Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Tool development for LCOE calculation for floating offshore wind

Bachelor's thesis in Renewable energy
Supervisor: Tania Bracchi and Axel Norman
May 2022

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Preface

This bachelor of science thesis is the final assignment as a part of the Bachelor program Renewable Energy Engineering at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim. This assignment is worth 20 credits as a part of the course: FENT2900 Bachelor Thesis Renewable Energy. All three students that has written this bachelor thesis attends the Renewable Energy program.

This thesis has as function to construct and develop a functional and user-friendly Excel tool to calculate the levelized cost of energy (LCOE) for a general floating offshore wind farm within some limits.

We would like to thank our external supervisor, study manager in Aibel, Axel Norman, for valuable guidance, advice, technical information, informative discussions and his commitment to the thesis through out the process. We would also like to thank our internal supervisor, associate professor Tania Bracchi, for valuable counselling, helpful-, engaging- and informative discussions and constructive feedback trough out the process.

We would also like to express our gratitude to Chief Scientist in Sintef, John Tande, whom shared valuable experience that helped our economical calculations greatly. We also want to send our utmost gratitude to associate professor Denis M.Becker for assisting us with important input values towards the sensitivity analysis.

Trondheim, 23. May 2022

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Abstract

To incentivize the development of renewable energy projects, profitability is critical. Floating offshore wind is still in an incipient phase, but is expected to enter the renewable market with industrial and economical strength. Levelized cost of energy (LCOE) is a method that compares investment and operation cost against anticipated energy production. It is a measure of cost per energy unit, and for this thesis given in NOK/kWh.

The purpose of this bachelor thesis is to construct a functional tool that calculates the LCOE for any given floating offshore wind farm within some limitations. The tool is designed in Microsoft Office Excel, and is constructed with a given design basis. The report examines floating offshore wind technology including a decomposition of the capital expenditures (CAPEX), operational expenditures (OPEX), and decommissioning expenditures (DECEX) for an offshore wind farm. Furthermore it discuss the LCOE reduction potential and an accompanying sensitivity analysis.

The CAPEX, OPEX and DECEX is decomposed into subcategories, which are facilitated for the user to include costs for their specific design basis. The focus of the tool is the decomposition of the categories and to construct a functional LCOE calculation tool for Aibel. The LCOE tool is constructed with functions that helps the user to understand, develop and optimise the final LCOE. It is important to mention that there are limitations and assumptions in the tool, but these are made transparent for the user.

To assess the sensitivity on the LCOE, and ensure the functionality of the tool, a sensitivity analysis was preformed on the most interesting input parameters. The accurate value of each cost element is not the main focus, as long as it is within the correct order of magnitude.

The results of the sensitivity analysis show that the capacity factor has the highest impact on the LCOE, followed by the wind turbine cost and the discount rate. The lifetime curve in the sensitivity analysis decreases unmistakably in first years, then hits the lowest LCOE at 25 years and thereafter the curve increases and shows a stagnating trend. The water depth and distance to shore show surprisingly small impact on the LCOE.

The main objective of this thesis has been accomplished by creating a well-functioning and comprehensive LCOE calculation tool in Excel. The calculations and the relations between them is thoroughly reviewed and the links between the sheet correspond in order to correctly calculate the LCOE. The obtained LCOE result, 0.76 NOK/kWh, from the sheet is within a reasonable limit from comprehensive research.

Norwegian abstract (Sammendrag)

Lønnsomhet er viktig for å insentivere utviklingen av fornybar energiprosjekter. Flytende havvind er fortsatt i en begynnende fase, men forventes å gå inn i det grønne markedet med industriell og økonomisk styrke. Utjevnet energikostnad (LCOE) er en metode som gjør det mulig å sammenligne investering – og operasjonskostander opp mot forventet energiproduksjon. Enkelt forklart er det et mål på kostnader per energienhet, og er i denne oppgaven gitt som NOK/kWh.

Hensikten med denne bacheloroppgaven er å konstruere et funksjonelt verktøy for Aibel, som regner ut LCOE'en for en gitt flytende vindpark innenfor gitte rammer. Microsoft Office Excel er brukt som programvare, og tar utgangspunkt i en gitt design base. Rapporten ser på flytende havvind teknologi og inkluderer en nedbrytning av kaptial-, operasjons-, og avviklingsutgifter (CAPEX, OPEX og DECEX) for en flytende havvindspark. Videre ser rapporten på LCOE som metode, samt en tilhørende sensitivitetsanalyse med LCOE som utgangspunkt.

CAPEX, OPEX og DECEX er nedbrutt i bestemte underkategorier, som er mulig for brukeren å endre ettersom brukeren har en egen spesifikk design base. Hovedfokuset til verktøyet er å regne ut LCOE'en, gjennom en velfungerende nedbrytning av kostnadene. LCOE verktøyet er konstruert med tanke på at brukeren skal ha mulighet til å forstå, utvikle og optimalisere LCOE resultatet. Likevel er det viktig å nevne at verktøyer inneholder begrensninger og antagelser, men disse er gjort transparent for brukeren.

For å vurdere sensitiviteten på LCOE'en, og sikre funksjonaliteten til verktøyet, er det blitt uført en sensitivitetsanalyse på de mest interessante inngangsparametrene. Den faktiske verdien fra de ulike kostnadene er ikke hovedfokuset i oppgaven så lenge de er inn under rett omfang.

Resultatene fra sensitivitetsanalysen viser at kapasitetsfaktoren har den høyeste innvirkningen på LCOE resultatet, etterfulgt av vindturbin kostnaden og diskonteringsrenten. Levetidskurven i analysen minker tydelig de første årene, og når sin laveste LCOE på 25 år. Deretter øker kurven og glir inn i en stagnerende trend. Vanndybden og distanse til land har overraskende lite innvirkning på LCOE resultatet.

Hovedmålet med denne oppgaven er oppnådd ved å lage et omfattende og velfungerende LCOE beregningsverktøy i Excel. Beregningene i verktøyet og linkene mellom arkene fungerer etter ønske, og regner ut et korrekt LCOE resultat. Resultatene viser også at arket er korrekt, da LCOE'en havner på 0.76 NOK/kWh, som er innenfor en rimelig grense satt fra innhentede kilder.

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List of Symbols

Symbols	**Description**	**Unit***
P	Power	[W]
A	Rotor swept area	[m^2]
v	Wind speed	[m/s]
r	Discount rate	[%]
n	Wind farm lifetime	[years]
t	Current year	
C_p	Power coefficient	[%]
ρ	Air density	[kg/m^3]
η	Efficiency	[%]
c	Scale parameter	[m/s]
k	Shape parameter	
$p(v)$	Weibull distribution function	

*Empty cells are dimensionless

List of Abbreviations

Abbreviation	**Definition**
AC	**A**lternating **C**urrent
AEP	**A**nnual **E**nergy **P**roduction
BEIS	Department for **B**usiness, **E**nergy & **I**ndustrial **S**trategy
BFWF	**B**ottom **F**ixed **W**ind **F**arm
BFWT	**B**ottom **F**ixed **W**ind **T**urbine
CAPEX	**C**apital **E**xpenditures
CF	**C**apacity **F**actor
CFD	**C**ontracts **F**or **D**ifference
C0	Project consenting and development to FID
C1	Wind turbine structure
C2	Electrical infrastructure
C3	Transport & installation
DECEX	**D**ecoommissioning **E**xpenditures
DC	**D**irect **C**urrent
DF	**D**iscount **F**actor
D1	**D**ecommissioning
EEZ	**E**xclusive **E**conomic **Z**one
EPC	**E**ngineering **P**rocurement **C**onstruction
FEED	**F**ront **E**nd **E**ngineering **D**esign
FID	**F**inal **I**nvestment **D**ecision
FOWT	**F**loating **O**ffshore **W**ind **T**urbine
FOWF	**F**loating **O**ffshore **W**ind **F**arm
HVAC	**H**igh **V**oltage **A**lternating **C**urrent
HVDC	**H**igh **V**oltage **D**irect **C**urrent
IRR	**I**nternal **R**ate of **R**eturn
LCOE	**L**evelized **C**ost **O**f **E**nergy
NOK	**N**orwegian **K**roner
NPV	**N**et **P**resent **V**alue

Abbreviation	**Definition**
OPEX	**O**perational **E**xpenditures
O1	Planned maintenance
O2	Corrective maintenance
O&M	**O**peration & **M**aintenance
PV	**P**resent **V**alue
TLP	**T**ension **L**eg **P**latform
T&I	**T**ransport and **I**nstallation
UN	**U**nited **N**ations
yr	**Y**ea**r**

1 Introduction

As a part of UNs 17 Sustainable Development goals to work towards a more sustainable future, addressing climate change and environmental degradation is crucial [1]. The Paris Agreement from 2015 is a treaty between 196 countries to limit the global temperature rise to 1.5°C. To achieve these goals, countries needs to reach their peak of greenhouse gas emissions as soon as possible. The development of renewable energy technologies will be one of the important contributions to reaching these goals. [2]

To achieve EU climate and energy targets, the European Wind Energy Association has set a goal to have a total installed wind energy capacity of 320 GW by 2030, where 66 GW is expected to come from offshore wind [3]. To contribute to the green shift in Europe, The Norwegian government presented ambitions to allocate 30 000 MW of offshore wind development within 2040. [4]

There is a significant amount of unexploited energy resources that bottom-fixed wind turbines (BFWTs) not are able to utilise, due to water depth restrictions. According to Equinor [5], around 80% of the wind resources in the world can be found in areas with a water depth of more than 60 meters. Large areas of Norway's continental shelf has a water depth best suited for floating wind [6]. Complementing the offshore wind sector, with floating wind is necessary to accommodate the rising energy demand and reaching the goals, as well as further developing the offshore wind field.

1.1 Background

Aibel's focus areas within offshore wind are primarily related to the transmission set-up for the wind farm development, in form of offshore substations. Main targets are projects using high voltage direct current (HVDC) technology, however larger high voltage alternating current (HVAC) projects are also of strategic importance.

LCOE is the net cost of producing electricity. LCOE is the capital expenditures (CAPEX), operational expenditures (OPEX) and decommissioning expenditures (DECEX), divided on the produced energy over the lifetime of the project. Reducing this number is the key within all energy projects as it determines the profitability.

The reason that Aibel is interested in LCOE assessments is that they need good insight into how their deliveries and services affects the overall LCOE of given projects. The HVDC stations can have different strategies for operation, maintenance and logistics. The overall best strategy is selected based on which one provides the lowest LCOE.

Another reason to have good insight into LCOE is to support the evaluation of which prospects to prioritise. Aibel is approached by many wind farm developers and their projects have varying degree of realism and probability to be executed. They are not able to tender for all projects and therefore Aibel need some metric to support the selection of projects to pursue. Several parameters can impact the assessment of a project, one of these can be to estimate the LCOE for the given project.

1.2 Project definition

The bachelor thesis given from Aibel has the main purpose to assess industry practice for estimating the LCOE for floating wind projects and develop a model on how to calculate LCOE for a given project.

The LCOE calculation tool is created in Microsoft Office Excel, and is constructed to work as a functional and comprehensive tool for the user. In order to solve the overall task, it is necessary to break down the cost elements for a floating offshore wind farm (FOWF). Further, it will be needed to develop a framework and methodology for the assignment with a specific project schedule on how to complete within the given time frame.

They key is not to get the exact numbers for each cost element, but to identify all elements and set up their relation to the overall LCOE. It should also be attempted to get the absolute costs with the correct order of magnitude. This model can then be used to assess the consequence of a different operational strategies. The thesis will also look into LCOE reduction potential for floating offshore wind.

The goal is therefore not to determine the profitability of the design basis (base case) wind farm, but to create a functioning tool for the calculation of LCOE for a given FOWF, within the limitations of the tool. The overall task is to:

- Identify, describe and document how LCOE for offshore wind projects are assessed.
- Develop a model of how to calculate LCOE for a floating offshore wind project.

1.3 Microsoft Office Excel

Microsoft Office Excel is a data program developed by Microsoft in 1987, and is the industry leading spreadsheet software program. The program is a data visualisation and analysis tool, and offers a computerised spreadsheet where one can for example execute calculations, analysis of data or create graphs. [7]

Microsoft Office Excel is the data program used to develop the LCOE calculation tool. Excel is structured, user-friendly and has great functions for calculation. In terms of constructing a tool that require different types of calculations, the integrated formulas makes Microsoft Excel the best suit.

1.4 Design basis: Utsira Nord

To be able to construct a generalised LCOE calculation tool that works for several potential FOWFs a design basis has been taken into consideration. Table 1.1 shows some of the parameters in the design basis, and the total design basis is explained in section 8.2.

The west coast of Norway is all over covered by open sea, with plenty opportunities. In 2020 the Ministry of Petroleum and Energy opened the Utsira Nord and Southern Nord Sea II areas for applications for renewable energy production at sea. Aibel sees Utsira Nord as a potential site to invest in, and therefor this site is a optimal location to base the LCOE tool on. [8]

Table 1.1: Some parameters from the design basis

Base case	
Location offshore	Utsira nord
Years of operation	25
Distance from shore	30 000 m
Water depth	267 m
Average wind speed	10 m/s
Wind farm capacity	450 000 kW
Number of turbines	30
Wind farm type	Floating
Floating AC substation	450 MW
Floater	Semi-submersible

2 Wind energy production

Utilising wind power further from shore will help unlock unexploited energy potential, and push the renewable energy sector further in the right direction. Investing in renewable energy leads to decarbonisation of electricity production. Wind power as a renewable- and emission free energy source has an increasingly important role in a carbon free future and is well suited for large scale energy production.

The most common technology for harvesting kinetic wind energy is a horizontal three blade wind turbine. The power in the wind (P_{wind}) is defined in equation 2.1, where A is the swept rotor area, ρ is the air density and v is the wind speed. Further on, wind velocity is an important parameter and significantly affects the power that can be extracted from the wind, since it is exalted in the third. Hence, the geographical location and design size of the wind turbine is fundamental for the amount of energy produced. [9]

$$P_{wind} = \frac{1}{2} \cdot A \cdot v^3 \cdot \rho \tag{2.1}$$

Based on the wind turbine design, each turbine type has a special power performance curve. The power curve of a given wind turbine, see figure 2.1, illustrate at which wind speed the wind turbine reaches the installed power. The figure is a generalised example. The wind turbine is designed with a cut-in and cut-out speed. These are respectively the low and high wind velocity creating the interval in between which the turbine can produce electricity. Cut-in speed is the minimum wind speed at which the turbine can deliver useful power to the grid. Cut-out speed is the maximum speed the turbine can operate and is allowed to deliver power. This cut-out point is normally constructed with engineering design and safety constraints. Rated wind speed is where the turbine reaches its installed power output. [9]

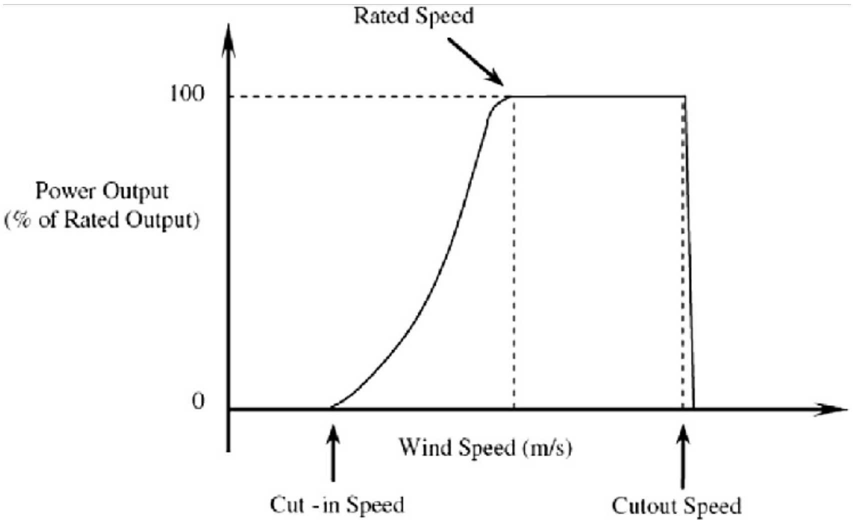


Figure 2.1: General wind turbine power curve [10]

2.1 Power coefficient

Betz limit is a well known fact in the wind energy field, and states that the rotor blades has a maximum limit of how much wind power they can utilise. This limit is $C_{p,max} = 0.593$ (59.3%), and is the maximum theoretical possible power coefficient for the wind turbine rotor. It is not possible for the rotor blades to operate at this maximum limit, due to various engineering requirements like strength and durability in particular, and therefore a real power coefficient is lower than Betz limit. The real power coefficient (C_p) is the rotor power (P_{mech}) divided on the power in the wind, shown in equation 2.2. The power coefficient is affected for instance by the rotation of the wake behind the rotor, a finite number of blades on the rotor. Tip and array losses and non zero aerodynamic drag also affects the power coefficient, and are also core challenges for a wind turbine. [9]

$$C_p = \frac{P_{mech}}{P_{wind}} \tag{2.2}$$

The overall wind turbine efficiency ($\eta_{turbine}$) is a function of the rotor power coefficient and the mechanical efficiency including electrical (η_{mech}) of a wind turbine, shown in equation 2.3. The total power output from a wind turbine ($P_{turbine}$) is shown in equation 2.4. Each turbine type has an unique C_p value due to design, and the C_p value is a function of the operating wind speed.

$$\eta_{turbine} = \frac{P_{turbine}}{P_{wind}} = \eta_{mech} \cdot C_p \tag{2.3}$$

$$P_{turbine} = P_{wind} \cdot \eta_{mech} \cdot C_p \tag{2.4}$$

2.1.1 Array losses

Planning a wind farm can present a number of technical challenges. Developers should design wind farms in such a way as to prevent excessive array losses. Array losses are caused by aerodynamic interaction between the wind turbines. The upwind turbines blocks the inflow, and when extracting energy from the wind, downstream turbines are affected by less powerful and more turbulent wind. This originates from the wake of the wind turbine. This leads to a lower overall energy production from the farm. When referring to wind turbine array spacing, figure 2.2 illustrates an example of downwind and crosswind spacing. These types of losses are often a function of different factors listed below [9]:

- The size of the wind farm and the number of turbines.
- The spacing between the wind turbines, both crosswind and downwind spacing.
- The operating characteristics for the wind turbine.
- Turbulence intensity.
- How much frequency distribution there is in the wind direction.

