Innovative decommissioning and upgrading concepts for offshore wind farms

Victoria Baden

Jarani Suntharalingam

Bachelor's thesis in Energy Technology

Bergen, Norway 2020

Høgskulen på Vestlandet

Assess concepts for future use of existing offshore wind farms for both fixed and floating structures

Victoria Baden

Jarani Suntharalingam

Department of Mechanical- and Marine Engineering

Western Norway University of Applied Sciences

NO-5063 Bergen, Norway

IMM 2020-M73

Høgskulen på Vestlandet

Fakultet for Ingeniør- og Naturvitskap

Institutt for maskin- og marinfag

Inndalsveien 28

NO-5063 Bergen, Norge

Norsk tittel:	Innovativ avvikling og oppgraderingskonsepter av havvindparker
Author(s), student number:	Victoria Baden, 572004
	Jarani Suntharalingam, 572006
Study program:	Energy Technology Engineering
Date:	May 2020
Report number:	IMM 2020-M73 (where XX: group ID.nr)
Supervisor at HVL:	Professor Richard J. Grant
Assigned by:	Equinor ASA
Contact person:	Dr. Wei He
Antall filer levert digitalt:	1

Preface

This thesis is carried out to conclude a Bachelor of Science. It is written at the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS), in the Energy Technology Engineering study programme. The internal academic supervisor from WNUAS is Professor Richard J. Grant. This thesis represents 20 credit points which corresponds to 540 working hours. The subject of the thesis was given by Dr. Wei He, of Equinor ASA.

The purpose of this thesis is to evaluate the end-of-life alternatives for offshore wind farms through a comprehensive analysis of costs. Important costs such as capital and operational expenditure will be considered. The thesis will evaluate the end-of-life scenarios; decommissioning, lifetime extension and repowering of offshore wind farms for both fixed bottom and floating structures. The offshore wind industry is relatively new and the market for end-of-life alternatives is still under development. However, the installation of offshore wind farms is increasing, thus decommissioning, lifetime extension and repowering will become important topics for the industry. It is our hope that this thesis can contribute to and inspire growth within the market for these end of life alternatives.

We highly appreciate the support and assistance received from a number of individuals and companies. Great thanks to our internal supervisor Professor Richard J. Grant at WNUAS. We would also like to thank Dr. Wei He, our supervisor at Equinor ASA. Furthermore, a special thanks goes to Christian Baden, for providing us with information and great help.

Bergen, May 2020

Abstract

The demand for more renewable and sustainable energy is rapidly growing. The enormous energy potential related to offshore wind, could potentially meet the increased global demand. In the period from year 2030 to 2040, roughly 20,000 wind turbines in Europe will reach the end of their service life. It is therefore urgent to assess the end-of-life alternatives for both fixed and floating offshore wind farms.

This thesis presents a comparison of the levelised cost of energy (LCOE) for different end-of-life alternatives for offshore wind farms. Two case-studies with two offshore wind farms; one with bottom-fixed foundations and one with floating foundations, have been examined for the following alternatives: decommissioning after 20 years, lifetime extension from 20 to 25 years, and innovative integration of early decommissioning and repowering.

The commercial offshore wind farms have been assessed by means of life-cycle cost analyses. It was revealed that both lifetime extension and repowering of a floating offshore wind farm would require a large capital expenditure.

An analysis of the relative LCOE, and a sensitivity analysis that enables the identification of potential cost savings, are included in this thesis. The relative LCOE revealed that the repowered scenarios will have significantly greater energy output compared to lifetime extension scenarios. Lifetime extension and repowering of the fixed offshore wind farm indicate an advantage over the base case by 5-11% on LCOE.

The sensitivity analysis clearly indicates that a reduction in installation time and turbine and floater costs, would provide a significant reduction in the LCOE for the floating concept. Even though the floating alternatives fail to surpass the economy of the base case, the calculated LCOE incorporating cost reductions indicates that repowering of floating offshore wind farms could potentially become a more favourable alternative. The expenses for the repowered scenarios will be offset by each operational year, thus bringing the LCOE down.

Overall, cost reductions will be possible for the following generations of offshore wind turbines, due to advancements in technology, manufacturing processes and a further developed market.

Sammendrag

Denne avhandlingen presenterer en sammenligning av levelised cost of energy (LCOE) for ulike alternativer når havvindparker når slutten av deres levetid. To casestudier med to havvindparker; en med fast fundament og en med flytende fundament, har blitt undersøkt for følgende alternativer: avvikling etter 20 år, forlengelse av levetid fra 20 til 25 år, og innovativ integrering av tidlig avvikling og oppgradering.

De kommersielle havvindparkene har blitt evaluert ut ifra livssyklus kostnadsanalyser. Resultatene viser at både forlengelse og oppgradering av en flytende havvindpark krever store kapitalutgifter.

En analyse av de relative LCOE verdiene, og en følsomhetsanalyse som muliggjør identifisering av potensielle kostnadsbesparelser, er inkludert i denne avhandlingen. De relative LCOE verdiene viste at oppgradering scenariene vil ha betydelig større energiproduksjon sammenlignet med forlengelse av levetid scenariene. Både forlengelse av levetid og oppgradering av havvindparken med fast fundament indikerer en fordel i LCOE i forhold til base case med 5-11%.

Følsomhetsanalysen indikerer tydelig at en reduksjon i installasjonstiden og turbin- og fundamentkostnadene vil gi en betydelig reduksjon i LCOE for den flytende havvindparken. Til tross for at de flytende alternativene ikke overgår økonomien til base case, indikerer den beregnede LCOE verdien som inkluderer kostnadsreduksjonene at oppgradering av flytende havvindparker potensielt kan bli et gunstigere alternativ. Utgiftene til de oppgraderte scenariene vil jevnes ut for hvert driftsår, og dermed redusere LCOE.

Helhetlig sett vil kostnadsreduksjoner være mulig for de følgende generasjonene av havvindmøller grunnet fremskritt og utvikling innen teknologi, produksjonsprosesser og et videreutviklet marked.

Table of Contents

PREFACE VI

ABSTRACT VIII

SAMMENDRAG X

ABBREVIATIONS AND TERMINOLOGY XV

1. INTRODUCTION 1

1.1 Background 1

1.2 Aim and objectives 2

1.3 Assumptions 3

1.4 Limitations 3

2. LITERATURE SURVEY 4

2.1 Offshore Wind 4

2.1.1 Offshore Wind Turbine - Generic design 4

2.1.2 Costs associated with offshore wind farms 9

2.2 The Market Today 9

2.3 End of Life Alternatives: decommissioning, lifetime extension and repowering 11

2.4 Economic models and analyses 12

2.4.1 Megavind's LCOE Model 14

3. CASE STUDY 16

3.1 End of life alternatives: decommissioning, lifetime extension and repowering 16

3.1.1 Comparing the three scenarios for OWFs with fixed foundations 17

3.1.2 Comparing the three scenarios for OWFs with floating foundations 17

3.2 Analyses **18**
3.2.1 Life-Cycle Cost Analysis 19
3.2.2 Levelised Cost of Energy 21
3.2.3 Sensitivity Analysis 22

4. RESULTS **27**

4.1 LCOE **27**

4.2 SA **29**
4.2.1 Reduction of LCOE for fixed concept 29
4.2.2 Reduction of LCOE for floating concept 32

5. DISCUSSION **33**

6. CONCLUSION AND FURTHER WORK **37**

6.1 Conclusion **37**

6.2 Suggestions to further work **39**

6.3 Sources of error **40**

7. REFERENCES **41**

LIST OF FIGURES **44**

LIST OF TABLES **45**

ATTACHMENTS **46**

Abbreviations and Terminology

ABEX = Abandonment expenditure

CAPEX = Capital expenditure

CB = Cost breakdown structure

DEVEX = Development expenditure

GW = Gigawatt [1 GW = 1000 MW]

LCCA = Life-cycle cost analysis

LCOE = Levelised cost of energy

m€ = Million euro

MW = Megawatt [1 MW = 1,000,000 W]

MWh = Megawatt hour [1 MWh = 1,000,000 Wh]

OPEX = Operating expenditure

OWF(s) = Offshore wind farm(s)

OWT(s) = Offshore wind turbine(s)

SA = Sensitivity analysis

SOV = Service operation vessel

WACC = The weighted average cost of capital

Wh = Watt hour, one watt (1 W) of power expended for one hour (1 h) of time

WT(s) = Wind turbine(s)

1. Introduction

1.1 Background

The offshore wind energy industry is rapidly growing, as the demand for renewable and sustainable energy increases. Offshore wind farms (OWFs) have enormous energy potential related to large areas and strong wind conditions which implies greater power generation. The two main concepts for OWFs are bottom-fixed and floating structures, and the use of these are determined by the water depth.

In 2019 Europe added 3.6 GW net offshore capacity, thereby gaining a total installed wind capacity of approximately 22 GW [1]. As Figure 1 shows the offshore wind market will grow significantly over the next three decades, with the total installed capacity rising from 23 GW in 2018 to 228 GW in 2030 and near 1000 GW in 2050 [2].

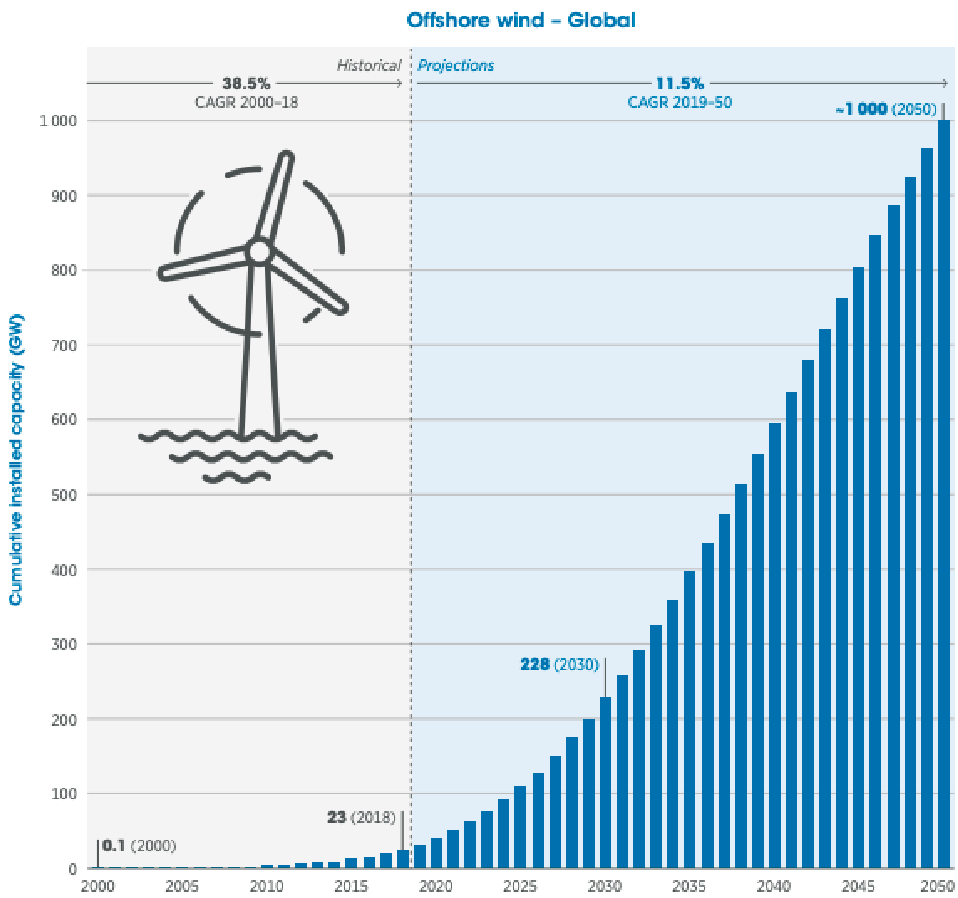

Figure 1 - Offshore wind power deployment growth (2000-2019) and predicted growth (2020-2050) [2]

With the demand and production of offshore wind increasing, end-of-life alternatives for OWFs has recently emerged as a topic of major interest. Nearly 30% of the total installed wind turbine capacity in Europe will surpass 15 years by 2020 [3].Given that the average wind turbine service life is 20 years, there is an urgent need to assess the different end-of-life alternatives, in which the cost of energy is an important issue. When the OWF has reached the end of its service life, wind farm operators will decide between decommissioning, lifetime extension or repowering the site.

