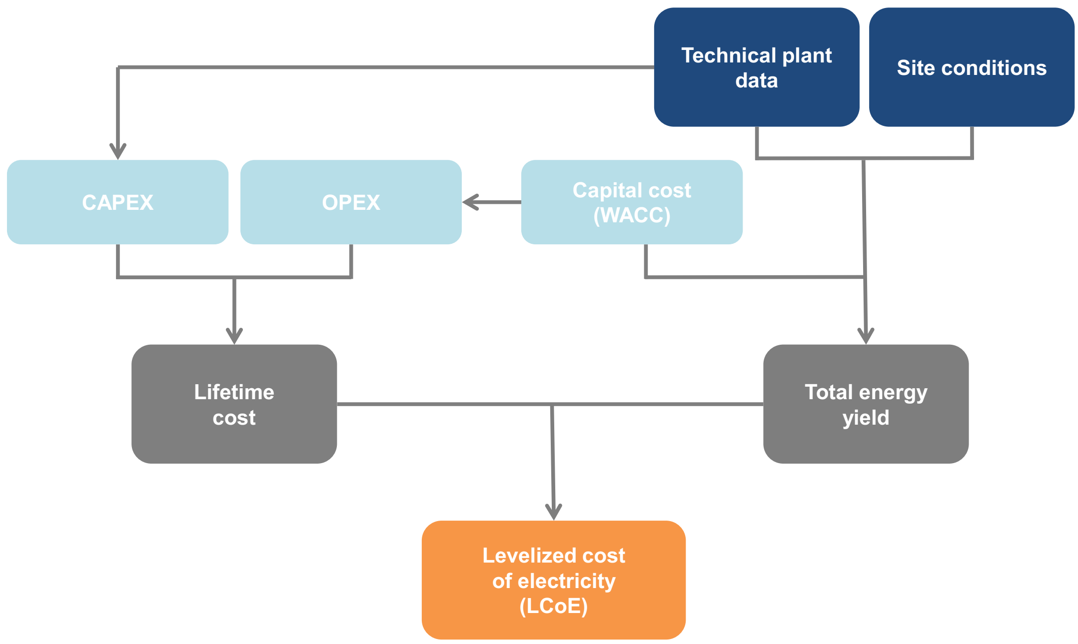


Figure 3-14: Components of LCoE [Author's illustration based on (Krohn 2009)]

Following parameters influence the LCoE (Hau 2016):

- Technical plant data + site conditions (mean annual wind speed)
- CAPEX (for annual values as annuities), mainly influenced by the production, logistics and installation of the power plant
- OPEX, mainly influenced by maintenance measures
- Cost of capital (WACC)
- Project life-time (20 or usually 25 years)

The LCoE method makes it possible to compare different kind of power plants or projects and their cost structures. (Kost et al. 2018) At the same time, this method is also the means of choice for evaluating innovations in terms of costs. (Jamieson 2011) It is not suitable for determining the profitability of a specific plant. For this purpose the financial model is needed to take into account all income and expenditure on the basis of a cash flow model. (Kost et al. 2018) The calculation of the LCoE can be made either on the basis of the net present value (NPV) method or the so-called annuity method. By application of the NPV method all cash flows throughout the life of the OWF are taken into account and they are discounted to a common reference date like the FID. (Kost et al. 2018) The LCoE of new projects can be calculated according to Equation (3-4):

$$LCoE = \frac{I_0 + \sum_{t=1}^{n} \frac{T_t}{(1+i)^i}}{\sum_{t=1}^{n} \frac{E_{t,el}}{(1+i)^i}} \tag{3-4}$$

LCoE	Levelized Cost of Energy in EUR/kWh
I_o	Investment costs in EUR
T_t	Total annual costs of year *t* in EUR
$E_{t,el}$	Total annual produced electricity of year *t* in kWh
i	Real calculated interest rate
n	Total operating time in years
t	Year of operating time (1, 2, …n)

The total annual costs are composed of fixed and variable components for the operation of the OWF, maintenance, service, repairs and insurance payments. Debt and equity share can be explicitly included in the analysis by the weighted average cost of capital (WACC) over the discount factor (calculated interest rate). It depends on the amount of the equity, the return on equity over the total operating time, the debt costs and the share of the contributed debt. (Kost et al. 2018) The WACC can be calculated according to the following Equation (3-5):

$$WACC = i_E \cdot \frac{Eq}{Tc} + i_D \cdot \frac{Db}{Tc} \cdot (1 - t) \tag{3-5}$$

WACC	Weighted average cost of capital
i_E	Equity cost rate
i_D	Debt cost rate[8]
Eq	Equity capital
Db	Debt capital
Tc	Total capital
t	Tax rate[9]

[8] Debt cost rate depends in particular on the creditworthiness of the debtor and his rating (Ernst et al. 2017).
[9] The applicable tax rate results from the tax savings due to the use of debt capital, which is called tax-shield (Ernst et al. 2017).

3.8 Operations and maintenance

Chapter 3.8 presents important aspects of the operating phase of an OWF. This includes definitions and important terms, the goals of O&M, regulatory requirements and an overview of different service concepts.

3.8.1 Definitions and important terms

The term operation relates to all functions contributing to the management of an OWF like remote monitoring, environmental monitoring, electricity sales, marketing, administration and other back office tasks. Compared to maintenance it stands for just a small share of the OPEX. (Prognos AG 2013)

Maintenance accounts for the larger share of O&M costs and risks. The maintenance activity can be explained as the upkeep and repair of the plant and system. According to DIN 31051 the term maintenance stands for the combination of all technical and administrative measures as well as management measures during the life-cycle, which serve to preserve or restore the functional condition so that the required function can be fulfilled. Maintenance is divided into four basic measures according to DIN 31051 (see Figure 3-15):

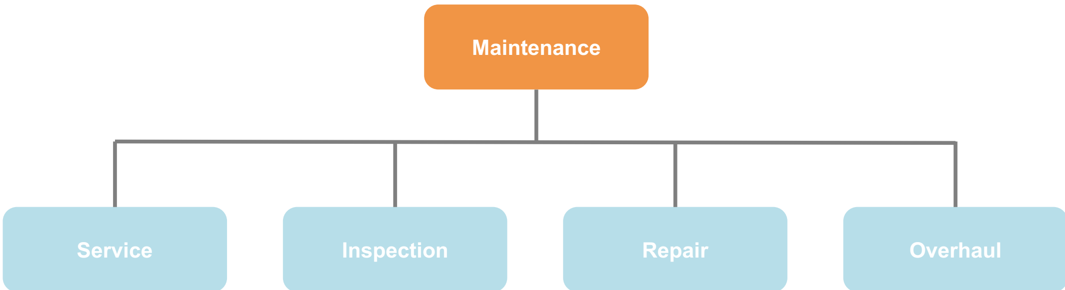


Figure 3-15: Basic measures of maintenance [Author's illustration based on (DIN 31051)]

According to DIN 13306, maintenance is differentiated into types corresponding to the timing of the maintenance action (see Figure 3-16). It distinguishes between preventive and corrective maintenance. As the term preventive maintenance already implies, the work is done preventively to avoid failure. There are two varieties of preventive maintenance, the first is condition-based maintenance. This type covers the condition monitoring, either physical inspection or remote monitoring, from which required measures are derived. It can be scheduled, requested or continuous. Instead, predetermined maintenance means that the maintenance is carried out after a predefined period (e.g. every half a year). Maintenance action in case of a failure is called corrective maintenance. It can be fixed immediately or postponed as deferred maintenance.

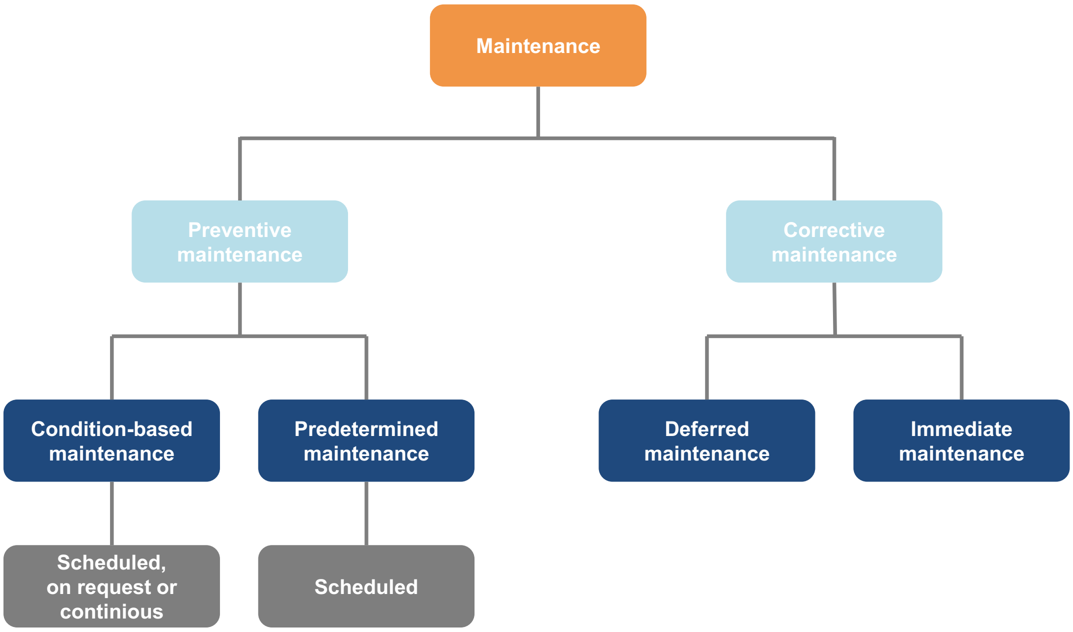


Figure 3-16: Types of maintenance [Author's illustration based on (DIN 13306)]

In general, maintenance is carried out to meet corporate internal and external requirements regarding the condition of the plant as well as to coordinate corporate and maintenance objectives, which can be:

- Meet particular technical availability goals
- Achieve quick reaction time for corrective maintenance.
- Cost reduction
- Safety and environment issues
- To keep the plant in good condition

MAINTENANCE STRATEGY

In order to reach the individual maintenance objectives, it is necessary to set up a maintenance strategy. Among others, this includes the planning and distribution of resources or the external assignment of services. Maintenance strategies indicate a measure and point in time to ensure certain availability. Current strategies are based on (DIN 13306):

- Reliability-centered maintenance
- Total productive maintenance
- Risk-based maintenance

The right strategy should be selected based on the probability of failure as well as the economic impacts of inspections and repairs. A lack of data is often an issue when it comes to decision making processes regarding the maintenance strategy. (Münsterberg 2017)

AVAILABILITY AND RELIABILITY

In general, the availability is defined as the time a plant is operating during a certain period in proportion to the total time of that period. Theoretically, the availability is influenced by the reliability, maintainability and serviceability (see Figure 3-17). To evaluate the actual availability it is necessary to consider the accessibility of the site, which means the time to gain access in case of a failure, as well as the overall maintenance strategy. (van Bussel 2001)

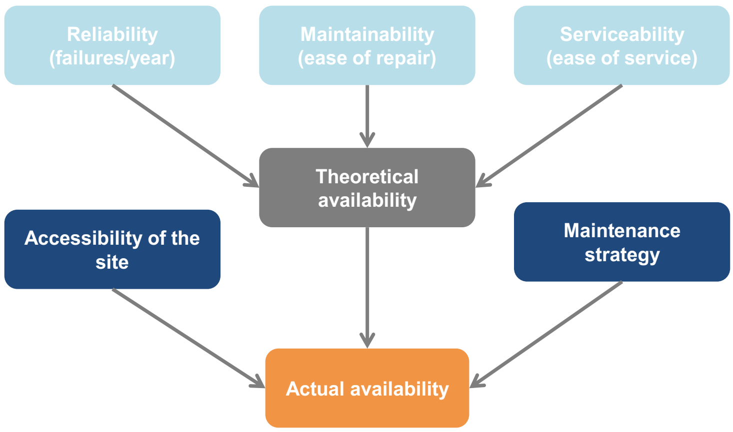


Figure 3-17: Availability of technical systems [Author's illustration based on (van Bussel 2001)]

The reliability is one of the key factors influencing the availability. It is expressed as the probability that a component or plant does not fail continuously over a defined period of time. The measure for reliability, which is determined by the failure rate of a component, is the mean time between failures (MTBF). This value can be derived from data bases or OEM data.

MTBF is the sum of the mean time to restore (MTTR) and the mean time to failure (MTTF) according to Equation (3-6). MTTF is bound to the reliability and MTTR relates to the maintenance strategy. The connection between MTBF, MTTR and MTTF is shown in Figure 3-18.

$$MTBF = MTTR + MTTF \tag{3-6}$$

MTTR is also called downtime and, in relation to an OWF, it consists of alarm duration, duration of spare part procurement, travel time, waiting time due to bad weather and the repair time itself. (Münsterberg 2017)

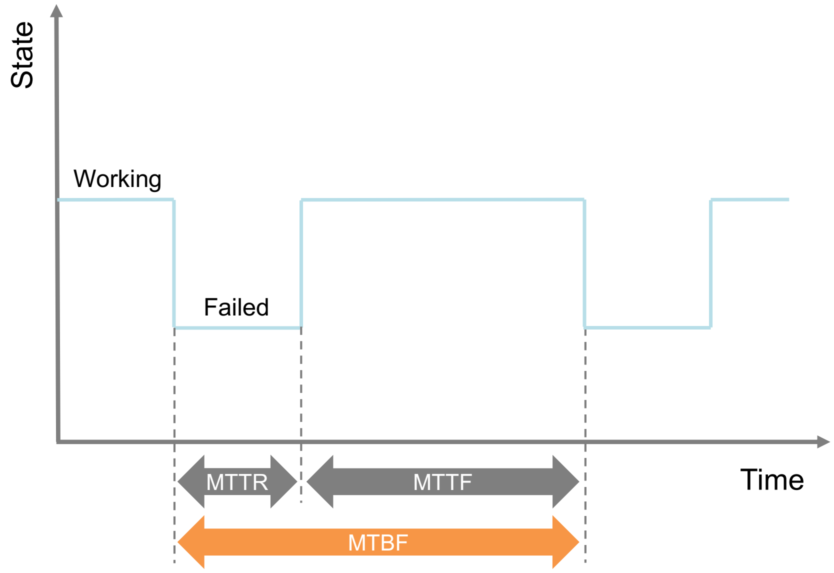


Figure 3-18: Mean time between failures [Author's illustration based on (Münsterberg 2017)]

The MTTF is determined by the failure rate λ of a component, which is not constant over the life-cycle of the OWF. This continuous process of changing failure rates is known as the so-called bath-tub curve and is illustrated in Figure 3-19.

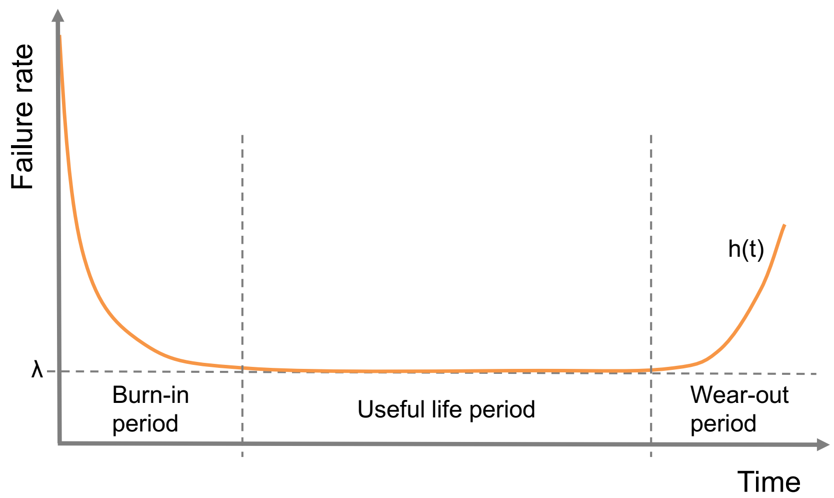


Figure 3-19: Bath-tub curve [Author's illustration based on (Dewan 2014)]

The bath-tub curve is divided into three sections. The first period is called the burn-in period and can be characterized in the beginning by high failure rates, which are decreasing while the OWF is in operation. At the point where the curve begins to be almost constant, the useful life period starts until the failure rates begin to increase again during the wear-out period. (Dewan 2014)

3.8.2 The goals of O&M

In Germany, the O&M phase of an OWF starts with the approval of the BSH and usually takes between 20 and 25 years according to the project life-cycle under Chapter 3.5.

With the exception of safety, the ultimate goal is to maximize the profitability of an OWF. Figure 3-20 shows qualitatively the dependence of cost on availability.

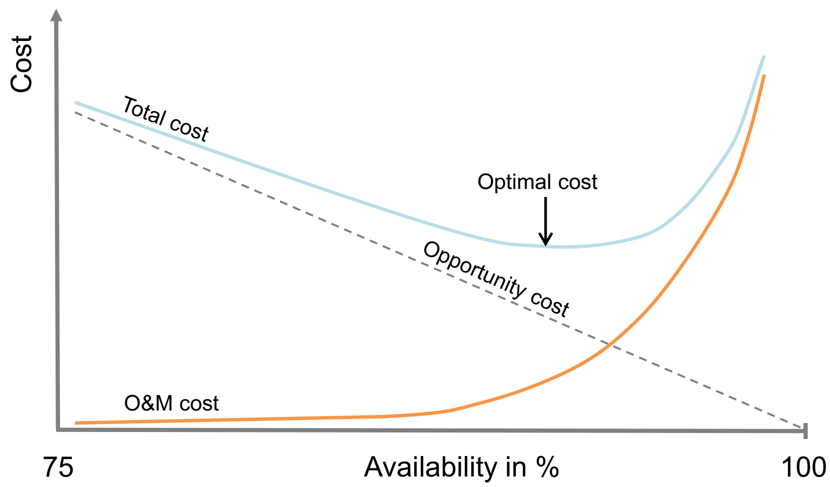


Figure 3-20: Cost vs. availability of OWFs [Author's illustration based on (Münsterberg 2017)]

The profit is maximized by reducing the O&M cost and/or increasing the energy yield. As previously explained, the energy yield is highly dependent on availability of the OWF and wind speed on site. Due to the fact that we are not able to influence the wind speed, the availability has to be increased, which can be managed by O&M of the OWF. On the one hand, higher O&M efforts increase the availability and opportunity cost decrease, because the energy yield increases as well. On the other hand, higher O&M cost lower the marginal profit. Thus, a balance between both energy yield and O&M cost have to be found, which is called point of optimal cost. At that point, marginal cost is equal to marginal profit. According to Hau (2016) the availability of wind farms varies in a range of 95 to 98 %. The optimal cost point also varies with production related reliability, which can take different values depending on the OEM of the installed WTGs. (Münsterberg 2017)

3.8.3 Regulatory requirements

OPERATION APPROVAL AND SUSTAIN APPROVAL

For the operation of an OWF within the German EEZ an approval in accordance with the Offshore Installation Ordinance is required. The approval for the installation and operation is the responsibility of the BSH and requires compliance with different technical standards. An operations manual and a maintenance specification sheet have to be available to enable the operation of the WTG. The operations manual contains operational procedures as well as communication channels, surveillance of the OWF and grid connection. The maintenance specification sheet contains maintenance requirements, procedures and data of wear parts. (BSH 2015) Regular inspections need to be carried out in order to ensure the structural and technical safety as well as to sustain the approval status to operate an OWF. The operator has to inspect 25 % of the WTG annually. The annual scope for the regular inspection is summarized in Table 3-2. (BSH 2007)

Table 3-2: Regular inspection of OWFs [Author's illustration based on (BSH 2007)]

Component group	**Test item**
Rotor blade	*Damage to the surface, cracks, structural irregularities of the blade body, pretension of the screw connections, damage to the lighting protection device*
Drive train	*Tightness, unusual noises, state of corrosion protection, lubrication condition, pretension of the screw connections, transmission conditions*
Nacelle force and torque transmitting components	*Corrosion, cracks, unusual noises, lubrication condition, pretension of the screw connections*
Hydraulic/pneumatic system	*Damage, leaks, corrosion, proper function*
Supporting structure (tower and substructure)	*Corrosion, cracks, pretension of the screw connections, improper scours, location*
Safety devices, sensors and brake systems	*Functional checks, compliance with critical values, damage, wear*
Control and electrical system	*Connectors, mounting, proper function, corrosion, pollution*
Documents	*Completeness, compliance with regulations, audit documents, regular conduction of maintenance, possible modifications / repairs according to approval*

WORKING HOURS

The working hours for offshore personnel associated with the Offshore Working Hours Regulation differ from the standard working hours according to BMJ and Juris (2013). Mainly the maximum daily working hours are extended from 10 to 12 h. All working time exceeding 8 h is considered as overtime and shall be compensated by days off. The sum of transportation from/to a collection point on land and working time should not exceed 14 h (see Figure 3-21). Any transportation time exceeding 2 h inevitable leads to a shorter available working time. Night work is defined by at least 2 h between 23:00 and 06:00. (BMJ and Juris 2013)

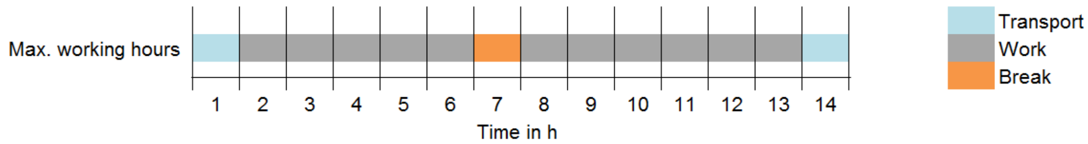


Figure 3-21: Working hours [Author's illustration based on (Münsterberg 2017)]

The permitted number of directly consecutive sea days is subject to the number of extended working days. Seven or more days of extended working time are allowed within a 14 day offshore stay. Within a 21 day offshore stay a maximum of 7 days with extended working time are allowed but in no case more than two days in a row. Crew members of the involved vessels are also allowed to extend their working hours up to 12 h per day. (BMJ and Juris 2013)

SAFETY

Maintenance in an offshore environmental implies safety critical activities such as work at sea and at high altitude as well as the lifting of heavy components. For this purpose and to get the BSH approval, a safety concept including project specific contingency planning is required. Besides private company arrangements, also organizations such as the Central Command for Maritime Emergencies (CCME) are involved. In practice, there is a helicopter plus crew and an emergency doctor always on standby. For example, maintenance works at the German OWF Alpha Ventus always require at least three technicians per WTG due to safety issues. (Münsterberg 2017)

3.8.4 Service concepts at a glance

At the moment, there are two common O&M service concepts which can be differentiated by the location of the base station (see Figure 3-22). An onshore-based service concept uses a base station on land mostly near to a port. Offshore-based service concepts have their base station within or at least close to the OWF at site.

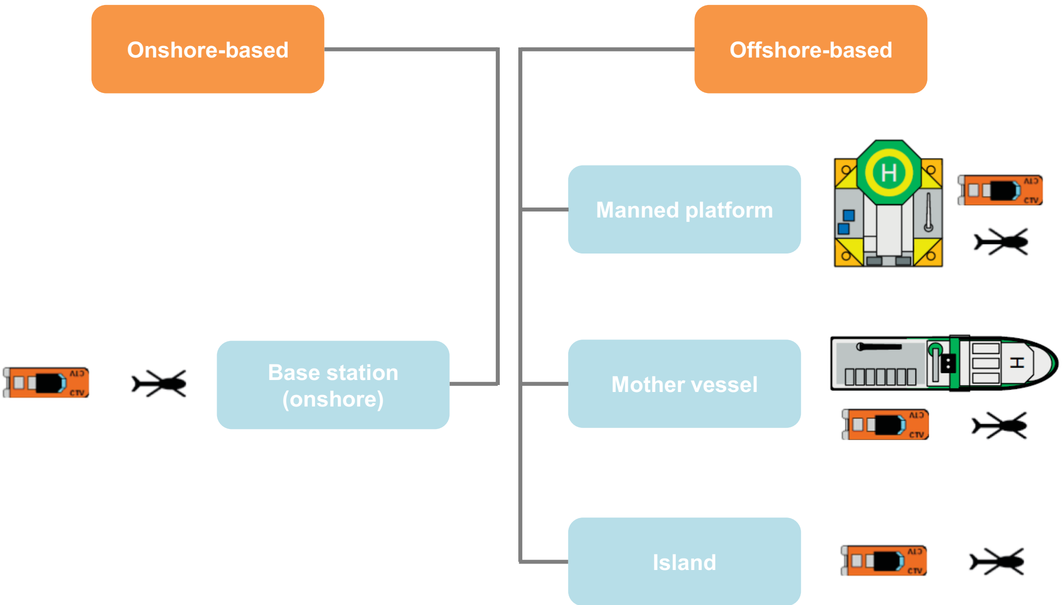


Figure 3-22: Service concepts [Author's illustration based on (Münsterberg 2017)]

ONSHORE-BASED CONCEPTS

All seizes of OWFs can be maintained by onshore-based concepts which are usually used for most of the near shore projects like the EnBW 'Baltic 1' OWF in the Baltic Sea. In general, onshore-based concepts are cost-effective at a coastline distance of 30 to 40 km and allow a short travel time of less than two hours (Münsterberg 2017).

There are two different transport options for onshore-based concepts:

- Crew transfer vessel (CTV)
- Helicopter

CTVs can be used to transfer the service crew from a base station to the OWF. The standard vessels are able to transport up to 12 technicians but they can only operate at a low significant wave height of 1.0 to 1.5 m due to dangerous transition of the technicians onto the WTG. More expensive, but also more stable vessels can operate at higher significant wave height (up to 2.0 m) and are referred to as advanced CTV (ACTV). The higher significant wave height is possible due to special transition equipment (e.g. Ampelmann). With ACTVs shorter weather windows can be used because of their higher speed.

The second option is a helicopter for the transfer to the OWF. A helicopter's advantages are high speed and high accessibility even in bad weather conditions.

Despite that, a helicopter is quite expensive, has limited space and capacity as well as a complex turbine transit procedure using a cable winch. Vessels and helicopters can also be combined in one concept. (Sperstad et al. 2016)

OFFSHORE-BASED CONCEPTS

If the OWF is located more than 30 to 40 km away from the base station on land and it consists of more than 50 WTGs, offshore-based concepts are considered as the most economical choice. Technicians are based and accommodated within or near the OWF. Three different types of offshore-based concepts are used and can be supported by a helicopter, involving (Münsterberg 2017):

- a mother vessel / floating hotel
- a manned offshore platform
- an island / artificial island

Mother vessels accommodate technicians and also provide space for repairs. Floating hotels also act as accommodation but offer no repair areas. Usually the mother vessel is located within the OWF and has berth opportunities for smaller CTVs and a helipad. The advantages of a mother vessel within the OWF and its short transfer times to the WTG as well as good accessibility throughout the year must be weighed against the high charter rate or investment for every individual project. During bad weather periods, the mother vessel can find shelter in a port. For a continuous stay in the OWF a separate supply vessel is necessary. The flexibility of a mother vessel is the biggest advantage as it is possible to change the dedicated OWF.

Manned platforms are another option. They can be used as accommodation for technicians and as warehouse for spare parts. For the well-being of the technicians the fixed platform has a huge advantage compared to a vessel as they do not suffer from sea sickness. Like a continuously staying mother vessel, the fixed platform is also expensive, a separate supply vessel is needed and the transfer of the technicians has to be managed by CTVs or a helicopter.

Neglecting the supply of the island, this concept is similar to onshore-based concepts. An Island like Helgoland in the German North Sea can act as base station for one or more OWFs. Compared to onshore-concepts, the shorter transfer time to the OWF is the main advantage.

A combination of different concepts or the use for not only one but a whole OWF cluster is also possible and might be beneficial when it comes to cost-effectiveness.

All concepts can be supported by a large jack-up repair vessel for major failures of WTGs. (Sperstad et al. 2016)

INFLUENCING FACTORS

The following main factors and parameters influence the economic viability and the choice of a service concept. Which service concept is appropriate has to be evaluated on an individual basis.