Array losses can be minimised by optimising the geometry of the wind farm. Using different turbine sizes and optimal placement of the wind turbines in terms of shape and size, will contribute to the reduction of wake effects that influence the energy consumption. The geometry of the turbines in relation to each other and the intensity of turbulence in the surrounding area, are the most important factors that affect array losses. Research shows that turbines that are placed eight to teen rotor diameters apart in the downwind direction and five rotor diameters apart in the crosswind direction, the array losses are normally less than 10%. [9]

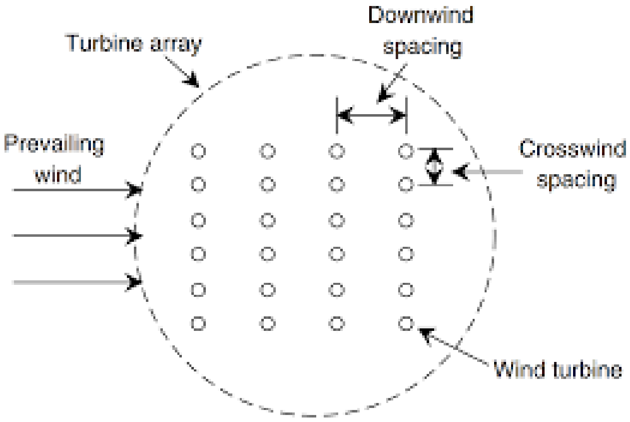


Figure 2.2: Multiple wind farm arrays illustrated [9]

2.2 Capacity factor

The probability distribution function of wind speed is often expressed using a Weibull function. This is one of the significant wind characteristics for estimating the wind energy potential and the wind energy conversion when wind data from the site is not available.

The capacity factor (CF) is defined by the ratio of the annual energy production (AEP) and the installed capacity of the wind farm ($P_{installed}$). Meaning the annual energy produced divided on the energy generated at rated capacity over the same time period. This is shown in equation 2.5, where this ratio is expressed in percentage. This ratio explains how much of a systems capacity is utilised, and is an important indicator when analysing and improving a wind turbine. Many offshore wind farms report capacity factors of about 50%, and for the next generations of turbines the CF will potentially increase. This compares with capacity factors of about 35% for windy onshore sites. [9]

$$CF = \frac{AEP}{P_{installed}} \tag{2.5}$$

The capacity factor for a wind farm depends mainly on two parameters; wind speed distribution and downtime. The CF is affected by the availability of wind. Hence the Weibull distribution function shows how often a wind speed occurs, referred to figure 2.3, which shows the probability that the speed will occur over a certain period of time. The second contribution is the downtime. This is the period when the turbine is out of service and the turbines do not produce energy. This can be caused by equipment failures, maintenance or that the output power is regulated based on demand. The transmission line capacity and the electricity demand are also factors that effect the capacity factor. [9]

AEP estimation without wind data

It is possible to predict how much wind energy that can be produced when wind data measurements are not available. Statistical methods such as probability distribution is used when measurements does not exist. Further, a common method used for this is the Weibull distribution.

The Weibull distribution function ($p(v)$) is illustrated in figure 2.3, and contains a scale parameter, c with unit [m/s], and a dimensionless shape parameter, k. Equation 2.6 illustrates the Weibull distribution function as a function of the wind speed. [11]

$$p(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^{k}} \tag{2.6}$$

Average rotor power ($\bar{P}_{turbin}$) is illustrated in equation 2.7 and has the unit kW or MW. It is the integral from zero wind speed to rated wind speed. The integrand is the product of the power at the given wind speed on the power curve ($P(v)$) and the Weibull distribution function.

$$\bar{P}_{turbine} = \int_0^{v_0} P(v) \cdot p(v) dv \tag{2.7}$$

Calculating the AEP using the Weibull distribution, is shown in equation 2.8.

$$AEP = \bar{P}_{turbine} \cdot 8760 \frac{h}{yr} \tag{2.8}$$

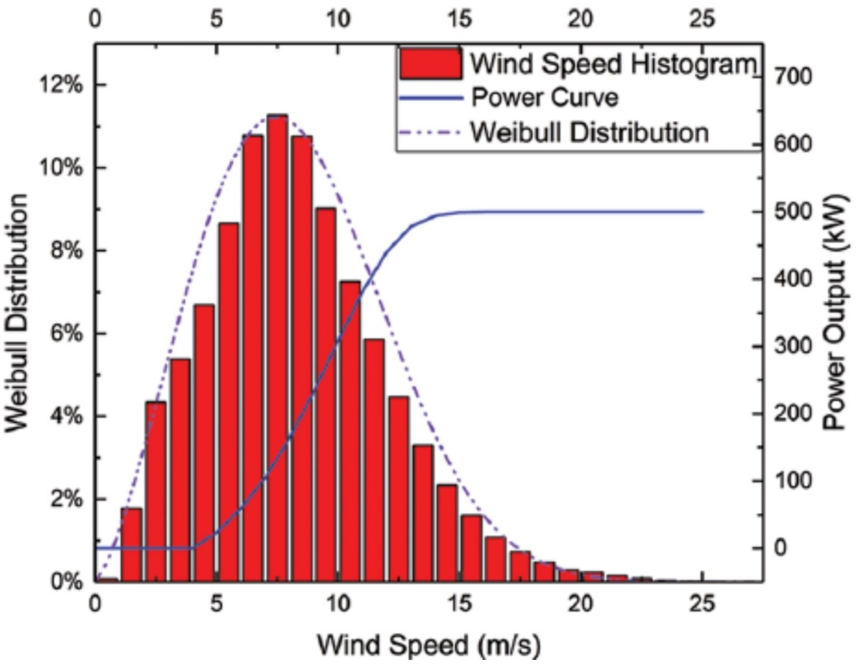


Figure 2.3: Weibull distribution of wind speed and power output curve [12]

3 Principles behind LCOE

Levelized cost of energy is used to compare different energy sources and to evaluate the profitability of an energy project. The LCOE of an energy project can be defined as the ratio between the total cost of the project and the total electricity produced over the projects lifetime. The total costs includes the investment costs, CAPEX, as well as the annual operation and maintenance cost, OPEX and the decommissioning cost, DECEX.

LCOE calculations has several functional areas for investors and developers. The method is understandable, transparent and a good way to examine if the energy project is economically feasible. LCOE is mainly used for comparing the minimum cost of producing energy using various technologies. To exemplify, it is common to compare the cost of applying conventional energy production with renewable energy production. Additionally conventional energy production typically has a high variable cost throughout the life of the project. The variable cost consist of annual fuel, CO_2 taxes as well as high operating and maintenance costs. On the other hand, renewable energy production has a high investment cost in the startup and a low variable cost throughout the lifetime. LCOE comparison can give an estimate of the competitiveness of different technologies. [13]

During the last couple of years, the LCOE for offshore wind has seen a decreasing trend, and it is estimated that this trend will continue. This is caused by the technology improving, increase in turbine capacity, and streamlining of production and installation. LCOE has been reduced with 28-51% in the time period from 2014 to 2020. [14]

LCOE for renewable is generally fluctuating due to uncertainty in different input values such as CAPEX and OPEX, capacity factor and discount rate [15]. WindEurope [16] estimates that a low LCOE for floating offshore wind is around 0.5-0.65 NOK/kWh. They also estimates that a typical LCOE for offshore wind farms are in the range 0.7 NOK/kWh to 1.25 NOK/kWh.

To calculate the LCOE for an energy project, equation 3.1 is used, where r is the discount rate, t is the respective year and n is the wind farm lifetime. This is a simplified LCOE model, and the preconditions for this equation is that the discount rate, AEP and OPEX is assumed constant through out the lifetime of the project. CAPEX includes the costs of DECEX. [17]

$$LCOE = \frac{\sum (CAPEX_t + OPEX_t) \cdot (1+r)^{-t}}{\sum_{t=1}^{n} AEP_t \cdot (1+r)^{-t}} \tag{3.1}$$

3.1 CAPEX, OPEX and DECEX

CAPEX is the capital expenditures of a project, including the manufacturing, transportation and installation of a project. Looking at the total costs of a wind farm, CAPEX has the highest share of costs. CAPEX includes all investments up until the start of operation [18]. Some parts of the CAPEX is fixed for all wind projects and some parts depend on site characteristics. Some concepts and technologies are still under development, especially floating concepts, and therefore there are uncertainties around costs. Regardless, renewable energy is immensely capital intensive [17]. The decomposition of CAPEX for this project will be further explained in detail in section 5.

The operational expenditures includes operational and maintenance costs. This is calculated as an annual cost through the whole lifetime of the project. OPEX can be divided into two categories, planned maintenance and corrective maintenance. Planned maintenance include the anticipated costs, and is taken in to account considering the planned downtime. This affects the value of the capacity factor of the project, which again affect the LCOE. Corrective maintenance consist of the unforeseen costs, like repair of components. There is uncertainty in conjunction with corrective maintenance, as it can be influenced by unexpected events. This will naturally also affect the energy production, and the capacity factor [19]. The decomposition of OPEX for this project will be further explained in detail in section 6.

DECEX is the decommissioning costs at the end of the projects operational lifetime. Decommissioning occurs the year or years after end of life, and must be discounted to present value of costs to estimate the investment cost for DECEX. Decommissioning of offshore wind farms has only been completed a few times, and therefor the cost is difficult to anticipate. At the end of life for an offshore wind farm, it is possible to extend the lifetime instead of fully decommissioning. This can be done either by re-powering the site with new turbines or by refurbishment with replacement of minor components. The properly financed decommissioning plans are required as a part of the projects planning approval to construct. [20]

3.2 Economical aspects

Considering the profitability of a project, the first checkpoint is to secure that the revenues exceed the costs. If a business accomplishes to procure more for the product than the cost of producing it, it is profitable in terms of business economics. It is also important minimize the cost during the products lifetime to secure profitability. Before an investment decision is made, preforming a feasibility analysis is advantageous to obtain information about present value of revenues and expenses. The investment expenses, economic lifetime, annual expenses, increases in current assets, disposal value and discount rate are important factors to determine if the project is viable. [21]

Along those lines, LCOE is a relevant and important parameter in determining whether or not to invest in a project. LCOE is a quality assured tool to determine the break even cost of the project. The electricity prices will determine if the project will be profitable or not. Calculating the LCOE is one of the preliminary fundamental steps in a project development. [21]

3.2.1 Present value method

The present value (PV) method is used to calculate the present value of a transaction in the future [22]. The LCOE method operates with the present value calculation to discount the annual costs of the projects to the present value that is applicable today. This makes it possible to compare costs and revenues which occur in different years. A discount rate (r) is used to determine the present value of future cash flows, and can also be interpreted as the project's required rate of return [23]. Figure 3.1 illustrates a simple relationship on how the discount rate affect the present value and the future value. Even a small change in discount rate can considerably affect the present value of investments, such as an energy project, that has long pay-off time. For instance, an investor can operate with this rate to determine what the investment will be worth in an unknown number of years into the future. Contradictory, an investor can take benefit of this rate to calculate the value of money that is needed to invest in a project today in order to achieve a future investment goal. [24]

$$DF = \frac{1}{(1+r)^t} \tag{3.2}$$

The discount factor (DF), equation 3.2, is a financial modelling used to calculate the present value of future cash flows [24]. Department for Business, Energy & Industrial Strategy from the United Kingdom (BEIS) [25], operate with a discount rate in the range of 6-10% for offshore wind projects, but for the LCOE method this discount rate is set to a constant due to simplifications in calculations. The advantage of operating with the discount rate is that it makes financial modelling in projects more accurate, when calculating the present value and the net present value which are important factors for LCOE calculations.

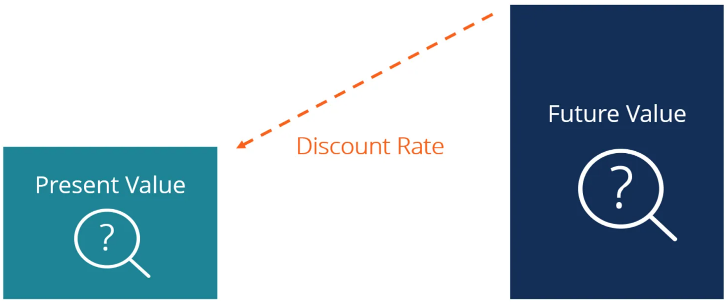


Figure 3.1: Visual illustration of how discount rate affects the present value [23]

In cost analysis of investment projects, it is necessary to compare costs or revenues that occur in different time periods of the project. To enable this comparison, a discount rate is used. In cost analysis the discount rate is often assumed to be constant throughout the lifetime of the project. Exponential discounting is often used and is based on constant risk assessment and is independent of the project lifetime. A disadvantage of this method is that future changes will have very little impact on the project. The assumption of a constant discount rate is based on the the premise of a stationary prosperity development in the future. If there is reason to anticipate that prosperity growth will slow down, the discount rate should decrease over time. [26]

$$PV_{costs} = DF \cdot OPEX \tag{3.3a}$$

$$PV_{energy} = DF \cdot AEP \tag{3.3b}$$

Present value is defined in equation 3.3. The value of the expenditure in year t needs to be discounted back to present value to evaluate the projects feasibility. The background for multiplying discount factor with OPEX is because it is a fixed expense for the energy project over all the relevant years the project is in operation. AEP is also discounted to the current year, further explained in section 3.2.2. On the other hand CAPEX will not be multiplied with the discount factor due to CAPEX being a one time payment when the final investment decision is made, in year zero. The value of CAPEX will therefore be equal to the present value of the investment. [17]

$$NPV = -CAPEX + \sum_{t=0}^{n} PV_{costs} \tag{3.4a}$$

$$NPV = \sum_{t=0}^{n} PV_{energy} \tag{3.4b}$$

Further, present value and lifetime of the energy project are important factors to calculate the net present value (NPV). Equation 3.4 illustrates how the NPV is the sum of present values of money or energy production in future years. All these equations are critical in the LCOE calculations and for the constructed LCOE Excel-tool. [21]

The internal rate of return (IRR) is defined by the discount rate that gives the net present value equal to zero. The NPV is usually a decreasing function of the discount rate. Higher discount rate equals to a lower NPV, and this can be seen from equation 3.4. The net present value will be positive if the IRR is bigger than the discount rate. According to this, there is a close connection between uncertainty related to future cash flow and the value of the discount rate. The more uncertainty that lies in a future cash flow, the higher the discount rate has to be. [26]

The LCOE calculations are influenced by being either real or nominal. At nominal LCOE calculation, inflation is taken into consideration. If calculated correctly, the influence of inflation will contribute to a correct end result. However, inflation rate development is difficult to predict in future years. Real LCOE does not take inflation into consideration, and will from a socio-economic perspective be more valid, as the value is predicted to increase due to the consumer price index. For this specific tool, real LCOE calculations has been used. [17]

3.2.2 Discount of energy production

LCOE is defined as a break-even cost for the energy project. Discounted income can be set equal to discounted net expenses, giving equation 3.5, where E is the expenses.

$$\sum_{t=0}^{n} \frac{AEP_t \cdot LCOE}{(1+r)^t} = \sum_{t=0}^{n} \frac{E_t}{(1+r)^t} \tag{3.5}$$

On the left side of the equation, revenues is set to LCOE times annual energy production, discounted, and the left side is the expenses discounted. Solving this equation with respect to LCOE gives equation 3.6.

$$LCOE = \frac{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{AEP_t}{(1+r)^t}} \tag{3.6}$$

Equation 3.6 shows that the LCOE is calculated as the discounted expenses divided on the discounted annual energy production. There are disagreements on whether the energy production should be discounted or not. The arguments against discounting the energy, is that the discount of energy production in equation 3.6 is just a result of the conversion of the equation, and that the intent of the original equation 3.5 is only to discount the revenues. [17]

There are two ways to calculate the LCOE for an energy project. The first method,

$LCOE_{BEIS}$, calculates the LCOE as the discounted sum of costs divided by the discounted energy production. The other method, $LCOE_{NREL}$, calculates the LCOE by dividing the total costs by the energy generated. [25]

The BEIS method is strongly in favour of discounting the energy production, and argues that this is necessary to be able to interpret LCOE as the break-even cost. The background for these arguments is that when the NPV equals zero, the IRR will equal the discount rate. Due to these assumptions, the NPV of costs can be replaced by NPV of revenues. Ergo, the LCOE is therefore calculated by dividing the NPV of revenue by the NPV of the energy production [25]. Transferring this to equation 3.6, LCOE can be seen as a measure of the energy price. The basis of BEIS argumentation is that even if 10 kW today is the same as 10 kW in five years, the income from the sold electricity is not the same. The discount of the energy production takes into consideration the time-varying value of income. [17]

3.3 LCOE - Strengths and weaknesses

LCOE offers easily understood methods for comprehending the value of electricity. It can also be customised to fit projects world wide as it can be easily translated to different currencies and energy measurements. With careful calculation, LCOE can contribute to an easy comparison of costs of a specific technology over time [27]. Aldersey-Williams et al [25] discuss that the LCOE reduces complex comparisons to one single number in a sophisticated and understandable way, so that its comprehensible to the general public.