In order to achieve WindEurope's target production capacity of 450 GW from OWFs in 2050 [4], effort has been directed towards evaluating and driving down the LCOE. According to IRENA the global weighted-average LCOE was 127 USD/Wh in 2018, which is 1% lower than in 2017 and 20% lower than in 2010 [5]. This thesis will analyse the profitability of the different end-of-life scenarios for upscaled OWFs for bottom-fixed and floating structures.

1.2 Aim and objectives

The aim for this thesis is to assess concepts for future use of existing OWFs for both fixed and floating structures. Thus, evaluating the end-of-life alternatives for upscaled OWFs considering the levelised cost of energy.

In order to achieve this aim, the thesis will be executed by accomplishing a number of objectives:

1. Conduct a life-cycle cost analysis (LCCA) for a fixed-bottom OWF with 88 units of 3.6 MW and a floating OWF with 50 units of 8 MW. This will be based on development, capital, operating and abandonment expenditure.

2. Evaluate the levelised cost of energy (LCOE) for both concepts considering the end-of-life alternatives.

3. Compare the total power generation and the LCOE of the two OWFs.

4. Generate a cost breakdown (CB) of the LCCA and perform sensitivity analyses (SA) to identify sensitive variables. This will reveal the factors that could give a significant change in the LCOE.

1.3 Assumptions

General assumptions have been made to give the reader some initial overall information. These assumptions are as follows:

1. All offshore wind turbines are configured with a horizontal axis (HAWT).

2. All fixed foundations that are being referred to are bottom-fixed monopile foundation.

3. All floating foundations that are being referred to are floating spar buoy foundations.

4. Cost analyses are mainly calculated through Megavind's simplified official open-source methodology for calculating LCOE for a wind project [6].

5. The OWF in the analyses are for commercial use, and not pilot projects.

6. The location used is taken as a Northern European site with an area of approximately 35 square kilometres.

7. Currency used is in euro (sign: €; code: EUR) if other is not specified. Any conversions are based on the conversion rate at 03.05.20
   → USD to EUR = 0.913

1.4 Limitations

There are many uncertainties related to the data used in the analyses due to lack of available information, which is as a result of commercial confidentiality and/or the emergence of new and developing technologies. Fundamentally, the offshore wind energy sector is a developing industry. In addition to the market for decommissioning, lifetime extension and repowering still being developed.

2. Literature survey

A literature survey of scientific reports, research articles, previous studies and statistical material has been undertaken to be able to analyse expenditures related to OWFs based on the given assumptions.

2.1 Offshore Wind

2.1.1 Offshore Wind Turbine - Generic design

On- and offshore wind turbine designs are quite similar, though exact designs may vary. The wind turbines operate on the simple principle of converting kinetic energy in the wind to mechanical rotational motion which in turn is used to drive an electric generator to produce electrical energy. Almost all wind turbines used today are horizontal axis machines. A simple turbine consists of a two or three bladed rotor spinning in a vertical plane. The rotor is attached to the front of the main shaft, which spins the generator – either directly or through a gearbox. This is all fitted inside a housing called the nacelle; named after the fairing around an aircraft engine. Occasionally a high-voltage transformer is also fitted inside the nacelle. These components are mounted on top of a tower, as shown in Figure 2.

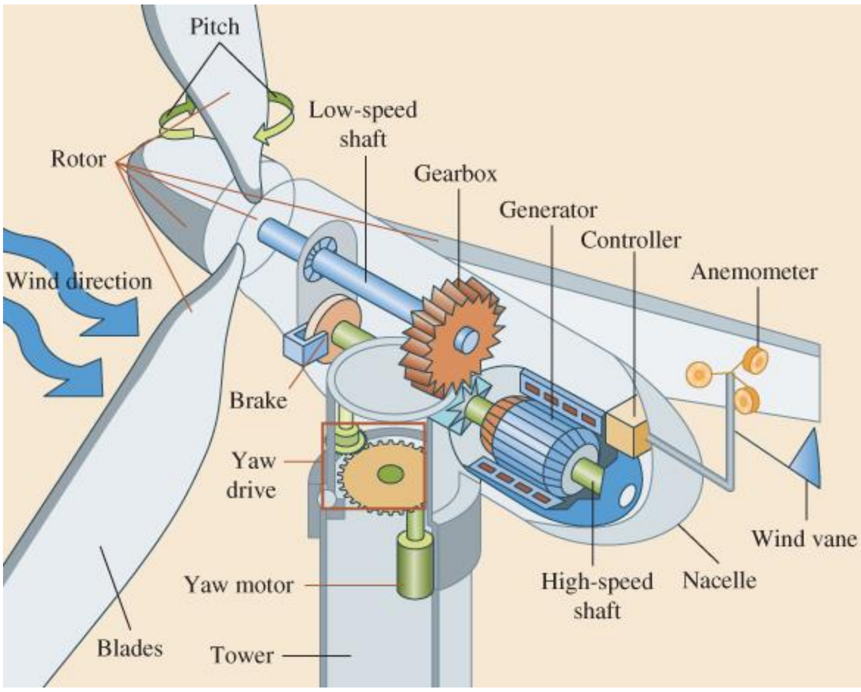

Figure 2 - The Inside of a Wind Turbine [7]

Wind turbines (WTs) are often classified by their power output, hence their physical size. The most powerful offshore wind turbine (OWT) in the world is the GE Haliade-X which features a 12 MW capacity. One such turbine can generate up to 67 GWh of gross annual energy production, which would be sufficient to provide electricity to an estimated number of 16,000 average EU households [8]. Compared to the onshore counterpart, the offshore wind energy has greater resource potential, which generally increases with distance from the shore [9]. Although offshore winds are not necessarily stronger, they are typically more consistent with a greater average wind speed [10].

The foundation of the OWT depends on various factors such as wind speeds, water depth, and soil conditions. Figure 3 gives an illustration of the different concepts.

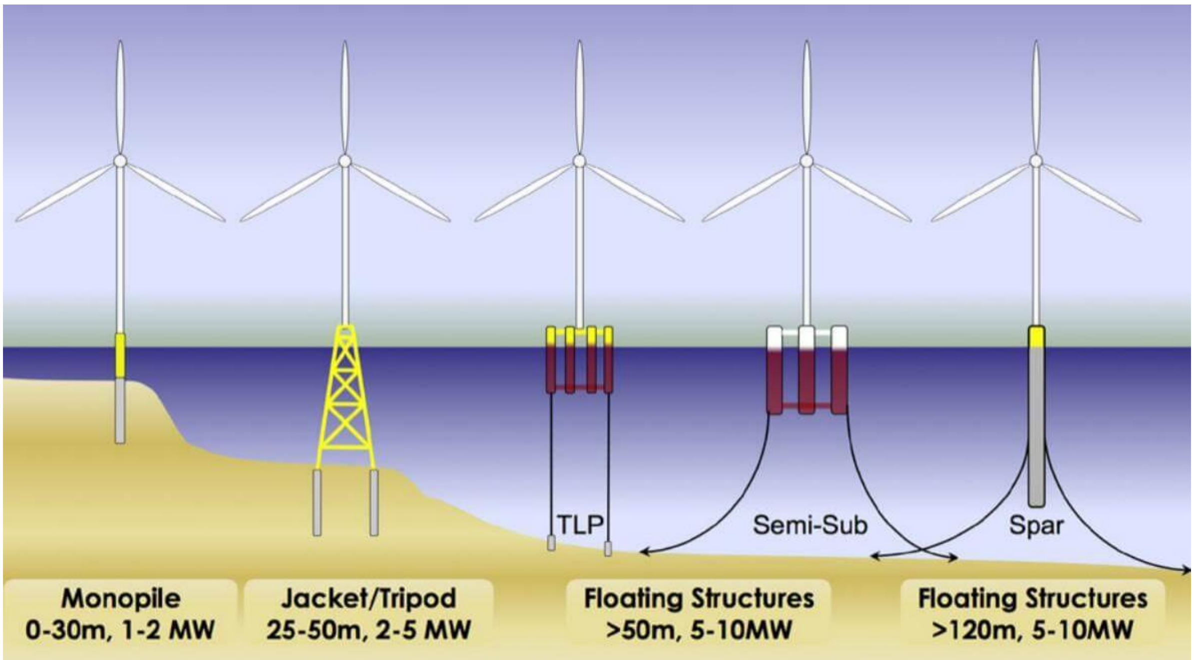

Figure 3 - Bottom-fixed foundations and floating offshore concepts* [11]

*The mooring systems are not to scale in the horizontal direction

The most used bottom-fixed concept is the monopile. The monopile is both the simplest and cheapest type of foundation, and it is frequently used in the North Sea. The need for more consistent wind resources has made developers explore floating concepts, as these concepts allow the possibility of harnessing higher quality wind energy in deeper waters. The most commonly used floating concept is the spar buoy [12]. This concept is widely used by Equinor ASA in their Hywind projects, where stability is provided by gravity. The floating support designs are familiar from the oil and gas industry. The WTs are moored to the seabed with multiple mooring lines and anchors, similar to how the floating oil platforms are moored [13].

The capacity factor is a measure of how much of the maximum capacity the WT is actually generating each day. A capacity factor of 100% would indicate that a WT was generating at the maximum power output every second of the day [14]. Elements that can influence the capacity factor are the geographic location, the rotor swept area, hourly wind profile, and the energy loss considering the expected downtime due to maintenance [15].

The installation time for OWFs varies, among other things, by the number of units in the farm, the capacity of the WTs and the foundation. Bottom-fixed WTs have an easier installation process as they are installed closer to shore in shallow water depths. Furthermore, Europe has a mature and well-proven monopile technology, as this foundation is the preferred technology for water depths between 36 and 60 metres [16]. Floating WTs require vessels to transport the WTs further at sea, which can prolong the installation time. The actual assembly and installation of the WTs may take a few days, but the installation of the foundation is time-consuming. According to WindEurope, a 10 MW wind farm can easily be built in two months, and a larger 50 MW wind farm can be built in six months [17]. Developers with more experience and better technology can presumably install OWFs at a faster rate.

Fixed foundation

OWTs with fixed foundations are suitable for depths up to ~50 metres. Figure 4 illustrates a monopile foundation. These are usually installed close to the shore and will therefore have a capacity factor of around 40-60% depending on the site [14]. An example is Equinor's Sheringham Shoal, located in the southern North Sea, where the capacity factor is roughly 40% [18]. The OWTs with fixed foundation use more mature technology and are therefore generally cheaper to install and operate than floating concepts.

Figure 4 - Monopile foundation [19]

Floating foundation

For waters deeper than 50 metres, there is a need for a different approach. Floating platforms are able to withstand both the powerful wave and wind force that occur. Figure 5 shows a spar buoy foundation, the most commonly used floating OWT. These WTs needs to be installed in waters deeper than 100 metres [20]. The floater is attached with mooring lines that are anchored to the seabed with multiple mooring lines and anchors. Equinor's Hywind Scotland, located offshore Aberdeenshire, Scotland, is an OWF using the spar buoy concept. This OWF has a capacity factor of roughly 50% [18].