- Weather conditions
- Distance between OWF and base station
- Service strategy
- Number of supplied WTGs
- Failure rates of components
- Number and type of equipment

THE O&M PROCESS

Figure 3-23 shows the O&M process in a simplified way. The OWF is monitored from the control room, respectively an OWF manager who works for the OWF operator. Via the control system the manager receives actual remote operational data. First, the manager tries to repair the failure remotely. If the failure cannot be resolved, the manager usually contacts the manufacturer and/or the maintenance team.

Figure 3-23: Simplified O&M process [Author's illustration based on (Münsterberg 2017)]

The maintenance team receives the necessary spare parts from the manufacturer or the operators stock. Depending on the failure and the weather conditions, the manager plans and decides which transportation is used and when the failure can be solved. After the repair of the WTG, the maintenance team returns to the base station and the WTG is restarted. (EnBW Offshore Service 2018)

4 Two-bladed wind turbines

This Chapter outlines the past and the current situation of two-bladed WTGs. Chapter 4.1 explains why two-bladed WTGs have not been able to assert themselves in the onshore sector in the past and why they might be an alternative to currently used three-bladed WTGs for the offshore sector in the future. Subsequently, Chapter 4.2 provides an overview of today's OEM activities and the background of two-bladed WTG concepts for offshore operation. An analysis of today's concepts including a critical design review and the CAPEX reduction potential is presented in Chapter 4.3.

4.1 Onshore issues and offshore solutions

The wind onshore and offshore market is nowadays dominated by three-bladed WTGs with which the manufacturers and operators have gained many hours of operating experience over the past decades. Although a huge variety of two-bladed WTGs have been developed and built since the beginning of modern wind energy (see Hau (2016) for a historical overview), up to now they could not gain acceptance or become state of the art due to diverse draw-backs (Hau 2016):

Visual impact: Three-bladed rotors give a much steadier view compared to the beam-like structure of a two-bladed rotor which causes a restless view. This was and still is one of the main acceptance problems of two-bladed WTGs for onshore application.

Noise impact: Another problem when it comes to public acceptance is the higher noise emission of two-bladed WTGs. For operation at maximum power output, higher rotational speeds are required and thus noise emissions increase.

Dynamic challenges: The complex dynamics of two-bladed WTGs are considered to be more challenging compared to three-bladed WTGs.

The draw-backs and their influences have led to three-bladed WTGs being state of the art today but a new evaluation for offshore use of two-bladed WTGs is necessary. The main acceptance problems like visual or noise impacts are of little importance for offshore use and new load reduction concepts offer possibilities to control the complex dynamic behavior. Additionally, they offer potential to solve key challenges arising from the harsh environmental conditions at sea. (Gasch, Twele 2016)

Offshore installation of WTGs is challenging and can only be done during moderate wind and weather conditions. Due to that fact it is of particular importance that logistics and installation are as easy and fast as possible in order to keep the costs low. The more turbines are transported on one ship, the lower the costs. New OWFs will be built at greater distances to shore (Fraunhofer 2018) which makes less ship travels even more important. At that point, a two-bladed rotor with its beam-like structure (long but not wide) offers numerical superiority compared to a three-bladed one. It can be transported fully pre-assembled and pre-tested on a ship's deck to the wind farm. Three-bladed rotors with large diameters usually have to be transported disassembled due to space problems. The trend of ever larger turbines will increase logistical challenges (Fraunhofer 2018). Pre-assembled rotors have the advantage that less crane lifts are necessary for installation on site, which in fact saves installation time and thus money. Also the weight saving potential of two-bladed WTGs can lead to installation advantages and cost reduction as it directly impacts the foundation. (Hau 2016)

Finally, extreme loads can be considerably reduced by using horizontal parking of the rotor which also allows to install a helicopter landing platform (Seawind 2017). Reduced extreme loads can also result in lighter tower and foundation design as well as less wear and tear of corresponding parts. The increased fatigue loads of a two-bladed rotor can largely be overcome in different ways which are part of the following Chapters.

4.2 Background and current situation

Two-bladed WTGs basically work in the same way as three-bladed WTGs. Obviously, the main difference is that their rotor only consists of two blades instead of three which brings some benefits but also new challenges. The following Chapters 4.2.1 and 4.2.2 present the technical basics, benefits and challenges as well as a short summary of today's concepts of different OEMs[10].

4.2.1 Technical basics, benefits and challenges

The theoretical maximum power coefficient c_p of a rotor according to Betz is 0.59 (Hau 2016). Three-bladed WTGs reach higher power coefficients then two-bladed WTGs. For example, at a tip speed ratio λ of 7.5, the power coefficient reaches its maximum

[10] The term OEM (Original Equipment Manufacturer) is used although the companies promoting two-bladed WTGs are mainly in a start-up or pure concept study phase and according to the author's valuation are far from being a turbine manufacturer and some even don't intend to become one.

of 0.50. Two-bladed WTGs realize lower power coefficients of up to 0.49 at a tip speed ratio of 8.5. In general, the two-bladed WTG needs a slightly higher tip speed to reach its optimal aerodynamic condition. (Dalhoff et al. 2013)

Thus, one design approach to optimize two-bladed WTGs is a 22.5 % higher tip speed ratio. A higher tip speed increases noise emission as discussed earlier but on the other side the torque of the WTG is positively influenced as well. Higher tip speed ratios lead to lower torque and the drive train is less stressed. (Burton 2011) This results in a simplified lighter design. Especially, material and therefore weight of components like the gearbox can be saved. At the same time, the diameter of the support structure has to be increased with rising tip speed ratio which ends up in more material and weight. Also pile driving of big diameter monopiles is challenging but not yet a limiting factor. (Paul 2010) Another optimized design approach is to increase the blade chord by 50 % with constant tip speed ratio to reduce blade tip losses. A greater blade results in higher weight and therefore eliminates the cost advantage of two-bladed rotors. (Burton 2011)

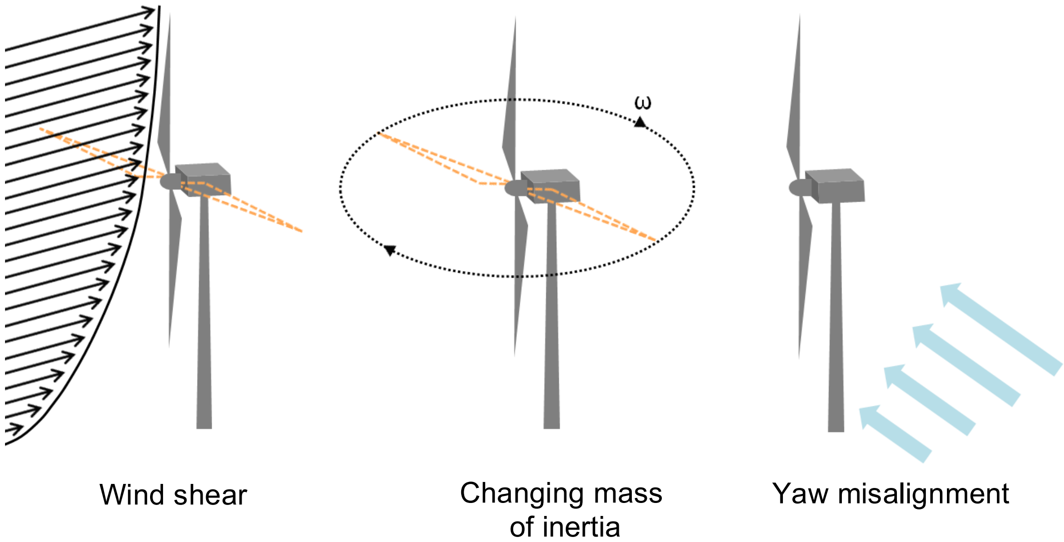


Figure 4-1: Sketch of two-bladed WTGs dynamic challenges [Author's illustration based on (Schorbach 2016)]

The main challenge of two-bladed WTGs is the dynamic behavior. Generally, WTGs are exploited to high fatigue loads during their life-cycle. Dynamic cyclic loads act on the WTG due to the revolution of the rotor and thus aerodynamics, gravitation and inertia. In every revolution, the beam-like rotor of a two-bladed WTG is in a vertical position twice. This means that twice per revolution, there is a large difference between both blade loads caused by wind shear[11] (see Figure 4-1).

Moreover, the inertia of the two-bladed rotor is dependent on the rotor position, which means that asymmetric wind flows can cause large yawing moments. The latter effects account for increased fatigue loads of a two-bladed WTG. On the other side, three-bladed rotors act more like a disk and are characterized by evenly distributed loads by wind shear because one blade is always in the area above the nacelle. (Gasch, Twele 2016) A two-bladed WTG is susceptible to any kind of skewed inflow or yaw misalignment due to its symmetry. For example, particularly high buoyancy at one blade due to skewed inflow most probably results in a very unfavorable flow and less buoyancy at the other blade. This creates a resulting moment around the center of the rotor. An unsymmetrical three-bladed rotor also has fewer problems with this circumstance. (Schorbach 2016)

According to Burton (2011) the increased loads acting on hub, rotor shaft, nacelle and yaw-system of a two-bladed WTG ultimately lead to higher wear and tear and thus higher costs and/or reduced life time. Modern load reduction concepts are discussed in Chapter 4.3.

Another challenge of two-bladed WTGs is rotor blade leading edge erosion due to high tip speeds of some turbines with up to 130 m/s (DeVries 2011). Erosion is mainly caused by rain droplets, hail stones and other airborne particles. Each impact on the leading edge adds an increment to the accumulated damage in the material. After a number of impacts the leading edge will crack and a drop of the power coefficient can be noticed. (Bech 2018) (Paul 2010) Major erosion can already be observed after an operational time of 3 years at the three-bladed WTGs of EnBW's OWF Baltic 2 with significantly lower tip speed of 82 m/s. The result is higher maintenance costs and energy yield loss (EnBW 2018g). Special anti-abrasive coatings to sensitive rotor blade surface areas (DeVries 2011) and other forms of leading edge protection (e.g. soft shell of PolyTech A/S) should remedy this issue. Appropriate precautions should be taken before installing the system, as offshore retrofitting is complex and expensive, although they have to be renewed a couple of times during the turbines life-time (EnBW 2018g).

[11] Wind shear is relevant to characterize the wind resource on site and describes the variation of the wind speed depending on the height which is called vertical profile. (Gasch, Twele 2016)

4.2.2 *Today's OEMs and concepts*

Today's three-bladed WTG concepts are usually an upscaling of already existing turbines and the concept diversity is rather small. The range of different two-bladed WTG concepts is much broader. There is no such thing as an industry standard when it comes to rotor orientation, load reduction, power or yaw control.

The following Figure 4-2 shows the analyzed two-bladed WTG concepts and focuses on turbines for offshore use even though up to now some are only tested onshore. This variety is differentiated into commercial / concretely planned turbines, prototypes and visionary concepts. Turbines older than 2010 are not considered due to a lack of interest for offshore use and are not a central part of this evaluation. For a complete overview reference is made to Dalhoff et al. (2013) and Schorbach (2016) at this point.

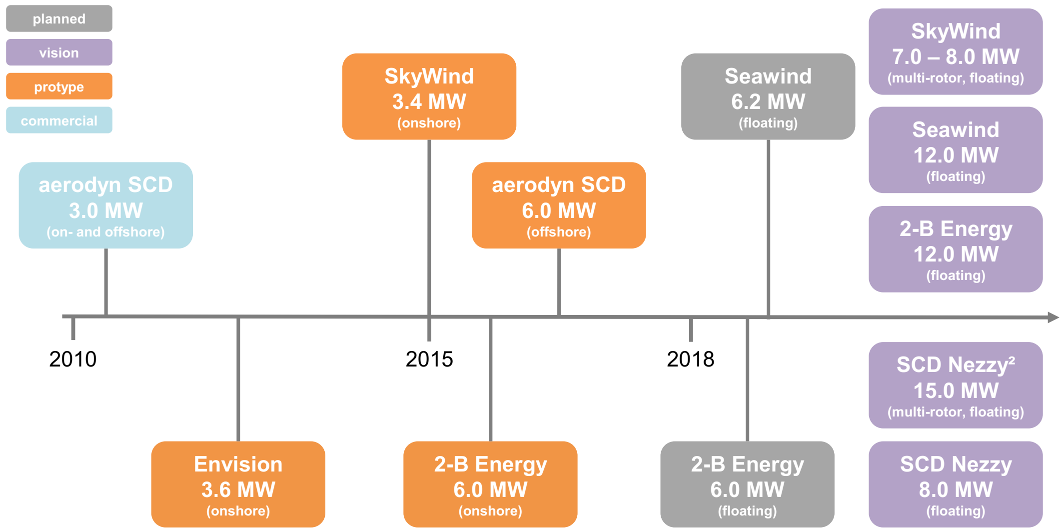


Figure 4-2: Overview offshore relevant two-bladed WTGs [Author's illustration based on (Schorbach 2016)]

A look at the concepts from 2018 onwards shows that the trend is towards a two-bladed design combined with a floating foundation. In the remainder of this section, the above-mentioned OEMs and concepts as well as upcoming projects are briefly discussed. The purpose of this overview is to give an impression of the variety of two-bladed WTG concepts, each having its own innovative and beneficial features. A project list (Appendix table 1) and turbine data sheets (Appendix table 2 – 9) are in the Appendix B (as far as detailed information is available).

AERODYN ENGINEERING / MINGYANG

The German company aerodyn has been developing wind turbine systems such as the Multibrid design since 1984. They are not an OEM but an engineering company developing technical solutions for licensees all around the world. One licensee is Mingyang from China. Up to now Mingyang erected 17 onshore and one near shore aerodyn designed two-bladed WTGs each with a rated power of 3 MW. More recently, a prototype of the SCD advanced class with 6 MW and a downwind design was installed offshore and connected to the Chinese grid as part of the Longyuan Rudong Intertidal project (see Appendix figure 1). The turbine has a rotor diameter of 140 m and a hub height of 100 m. (aerodyn 2018) Another 29 turbines with 3 MW are under construction at the Zuhai Guishan Hai demonstration OWF of which three are already connected to the grid (4C Offshore 2018). Nevertheless, the cooperation between aerodyn and Mingyang ended after the installation of the 6 MW SCD advanced prototype. Mingyang has full rights to further develop the 3 MW and the 6 MW turbines. According to aerodyn, Mingyang is focusing on redesigning the turbines to use them with a different hub and a three-bladed rotor for the Chinese market. (aerodyn 2018)

SCD means 'Super Compact Drive' and aims to increase the cost-effectiveness by reduction of manufacturing, maintenance and repair costs and further improve energy output and reliability. The basic idea is to align rotor bearing, gearbox and generator linearly with nearly identical diameters and the housings of the components that are used for load transfer from the rotor to the tower top. The result is a compact light weight design with small dimensions. Another important characteristic of the SCD turbines is the use of redundant components. For example, the 6 MW turbine has three 3.0 MW inverters and a surplus of hydraulic pumps and other components. In case of failures, the use of redundant components increases the level of reliability. Another advantage of the two-bladed design combined with a downwind alignment is the horizontal parking position of the rotor. In this case, the hydraulic yaw brakes are released which means that the rotor-nacelle unit can freely rotate and this minimizes structural loads during extreme winds. The downwind rotor design naturally aligns with the wind and is able to follow rapid wind direction changes. (aerodyn 2018)

With its SCD nezzy concept aerodyn has an 8 MW two-bladed downwind turbine on a floating foundation in the design pipeline (see Appendix figure 1) Small-scale tests have been performed and a 1/10 scale turbine has been extensively tested in Japanese inland waters under high wind loads as well as strong currents. The 1/10 scale turbine is equipped with all the same features as the full-scale turbine and uses the same materials. The next steps are open water tests with the proven 6 MW turbine design and a further up-scaling to 8 MW. Aerodyn provides a visionary outlook by

2025 named SCD nezzy² based on the SCD nezzy design. The 15 MW are supplied by a multirotor concept including two 7.5 MW two-bladed downwind turbines on one foundation and first small-scale water basin tests are running (see Appendix figure 1). (aerodyn 2018)

Additionally, in 2018 aerodyn has built a 3 MW two-bladed WTG on its own at Nobiskrug shipyard for a floating offshore project off the Japanese coast. The project is initiated and financed by NEDO (New Energy and Industrial Technology Development Organization, Japan) to test a floating foundation supplied by Ideol. Commissioning is planned for late 2018. (aerodyn 2018)

ENVISION

Envision Energy is a leading global smart energy solutions provider. It is the second largest wind turbine company in China and it is ranked top six globally. They installed over 10 GW of what the company calls 'smart wind turbines'. The company is specialized on low wind speed areas in China and smart control systems to optimize the wind farm performance by means of machine learning. Envision Energy is China's largest provider of offshore wind power solutions with nearly 1 GW offshore capacity. Their 2009 established Global Innovation Centre is located in Denmark to benefit from the Danish wind energy know-how and to bring the products to the European market. (Envision 2018a)

The EN-128/3.6 PP 2B or short GC1 (Game Changer 1) is Envision’s first and only two-bladed WTG with a rated power of 3.6 MW designed for offshore operation. It was launched in 2012 after a two-year development phase. A demonstrator turbine has been erected near-shore in Thyborøn, Denmark to show the validity of the concept and is still running but the tests are closed (see Appendix figure 2). The design is based on an upwind two-bladed rotor with a rigid hub and a partial-pitch mechanism. Besides the already discussed advantages of a two-bladed rotor when it comes to transport and installation, the GC1 offers further transport and handling benefits due to the segmented blades. Both 62 m long blades consist of a 20 m inner section (extender) with a fixed blade angle and a pitchable 42 m outer blade (partial-pitch). According to Envision the partial-pitch virtually eliminates the huge design loads of conventional two-bladed WTGs in the event of a single-pitch-system failure. This results in reduced blade, nacelle and tower mass and addresses the main concerns regarding two-bladed WTG application. (Envision 2018b) (DeVries 2012)

Ecoswing is a new project of a consortium of 9 partners from 5 countries around project leader Envision which aims to develop a generator on a superconductor basis. A so-called superconducting tape produced by ECO 5 GmbH is used to build a full-scale multi-megawatt direct-drive generator, which is up to 40 % smaller than conventional generators due to the high current density of the tape compared to copper. This results in a compact lightweight design and saves weight of the nacelle. The generator was tested in May 2018 by Fraunhofer IWES Bremerhaven and will be built in Envision's existing GC1 demonstrator at the test site in Thyborøn for further testing in operation. (EcoSwing 2015)

SKYWIND

SkyWind is a German based company and belongs to the GEO Group. The GEO Group has expertise in project development, installation, technical operation and maintenance of 250 different turbines as well as condition monitoring. Based on that expertise, SkyWind developed a two-bladed WTG to reduce the offshore LCoE by taking CAPEX and OPEX into account. Using conventional technology put together in a new way is an attempt to bring down risks as well. (SkyWind 2016)

A full-scale 3.4 MW prototype was erected onshore in 2015 at a wind test field near Husum in Germany (see Appendix figure 2). The hub unit including the 107 m wide upwind rotor on a rigid hub can be assembled at the ground level due to the two-bladed technology. It is then lifted on top of the tower via a steel cable winch-system, which is integrated in the tower. The traditional nacelle is replaced by a load-bearing house with two separate units (hub unit and tower unit) which are brought together on top of the tower automatically. Thus, the turbine can be assembled and put into position without the use of a lifting crane or vessel. This idea can save installation time and costs, especially for offshore application. Replacements during O&M can be done by the winch-system as well and should be easier according to SkyWind. The load-bearing house including the rotor is said to be 25 % lighter than comparable turbines. (SkyWind 2016)

In the future, SkyWind focuses on international markets with good wind conditions but difficult sites in terms of logistic and installation infrastructure. 2016 they wanted to build an offshore prototype in Norway. They explored two main options: A jacket-mounted model with a Y-shaped tower including one central yaw-system topped with a pair of two-bladed WTGs (one downwind and one upwind, (see Appendix figure 2). The second option was a twin-headed floating concept. Both designs have an overall capacity of 7 to 8 MW. These concepts also use the integrated winch-system and need no expensive lifting vessel. A floating foundation spares the pile driving of the foundations. The test site would have been off Karmøy near Statoil’s Hywind 1 and the turbines intend to be used to power oil and gas platforms. (Recharge 2016)

At the moment, there is no specific information available about the status of this project or other SkyWind activities.

2-B ENERGY

Dutch based company 2-B Energy is financed by both equity funders and different other funding mechanism. The parties vary from venture capital, strategic investors and local interest groups. They designed a radical two-bladed downwind WTG with a capacity of 6 MW and claim a 40-year service life. A prototype with a 140 m rotor diameter was erected and tested in 2015 onshore at Eemshaven, Netherlands. (2-B Energy 2018)

The design has two nacelle levels, a passive cooler platform, a self-aligning 'soft yaw' system and a lattice-type welded truss tower (see Appendix figure 3). The latter open structure extends from the seabed to the nacelle yawing bearing and is one of the main innovations of the turbine. In normal operation, the 'soft yaw' capability means the rotor automatically follows wind direction changes and then only requires some nacelle yaw damping motion. In emergency situations, like a combination of extreme weather/and or turbine failure, eight yaw motors are activated to bring the turbine in a safe non-operating position. A ninth motor is used as redundant component. On top of the turbine is a helicopter landing platform for service visits which can be used up to wind speeds of 25 m/s due to the ability to park the rotor in a horizontal position. (Renews 2016)

2-B Energy’s next step is a wind farm development project in the UK named Forthwind where they have planned to install two of their 6 MW turbines in a first phase until 2017. The Crown Estate awarded the demonstration site and an agreement was signed. No consent in financial closure could be found in time, thus the project is delayed as the agreement for the demonstration site expires end of September 2018 if the turbines are not connected to the grid. The developers along with RenewableUK, ORE Catapult and others have applied for an extension of the deadline to be able to realize the project. A second phase of the Forthwind project is planned with another seven turbines and a capacity of 6 to 12 MW each, although the sites total capacity is capped to 65 MW. Originally the second phase should be installed and ready for grid connection by the end of 2019. Due to the delay of phase 1, the phase 2 is also postponed indefinitely (4C Offshore 2018). This is also confirmed by 2-B Energy's management (2-B Energy 2018).

SEAWIND

Seawind Ocean Technology is a start-up company from the Netherlands which claim to be a 'leading turnkey offshore wind farm supplier' due to strategic partner-ships with companies such as Olav Olsen (oil & gas concrete foundations) and Carbon Rotec (rotor blade manufacturer, bankrupt beginning 2018). (Seawind 2017)

Together with their partners Seawind planned to install a 6.2 MW prototype with a 126 m two-bladed rotor and a gravity based foundation designed by Olav Olsen off the Norwegian coast in the Rogaland region. (4C Offshore 2018) The project is postponed indefinitely due to financial issues of Seawind's Norwegian affiliated company in 2018. At the moment, the partners are looking for new investors to drive on with the prototype project. Seawind also signed an agreement with wind farm and solar park operator WRE Hellas to develop small scale wind farms in the Greek Aegan Sea. According to Seawind these projects are not directly affected by the financial problems of their Norwegian affiliated company but they are also delayed and need to wait for a prototype to run first. (Offshorewind.biz 2018a)

The design of Seawind's two-bladed WTG is a further development and up-scaling based on the upwind 1.5 MW Gamma 60 prototype with a teetering hinge and a yaw control principle which was installed in Italy in 1991. Power control via yawing means, turning the head out of or into the wind depending on the wind speed and in theory that keeps the system simple by eliminating the need for a pitch-system. A helicopter landing platform can be installed on top of the nacelle because of the horizontal parking position of the blades. Heavy helicopters transporting personnel and material for maintenance can safely land on the turbine. In heavy storms or typhoons, the blade tips are automatically pointed into the wind in a 'flexible configuration', which shall decrease loads. (Seawind 2017)

One of the keys to the company's LCoE estimation of below 7 $€_{cent}$/kWh is that the turbine and the foundation are designed as a system which offers the possibility of a low cost offshore installation. Together with Olav Olsen a buoyant concrete foundation has been designed. The entire system is completely mounted onshore with land based cranes, moved onto a semi-submersible vessel and shipped to the OWF site. The vessel carries 4 - 6 units at a time to the OWF site where the units are launched into the water by sinking the entire vessel with the units (see Appendix figure 3). Once the units are afloat they are positioned by tug boats and lowered to the ground adding water ballast by pumping. After touch-down at the previously prepared seabed, additional sand and water ballast is added to secure stability in operation. For water depth beyond 90 m, Seawind is designing a 12 MW two-bladed WTG with 220 m rotor diameter on a floating concrete foundation at the moment. The concept is planned to be finished by the end of 2019 and shall be ready for installation by 2021. Another design approach with positive effect on the LCoE is the extended 30-year life-time compared to 20 - 25 years of current three-bladed WTGs. (Seawind 2017)

4.3 Analysis of today's concepts

What follows is a critical design review (Chapter 4.3.1) of the concepts presented in Chapter 4.2.2 and a look at the CAPEX reduction potential (Chapter 4.3.2). The morphological box shows the design configurations of the concepts (see Figure 4-3).

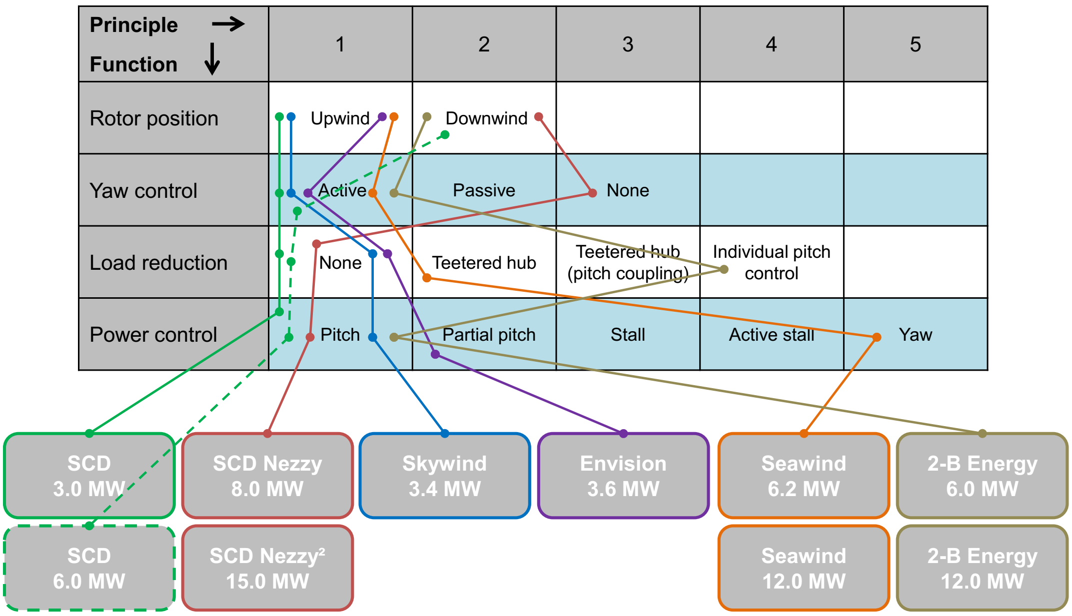


Figure 4-3: Design configurations of two-bladed WTG concepts [Author's illustration based on (Dalhoff et al. 2013)]

4.3.1 Critical design review

A detailed look at the wide range of technical concepts shows that every concept is unique but the main design aspects of offshore two-bladed WTGs can be classified as follows and will be further discussed in detail:

- Rotor position: *downwind, upwind*
- Yaw control: *active, passive, none*

- Load reduction: *none, teetered hub, teetered hub/pitch coupling, individual pitch control*
- Power control: *pitch, partial-pitch, yaw*

ROTOR POSITION – DOWNWIND vs. UPWIND

When it comes to the position of the rotor there are two design possibilities: An upwind rotor which is commonly used for actual three-bladed WTGs or a less favored downwind rotor. Figure 4-3 shows an equal distribution of 5 two-bladed concepts with an upwind and 5 with a downwind rotor. If only turbines in the +6.0 MW class are considered, it can be seen that even 5 out of 7 turbines are designed with a downwind rotor.