On the other hand, Aldersy-Williams et al [25] also discuss that LCOE is overly simplified and can lead to deviating results. For example, it does not take into account the impact of the varying value of electricity through out one single day. Hvidevold and Karlsen [17] writes that the LCOE method treats energy production as a homogeneous product available at one fixed price, while experience shows that it varies greatly out from different countries and different global situations. This makes the relationship between production and revenue imprecise, because wind power production has a high level of unpredictability compared to for example hydro power. Therefore Hvidevold and Karlsen [17] argues that LCOE for wind power should be a measure for cost efficiency and not profitability.

Choosing the discount rate will in many cases be the most uncertain type of parameter for LCOE calculations, as it consists of a risk rate as well as a risk free rate. This can make it hard to compare different projects because companies have different levels of risk taking, making the basis of comparison uneven. Sergei Manzhous [28] argues that when comparing LCOE for different renewable technologies, only the risk-free rate should be used in the discount calculations.

4 Floating offshore wind

As offshore wind farms increases worldwide, bottom-fixed wind farms are the most common concept offshore. However, this technology will only be an option in shallower areas. Floating wind farms are a relatively new concept, but the field is evolving quickly. There is a lot of unexploited wind resources further from shore, and floating structures is a method to unlock greater potential for harvesting wind at sea. Hywind Scotland was completed in 2017 and is the world's first commercial floating wind farm in operation [5]. In recent years FOWFs such as Hywind Tampen, Windfloat Atlantic, Fukushima and Kincardine are all in commissioning. However, all these projects have small capacity and a low number of turbines, although they contribute to the further development of FOWFs.

In 2022 Hywind Tampen is to be completed and will be the worlds largest floating offshore wind farm, with a planned installed capacity of 88 MW. The wind farm is intended to deliver energy to offshore oil and gas platforms as a electrification project [29]. FOWFs are still in the early ages, but with continuous development of farms and the beneficial aspects, like higher mean wind speed, utilisation of large unexploited areas at sea, less visual impact and reduced wave loading, floating wind is moving towards the goal of commercialisation. [30]

4.1 Experience from established industries

Floating offshore wind can make a substantial contribution in meeting the rising energy demand. The main difficulties lies in lack of innovative, cost efficient and effective technology. This is due to floating offshore wind being a new and inexperienced field. Using the learning effect, further explained in section 4.1.1, and cost reduction techniques from BFWF as well as the oil and gas industry, can contribute to decreasing the costs for developing FOWFs. [16, 31]

Many of the floating wind solutions can be found in oil and gas industry. The stabilisation of the floater and the mooring system of a FOWF has many similarities to floating oil platforms, as seen in figure 4.1. The design of a FOWT can also somewhat take inspiration from floating oil platform constructed for harsh weather conditions. Though, being able to build multiple single floating wind turbines that can withstand this type of climate requires a design that distributes the mass of the turbine and has a strong and dynamic mooring system. [5]

Considering that the knowledge of the floating offshore field is deficient, using inspiration from construction, structure and design of BFWTs will contribute to a cost reduction when harvesting technology that already exist [16]. In the bottom-fixed and onshore wind fields, there has already been a significant reduction in costs. FOWFs can utilise the cost reduction techniques for especially BFWFs, as well as using the learning curve (ref. section 4.1.1). This can contribute to a rapid growth in conjunction with decrease in costs, eventually reaching competitive energy prices for floating offshore wind [5]. Due to experience and cost reduction techniques from BFWFs it is expected a 38% decrease in costs for the floating offshore wind sector towards 2050 [16]. The investment cost for floating offshore wind is still higher than for onshore and bottom-fixed wind, but is expected to decrease. The high investment cost is due to FOWTs having more complex systems, and requiring more components compared to other wind technologies. [32]

Political commitment and investment in research and innovation is necessary to obtain commercialisation. Floating offshore wind will increase the capacity in the wind sector and supply chain, and therefore supplement bottom-fixed wind by initiating new technology and developers. Commercialisation will contribute to opening up new markets and giving space for more developers. This will create a possibility for further evolving the technology of offshore wind, as well as increasing the extent of the offshore field. Floating offshore wind gives more countries the opportunity to utilise the offshore potential in places the environment is not especially suited for BFWTs. [16]

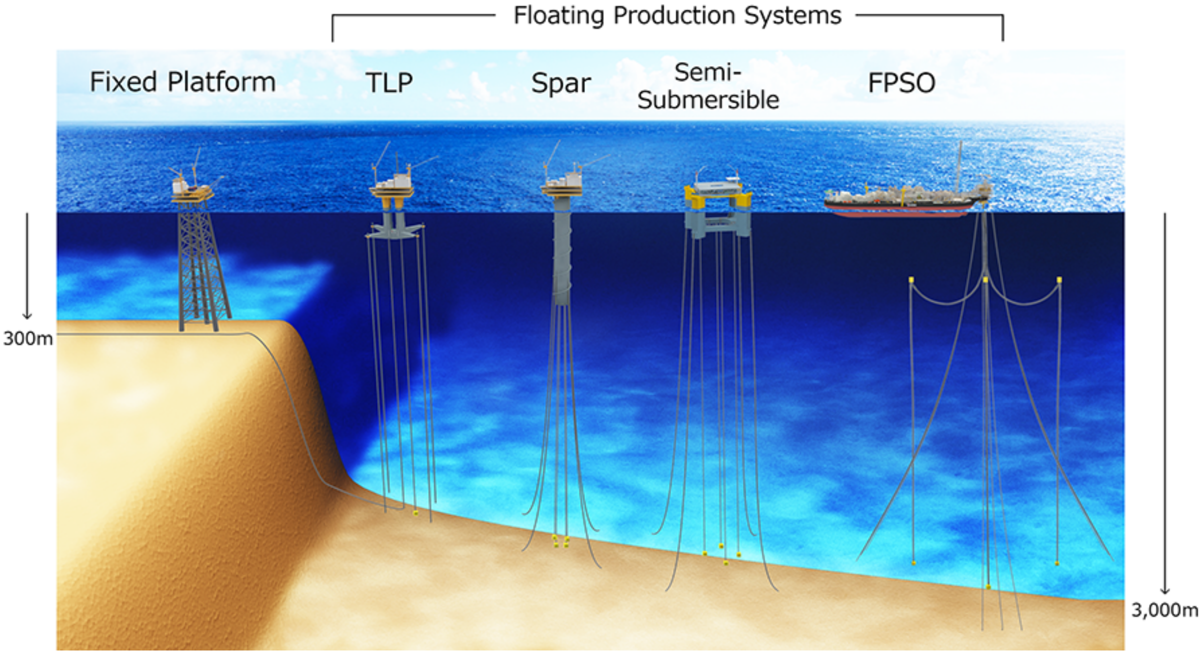


Figure 4.1: Different floating oil and gas systems [33]

4.1.1 Learning curve

The theory behind learning curves implies that when the production increases and the process is repeated, the efficiency increases. As the efficiency increases, the exploitation of the inputs increase, causing a decrease in the unit cost of the output. In the view of a floating offshore wind farm, an efficiency increase in production and installation will result in a cost reduction for the wind farms. By standardisation and repetitive procedures, it gets easier to streamline the processes. As technology develops, installed capacity increases and production is streamlined, the LCOE for floating offshore wind is anticipated to decrease. [17]

Until the completion of Hywind Scotland in 2017, the main measures to reduce costs, was to evolve the technology. Today, streamlining the production and installation will have the highest impact on cost reduction. Equinor [5], a world leading company in the development of floating offshore wind, is in the process of commercialising floating wind. Figure 4.2 illustrated how Equinor predict the further decreasing development of the LCOE for FOWFs. Between the pilot project and Hywind Scotland there were a 70% reduction in CAPEX per MW, showing the benefits of commercialising. Equinor also estimates an additional reduction of 40% between Hywind Scotland and Hywind Tampen, a good example on the effects of the learning curve [5]. According to the LIFES 50+ [34] report from European Union, developing projects on a larger scale will also enable larger funding and investments from government, as well as potential investors.

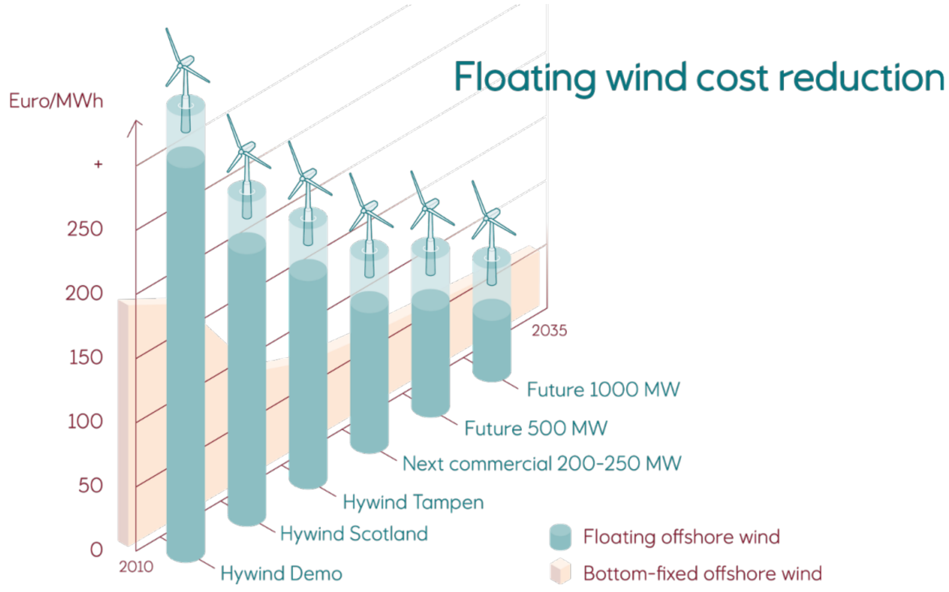


Figure 4.2: Further cost reduction for floating offshore wind [5]

4.2 Challenges with floating offshore wind

Floating offshore wind offers many solutions related to offshore wind power, but also presents a number of challenges. Firstly, floating offshore wind is a huge challenge from an engineering point of view. Naturally there are intrinsic challenges tied to getting a large wind turbine to float in a demanding marine climate. The unpredictability at sea is immense, considering the exhaustion of components. Floating offshore wind requires technological excellence in engineer disciplines such as aerodynamics, hydrodynamics, material science, control engineering and structure mechanics to avoid unforeseen and drastic damages which affect the production. [35]

The aerodynamic testing is challenging due to insufficient testing facilities, as well as a number of different floaters are constantly evolving and presented in the market. There is also a rapid development in rotor blade designs, that needs to accommodate the physical demands at sea [36]. Chen et al [35], points out that performing hydrodynamic simulations has challenges tied to scaling issues, blade pitch control and calibration methods. These problems are all linked to dissimilar Reynolds numbers. Being able to perform dynamic tests, these presumes similar Reynolds numbers.

FOWTs also faces challenges in terms of logistics. An increase in development and construction will occupy port facilities all across the world. To date, most of these ports are not regularised to construct FOWTs. To enable updates, political support is pivotal [32]. The grid connection is also a challenge for the offshore wind sector, and requires access to connection points to existing regional grids. Wieczorek et al [37] points out the importance of a common European vision and strategy to develop cooperative grid systems to empower more renewable energy production.

4.3 Financial incentives

Countries and companies have different strategies to secure green energy production. This is seen through pre-established contract models to secure developers and subcontractors. These are important to relieve some risk from the production companies.

Whether to include subsidies or not in the LCOE calculations are not standardised, but will have a pivotal impact on the final result. The BEIS method states that the subsidies is viewed upon as revenue, and not something to include in the investment or maintenance cost. Because subsidy schemes vary locally, the inclusion of these should be transparent from the analyst when presenting the LCOE result. [38]

To increase offshore wind in the UK and Germany, their respective governments has launched contracts for difference, CFD, which works as funds to enable offshore wind as well as other uprising renewable technologies. The CFD will guarantee a minimum price for every MWh of electricity that is being produced. This means that a company can bid on becoming the CFD developer, and makes a commitment to produce the cheapest energy possible. [39]

The norwegian strategy for offshore wind is highly relevant as the government published a press realise in February 2022 stating that the norwegian model will be to allocate projects through auctions, and are currently working on designing an auction model. This is to secure local contractors developing offshore wind projects on the norwegian continental shelf [40]. Due to its early stage the subsidy practice for offshore wind is not yet decided, but the government has set aside money in the state-budget for 2022 to secure a larger commitment going forward. [41]

In 2019, ENOVA decided to fund Hywind Tampen with 2,3 billion norwegian kroners (NOK), stating that economical support to offshore wind is important in Norway [42]. At the same time, in comparison to other European countries the norwegian support schemes is rather minimal, and government investment is important for streamlining the development of offshore wind. [17]

4.4 Location characteristics for floating offshore wind

Offshore wind projects are currently restricted to the exclusive economic zones (EEZ) where only the country that it belongs to can utilise and govern over the use of marine resources. The purple area in figure 4.3 shows the EEZ of Norway. In 1982 the United Nations Convention on the Law of the Sea prescribed which country has the rights considering the use of marine resources, this includes energy production from water and wind resources. All of the already established offshore wind energy projects are located within the EEZ of a coastal state or within the territorial sea. This means that the complete jurisdiction and control of the offshore wind farm are under the coastal state of which the sea area belongs. Wind energy generation within the EEZ as well as the construction, maintenance and removal of any offshore wind installation or structure, the coastal state have the exclusive jurisdiction and control over. [44]

Figure 4.3: Exclusive Economic Zone of Norway [43]

The advantage of being far out at sea is being less intrusive to neighbouring countries and no visual impact, which allows for larger farms to be created. The opportunity to be located far from shore is one location characteristic for floating offshore wind farms. The distance to shore and the type of substructure is the two characteristics that primarily differentiate floating and bottom-fixed wind. These two components likely have a big impact on the total costs of the farm. Myhre et al [30] points out that distance to shore is among the most influential parameters influencing the LCOE. The electrical infrastructure make up a big share of the costs for a wind farm, where distance to shore affects the length of export cable.

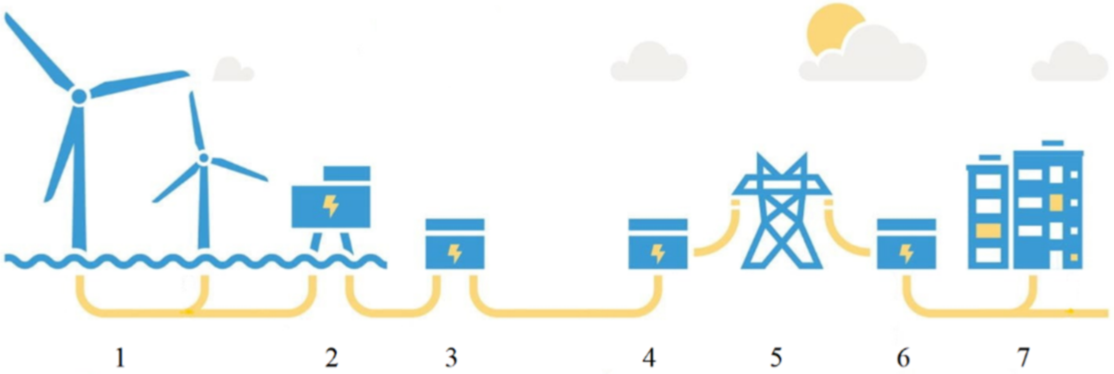
When establishing FOWFs far from shore, the water depth usually also increase. Bottom-fixed wind farms is constrained to a water depth of 90 meters due to economic viability. A water depth further that 90 meters gives the need for floating substructures as well as a floating substation. FOWFs can as of today be feasible at depths between 60 meters and 300 meters [45, 46]. The technology for floating substructures and substations is less established than the bottom-fixed structures and therefore also more expensive. Floating semi-submersible technology is not dependent on direct sea bed contact, and mooring lines can be designed to the desired length which gives more opportunities for location sites for this renewable technology. At sea it is possible to establish larger wind turbines with greater rotor blade diameter. That, together with higher wind speeds at sea, allows for more energy harvest. [47]

5 Decomposition of CAPEX

The LCOE calculation tool is constructed in Microsoft Office Excel. To understand the tool's design, its important to know how a FOWF is constructed and to be aware of which cost items fall under the different decomposition's. In the two following sections, 5 and 6 the decomposition of CAPEX and OPEX will be explained in detail, as well as the background for the different cost items. The sections also include the approximate costs used in the Excel tool. Some elaborations in this section are based on the design basis, that are further explained in section 7.

Offshore wind farm system

Figure 5.1 illustrates how a FOWF can be connected. Green electricity is transported through inter-array cables from the turbines (1) via an offshore substation (2) to the onshore substation (3), which is connected to the grid (4,5,6). The export cables, which is buried beneath the sea bed, transfer the electricity to an onshore substation where it is scaled down to the desired voltage level and fed into the grid. There is a need for several engineering technologies, constructions and components to connect the different components in the floating offshore wind farm to ensure delivery of electricity to the desired recipient (7) [48].