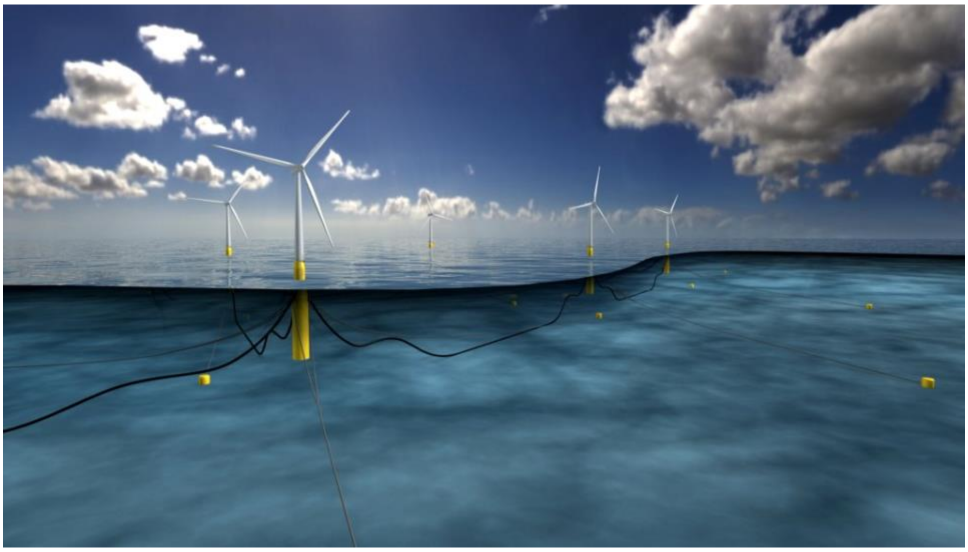

Figure 5 - Spar buoy foundation [21]

The spar buoy platform consists of a cylinder with low water plane area, installed with a ballast to keep the centre of gravity below the centre of buoyancy. The platform is held in place by catenary or taut spread mooring lines with drag or suction anchors [20].

Some beneficial aspects of floating concepts are the improved wind conditions which are prevalent where there are deeper waters, less visual impact, and reduced wave loading and installation costs. The disadvantages are mainly the high capital and operating expenses, and the need for more accurate simulation tools that are capable of analysing and optimising these complex systems [22].

2.1.2 Costs associated with offshore wind farms

As the technology in the offshore wind sector is improving, in the future, it is likely that the OWFs will have similar costs to onshore wind farms. With a lower cost and higher capacity, it is reasonable to consider OWFs to be a more appealing energy source in the future [9]. A frequently used method to determine whether an energy project is an attractive business investment or not, is by calculating the levelised cost of energy (LCOE).

There are often unpredicted weather and logistical challenges associated with OWTs, as these turbines are harder to reach when installed at sea. Maintenance of OWTs is more expensive than similar maintenance of onshore WTs. This is mainly due to increased complexity of offshore access and associated weather limitations. Costs associated with the operating expenditure can vary with the day rate of the service operation vessels (SOV), the salary rate of manpower, the number of workers, and days required for maintenance per turbine.

2.2 The Market Today

The market for offshore wind energy is growing rapidly and offshore wind has emerged as an essential part of the future electricity mix. As the market for wind energy advances, the costs will potentially be driven down. The LCOE for offshore wind projects declined by 1% from 2017 to 2018 [5]. The main factors for this reduction have been innovations in WT technology; larger rotor diameters, improved capacity factors due to higher hub heights and better wind resources.

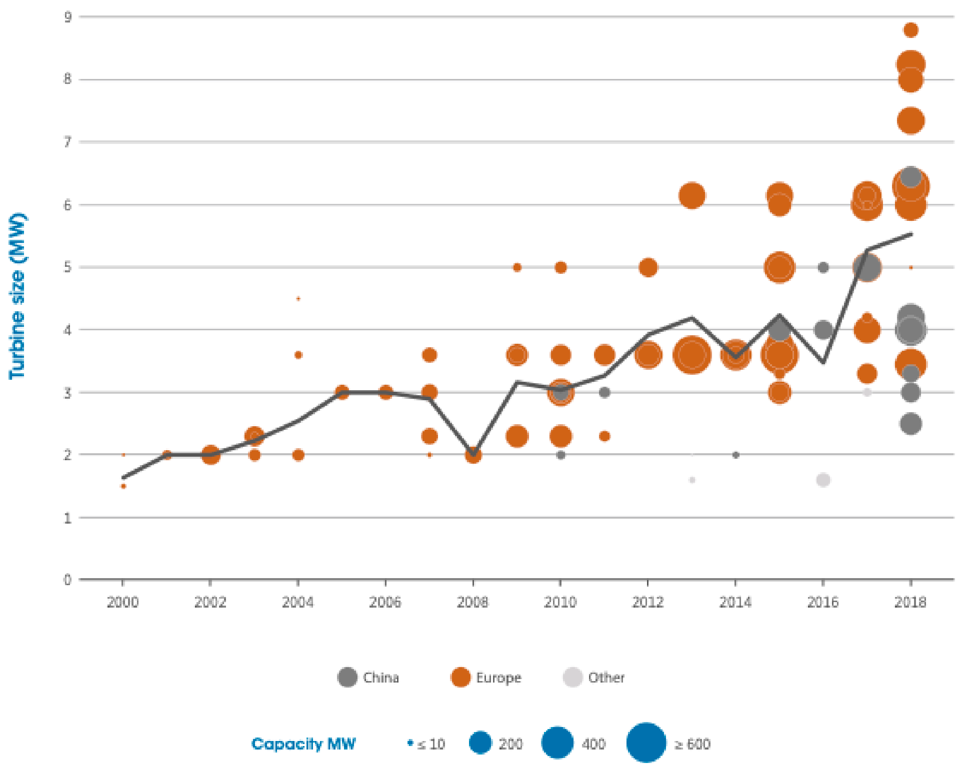

Figure 6 - Turbine size for commissioned offshore wind projects and global weighted average (2000-2018) [5]

Figure 6 shows the trend of larger turbines for offshore wind projects. The increase in capacity, which scales down the number of turbines required for a given capacity, reduces development and installation costs [5]. The average capacity factor for OWFs in 2018 was 43%, while an increment up to 60% can be achieved in 2050 [2].

Furthermore, a shift to OWFs being located in deeper waters, using floating WTs, allows the turbines to operate at higher efficiency with better wind resources. Equinor has estimated that 80% of the world's offshore wind resource potential lies in waters deeper than 60 metres [13]. Thus, floating OWFs may be the next breakthrough in renewable energy. It is a growing market and as of 2017, the first operational floating wind farm, Hywind Scotland, was commissioned with five floating turbines with a total capacity of 30 MW [23]. In the third quarter of 2022, Hywind Tampen is due to start up. It will be the world's first floating wind farm which powers offshore oil and gas platforms. This OWF will be a testing ground for further development of floating wind and the use of new and larger WTs.

The market for decommissioning and/or repowering for OWFs is still immature. However, it is estimated that between 4.3 and 5.3 GW of new installations will come from repowering projects during 2019 to 2023. The repowering volume could increase from 400 MW in 2019 to 1.5 GW by 2023 [24]. In 2016, Yttre Stengrund, the first offshore wind energy project was decommissioned [25]. In the years to come, the volume of decommissioned OWFs will rapidly increase as more wind farms reach the end of their service lives, thus expanding and further developing the decommissioning market.

The existing SOVs are not sufficient to support installation demand after 2020. As the WTs are becoming greater in size and capacity, the SOVs are forced to develop to handle the upscaled WTs. The projected growth in this market over the next decade insinuate that there is a need for specifically built vessels and modifications of existing ones. Especially for floating OWFs, which is further from shore, the requirement for larger vessels is expected to increase [26].

2.3 End of Life Alternatives: decommissioning, lifetime extension and repowering

An OWF is expected to have a lifetime of 20 to 25 years [27]. Figure 7 shows the annual number of OWTs that reaches the end of their service life in Europe. This leads to a question of what happens to an OWF when it reaches the end of its service life. It is therefore important to look into innovative decommissioning and upgrading concepts for an OWF.

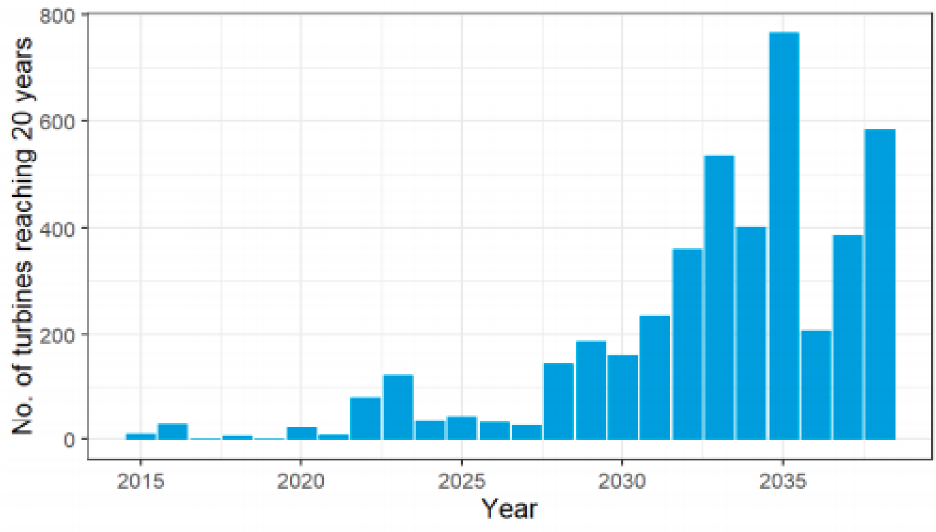

Figure 7 - Number of OWTs reaching 20 years of operation annually in Europe [28]

There are a few alternatives to consider when wind farms reach the end of their service life and no longer generating power. Between year 2030 and 2040, roughly 20,000 WTs in

Europe will be facing these end-of-life alternatives [28].

One alternative is to fully decommission the wind farm after 20 years, as the turbines will no longer be able to generate energy efficiently. In this thesis decommissioning is referred to as all the measures performed to return the site as close to its original state as reasonably possible. Parts of the WT that are weakened in strength or worn out, will most likely go through material recycling or energy recovery [29]. However, there is a possibility of parts being reused directly or after refurbishment, for other purposes or in other turbines.

In some cases, with refurbishments and upgrades, lifetime extension could be a viable alternative. The wind farm will then be able to operate an additional ~5 years before being decommissioned, depending on the condition of the WTs. Lifetime extension updates some of the components, despite that the overall external layout of the wind farm remains unchanged.

Lastly, the farm could be repowered to be able to operate for an additional ~20 years before being decommissioned. This requires replacing the WTs with fewer, greater power output turbines. Repowering intends to create higher power generation within the same ocean space.

2.4 Economic models and analyses

In order to calculate the costs associated with OWFs, available data needs to be collected. Where data is unavailable, reasonable assumptions will be made. Economic models and analyses will be performed in order to get a techno-financial insight into the offshore wind industry, especially considering decommissioning and upgrading concepts for OWFs.

Quantitative research

Numerical data has been obtained from the literature survey in order to be able to populate the models and carry out analyses.

Life-cycle cost analysis (LCCA)

This analysis involves costs from a cradle-to-grave perspective, related to development (DEVEX), capital (CAPEX), operating (OPEX) and abandonment expenditure (ABEX).

The DEVEX is defined as the costs associated with research and development. This expenditure involves the money spent on the research process for developing a new project.

The CAPEX covers the expenses of new capital, which includes all costs from the chosen foundation concept, to the WT and its structure. This expenditure is a summation for all the WTs on a farm.

The OPEX includes the costs of operating and the maintenance of the wind farm. This includes the cost of a SOV, and the number of days required for service.

The ABEX is defined as all expenses related to abandonment of the farm from the termination date. This concerns the cost of abandonment vessel and the disposal of non-recyclable components.

Levelised cost of energy (LCOE)

LCOE is often used as an alternative for the average price that the power generating system must receive in a market to break even over its lifetime [30]. The LCOE is given as

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Equation 1 - LCOE formula

where the terms are

I_t: Investment expenditures in year t

M_t: Operations and maintenance expenditures in the year t

F_t: Fuel expenditures in the year t

E_t: Electrical energy generated in the year t

r: discount rate

n: expected lifetime of the system [31].

In the article “*Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*” by Bjerkseter and Ågotnes, the scope is to investigate the LCOE of current state-of-the-art offshore floating concepts, where both floating and fixed wind farms are discussed.