The introduction of active yaw-systems allowed upwind rotors to have some advantages in the past. Particularly, downwind rotors have found little favor because of an effect called tower shadow. Blades passing behind the tower are affected by sharp reduction in incident wind speed as the tower blocks the flow and highly impulsive loads are transmitted into the system. This effect can be positively influenced by a full-height lattice tower or full-jacket which is considered by 2-B Energy's concept (2-B Energy 2018). This tower partly lets the wind flow through instead of blocking it completely. Additionally a full-height lattice tower offers advantages such as weight saving and replacement of the expensive transition piece for conventional fixed support structures. (Koh, Ng 2015) With its SCD nezzy concept, aerodyn is aiming to reduce the effect of tower shadow with a droplet tower shape and a significantly lower drag coefficient of 0.3 – 0.4 instead of about 1.3 for a tubular tower (DeVries 2014).

The tower shadow and non-uniform in-flow impact of a downwind rotor on the power performance is regarded as generally small. A variation in rotor power of less than 5 % is expected between upwind and downwind rotors (Koh, Ng 2015). This might be true for a single turbine but for an OWF with for example 80 turbines 5 % per turbine is a significant drop in power performance. Power performance needs to be reviewed in more detail as computational and experimental work on a Hitachi 2 MW downwind turbine even shows a higher power and thrust compared to a corresponding upwind configuration (Koh, Ng 2015).

Comparable to the noise issue of two-bladed WTGs the downwind design for onshore application was also dismissed due to higher noise compared to the upwind design. This is mainly caused by interaction between downwind rotor and the aerodynamic wake of the tower. Like for two-bladed WTGs it is not much of a problem for offshore application. (Koh, Ng 2015) Besides all challenges, aerodyn states the following advantages of their two-bladed WTGs with downwind rotor design which are not only attributable to their particular design but for downwind rotors in general (aerodyn 2018):

- Natural way of reaching low resistance state
- Wind vane principle
- Blade turns away from tower, no tower clearance issues
- Yaw-system acts with gyro forces
- Free yawing is possible
- Coning rotor at high thrust
- Self-aligning in typhoon environments

This does not automatically mean that a downwind rotor is the superior design. For example, either coning of the blades, tilting of the shaft axis, curved blades or an extra overhang, mitigates the tower clearance issue of an upwind rotor. But although the above options are available they can only be used to a limited extent. Tilting beyond 4 or 5 degrees may introduce unwanted cyclic loads. Coning results in a moment at the blade root due to centrifugal forces on the blade elements that may have adverse effect in over-speed condition. Curved blades and increasing overhang distance are costly options while the latter causes increased loads on nacelle structure and rotor bearings. Coning and tilting options also result in a slight reduction of power or require marginally longer blades to maintain power. (Jamieson 2011) For example, a downwind rotor combined with a floating system such as aerodyn's SCD nezzy concept is expected to have a better power performance compared to a tilted upwind rotor as the floating system pitches in the wind direction (aerodyn 2018). This is due to the fact that the angle between the rotor axis and the wind inflow increases for an upwind system but decreases for a downwind system (Koh, Ng 2015).

Especially the combination of a high speed two-bladed rotor and a downwind design brings further advantages due to the possibility of a lightweight rotor, drive train and nacelle structure caused by reduced torque at rated power. The result can be a more slender tower and the effects can combine to mitigate impacts of tower shadow on blade and system loads. After all the influence of tower shadow can't be remedied entirely. Another effect of a lightweight turbine is the reduced material costs. About 15 % cost reduction in tower top mass is estimated for a high speed rotor with a design tip speed of 120 m/s compared to standard design with 75 m/s. (Jamieson 2011) But as discussed earlier, an increased tip speed requires an increased tower stiffness to increase its natural frequency. This can be accomplished by an increased thickness and/or diameter. Therefore, the competing effects of a lower tower top mass and an increased natural frequency on the tower design are estimated to approximately cancel each other out. (Loth et al. 2015)

YAW CONTROL – ACTIVE vs. PASSIVE

Some studies imply that the yaw-system amounts to about 1.3 – 5 % of the entire costs of an upwind wind turbine for a land-based system. Further analysis show that the cost and mass trend exponent of the yaw-system is the second highest of all components. Thus, the costs and mass of the yaw-system are heavily influenced by upscaling of a turbine. (Koh, Ng 2015)

Yaw control can be either active or passive. Multi-megawatt turbines with an upwind rotor use active yaw-systems to track the optimal wind inflow direction. Theoretically it is possible that an upwind rotor can be stable in the free-yaw but compared to a downwind rotor it is less stable as the yaw stability depends on wind speed, yaw angle and coning angle. For a downwind rotor, it is theoretically possible to remove the active yaw-system of the turbine as the downwind rotor is able to passively yaw into the wind. With removal of the active yaw-system it is possible to directly reduce turbine costs and lower operating and maintenance costs as well. A mass reduction to the rotor-nacelle system is technically beneficial for an offshore turbine, especially in combination with a floating foundation, and this will bring indirect cost reduction to other components of the system. (Koh, Ng 2015)

Floating foundations with a single point mooring even offer the possibility to use no yaw-system at all as the turbine-foundation system aligns with the wind around the mooring point. SCD nezzy and SCD nezzy² are based on this design approach. All other eight turbines are equipped with an active yaw-system (see Figure 4-3) although the SCD advanced is designed to yaw freely during extreme loads, which is possible due to its downwind rotor. 2-B Energy's turbine is equipped with a feature called 'soft yaw-system', which during normal operation allows the rotor to freely follow wind-direction changes with some degree of dampening (DeVries 2016). Faster respond to changes in wind direction and improved yaw stability of such a downwind rotor has been observed compared to an upwind rotor (Koh, Ng 2015).

LOAD REDUCTION CONCEPTS – IPC vs. TEETERING HUB

One of the key design parameters of a two-bladed WTG is certainly the load reduction concept. Despite that, Figure 4-3 indicates that 3 of 5 OEMs designed their turbines without special load reduction mechanism. One uses a mechanical solution in form of a teetered hub (Seawind) and one uses control based individual pitch control (2-B Energy). The two considerable advantages of load reduction are: Less loads resulting in a lighter turbine design and longer lifetime with less maintenance efforts. A lighter design means that in cases where components are designed according to fatigue loads, a reduction of these loads allows savings in costs and material notably for the rotor blades and the tower structure. (El-Henaoui 2012)

Individual pitch control (IPC) is a concept based on the recent developments of control technology for wind turbines. Collective pitch control (CPC) adjusts the pitch of all rotor blades at the same angle and time while individual pitch control dynamically and individually adjusts the pitch of each rotor blade in real time. (El-Henaoui 2012) Individual pitching of each blade influences the buoyancy and thus the loads on the rotor blades, the hub, the mainframe and the tower structure. A cyclic pitch depending on the rotor azimuth can be used to reduce predictable loads such as tower shadow induced loads. Compensation of loads coming from shaft tilt can be compensated by a cyclic pitching as well. Less predictable loads, such as loads from yaw misalignment, are more challenging to mitigate by IPC and require additional sensor information as this is changing permanently. The impacts of wind shear can also be mitigated only to a certain extent by a cyclic pitch as in turbulent wind conditions the highest wind speed does not necessarily occur at the top. Information about the current wind speed in front of each blade can possibly mitigate loads from wind shear. Another possible solution can be information about the current blade root bending moments as input for the IPC. (Burton 2011) Compared to CPC, the IPC system requires higher investment costs as the control strategy is more complex and there are higher requirements for the pitch drives as well as increased fatigue loads on the pitch bearings and gears. These investment costs have to be compared with the possible savings in other components due to reduction of fatigue loads by IPC. Investment costs as well as operational costs need to be considered. A possible increased turbine life-time can positively affect the LCoE as well. (El-Henaoui 2012)

A teetering hub is a mechanical solution and also intends to reduce the dynamic cyclic loads coming from wind shear, yaw, shaft tilt and tower shadow. (Jamieson 2011) The heavier-loaded blade is able to teeter the rotor a few degrees backwards, which ideally means that no torque is transmitted to the structure of the turbine. (Schorbach 2016) The centrifugal force acts as the restoring moment of a teetering rotor which is why the teeter motion is difficult to manage during low rotational speeds or high wind start-up or shut-down. Large teeter end stops are considered as the key issue and can be caused by pitch faults or extreme turbulence. (Burton 2011) However, it is mentioned that a teeter hub might in theory be more effective compared to IPC (Dalhoff et al. 2013).

Some smaller turbines also use other load reduction concepts such as teetered hubs with a delta-3 angle, a pitch-teeter-coupling or a flap hinge. These turbines are not part of the analysis of this thesis due to their small capacity and their design for onshore application and reference is made to Dalhoff et al. (2013) and Schorbach (2016).

The most advantageous load reduction concept remains uncertain. There is no theoretical consensus (Burton 2011) (Hau 2016) and especially long-term operational data of large two-bladed WTGs is missing for a clear comparison. Concepts with no special load reduction concept have to be treated with caution as the complex dynamic load behavior of two-bladed WTGs has been mentioned earlier. According to Jamieson (2011), dynamic extreme loads and cumulative fatigue loads mainly from operation in normal wind turbulence are the influencing factors that drive the design of most WTG components. The benefit of no special load reduction concept is a less complex mechanical and/or control system which can be at the expense of the turbine’s life time due to wear and tear.

POWER CONTROL – PARTIAL-PITCH vs. YAW CONTROL

During high wind speeds the mechanical power consumption of the rotor which is extracted from the wind by far exceeds the limits set by the construction of the turbine structure. In addition, the maximum permissible generator output forms a limit for the power output of the rotor. Keeping the rotor speed at a constant value or within specified limits is another challenge. Speed limitation becomes a question of survival in the event of a malfunction or failure, such as a grid failure, when the generator torque suddenly disappears. In such a case, the speed of the rotor increases extraordinarily fast and leads with certainty to destruction of the system if countermeasures are not taken immediately. Therefore, it is inevitable that the rotor must have an aerodynamically effective method for limiting power and speed. (Hau 2016)

Figure 4-3 indicates that a regular pitch-system for power control is used by 7 of 10 concepts. Envision and Seawind use different methods to control power and speed. A pitch-system is also the commonly used system for power control of modern on- and offshore three-bladed WTGs (Hau 2016). The obvious main difference between two- and three-bladed pitch controlled WTGs is that with only two blades also one pitch-system and its investment as well as operational costs can be spared. An issue can be the emergency stop of a two-bladed WTG in case of a single pitch failure. In this case, a three-bladed WTG still has two pitch-systems to safely stop the turbine aerodynamically. The one residual pitch-system of a two-bladed WTG might not be able to stop the turbine and a secondary brake system needs to be able to stop the turbine in such an event.

The GC1 concept of Envision uses a method called ***partial-pitch***. From an aerodynamic point of view, it is not necessary to pitch the rotor blade over the whole length. For that reason, only the outer blade part of the GC1 is pitched. This idea was already used by older two-bladed WTG concepts, such as the MOD-2 (Hau 2016). The result is a relatively robust combination of pitch and stall control (Kim et al. 2014). In this case, the bearing and pitch actuator need to be placed at the outer part of the blade. This brings additional design issues in terms of the space and weight at an unfavorable place of the blade. (Hau 2016)

According to Hau (2016) it is disadvantageous for extreme wind situations that the inner part of the blade can’t be brought into feathering position and standstill loads are increased. An analysis of the behavior of the GC1 in a 50 year recurrence extreme wind speed case at standstill condition by Kim et al. (2014) shows contrary results. The study shows that the GC1 design can reduce extreme loads in storm situations of up to 20 % compared with a three-bladed WTG, if the rotor during side wind aligns in a horizontal T-configuration and yawed 90 degrees in relation to the wind direction. In normal operation, an extreme gust event accelerates the rotor rapidly which makes the controller to stop the turbine to prevent over speed, however it is seen from the analysis that the rotor speed is not dramatically increased while the extreme gust occurs. The reason for this turbine behavior can, to some extent, be explained by the large rotor inertia, caused by the blade pitch bearings placed 20 m from the blade root. Envision itself states 30 % extreme load reduction. During normal operation Envision’s calculations indicate similar load levels compared with a conventional three-bladed WTG with the same blade length. This was independently verified by Danish research institute Risø’s calculations. Compared to conventional three-bladed

WTGs, which put their full length into a feathering position, the partial-pitch blades experience two different counteracting load-vector directions due to the extender and the feathered outer part. This is the company's explanation for a reduction in extreme loads and a 10 % saving in overall turbine costs, concentrated at mass reductions in the tower and foundation. (Envision 2018b) (DeVries 2012)

Yaw control is a completely different approach of two-bladed WTG power control. First introduced with the 1.5 MW Gamma 60 research turbine, which was tested with European Commission financial support at Sardinia, Italy from 1991 until 1997 when the program was closed. According to Seawind the turbine functioned well for about four years but due to an unspecified human error during a 1995 storm it was damaged but repaired and put back in operation for another two years. (DeVries 2011) Seawind's concept is basically an up-scaling of the Gamma 60 and uses nearly the same technical design. The two-bladed WTG with a teetering hub is controlled by yawing the rotor rather than by pitching the blades. This means during low wind speeds the rotor is kept into the wind as for three-bladed WTGs. At high wind speeds the Seawind turbine controls power by turning the turbine head out of or into the wind with a yaw drive system. Four yaw drives are installed but one acts as redundant component as only three are used during operation. The yaw-system also acts as the primary braking system backed up by a double disc brake which is able to stop the turbine from full load together with the generator electrical torque. The idea behind this concept is to eliminate the pitch-system, which is a major failure source of a turbine according to Seawind and thus to reduce complexity as well as investment and operational costs. Seawind's analysis and tests showed that nacelle yaw moments introduced by the wind of a two-bladed rotor are only about 15 % compared to these values for an equivalent three-bladed rigid rotor. The maximum yaw speed is 10 °/second, which is faster than pitching. (Seawind 2017)

Due to a lack of turbine concepts with a yaw control design as well as no Seawind prototype and correspondingly a lack of research and practical data it is difficult to evaluate Seawind's statements without further studies and simulations which would exceed the scope of this thesis.

4.3.2 CAPEX reduction potential

This section contains a short consideration of the CAPEX reduction potential of two-bladed WTGs for offshore operation as the focus of this thesis is on the operating phase. The impacts on the operational phase including the energy yield and the OPEX as essential parts of the LCoE are assessed in Chapter 6.

In a first step Figure 4-4 shows the total cost split of an OWF with conventional three-bladed WTGs derived by two different studies. This total cost split is important to understand the cost share that can be influenced directly or indirectly by the use of two-bladed WTGs.

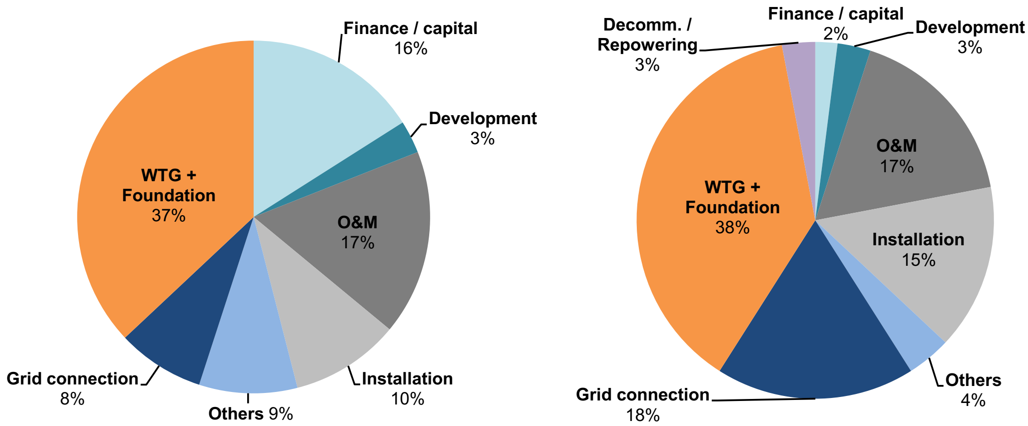


Figure 4-4: Total cost split of an OWF by IEA 2016 and Wind:research 2013 [Author's illustration based on (Fraunhofer 2017) (Böttcher 2013)]

A detailed look at the cost fractions indicates that both studies estimate 37 % respectively 38 % for WTG and foundation, which is the biggest share on total cost of an OWF. In addition, the development costs with 3 % and the O&M costs with 17 % are estimated equally. The studies are based on a project lifetime of 20 years. In practice, 25 years is the most common period, which would increase the impact of O&M costs respectively OPEX and reduce CAPEX impact. A difference of 5 % in other costs can be explained by assuming that the 3 % decommissioning / repowering costs of the Wind:research 2013 study are included in the other cost fraction of the IEA-Baseline Scenario 2016. A big difference of 10 % can be identified in the grid connection costs. This difference can be justified by the fact that the Wind:research 2013 study is based on European data and refers the grid connection costs that go beyond the inner array grid to the OWF operator. In Germany, these costs must be borne by the grid operator and thus the grid connection cost fraction of the IEA-Baseline Scenario 2016 is significantly lower. The 5 % difference in installation costs can be attributed to improved installation concepts and equipment as the IEA-Baseline Scenario 2016 uses more recent figures. A cost share of 2 % for finance / capital of the Wind:research 2013 study seems exceptionally low according to various sources on costs and cost reduction that identify the finance / capital expenses as a strong cost driver of OWF projects (Fraunhofer 2017) (Stehly et al. 2016) (Prognos AG 2013).

Two-bladed WTGs can mainly influence the WTG and foundation share of the total OWF CAPEX due to the already discussed weight reduction potential of tower top mass and thus of tower as well as foundation. Figure 4-5 shows the power-to-weight ratio of various two-bladed and three-bladed WTGs. The expected reduction in tower top mass of two-bladed WTGs can be recognized in almost every rated power class. Especially the aerodyn SCD turbines have a high power-to-weight ratio. These high ratios can be attributed to the SCD 'Super Compact Drive' technology used by aerodyn.

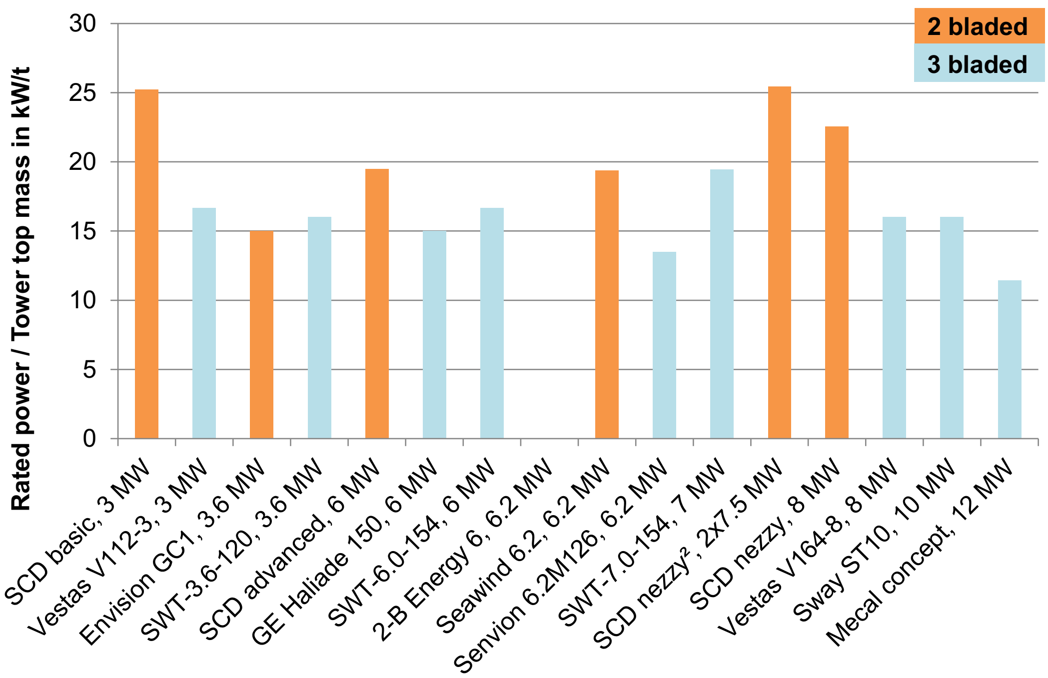


Figure 4-5: Comparison of power-to-weight ratio of two-bladed and three-bladed WTGs (2-B Energy 6.2 n/a) [Author's illustration]

The difference in power-to-weight ratio between 22.5 kW/t of the SCD nezzy and Vestas V164-8 with its 16.0 kW/t is quite high. Comparing the SCD nezzy² two-bladed multi-rotor concept with 15 MW (2x 7.5 MW) and the highest power-to-weight ratio of 25.4 kW/t to 11.4 kW/t of the three-bladed Mecal 12 MW concept indicates, that the power-to-weight ratio advantage of two-bladed WTGs may become even more relevant in the future as the trend towards ever larger offshore turbines continues. Particularly, the combination of a two-bladed rotor with a multi-rotor concept can be of interest. Reference is made to Warner (2018) on the subject of multi-rotor WTGs.

This qualitative interpretation shows that a CAPEX reduction of WTG and foundation in terms of material costs due to the lightweight design of two-bladed WTGs is more than likely. In addition, installation costs can be reduced by easier and faster installation as already discussed in Chapter 4.1. A detailed comparison between installation costs of an OWF with two-bladed or three-bladed WTGs is necessary for a quantification of that assumption. The costs for grid connection, development, others and finance are neglected, as no specific cost reduction or increase potential of two-bladed WTGs in these areas can be identified in the literature. It is necessary to further split the tower top mass into single component weights to be able to discuss a possible impact on OPEX due to easier transport, handling and change of main components such as gearbox or generator. As already mentioned, impacts on O&M and OPEX are discussed in more detail in Chapter 6. However, it is already evident here that a reduction in CAPEX with an assumed share of 37 % (WTG and foundation) plus 10 % (installation) on total OWF costs has a greater impact than a reduction in OPEX with a share of 17 %.

A detailed look at the CAPEX of an offshore WTG is necessary to indicate the components and cost share which can be influenced by a two-bladed WTG either positive or negative. In addition to Dalhoff et al. (2013) data (respectively Jamieson (2011)), further studies such as The Crown Estate 2010, EWEA 2007, NREL 2016 and Make 2016 are used to calculate an average CAPEX split of an offshore three-bladed WTG as a basis for the cost reduction or increase potential of a two-bladed WTG. Table 4-1 shows the CAPEX split results for an offshore three-bladed WTG and the assumed cost reduction potentials as well as the CAPEX split results for an offshore two-bladed WTG.

The cost reduction potentials are explained as follows (Dalhoff et al. 2013): A two-bladed WTG saves one blade which ideally leads to a 33 % cost decrease for the rotor. Increased stiffness, mass and blade tip speed negate some savings so only 25 % are considered. A higher tip speed offers mass and cost savings (10 %) in the drive train (shaft, gearbox, generator, brakes, coupling) and thus decreased tower top mass. This decrease in tower top mass in turn allows mass and cost reductions for the offshore support structure. Balance of plant (BoP) accounts for about 55 % of the overall CAPEX and its cost can be reduced due to easier logistics. Nacelle and rotor can be pre-assembled and tested onshore. It can be efficiently stacked on the transportation vessel and installed in a single crane lift.

Table 4-1: CAPEX reduction / increase potential of offshore two-bladed compared to three-bladed WTGs [Author's illustration based (Dalhoff et al. 2013)]

Component	Three-bladed WTG [%]	Reduction (-) / increase (+) potential [%]	Two-bladed WTG [%]
Shaft & bearings (+brakes)	4.7	-10.0	4.2
Gearbox	15.5	-10.0	14.0
Generator	5.9	-10.0	5.3
Power and control system	8.4	0.0	8.4
Other nacelle (+yaw)	7.1	0.0	7.1
SUM Nacelle	**41.6**		**39.0**
Blades	17.6	-25.0	13.2
Hub	4.5	0.0	4.5
Pitch-system	3.4	-25.0	2.6
Other rotor components	2.2	0.0	2.2
SUM Rotor	**27.7**		**22.4**
Tower	19.2	-5.0	18.2
Others	11.5	0.0	11.5
SUM Turbine	**100.0**		**91.1**
CAPEX Turbine	**44.9**	**-8.9**	**40.9**
CAPEX BoP	**55.1**	**-2.5**	**53.7**
SUM CAPEX	**100.0**		**94.6**

The overall CAPEX reduction potential of an offshore two-bladed is estimated to be around 5 to 6 %. Further cost reduction seems possible but all concepts and their advantages need to be analyzed in detail. For example, Seawind's yaw control concept eliminates the pitch-system which in fact eliminates the whole 2.6 % cost fraction of the two-bladed WTG cost split. The SCD nezzy concept spares the yaw-system which would also lead to direct cost reduction. But the indirect impacts on other cost fractions due to other load cases and stress on the components need to be carefully considered.

Table 4-2 shows the results of a CAPEX comparison between three-bladed and two-bladed WTGs considering the above-mentioned reduction potentials of two-bladed WTGs. The CAPEX Turbine can be reduced by around 190,000 €/MW and the CAPEX BoP decrease by approximately 130,000 €/MW. A reduction in total CAPEX of around 83 Mio€ can be achieved. These figures are not finally conclusive, as they are based on third party information and the reduction potentials are based on estimates. Detailed calculations of cost reduction potentials are warranted to receive fully conclusive data. However, the results show that a CAPEX reduction seems to be possible with offshore two-bladed WTGs.

Table 4-2: CAPEX reduction of a 504 MW OWF with two-bladed compared to three-bladed WTGs, based on CAPEX estimate of Fraunhofer ISE study[12] [Author's illustration]

Description	**a) Three-bladed WTG**	**b) Two-bladed WTG**	**Difference**
OWF total capacity [MW]	504	504	-
Turbine rated power [MW]	7.0	7.0	-
No. of turbines	72	72	-
SUM Turbine [%]	100.0	91.1	-8.9
CAPEX Turbine [%]	44.9	40.9	-4.0
CAPEX BoP [%]	55.1	53.7	-1.4
SUM CAPEX [%]	100.0	94.6	-5.4
SUM CAPEX [€/MW]	3,100,000.0	2,933,836.0	-166,164.0
CAPEX Turbine [€/MW]	1,391,900.0	1,200,448.5	-191,451.5
CAPEX BoP [€/MW]	1,708,100.0	1,576,130.0	-131,970.0
Total CAPEX [€]	**1,562,400,000.0**	**1,478,653,344.0**	**-83,746,656.0**

On the one hand, Chapter 4.2.2 shows that there is currently hardly any further movement in the two-bladed WTG market. But on the other hand, the above analysis shows that a CAPEX reduction potential of roughly 5 to 6 % seems realistic for two-bladed compared to three-bladed WTGs. As described by the OEMs, the WTGs have cost advantages, mainly due to weight savings, simpler logistics and faster installation. So, is the industry either not aware of the cost reduction potential or is it simply not worth changing their product portfolio from the established and proven three-bladed to two-bladed WTGs? This question is part of the conducted expert interviews and is presented in Chapter 5.

[12] Value of the LCoE of renewable energies study (Kost et al. 2018). For future projects with 12 MW turbines a CAPEX Turbine of 1.1 – 1.2 Mio€/MW is assumed.

5 Expert interviews

The following interviews, serve to gather detailed expert information to align the theoretical fundamentals with the practical experience of the participants. A look at the initial research questions shows that different technical and economic experts are necessary. The participants are either related directly to the wind industry and research or the finance and insurance sector. All of them are key decision-makers and have vast experience within their fields of expertise.