*1. Wind turbines 2.Offshore substation 3.Onshore substation 4-6.Onshore grid 7.Desired recipient

Figure 5.1: A complete offshore wind farm system [48]

CAPEX distribution

The contributions to the CAPEX cost are mainly results from literature studies, experience from Aibel and already established FOWFs. Some of the cost elements are a best guess estimation due to lack of data. Figure 5.2 illustrates an example of a CAPEX cost distribution, and is collected from the report LIFES 50+. [34]

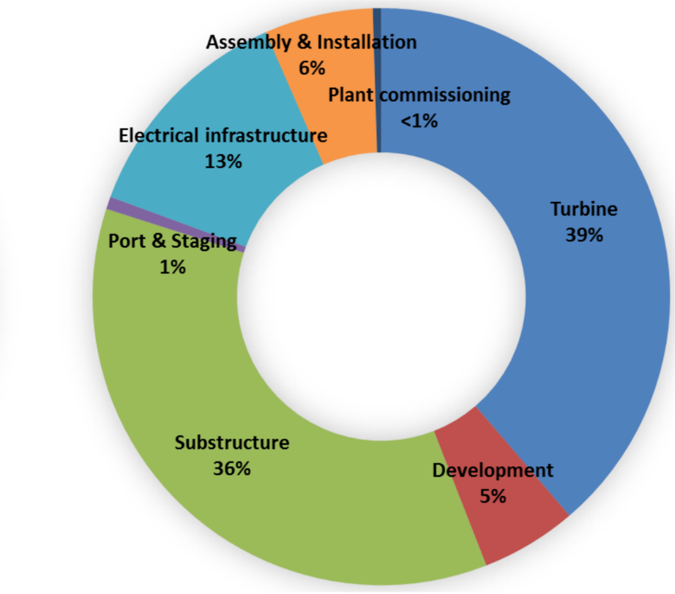


Figure 5.2: CAPEX distribution for a 10 MW FOWT at 50 m water depth [34]

CAPEX is the total investment costs of the project, and the following decomposition is chosen based on preliminary research and discussions with supervisors. This is shown in equation 5.1, where C0 is project consenting and development up to final investment decision (FID), C1 is the wind turbine structure, C2 is the electrical infrastructure and C3 is transport & installation.

$$CAPEX = C0 + C1 + C2 + C3 \tag{5.1}$$

Decommissioning, D1, shown in equation 5.2, will take place in the year after end of lifetime for the project. This is why the decommissioning cost must be discounted according to the current year.

$$DECEX = D1 \cdot \frac{1}{(1+r)^{n+1}} \tag{5.2}$$

5.1 C0: Project consenting and development to FID

Development and consenting up to FID covers the process up to the point of the major financial commitment from the wind farm developer.

5.1.1 Development and consenting services

Before a wind farm development is approved, developers needs to obtain consents. These procedures vary depending on what country one is applying in. For example, in England establishing wind farms requires a development consent order, a S36 consent, a marine licence and planning permission for the onshore grid [49]. In the US, the bureau of Ocean Energy Management permits project development through four different phases. The phases are called; planning and analysis, leasing, site assessment and construction an operations. [50].

Development of offshore wind in Norway requires a concession. A concession is a type of government allocation and holds a sosio-economic criteria to secure future generations [51]. The process for the concession rounds are shown in figure 5.3. In the announcement process the Ministry of Petroleum and Energy announced an invitation to participate in a ”competition” to have exclusive right to develop a project within the pre-determined area of development. The announcement contains the maximum installed effect that can be developed within this area. The prequalifiation process means that all appliers for the development area needs to meet the requirements stated in The Offshore Energy Act [52]. This is to secure that competitors for the site fullfills the requirements and holds the necessary competence. In the auction process the developers can bid on the pre-determined area. The exact auction model can vary from different areas, and will be announced by the Ministry of Petroleum and Energy. The auction winner will be announced six to twelve months after the first announcement of concession. [53]

In the allocation of area process, the auction winner has six weeks to send in a project description to the ministry, which will undergo ministry consultations. If the project description is decided, the developer has a two year deadline to send in a concession application, where the project description is used as the basis. If the concession is approved from the ministry, a more detailed plan containing important dates and technical descriptions, must be sent to the Norwegian Water Resources and Energy Directorate. The wind farm developer must start building the farm three years after approval date of this plan. [53]

Figure 5.3: Conseccion process for floating offshore wind [53]

5.1.2 Preliminary surveys

When constructing FOWFs, several preliminary surveys are required before undergoing wind farm construction. The environmental surveys include animal surveys, studying fish, birds, marine mammals and the general sea bottom habitat. They also cover noise analysis, aviation impact, visual effect, sosio-economic surveys and marine navigation studies. These surveys are required to apply for consent to develop a wind farm, and can take up to two years. A wind farm also requires an onshore environmental impact survey to examine the impact of laying cables onshore. [54]

A resource, meteorology and oceanography (metocan) assessment is performed to provide data sets with valuable information to the engineering team to design the wind farm. The meteorology assessment provides data about the wind conditions at the specific site. These assessments requires equipment being able to measure wind speed data in the correct height, which can be 100 meter or more above sea level [20]. This can be executed by using a meteorological mast that are installed at sea carrying wind measuring equipment. The oceanographic measurements looks at ocean currents, properties of sea water and marine conditions. [55]

It is also necessary to explore the sea bed environment in terms of cable laying possibilities and mooring. These are called geological and hydrological surveys. These surveys require distinctive vessels with a specialised crew to collect the relevant data. These surveys examines the sea bed soil, impacts on the local sedimentation and erosion. [20]

5.1.3 Engineering and design

To prepare the project for development, a front-end engineering design (FEED) study is an important component. The goals for such a study is to clarify the scope of the project, produce technical documents and verify product specifications. The study seeks to understand the totality of the wind farm project, and will contribute to minimise the LCOE. The duration of a FEED study varies from between two to six years, and requires massive cooperation and compilation across disciplines and companies. A FEED study will be used by the constructing team to further construct the project. [54]

FEED is followed by the final investment decision. The following step is an engineering, procurement and construction (EPC) phase. The EPC phase is the execution stage where the developer will provide details about the engineering, construction and the required materials and equipment. This stage also specifies crew/technician requirement for the project [56]. Since the EPC phase succeeds the FID, the phase costs are assumed to be included in the subsequent costs.

5.1.4 C0 costs

In table 5.1 all included cost in the Excel tool are listed. All the costs are based on information given above and the referred source.

Table 5.1: C0 costs items used in LCOE tool

	Cost value	**Source**
Development and consenting services	260 million NOK	[54]
Environmental surveys	20,6 million NOK	[54]
Resource and metocean assessment	80 million NOK*	[54]
Geological and hydrological surveys	20,6 million NOK	[54]
Engineering and design	20,5 million NOK	[54]

*These costs includes installing a physical met mast at sea.

5.2 C1: Wind turbine structure

The purpose of a wind turbine is to convert kinetic energy from the wind to electrical energy. The generator in the wind turbine produce three-phase alternating current (AC) electricity which is feed into the grid after first going trough an offshore- and then an onshore substation. [54]

5.2.1 Wind turbine

The turbine cost is decomposed into rotor nacelle assembly and tower and floater. A basic wind turbine construction is illustrated in figure 5.4. The background for the total cost of the wind turbine is explained further below, the floater will be explained in section 5.2.2 and the mooring system is explained in section 5.2.3.

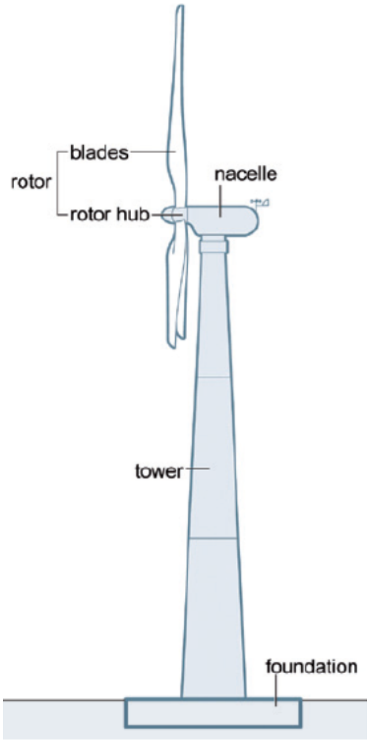


Figure 5.4: Basic wind turbine construction [57]

The function of the nacelle is to support the rotor and convert the rotational energy from the rotor into AC electrical energy. In modern offshore wind turbines the nacelle mass is kept at the minimum to help with general system dynamics and decrease logistics costs. To keep the nacelle mass down, the turbine can be designed with the transformer and much of the power electronics in the tower base. Since the nacelle is located in the centre of the rotor blades, this lowers the center of gravity. The nacelle consists of several sub-components. A few of the sub-components that has an impact on the total cost of the nacelle, are the generator, the main shaft, the control system, the gearbox and several more. [54]

The rotor consist of blades, the hub, blade bearings, pitch system and other practical parts. The rotor harvest kinetic energy from the air that hits the swept area created by the blades, and converts this into mechanical energy in the drive train. New turbine designs has larger swept areas compared to the generator rating, resulting in higher capacity factor. The blades are connected to the drive train via a hub. In regards to offshore wind turbines the blades are connected via bearings to achieve independent adjustment of the pitch angle of the blades. The total rotor for a 15 MW turbine has a mass of approximately 225 tons, and a total rotor diameter around 230 meters. The size of rotors for an offshore turbine has no fundamental limits, though the mass of the rotor increases more than the amount of energy produced. The cost also increases more than the yield of increasing the rotor. [20]

The tower is a steel construction that supports the nacelle. It also has a function to provide access to the nacelle and store electrical, control and safety equipment. The optimal height of the tower is normally as low as needed to follow the maritime safety regulations for blade space above the water. The wind shear is low offshore, hence the wind speed do not increase drastically with increasing height of the hub, meaning there is no benefit to invest in a higher tower. Typically, the tower is about 100 meter high and has a mass of over 600 tons, and 90% of the mass are steel plates. [20]

In general a FOWT has a higher resource intensiveness compared to a BFWT, due to demanding more materials, especially steel. The cost of steel is high, and is currently increasing due to global challenges [58]. This affects the cost of the turbine and floater, which contains a high amount of steel [59]. According to Wind Europe [16], FOWF costs are expected to decrease, which will increase deployment of FOWFs, resulting in a increasing demand for steel.

5.2.2 Floater

Floating offshore wind differs from other wind technologies as it depends on having a floating substructure that can handle the rapid motion from sea. Fortunately, developers across the world has useful experience constructing floating offshore oil and gas rigs. Due to this previous experience, different floater solutions has been developed. Figure 5.5 shows the different types of substructure for floating wind turbines, clearly inspired from the oil and gas industry (ref. figure 4.1).

There are several different types of floating structures, and they are at different stages in the development phase. The four most common floating technologies are: spar buoy, barge, tension leg platform (TLP) and semi-submersible, all illustrated in figure 5.5. Spar buoy, barge and semi-submersible are loosely moored to the seabed which causes easier installation. The semi-submersible- and the barge floater is stabilised by buoyancy, while the spar buoy is a ballast stabilised structure utilising gravity. The TLP is more firmly connected to the seabed, using the tension in the mooring system, which causes a form and stable structure. [5, 16]

Semi-submersible floating foundation is a fully welded steel structure which uses three hollow columns to provide necessary buoyancy. Semi-submersible floating technology was first adapted for offshore oil and gas industry, and later the foundation was suggested for supporting offshore floating wind turbines. Due to the *wave cancellation effect*, a phenomenon where the wave forces acting on the submerged objects with different phases cancelled each other due to phase shift, semi-submersible floating system is a good solution to regulate offshore turbines. Nevertheless, sea currents, floating ice, storm surges and tidal variations influence the semi-submersible foundation and must be considered when designing the structure. Complex design, steel materials and good engineering calculations affect the total price of producing the wind turbine floater. [60]

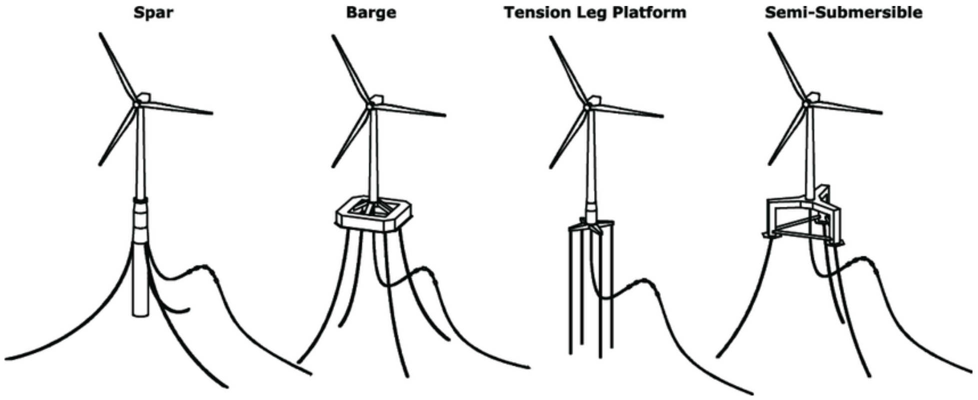


Figure 5.5: Different substructures for floating wind turbines [16]

Stochastic loads
As a result of various floating technologies the reaction to weather loads differ due to different dynamic properties. If beholding the floating wind turbine as a system, it is characterised as nonlinear with stochastic load. Calculating how the wind turbine withstands unpredictable and random loads is challenging and is as of today insufficiently researched, although there is some experience to take from the oil and gas industry (ref. section 4.1). The foundation for bottom-fixed wind turbines is attached to the seabed, giving a less dynamic response to the loads that the structure is exposed to. Given the prerequisites off the open sea in terms of loads, compared to how the the sea behaves closer to shore, FOWTs will have an advantage, although the technology is somewhat more challenging with FOWTs. [61]

5.2.3 Mooring system

When using semi-submersible floaters in offshore wind projects, catenary mooring lines are usually employed. The anchoring system from the semi-submersible floater is horizontal at the seabed and the mooring needs to be longer than the water depth. Therefore the consumption of mooring lines is mainly dependent on the configuration, but also on the number of mooring lines. Mooring lines is a difficult cost to estimate, due to uncertainty in calculating the length on the line. The length of the mooring line is often estimated to be three to five times the water depth [62]. The materials used for the mooring chain and wire is often steel. Mooring lines are used to stabilise the FOWTs and consists of reliable and flexible tensioners, chain stoppers, winches and subsea connectors to the anchor. When maintenance on the floating wind turbine is needed, the mooring lines can be disconnected, which allows the turbine to be towed back to the port. [60, 62]

Due to different soil conditions on the sea bed as well as varying water depths, different anchor types have been developed to optimise the mooring systems in terms of installation and cost. For a soft clay soil, a suction pile anchor is the best fit. They are long steel cylinders constructed with a pile cap that penetrates the soil during installation. The part of the construction that still remains surfaced can be reached with a remote-operated vehicle that is able to pump the water out of the suction port, and close the valves [63]. The suction pile anchor can be seen as number 4 in figure 5.6.

Figure 5.6 illustrated five other anchor types. From the left there is dead weight (1), driven pile (2), drag anchor (3), torpedo pile (5) and vertical load anchor (6). All have theirs functions depending on seabed and area specifics. [64]

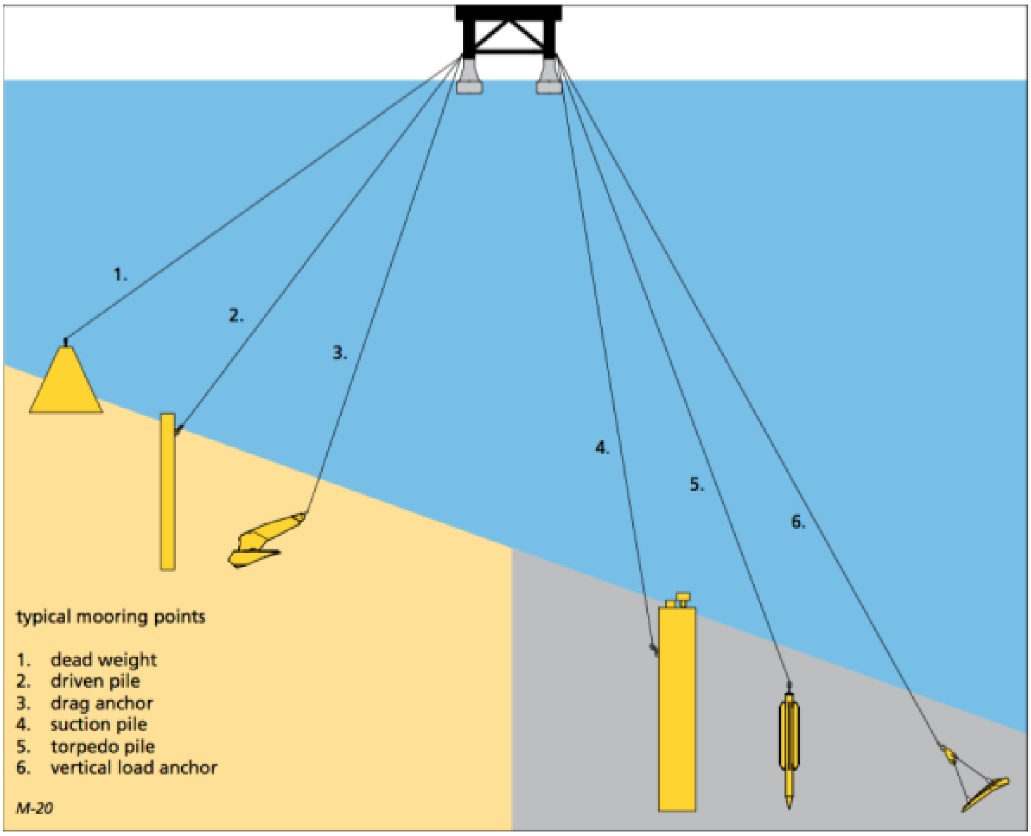


Figure 5.6: Types of anchoring technologies [64]

5.2.4 C1 costs

Below in table 5.2, the costs of a wind turbine structure and the mooring system that is used in constructed LCOE tool is listed. All costs are based on information given above and the linked sources.