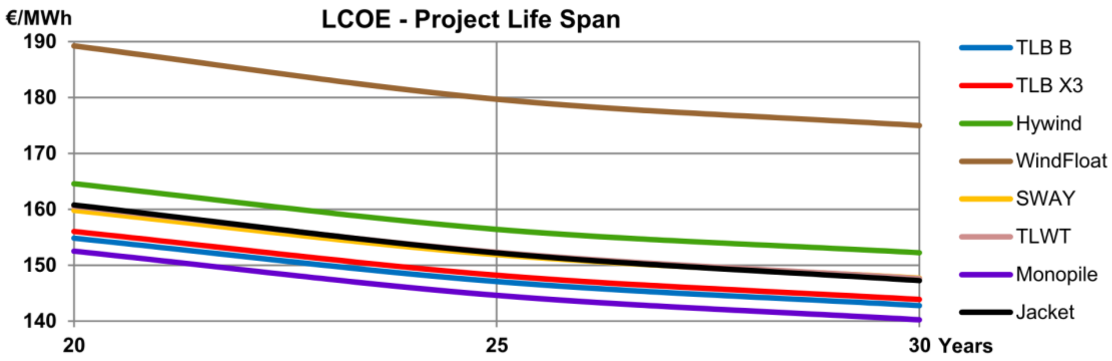

Figure 8 - LCOE - Project Life Span [22]

Based on the assumptions in the article, one would expect to find an economical advantage with respect to the LCOE when increasing the turbine lifetime to 30 years. [22]. This thesis will mainly look into the Hywind (spar buoy) and the monopile concept. Figure 8 shows that the LCOE for both of these concepts improves as the project life span increases. After 20 years of operating, the LCOE for the Hywind and the monopile concept is roughly €165 per MWh and €152 per MWh, respectively.

Sensitivity analysis (SA)

The purpose of this analysis is to evaluate how changes in different parameters in the LCCA will affect the LCOE. By creating a cost breakdown structure (CB), one can identify which variables that have the most significant effect on the LCOE. This analysis will ultimately quantify the degree of uncertainty in a parameter.

2.4.1 Megavind’s LCOE Model

Megavind is Denmark’s national partnership for wind energy, and acts as a catalyst and initiator for a stronger strategic agenda for research, development and demonstration [32]. The Megavind’s simplified official open-source methodology for calculating LCOE allows the user to enter data in a standardised way and obtain realistic LCOE values. However, the output values depend on the methodology used. Thus, one planned wind farm can have different estimates of the LCOE value due to different calculation methods. The calculator, which is a mathematical formula, mirrors methods that are already used by the offshore wind industry to assess the cost elements when deciding to invest in a wind project.

$$LCOE = \frac{Present\ value\ (Cost)}{Present\ value\ (Production)}$$

Equation 2 - Megavind's simplified LCOE formula

The equation above is a simplified version of Equation 1 - LCOE formula, and the formula in Megavind's LCOE model. This expresses the levelised unit cost of 1 MWh over the wind farms lifetime.

The structure of the LCOE model is illustrated in Figure 9. An appendix of the guidelines and documentation for the LCOE model is attached to give the reader a clearer understanding of the cost analyses.

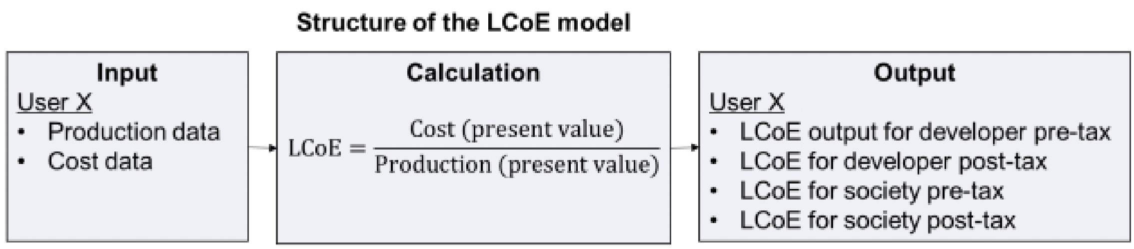

Figure 9 - Structure of Megavind's LCOE model [32]

3. Case study

3.1 End of life alternatives: decommissioning, lifetime extension and repowering

Two case studies are being performed for two types of OWFs; one with fixed foundations and one with floating foundations. For both case studies their expected lifetime is shown in Figure 10, and the scenarios that are being examined are as follows:

Scenario 1) Decommissioning of the OWF after 20 years (base case)

Scenario 2) Lifetime extension from 20 to 25 years

Scenario 3) Decommissioning of the OWF after 15 years and then repowering the site

For the lifetime extension scenario, it is likely that the failure rate for the OWTs may increase somewhat for the final 5 years of service. Also, some of the OWTs may fail with a failure mode that results in them being decommissioned rather being repaired. Consequently, there may be a loss of output for this alternative, but this has not been quantified and not been incorporated in the analyses.

The repowering alternative has not been optimised in terms of service life for the initial development. Likewise, a potential life extension of the repowered plan has not been considered. Such optimizations lie outside the scope of this thesis.

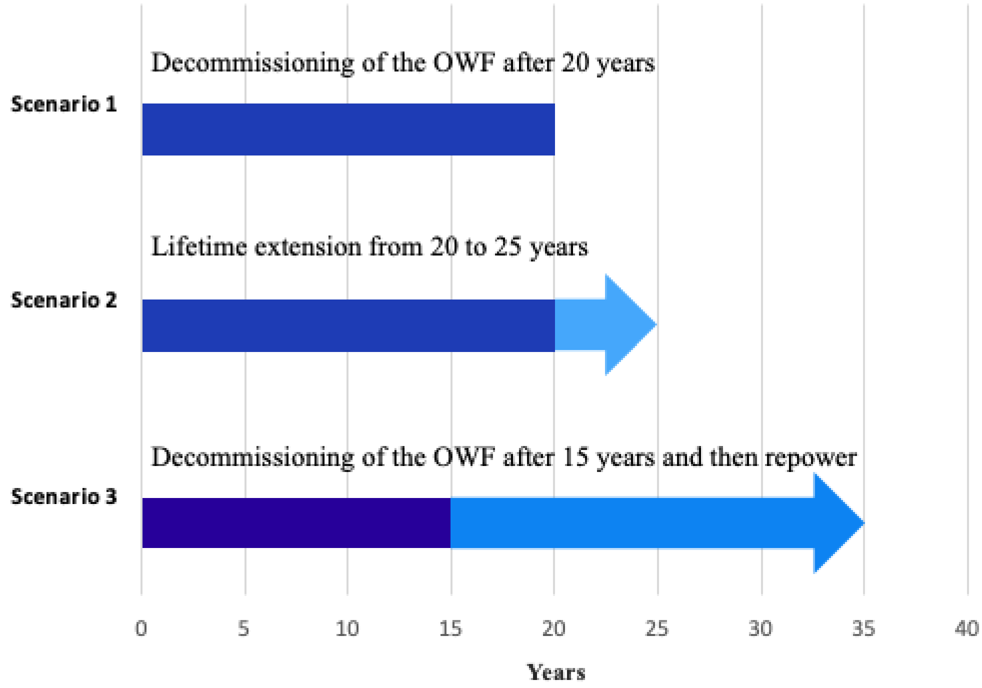

Figure 10 - Assumed lifetime of the OWF during different scenarios

3.1.1 Comparing the three scenarios for OWFs with fixed foundations

Scenario 1 is the base case, which is already designed and installed, and will be the case to compare the other scenarios to. The OWF has 88 units of 3.6 MW WTs with a design life of approximately 20 years. It will be decommissioned after these 20 years have elapsed. Scenario 2 has the same number of WTs and capacity as scenario 1, however the lifetime of the OWF will be extended from 20 to 25 years and decommissioned afterwards. Lastly, scenario 3 is an innovative integration of early decommission and repowering. It will replace the 88 units of 3.6 MW with 40 units of 20 MW WTs, after year 15. The 40 new units will then operate for 20 years; thus, the total power generation capacity will increase from 317 MW to 800 MW, using the exact same site.

3.1.2 Comparing the three scenarios for OWFs with floating foundations

Similarly, to the three scenarios for the OWF with fixed foundations, scenario 1, the base case is already designed and installed. It has 50 units of 8 MW which is decommissioned after their design life of 20 years. Scenario 2 has the same capacity and the number of WTs as scenario 1, but its lifetime is extended from 20 to 25 years, before it is decommissioned. Scenario 3, which incorporates early decommissioning and repowering, will replace 50 units of 8 MW with 40 units of 20 MW WTs. This results in the total electrical power generation capacity being doubled, from 400 to 800 MW.

3.2 Analyses

Cost assumptions

In order to assume how the 20 MW OWTs would be designed, assumptions and calculations had to be made, as currently no such turbines are available; not even in prototype form. All assumptions have been made based on the literature and data collected, including data from the wind industry, and the oil and gas sector. These assumptions are as shown below:

- Capacity factor for fixed foundations: 40%
- Capacity factor for floating foundations: 50%
- Day rate of a service operation vessel: €100 thousand
- Days required for maintenance: 4.15 days per turbine per year
- Norwegian corporate tax rate: 22% [33]
- Turbine cost: €1.2 per watt [34]
- Floater cost: €1.075 per watt [34]
- Cost of mooring lines: €0.45 per watt [34]
- Installation cost per fixed turbine: €0.055 million per turbine
- Installation cost per floating turbine: €4 million per turbine
- Day rate of an abandonment vessel: €100 thousand
- Cost of disposal of non-recyclable components per turbine: €0.3 million per turbine

3.2.1 Life-Cycle Cost Analysis

The life-cycle cost is calculated based on the assumptions given in 3.2 - Analyses and will be referred to throughout this chapter. For each parameter in the LCCA, the input variables and calculated costs are shown in the tables below.

The development phase generally consists of finding a site, examine the site characteristics and planning of the farm design. It is also necessary to apply for permissions and licenses, calculate the financing, and survey public engagement. This phase will usually take 1.5 to three years [35]. For the DEVEX, it is assumed that there are 20 workers with a cost of €280 per hour each, working 1,700 hours a year for presumably three years. The three-year research and development period is set as the time spent on planning the wind farm design and calculating the financial aspects. Thus, this expenditure is only associated with the research process of developing the project.

Table 1 - Development Expenditure

DEVEX		
Manpower	20.00	
Cost per year	9.52	m€
No. of years	3.00	years
Total:	28.56	m€

The CAPEX includes the assumptions for cost of turbines, floater, mooring lines and the installation. The total installation cost for the fixed concept incorporates the cost of a drill vessel of €0.25 million per day and a three-day installation cost per turbine. The total installation cost for the floating concept is calculated excluding a drill vessel cost. The cost of life extension is calculated for scenario 2 purposes only and contains the cost for 10 workers with a cost of €0.476 million per worker. This calculation is independent of time i.e. the time needed to refurbish, and the downtime is not taken into account.

Table 2 - Capital Expenditure

CAPEX (FIXED 3.6MW)		
No. of turbines	88.00	units
Turbine rating	3.60	MW
Total cost turbines:	380.16	m€
Total installation cost:	70.84	m€
Cost life extension:	4.76	m€
Total w/o extention:	451.00	m€

CAPEX (FLOATING 8MW)		
No. of turbines	50.00	units
Turbine rating	8.00	MW
Total cost turbines:	1,090.00	m€
Total installation cost:	200.00	m€
Cost life extension:	4.76	m€
Total w/o extention:	1,290.00	m€

CAPEX (FIXED 20MW)		
No. of turbines	40.00	units
Turbine rating	20.00	MW
Total cost turbines:	960.00	m€
Total installation cost:	32.20	m€
Total:	992.20	m€

CAPEX (FLOATING 20MW)		
No. of turbines	40.00	units
Turbine rating	20.00	MW
Total cost turbines:	2,180.00	m€
Total installation cost:	160.00	m€
Total:	2,340.00	m€

The operation, maintenance and service per turbine cost is calculated as a function of the day rate for SOV and the days of work per turbine, which are given in the assumptions. To simplify future calculations, these costs have been calculated for 5, 15 and 20 years.