Depending on the topic and thus the field of expertise the following main questions are assessed:

Experts from the wind industry and research:

"Do you believe that two-bladed WTGs offer the possibility to reduce offshore OPEX in the future and what are the essential features that bring advantages from an O&M perspective?"

Experts from finance and insurance sector:

"Which key questions and concerns do you have when it comes to financing and/or insurance of offshore projects with innovative technology such as two-bladed WTGs?"

The following Chapters present the participants and their expertise (Chapter 5.1), the interview and question build up (Chapter 5.2), the transcription and evaluation methodology (Chapter 5.3) as well as the key statements (Chapter 5.4).

5.1 Participants and expertise

This thesis is based on the widely held opinion that the status of an expert is attributable to the research interest and the conception of the study. So experts are those who can offer relevant knowledge for the investigation. (Bogner et al. 2014)

A broad selection of participants with different perspectives on the topic is chosen to get an analysis which is as differentiated as possible. External experts from the wind industry and research who participated can be found in Table 5-1 and finance and insurance experts are listed in Table 5-2. EnBW internal experts who are interviewed on different topics such as finance of OWFs, the financial model, O&M expertise or other questions related to internal data are named in the Appendix B (Appendix table 10). Internal experts did not participate directly in the evaluation of this Chapter.

Table 5-1: Experts from the wind industry and research [Author's illustration]

Name	Company	Field	Expertise
Cheng, Po-Wen	University of Stuttgart	Institute for aircraft constr.	Professor for Wind Energy
Craig, Lucy	DNV GL	Certification	Director Technology and Innovation
de Vries, Eize	Wind power monthly	Professional wind journal	Journalist and Wind Energy Expert
Friedrich, Michael	Envision	2-B and 3-B OEM	Chief Wind Turbine Engineer
Henderson, Geoff	Windflow	2-B OEM	CEO and Developer of 2-B WTGs
Jakobsson, Mikael	2-B Energy	2-B OEM	COO and Developer of 2-B WTGs
Jakubowski, Martin	Seawind	2-B OEM	CEO and Developer of 2-B WTGs
Junge, Monika	Wind Kraft Journal	Professional wind journal	Journalist and Wind Energy Expert
Siegfriedsen, Sönke	aerodyn engineering	2-B OEM	CEO and Developer of 2-B WTGs
Valpy, Bruce	BVG Associates	Consulting	CEO and Consultant within Wind Energy
Weinstein, Alla	Trident Winds	Floating Foundations	Founder and CEO (ex Principle Power)

Table 5-2: Experts from the finance and insurance sector [Author's illustration]

Name	Company	Field	Expertise
Bornhorst, Klaus	Commerzbank	Finance	Director Offshore Finance
Gebhardt, Rolf	KfW IPEX	Finance	Technical Consultant for Finance Institute
Schäfer, Peter	KfW IPEX	Finance	Team Head Wind Power
Weidtke, Lutz	Marsh	Insurance	Head of Engineering and Renewables

5.2 Interview and question buildup

An expert interview buildup has to be carefully planned in advance due to the fact that the above-mentioned participants are important decision-makers and highly demanded in their companies, thus their time is valuable. The basic buildup of the interviews can be summarized as follows:

- Requested interview time: *30 - 45 minutes per participant*[13]
- Setting: *in person, via telephone, via e-mail (descending preference)*
- Preparation interviewer: *personal for each participant, short introduction with reference to the participant / company*
- Preparation participants: *no preparation necessary, unless questions / briefings in advance are requested*
- Record keeping: *handwritten by the interviewer on prepared form (no voice recordings)*

Compared to systematic expert interviews, the interview guideline of this thesis is not a dense network but rather an open and loose sketch with a certain thematic structuring (Bogner et al. 2014). The questions are centered on similar aspects but are not necessarily standardized. One aim is to start with a widely open question and let the participants freely reflect their experience and opinion on different topics. Where appropriate, further information is obtained through targeted inquiry and an internal question catalogue is used, which is explained in the following section.

All technical and O&M questions asked or commented on during the implementation of the interviews are summarized in Table 5-3. Table 5-4 shows all financial and insurance related questions. The 'Experts' column shows which question concerns which group of experts.

The following opening question for all participants independently from their field of expertise is asked:

'In your opinion, what are the reasons and obstacles that there are still very few pilot and especially commercial offshore projects with two-bladed WTGs?'

[13] Actual interview time is often between 45 mins and 1 hour (after approval of the interview partners).

Table 5-3: Technical and O&M related questions [Author's illustration]

No.	Question	Experts
1	What key questions or concerns do you experience when it comes to two-bladed WTGs/innovations such as two-bladed WTGs (technical, bankability, insurance)?	OEM, Research, Journalist, Consultant
2	How is the status of your concept/prototype and are you or when are you ready to set up a pilot project? What other projects are planned and what is the outlook for 2025?	OEM
3	How do you assess the current OEM landscape of two-bladed WTGs compared to established three-bladed OEMs? What input would help the OEMs to further develop and speed up the market entry of two-bladed WTGs?	OEM, Research, Journalist, Consultant
4	What is your opinion on the trend towards ever larger turbines? Where do you see the two-bladed WTG rated power of a) prototypes and b) commercial offshore turbines in 5 years?	OEM, Research, Journalist, Consultant
5	From your point of view, is it possible to reduce the (offshore) OPEX by using two-bladed instead of three-bladed WTGs? Which features do you see as particularly a) valuable and b) disadvantageous from an O&M point of view?	OEM, Research, Journalist, Consultant
6	In your opinion, what is or could be the next possible game changer in the offshore wind industry?	OEM, Research, Journalists, Consultant
7	Do you see a combination of two-bladed WTGs and floating foundations as a new business case or opportunity for OEMs of two-bladed WTGs?	OEM, Research, Journalist, Consultant
8	What do you think is a realistic time horizon for the first commercial offshore wind farm with two-bladed WTGs?	OEM, Research, Journalist, Consultant

Table 5-4: Financial and insurance related questions [Author's illustration]

No.	Question	Experts
1	What would be your key questions about an offshore project with two-bladed WTGs from a financial/insurance point of view? *Scenario 1: EnBW plans to set up 80 x 6 MW two-bladed WTGs in the North Sea* *Scenario 2: EnBW plans to install 80 x 6 MW three-bladed WTGs (known OEM) + 1 - 3 x 6 MW two-bladed WTG*	Bank, Insurance
2	Which parameters are decisive for the risk assessment of new technologies when it comes to financing/insurance?	Bank, Insurance
3	What influence does the use of innovative technology or the topic 'proven technology' have on the financing/insurance costs of offshore projects?	Bank, Insurance
4	Which OEM KPIs have a positive / negative impact on financing / insurance costs and which are considered as 'show stoppers'?	Bank, Insurance
5	What similarities or synergies do you see between two-bladed WTGs and floating foundations?	Bank, Insurance

5.3 Transcription and evaluation

As already discussed, the conducted expert interviews serve as an instrument of information gathering and the selection of a transcription and evaluation method must be appropriate.

For this thesis, there are two relevant transcription methods, although the term 'transcription' is not completely accurate in this context as the record keeping is done by handwriting instead of voice recording. The two methods are namely selective and paraphrased transcription.

Selective transcription means that the statements of the respondent, classified as relevant, are already interpreted at the time of transcription which therefore bears the risk of losing knowledge. This method demands, that a selection should only be made by persons participating in the expert interview. A paraphrase means that the transcription of the statements is not literal. In this case the statements are merely summarized in the own words of the interviewer. (Bogner et al. 2014)

The interviews of this thesis are made by the main researcher who also took the role of the interviewer. Thus, a selective and paraphrased transcription can be used. A loss of relevant information due to this approach is considered to be comparatively low.

The literature recommends the qualitative content analysis for the evaluation of guided expert interviews with the focus on gathering information (Bogner et al. 2014). Qualitative content analysis procedures essentially consist of attributing the relevant passages of the interview transcript to categories derived from the research interest. Key statements for each category are outlined from a holistic view of the expert knowledge. Problems of understanding the content, context and knowledge gaps are remedied by further questions.

Figure 5-1 shows an example of the evaluation procedure for the category 'Obstacles of 2-B WTGs market entry' with three experts to provide an idea of the structure. The complete answers of all relevant participants on each derived category are compared in a matrix form. In a further step, the key statements of all answers for each category are extracted. The derived categories and the key statements are presented in Chapter 5.4.

Category	Interview: Ex_01	Interview: Ex_02	Interview: Ex_03	Key statements
Obstacles of 2-B WTGs market entry	No trust in new technologies from banks, insurance companies and operators. All want standard 7 MW turbines with full service agreement. Somebody needs to prove the technology under real offshore condition (track record).	Two-bladed WTGs are no proven technology but there is also no trust in new 2-B start-ups. Lack of prototypes and thus lack of track record and operation experience in offshore environment.	No one wants to take the risk of building 2-B WTGs on a large scale. Banks and insurance companies are very risk-averse. Small start-ups cannot prevail against strong and established 3-B OEMs.	• Missing track record • No trust in technology and especially in 2-B OEMs • Risk-averse offshore players

Figure 5-1: Example of the evaluation procedure [Author’s illustration]

5.4 Key statements

The methodology presented in Figure 5-1 is used for the entire transcripted interview material. Derived categories are based on the interview question complexes presented in Chapter 5.2. The categories and the extracted key statements of the expert interviews are listed in Table 5-5. Mind maps including all statements of each category and the number of times they are mentioned can be found in the Appendix A (see Appendix figure 4 - 9) for a better visualization.

Table 5-5: Categories and key statements of the conducted expert interviews [Author's illustration]

Category	Key statements
Missing presence of 2-B WTGs onshore	• visual impact and noise issues • high dynamic loads and complexity • market adjustment and bankruptcy
Missing presence of 2-B WTGs offshore	• high dynamic loads and complexity • missing proof of concept • no need for innovations in the past due to subsidies under the EEG
Obstacles of 2-B WTGs market entry	• missing track record • no trust in technology and especially in 2-B OEMs • risk-averse offshore players
Opportunities for 2-B WTGs market entry	• only real chance if strong 3-B OEM picks up 2-B • if cost reduction potential is proven • further need for cost reductions (auction model)
Favored support to speed up 2-B WTGs market entry	• major industry players as partners (3-B OEMs, operators…) • large project scale proof of concept/cost reduction • capital and offshore contracting/operation know-how
Status of actual projects and planned projects	• some demonstration/prototype projects but no commercial scale planned • further demonstrator projects delayed due to financial issues • up-scaled concepts of 6 MW turbines planned
Rated power of 2-B WTGs in 5 years time	• 12-15 MW (irrespective if 2-B or 3-B) • no trend towards 2-B technology • rather multi-rotor concepts (e.g. 2x 7.5 MW = 15 MW)
Assessment of the trend to ever larger turbines	• trend goes on as long as LCoE reduction is achievable • 6 MW turbines are already no promising business case anymore due to insufficient rated power • physical limits around 15-20 MW

Offshore cost reduction potential of 2-B WTGs	• slight CAPEX potential due to high power-to-weight ratio and logistic/installation advantage • no significant OPEX potential is recognised • main components influencing OPEX are the same for 2-B and 3-B
Valuable 2-B features from O&M perspective	• 2-B WTGs have no substantial O&M advantages • possibly suitable for typhoon areas • helicopter landing platform maybe an advantage due to higher accessibility
Disadvantageous 2-B features from O&M perspective	• high tip speed and leading edge blade erosion • lower power performance and energy yield • complexity of load reduction systems
Assessment of the current 2-B OEM landscape	• no real 2-B OEM landscape visible at the moment • actual 6 MW turbines are too small, thus there is a lack of business case • strong 3-B OEMs not interested and 2-B OEMs too small for offshore business
Differences between newcomers and established OEMs	• newcomers have not enough financial resources for offshore business • newcomers have insufficient or no track record and experience • more trust in established OEMs due to experience, financial background, track record
Key questions or concerns towards 2-B WTGs and OEMs	• concerns regarding financial outfit of new OEMs rather than technology • but also proven technology is demanded • unforeseen costs and risks of innovative technology (track record needed)
What can be a realistic OWF scenario including 2-B WTGs	• no chance for an OWF with only 2-B WTGs at the moment • 2-3x 2-B WTGs as demonstrator in a commercial OWF with 3-B WTGs is possible • demonstrator possible as long as no negative influence on repayment of debts and cash flow
Key parameters for risk assessment of innovative technologies	• proven technology with sufficient track record (around 100 turbine years) • financial situation, possible guarantees, quality assurance and supply chain of OEM • cash flow plan of the project for repayment of depts

Impact of innovative technology on finance/insurance costs	• impact is negligible small and it is more of a binary yes/no decision • strong OEM with experience needed for trust • financing costs are only marginally influenced but an extended liability is needed
Company KPI's that influence finance/insurance decision and/or costs	• financial background, strong balance sheet and experience of OEM • guarantees are essential as only 30-35 % of all damage cases are insured • general contractor with long term full service agreement favorable
Similarities or synergies between floating and 2-B WTGs	• generally same risk concerns for 2-B WTGs and floating • combination of 2-B WTGs and floating maybe advantageous due to lower turbine weight • use of two unproven technologies at the same time bears higher risks
Others	• offshore hydrogen production with excess OWF electricity can solve fluctuation issue • game changer maybe airborne wind as a disruptive technology • competitiveness of new technologies is always a matter of development time

Based on the results of the expert interviews, O&M fields of interest are derived and further assessed in Chapter 6. The expert interviews initially allow the broader conclusion that despite any technical and economic potential there are various other factors that influence the success of an innovative technology. These factors are for example, the market and industry situation, financing and insurance issues, political frameworks, the public perception as well as the point in time at which a technology is established. Related to the example of two-bladed WTGs more specific conclusions are drawn in Chapter 7.

6 Assessment of impacts on the O&M phase

The expert interviews conducted as part of this thesis show that no large impact of two-bladed compared to three-bladed WTGs on the O&M phase is expected and it is almost no corresponding research work available at the moment. This is to some extent due to the fact that there is insufficient data on the operational performance of two-bladed WTGs available as only a few machines are running and they are mainly operated onshore with wind conditions similar to offshore. The minor possible advantages and drawbacks mentioned in the expert interviews will be discussed in this chapter. Chapter 6.1 critically assesses the theoretical economic impacts on the O&M phase and Chapter 6.2 evaluates health and safety issues. Further conclusions are derived in Chapter 7.

6.1 Technical and economic impacts

First of all, the O&M cost reduction potential is evaluated. A survey including 163 interviews with leading international experts on costs of wind energy has been conducted by Lawrence Berkeley Lab in cooperation with IEA Wind in 2016. The main objective was to gain insights into the extent of future cost reductions, their causes and the conditions necessary for their implementation. Onshore and offshore wind energy is part of the survey. The latter is further subdivided into turbines with a bottom fixed support structure and floating foundations. In all three fields of application, a total cost reduction of 24 to 30 % in 2030 and 35 to 41 % in 2050 is assumed in relation to the base values of 2014. The absolute base values for the reference year 2014 are 79 €/MWh for onshore turbines and 169 €/MWh for classic offshore turbines. It should be noted that this is only the mean value of the expert's responses and has no relation to a specific region of the world. (Fraunhofer 2017)

The causes of the cost reductions are manifold but the five most important drivers are: Investment costs (CAPEX), O&M costs (OPEX), the capacity factor, the life-time and financing costs (WACC) and describe the relative development between 2014 and 2030. Figure 6-1 shows the relative influence of the drivers on the total cost reduction of the median scenario. For classic bottom fixed offshore, improvements in investment and financing costs in particular have the highest contribution to cost reduction. A life-time extension and an increased capacity factor also have a significant impact on the OWF cost reduction. The OPEX are also mentioned as a driver on the total cost reduction but have the least impact of 6 %. (Fraunhofer 2017)

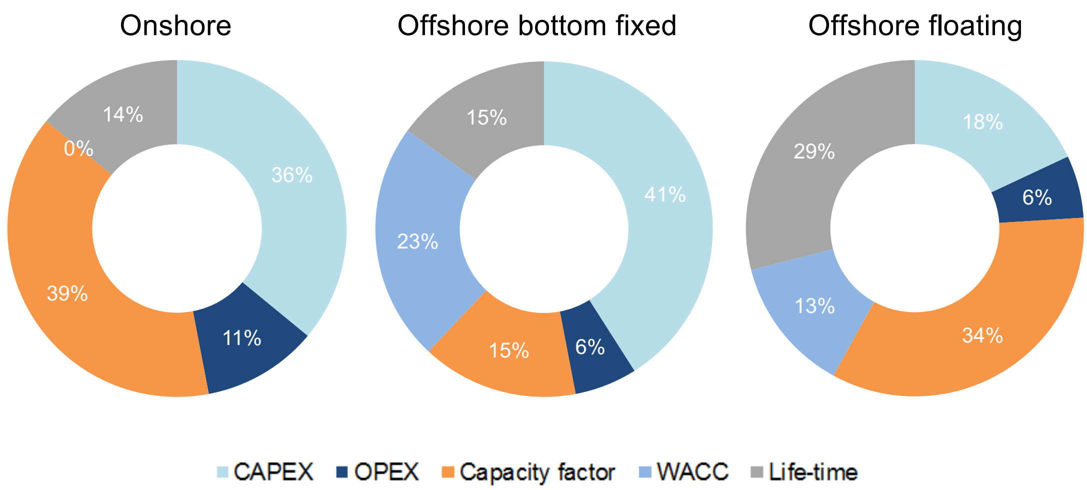


Figure 6-1: Relative influence of the drivers on the total cost reduction in 2030 (median scenario) [Author's illustration based on (Fraunhofer 2017)]

One of the initial inquiries of this thesis is the possibility to significantly reduce OPEX by utilizing two-bladed WTGs. The conducted expert interviews and the key statements show that the OPEX reduction potential is seen as rather small or non-existent. Most experts including two-bladed OEMs see the advantages of the concepts primarily on the CAPEX side, which has already been assumed based on Chapter 4.3.2 of this thesis. Possible economic advantages from an O&M point of view are for example the feasibility of a helicopter landing platform to set up solely helicopter based O&M strategies or the omission of the pitch or yaw-system in some concepts. However, it is difficult to come to a general conclusion about O&M advantages of a two-bladed WTG because the individual concepts differ greatly and there is no consistent design at the moment. Nevertheless, some aspects, which have been noticed in the context of the expert interviews and the analysis of this thesis, are to be considered in the following sections.

The typical compound of the O&M cost block is shown in Figure 6-2 in order to become aware of the influence of each section on cost reduction. Labour and material costs have a rather small influence on the total O&M costs, but the necessary equipment has a huge impact of 79 %. Almost 50 % are due to any unplanned corrective maintenance measures. A mother vessel (offshore based service concept) causes 32 % of the total equipment costs. The rest is divided between O&M port (6 %), maintenance vessels (9 %) and condition based (4 %) costs. (ECN 2010) If it is possible to reduce the failure rates of important components or to eliminate certain components with high failure rates it is possible to have a significant impact on unplanned corrective measures and thus on the total O&M costs. The impact of the two-bladed WTG concepts on the reliability and failure rates is expanded upon in

Chapter 6.1.1. The repair cases (Chapter 6.1.2) are another factor influencing the equipment cost block as a use of expensive lifting equipment for unplanned corrective maintenance is necessary in case of a big component change due to its high weight. The impact on time for unplanned corrective maintenance and thus also availability of the WTGs due to new possible helicopter based service concepts is discussed with a case study in Chapter 6.1.3.

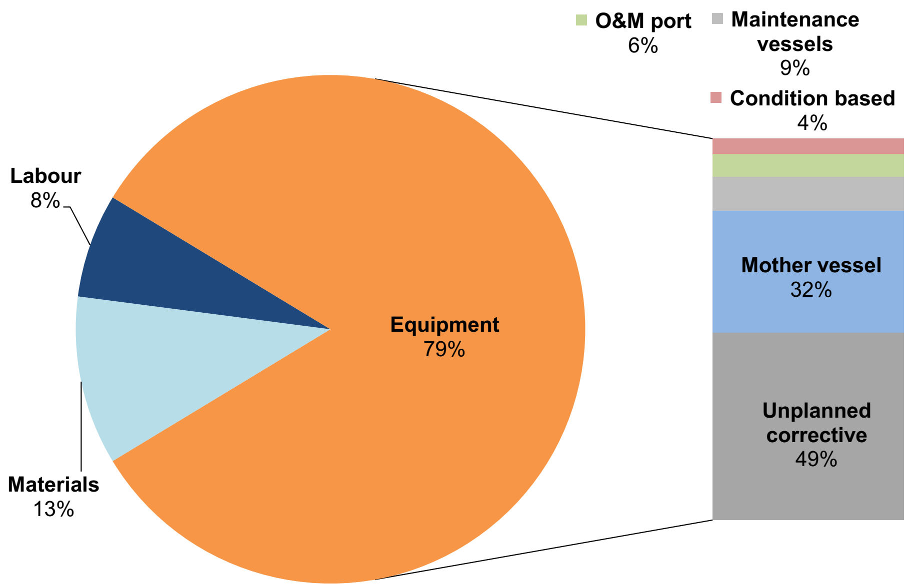


Figure 6-2: Total O&M cost split [Author's illustration based on (ECN 2010)]

Typhoon proof operation of two-bladed WTGs is analyzed in Chapter 6.1.4. The theoretical power performance and energy yield of a two-bladed and a three-bladed WTG is compared in Chapter 6.1.5 as this directly influences the LCoE. Financing costs have a 16 – 20 % share of the total cost split of an OWF and thus a negative or positive influence on this cost share has a huge impact on the LCoE as well (Fraunhofer 2017). This impact is discussed in Chapter 6.1.6 together with the insurance costs.

6.1.1 Reliability and failure rates

The impact of two-bladed WTGs on turbine reliability and failure rates of sub-components is assessed in this Chapter 6.1.1. In a first step, the critical components of a WTG are identified. Within any complex system, certain components will stand out as high-risk items, either because they are weak points that are demonstrated to be failure prone, are absolutely essential to turbine operation, or are expensive and time-consuming to diagnose and repair. Identifying the critical components allows O&M to direct their monitoring, training, inventory, and logistics efforts on areas that provide the most benefit. Although to some extent the critical components depend on the manufacturer, configuration, and operating environment, certain candidates for attention are well known throughout the industry. Minor components, though perhaps less costly to replace or repair, may be elevated to a critical status if their frequency of failure is high. (Walford 2006)

Looking at the average annual failure rate of various subcomponents, it can be recognized that besides the electronic and the control system including sensors, control and inverter cabinet also the yaw-system, the gearbox and the blades have high failure rates. Typically, it is the gearbox, bearings and hydraulics that result in the highest turbine downtime. This is because the failure rates for the latter components are not the highest, but a failure leads to longer outages due to extensive maintenance measures (McKenna 2014). Tavner (2011) states that this results in 75 % of failures cause only 5 % downtime but 25 % failures of maintenance intensive components cause 95 % downtime of a turbine.

A 2/3 failure rate for blades and pitch-system is assumed since the two-bladed WTG has 2/3 of the components. Only direct influences on the failure rates are considered because a statement of indirect influences on other components (e.g. different load cases) cannot be considered quantitatively in the context of this thesis. That means, according to the above assumption on failure rates and downtimes, the largest contributors of downtime are not affected directly by two-bladed WTGs. However, this can be argued from a qualitative point of view, since mainly the same components with the same failure rates and downtimes as for three-bladed WTGs are used, which is confirmed by the interviews with several two-bladed WTG OEMs and other experts.

It can be assumed at the present time and with the current component materials that the 2/3 blades advantage of a two-bladed WTG is to some extent equalized by stronger blade erosion due to the higher tip speeds and thus increased maintenance measures. Additionally, failure rates for a teetering hub or an increased failure rate for an IPC system may have to be taken into account depending on the two-bladed WTG concept. It is also possible that heavily loaded components such as the drive train, gearbox or the structure will be relieved by less torque and therefore show less wear and lower failure rates. However, these components of a two-bladed WTG are designed according to these specific torque and load figures. The components are therefore unlikely to have increased design reliability compared to three-bladed WTG components, which would justify the assumption of less wear and lower failure rates.

6.1.2 Repair cases and major component exchange

As described, there are no significant differences in failure rates between three-bladed and two-bladed WTGs except for the blades and pitch-system. Even without significant failure rate benefits, the two-bladed WTG may have advantages in terms of logistics and large component replacement in the O&M phase due to lower weight of certain components. A consequence of lower weights can be the use of smaller transport and lifting equipment which can result in reduced equipment costs. Table 6-1 compares the weights of various components of two-bladed and three-bladed WTGs. Data input is based on a study by Goetz (2012). The comparison is based on a 5 MW three-bladed reference WTG with a rotor diameter of 126 m and a two-bladed WTG with the same parameters. The weights were determined as part of the investment cost calculation of a two-bladed WTG for a financial model with a validity of up to 20 MW via the cost per mass approach. The weight calculation of the two-bladed WTG components is either dependent on the weight of other parts (e.g. pitch-system depends on blade bearing weight), the WTGs rated power (e.g. generator), the rotor diameter (e.g. yaw-system) or the shaft torque (e.g. gearbox).

Table 6-1: Weights of various components of a two-bladed compared to a three-bladed WTG (5 MW, 126 m) [Author's illustration based on (Goetz 2012)]

Component	**a) Three-bladed WTG [kg]**	**b) Two-bladed WTG [kg]**	**Difference [%]**
Blades	52,200	34,800	-33.3
Hub	24,090	24,090	0.0
Pitch-system	10,185	7,192	-29.4
Generator	16,690	16,690	0.0
Gearbox	34,451	28,468	-17.4
Yaw-system	13,739	13,739	0.0
Shaft and bearings	21,927	21,927	0.0

The study identifies a weight reduction of three main components. A theoretical reduction of 33 % of the total blade weight as only two instead of three blades are considered Goetz (2012). Thus, the single blade weight is assumed to be constant. The tip speed of a two-bladed WTG is normally higher and the blade geometry is kept constant. That means, the blades are exposed to a higher number of load cycles throughout their lifetime, so they have to be designed stiffer. It is therefore likely that the single blade weight of a two-bladed WTG is higher than that of a three-bladed

WTG and a 25 % overall blade weight reduction in accordance with the CAPEX calculations of Chapter 4.3.2 seems more realistic. The overall pitch-system is considered to be around 30 % lighter due to the fact that one pitch drive and accessories can be omitted. As a result of less torque, the gearbox weight is cut by 17 %. All other component weights are considered to be the same for two-bladed compared to three-bladed WTGs.

A nacelle crane on top of the WTG usually has a lifting capacity of up to 15 t (Palfinger 2018). Thus, the lifting capacity is insufficient for a gearbox change even in case of the reduced two-bladed WTG component weight. It is already possible to change pitch-system components of three-bladed WTGs with the help of the nacelle crane (except bearing). A jack-up barge or crane vessel is still needed for the change of major components and there is no cost reduction potential assumed at this point.

6.1.3 Service aspects and concepts

A general statement on service advantages of a two-bladed WTG is complicated, because the available concepts differ greatly in some respects and therefore not all advantages or disadvantages apply to all designs. As an example, the 2-B Energy 6.2 WTG is explained in more detail. Deviations from other concepts are also explained at the corresponding points. 2-B Energy sees the great service advantage of its concept in the high accessibility of the WTG with a helicopter via a landing platform on top of the nacelle as well as the good accessibility of individual components in the nacelle itself.

The 2-B Energy concept has two favorable rotor service positions: A vertical and a horizontal one. Both positions offer different advantages. Figure 6-3 shows the nacelle level 1 and level 0 below in a vertical rotor position. The advantage of the vertical rotor position is the convenient and safe walkway access around the hub and pitch-system on level 1. Service and maintenance of the pitch-system is therefore easy for the service technicians. The horizontal rotor position is advantageous for inspection and repair of the rotor blades as both blades can be climbed at the same time. In contrast, with a three-bladed WTG it is only possible to inspect one blade at a time due to the rotor star arrangement. Time and thus labour costs can possibly be saved, which needs further research and an O&M modeling to quantify the impacts.