Table 5.2: C1 costs items used in LCOE tool

	Cost value	Source
Wind turbine structure		
Rotor nacelle assembly and tower	2733 million NOK*	[54]
Floater	2135 million NOK*	[30]
Mooring system		
Catenary mooring lines	5180 NOK/m	[65]
Anchors, suction pile	800 800 NOK/anchor	[66]

*Including all 30 wind turbines

5.3 C2: Electrical infrastructure

The electrical infrastructure of a FOWF consists of the inter-array cables, the export cable, the land cable, as well as offshore and onshore substation. By optimising the electrical layout of the farm, the cost can be reduced. The layout also affects the energy yield through transmission losses, again affecting the LCOE of the farm. The cost of the electrical infrastructure for BFWFs is estimated between 15% and 30% of the total CAPEX. As for FOWFs the cost is likely even higher, due to new technologies and procedures for installation. [67]

Inter-array cables is used to connect the FOWTs and to transmit the generated energy from the turbines to the floating substation. Figure 5.7 shows how the inter-array cables is connected to the offshore substation and how the energy is transmitted to the onshore substation through the export cable. The energy is transmitted from the offshore substation through a dynamic cable connected to a static cable through an inter-connector joint.

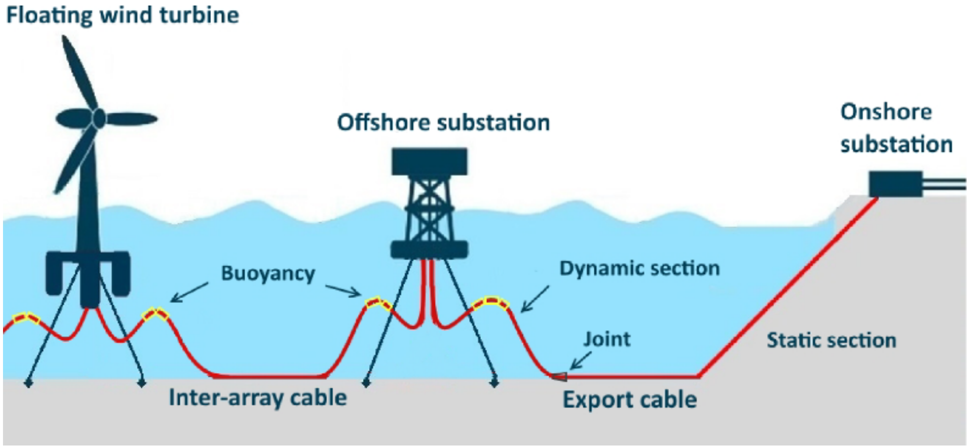


Figure 5.7: Components in the electrical layout of a floating offshore wind farm [67]

5.3.1 Cables

The export cable consist of a dynamic cable section, the inter-connector joint and a static cable section. The inter-array cables can either only consist of a dynamic cable, or have the same layout as the export cable. The dynamic section of the inter-array cables and export cable uses buoyancy elements to reduce mechanical stress, but the specific design vary depending on the type of cable configuration. The cable configuration is chosen based on external constraints such as floater motion and environmental conditions such as water depth and marine growth. In addition to the buoyancy elements the dynamic cable needs to be highly flexible and have great mechanical strength to withstand the loads from the currents and floater motions. The inter-connector joint is used to connect the dynamic and static cable. The inter-connector joint is classified as either a dry-mate or the wet-mate connector, where the choice depends on the installation method. A static cable is used for the export to the onshore substation, and can also be used in the inter-array connections. The static cable is laid beneath the seabed and is covered with scour protection. [67, 68]

The cable cost is a function of the length. The cost of the inter-array cables is mainly dependent on the number of turbines, but also slightly vary with the distance between the turbines. The installed capacity of the turbine determines the size of the cable. 33 kV or 66 kV cables, normally consisting of three-core copper conductors with steel wire armoured and insulation components, is used to transmit the energy. The choice depends on the turbine size. The current development of wind turbines leads to constantly increasing turbine sizes. Larger swept area causes the turbines to be positioned further apart to reduce wake losses, resulting in slightly longer inter-array cables. The dynamic cable has a higher cost than the static cable due to the need for increased armor and a larger outer sheath. For the inter-array cables it is necessary to assess if it is most profitable to have only a dynamic cable connecting the turbines, or dynamic and static cable. Although static cables is less expensive than dynamic cables, there is a cost related to connecting the two cables through the inter-connector joint. This procedure is comprehensive and needs specific vessels and equipment. [69]

The length and the size of the export cable is respectively dependent on the distance to shore and the capacity of the farm. Transmitting energy over long distances, gives more losses. Cables designed for higher voltages reduce transmission losses. The export cable is similar to the inter-array cables, only the voltage is higher, usually 100 kV or 220 kV. [70]

5.3.2 Substations

Aibel has secured a position in the European offshore wind market, delivering substations and expertise to several existing offshore wind projects [71]. Understanding the background for optimal electrical transmission from sea is important to optimise the projects output in electrical production and project revenue.

Substations increase the voltage and prepares the current to be shipped over long distances. The substation receives alternating current from the wind turbines, and can thereafter transport it as either high voltage alternating current (HVAC), or high voltage direct current (HVDC). HVAC is the most common in terms of offshore wind projects. The leading transmission company, ABB [72], writes that the choice between AC or direct current (DC) is a matter of costs and losses in the export cables, and therefore depends on the distance to the onshore grid. Because HVDC equipment is more expensive, HVAC is most favourable, but at some distances the loss will be too great and therefore too costly for AC transmission. During AC transmission, the losses will increase with higher voltage and cable length. DC transmission also experience losses, but will at a certain distance be lower than with AC transmission. The reason for choosing HVAC in most projects is due to the cost of production being lower compared to the loss cost. Generally, HVDC is employed for wind farms further than 100 km to shore, and HVAC is chosen when this distance is less than 100 km. [72]

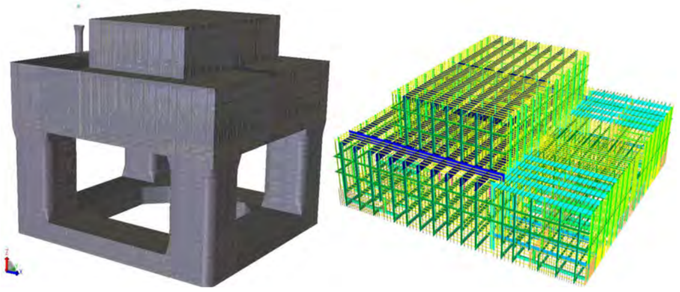


Figure 5.8: Floating HVDC converter station including floater and topside [73]

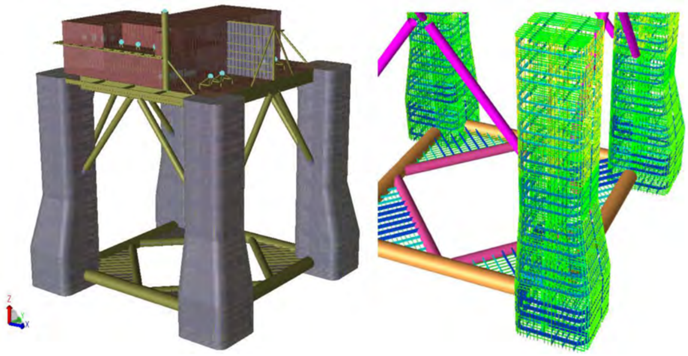


Figure 5.9: Floating HVAC converter station including floater and topside [73]

Both transmission methods are in commissioning for bottom-fixed offshore wind, with bottom fixed constructions. To enable FOWFs both floating HVAC and HVDC concepts needs to be accessible. According to a report done by Society of Petroleum Engineers [73], the HVDC equipment requires a larger volume compared to a HVAC station. The HVDC solution needs a larger distance in between the equipment, and therefore requires a bigger area protected from climate. This makes the HVDC solution a more recourse intensive and heavy construction compared to the HVAC. Developing a lower standing HVDC structure to secure stability is more suitable [73]. This solution can be seen in 5.8.

Since the HVAC equipment is more compact, it requires a smaller area and a different design. The report suggests that both solutions requires a semi-submersible floater, but the HVDC requires a more conventional semi-submersible design, and the HVAC requires a deep-draught design as seen in figure 5.9.

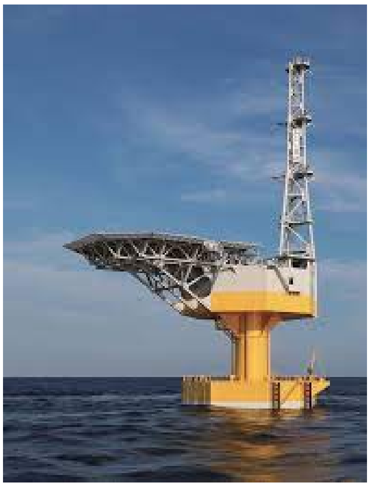


Figure 5.10: Floating offshore substation, Fukushima Kizuna [74]

Floating offshore HVAC substation is the most suitable for wind farms less than 100 km from shore, also considering that floating HVDC has yet to be developed. Onshore substation is available in both HVAC or HVDC. Floating offshore substations have a significant contribution to the total electrical expenditures. The floating substation consists of a topside mounted on top of the floater, constrained with a mooring system [67]. The electrical equipment of the offshore substation is similar to the onshore substation, but offshore there is a need for advanced environmental protection. The onshore substation transforms the energy received from the offshore substation into the required grid voltage. The design of the onshore substation depends on the network operator. [70]

Because floating wind farms are still a relatively new part of the offshore wind sector, the technology and experience with floating substations is still in the early stages. Neither of the floating wind farms; Hywind Scotland, Windfloat and Kincardine has a substation at sea, due to only consisting of a few turbines. The only wind farm designed with a floating offshore substation is Fukushima located in Japan, but Fukushima is not a commercial size wind farm [70]. Figure 5.10 shows the floating offshore substation, Fukushima Kizuna. Due to only one operating floating substation existing, there is a lot of uncertainty around cost of floating offshore substations. The cost of a onshore substation is estimated to 30 000 £/MW acing to BVG associates [54]. For the current design basis, the onshore substation cost is set to zero, since it is assumed that a onshore substation already exists in the Haugesund area, see table 5.3.

5.3.3 C2 costs

In table 5.3 the costs of the electrical infrastructure needed to construct this design basis are listed. Due to both the inter-array cables and export cable possibly consisting of a dynamic and static cable, they are summed respectively in the table. All costs are based on information given above and the linked source.

Table 5.3: C2 costs items used in LCOE tool

	Cost value	Source
Cable		
Dynamic cable and inter-connector joint	15 million NOK	[75]
Static cable	9490 NOK/m	[75]
Land cable	20 million NOK	[75]
Floating offshore substation	1430 million NOK*	[75]
Topside offshore floating		
Mooring offshore floating		
Floater offshore floating		
Onshore substation cost	0 NOK**	[75]

*Total cost value given from Aibel [75]. Including topside-, mooring- and floater offshore floating.
**Onshore substation cost assumed zero, already assumed to exist in Haugesund area.

5.4 C3: Transport & installation

The transport and installation section, shortened to T&I in industry setting, covers the cost of transporting the different components to sea as well as installing the different components at the given location. This includes cost items such as vessels, staff, insurance and port expenses. Wind farm developers choose different types of T&I strategies, and the following method does not necessarily apply to all installation scenarios.

5.4.1 Vessels and transport

Extensive vessels are needed to perform offshore wind installations at sea. Floating offshore wind requires transportation and installation of the constructed wind turbine, the floater, the mooring system, the electrical system and the interconnection between every component. Table 5.4 shows the necessary vessels as well as their associated costs. An installation process also requires large resources onshore, and will occupy port facilities in longer periods of time. [76]

Figure 5.11: A tug vessel dragging a floating wind turbine in constructing the Kincardine wind farm [77]

Figure 5.12: A cable laying vessel performing dynamic cable assembly at China's Yangxi Shapa III pilot project [78]

- A **tug vessel** is required for tugging the pre-assembled floating turbines efficiently out to the desired location. The tug vessel process is shown in figure 5.11. [79]
- A **barge vessel** is needed in the installation process to supply different components that are needed for the wind turbine. The vessel is characterised by having long and flat bottom and is designed to transport cargo or passengers. [79]
- A **cable laying vessel** is needed for both the array cables and the export cable. This boat requires room to store several kilometres with electrical cables, and also contain installation infrastructure to install the cables at the seabed and in between the the turbines. A cable laying vessel is shown in figure 5.12. [79]
- A **anchor handling vessel** is a vessel designed for installing and retrieving anchors that are being installed at the seabed. These vessels require dynamic and powerful systems to give the vessel the proper bollard pull to execute the transportation and installation of the anchors that are supporting the mooring systems. [64].
- A **semi-submersible** vessel is usually used for installing large constructions such as a floating substation. It has the opportunity to lower its body to launch the desired construction at sea. [80]
- A **rock handling vessel** is required to perform scour protection of the installed cables to protect it from the sea environment. [79]
- A **service operating vessel** offers different service operations onboard the specific ship. It host the technicians, allowing operation and maintenance tasks to be efficiently conducted and are used for a longer periods of time offshore. [81]
- A **crew transport vessel** is the most common way to access the turbines. It is cost effective and the use depend on the capacity of technicians, the spare parts required and the distance from the shore to the turbine. [81]

The crane at port has as function to lift different items and components from the port onto the needed vessels. If components are constructed on port, this crane is used for lifting and assembling different components and strategically move items into place. Floating cranes are useful for unloading and loading heavy cargo to and from vessels at the sea. Floating cranes are necessary for lifting an manoeuvring extremely large sub-assemblies into position. Floating cranes has made the assemble of FOWFs possible in bigger scale by streamlining and facilitating the process. [20, 82]

A floatel is a vessel accommodation used for the crews required during the offshore construction process of developing a wind farm. Floatel Triumph [83] is an example of a semi-submersible floatel which can accommodate 500 people. It is equipped with a helicopter deck, a large lay-down area, two deck cranes, workshops and warehouses. Helicopter is used in the T&I phase to transport people and cargo from port to the offshore wind farm. Like the floatel, the substation also has a helicopter deck. A helicopter can also be used for the operation and maintenance to quickly transport people and equipment to the site. [84]

5.4.2 Installation

The installation process needs to be planned far ahead of time, due to acquiring port facilities, components and vessel availability. Although, when planning ahead of time, factors such as weather conditions are uncertain. Installation requires satisfying weather conditions to optimise vessel usage and installation time. [85]

The mooring system is installed before the floating wind turbine. When installing a suction pile anchor to the seabed, several alternatives can be used. One alternative is to start by installing a suction pump on the top of the anchor before dropping it from deck into the water towards the seabed. Then, closer to the seabed, the crew must orientate and position the anchor with a remotely operated vehicle, and lower the suction pile connected to the anchor to self-weight penetration. Further, the crew must close the vent valve in the suction pump and preform the suction operation into the seabed. When the suction pile anchor is installed in seabed, the vent valve is open and the crew recovers the suction pump back to deck. Mooring lines are connected to the anchor throughout the process. [86]

A semi-submersible floater offers a simpler installation at site compared to other floating technologies. This is due to the wind turbine being assembled and completed by staff at the predetermined port, and thereafter tugged out to the selected sea site by a tug vessel and mounted to the pre-installed mooring structure. The substation is also constructed at port and transported from the substation construction site to the wind farm site. Also the floating substation installation requires a tug vessel, or a semi-submersible vessel to transport the floating substation from the construction site and mount it to the pre-installed mooring. [87]

Installation of the electrical infrastructure takes place after the installation of the wind turbine structures. When installing all types of cables, the most important task is to secure the minimum bend radius, which is the smallest allowed radius a cable is permitted to be bent [88]. This is so no damage is done to the cables during installation. The cable laying vessel requires a number of qualifications to perform the cable laying as intact as possible. DNV [88] has identified several challenges for cable installation for an offshore wind project in *Guidelines for Offshore Wind Farm Infrastructure Installation*. Following is a selection of challenging factors mentioned in the report:

- Compression forces
- Varying ground conditions
- Direction of lay
- Installation of cable protection

The cable laying process with belonging prominent parameters are shown in figure 5.13. The departure angle is determined from the cable exit angle out from the wheel tensioner machine on the cable laying vessel. The touchdown point is a critical part of the installation process, as the minimum bend radius is at risk due to bottom tension. Proper knowledge about the seabed landscape is critical in this installation stage [89].