Table 3 - Operating Expenditure

OPEX (FIXED 3.6MW)		
Operation, maintenance and service per turbine	0.42	m€/year
No. of years	20.00	years
Total:	730.40	m€
No. of years	15.00	years
Total:	547.80	m€
No. of years	5.00	years
Total:	182.60	m€

OPEX (FLOATING 8MW)		
Operation, maintenance and service per turbine	0.42	m€/year
No. of years	20.00	years
Total:	416.00	m€
No. of years	15.00	years
Total:	312.00	m€
No. of years	5.00	years
Total:	104.00	m€

OPEX (FIXED 20MW)		
Operation, maintenance and service per turbine	0.91	m€/year
No. of years	20.00	years
Total:	730.40	m€

OPEX (FLOATING 20MW)		
Operation, maintenance and service per turbine	0.42	m€/year
No. of years	20.00	years
Total:	332.80	m€

The total ABEX is calculated as a function of the day rate for the abandonment vessel and the cost of disposal of non-recyclable components per turbine, which is given in the assumptions.

Table 4 - Abandonment Expenditure

ABEX (FIXED 3.6MW)		
No. of days per turbine	3.00	days
Total:	26.70	m€

ABEX (FLOATING 8MW)		
No. of days per turbine	3.00	days
Total:	15.30	m€

ABEX (FIXED 20MW)		
No. of days per turbine	3.00	days
Total:	12.30	m€

ABEX (FLOATING 20MW)		
No. of days per turbine	3.00	days
Total:	12.30	m€

3.2.2 Levelised Cost of Energy

MegaVind's simplified LCOE model

The calculations for the LCOE in this thesis are calculated through Megavind's official open-source methodology for calculating LCOE for a wind project. The analysis includes calculations considering the parameters in the LCCA; DEVEX, CAPEX, OPEX and ABEX. Neither annual degradation nor the internal rate of return (IRR) has not been taken into account due to the analysis focusing on calculating the LCOE with a simplified method and emphasising the total expenditures. Default assumptions have been used when available, except for when custom values were required in order to reflect the instances considered. Some of the costs such as cables, substations, and grid-connection are not included in the calculation. Excluding the cost of these items may affect the results and provide a lower LCOE than realistically attainable. The numbers are plotted into the Megavind LCOE model following the model's guidelines [32].

The output variables obtained from Megavind's LCOE model are shown in the tables below.

Table 5 - LCOE for fixed concept

	Parameter	LCOE EUR/MWh
Scenario	**LCOE**	
1 (base case)	LCOE, developer, post-tax	119.7
2	LCOE, developer, post-tax	114.2
3	LCOE, developer, post-tax	106.2

Table 6 - LCOE for floating concept

	Parameter	LCOE EUR/MWh
Scenario	**LCOE**	
1 (base case)	LCOE, developer, post-tax	181.2
2	LCOE, developer, post-tax	174.3
3	LCOE, developer, post-tax	172.0

The LCOE shown in the tables are calculated for the purpose of the developer. When comparing the LCOE of the different scenarios, the result will give a relative LCOE with respect to the base case, scenario 1.

3.2.3 Sensitivity Analysis

A cost breakdown (CB) of the LCCA gives an overview of what percentage of the total expenditure each component makes up. It is important to look at the major expenditures to acknowledge where potential savings can be made, as the largest item of expenditure will yield the greatest saving. It is common to include both high- and low cases to present the bestand worst-case scenarios. However, a worst case, with increased costs, has not been considered as such for this thesis. Due to the general trend of decreasing prices in the wind sector, the cost information used in this thesis is considered conservative as the cost-data mainly stems from 2017-2019. Consequently, the costs (before applying reductions) can be regarded as worst case costs. The focus in the sensitivity analyses is on revealing which factors contribute the most to potentially lowering the LCOE

Scenario 2 will only extend the service life by 5 additional years. It is therefore reasonable to assume that the wind farm will not require any excessive investments due to the moderate increase in service life. The changes made in the SA will show variables that will not be considered as an option for the extra 5 years. Accordingly, this analysis has only been performed for the base case and scenario 3, since the expenditures in scenario 3 differs the most from the base case.

Fixed concept

The figures below illustrate the CB of the LCCA for the base case and scenario 3. The OPEX constitutes the largest portion of the expenditures for the base case, whereas the CAPEX makes up 52% of the expenses for scenario 3. The CAPEX accounts for 52%, while the OPEX accounts for 46%. Even though the CAPEX is marginally larger than the OPEX for scenario 3, the first 15 years of the farm will have a similar CB of the LCCA as scenario 1, hence reducing the factors in the OPEX for both the base case and scenario 3.

Scenario 1 - fixed concept

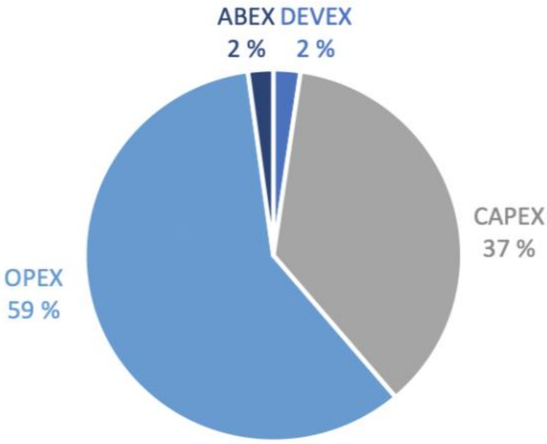

Figure 11 - CB of the fixed concept OWF (Scenario 1)

Scenario 3 - fixed concept

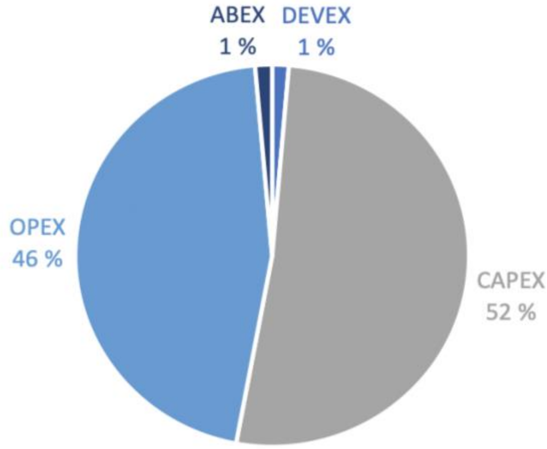

Figure 12 - CB of the fixed concept OWF (Scenario 3)

The two factors that contribute to the OPEX is; the number of days of work per turbine per year and the day rate for a SOV. Sensitivity analyses for these factors will be performed for scenario 1 and 3, for the fixed OWF, to see how it affects the LCOE. Thus, reducing the cost for number of days of work per turbine by a percentage of 5, 10 and 20 for the base case and scenario 3. In addition to also reducing the day rate for the SOV by a percentage of 20, 30 and 40, hence lowering the total value of the OPEX and the LCOE.

Floating concept

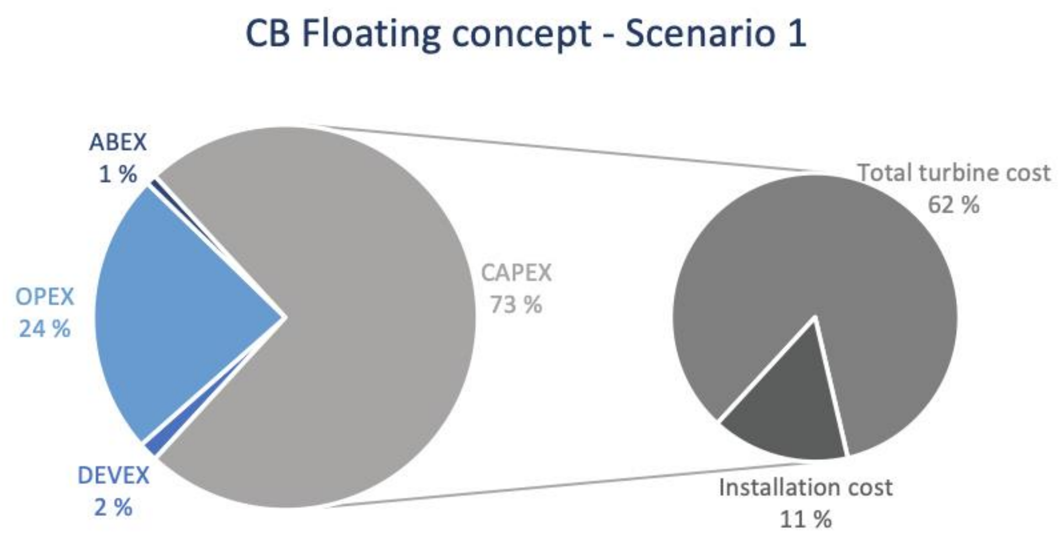

Figure 13 - CB of the floating concept OWF

As shown in Figure 13, the CB is dominated by the CAPEX. It amounts to 73% of the total LCCA. The CAPEX involves costs associated with the total turbine cost and installation, where the total turbine costs at 62% is the largest expense.

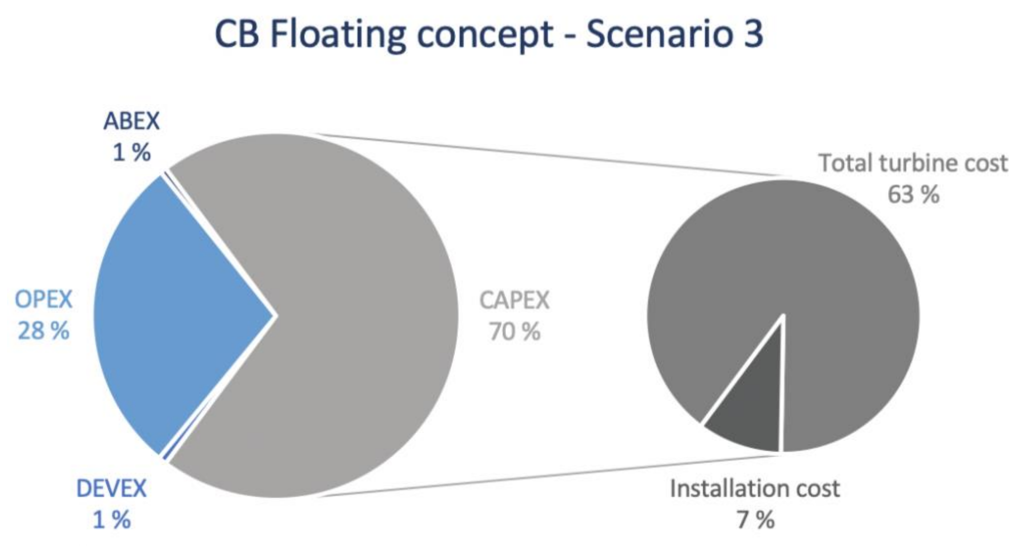

Figure 14 - CB of the floating concept OWF

Figure 14 shows the CB of the LCCA for scenario 3, where the CAPEX accounts for 70% of the total. Accordingly, the CB of the CAPEX shows that the total turbine cost is the largest expense.

For both the base case and scenario 3, the total turbine cost is the largest expense involved in the CAPEX. This total cost is estimated at €1090 million and €3270 million for scenario 1 and 3, respectively. From the set assumptions, the cost of each turbine is at €1.2 per watt.