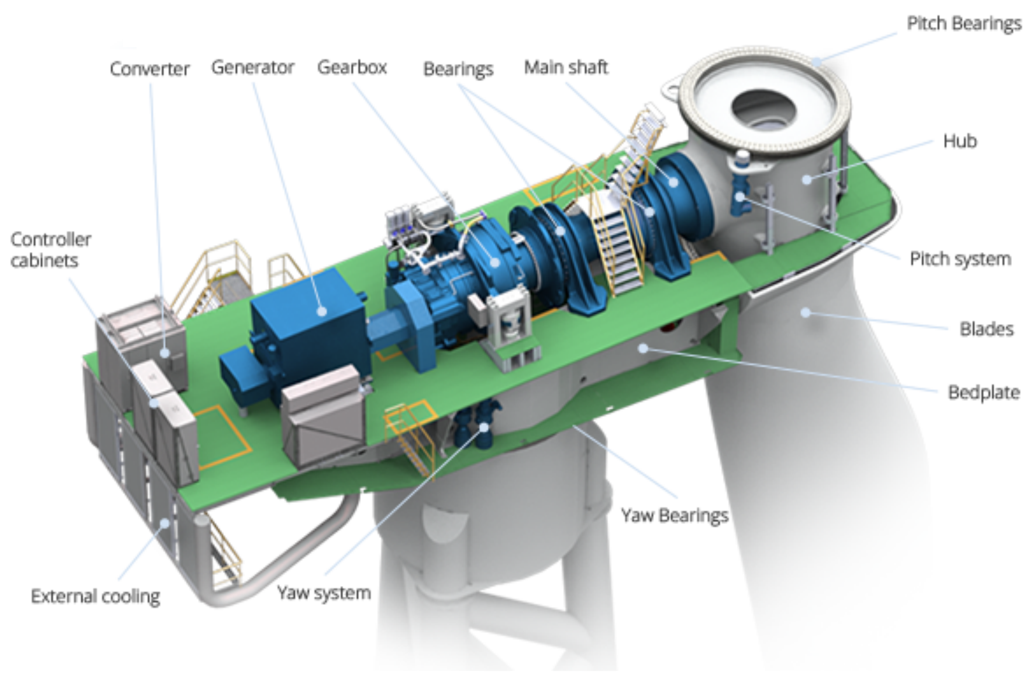


Figure 6-3: Nacelle level 1 and 0 of the 2-B Energy 6.2 WTG in vertical rotor position (2-B Energy 2018)

The Seawind turbine does not provide the same easy access to the hub. Access is granted via one of two manholes on the hub (see Figure 6-4).

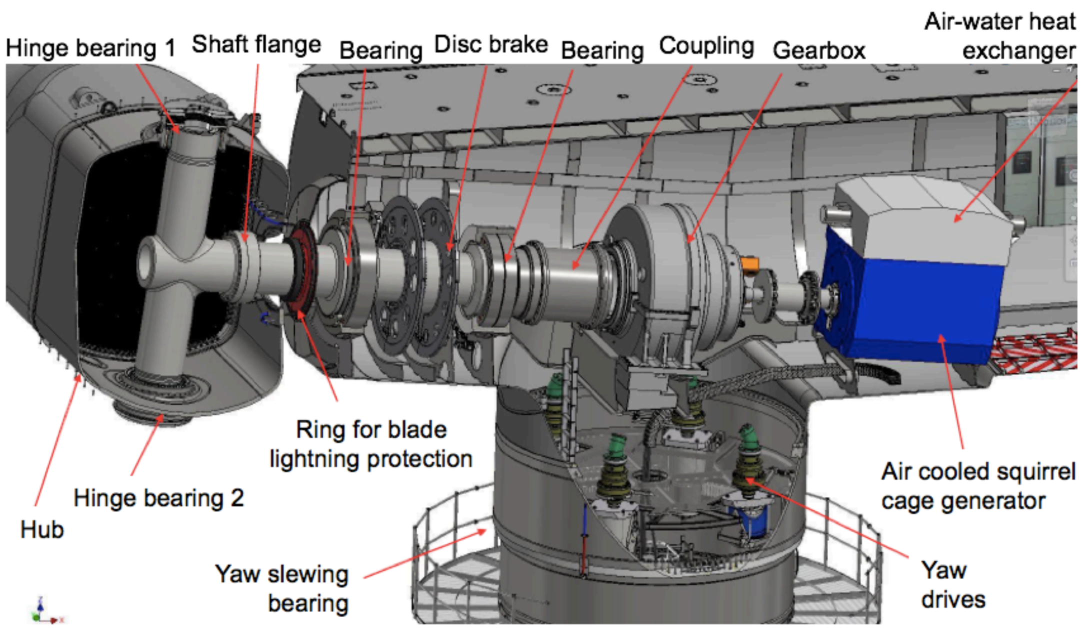


Figure 6-4: Nacelle of the Seawind 6 in horizontal rotor position (Seawind 2017)

However, the WTG does not have a pitch-system, so the easy walkway access around the hub is less of an advantage for this concept. The aerodyn SCD WTGs also offer less convenient access due to their compact design. Envision's partial-pitch concept is also less comfortable to service as the pitch-system is located between the inner and the outer blade part. The blade diameter is 2.3 m at the pitch bearings and a technician can walk the 20 m inside the inner blade part to reach it. The horizontal rotor position of a two-bladed WTG additionally offers the possibility to install a helicopter landing platform on top of the nacelle (see Figure 6-5). Due to the third rotor blade, three-bladed WTGs only have a hoisting platform on which components, equipment and technicians can be hoisted. The possibility to operate a helicopter instead of a CTV and to land it instead of hoisting offers the following advantages (2-B Energy 2018):

- better accessibility of the WTGs during bad weather conditions, thus less downtime due to unscheduled maintenance
- faster transport, thus less travel time and more time for repairs, which saves labour costs
- half of the operational time compared to hoisting, thus half the costs
- safer for technicians than hoisting
- no expensive nacelle crane is necessary, big helicopters can bring around 5 t of components/equipment to the remotely controlled hatch on top of the nacelle (see Figure 6-5, right)

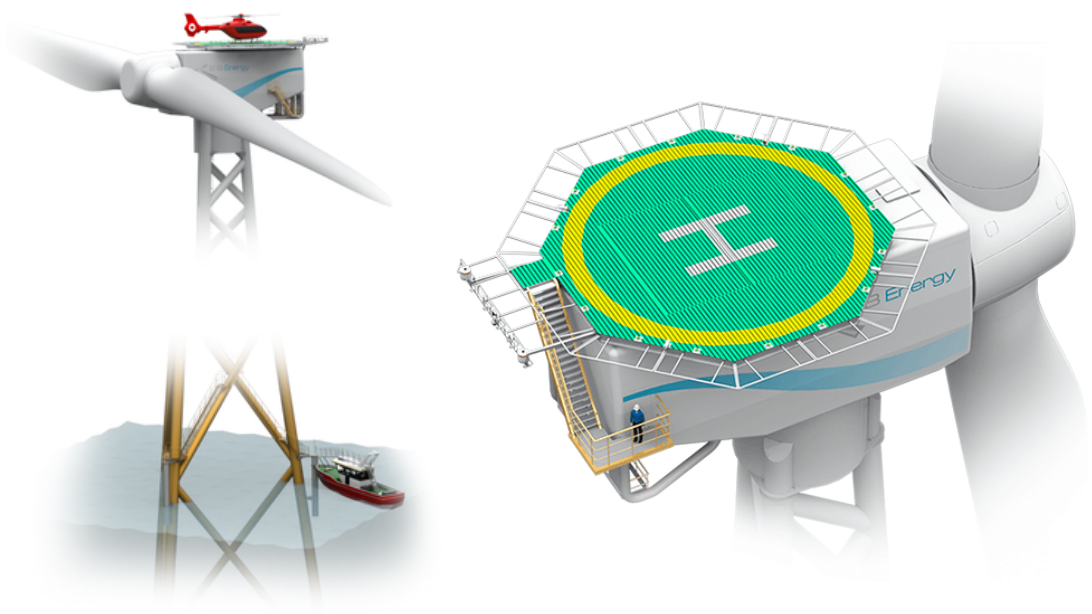


Figure 6-5: Helicopter on a two-bladed WTG's landing platform (left) and the landing platform plus hatch in detail (right) (2-B Energy 2018)

In case of unscheduled maintenance, the accessibility with a helicopter is higher compared to a CTV or any other vessel. This relates mainly to the maximum wind speed and the significant wave height at which both are allowed to operate for safety reasons. A helicopter can be operated up to wind speeds of 25 m/s for personnel and 20 m/s for material transported in the cargo hook, whereas a CTV is mainly limited by the significant wave height of maximum 1.5 m (see Table 6-2).

Table 6-2: Significant wave height H_s and maximum wind speed v_{max} of different logistic equipment [Author's illustration based on (Warner 2018)]

Equipment	H_s [m]	v_{max} [m/s]
Crew transfer vessel (CTV)	1.5	12.0
Service operation vessel (SOV)	2.5	12.0
Helicopter	5.0	25.0[14]
Crane vessel (> 500 t)	1.5	10.0
Crane vessel (> 500 t, hook height > 180 m)	1.5	10.0
Jack-up barge (100 t)	2.5	10.0
Tower crane (< 10-15 t)	2.0	15.0
Nacelle crane (< 10-15 t)	2.0	6.0

A case study of Airbus on unscheduled maintenance roughly evaluates the cost difference between a helicopter hoist and a CTV mission. The following scenario and figures are adopted for the case study (Airbus 2018).

<u>Hoist mission for an OWF ~80 km offshore</u>

- 4 troubleshooters with 100€/h
- 2 broken WTGs with 5 MW each and 950€/h loss

<u>Crew transfer vessel (CTV) data</u>

- Approx. 7 h transfer time
- ~2 t fuel burned (~2 t CO_2)
- Total cost of the mission ~5,000 € charter & fuel
~6,300 € loss of WTG revenue
~2,800 € technician salary loss (transfer time)

<u>Helicopter (Airbus H145) data</u>

- Approx. 1 h transfer time
- ~400 kg fuel burned (~1 t CO_2)
- Total cost of the mission ~5,500 € charter & fuel
~1,000 € loss of WTG revenue
~400 € technician salary loss (transfer time)

[14] 25.0 m/s for transportation of personnel and 20.0 m/s for materials in cargo hook.

The overall savings per mission are ~7,000 € and ~50 Mio€ over a life-time of 25 years if 280 days/year described mission is used instead of a maritime concept. This figures need to be critically reviewed and calculated independently as a helicopter manufacturer is certainly not neutral. The figures are related to a hoist mission which is also possible with three-bladed WTGs. It is assumed by 2-B Energy that the costs for a helicopter landing mission is half of the hoisting costs as the helicopter is only half of the time in operation. Airbus confirmed that using a landing instead of a hoisting platform significantly cuts costs of a helicopter mission (Airbus 2018).

The magnitude of 50 Mio€ shows that there is a general cost reduction potential when using helicopters instead of CTVs. However, the comparison between helicopters and CTVs is not necessarily a realistic scenario at a distance of 80 km offshore, because in this case it is more likely that a mother vessel or SOV is operated in the OWF from which the maintenance missions start with CTVs. Thus, the transport time is less of a cost factor on labour and downtime. The overall scenario and the cost difference need to be modelled and recalculated.

6.1.4 Typhoon proof operation

The name of a tropical storm depends on the region in which it originates (see Figure 6-6).

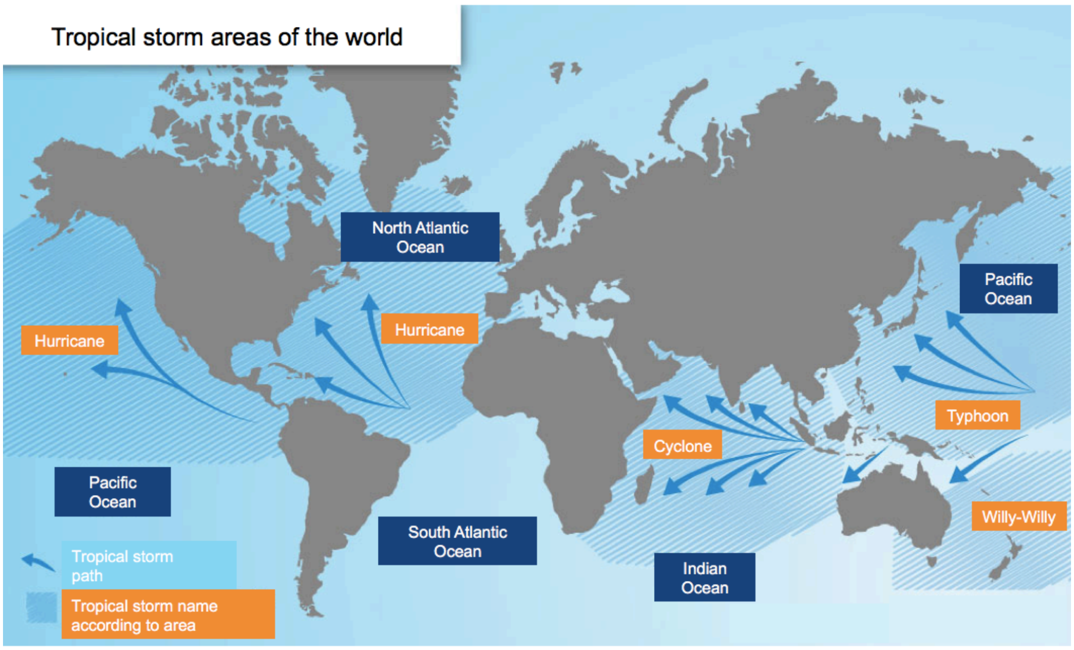


Figure 6-6: Tropical storm areas of the world [Author's illustration based on (AktionDeutschlandHilft 2018)]

Wind speed is the decisive factor in the categorization of a storm. If the wind speed exceeds 118 km/h, it is called a tropical storm. The latter is divided into five categories and is based on the Saffir-Simpson-Scale (see Table 6-3). As a simplification, tropical storms are referred to as typhoons in this thesis. Typhoons are tropical storms that regularly occur in various strengths for example in the Asian/Southeast Asian area of the Pacific Ocean, such as China, Taiwan, Japan or the Philippines.

Category 5 typhoons or super typhoons with a wind speed of ≥ 70 m/s are considered the strongest storms in the Asian/Southeast Asian Pacific region. They are formed by a strong tropical depression. All tropical storms generally occur only at latitudes 5° and 20° north and south of the equator. Appendix table 11 shows a variety of the strongest recorded typhoons over the last decades including its name, main location, year and category as well as the maximum measured wind speed (duration 1 min and 10 min). The table documents that typhoons of the highest category 4 and 5 occur at regular intervals. (Schwanke 2009)

Table 6-3: Saffir-Simpson-Hurricane-Wind-Scale [Author's illustration based on (AktionDeutschlandHilft 2018)]

Category	**Wind speeds**			
	m/s	**knots (kn)**	**mph**	**km/h**
Five	≥ 70	≥ 137	≥ 157	≥ 252
Four	58 - 70	113 - 136	130 - 156	209 - 251
Three	50 - 58	96 - 112	111 - 129	178 - 208
Two	43 - 49	83 - 95	96 - 110	154 - 177
One	33 - 42	64 - 82	74 - 95	119 - 153

Abnormal wind conditions are the key factor for different WTG failures during typhoon activities. Violent wind speeds, drastic turbulence variations and sudden changes of wind direction bring WTGs in critical situations. During a typhoon passage, the wind direction changes by 180° and no grid access is available. Failure modes can include loss of blades and buckling of the supporting tower. (Rose 2012) Some OEMs of two-bladed WTGs promote that their concepts are 'typhoon proof' for various reasons, which are explained hereafter.

All two-bladed WTG concepts of aerodyn have a survival wind speed of 70 m/s, which is sufficient to withstand category 4 typhoons. The explanation for the high survival wind speed is mainly the downwind rotor design. This reduces loads due to the wind vane principle and is necessary to enable a WTG to be used in areas affected by typhoons. The rotor is in a passive yaw mode that is able to follow the wind direction for optimal inflow conditions. Decreased thrust load in survival conditions leads to less material usage and less tower top weight, enabling an additional cost-saving potential. (aerodyn 2018)

Seawind promises a survival wind speed of up to 90 m/s based on a different approach, which enables the WTG to withstand even category 5 typhoons according to their simulation. In typhoons, the Seawind two-bladed WTG points the blade tips into the wind in a 'flexible configuration' (see Figure 6-7). A three-bladed WTG is normally parked with blades pitched at 90°, the tip chord parallel to the rotor shaft and its leading edge into the wind. The alignment of the Seawind 6 blade tips is based on the data of the LIDAR measuring device of the turbine, which detects typhoons or strong gusts ahead. According to Seawind, the 'flexible rotor' behaves like a palm tree and is compliant with the forces of nature instead of facing them, which reduces the extreme loads on blades and drive train. Seawind claims, that a three-bladed configuration cannot eliminate the risk of major damage or total loss. (Seawind 2017)

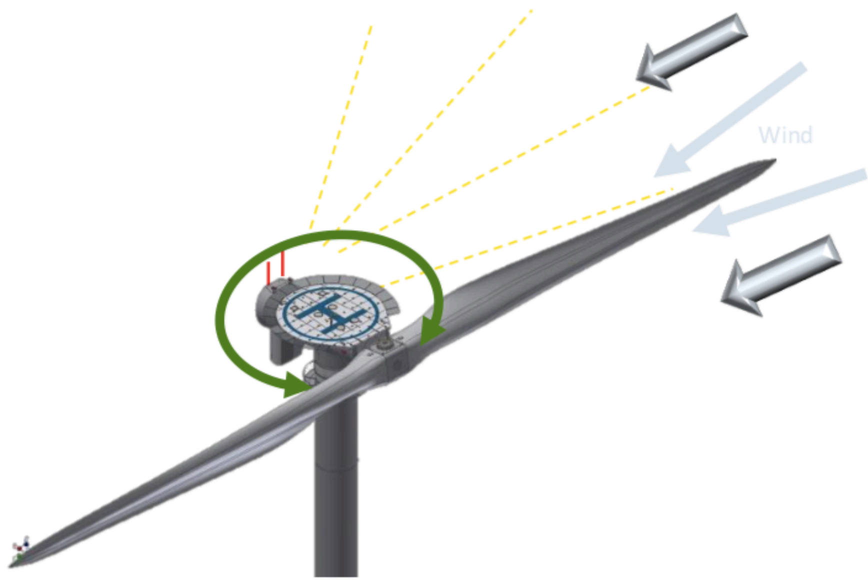


Figure 6-7: Typhoon position of the Seawind 6 (Seawind 2017)

Contrary to this statement by Seawind, MingYang recently installed what the company described as the world's largest typhoon-resistant wind turbine – the MySE5.5-155 – offshore the Fujian Province in China. The 5.5 MW WTG is the first of two to be installed on the 79.4 MW Fujian Xinghua Gulf (Fuqing Xinghua Bay) demo OWF. The semi-direct drive WTG is lightweight and smaller in size compared to other units with similar capacity. The length of the blades is 76.6 m. (Offshorewind.biz 2018b)

6.1.5 Power performance and energy yield

The evaluation of an innovative WTG concept focuses initially on the power performance and the AEP. Whatever the merits of the proposed technology, it cannot underperform very much in AEP compared to state of the art WTGs to stand a good chance of being cost effective. (Jamieson 2011)

The power output P_{el} of a WTG depends on the wind speed *v*, the power coefficient c_p, the air density ρ and the rotor swept area A_R. Compared to a three-bladed WTG with the same dimensions operated at the same site the c_p is the only factor that changes for a two-bladed WTG. The c_p of a two-bladed WTG is around 2 % lower and thus the AEP is 2 % lower as well (see Equation 6-6), as it is directly dependent on the power performance.

$$P_{2-B} = c_{p,2-B} \cdot \frac{\rho}{2} \cdot A_R \cdot v^3 \tag{6-1}$$

$$P_{3-B} = c_{p,3-B} \cdot \frac{\rho}{2} \cdot A_R \cdot v^3 \tag{6-2}$$

$$\frac{P_{2-B}}{P_{3-B}} = \frac{c_{p,2-B} \cdot \cancel{\frac{\rho}{2}} \cdot \cancel{A_R} \cdot \cancel{v^3}}{c_{p,3-B} \cdot \cancel{\frac{\rho}{2}} \cdot \cancel{A_R} \cdot \cancel{v^3}} = \frac{c_{p,2-B}}{c_{p,3-B}} = \frac{0.49}{0.50} \tag{6-3}$$

$$E_{2-B} = \sum_{i=1}^{n} h_i \cdot P_{2-B} \cdot t \tag{6-4}$$

$$E_{3-B} = \sum_{i=1}^{n} h_i \cdot P_{3-B} \cdot t \tag{6-5}$$

$$\frac{E_{2-B}}{E_{3-B}} = \frac{\sum_{i=1}^{n} \cancel{h_i} \cdot P_{2-B} \cdot \cancel{t}}{\sum_{i=1}^{n} \cancel{h_i} \cdot P_{3-B} \cdot \cancel{t}} = \frac{P_{2-B}}{P_{3-B}} = \frac{0.49}{0.50} = 0.98 \tag{6-6}$$

Knock-down factors such as the availability, the OWF efficiency and electrical losses have an influence on the AEP as well. Availability, OWF efficiency and electrical losses can theoretically be considered on the same level for two-bladed and three-bladed WTGs, as they are not dependent on the rotor type. The availability is mainly dependent on the service concept and the operator's experience. An influence of differences in failure rates on the availability is neglectable small (see Chapter 6.1.1). The OWF efficiency depends on the park layout and other factors that can be considered independent of the WTG concept. Wake effects of the WTGs are possilby different to some extent and need further investigation for a clear statement. Electrical losses within the OWF are also independent of the WTG concept.

A lower AEP of 2 % for one WTG seems to be rather small but for a big OWF with 80 WTGs or more it can’t be neglected. Additionally, it need to be considered that a lower AEP of 2 % directly influences the LCoE. For example, if a life-time cost fraction of around 0.1 is assumed for the rotor blades, that means a c_p gain that directly affects the energy output may have up to 10 times the value of a rotor blade cost saving. Conversely it indicates that using blades that sacrifice more than 10 % of annual energy, even if they cost nothing, will increase and not reduce the LCoE. (Jamieson 2011) Thus, increasing or reducing the AEP is always a powerful way to influence the LCoE (Kost et al. 2018).

6.1.6 Financing and insurance costs

New technologies must meet various requirements in order to be insurable. Sufficient insurance is necessary for financing of the project. Insurance companies regard a technology with 6000 - 8000 hours of uninterrupted operation and corresponding certification as generally insurable. Banks have significantly higher requirements and demand about 100 turbine years of operation to classify a technology as proven. The main concerns of both parties are unknown and unforeseeable risks introduced by a new technology as well as by an unexperienced and small OEM behind the technology.

Known risks can be calculated and quantified but lead to higher costs. Thus, reducing risk reduces finance (or weighted average cost of capital, WACC) and insurance costs (Kost et al. 2018). As risk evaluations affect the WACC they have a strong impact on the LCoE. Offshore wind power is a capital-intensive technology. Therefore, changes in the rate of return have an immediate effect on the LCoE. If the WACC increases by 1 %, LCoE will go up by about 6 %. (Prognos AG 2013)

The possible effect of two-bladed WTGs as an unproven technology on financing can be summed up as follows. Firstly, the portion of equity that debt suppliers demand increases from 30 % to around 40 % or more. Simultaneously, this will decrease the portion of debt from 70 % to 60 % or more and result in a corresponding leverage effect. As debt usually carries lower return requirements than equity, a higher equity portion results in an increased WACC. Secondly, market margins for debt financing increase due to the less favorable risk evaluation of two-bladed WTGs and OEMs.

Thirdly, higher project-specific risks result in increased risk premiums regarding equity financing. But generally, it is more of a binary yes or no decision if a project is financed.

The impact on the insurance of the offshore wind project are manifold as well. Exclusions on the WTG insurance increase to complete design exclusion for the WTG (LEG1[15] exclusion). That means, insurers don't pay for any property damage resulting from a design defect, including any resulting loss of earnings (Böttcher 2013). This is the most restrictive form of design exclusion and is used in cases where the technology is considered to be not or insufficiently proven. In addition, the deductible of the project company increases. This exclusion increases the risks for the banks return on debt. Only 30 - 35 % of cases are insured at all and the first 30 days loss of earnings are at the expense of the project anyway. Thus, a strong OEM who can offer sufficient guarantees is demanded by the banks and may be even more important than the insurance as the claims against third parties have priority over the insurance cover. A strong full-service contract with a long duration and a good service concept that guarantees remedy of defects within 30 days, can reduce insurance costs and financing risks. The two-bladed WTG OEMs are not able to offer such guarantees and full-service contracts at the moment.

6.2 Health and safety

The health and safety (HSE) of staff working on both onshore and offshore operations is important to the offshore wind industry. Any innovative technology needs to at least preserve existing levels of HSE. It is difficult to quantify HSE impacts but in some cases, preserving similar levels of HSE precluded some innovations in the past. Many of the innovations considered to reduce the LCoE over time have an intrinsic influence on HSE performance. These include (InnoEnergy 2017):

- The increased rated capacity of WTGs, hence fewer WTGs to transfer to per GW installed. All other things being equal, reducing the number of transfers reduces the risk of incidents during transfer.
- WTG design with increased onshore assembly. All other things being equal, reducing the amount of offshore activity decreases the risk of incidents
- The increased reliability of WTGs and hence fewer transfers to WTGs and less time working in the offshore environment.

[15] LEG 1 means complete design exclusion. Insurers will not pay for any property damage resulting from a design defect, including any resulting loss of earnings. This is the most restrictive form of design exclusion and is used in cases where the technology is considered to be not proven. (Böttcher 2013)

- Condition monitoring and remote diagnostics, which enable a more effective and proactive service and hence result in fewer complex maintenance measures.
- The introduction of systems that allow for easier access to WTGs, for example walk-to-work access systems and crane-less transfer systems.

Two-bladed WTGs have the following impact on the above-mentioned aspects. The rated capacity is considered independent of the WTG’s rotor design. As discussed earlier, a two-bladed WTG offers the possibility that the nacelle and rotor can be pre-assembled and tested onshore without compromising the transport capacity due to its beam-like structure. This reduces the offshore activities and the risk of incidents decreases. The reliability is not significantly influenced by the use of a two-bladed WTG and condition monitoring or remote diagnostics can be used likewise for three-bladed and two-bladed WTGs. Easier access is an essential HSE issue, which can be positively influenced by two-bladed WTGs due to the helicopter landing platform. The possibility to land a helicopter mitigates the risks implied with hoisting or boat landing. Other HSE risk reduction potential or differences compared to three-bladed WTGs cannot be identified.

7 Conclusions and outlook

The evaluation of the background and current situation of two-bladed WTGs as well as the analysis of today's concepts in Chapter 4 lead to the following conclusions. Visual and noise issues of onshore two-bladed WTGs can mostly be ignored for offshore operation. Dynamic challenges can be mitigated by either a teetering hub or an individual pitch control and some concepts use no special load reduction to decrease turbine complexity. There is no consensus as to which solution is the most effective one. If the statements of the OEMs are found to be accurate, then various load cases can even be reduced compared to three-bladed WTGs. Especially load reduction in extreme wind or typhoon situations due to the horizontal rotor position are of interest for areas such as China, Taiwan or Japan. The trend of +6 MW offshore two-bladed WTGs is towards a downwind rotor design which is also beneficial in storm or typhoon situations because of the free yaw possibility. Almost all concepts use an active yaw-system for normal operation as well as a pitch-system for power control. Despite these trends, concepts with less common designs such as yaw control instead of pitch control remain interesting but need further real-life proof of concept in form of a demonstrator or prototype.