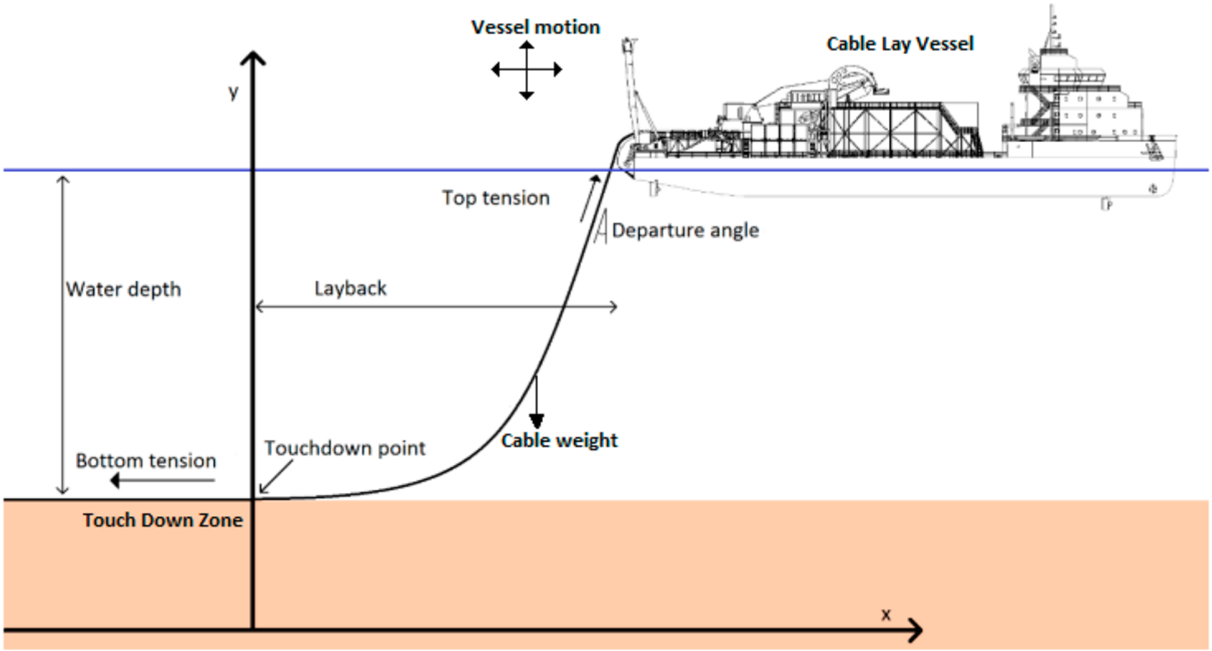


Figure 5.13: Cable laying process [89]

5.4.3 Crew and other costs

In addition to vessels, decomposition of T&I also includes crew, insurance and port operation. An extensive project such as a wind farm requires a large amount of staff with different traits and backgrounds. It requires a team of mechanics, technicians, engineers, boat personnel, project managers, logistics responsible and more [90]. Estimating staff cost can be difficult, as the necessities vary. Port operation is also a cost that needs to be included, as the entire T&I depends on port facilities, to load the constructed equipment onboard the required installation vessels. Also, the wind farm installation requires different types of insurances, because it can offer challenges tied to unanticipated conditions, and must be included in the CAPEX. [91]

5.4.4 C3 costs

In tables 5.4 and 5.5 the costs of the T&I needed to construct and assemble this design basis are listed. Table 5.4 shows the vessel costs and table 5.5 show the crew costs and other costs. The costs are based on researched sources, information from Aibel [75] and a best guess where there is lack of data.

Table 5.4: Vessel and transportation costs items used in LCOE tool (C3)

Vessel	**Cost value**	**Source**
Tug vessel	213 525 NOK/day	[18]
Barge vessel	332 150 NOK/day	[18]
Cable laying vessel array	863 590 NOK/day	[18]
Cable laying vessel export	1 081 860 NOK/day	[18]
Anchor handling vessel	464 061 NOK/day	[18]
Rock-dumping vessel	130 962 NOK/day	[18]
Crane at port	189 800 NOK/day	[18]
Floating crane with storage area	1 100 840 NOK/day	[18]
Floating crane without storage area	7 704 931 NOK/day	[18]
Service operating vessel	263 603 NOK/day	[81]
Crew transport vessel	37 505 NOK/day	[92]
Floatel	500 000 NOK/day	Best guess
Helicopter	2 000 000 NOK/day	Best guess

Table 5.5: Crew and other costs items used in LCOE tool (C3)

	Cost value	Source
Crew		
Technician crew	9600	[75]
Technician crew- Asia	4200 NOK/day	[75]
Port crew	9600 NOK/day	[75]
Port crew- Asia	4200 NOK/day	[75]
Administration crew	9750 NOK/day	[75]
Engineering crew	7500 NOK/day	[75]
Other		
Port operation	50 000 000 NOK	Best guess
Insurance	3 000 000 NOK	Best guess

5.5 D1: Decommissioning

Decommissioning is the last stage in the project's life cycle, where the operator need to follow the applicable rules regarding removal of structures and facilities. Depending on rules, the site must be left in similar condition as before the construction. The decommissioning of a wind farm involve logistical difficulties, potentially large costs as well as environmental impact. To optimise this stage, it needs to be considered from the start of the project. If decommissioning is considered already in the design phase, impacts and costs can be reduced. Regardless, a decommissioning plan must be presented for the installation to get approved. [93, 94]

The decommissioning of a FOWF has not taken place yet, because FOWFs is a relatively new domain. Operators are currently most concerned with improving installation techniques and optimising efficiency, rather than improving the decommissioning phase. Several similarities can be drawn to BFOW, therefore it is possible to learn from the challenges which occurs in the decommissioning of BFOW projects (ref. section 4.1). The first decommissioning of an offshore wind project was in 2016, where the farm consisted of five 2 MW turbines. An important observation from the first several decommissioning, was that it was severely dependent on the site characteristics. Types of structures, equipment used and contractual terms are factors that makes it difficult to develop a general methodology for decommissioning of offshore wind farms. [93]

Figure 5.14: Decommissioning of an offshore wind turbine [95, 96]

A floating offshore wind farm consists of the rotor nacelle and tower, floater, mooring system for all of the turbines as well as all the electrical infrastructure. All of these components needs to be dismantled and transported to shore. This requires a lot of the same vessels and equipment as the installation phase. The main goal is do the majority of the disassembly onshore, to reduce the time and economic expenditure. Figure 5.14 shows the disassembly of an offshore wind turbine. [93]

After the decommissioning of the wind farm, there are several components that can be recycled and some parts can be sold as scrap. Another possibility is to convey a re-powering or refurbishment study of the farm. Instead of a complete dismantling of the site, respectively replacing the turbines to increase capacity or replacing minor components of the project might be more profitable. It could either be a final decision, or be considered from the beginning of the wind project. This decision also affects the total costs [93]. With that said, this must be seen in the light of each individual project, as the financial, technical and situational outlooks are different. According to Pakenham et al [97], life extension solutions will in some cases be the most economically reasonable. Although this might reduce the costs of decommissioning, neither of these solutions are taken into account in LCOE calculations.

The number of offshore wind farms is rapidly increasing and the number of decommissioning will follow. Decommissioning of FOWFs is an unexplored domain and therefore the legislation is absent. It will be dependent on country, and range from full removal and recycling of whats possible, to possibly no removal from the site. The wind farm need to follow the rules within the respective country's EEZ. The number of decommissioning or re-powering of offshore wind farms will continue increase in the years to come. [93]

It is difficult to anticipate the costs of decommissioning a FOWF. The decommissioning of offshore wind will likely adapt techniques from the offshore oil and gas industry together with the onshore wind industry. Regardless, the planning will be more challenging due to the dependence on the weather conditions at sea. Availability of vessels must also be taken into account, in the case of unexpected early decommissioning. This will directly influence the total costs of operation. The costs of decommissioning an offshore wind project is estimated to around 2 to 3% of the CAPEX. The decommissioning costs can be divided into offshore preparation, vessel mobilisation and demobilisation, disassembly and foundation removal. Offshore preparation and foundation removal has the highest costs. [93]

5.5.1 D1 costs

Table 5.6 shows the cost of decommissioning, but due to decommissioning of FOWFs being an unexplored domain, this is a best guess estimation.

Table 5.6: D1 costs items used in LCOE tool

	Cost value	**Source**
Offshore preparation		
Vessel mobilisation and demobilisation		
Disassembly		
Foundation removal		
Decommissioning	NOK 800 000 000*	Best guess

*This cost is meant to be the sum of all above subcategories.

6 Decomposition of OPEX

Operation and maintenance cost are an important expense in the total costs over the lifetime in offshore wind projects. OPEX is fed into the LCOE cash flow sheet and is the project costs on an annual basis over the lifetime. In the developed LCOE calculation tool, OPEX is decomposed into planned- and corrective maintenance. The total operation cost is shown in equation 6.1 and is discounted to the respective year. O1 is the planned maintenance cost and O2 is the corrective maintenance cost.

$$OPEX = (O1 + O2) \cdot DF \tag{6.1}$$

OPEX for renewable energy projects has seen a decrease in the last years. This trend also applies to offshore wind projects, where the costs reduction is affected by larger turbine sizes and higher capacities [98]. From a comparison of 47 different offshore wind farms across Europe, the analysis shows a general reduction in OPEX over the years of operation. The concept of floating offshore wind farms is still relatively young, and therefore lacks statistics on OPEX development over the lifetime. The general down-going trend in OPEX may be explained from simple learning effects, advanced technology and retrofits. It is still uncertain how the OPEX will evolve towards the end of life of the wind farms. It is important to address that the annual OPEX/MW differ depending on country for the site location, considering the EEZ. The analysis is preformed on offshore wind projects in general, where the major part of offshore projects today is bottom-fixed. Although some of the statistics and trends might be transferable to floating wind, the concept of floating wind farms is too young to have any certain knowledge on the development of OPEX throughout the lifespan of the farm. [99]

FOWFs are exposed to great impact, due to the harsh weather conditions far out at sea. This results in higher failure rates for floating turbines, rising the costs of planned and corrective maintenance. Wind turbines at sea also exists in a demanding climate when it comes to corrosion. The saltwater creates an aggressive environment due to PH-levels, temperatures and salinity. To avoid this issue, the exposed areas of the turbine are designed so there is no need for maintenance caused by corrosion, throughout the lifetime. [100]

Floating wind turbines are unmanned structures and therefore maintenance becomes more demanding considering accessibility. Consequently maintenance of FOWTs are more extensive causing an impact on the LCOE for offshore wind [100]. The logistics behind the maintenance for FOWFs are also complex. The vessels are constrained by weather conditions, possibly causing longer down-time, due to the response time. This is one of the main contributors to high operation and maintenance (O&M) costs, as well as lost production. [19]

6.1 O1: Planned maintenance

Planned maintenance is scheduled in the development and consent phase. It is often based on components suppliers recommendations or other owners experience of when maintenance on the given components are needed. This includes time- and condition based maintenance programmes, but also planned safety, health and the projects condition inspections. Planned maintenance also involve operations related to management of the project. [20]

Planned maintenance costs is divided into finances, vessels and transportation, port facilities and equipment, and crew. Each of these have several subcategories. Finance cost contains several expenses which the investors has to pay to be allowed to operate the wind farm. Annual and monthly expenses like insurance, annual lease, annual property taxes and transmission charges needs to be included in the planned finance costs. There is also need for different vessels and helicopter, different crew members, spare parts and consumables. This includes for example filters and oils that needs to be changed regularly.

6.1.1 O1 costs

In table 6.1 the costs of the annual planned maintenance are listed. The costs deprive from researched sources, information delivered by Aibel [75] or a best guess where there is lack of data.

Table 6.1: O1 costs items used in LCOE tool

	Cost value	**Source**
Finances		
Insurance	4 500 000 NOK	[101]
Annual lease	3 000 000 NOK	[102]
Annual property taxes	21 000 NOK	[103]
Transmission charges	270 000 000 NOK	[104]
Vessels and transportation		
Service operating vessel	1 000 000 NOK/day	Best guess
Crew transport vessel	400 000 NOK/day	Best guess
Flotel	500 000 NOK/day	Best guess
Helicopter cost	2 000 000 NOK/day	Best guess
Port facilities and equipment		
Spare parts	1 000 000 NOK	Best guess
Consumable	500 000 NOK	Best guess
Port operation	50 000 000 NOK	Best guess
Crew		
Maintenance crew	9600 NOK/day	[75]
Port crew	9600 NOK/day	[75]
Maintenance crew Asia	4200 NOK/day	[75]
Port crew Asia	4200 NOK/day	[75]
Administration crew	9750 NOK/day	[75]
Engineering crew	7500 NOK/day	[75]

6.2 O2: Corrective maintenance

This maintenance method takes into account service and repair of the wind project based on unexpected failure of components. Specifically when the components does not function properly, and is not fulfilling its task. It is required that the project operates at functional state and if not, the component will either be repaired or replaced. A key goal to reduce O&M costs is to reduce corrective maintenance, due to the high costs in conjunction with increasing downtime caused by preparation and reaction time [105]. Corrective maintenance include spare parts and consumables for the repair or replacement of an component, port operation costs during the maintenance period, vessel costs for the different vessels needed and crew costs for the different personnel needed for the administration and execution of the maintenance work.

Due to the field being relatively new, the experience with operation and maintenance is not adequate. The unforeseen maintenance can therefore be higher than expected. As in other fields for FOWFs, the O&M methods can be adapted from both the oil and gas industry as well as the BFWF industry [19]. Corrective maintenance is unscheduled interventions, that can either be a response to a component failing, or a proactive response discovered during inspections [54].

6.2.1 O2 costs

In table 6.2 the costs of the annual corrective maintenance are listed. The costs deprive from researched sources, information delivered by Aibel [75] or a best guess where there is lack of data.

Table 6.2: O2 costs items used in LCOE tool

	Cost value	**Source**
Port facilities and equipment		
Material costs	NOK 150 000 000	Best guess
Operation port	NOK 50 000 000	Best guess
Vessels and transportation		
Service operating vessel	NOK/day 1 000 000	Best guess
Crew transport vessel	NOK/day 400 000	Best guess
Floating crane without a storage area	NOK/day 1 100 840	[18]
Floating crane with a storage area	NOK/day 7 704 931	[18]
Helicopter cost	NOK/day 2 000 000	Best guess
Crew		
Maintenance crew	NOK/day 9600	[75]
Port crew	NOK/day 9600	[75]
Maintenance crew Asia	NOK/day 4200	[75]
Port crew Asia	NOK/day 4200	[75]
Administration crew	NOK/day 9750	[75]
Engineering crew	NOK/day 7500	[75]

7 Design basis

The prerequisites for this bachelor thesis is to use a method to calculate the LCOE for a general FOWF. To generate a generalized and user-friendly LCOE calculation tool, a socially relevant and realistic design basis is taken into consideration. The purpose of this bachelor thesis is to develop a tool that correctly calculates the LCOE for a floating offshore wind farm, not to guarantee that the specific cost inputs is exact for this design basis. Hence, the LCOE calculated does not correctly represent the LCOE for Utsira Nord, but all the calculations and connections between the sheets are thoroughly reviewed.

7.1 Utsira Nord

In 2020 the Ministry of Petroleum and Energy opened the Utsira Nord and Southern Nord Sea II areas, see figure 7.1, for applications for renewable energy production at sea. On the island Utsira is it natural to establish a base for the activity at sea and it is a good opportunity for delivery of services from here. This will result in lower operating and maintenance costs. Spare parts for substations and other electrical components can be stored at the island. There are several costs that can be reduced if this island is actively used for the development and production of renewable energy at this location [8]. It is also recommended that the development of new FOWFs mainly to take place in southern waters to be closer to the energy demand center in Europe, because development in northern waters will require a larger and costly development of the grid connection. [8]

This justifies the chosen location for the constructed Excel tool, Utsira Nord, due to opportunities as a current and relevant area. Aibel considers this area to be very relevant, with respect to delivery of substations. Nevertheless, found and assumed costs used in the LCOE calculations tool does not take into account this island as an advantage since FOWFs are relative new to the market and relevant cost data is difficult to collect.

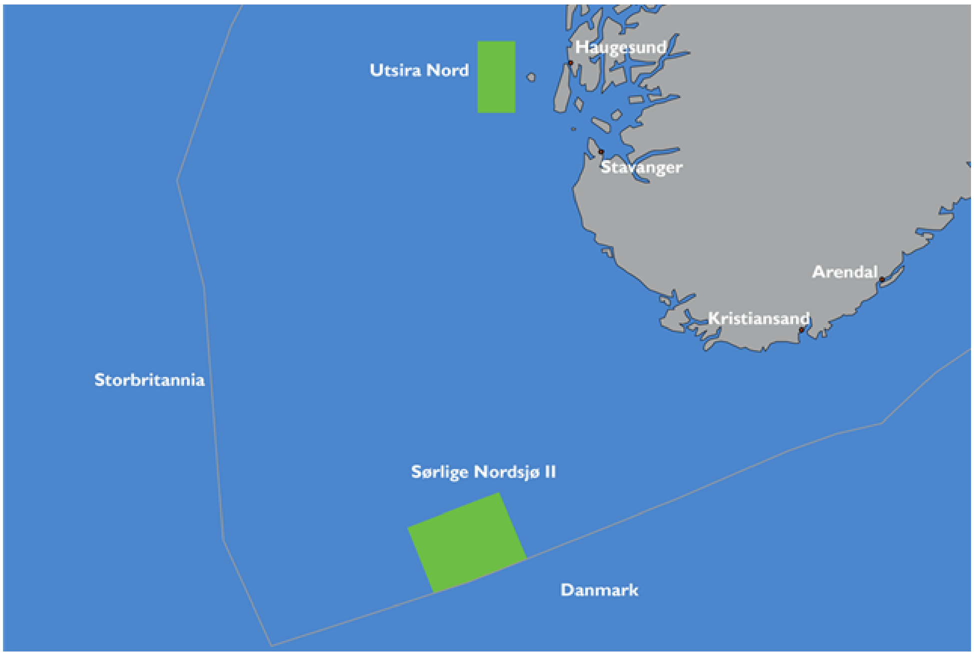


Figure 7.1: Location of Utsira Nord [8]

In tables 7.1, 7.2 and 7.3 specifics for the design basis are listed. The total design basis is also attached in appendix . These variables will change based on the specific project and is used to carry out this LCOE calculation.