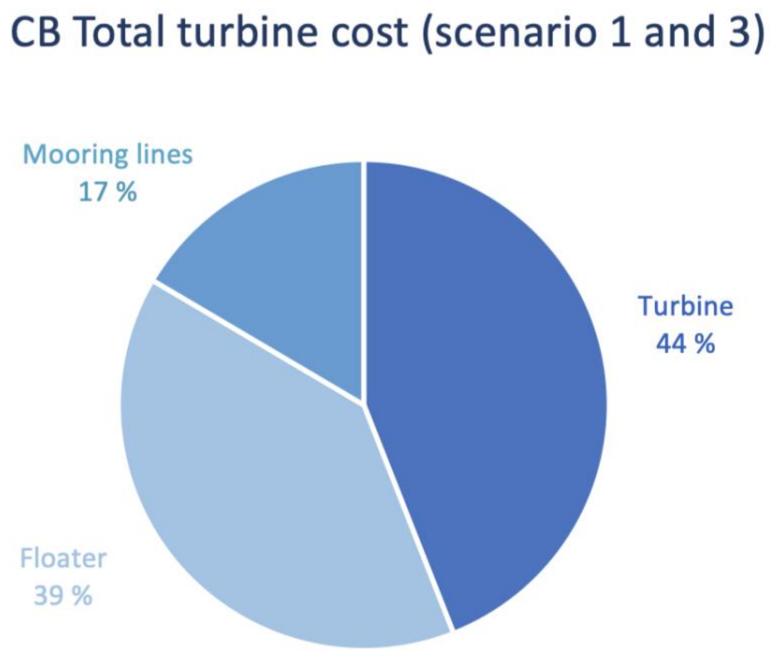

Figure 15 - CB of the turbine cost for the floating concept

The CB of the total turbine cost shows that the expense of the turbine accounts for 44% of the total turbine cost for both scenarios. The costs associated with the total turbine costs are dependent variables. These variables depend on the power output of the turbine given in watts [W]. Due to the turbine cost being the largest expense, it is necessary to look into the sensitivity associated with the turbine itself. An analysis of this cost will reveal how sensitive this factor is and give perspective on how it affects the LCOE. For that reason, a percentage reduction of 20, 30 and 40 has been made for the base case and scenario 3.

Comparing change in installation time

To achieve a higher power output the installation time can be shortened. By reducing this variable, the wind farm gains additional operating time, which results in a higher revenue stream. Accelerating the installation time will typically result in some increased costs due to the extended operating time, this is however not taken into account for this analysis. As this cut in installation time will potentially decrease the LCOE, a reduction of 3, 6 and 9 months has been made and examined for the base case and scenario 3.

4. Results

The following section includes results of the LCOE calculations for the three scenarios, for both concepts. A sensitivity analysis has been performed, to understand what variable changes are necessary in order to decrease the LCOE.

4.1 LCOE

The relative LCOE is calculated to be able to compare the results for scenario 2 and 3 with the base case.

Table 7 - Relative LCOE for fixed concept OWF

FIXED CONCEPT					
	Scenario 1: Decommissioning after 20 years (base case)	**Scenario 2: Lifetime extension from 20 to 25 years**	**Scenario 3: Decommissioning & repowering**		
Return Period	*20 years*	*25 years*	*20 years*	*25 years*	**35 years*
Power generation over period (capacity factor: 0.4) [TWh]	22	28	31	45	73
LCOE (relative to the basecase)	1	0.95	0.99	0.94	0.89

* Total 35 years consists of the original OWF operation of 15 years plus the repowered OWF operation for another 20 years.

In scenario 2 there is a reduction of 5% relative to the base case. The extension of five years gives an increased power generation of 6 TWh. The results for scenario 3 are shown at 20, 25 and 35 years to be able to give a meaningful comparison to scenario 1 and 2. After 20 years the LCOE compared to the base case will decrease by 1%, while the power generation increases by 9 TWh. An additional 5% reduction of the LCOE will follow after the next five years, which gives a total output of 45 TWh after 25 years. However, the results for the total lifetime of 35 years, show a LCOE reduction of 11%, as well as 73 TWh generated power.

Table 8 - Relative LCOE for floating foundation

FLOATING CONCEPT					
	Scenario 1: Decommissioning after 20 years (base case)	**Scenario 2: Lifetime extension from 20 to 25 years**	**Scenario 3: Decommissioning & repowering**		
Period	*20 year*	*25 year*	*20 year*	*25 year*	**35 year*
Power generation over period (capacity factor: 0.5) [TWh]	35	44	44	61	96
LCOE (relative to the basecase)	1	1.05	1.11	1.07	1.03

* Total 35 years consists of the original OWF operation of 15 years plus the repowered OWF operation for another 20 years.

The LCOE in scenario 2 increases by 5% relative to the base case, as the power generation gains an output of additional 9 TWh. Similar to Table 7, the results for scenario 3 are shown at 20, 25 and 35 years. 20 years into scenario 3, the relative LCOE will be 11% greater than for the base case. The power generated will be 44 TWh, which is an increase of 9 TWh. An additional five years will give a power output of 61 TWh over the 25-year period. The LCOE will have declined 4% from 20 to 25 years. Furthermore, the power generated will be an additional 35 TWh with a LCOE reduction of 4% from year 25 to 35.

4.2 SA

4.2.1 Reduction of LCOE for fixed concept

Reduction of number of days of work per turbine (per year)

The loss of energy production, due to heavy maintenance on the WTs, is taken into account (with loss of production) and compared to less demanding maintenance where the WTs are still operating (without loss of production). The calculated LCOE will be given in percentage relative to the base case.

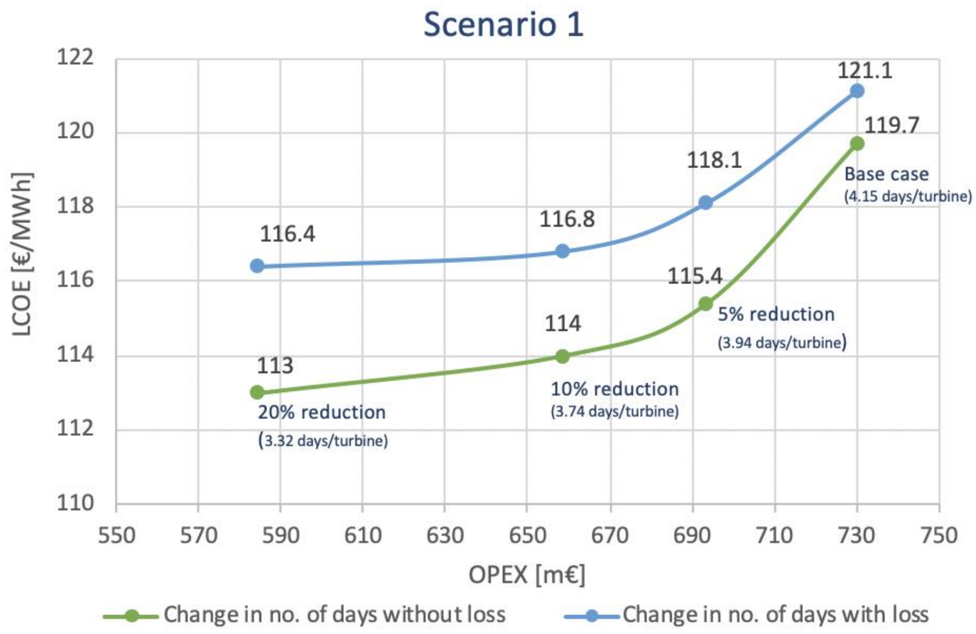

Figure 16 - Comparing change in no. of days of work per turbine with and without loss of production

If the number of maintenance days per turbine is reduced by 5% for the OPEX, with and without loss of production, the LCOE will decrease by approximately 2.5% and 3.6%, respectively. With a reduction of 10%, the LCOE will decrease by 3.6% with loss, and 4.8% without loss of production. The 20% reduction gives a lower LCOE by 3.9% with loss and 5.6% without loss.

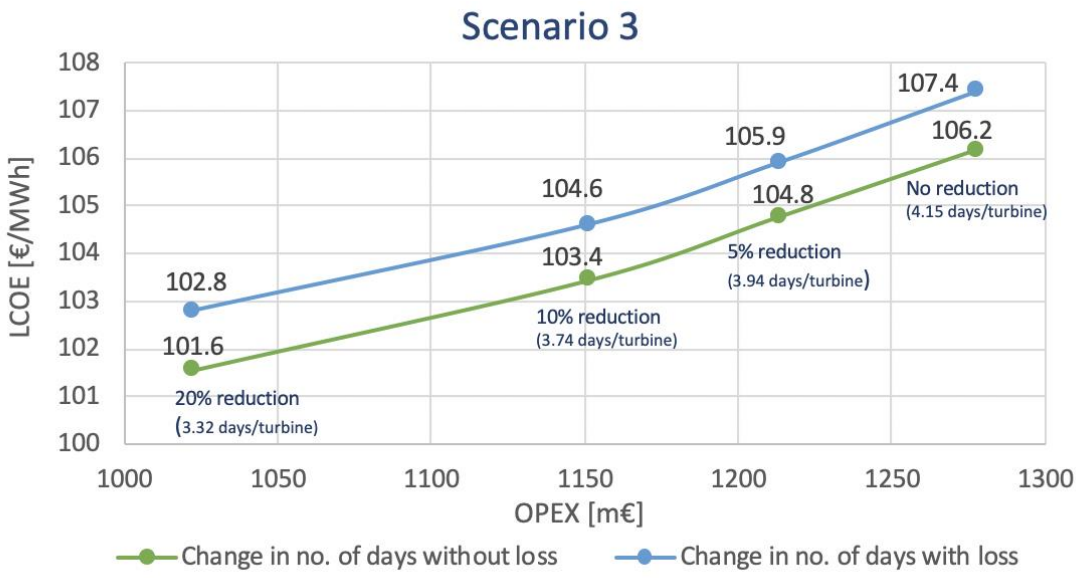

Figure 17 - Comparing change in no. of days of work per turbine with and without loss of production

When reducing the number of maintenance days per turbine by 5% for with and without loss of production, the LCOE will decrease by almost 1.4% and 1.3%, respectively. The 10% reduction reduces the LCOE by 2.6% for both with and without loss of production. The reduction of 20% gives a lower LCOE by 4.3% for both cases of reduction in number of days of work.

Reduction in the day rate for SOV

The LCOE acquired by the analysis, will be given in percentage relative to the base case or the case of no reduction.

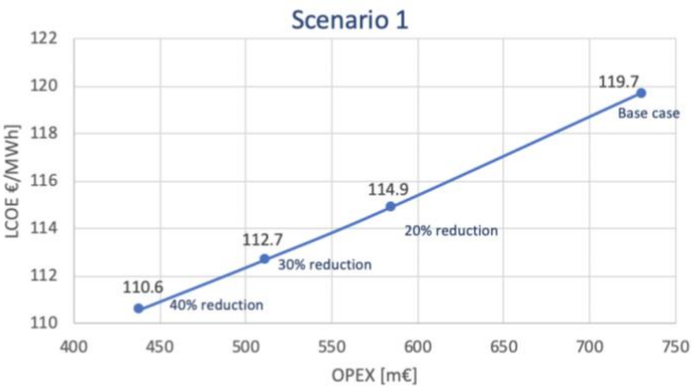

Figure 19 - Change in day rate for SOV (scenario 1)

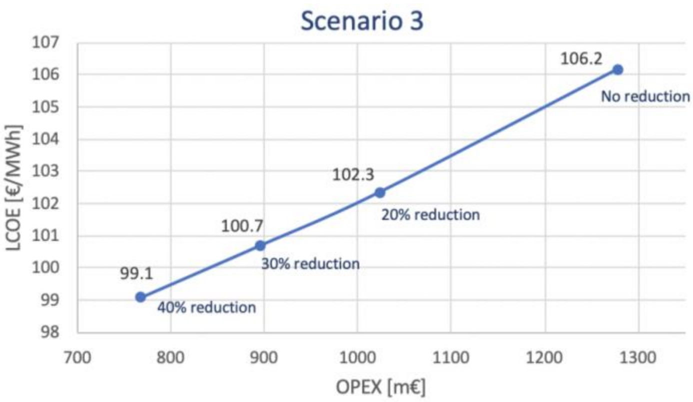

Figure 18 - Change in day rate for SOV (scenario 3)

For the base case, a reduction of 20, 30 and 40% decreases the relative LCOE by roughly 4, 6 and 8%, respectively. The 20% reduction in day rate for scenario 3, will reduce the relative LCOE by almost 4%. While a reduction of 30% in day rate, reduces the LCOE by roughly 5% compared to no reduction. Lastly, the 40% reduction in day rate gives a relative LCOE reduction of almost 7%.