On the one hand, most of the concepts try to reduce complexity and/or weight of the turbine in some way to reduce the costs. On the other hand, the price of less complexity can be that primary safety of the rotor is not addressed (Jamieson 2011). However, the concepts also raise new questions in addition to presenting solutions. One major concern is the appreciably higher tip speed of the two-bladed WTG concepts for optimal aerodynamic condition. Higher tip speeds between 100 and 130 m/s raise the question whether such systems can actually be operated economically due to increased wear and tear of the blades. OEMs need to present real solutions in order to alleviate the concerns and more research on this topic is necessary.

The trend of ever larger WTGs and the use of floating foundations in the offshore wind sector can be recognized for the two-bladed WTG concepts as well. Most OEMs are working on ideas or concepts of 8 to 15 MW WTGs in combination with a floating foundation to be able to serve the increasing demand of the industry for such technologies in the future. A big issue for the two-bladed OEMs is certainly the fact that almost all +6 MW WTGs have not been tested to a relevant extent and that not enough offshore track record is available. Some have not even tested their concepts in form of a demonstrator or prototype. Time is not on the side of the two-bladed OEMs as the big three-bladed OEMs already released market ready 8 to 9 MW WTGs and will further up-scale these WTGs in the near future.

The market overview shows that there are currently five OEMs with two-bladed WTG concepts of 3 to 6 MW but some seem to have dropped the idea of a two-bladed WTG already for different reasons. Mingyang who licensed aerodyn's SCD basic and advanced turbines change back to three-bladed WTGs after building various on- and some offshore two-bladed WTGs. The company aerodyn currently focuses on the Japanese market with its floating concepts SCD nezzy and nezzy[2] instead of the Chinese market. According to aerodyn the Chinese market uses the European market and its three-bladed WTGs as a role model but the floating technology is without any alternative for the Japanese market due to great water depths. Chinese based company Envision also shows no further two-bladed WTG activities after the end of the demonstrator test phase in Denmark. They focus on their already established three-bladed WTG business. The Danish competence center now focuses on the EcoSwing project and a generator on a superconductor basis. German based SkyWind did not respond to enquiries regarding the status of their planned projects and no updates since 2016 can be found. 2-B Energy managed to set up a prototype in Eemshaven and tested it successfully. They are now trying to set up demonstrators off the Scottish coast including floating foundations but due to financial issues the projects are postponed indefinitely and 2-B Energy confirmed that the building permission deadline this year cannot be met. Seawind is also in a similar situation with financial difficulties to set up its prototype project in Norway and thus other planned projects are indefinitely postponed. In summary, the big Chinese OEMs Mingyang and Envision have lost their interest in two-bladed WTGs at the moment and small OEMs, respectively start-ups, struggle with financial issues to set up prototypes and prove their technology as well as gain a track record.

The analysis of Chapter 4.3.2 shows that a CAPEX reduction potential of roughly 5 to 6 % seems realistic for two-bladed compared to three-bladed WTGs. The CAPEX advantage is mainly due to weight savings, simpler logistics and faster installation. This leads to the first expert interview question of Chapter 5. Why are two-bladed WTGs not used on- or offshore despite the CAPEX advantage? This question is partly already answered in the literature by Hau (2016), Gasch and Twele (2016) and others. At least for the onshore sector it is attributed to public acceptance problems due to the visual impact and higher noise emissions compared to three-bladed WTGs. They also state that these problems can be neglected for the offshore sector. Another important issue which is also of great importance to the offshore sector is the technical complexity of the system and the high dynamic loads that used to cause major problems in the past.

This analysis aligns with the statements obtained in the expert interviews of this thesis. Furthermore, the benefits and cost reduction potentials for the onshore sector are assessed as too small to compensate for the disadvantages. Additionally, market adjustment due to bankruptcy and acquisition of former two-bladed WTG companies is stated as a factor which also influenced the historical development of the offshore sector. Some tend to attribute this development partly to the introduction of the German electricity feed-in law (later EEG) in 1991 and argue that the guaranteed feed-in tariff eliminated the need for innovative technologies and a drastic cost reduction. This argument alone is not convincing since many companies already turned their backs on the technology in order to further develop three-bladed WTGs at the time that the electricity feed-in law came into force. In part, the assessment that subsidies can be both an engine and a brake for innovative technology may be correct, whether this applies to the case of the two-bladed WTG remains pure speculation, since this technology was not only providing solutions but was facing real problems and disadvantages at that time.

The missing presence of two-bladed WTGs in the offshore sector can be partly attributed to the former onshore issues like high dynamic loads, although this thesis presented advanced solutions to mitigate these loads. It seems to be less a question of insolvable technical problems of the two-bladed WTG than rather a question why one should scrap the on- and offshore proven three-bladed WTG concept. In this respect, today's obstacles of establishing the two-bladed WTG in the offshore sector are still historically grown, since the three-bladed WTG has reached the commercial scale in the onshore sector a long time ago. This vast experience and the corresponding track record helped to successively develop the offshore versions and build up stakeholder's[16] trust in the technology as well as the OEMs behind it. The missing track record of two-bladed WTGs is also one of the most frequent answers of the expert interviews when it comes to the further development of the technology as well as financing and insurability. At this point the chicken-and-egg question arises. What comes first, a somehow self-financed prototype and the corresponding track record to proof the technology's usability for financing of larger projects or the

[16] In this case, stakeholders are OWF developers, operators, banks and other finance/capital institutes, insurance companies as well as other commercial OWF related parties.

stakeholder's commitment and financial support for demonstration or prototype projects? One thing is clear, the risks of early development of a technology are never borne by banks and insurance companies whether it is a demonstration, prototype or commercial project. More risk-friendly stakeholders like venture capital companies may assess this differently and invest in an earlier product stage.

Although an operator is able and in some beneficial cases might be willing to demonstrate innovative technology with for example two to three units as part of a commercial OWF, the operation of the commercial part of the OWF cannot be endangered at any time and there must be no costs for the operator. If necessary, the operator supports with logistics, installation, grid connection and operation as well as transmission and remuneration of the produced electricity. As part of the expert interviews, financial institutes and insurance companies confirm that this type of combination between commercial OWF and demonstration project has no influence on finance and insurance costs of the commercial part as long as the performance of the commercial turbines is not affected. In particular, the repayment of debts as well as the cash flow must be secured. This is a positive sign for two-bladed WTG OEMs as they need big industry players as partners who, in addition to financial support, also support with experience and know-how in contracting and operations among other fields. One possible obstacle from an operator's point of view is that the legal regulation does not provide for an increase in the grid capacity of the OWF for prototypes (§ 70 para. 1 WindSeeG).

On the one hand, the offshore wind industry intends to reduce costs in all areas, but in case of the two-bladed WTG it seems that no one wants to be a first mover and drive development forward at their own risk and expense. It appears that a market actor (or a consortium of several actors) need to demonstrate on a large scale and under real offshore conditions that the two-bladed technology works and that benefits as well as cost reduction potentials are real. On the other hand, there is not much doubt about a general cost reduction potential. However, its extent may not be sufficient to arouse further industry interest. The cost reduction potential is mainly assigned to the CAPEX of a two-bladed WTG due to higher power-to-weight ratios. A reduction in OPEX is considered unlikely by almost all interviewed experts and even by some two-bladed WTG OEMs. The main reason given is that the electrical components in particular are responsible for failures and thus influence the OPEX. But the electrical and other components used for three-bladed and two-bladed WTGs are usually the same. The advantage of saving one blade and one pitch-system that does not require any service or maintenance is considered to be rather small or without much influence on the OPEX and especially overall costs. It has also been mentioned in the course of the conducted interviews of this thesis that the same components are used for different load profiles of two-bladed WTGs and due to a lack of experience, no verifiable statements can be made about the effects on the components. There is certainly a need for further research and clarification at this point. The only possible operational advantage mentioned by some OEMs is a generally good accessibility of the WTG and blades in horizontal (blade access) or vertical (hub and pitch-system access) position as well as the helicopter landing platform, which makes it possible to be more independent of weather conditions and to develop purely helicopter-based O&M concepts. If this indeed results in real benefits and cost reductions is investigated in Chapter 6.

The majority of the surveyed experts of this thesis consider the whole two-bladed WTG potential to be insufficient to outweigh the implied risks. In addition, the development of the industry and the value chain, which the three-bladed technology is part of, also play an important role, since all areas of the value chain are already optimized and specialized on three-bladed WTGs to such an extent that the alleged cost reduction potential of two-bladed WTGs in the past was probably greater compared to the high costs for OWFs with three-bladed WTGs in the early offshore wind days. This advantage may have been relativized over time. In addition, there are legitimate doubts as to whether a 6 MW two-bladed WTG still is or in the future will be a business case at all, since the trend is towards larger turbines between 12 to 15 MW and 9 MW turbines are already commercially available today. An up-scaling of the two-bladed concepts is of course conceivable and technically feasible in principle, but first the WTGs in the 6 MW class need to be sufficiently tested in order to make them proven technology and to gain important experience for up-scaling. It is also doubtful that the time advantage and the development status of the three-bladed WTG can still be caught up with by the two-bladed WTG.

If one assumes a significant cost reduction potential of the two-bladed WTG, the new offshore capacity auction model in Germany may be an opportunity as the cost pressure on the offshore wind sector further increases. The recent 0.0 $€_{cent}$/kWh bids are also based on the assumption that cheaper technology and advanced installation as well as operation strategies will be available by the time the projects start. The offshore capacity auction model can also be seen as a disadvantage for two-bladed WTGs rather than an advantage, since further cost pressure means that the focus is even stronger on project risks and thus primary on mitigation of project's debt service and cash flow risks. Therefore, the consequence may also be a sharper focus on proven technology and the experience of strong OEMs, instead of relying on risky innovative technology by newcomer OEMs.

Innovative technologies and especially disruptive technologies[17] are always an opportunity to reduce costs and/or increase efficiency, but they are also associated with high risks. The experts interviewed in Chapter 5 classify the offshore sector as a more risk-averse industry. This is mainly due to the necessary high investments for OWF projects and negative experiences in the past. From a financial or insurance risk assessment point of view, it is more about the two-bladed WTG OEM as a company and not exclusively about the provided technology. Proven technology is certainly an important parameter and thus sufficient track record is essential to be verified by the OEMs. The number of approximately 100 turbine years of track record was stated as a minimum during the interviews. Even if the 100 turbine years are only an indication it shows that massive effort is necessary to gain sufficient track record, which is not possible with only one or two prototypes of a single OEM. In general, prototypes are essential, as they are necessary to obtain appropriate certifications, which of course are considered key parameters by banks and insurance companies.

As already mentioned, the OEM's background is even more interesting for a risk assessment as the technology itself. Size and background or the financial resources directly influence important parameters such as the ability of an OEM to provide sufficient securities and guarantees for a project. Especially guarantees are important as third-party obligations prevail over insurance cover and only 30 – 35 % of all damages are insured. The remaining cases will be at the expense of the project in case of insufficient OEM guarantees. Also, the first 30 days of interrupted operation are always borne by the project. A lack of guarantees bears a huge risk for all OWF stakeholders as damages directly influence the projects debt service and cash flow. The best case is an OEM as general contractor offering comprehensive guarantees and a full-service agreement with the longest possible contractual term. The more parties are involved and the more contracts need to be concluded the higher the risk for the bank. Thus, extended securities are necessary. These parameters are the main differences between newcomers and established OEMs who can act as general

[17] Disruptive technologies are innovations that replace the success story of an existing technology or product or completely displace it from the market. (Fraunhofer IPT 2018)

contractor with the necessary securities and guarantees as well as full-service agreement whereas newcomers are normally not able to provide any of that.

Additional production parameters such as a redundant supply chain or a sufficient quality management are important as well. The main argument is that if a concept is good that doesn't necessarily mean that the production of the WTGs is qualitatively good as well. Especially the first series of a new technology often has significant problems with poor quality in production and corresponding production or series failures. That can lead to huge unforeseen costs in the operating phase of an OWF. Unpredictable and incalculable risks are a show stopper for insurance companies whereas predictable risks can be quantified and lead to higher premiums, higher deductibles and comprehensive exclusions. Technology which is not proven from an insurance point of view will always lead to the most comprehensive exclusion of insurance cover. In addition, generic bankability reports by external consultants are highly welcomed by banks and insurance companies. Overall, for a bank it is less a question of what influence innovative technology has on the financing costs, but it is rather a binary yes or no decision.

The question regarding the two-bladed WTG OEM landscape was answered similarly by almost all experts and underline the conclusion of the analysis in Chapter 4.2. It can be concluded that there is no so-called 'OEM landscape' at the moment. Most OEMs are stuck in the start-up phase struggling to demonstrate their technology. Some OEMs managed to set up a demonstrator turbine but now face primarily financial difficulties to implement new projects. There are no concrete small size multi-turbine projects that can be realized in the near future. It seems that there is not much investment interest in the two-bladed technology at the moment. According to the experts or the OEMs itself, the two big companies Mingyang and Envision have dropped the two-bladed WTG idea completely and are not pursuing any further commercialization. Instead they focus on their three-bladed WTG portfolio as they see no possibility for a market entry with a two-bladed WTG in the near future. Mingyang and Envision are Chinese OEMs, which makes their drop of the two-bladed technology particularly interesting. A possible advantage that is always mentioned in connection with two-bladed WTGs is their advantageous behavior in extreme winds and typhoons. The fact that OEMs, whose home market is partly classified as a typhoon area, nevertheless have no further interest in this technology is clearly a negative sign. This is maybe due to the fact that no one dares to develop large scale offshore projects in real typhoon areas at the moment and therefore the market is simply missing. A question that needs to be answered in this regard is: How big is the typhoon market size? Is the potential market size big enough to reach return on investment? The worst-case scenario is low market potential but high development costs for a new technology.

According to several interviewed experts, the only real chance for a market entry of two-bladed WTGs is seen as the hypothetical possibility that one of the big OEMs finds interest in the technology and pushes it forward with all its strength. Then competitors cannot avoid further investigating the technology. However, the prospects for this are low, as there is certainty that all major OEMs have already considered the topic, but have rejected the technology for various technical and economic reasons. A key reason might also be that the two-bladed WTG has no substantial unique selling proposition for the standard offshore wind market. Compared to that, the fairly new floating foundation technology has a massive unique selling proposition as it opens up new markets that could not do offshore wind before. OWFs with floating foundations can be built in areas with waters deeper than 50 m and easily up to 100 m deep waters with better wind conditions.

The conducted expert interviews as well as the further analysis and assessments of this thesis show that the challenges of two-bladed WTGs as an innovative technology are manifold, complex and certainly not just a question of technological maturity or cost reduction potential. Innovative technologies presented by newcomer OEMs always have a hard time entering the market, especially in investment-intensive industries such as the offshore wind sector. This differentiates OEMs from newcomers or start-ups in other industry sectors such as the mobile technology scene. For example, a start-up that builds mobile applications cannot be compared to a developer of WTGs in terms of the necessary investment to develop the product. The development of a new WTG is extremely investment-intensive and can cost between 200 and 250 Mio€ (Renews 2016).

The evaluation of the expert interviews of this thesis reveals that not much impacts of two-bladed WTGs on the O&M phase are expected. Chapter 6 comes to the same conclusion although the assessment is only theoretical due to a lack of operational experience with offshore two-bladed WTGs. Generally, the share of O&M on total offshore wind cost reduction potential is rather small compared to investment and finance costs. On the one hand, two-bladed WTGs have a slight CAPEX reduction potential in theory as already discussed in Chapter 4.3.2. On the other hand, it is likely that the finance and insurance costs over the life-time of the WTG are negatively influenced by the use of two-bladed WTGs. However, they remain at least at the same level of three-bladed WTGs but with reasonable certainty there is no cost reduction potential at this point in the near future, which in fact is a huge disadvantage compared to the finance cost reduction potential of three-bladed WTGs due to increased experience and risk reduction.

Equipment expenditure and unplanned maintenance measures have the main influence on O&M costs. Thus, an increased WTG reliability and lower failure rates of single components can reduce these costs. The failure rate comparison of a three-bladed and a two-bladed WTG shows no important benefits of a two-bladed WTG as the components and failure rates, which are attributable to around 95 % of the WTG downtime, are similar compared to the components of a three-bladed WTG. Furthermore, leading edge blade erosion due to higher tip speeds is a clear disadvantage which leads to higher maintenance effort.

The single large components of a two-bladed WTG have no significantly lower weight, so that no smaller logistics and especially lifting equipment can be used during the O&M phase. Therefore, there is no discernible cost advantage over a three-bladed WTG at this point. The helicopter service concept case study is more promising and a cost reduction compared to CTV missions is assumed even for hoisting. Thus, the two-bladed WTG with its helicopter landing platform further increases this cost reduction advantage. Of course, this depends strongly on the individual case and above all on the distance between the OWF and the land. A comparison between helicopter and SOV concept is also necessary for a complete assessment of the possible landing platform benefits as this is the chosen service concept for the new EnBW North Sea OWFs. It is possible to exploit synergy effects between the different OWFs with the SOV concept. Additionally, a landing platform has non monetary HSE advantages as landing a helicopter is way safer than a hoisting mission or a boat landing.

Some OEMs like aerodyn or Seawind claim an advantage over three-bladed WTGs due to the high survival wind speeds of their concepts for typhoon areas of the world. In particular, practical experience and operational data is missing to confirm these values but in general typhoon proof WTGs are of interest for certain growing markets like China, Taiwan, Japan or the US. However, the latest release and installation of Mingyang’s typhoon ready three-bladed WTG for demonstration removes this advantage and another selling point of two-bladed WTGs.

Finally the lower AEP of two-bladed WTGs, which directly influences the LCoE, strengthens the doubts that the supposed rather small impacts on the OPEX prevail and positively influence the LCoE. The initial research question if it is possible to significantly reduce offshore OPEX by utilizing two-bladed WTGs has to be negated at this point. A detailed O&M simulation can quantify the exact OPEX for two-bladed WTGs but the conclusions of this thesis and the need for extended input data so far does not seem to justify the effort.

For example, the impact on the O&M phase of a floating WTG like the SCD nezzy or SCD nezzy^2 is expected to be greater. Totally new service concepts can be considered. For example, the whole floating system is towed to the quay side by local non-specialized offshore tug boats (one or two days travel time for ~100 km to shore), so that big component repair or exchange is carried out with cranes from onshore. Large expensive logistics and lifting equipment is omitted as well as costly and risky offshore operation of technicians. This is also interesting for new markets with insufficient infrastructure. A plug and play maintenance approach is also conceivable. That means replace a unit offshore and fix the replaced unit onshore. According to Principle Power, it is likely to save around ~40 % costs for large corrective maintenance and ~16 % in overall OPEX by tow-in approach. (Principle Power 2017) This is certainly not a specific two-bladed WTG service approach as almost all actual demonstration floating systems are equipped with three-bladed WTGs.

In summary, market breakthrough with radical concepts for the offshore wind sector has so far proven hard, typically hampered by already mentioned factors like bankability and track record demands, real risks and risk perception. These factors above all explain why proven conventional wind technology is preferred, pushed by powerful established OEMs with the necessary financial background. Thus, topics like bankability and insurability need to be an essential part of the concept and development phase of a new technology. This process has to be taken up as early as possible to prevent a situation as it is the case with the two-bladed technology now. Namely that interesting concepts are developed but in the end, they fail not due to technical issues or a lack of cost reduction potential but rather because of the insufficient alignment to the target market and its peculiarities. The question that always arises and needs to be carefully considered is: What problem am I solving with my new technology? This question seems to be answered insufficiently by two-bladed WTGs or the need for cost reduction of the offshore wind sector is not big enough yet to consider this technology. Despite that, the whole offshore wind sector with all its stakeholders needs to take responsibility for producing or at least supporting innovative technology in order to have a market as diversified as possible. Competition stimulates business and reduces prices. This fact certainly also applies to the WTG market and ultimately helps to further expand the competitiveness of green offshore wind energy and increase capacity in order to achieve the world's important climate policy goals.

Bibliography

2-B Energy (2018): Company website, product and project information. 2-B Energy BV. Hengelo, NL. Available online at http://2benergy.com/, checked on 7/18/2018.

4C Offshore (2018): Company website and offshore project information. 4C Offshore Ltd. Suffolk, UK. Available online at https://www.4coffshore.com/, checked on 7/18/2018.

aerodyn (2018): Company website, product and project information. aerodyn engineering GmbH. Büdelsdorf. Available online at https://www.aerodyn-engineering.com/, checked on 7/18/2018.

Airbus (2018): Presentation and personal talk at Wind Energy Hamburg, product and project information. Airbus Helicopters Deutschland GmbH. Donauwörth. checked on 9/25/2018.

Aktion Deutschland Hilft (2018): Website. Aktion Deutschland Hilft e.V. Berlin Available online at https://www.aktion-deutschland-hilft.de/de/fachthemen/natur-humanitaere-katastrophen/hurrikane-und-wirbelstuerme/namen-von-wirbelstuermen/, checked on 10/10/2018.

Bech, J. (2018): Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events. EAWE. Roskilde, DK.

BMJ and Juris (2013): Arbeitszeitgesetz: ArbZG. Bundesministerium der Justiz. Berlin.

BMWi (2018): Nationale Ausschreibungen und Ergebnisse. Available online at https://www.erneuerbare-energien.de/EE/Redaktion/DE/Dossier/nationale-ausschreibungen-und-ergebnisse.html?cms_docId=577128, checked on 5/17/2018.

BMWi (2014): Gesetz für den Ausbau erneuerbarer Energien (EEG). Bundesministerium für Wirtschaft und Energie. Berlin, checked on 5/29/2018.

BMWi (2015): Offshore wind energy. An overview of activities in Germany. Bundesministerium für Wirtschaft und Energie. Berlin, checked on 5/16/2018.

Bogner, A.; Littig, B.; Menz, W. (2014): Interviews mit Experten. Eine praxisorientierte Einführung. Wiesbaden: Springer VS.

Bontrup, H.-J.; Marquardt, R.-M. (2015): Die Zukunft der großen Energieversorger. Greenpeace. Hamburg.

Böttcher, J. (2013): Handbuch Offshore-Windenergie. Rechtliche, teschnische und wirtschaftliche Aspekte. 1. ed. München: München Oldenbourg.

BSH (2007): Standard Konstruktive Ausführung von Offshore-Windenergieanlagen. Bundesamt für Seeschifffahrt und Hydrographie. Hamburg

BSH (2015): Standard Konstruktion. Mindestanforderungen an die konstruktive Ausführung von Offshore-Bauwerken in der ausschließlichen Wirtschaftszone (AWZ). Bundesamt für Seeschifffahrt und Hydrographie. Hamburg

Bundesnetzagentur (2017): Bundesnetzagentur erteilt Zuschläge in der ersten Ausschreibung für Offshore-Windparks. Available online at https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2017/13042017_WindSeeG.html, checked on 5/17/2018.

Burton, T. (2011): Wind energy handbook. 2. ed. West Sussex: Wiley.

CFI (2018): Adjusted EBITDA. Corporate Finance Institute. Available online at https://corporatefinanceinstitute.com/resources/knowledge/valuation/adjusted-ebitda/, checked on 5/23/2018.

Dalhoff, P.; Schorbach, V.; Gust, P. (2013): Two bladed offshore wind turbines: state of the art and prospects. Hamburg University of Applied Sciences. Hamburg.

Deloitte/Norton Rose (2013): Die deutsche Energiewende. Chancen und Herausforderungen für Investoren. Deloitte; Norton Rose

DeVries, E. (2011): Development of two-bladed offshore wind turbine. Wind Stats Report. London (Vol. 24, No. 2).

DeVries, E. (2012): Close up - Envision's 3.6 MW offshore machine. Windpower Monthly.

DeVries, E. (2014): Windtech: Aerodyn two-blade floating 8MW SCD. Windpower Monthly.

DeVries, E. (2016): Windtech: Two-bladed concept claims 40-year life. Windpower Monthly.

Dewan, A. (2014): Logistic & service optimization for O&M of offshore wind farms. Model development & output analysis. Master thesis. Delft University of Technology, Delft, Netherlands. Faculty of Aerospace Engineering.

DIN 13306 (2018): Maintenance terminology.

DIN 31051 (2012): Fundamentals of maintenance.

DNV GL (2014): Offshore wind cost reduction manifesto. DNV GL. Oslo, Norway.

ECN (2010): User Guide and Model Description of ECN O&M Tool Version 2. Energy Research Centre of the Netherlands. Petten, NL.

EcoSwing (2015): Ecoswing project website. ECO 5 GmbH. Bonn. Available online at https://ecoswing.eu/, checked on 7/18/2018.

El-Henaoui, S. (2012): Individual pitch control and its impacts. Wind Systems. Available online at http://www.windsystemsmag.com/article/detail/394/individual-pitch-control-and-its-impact, checked on 8/8/2018.

EnBW (2018c): EnBW acquires 37.5 percent stake in each of three offshore wind projects in Taiwan. Karlsruhe. Available online at https://www.enbw.com/company/press/press-releases/press-release-details_178496.html, checked on 4/26/2018.

EnBW (2016): EnBW bleibt in schwierigem Umfeld auf Kurs. Erneuerbare Energien mit starkem Ergebnisschub. Karlsruhe. Available online at https://www.enbw.com/unternehmen/, checked on 5/22/2018.

EnBW (2018d): EnBW Corporate Website. EnBW Energie-Badenwürttemberg AG. Available online at https://www.enbw.com/unternehmen/, checked on 8/2/2018.

EnBW (2017a): EnBW gains approval for first German offshore wind auction for the 900 megawatt 'He Dreiht' offshore wind farm. Available online at https://www.enbw.com/company/press/press-releases/press-release-details_157185.html, checked on 5/23/2018.

EnBW (2018f): EnBW take its first steps in the North American market for offshore wind. Karlsruhe. Available online at https://www.enbw.com/company/press/press-releases/press-release-details_188032.html, checked on 8/1/2018.

EnBW (2018a): Energy mix 2016. EnBW Energie-Badenwürttemberg AG, checked on 5/22/2018.

EnBW (2017b): Floating Offshore Wind. Internal presentation / study. EnBW Energie-Badenwürttemberg AG. Hamburg

EnBW (2018g): Internal documentation of leading edge blade erosion of Baltic 1 and 2 turbines. Hamburg.

EnBW (2018b): Offshore wind farms. EnBW Energie-Badenwürttemberg AG. Available online at https://www.enbw.com/renewable-energy/wind-energy/our-offshore-wind-farms/, checked on 5/22/2018.

EnBW (2018e): Wind energy of the future: Research project on the use of high-altitude wind. Karlsruhe. Available online at https://www.enbw.com/company/press/press-releases/press-release-details_189120.html, checked on 8/2/2018.

EnBW (2013): Strategy EnBW 2020. EnBW launches new strategic orientation. Karlsruhe. Available online at https://www.enbw.com/company/press/press-releases/press-release-details_36928.html, checked on 5/22/2018.

EnBW Interviews (2018): Info obtained by interview of EnBW personnel. Hamburg.

EnBW Offshore Service (2018): Info obtained by interview of EnBW Baltic 1 Operating Manager and service personnel. Barhöft.

Envision (2018a): Corporate website, product and project information. Envision Energy Ltd. Available online at http://www.envision-group.com/, checked on 7/18/2018.

Envision (2018b): Game Changer 1 website. Envision Energy Ltd. Silkeborg, DK. Available online at http://www.project-gc1.com/, checked on 7/18/2018.

Ernst et al. (2017): Unternehmensbewertungen erstellen und verstehen. Ein Praxisleitfaden. 6. ed. München: Vahlen.

Fraunhofer, IWES (2017): Windenergie Report 2016. Fraunhofer Verlag. Stuttgart.

Fraunhofer, IWES (2018): Windenergie Report 2017. Fraunhofer Verlag. Stuttgart.

Fraunhofer IPT (2018): Disruptive Technologien. Fraunhofer. Available online at https://www.ipt.fraunhofer.de/de/kompetenzen/Technologiemanagement/disruptive-technologien.html, checked on 9/12/2018.