Table 7.1: Site assumptions for the reference wind farm [8]

Site assumptions	
Location offshore	Utsira nord
Location onshore	Haugesund area
Years of development	7
Years of engineering and construction	3
Years of commissioning	1
Years of operation	25
Years of decommission	1
Water depth	267 m
Distance from shore	30 000 m
Average wind speed at site	10 m/s
Soil conditions	Soft clay
Site area	1010 km^2

Table 7.2: Capacity assumptions for the reference wind farm [75]

Capacity assumptions	
Wind farm capacity	450 000 kW
Turbine capacity	15 MW
Number of turbines	30
Wind farm type	Floating
Rated windspeed	11 m/s
Floating AC substation	1 x 450 MW

Table 7.3: Construction assumptions for the reference wind farm [75]

Construction assumptions	
Floater	Semi-submersible
Catenary mooring lines	3
Catenary mooring length	1068 m*
Dynamic cable configuration	Lazy s
Construction site	Norwegian west coast
Substation construction site	Thailand
Export cable length	60 000 m

*Length estimated to four times the rope length. [62]

7.2 Limitations for LCOE calculation tool

The provided LCOE calculation tool will be valid for FOWFs, given that one stays within specified limitations and assumptions. Economical and capacity limitations has been taken into account to construct a valid and user-friendly LCOE calculation tool. The limitations that are assumed to be constant is shown in table 7.4. Aibel can base further investments on this constructed calculations tool.

The LCOE tool assumes linear costs given that the distance to shore not exceeds 70/80 km. Surpassing this distance will lead to a more substantial situation. The export cables will not just be longer and more expensive, but the alternative of installing two offshore substations or installing a reinforcements will not increase the costs linearly. Longer distance will need new technology to compensate for long transport lines and risk of high power losses. The LCOE tool is not constructed for these complicated alternatives, and distance to shore can not exceed 70/80 km. [75]

Midlife upgrade is not included in the LCOE tool. This is due to the lifetime for this base case is decided to be 25 years. The LCOE tool has a function to calculate the LCOE for a lifetime up to 50 years, and not further. It is also assumed that the decommissioning process only takes one year after end of life. Re-powering or refurbishment is not included and must be entered if desired by the user.

Economic inflation is not included in the LCOE calculation analysis. If needed, the inflation regulation will happened after the LCOE is calculated since this is very market-specific. The subsidies are seen as revenue and are not taken into account when calculating the LCOE. However, it is beneficial for developers to know that subsidies will be provided when deciding to develop or not. According to BEIS [25], the energy production is discounted in a LCOE calculation analysis. This tool will also discount the energy, further explained in section 3.2.2.

Array- and wake losses are neglected in this tool, as the capacity factor takes this issue into account as a pre-determined value. Stated capacity factor has has taken wind speed and maintenance into consideration (ref. section 2.1.1).

Table 7.4: Limitations for variables that affect the LCOE

Wind speed	Assumed constant
AEP	Assumed constant
Capacity factor	Assumed constant
Discount rate	Assumed constant

8 LCOE calculations

In the produced LCOE Excel tool, the set design is thoroughly constructed. The design of the tool will be shown and explained in this section. For Aibel, it is important with a user-friendly and well-structured calculation tool, where the design basis, discount rate and cost elements are factors that greatly impact the LCOE. Figures of all the sheets in its entirety is attached in the appendix A.

The purpose of this Excel tool is to calculate the LCOE for any general floating offshore wind park, within the given limitations (ref. section 7.2). The tool contains an instruction sheet, design basis, decomposition of CAPEX and OPEX, LCOE calculation and sensitivity analysis. The calculated LCOE can be found in the *LCOE calculation sheet*. The total LCOE calculation tool is sectioned into six different sheets, as mentioned above, including links between the sheets for an optimal function. A brief description of the different sheets is shown in table 8.1.

Table 8.1: Sheets explanation of the LCOE tool

Sheet name	**Description**
1. Instructions	The function of this sheet is to give the user the necessary inputs and information to use the tool.
2. Design basis	The tool is based on the given design basis, but is developed to work for any floating wind farm with some limitations.
3. LCOE calculation	Calculation of the LCOE, including discount of cash flow and energy production.
4. CAPEX	A detailed overview over investment costs and decommissioning costs.
5. OPEX	A detailed overview over annual operation and maintenance costs.
6. Sensitivity analysis	This sheet analyze the uncertainty in the LCOE by adjusting some of the input parameters.

8.1 Introduction sheet

This sheet shows the principal instructions, explanations, limitations and assumptions for the developed tool. This is meant to give anyone the opportunity to understand and use the tool. The different sheets have a direct or indirect link to each other, and some values can be found in multiple sheets. Therefore there are some instructions explaining where it is allowed to change the cells. These are listed bellow.

- Green cells: the *LCOE calculation*- and *design basis sheet* contains a number of different formulas. Only the green cells in these sheets can be changed.

- Grey cells: in the *CAPEX*- and *OPEX sheet*, the grey cells are obtained from the design basis, and must be altered in the *design basis sheet*.
- Orange cells: in several of the sheets there are orange cells that links a value in a cell to the *Sensitivity sheet* to enable the possibility to run a sensitivity analysis on a value not originating in the *Sensitivity sheet*.
- For every decomposition category in *CAPEX*- and *OPEX sheet* lies an opportunity to *add new lines*. This allows the user to add missing cost items.
- In both *CAPEX*- and *OPEX sheet* there is space to write comments and add a sources and a link to where the cost value is collected. An example is illustrated in table 8.2.

Table 8.2: Example on comment and source columns from CAPEX- and OPEX sheet

Comment	**Source**
Cost includes installation of met mast	[20]

8.2 Design basis sheet

The *design basis sheet* contains the background information relevant for the specific project. It elaborates the details of the project, containing site, capacity and construction assumptions. This design basis is shown in section 7. Some of the cells in the design basis sheet are connected to different cells in the other sheets. These are marked in green as illustrated in table 8.3, meaning that editing these will affect the calculations and the LCOE. Grey cells can not be altered in this sheet. This provides the opportunity for the Excel-sheet to be altered to fit any selected project, within the limitations of the tool. The rest of the cells are not linked to any calculations in the other sheets, but can be changed to have a good overview over the details of the project.

To exemplify the green cell function, see table 8.3, where the number of wind turbines are marked green. As explained, this cell is linked another sheet to execute the correct cost calculations. The number of turbines in the *design basis sheet* is connected to the calculation of the total cost of the wind turbines and the mooring systems, directly influencing the LCOE.

Table 8.3: Green and grey cells illustrated in design basis

Capacity assumptions	
Wind farm capacity [kW]	450 000
Wind turbine capacity [MW]	15
Number of wind turbines	30
Type	Floating
Rated wind speed [m/s]	11
Floating AC substation [MW]	450

8.3 LCOE calculation sheet

The complete *LCOE calculation sheet* is attached in appendix A, and shows the final LCOE value with the given design basis. The LCOE value divides the net present value of the costs with the net present value of the electricity production, referred to equation 3.6. The cost development as well as the energy production development is included to show the spread over the span of the wind farm's lifetime. The decreasing values is a result of discounting, a method further elaborated in section 3.2.2. Both cost and energy must be discounted, as they both withhold a specific value that will decrease in the future.

The discount rate in the input box can also be altered, shown in table 8.4, as it is pivotal for the final LCOE outcome. The discount rate is set to a constant throughout LCOE calculations. The discount factor is calculated as shown in equation 3.2. The user of the tool is free to choose the type of discount rate suitable, thereafter calculate it and use it as an input parameter for the discount rate in table 8.4. The different type of discount rates are listed below [23].

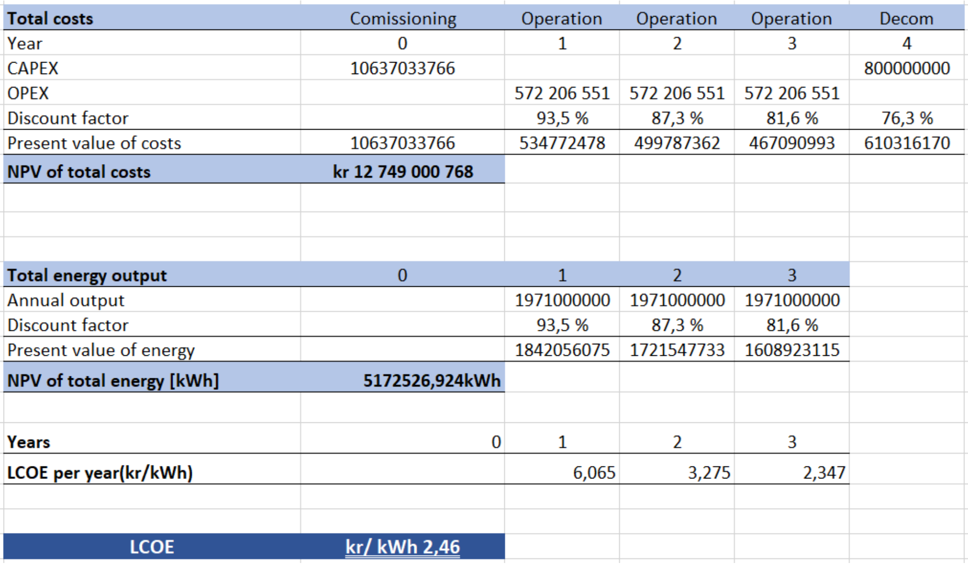
- Weighted Average Cost of Capital, used to calculate the enterprise value of a firm
- Cost of Equity, used to calculate the equity value of a firm
- Cost of Debt, used to calculate the value of a bond or fixed-income security
- A pre-defined hurdle rate, used for investing in internal corporate projects
- Risk-Free Rate, used to account for the time value of money

Table 8.4: Input variables in LCOE calculation

CAPEX	NOK 10 784 548 766
OPEX	NOK 575 306 551
DECEX	NOK 800 000 000
Capacity factor (CF)	50,0 %
Installed capacity	450 000
Annual energy production [kWh]	1 971 000 000
Lifetime (n)	25
Discount rate (r)	7,0 %

CAPEX, OPEX and DECEX shown in table 8.4 are linked to the *CAPEX-* and *OPEX sheet*. These affects the cost development. Capacity factor and installed capacity affects the annual energy production, which is discounted in the energy flow. By using equation 3.3 and 3.4 the total net present value of costs and energy are calculated, illustrated in appendix A.2. Due to the visibility of the numbers, the figure in appendix A.2 is cropped to a shorter lifetime.

The lifetime cell can be changed, and the sheet will automatically follow the input data. This is shown in figure 8.1 and 8.2. Here, the lifetime is set to three years and seven years to visualise how the LCOE tool adjusts to varying lifetime values. This is so the cost and energy production development is accurate. Figure 8.1 and 8.2 also shows how the decommissioning adapts to the lifetime input. The decommissioning will always occur one year after the lifetime (decided in design basis), giving the decommissioning cost the right discount factor in the calculations.



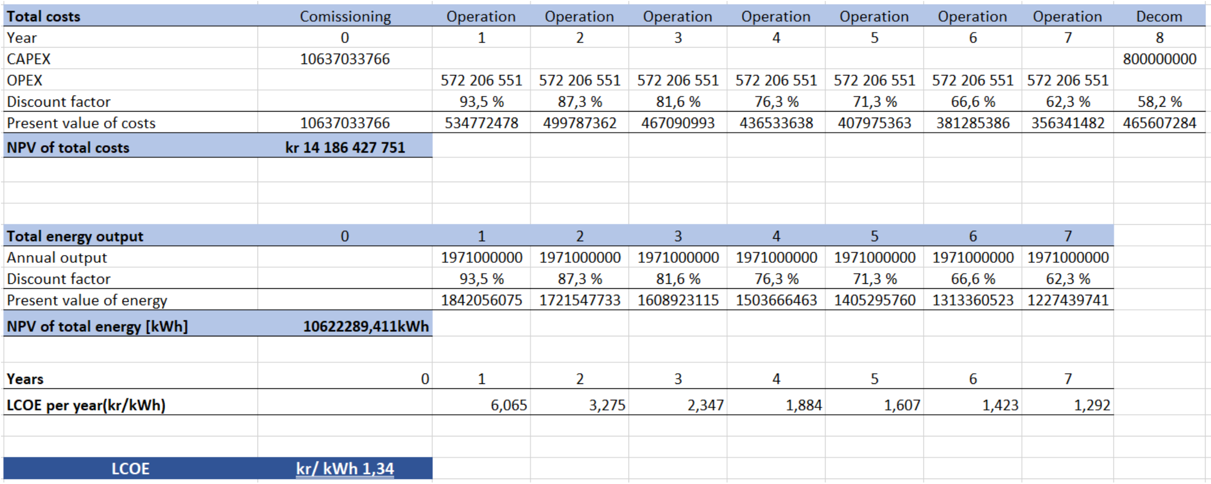
Total costs	Comissioning	Operation	Operation	Operation	Decom
Year	0	1	2	3	4
CAPEX	10637033766				800000000
OPEX		572 206 551	572 206 551	572 206 551	
Discount factor		93,5 %	87,3 %	81,6 %	76,3 %
Present value of costs	10637033766	534772478	499787362	467090993	610316170
NPV of total costs	**kr 12 749 000 768**				

Total energy output	0	1	2	3
Annual output		1971000000	1971000000	1971000000
Discount factor		93,5 %	87,3 %	81,6 %
Present value of energy		1842056075	1721547733	1608923115
NPV of total energy [kWh]	**5172526,924kWh**			

Years	0	1	2	3
LCOE per year(kr/kWh)		6,065	3,275	2,347

LCOE	**kr/ kWh 2,46**

Figure 8.1: LCOE calculation, lifetime three years



Total costs	Comissioning	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Decom
Year	0	1	2	3	4	5	6	7	8
CAPEX	10637033766								800000000
OPEX		572 206 551	572 206 551	572 206 551	572 206 551	572 206 551	572 206 551	572 206 551	
Discount factor		93,5 %	87,3 %	81,6 %	76,3 %	71,3 %	66,6 %	62,3 %	58,2 %
Present value of costs	10637033766	534772478	499787362	467090993	436533638	407975363	381285386	356341482	465607284
NPV of total costs	**kr 14 186 427 751**								
Total energy output	0	1	2	3	4	5	6	7	
Annual output		1971000000	1971000000	1971000000	1971000000	1971000000	1971000000	1971000000	
Discount factor		93,5 %	87,3 %	81,6 %	76,3 %	71,3 %	66,6 %	62,3 %	
Present value of energy		1842056075	1721547733	1608923115	1503666463	1405295760	1313360523	1227439741	
NPV of total energy [kWh]	**10622289,411kWh**								
Years	0	1	2	3	4	5	6	7	
LCOE per year(kr/kWh)		6,065	3,275	2,347	1,884	1,607	1,423	1,292	
LCOE	**kr/ kWh 1,34**								

Figure 8.2: *LCOE calculations, lifetime seven years*

8.4 CAPEX sheet

The *CAPEX sheet* is divided into four investments cost categories and one decommissioning cost. These categories are respectively project consent and development to FID-, wind turbine structure-, electrical infrastructure-, transport and installation- and decommissioning costs. In this sheet, it is possible to *add new lines* to every category. The currency of euros is added in a cell in the top of the sheet, so the costs are accurately converted, considering that currency is a time-varying variable. Other functions which is equal trough out the *CAPEX sheet* is the comment and source column. Here it is possible to explain where the costs of each cost item originate from and add a hyperlink to the source.

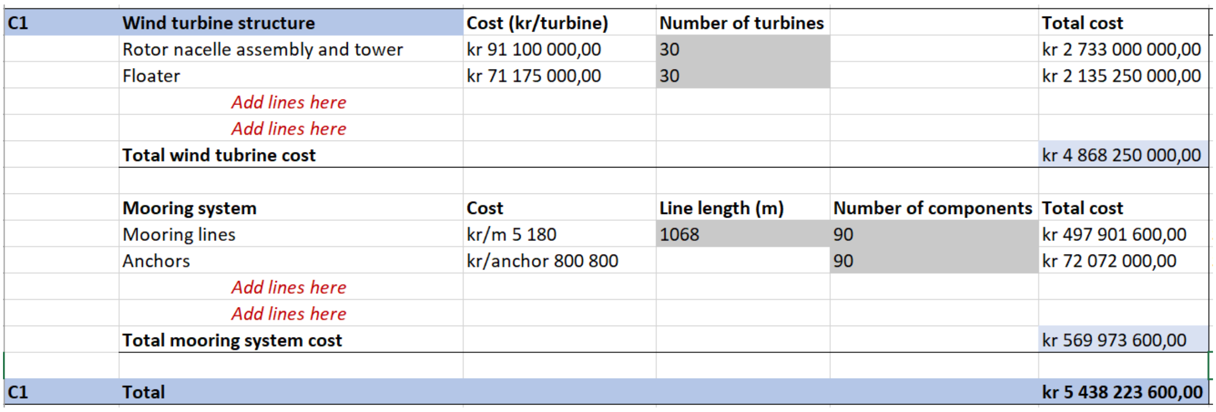
Project consent and development to FID

The decomposition of project consent and development to FID is decomposed to five different costs items. All of these costs items are summed to a total up to FID cost: C0. The five cost items are; development and consenting services, environmental surveys, resource and metocean assessment, geological and hydrological surveys and engineering and design.