4.2.2 Reduction of LCOE for floating concept

Reduction in turbine and floater costs

The improvement in LCOE resulting from the reductions in acquisition and installation costs, will be expressed as a percentage relative to the base case or the case of no cost reduction.

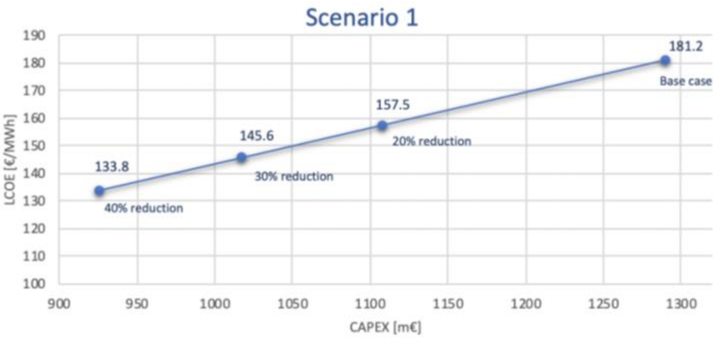

Figure 20 – Turbine and floater cost (scenario 1)

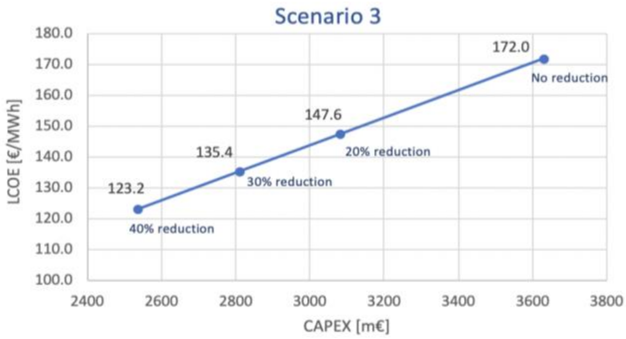

Figure 21 - Turbine and floater cost (scenario 3)

For the base case, a reduction of 20% in acquisition and installation costs decreases the LCOE by roughly 13.1%. A cost reduction of 30 and 40% reduces the LCOE by 19.6% and 26.2%, respectively. For scenario 3, a reduction of 20% in turbine and floater costs gives a reduced LCOE by 14.2%. Reductions of 30 and 40% reduces the LCOE by 21.3% and 28.4% respectively.

Reduction in installation time

The change in installation time has been reduced from twelve months to nine, six and three months. The improvement of the LCOE resulting from the reductions will be expressed as a percentage relative to no reduction in installation time (12 months).

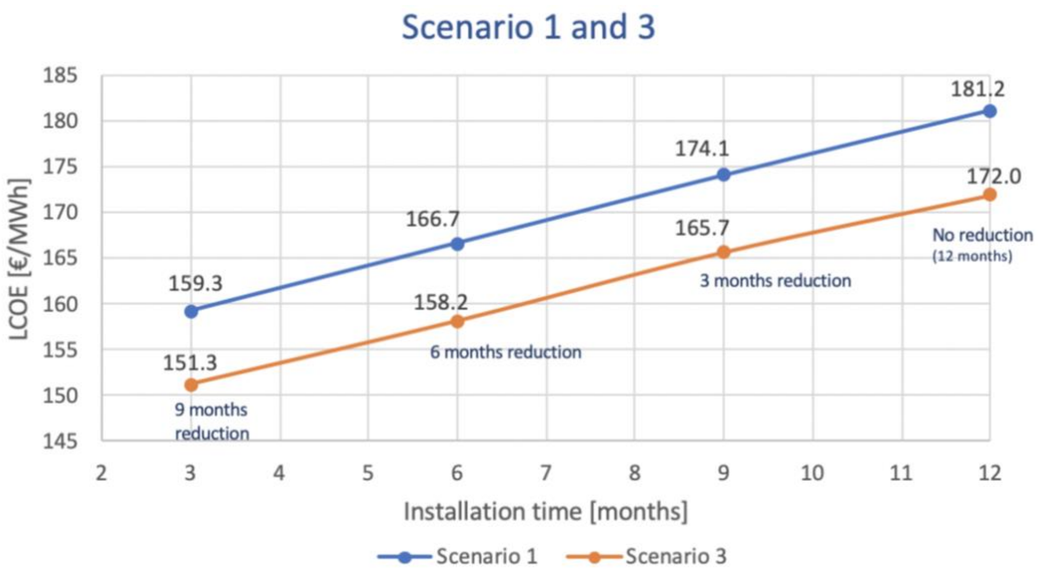

Figure 22 - Comparing change in installation time for floating foundations

Reducing the installation time by 3 months implies that the WTs are installed in 9 months. A reduction of 3, 6 and 9 months in installation time for both the base case and scenario 3, reduces the LCOE by roughly 4, 8 and 12%, respectively.

5. Discussion

The results discussed are relative to the base case and rounded up to the nearest whole number.

Scenario 2 - Lifetime extension

The reduction in LCOE shows that lifetime extension of a fixed OWF is effective in reducing the LCOE by 5%, as seen in Table 7. The additional operating years did result in an increased OPEX and CAPEX due to refurbishment, but this was offset by the farm producing an additional 6 TWh over the 5-year extension period, providing an enhanced revenue stream of ~5%. This clearly shows a marginal, but potentially worthwhile benefit in reducing the LCOE.

In contrast to the fixed concept, the LCOE for lifetime extension of the floating OWF increased as a result of a larger CAPEX. The CAPEX is €839 million more costly for the floating than fixed concept. This may have been caused by the turbine and floater cost, in addition to the cost for mooring lines. However, the refurbished WTs had a power output of 9

TWh for the additional operating years. The 5% increase in the LCOE indicates that this may not currently be a profitable investment.

Scenario 3 - repowering

Repowering of the OWF, requires a large CAPEX for both concepts. The developer invests in two projects: 15 years with more units, but less capacity, and 20 additional years with less units of greater capacity. It is likely that the expenses will decline as the market for commercial use of OWFs matures. The fixed concept clearly showed a significantly lower LCOE relative to the base case. The LCOE for the floating concept was increased by 3%, yet the power generated will be an additional 61 TWh. For both the fixed and floating concept, the LCOE will decrease for each year during the farms service life of 35 years. It is therefore reasonable to expect an even lower relative LCOE value for the next generations of OWFs that will be decommissioned and repowered; the model used for the future cost estimates is based on current technological development.

Reductions in the OPEX

Table 9 - Comparison of the LCOE for the fixed concept with cost reductions

FIXED CONCEPT				
Days of work per turbine				
	No reduction LCOE [€/MWh]	Reduction	LCOE with reduction	Potential savings
Base case:	119.7	20%	113.0	6.7 €/MWh
Scenario 3:	106.2	20%	101.6	4.6 €/MWh
Day rate for SOV				
	No reduction LCOE [€/MWh]	Reduction	LCOE with reduction	Potential savings
Base case:	119.7	40%	110.6	9.1 €/MWh
Scenario 3:	106.2	40%	99.1	7.1 €/MWh

Table 9 shows the greatest reductions from the SA and the potential savings that could be made. The reduction in number of days of work per turbine was performed considering both with and without loss of production. In this table, only the WTs without loss of production are shown, since this option resulted in a larger reduction of the LCOE. It is clear that the LCOE for either scenarios are not significantly affected by the reduction of maintenance days; hence, the LCOE is not overly sensitive to this change in variable. These savings are only applicable for future wind farms; therefore, this reduction is not achievable for the base case, which is already designed and installed. There are, however, potential savings to be made in scenario 3, through advancements in design with specification driven to minimise the maintenance requirement, a reduction in LCOE could be achievable.

As seen in Table 9, a 40% reduction of the day rate for a SOV provided a potential saving of €7.1 per MWh for the repowering scenario. This shows that the use of cheaper vessels could significantly affect the LCOE. The literature survey has revealed that the cost of these vessels is increasing, it is therefore reasonable to assume that this cost reduction is not likely to happen in the near future; but highlights the importance of keeping costs down in this area.

Reductions in the CAPEX

Table 10 - Comparison of the LCOE for floating concept with cost reductions

FLOATING CONCEPT				
Turbine and floater costs				
	No reduction LCOE [€/MWh]	Reduction	LCOE with reduction	Potential savings
Base case:	181.2	40%	133.8	47.4 €/MWh
Scenario 3:	172.0	40%	123.2	28.8 €/MWh
Installation time				
	No reduction LCOE [€/MWh]	Reduction	LCOE with reduction	Potential savings
Base case:	181.2	9 months	159.3	21.9 €/MWh
Scenario 3:	172.0	9 months	151.3	20.7 €/MWh

The reductions and possible savings of the LCOE for the floating concept is shown in Table 10. A reduction in turbine and floater costs would drive down the CAPEX; a dependent variable of the LCOE. The base case obtained a greater saving, however, a significant reduction of the LCOE was seen for both the base case and scenario 3. The LCOE is markedly sensitive to changes in this variable, accordingly, turbine and floater costs should be given a prominent position when considering an investment in new energy projects. These costs are expected to reduce as the floating wind industry develops and matures. Based on this, the potential savings modelled should be highly attainable in the future.

The reduction in installation time results in additional available operating time, thus a greater power output for the farm. The results in Table 10 showed that the LCOE is highly sensitive to this variable change. A significant LCOE reduction is attainable, since this thesis has assumed a very generous estimated installation time of 12 months.

Relative LCOE incorporating the cost reductions

Table 11 - Comparison of the relative LCOE for scenario 3 with cost reductions

Scenario 3	
Fixed concept	
Relative LCOE without reductions	0.89
Relative LCOE with reductions	0.79
Floating concept	
Relative LCOE without reductions	1.03
Relative LCOE with reductions	0.68

The reduction in days of work per turbine and the day rate of SOV, resulted in a decreased relative LCOE of 10%. This confirms that the LCOE is not significantly sensitive to change in these variables. While, a reduction in turbine and floater cost and installation time, reduced the relative LCOE by 35% and achieved a relative value of 0.68. Thus, clearly indicating that repowering of a floating offshore wind farm has the potential to become a more favourable alternative.

Most importantly, these cost reductions are expected to be possible for the following generations of OWTs due to advancements in technology, manufacturing processes, manufacturing scale, and a further developed market.

6. Conclusion and further work

6.1 Conclusion

This thesis has assessed concepts for future use of existing OWFs for both fixed and floating structures with the end-of-life alternatives; lifetime extension, decommissioning and/or repowering, considering the levelised cost of energy.

- The relative LCOE for the fixed concept, scenario 2, indicates that lifetime extension of a farm is effective in reducing the LCOE. The additional power output shows a potentially significant financial benefit in reducing the LCOE.
- The floating concept with lifetime extension had a relative LCOE increase of 5%. This

indicates that this project may not be a profitable investment, unless costs associated with the lifetime extension can be reduced

- Early decommissioning and repowering require the developer to invests in two projects: 15 years with more units, but less capacity, and 20 additional years with less units of greater capacity. This project is therefore costly; however, it is reasonable to conclude that the expenses will be offset by each operational year and thus bringing the LCOE down.
- The relative LCOE for the fixed concept, scenario 3, revealed a substantially lower value. It is also reasonable to state that the maintenance costs associated with the OPEX will further decline for the next generation of OWFs.
- In addition, with potential savings revealed in the SA, scenario 3 FX might be an even more attractive investment decision.
- To achieve an even lower LCOE for the fixed concept with repowering, a cheaper service operation vessel (SOV) will have a significant impact on the LCOE.
- For the floating concept with decommissioning and repowering, the LCOE increased by 3%, although the farm produced 96 TWh over the 35-year period.
- A reduction in turbine and floater cost for the floating OWF with decommissioning and repowering, will decrease the LCOE considerably. The LCOE is highly sensitive to changes in the installation time. Thus, reducing the installation time and gaining additional operating time, gives an even lower LCOE and an enhanced revenue stream.
- It is highly plausible that the expenses related to scenario 3, will decrease as the market for commercial use of OWFs matures: the floating foundation and mooring systems are currently at a 1st generation stage. Cost reductions will be possible for the following generations of OWTs, due to advancements in technology, manufacturing processes, manufacturing scale, and a further developed market.