Gasch, R.; Twele, J. (2016): Windkraftanlagen. Grundlagen, Entwurf, Planung und Betrieb. 9. ed. Wiesbaden: Springer Vieweg.

Goetz, C. (2012): Finanzmodell für Zweiblatt-Offshore-Windenergieanlagen. Hamburg University of Applied Sciences. Hamburg.

Gonzalez-Rodriguez, A. G. (2017): Review of offshore wind farm cost components. Energy for sustainable development.

Graeber, D. R. (2014): Handel mit Strom aus erneuerbaren Energien. Kombination von Prognosen. Wiesbaden: Springer Gabler.

Handelsblatt (2018): Offshore Windparks - Die riskante Wette auf eine Zukunft ohne Subventionen. Available online at http://www.handelsblatt.com/my/unternehmen/energie/offshore-windparks-die-riskante-wette-auf-eine-zukunft-ohne-subventionen/21226662.html?ticket=ST-892808-4rmt53vM9Ig4J69rpuXE-ap2, checked on 5/17/2018.

Hau, E. (2016): Windkraftanlagen. Grundlagen, Technik, Einsatz, Wirtschaftlichkeit. 6. ed. Berlin: Springer Vieweg.

InnoEnergy (2017): Future renewable energy costs: Offshore wind. InnoEnergy. Eindhoven, NL.

Jamieson, P. (2011): Innovation in wind turbine design. 1. ed. Hoboken, USA: Wiley.

Kaltschmitt et al. (2014): Erneuerbare Energien. Systemtechnik, Wirtschaftlichkeit, Umweltaspekte. Berlin: Springer Vieweg.

Kim, T.; Petersen, M. M.; Larsen, T. J. (2014): A comparison study of the two-bladed partial pitch turbine during normal operation and extreme gust conditions. Journal of Physics.

Koh, J. H.; Ng, E. Y. K. (2015): Downwind offshore wind turbines. Opportunities, trends and technical challenges. Renewable and Sustainable Energy Reviews.

Kost, C.; Shammugam, S.; Jülch, V.; Nguyen, H-T.; Schlegl, T. (2018): Stromgestehungskosten Erneuerbarer Energien. Edited by Fraunhofer. Fraunhofer-Institut für Solare Energiesystem ISE. Freiburg.

Krohn, S. (2009): Economics of wind energy. A report by the European Wind Energy Association. EWEA. Brussels, BEL.

Loth, E.; Ichter, B.; Selig, M.; Moriarty, P. (2015): Downwind Pre-Aligned Rotor for a 13.2 MW Wind Turbine. Florida, USA (Wind Energy Symposium, 33).

McKenna, R. (2014): Key challenges and prospects for large wind turbines. Karlsruhe Institute for Technology. Karlsruhe.

MHI Vestas (2018): Turbines & Innovations. MHI Vestas Offshore Wind A/S. Available online at http://www.mhivestasoffshore.com/innovations/, checked on 5/23/2018.

Münsterberg, T. (2017): Simulation-based evaluation of operation and maintenance logistics concepts for offshore wind power plants. Dissertation. 1. ed. Hamburg: Fraunhofer Verlag.

Offshorewind.biz (2018a): Game not over for Seawind. Offshorewind.biz. NL. Available online at https://www.offshorewind.biz/2018/01/22/game-not-over-for-seawind/, checked on 7/18/2018.

Offshorewind.biz (2018b): Largest Typhoon-Ready Wind Turbine stands offshore China. Offshorewind.biz. NL. Available online at https://www.offshorewind.biz/2018/05/07/largest-typhoon-ready-wind-turbine-stands-offshore-china/, checked on 10/11/2018.

Palfinger (2018): Foldable Knuckle Boom Cranes. Palfinger. Available online at https://www.palfingermarine.com/en/products/wind-cranes/foldable-knuckle-boom-cranes/range, checked on 5/25/2018.

Paul, A. J. (2010): A comparative analysis of the two-bladed and the three-bladed wind turbine for offshore wind farms. Master thesis. Delft University of Technology, Delft, Netherlands. Faculty of Aerospace Engineering.

Perveen, R.; Kishor, N.; Mohanty, S. R. (2013): Off-shore wind farm development. Present status and challenges. Renewable and Sustainable Energy Reviews.

Principle Power (2017): WindFloat1. Providing ground for a radically new approach to O&M. New Energy Update, London, UK.

Prognos AG, Fichtner Gruppe (2013): Kostensenkungspotenziale der Offshore-Windenergie in Deutschland. Langfassung. Berlin. Available online at http://www.prognos.com/publikationen/alle-publikationen/338/show/.

Recharge (2016): Two-bladed SkyWind may deploy offshore prototype in Norway. Recharge News. Available online at http://www.rechargenews.com/, checked on 7/18/2018.

Renews (2016): Offshore Turbine Yearbook 2016. Renews Ltd. Winchester, UK. Available online at http://renews.biz/category/offshore-wind/, checked on 7/18/2018.

Rodrigues, S.; Restrepo, C.; Kontos, E.; Teixeira Pinto, R.; Bauer, P. (2015): Trends of offshore wind projects. Renewable and Sustainable Energy Reviews.

Rose, S.; Jaramillo, P.; Small, M.; Grossmann, I.; Apt, J. (2012): Quantifying the hurricane risk to offshore wind turbines. Carnegie Mellon University.

Schorbach, V. (2016): Pendelanschläge bei Zweiblatt-Windenergieanlagen. Dissertation. Düsseldorf: VDI Verlag.

Schwanitz, V. J.; Wierling, A. (2016): Offshore wind investments. Realism about cost developments is necessary. Energy.

Schwanke, K. (2009): Naturkatastrophen. Wirbelstürme, Beben, Vulkanausbrüche. Entfesselte Gewalten und ihre Folgen. 2. ed. Heidelberg: Springer.

Seawind (2017): Seawind, an offshore wind revolution. Abundant, sustainable, low cost energy generation. Seawind Ocean Technology B.V. Amsterdam, NL. Available online at http://seawindtechnology.com/, checked on 7/18/2018.

SkyWind (2016): Company website, product and project information. Skywind GmbH. Husum. Available online at http://skywind.de/, checked on 7/18/2018.

Sperstad, I. B.; McAuliffe, F. D.; Kolstad, M.; Sjomark, S. (2016): Investigating key decision problems to optimize the operation and maintenance strategy of offshore wind farms. Deep Sea Offshore Wind R&D Conference.

Stehly, T.; Heimiller, D.; Scott, G. (2016): 2016 Cost of Wind Energy Review. National Renewable Energy Laboratory. Denver, USA.

Tavner, P. J. (2011): Offshore Wind Turbine Reliability. Durham University. Manchester, UK.

Thomsen, K. (2014): Offshore Wind. A Comprehensive Guide to Successful Offshore Wind Farm Installation. 2. ed. London, UK: London Academic Press.

van Bussel, G. J. W. (2001): Reliability, Availability and Maintenance aspects of large-scale offshore wind farms, a concepts study. Delft University of Technology. Newcastle, UK.

Walford, C. A. (2006): Wind Turbine Reliability. Understanding and Minimizing Wind Turbine Operation and Maintenance Costs. Sandia National Laboratories. Livermore, USA.

Warner, M. (2018): Untersuchung einer Multirotor-Windenergieanlage hinsichtlich der technischen Betriebsführung in einem Offshore-Windpark. EnBW Energie-Badenwürttemberg AG. Hamburg.

WindEurope (2017c): Floating Offshore Wind Vision Statement. WindEurope, checked on 5/25/2018.

WindEurope (2017a): Wind energy in Europe - Scenarios for 2030. WindEurope. Available online at www.windeurope.org, checked on 5/23/2018.

WindEurope (2017b): Wind energy in Europe: Outlook to 2020. WindEurope. Available online at www.windeurope.org, checked on 5/23/2018.

WindEurope (2016): Financing and Investment Trends 2016. WindEurope. Available online at www.windeurope.org, checked on 7/26/2018.

WTM (2018): Power curve Siemens SWT-3.6-130, checked on 5/28/2018.

Appendix

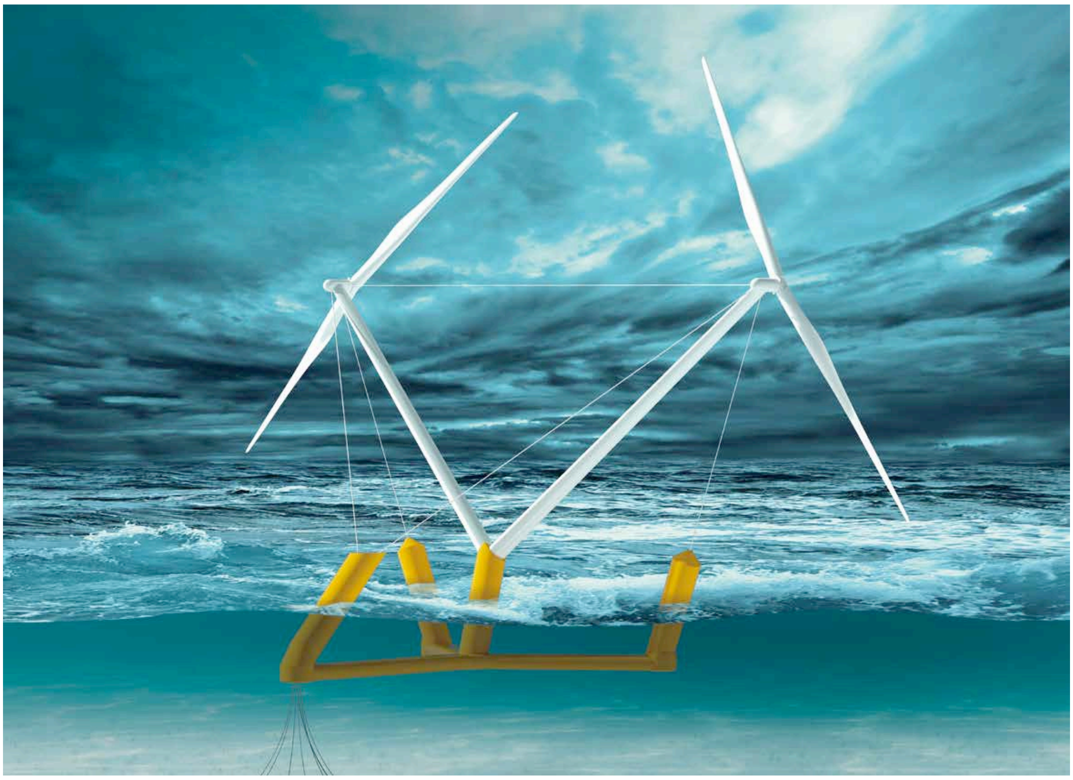
Appendix A: Figures

Appendix B: Tables

Appendix A: Figures

(1) aerodyn SCD advanced 6 MW at Longyuan Rudong Intertidal OWF

(2) SCD nezzy 8 MW (illustration)



(3) SCD nezzy² 15 MW (illustration)

Appendix figure 1: Photographs and illustrations of aerodyn SCD two-bladed WTGs (aerodyn 2018)

(1) Envision EN-128/3.6 PP 2B (or GC1) 3.6 MW at Thyborøn test field in Denmark

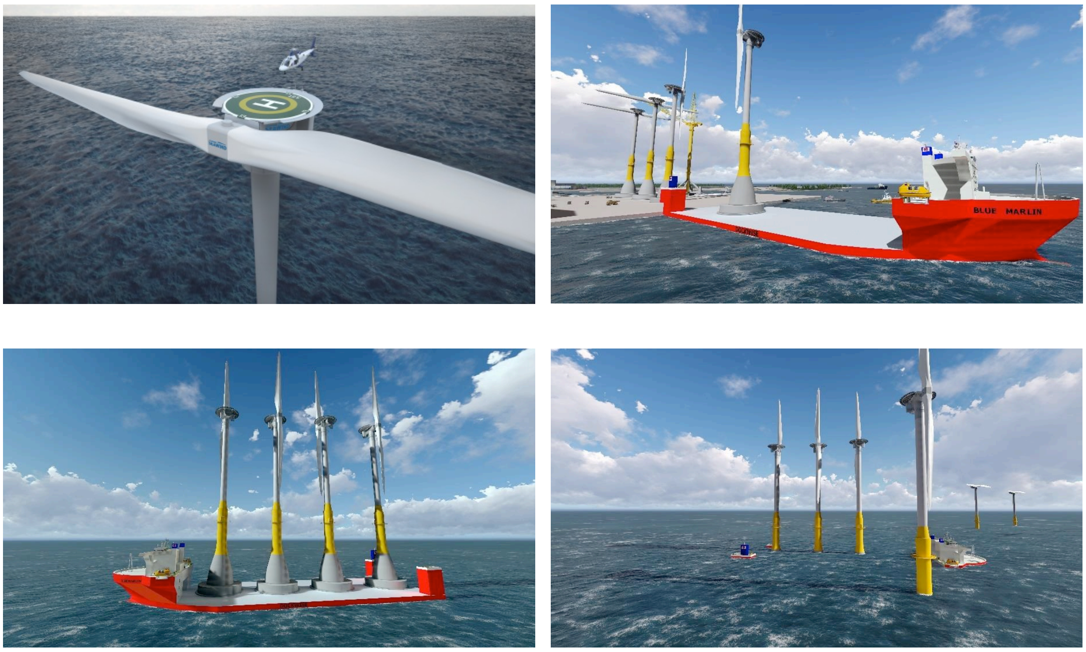
(2) SkyWind SW 3.4 MW during installation via the integrated winch system at Husum

(3) SkyWind multirotor concept with two SW 3.4 turbines and 7 MW capacity (illustration)

Appendix figure 2: Photographs and illustrations of Envision and SkyWind WTGs (Envision 2018b) (SkyWind 2016)

(1) 2-B Energy 6 MW downwind prototype without optional helicopter landing platform at Eemshaven, NL

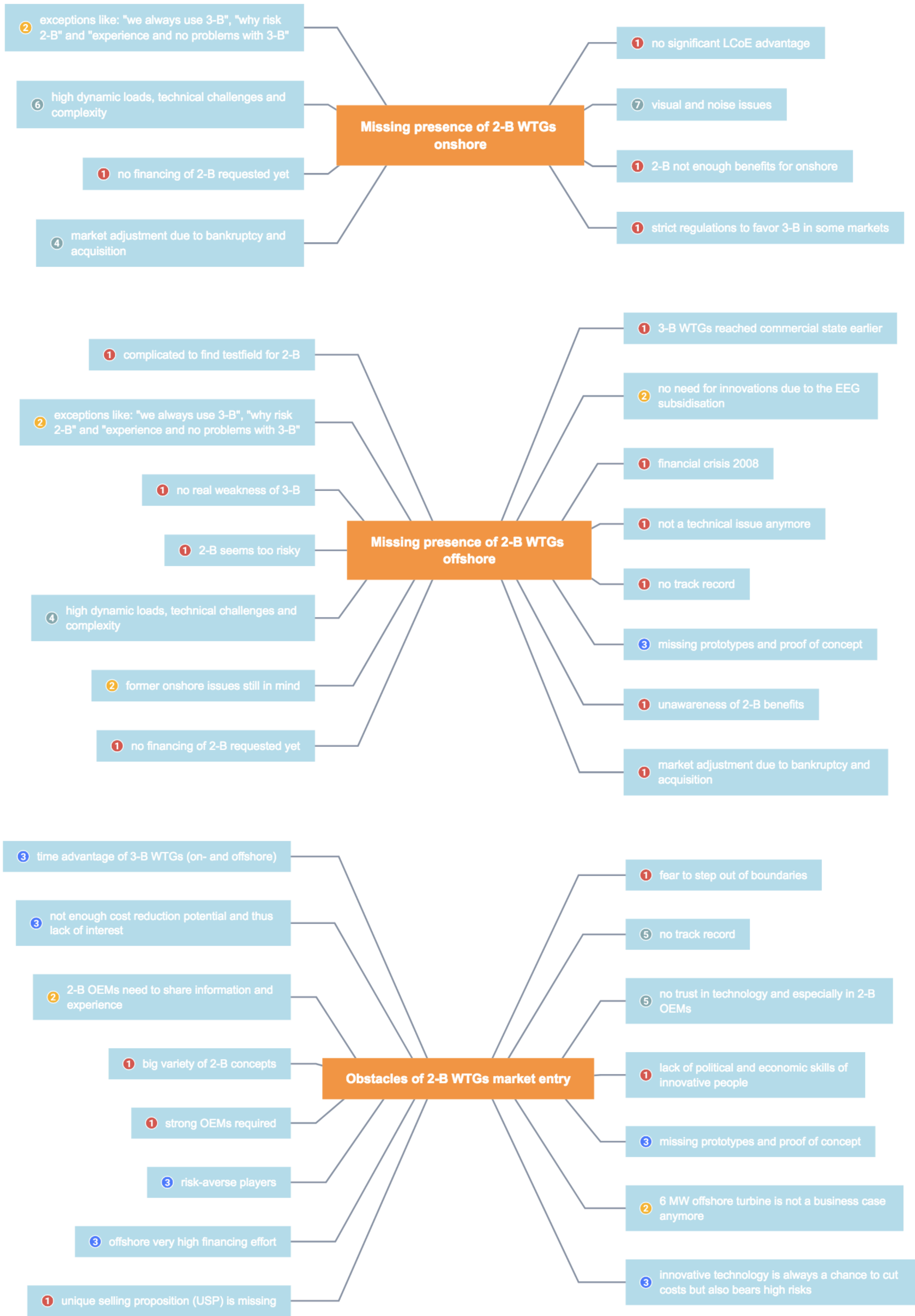
(2) full structure for off-shore use (illustration)



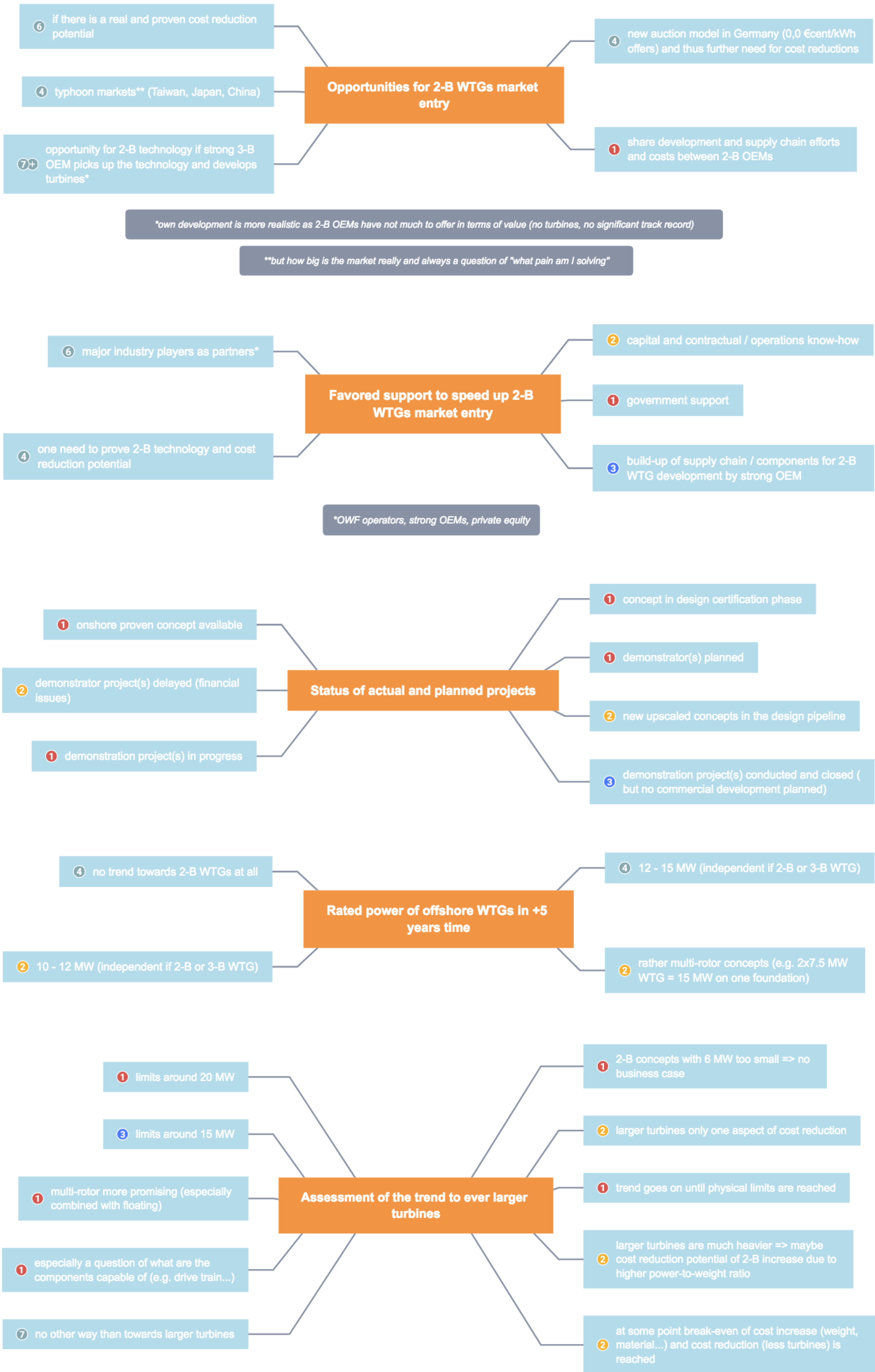
(3) Seawind 6.2 MW turbine with helicopter landing platform and installation procedure (illustration)

1. *Moving completely mounted WTG system onto semi-submersible vessel*
2. *Shipping of 4 – 6 units to the OWF site*
3. *Units launched into water by sinking the vessel, tug boats are used to align them, concrete foundation filled with water and sand to sink and fix them onto seabed*

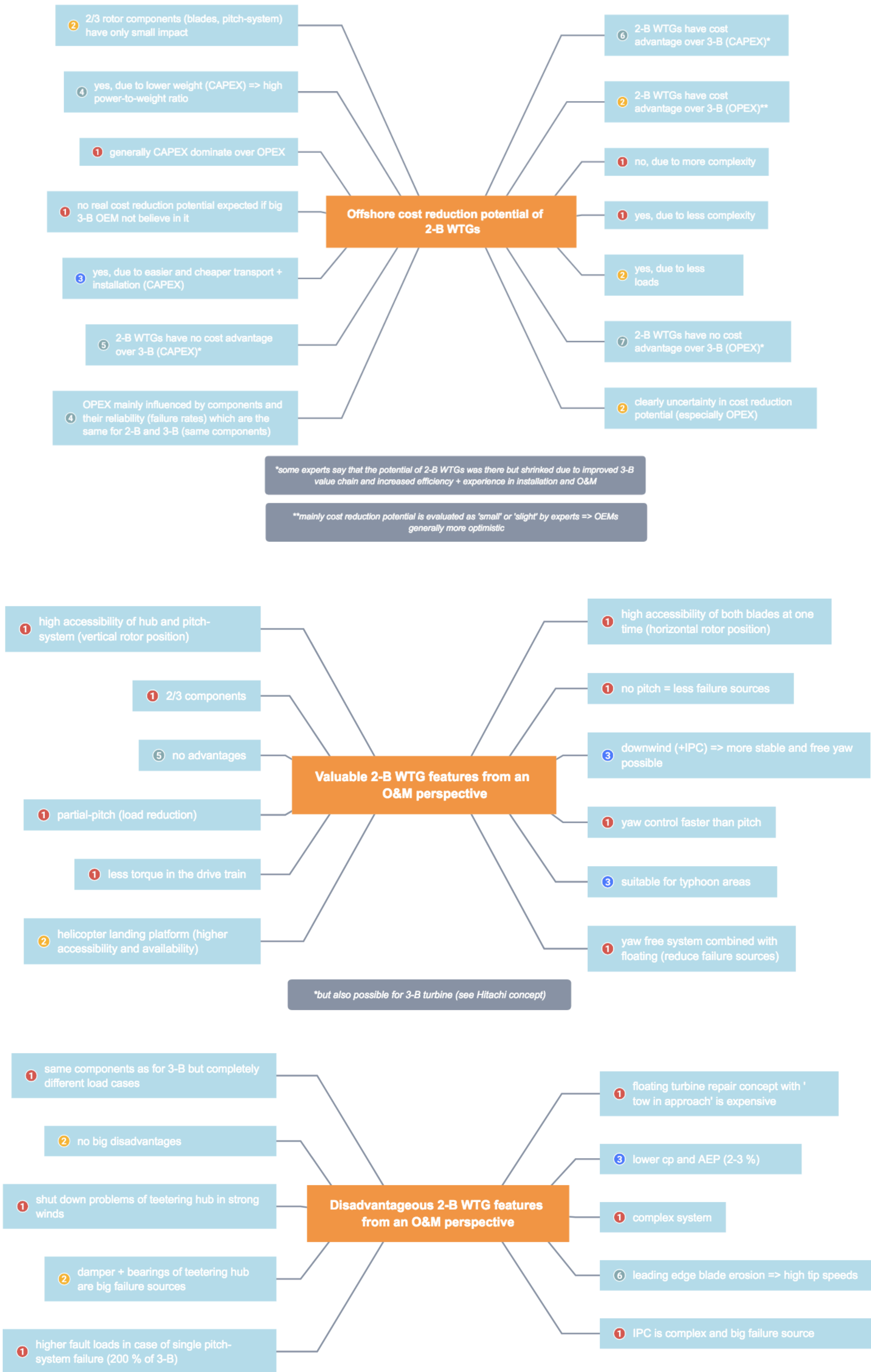
Appendix figure 3: Photographs and illustrations of 2-B Energy and Seawind WTGs (2-B Energy 2018) (Seawind 2017)



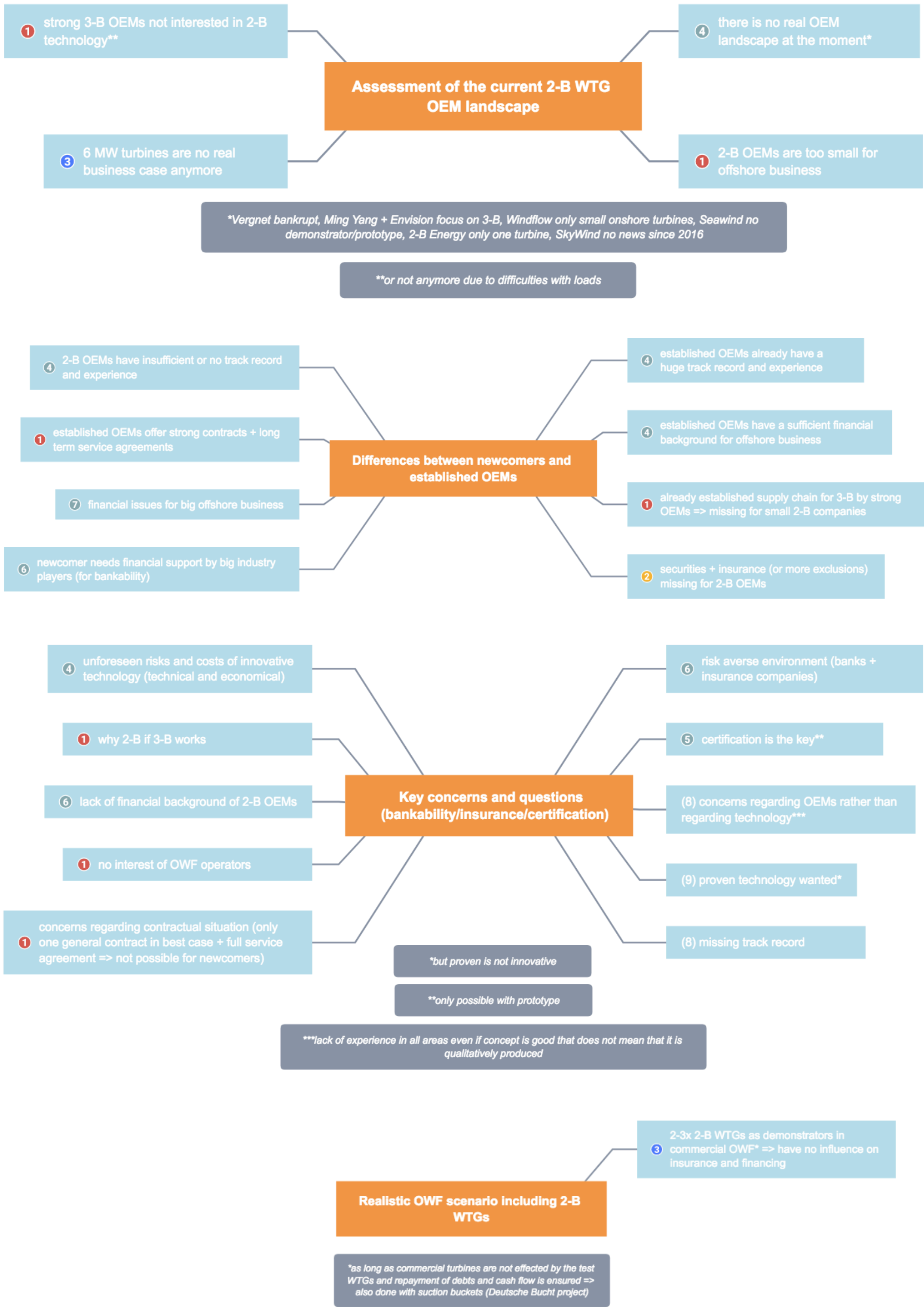
Appendix figure 4: Key statement mind maps 1 – 3 [Author's illustration]



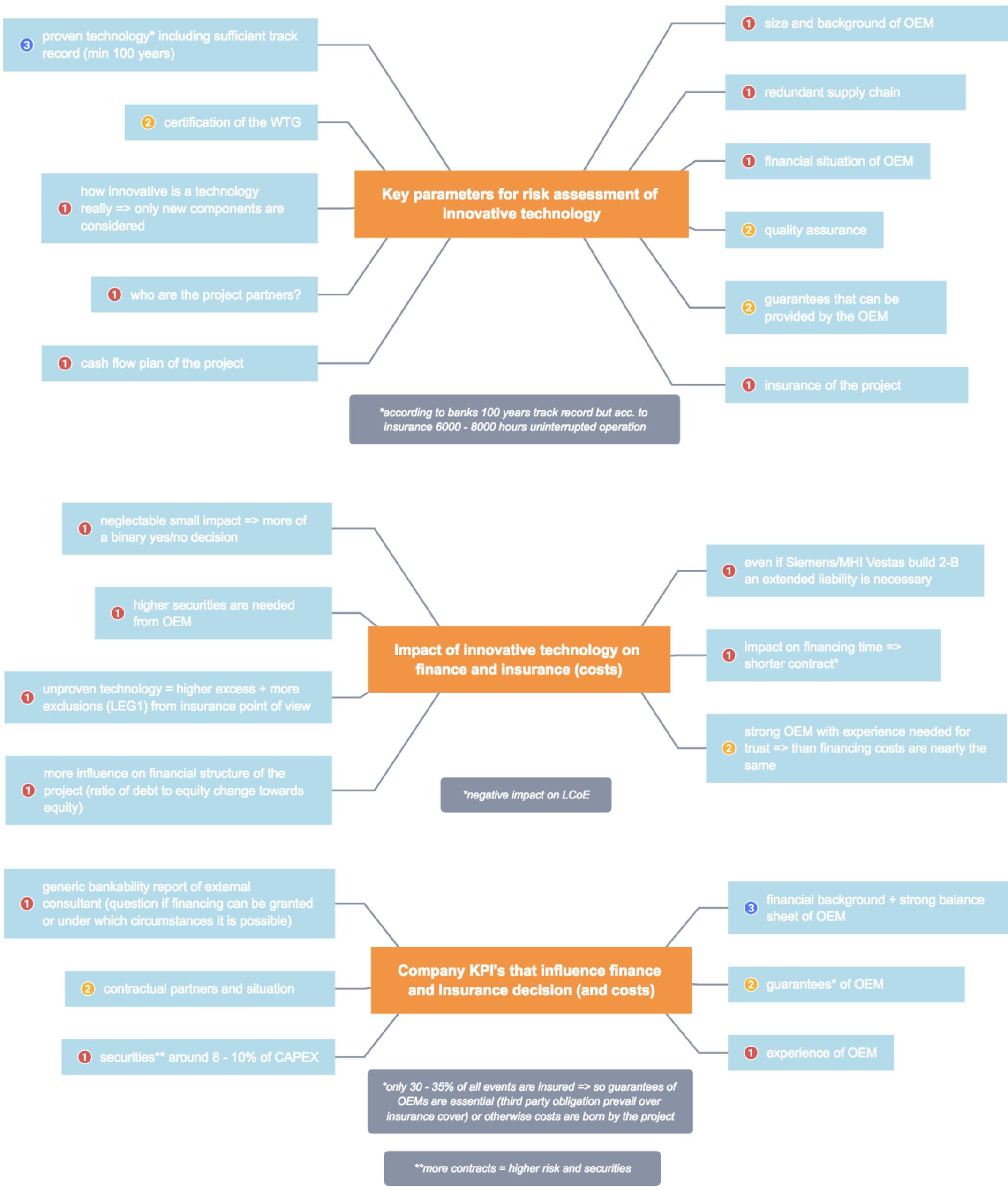
Appendix figure 5: Key statement mind maps 4 – 8 [Author's illustration]



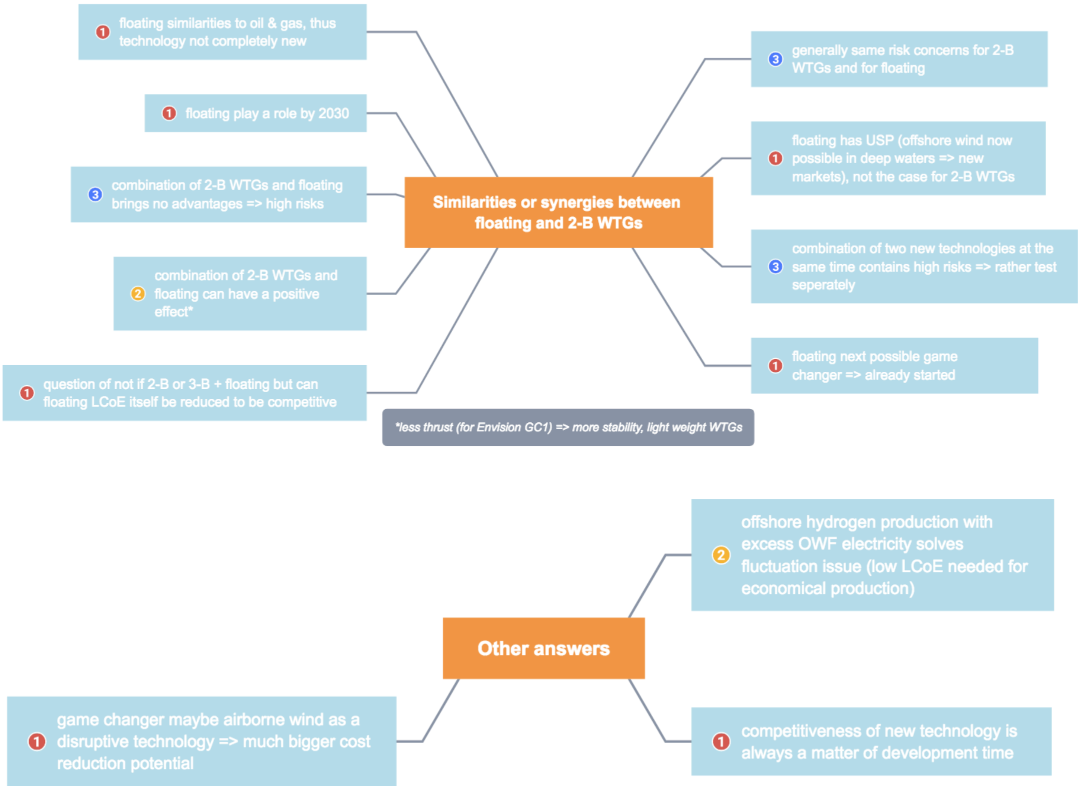
Appendix figure 6: Key statement mind maps 9 – 11 [Author's illustration]



Appendix figure 7: Key statement mind maps 12 – 15 [Author's illustration]



Appendix figure 8: Key statement mind maps 16 – 18 [Author's illustration]



Appendix figure 9: Key statement mind maps 19 – 20 [Author's illustration]

Appendix B: Tables

Appendix table 1: Two-bladed WTG project list [Author's illustration]

Company	Turbine	Project type	Project name	Location	Application	Distance to shore [km]	No. of turbines	Rated power per turbine [kW]	Total installed capacity [MW]
Windflow	33/500 1A	commercial	multiple	New Zealand	onshore	-	100+	500	50+
2-B Energy	2-B 6	prototype	-	Eemshaven, Netherlands	onshore	-	1	6,200	6.2
2-B Energy	2-B 6	planned (demonstrator)	Phase 1	Methil, Scotland	offshore	1.5	2	6,000	12.0
2-B Energy	2-B 6	planned (demonstrator)	Phase 2	Methil, Scotland	offshore	1.5	7	6,000	42.0
Envision	GC1	prototype	-	Thyboron, Denmark	onshore	-	1	3,600	3.6
Seawind	6.2	planned (prototype)	-	Karmoy, Norway	offshore	? (water depth 40 - 45 m)	1	6,200	6.2
Seawind	?	planned (small commerical)	-	Aegean Sea, Greece	offshore	?	?	?	?
Seawind	6.2	planned (small commerical)	Phase 1	Mauritius	offshore	10 - 14	4	6,200	24.8
	12.0	planned (small commerical)	Phase 2		offshore	10 - 14	3	10,400	36.0
	12.0	planned (commercial)	Phase 3		offshore	?	20	10,400	240.0
Seawind	6.2	planned (commercial)	-	Madagascar	offshore	5	8	6,200	49.6
aerodyn / MingYang	SCD basic	prototype	Urumqi 1	Urumqi, Xianjang Province, China	onshore	-	1	2,750	2.75
aerodyn / MingYang	SCD basic	commercial	Urumqi 2	Urumqi, Xianjang Province, China	onshore	-	16	3,000	48.0
aerodyn / MingYang	SCD basic	prototype	Rudong	Rudong, Jiangsu Province, China	near shore	-	1	3,000	3.0
aerodyn / MingYang	SCD advanced	commercial	Zuhai	Zuhai, Guishan Island, China	offshore	13	29	3,000	87.0
aerodyn / MingYang	SCD advanced	prototype	Longyuan Rudong Intertidal	Rudong, Jiangsu Province, China	offshore	4.5	1	6,000	6.0
aerodyn / Ideol	SCD basic (floating)	prototype	NEDO	Kitakyushu, Japan	offshore	15	1	3,000	3.0
SkyWind	SW 3.4	prototype	-	Husum, Germany	onshore	-	1	3,400	3.4

Appendix table 2: Turbine data sheet SkyWind SW3.4 [Author's illustration]

	Company	Skywind
	Type	SW 3.4
		Technical Specification
Rotor	Number of blades	2
	Rotor diameter [m]	107
	Rotor speed [rpm]	6 - 17
	Swept area [m²]	8.992
	Power densitity [W/m²]	378,1
	Orientation	Upwind
	Power control	Collective pitch control (CPC)
	Load control	None
	Hub	Rigid
	Blade material	GRP
	Yaw system	Active - soft damped
	Yawing [°/second]	-
	Yaw brake	-
	Brake system	-
	Aerodynamic efficiency	-
	Max. tip speed [m/s]	-
Gearbox	Type	Planetary
	Stages	2
	Rated inlet torque [kNm]	-
	Peak inlet torque [kNm]	-
Generator	Type	Squirrel Cage Induction
	Nominal power [kW]	>3,400
	Number of poles	8
	Cooling system	Water-air heat exchanger
Tower	Type	Tubular (concrete + steel)
	Diameter [m]	-
	Tower height [m]	-
	Hub [m]	133,5
	Tip [m]	187
	Mass [t]	-
Control		
	Cut-in system	-
	Logic system	-
Masses	Blade [t]	- per blade
	Rotor [t]	-
	Nacelle (incl. Helideck) [t]	-
	Total [t]	>100
Performance	Lifetime [a]	-
	Maximum power [kW]	3.400
	Low wind cut-in [m/s]	4,0
	Rated power at [m/s]	-
	High wind cut-out [m/s]	24,0
	Survival wind speed [m/s]	-
	Helicopter landing platform	No
Certification		
	Class	IEC IIA
	Type approved	-
	Turbine design	-
	Quality accreditation	-

Appendix table 3: Turbine data sheet 2-B Energy 2-B 6 [Author's illustration]

	Company	2-B Energy
	Type	2-B 6
		Technical Specification
Rotor	Number of blades	2
	Rotor diameter [m]	140,6
	Rotor speed [rpm]	-
	Swept area [m²]	15.526
	Power densitity [W/m²]	399,3
	Orientation	Downwind
	Power control	Collective pitch control (CPC)
	Load control	Individual pitch control (IPC)
	Hub	Rigid
	Blade material	-
	Yaw system	Active - soft damped (9 yaw motors, 1 redundant)
	Yawing [°/second]	-
	Yaw brake	-
	Brake system	-
	Aerodynamic efficiency	-
	Max. tip speed [m/s]	78
Gearbox	Type	Spur/planetary
	Stages	-
	Rated inlet torque [kNm]	-
	Peak inlet torque [kNm]	-
Generator	Type	Double fed induction
	Nominal power [kW]	-
	Number of poles	-
	Cooling system	Passive cooling
Tower	Type	Full 3 leg jacket (lattice-type welded truss tower)
	Diameter [m]	-
	Tower height [m]	-
	Hub [m]	95 - 100
	Tip [m]	165.3 - 170.3
	Mass [t]	-
Control		
	Cut-in system	-
	Logic system	-
Masses	Blade [t]	- per blade
	Rotor [t]	-
	Nacelle (incl. Helideck) [t]	-
	Total [t]	-
Performance	Lifetime [a]	40
	Maximum power [kW]	6.200
	Low wind cut-in [m/s]	3,0
	Rated power at [m/s]	13,0
	High wind cut-out [m/s]	-
	Survival wind speed [m/s]	-
	Helicopter landing platform	Yes (optional)
Certification		
	Class	IEC I
	Type approved	-
	Turbine design	-
	Quality accreditation	-

Appendix table 4: Turbine data sheet Envision Energy GC1 [Author's illustration]

	Company	Envision Energy
	Type	EN-128 3.6 PP 2B (or GC1)

Technical Specification

Rotor	Number of blades	2
	Rotor diameter [m]	128
	Rotor speed [rpm]	4 - 15 (nom. 14)
	Swept area [m²]	12.868
	Power densitity [W/m²]	279,8
	Orientation	Upwind
	Power control	Partial pitch control (PPC)
	Load control	None
	Hub	Rigid
	Blade material	-
	Yaw system	Active
	Yawing [°/second]	-
	Yaw brake	Passive spring pretension
	Brake system	Primary: Blade pitch Secondary: Mechanical hydraulic brake
	Aerodynamic efficiency	-
	Max. tip speed [m/s]	93
Gearbox	Type	None (direct drive)
	Stages	-
	Rated inlet torque [kNm]	-
	Peak inlet torque [kNm]	-
Generator	Type	Direct drive permanent magnet
	Nominal power [kW]	2x 1,900
	Number of poles	-
	Cooling system	-
Tower	Type	Tubular
	Diameter [m]	-
	Tower height [m]	-
	Hub [m]	88
	Tip [m]	152
	Mass [t]	-
Control		
	Cut-in system	-
	Logic system	PLC
Masses	Blade [t]	- per blade
	Rotor [t]	-
	Nacelle (incl. Helideck) [t]	-
	Total [t]	240
Performance	Lifetime [a]	-
	Maximum power [kW]	3.600
	Low wind cut-in [m/s]	3,0
	Rated power at [m/s]	approx. 9.5
	High wind cut-out [m/s]	25,0
	Survival wind speed [m/s]	-
	Helicopter landing platform	No
Certification		
	Class	IEC III
	Type approved	-
	Turbine design	-
	Quality accreditation	-

Appendix table 5: Turbine data sheet aerodyn SCD basic [Author's illustration]

	Company	aerodyn SCD		
	Type	Basic 3 MW		

Technical Specification

Rotor	Number of blades	2			
	Rotor diameter [m]	108	100	92	
	Rotor speed [rpm]	14,95	19,1	-	
	Swept area [m²]	9.161	7.854	6.648	
	Power densitity [W/m²]	327,5	382,0	451,3	
	Orientation	Upwind			
	Power control	Collective pitch control (CPC)			
	Load control	None			
	Hub	Rigid			
	Blade material	Glass - reinforced plastic			
	Yaw system	Active			
	Yawing [°/second]	0,5			
	Yaw brake	-			
	Brake system	Primary: Hydraulic single pitch	Secondary: Disc brake		
	Aerodynamic efficiency	0,461			
	Max. tip speed [m/s]	89,5			
Gearbox	Type	Planetary			
	Stages	2			
	Rated inlet torque [kNm]	-			
	Peak inlet torque [kNm]	-			
Generator	Type	Synchronous permanent magnet			
	Nominal power [kW]	3.110			
	Number of poles	-			
	Cooling system	-			
Tower	Type	Tubular			
	Diameter [m]	-			
	Tower height [m]	100 / 90 / 85 / 75			
	Hub [m]	85			
	Tip [m]	139			
	Mass [t]	-			
Control					
	Cut-in system	-			
	Logic system	PLC			
Masses	Blade [t]	-	-	-	per blade
	Rotor [t]	-	-	-	
	Nacelle (incl. Helideck) [t]	-	-	-	
	Total [t]	-	119	-	
Performance	Lifetime [a]	20			
	Maximum power [kW]	3.000	3000	3000	
	Low wind cut-in [m/s]	3,0	-	-	
	Rated power at [m/s]	11,0	-	-	
	High wind cut-out [m/s]	25,0	-	-	
	Survival wind speed [m/s]	59,5 - 70,0	-	-	
	Helicopter landing platform	No			
Certification					
	Class	IEC II A			
	Type approved	-			
	Turbine design	-			
	Quality accreditation	-			

Appendix table 6: Turbine data sheet aerodyn SCD advanced [Author's illustration]

	Company	aerodyn SCD	
	Type	Advanced 6 MW	
		Technical Specification	
Rotor	Number of blades	2	
	Rotor diameter [m]	140	130
	Rotor speed [rpm]	13,6	
	Swept area [m²]	15.394	
	Power densitity [W/m²]	389,8	
	Orientation	Downwind	
	Power control	Collective pitch control (CPC)	
	Load control	None	
	Hub	Rigid	
	Blade material	GFRP	
	Yaw system	Active	(passive in extreme load situations)
	Yawing [°/second]	0,5	
	Yaw brake	Hydraulic, 3 caliper	
	Brake system	Primary: Active yaw	Secondary: Disc brake
	Aerodynamic efficiency	0,461	
	Max. tip speed [m/s]	100	
Gearbox	Type	Planetary	(medium speed)
	Stages	2	
	Rated inlet torque [kNm]	4.755	
	Peak inlet torque [kNm]	?	
Generator	Type	Synchronous permanent magnet	
	Nominal power [kW]	>6000	
	Number of poles	24	
	Cooling system	-	
Tower	Type	Tubular	
	Diameter [m]	Foundation depending	
	Tower height [m]	Foundation depending	
	Hub [m]	100	
	Tip [m]	170	
	Mass [t]	Foundation depending	
Control			
	Cut-in system	-	
	Logic system	-	
Masses	Blade [t]	-	per blade
	Rotor [t]	-	
	Nacelle (incl. Helideck) [t]	-	
	Total [t]	308	
Performance	Lifetime [a]	20	
	Maximum power [kW]	6.000	6500
	Low wind cut-in [m/s]	3,5	
	Rated power at [m/s]	11,8	
	High wind cut-out [m/s]	25,0	
	Survival wind speed [m/s]	70,0	
	Helicopter landing platform	Yes	
Certification			
	Class	IEC II B	IEC I (North Sea)
	Type approved	B-Design Assessment	
	Turbine design	-	
	Quality accreditation	-	

Appendix table 7: Turbine data sheet aerodyn SCD nezzy [Author's illustration]

	Company	aerodyn SCD
	Type	Nezzy 8 MW (floating)
		Technical Specification
Rotor	Number of blades	2
	Rotor diameter [m]	168
	Rotor speed [rpm]	11,4
	Swept area [m²]	22.167
	Power densitity [W/m²]	360,9
	Orientation	Downwind
	Power control	Collective pitch control (CPC)
	Load control	None
	Hub	Rigid
	Blade material	GFRP, CFRP posible
	Yaw system	None
	Yawing [°/second]	-
	Yaw brake	-
	Brake system	4 caliper, electric
	Aerodynamic efficiency	0,461
	Max. tip speed [m/s]	100
Gearbox	Type	Planetary (medium speed)
	Stages	2
	Rated inlet torque [kNm]	7.187
	Peak inlet torque [kNm]	?
Generator	Type	Synchronous permanent magnet
	Nominal power [kW]	>8000
	Number of poles	24
	Cooling system	-
Tower	Type	Tubular
	Diameter [m]	Foundation depending
	Tower height [m]	Foundation depending
	Hub [m]	110
	Tip [m]	194
	Mass [t]	Foundation depending
Control		
	Cut-in system	-
	Logic system	-
Masses	Blade [t]	- per blade
	Rotor [t]	-
	Nacelle (incl. Helideck) [t]	-
	Total [t]	355
Performance	Lifetime [a]	25
	Maximum power [kW]	8.000
	Low wind cut-in [m/s]	4,0
	Rated power at [m/s]	11,8
	High wind cut-out [m/s]	25,0
	Survival wind speed [m/s]	70,0
	Helicopter landing platform	No
Certification		
	Class	IEC I B
	Type approved	C-Design Assessment
	Turbine design	-
	Quality accreditation	-

Appendix table 8: Turbine data sheet aerodyn SCD nezzy² [Author's illustration]

	Company	aerodyn SCD
	Type	Nezzy² 15 MW (floating)
		Technical Specification
Rotor	Number of blades	2
	Rotor diameter [m]	150
	Rotor speed [rpm]	12,7
	Swept area [m²]	35.343
	Power densitity [W/m²]	424,4
	Orientation	Downwind
	Power control	Pitch controlled
	Load control	IPC over blade bending moment
	Hub	Rigid
	Blade material	GFRP, CFRP possible
	Yaw system	None
	Yawing [°/second]	-
	Yaw brake	-
	Brake system	4 caliper, electric
	Aerodynamic efficiency	0,461
	Max. tip speed [m/s]	100
Gearbox	Type	Planetary (medium speed)
	Stages	2
	Rated inlet torque [kNm]	6.250
	Peak inlet torque [kNm]	-
Generator	Type	Synchronous permanent magnet
	Nominal power [kW]	2x >8000
	Number of poles	24
	Cooling system	-
Tower	Type	Tubular
	Diameter [m]	-
	Tower height [m]	-
	Hub [m]	90
	Tip [m]	165
	Mass [t]	-
Control		
	Cut-in system	-
	Logic system	-
Masses	Blade [t]	- per blade
	Rotor [t]	-
	Nacelle (incl. Helideck) [t]	-
	Total [t]	295
Performance	Lifetime [a]	25
	Maximum power [kW]	15.000
	Low wind cut-in [m/s]	3,0
	Rated power at [m/s]	12,3
	High wind cut-out [m/s]	25,0
	Survival wind speed [m/s]	70,0
	Helicopter landing platform	No
Certification		
	Class	IEC I B
	Type approved	Design Verification
	Turbine design	-
	Quality accreditation	-

Appendix table 9: Turbine data sheet Seawind 6.2 [Author's illustration]

	Company	Seawind	
	Type	6.2	
		Technical Specification	
Rotor	Number of blades	2	
	Rotor diameter [m]	126	
	Rotor speed [rpm]	20,8	
	Swept area [m²]	12.469	
	Power densitity [W/m²]	497,2	
	Orientation	Upwind	
	Power control	Active yaw controlled var. speed	(blades fixed angle)
	Load control	Teetered hub	
	Hub	Teetered	
	Blade material	-	
	Yaw system	Active	with four yaw motors (3 in operation)
	Yawing [°/second]	8	(with peaks of 10°/second)
	Yaw brake	-	
	Brake system	Primary: Active yaw	Secondary: Double disc brake (4,800 kNm)
	Aerodynamic efficiency	0,485	
	Max. tip speed [m/s]	131.9	
Gearbox	Type	Planetary	
	Stages	2,5	
	Rated inlet torque [kNm]	3.000	
	Peak inlet torque [kNm]	3.700	
Generator	Type	Asynchronous squirrel cage	
	Nominal power [kW]	6.600	
	Number of poles	8	
	Cooling system	Air with air-water heat exchanger	
Tower	Type	Tubular	
	Diameter [m]	5	
	Tower height [m]	-	
	Hub [m]	-	
	Tip [m]	-	
	Mass [t]	-	
Control			
	Cut-in system	-	
	Logic system	-	
Masses	Blade [t]	16,9	per blade
	Rotor [t]	-	
	Nacelle (incl. Helideck) [t]	-	
	Total [t]	320	
Performance	Lifetime [a]	>30	
	Maximum power [kW]	6.200	
	Low wind cut-in [m/s]	3,4	
	Rated power at [m/s]	12,4	
	High wind cut-out [m/s]	25,0	
	Survival wind speed [m/s]	90,0	
	Helicopter landing platform	Yes	
Certification			
	Class	IEC I	
	Type approved	-	
	Turbine design	-	
	Quality accreditation	-	

Appendix table 10: EnBW internal experts [Author's illustration]

Name	**Company**	**Field**	**Expertise**
Hentschel, Alexander	EnBW	O&M Offshore	Manager Operation EnBW Baltic 1
Kesch, Ludwig	EnBW	Controlling	Financial Model Specialist
Kuppe, Sebastian	EnBW	O&M Offshore	Manager Operation EnBW Baltic 2
Pietrzak, Karolina	EnBW	Project Development	Manager Project Development
Schlötels, Thomas	EnBW	Purchase	Project Purchasing Manager
Steinberg, Jan	EnBW	M&A	Finance, M&A and Investor Relations
Unterberger, Sven	EnBW	Technology Transfer	Consultant Business Development Generation
Warner, Markus	EnBW	Production Service	Project Engineer

Appendix table 11: Variety of the strongest recorded typhoons over the last decades [Author's illustration based on (Schwanke 2009)]

Typhoon name	Main location	Year	Category	Max wind speed m/s (1min)	Max wind speed m/s (10min)
Vera	Japan	1959	5	85	-
Nina	China	1975	4	69	-
Tip	Japan	1979	5	85	72
Herb	Taiwan/China	1996	5	72	49
Saomai	China	2000	5	72	49
Nari	Taiwan	2001	3	51	39
Tokage	Japan	2004	4	64	43
Haitang	Taiwan	2005	5	72	54
Matsa	China	2005	2	46	42
Talim	China	2005	4	67	49
Nabi	Japan	2005	5	72	49
Khanun	China	2005	4	-	43
Damrey	China	2005	2	46	42
Longwang	China	2005	4	64	49
Chanchu	Philippines/China	2006	4	64	49
Saomai	China	2006	5	72	54
Wipha	Taiwan/China	2007	4	61	46
Nuri	Hong Kong/China	2008	3	51	39
Morakot	Taiwan/China	2009	1	42	39
Roke	Japan	2011	4	60	43
Haiyan	Philippines	2013	5	88	64
Mangkhut	Philippines	2018	5	79	57

Affidavit

I hereby declare on oath that I have made the present thesis independently and without the use of other than the specified aids. The thoughts taken directly or indirectly from other sources (including electronic documents and the internet) are identified as such.

Place, date

Signature