When comparing scenario 2 and 3, the repowered cases will have a significantly greater power output with a longer total lifetime. For the future, with advances in technology and a more developed market, the floating OWF with greater capacity might be more favourable. The OWFs should be designed with repowering in mind. Planning ahead of this, will reduce the costs associated with early decommissioning and repowering, in addition to making the process easier; so, reducing costs.

6.2 Suggestions to further work

Further research should focus on detailed costs which can contribute to evaluate factors sensitive to changing the LCOE. Seeing as the cost analyses are based on rough assumptions, it is crucial to compose a more detailed cost breakdown. One should also examine the CAPEX for a floating OWF that is being repowered, as this cost was shown to be greater than the OPEX but not explored. To be able to get improved results, a more accurate simulation tool that is capable of analysing and optimising these complex systems, is necessary.

Another suggested work for the future is to include the annual degradation losses when calculating the annual energy generation, as this impacts the LCOE. It would also be beneficial to investigate the costs related to cables, substations and grid-connection to potentially yield a higher energy generation. The costs for the monopile foundation should also be included in future cost analyses.

The reuse and reselling of WTs or their components should be examined, as this could drive down the CAPEX, which further decreases the LCOE. It will also be important to find a good solution for recycling the blades and assessing the environmental impact.

The failure rate for the OWTs which may increase in the lifetime extension scenarios, could lead to loss of output and should be incorporated in the analyses. Also, a potential life extension of the repowered plan should be looked into.

6.3 Sources of error

- The assumptions made were specified for this thesis, thus details presumed to be irrelevant considering the thesis' aim were excluded.

- Due to limited information and restricted access to scientific reports, rough assumptions about the WTs and upgrading concepts were made, and this may diverge from a more realistic dataset.

- Simplified methods were used when available and might result in lower calculated revenue flow for the investment project.

- Errors such as: manual calculations and interpretation of the analyses, may be subject to differences associated with the how they are interpreted, and the perspective of the analysis.

- Due to the ongoing pandemic, COVID-19, some costs and expenses in this thesis may be subject to change from the market value assumed during and after the pandemic. Additionally, some offshore wind projects have been delayed, and this could affect the statements about the next generations of WTs and the costs related to these projects.

7. References

[1 WindEurope, "Offshore Wind in Europe," 2020. [Online]. Available: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2019.pdf. [Accessed 2020].

[2 IRENA, "Future Of Wind," 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019. [Accessed 2020].

[3 L. Ziegler and T. Gionzalez, "Lifetime extension of onshore wind turbines: A review covering Germany, Spain, Denmark, and the UK"," in *Renewable and Sustainable Energy Reviews*, 2018, pp. 1261-1271.

[4 WindEurope, "Our Energy, Our Future," 2019. [Online]. Available: https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf. [Accessed 2020].

[5 IRENA, "Renewable Power Generation Costs in 2018," 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf. [Accessed 2020].

[6 Megavind, "LCOE Calculator Model," [Online]. Available: https://megavind.winddenmark.dk/lcoe-calculator-model]. [Accessed 2020].

[7 Electrical Academia, "Basic Parts of a Horizontal-Axis Wind Turbine," [Online]. Available: https://electricalacademia.com/renewable-energy/horizontal-axis-wind-turbine-hawt-working-principle-single-blade-two-blade-three-blade-wind-turbine/attachment/figure-1-13/. [Accessed 2020].

[8 GE Renewable Energy, "Driving efficiency and decreasing the cost of offshore wind energy," GE Renewable Energy, [Online]. Available: https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine. [Accessed 2020].

[9 J. Kaldellis and M. Kapsali, "Shifting towards offshore wind energy - Recent activity and future development," Elsevier Ltd, 2012.

[1 B. Byrne and G. Houlsby, "Foundations for offshore wind turbines," University of Oxford, 2003.

[1 H. Bailey, P. Thompson and K. Brookes, "Assessing Environmental Impacts of Offshore Wind Farms: Lessons Learned and Recommendations the Future," 2014.

[1 E. Konstantinidis and P. Botsaris, "Wind Turbines: Current status, obstacles, trends and technologies," 2016. [Online]. Available: https://www.researchgate.net/publication/311339042_Wind_turbines_current_status_obstacles_trends_and_technologies. [Accessed 2020].

[1 Equinor, "Floating Offshore Wind in Equinor," Equinor ASA, [Online]. Available: https://www.equinor.com/en/what-we-do/floating-wind.html. [Accessed 2020].

[1 Power Engineering, "World's First Floating Wind Farm Achieves 65 Percent Capacity Factor," POWERGEN International, 2018. [Online]. Available: https://www.power-eng.com/2018/03/05/world-s-first-floating-wind-farm-achieves-65-percent-capacity-factor/. [Accessed 2020].

[1 NREL, "Offshore Wind," 2016. [Online]. Available: https://www.nrel.gov/docs/fy16osti/66599.pdf. [Accessed 2020].

[1 R. Lacal-Arántegui, J. Yusta and J. Domínguez-Navarro, "Offshore wind installation: Analysing the evidence behind improvements in installation time," in *Renewable and Sustainable Energy Reviews*, Elsevier Ltd, 2018, pp. 133-145.

[1 WindEurope, "Wind energy's frequently asked questions," WindEurope, [Online]. Available: https://www.ewea.org/wind-energy-basics/faq/. [Accessed 2020].

[1 Energy Numbers, "UK offshore wind capacity factors," Energy Numbers, 2020. [Online]. Available: https://energynumbers.info/uk-offshore-wind-capacity-factors. [Accessed 2020].

[1 R. Pedersen and S. Petersen, "Smarter calculations can cut offshore wind costs further," Ramboll, 2018. [Online]. Available: https://ramboll.com/-/media/images/rgr/ingenuity/smarter-calculations-offshore-wind.jpg. [Accessed 2020].

[2 IRENA, "Floating Foundations: A Game Changer for Offshore Wind Power," IRENA, 2016. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Offshore_Wind_Floating_Foundations_2016.pdf. [Accessed 2020].

[2 Equinor, "How Hywind works," Equinor ASA, [Online]. Available: https://www.equinor.com/en/what-we-do/floating-wind/how-hywind-works.html. [Accessed 2020].

[2 A. Myhr, C. Bjerkseter, A. Ågotnes and T. Nygaard, "Levelised cost of energy for offshore floating wind turbines in a life cycle perspective," in *Renewable Energy*, Elsevier Ltd, 2014, pp. 714-728.

[2 O. Krogsæter, "The Future is Bright for Floating Wind Turbines," StormGeo, [Online]. Available: https://www.stormgeo.com/solutions/renewables/ articles/the-future-is-bright-for-floating-wind-turbines/ . [Accessed 2020].

[2 WindEurope, "Wind Energy in Europe: Outlook to 2023," 2019. [Online]. Available: https://www.anev.org/wp-content/uploads/2019/10/Market-outlook-2019.pdf. [Accessed 2020].

[2 The Maritime Executive, "First Offshorw Wind Farm Decommissioning Complete," The Maritime Executive, 2016. [Online]. Available: https://www.maritime-executive.com/article/first-offshore-wind-farm-decommissioning-complete. [Accessed 2020].

[2 New Energy Update, "Offshore wind installation vessel capacity to tighten after 2020," New Energy Update, 2016. [Online]. Available: http://newenergyupdate.com/wind-energy-update/offshore-wind-installation-vessel-capacity-tighten-after-2020. [Accessed 2020].

[2 E. Topham and D. McMillian, "Sustainable decommissioning of an offshore wind farm," in *Renewable Energy*, 2017, pp. 470-480.

[2 E. Topham, D. McMillian, E. Gonzalez and E. Joao, "Challenges of decommissioning offshore wind farms: Overview of the European experience," 2019. [Online]. Available: https://www.researchgate.net/publication/333238033_Challenges_of_decommissioning_offshore_wind_farms_Overview_of_the_European_experience. [Accessed 2020].

[2 N. Andersen, O. Eriksson, K. Hillman and M. Wallhagen, "Wind Turbines' End-of-life: Quantification and Characterisation of Future Waste Materials on a National Level," University of Gävle, 2016.

[3 M. Bruck, P. Sandborn and N. Goudarzi, "A Levelized Cost of Energy (LCOE) Model for Wind Farms That Includes Power Purchase Agreement (PPA) Energy Delivery Limits," International Conference on Energy Sustainability and the ASME 2016, 2016.

[3 Office of Indian Energy, "Levelized Cost of Energy (LCOE)," U.S. Department of Energy, 2015. [Online]. Available: https://www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf. [Accessed 2020].

[3 Megavind, "Megavind LCOE Model Guidelines and documentation," 2015. [Online]. Available: https://megavind.winddenmark.dk/sites/megavind.windpower.org/files/media/document/1500318%20Documentation%20and%20guidelines.pdf. [Accessed 2020].

[3 Trading Economics, "Norway Corporate Tax Rate," 2020. [Online]. Available: https://tradingeconomics.com/norway/corporate-tax-rate. [Accessed 2020].

[3 Y. Kikuchi and T. Ishihara, "Upscaling and levelized cost of energy for offshore wind turbines supported by semi-submersible floating platforms," 2019. [Online]. Available: https://www.sintef.no/globalassets/project/eera-deepwind-2019/presentations/e2_yukakikuchi20190117r.pdf.

[3 V. Nelson, Wind Energy: Renewable Energy and the Environment, Second Edition, CRC Press, 2013.

List of figures

Figure 1 - Offshore wind power deployment growth (2000-2019) and predicted growth (2020-2050) [2] 1

Figure 2 - The Inside of a Wind Turbine [7] 5

Figure 3 - Bottom-fixed foundations and floating offshore concepts* [11] 6

Figure 4 - Monopile foundation [19] 7

Figure 5 - Spar buoy foundation [21] 8

Figure 6 - Turbine size for commissioned offshore wind projects and global weighted average (2000-2018) [5] 10

Figure 7 - Number of OWTs reaching 20 years of operation annually in Europe [28] 11

Figure 8 - LCOE - Project Life Span [22] 14

Figure 9 - Structure of Megavind's LCOE model [32] 15

Figure 10 - Assumed lifetime of the OWF during different scenarios 17

Figure 11 - CB of the fixed concept OWF (Scenario 1) 24

Figure 12 - CB of the fixed concept OWF (Scenario 3) 24

Figure 13 - CB of the floating concept OWF 25

Figure 14 - CB of the floating concept OWF 25

Figure 15 - CB of the turbine cost for the floating concept 26

Figure 16 - Comparing change in no. of days of work per turbine with and without loss of production 29

Figure 17 - Comparing change in no. of days of work per turbine with and without loss of production 30

Figure 18 - Change in day rate for SOV (scenario 3) 31

Figure 19 - Change in day rate for SOV (scenario 1) 31

Figure 20 – Turbine and floater cost (scenario 1) 32

Figure 21 - Turbine and floater cost (scenario 3) 32

Figure 22 - Comparing change in installation time for floating foundations 33

List of tables

Table 1 - Development Expenditure 19

Table 2 - Capital Expenditure 20

Table 3 - Operating Expenditure 20

Table 4 - Abandonment Expenditure 21

Table 5 - LCOE for fixed concept 22

Table 6 - LCOE for floating concept 22

Table 7 - Relative LCOE for fixed concept OWF 27

Table 8 - Relative LCOE for floating foundation 28

Table 9 - Comparison of the LCOE for the fixed concept with cost reductions 34

Table 10 - Comparison of the LCOE for floating concept with cost reductions 36

Table 11 - Comparison of the relative LCOE for scenario 3 with cost reductions 37

Attachments

Megavind LCOE Model Guidelines and documentation [32].