Wind turbine structure

A segment of the wind turbine structure, illustrated in figure 8.3 has a more complicated construction. The complete sheet is attached in appendix A.3. The main categories are the wind turbine and mooring system cost. The wind turbine is divided into rotor nacelle assembly and tower and the floater. These has a cost per turbine, which is multiplied with number of turbines. These two costs are then summed to a total wind turbine cost.

Further on, mooring system is divided into mooring lines and anchors. The mooring line cost is calculated by multiplying the cost per meter with the length of the line, then multiplied with number of mooring lines needed. The number of mooring lines needed, is calculated by multiplying number of turbines with number of mooring lines for each turbine, both retrieved from the *Design basis sheet*. When using mooring lines there is a need for anchors, this cost is calculated by multiplying the cost per anchor with the number of anchors needed. The number of anchors is equal to the number of mooring lines needed. The sum of mooring line and anchor costs are summed to a total mooring system cost. The number of turbines, length of the mooring line and number of components are marked grey and must be changed in the *Design basis sheet*. The total cost is the sum of the total wind turbine cost and total mooring system cost, which is equal to the cost of C1: Wind turbine structure.



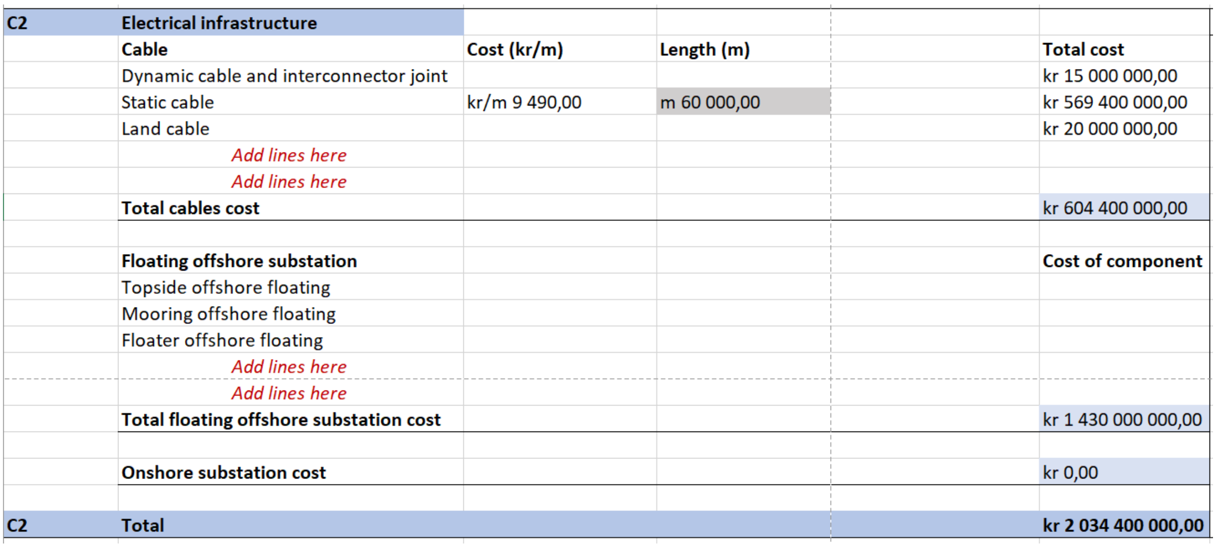
C1	Wind turbine structure	Cost (kr/turbine)	Number of turbines		Total cost
	Rotor nacelle assembly and tower	kr 91 100 000,00	30		kr 2 733 000 000,00
	Floater	kr 71 175 000,00	30		kr 2 135 250 000,00
	Add lines here				
	Add lines here				
	Total wind tubrine cost				kr 4 868 250 000,00
	Mooring system	**Cost**	**Line length (m)**	**Number of components**	**Total cost**
	Mooring lines	kr/m 5 180	1068	90	kr 497 901 600,00
	Anchors	kr/anchor 800 800		90	kr 72 072 000,00
	Add lines here				
	Add lines here				
	Total mooring system cost				kr 569 973 600,00
C1	**Total**				**kr 5 438 223 600,00**

Figure 8.3: Wind turbine segment of the CAPEX Excel sheet

Electrical infrastructure

Electrical infrastructure is decomposed as illustrated in figure 8.4, into cables, floating offshore substation and onshore substation costs. The cable cost is a function of the length of the cable, and is divided into dynamic cable and inter-connector joint, static cable and land cable. The cable length of the static cable is a parameter collected from the *Design basis sheet*. The length is multiplied with cost per meter, seen in the calculation of the static cable cost. The two other cables have a fixed cost due to lack of sources, but it is intended to calculate these such as the static cable. All the cable costs are summed into a total cables cost.

The floating offshore substation is decomposed into topside offshore floating, mooring offshore floating and floater offshore floating. The onshore substation is just one cost. The offshore substation is an important component to analyse for Aibel. The cost of the floating offshore substation is a sum of the cost for the topside, mooring and floater, but in this case there is just a total floating offshore substation cost due to lack of data. The cost of the cables, offshore substation and onshore substation adds up to a total electrical infrastructure cost: C2.



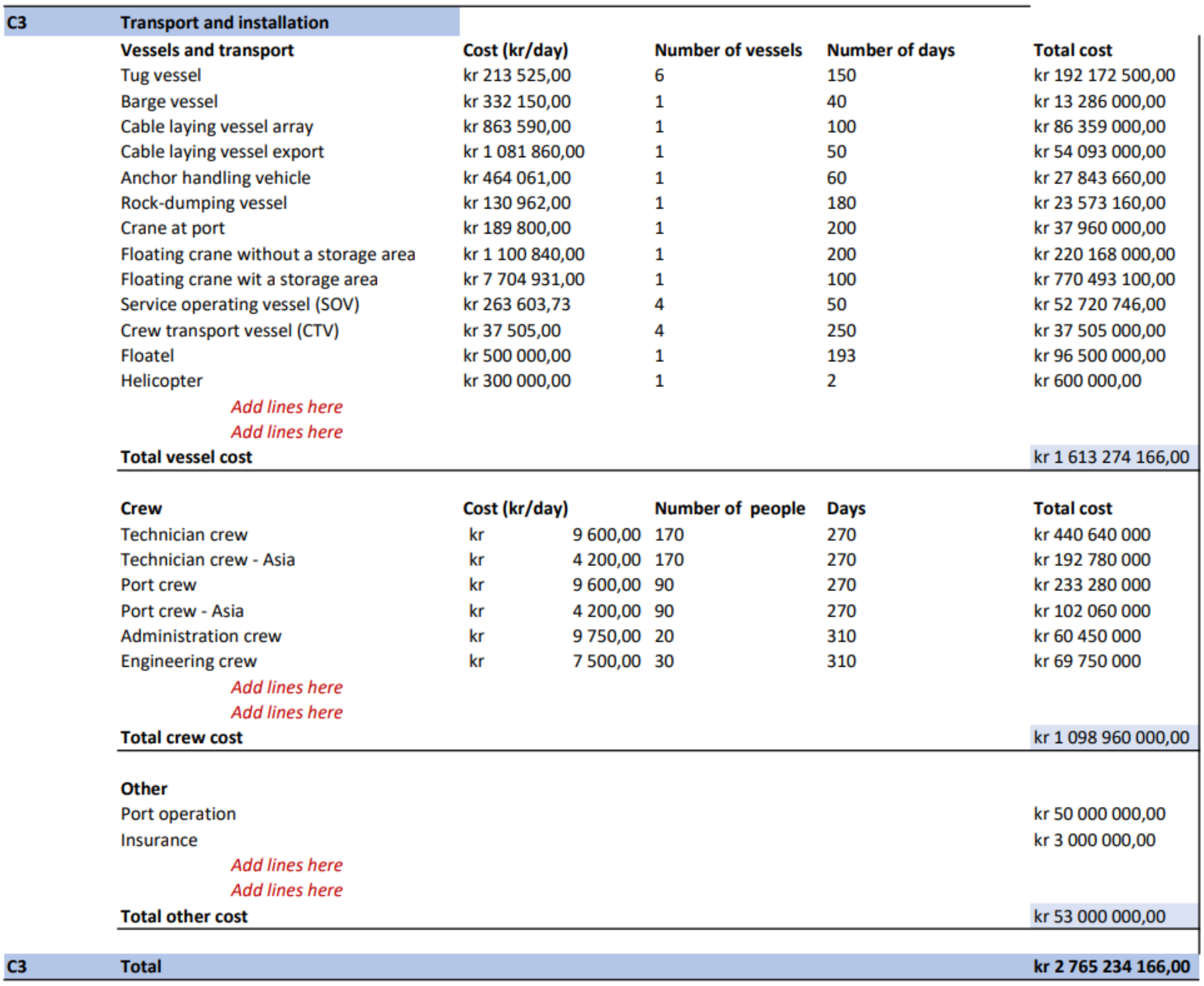
C2	**Electrical infrastructure**				
	Cable	**Cost (kr/m)**	**Length (m)**		**Total cost**
	Dynamic cable and interconnector joint				kr 15 000 000,00
	Static cable	kr/m 9 490,00	m 60 000,00		kr 569 400 000,00
	Land cable				kr 20 000 000,00
	Add lines here				
	Add lines here				
	Total cables cost				kr 604 400 000,00
	Floating offshore substation				**Cost of component**
	Topside offshore floating				
	Mooring offshore floating				
	Floater offshore floating				
	Add lines here				
	Add lines here				
	Total floating offshore substation cost				kr 1 430 000 000,00
	Onshore substation cost				kr 0,00
C2	**Total**				**kr 2 034 400 000,00**

Figure 8.4: Electrical infrastructure segment of the CAPEX Excel sheet

Transport and installations

The transport and installations section is illustrated in figure 8.5 and is decomposed into vessels and transportation, crew, and other costs. The vessel and transportation cost is divided into all the vessels needed for the installation and transportation of the massive parts needed to construct the farm. The vessel and transportation also has a floatel cost and a helicopter cost. Each of these vessels has a cost per day, which is multiplied with the number of days it is needed, then multiplied with the number of vessels needed. Then the cost of all the vessels is summed to a total vessel cost.

The crew is divided into technician crew, technician crew - Asia, port crew, port crew - Asia, administration crew and engineering crew. The crew cost is calculated using the daily salary for a specific crew member times the number of personnel needed times the number of days needed. Other costs consist of port operation and insurance, these cost are summed to a total other costs. The vessel, crew and other costs are summed to a total transport and installation cost: C3.



C3	**Transport and installation**				
	Vessels and transport	**Cost (kr/day)**	**Number of vessels**	**Number of days**	**Total cost**
	Tug vessel	kr 213 525,00	6	150	kr 192 172 500,00
	Barge vessel	kr 332 150,00	1	40	kr 13 286 000,00
	Cable laying vessel array	kr 863 590,00	1	100	kr 86 359 000,00
	Cable laying vessel export	kr 1 081 860,00	1	50	kr 54 093 000,00
	Anchor handling vehicle	kr 464 061,00	1	60	kr 27 843 660,00
	Rock-dumping vessel	kr 130 962,00	1	180	kr 23 573 160,00
	Crane at port	kr 189 800,00	1	200	kr 37 960 000,00
	Floating crane without a storage area	kr 1 100 840,00	1	200	kr 220 168 000,00
	Floating crane wit a storage area	kr 7 704 931,00	1	100	kr 770 493 100,00
	Service operating vessel (SOV)	kr 263 603,73	4	50	kr 52 720 746,00
	Crew transport vessel (CTV)	kr 37 505,00	4	250	kr 37 505 000,00
	Floatel	kr 500 000,00	1	193	kr 96 500 000,00
	Helicopter	kr 300 000,00	1	2	kr 600 000,00
	Add lines here				
	Add lines here				
	Total vessel cost				kr 1 613 274 166,00
	Crew	**Cost (kr/day)**	**Number of people**	**Days**	**Total cost**
	Technician crew	kr 9 600,00	170	270	kr 440 640 000
	Technician crew - Asia	kr 4 200,00	170	270	kr 192 780 000
	Port crew	kr 9 600,00	90	270	kr 233 280 000
	Port crew - Asia	kr 4 200,00	90	270	kr 102 060 000
	Administration crew	kr 9 750,00	20	310	kr 60 450 000
	Engineering crew	kr 7 500,00	30	310	kr 69 750 000
	Add lines here				
	Add lines here				
	Total crew cost				kr 1 098 960 000,00
	Other				
	Port operation				kr 50 000 000,00
	Insurance				kr 3 000 000,00
	Add lines here				
	Add lines here				
	Total other cost				kr 53 000 000,00
C3	**Total**				**kr 2 765 234 166,00**

Figure 8.5: T&I segment of the CAPEX Excel sheet

Decommissioning

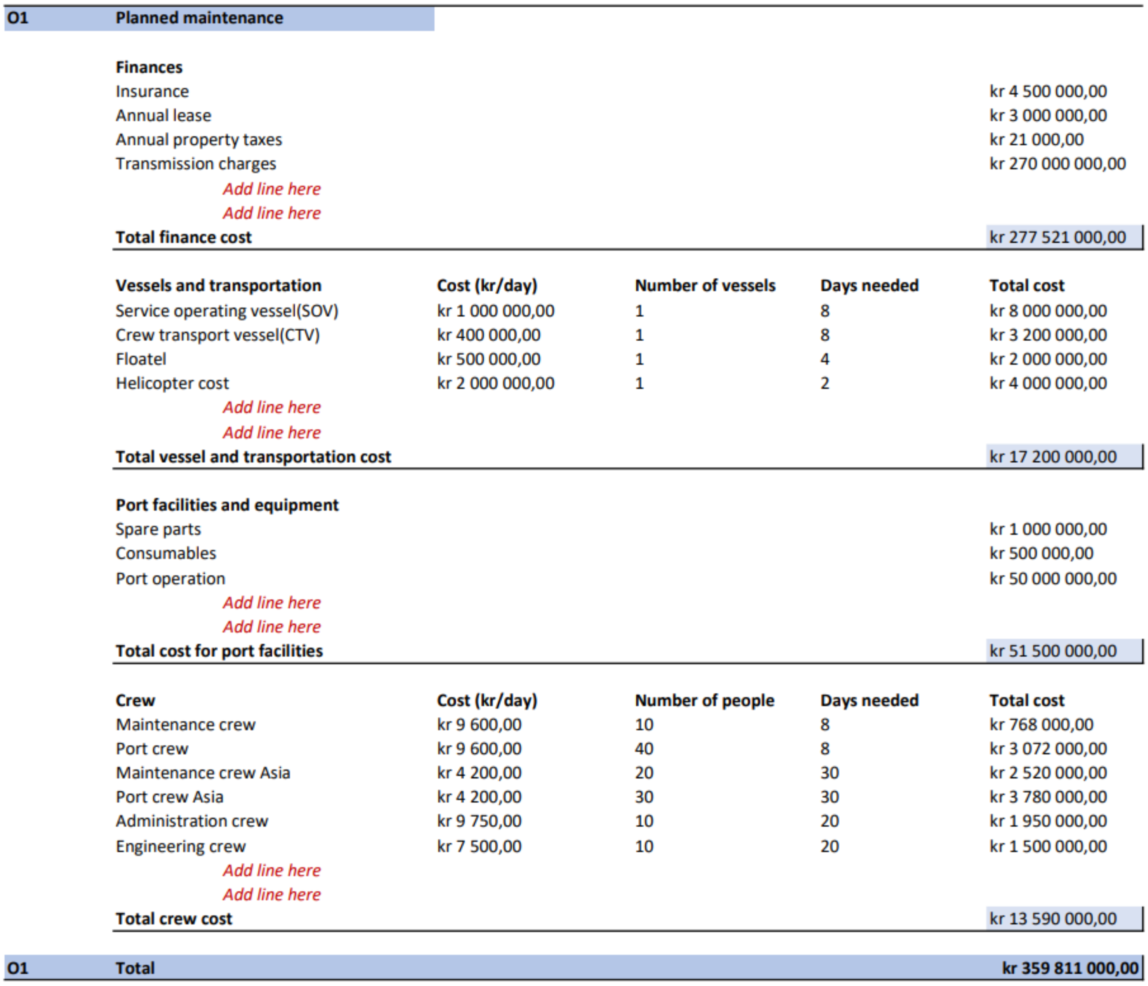
The decommissioning is divided into the subcategories offshore preparation, vessel mobilisation and demobilisation, disassembly and foundation removal. Each of these has a cost for the decommissioning the year after end of life, which then is summed up to a total decommissioning cost: D1. The DECEX decomposition and the rest of the CAPEX sheet is attached in appendix A.3.

8.5 OPEX sheet

The *OPEX sheet* is divided in to planned maintenance and corrective maintenance, the total sheet are attached in A.4. The costs of the planned maintenance is divided in to finances, vessels, crew, port facilities and equipment. Corrective maintenance is divided in to the same categories excluding the finance costs, but they have different subcategories due to different needs for planned and corrective maintenance. As in the *CAPEX sheet*, the currency of euros is added in the top of the sheet, to accurately convert costs from euros to NOK in the calculations. In each subcategory in the decomposition there is the possibility to *add new lines*, in case the need for new cost items appear. Every cost item also has a column to add a comment and source explaining where the cost originate from.

Planned maintenance

Figure 8.6 shows a segment of the *OPEX sheet*, visualising the decomposition of planned maintenance. The subcategories for the finances costs is insurance, annual lease, annual property taxes and transmission charges, where the cost of each is summed to a total finance cost. The vessels and transport needed for planned maintenance is maintenance boat, crew boat and helicopter. Each of these has a cost per day, which is multiplied with the number of days it is required, then multiplied with the number of vessels or helicopters needed. Then the cost element of the maintenance boat, the crew boat and the helicopter is summed to a total vessel and transportation cost.



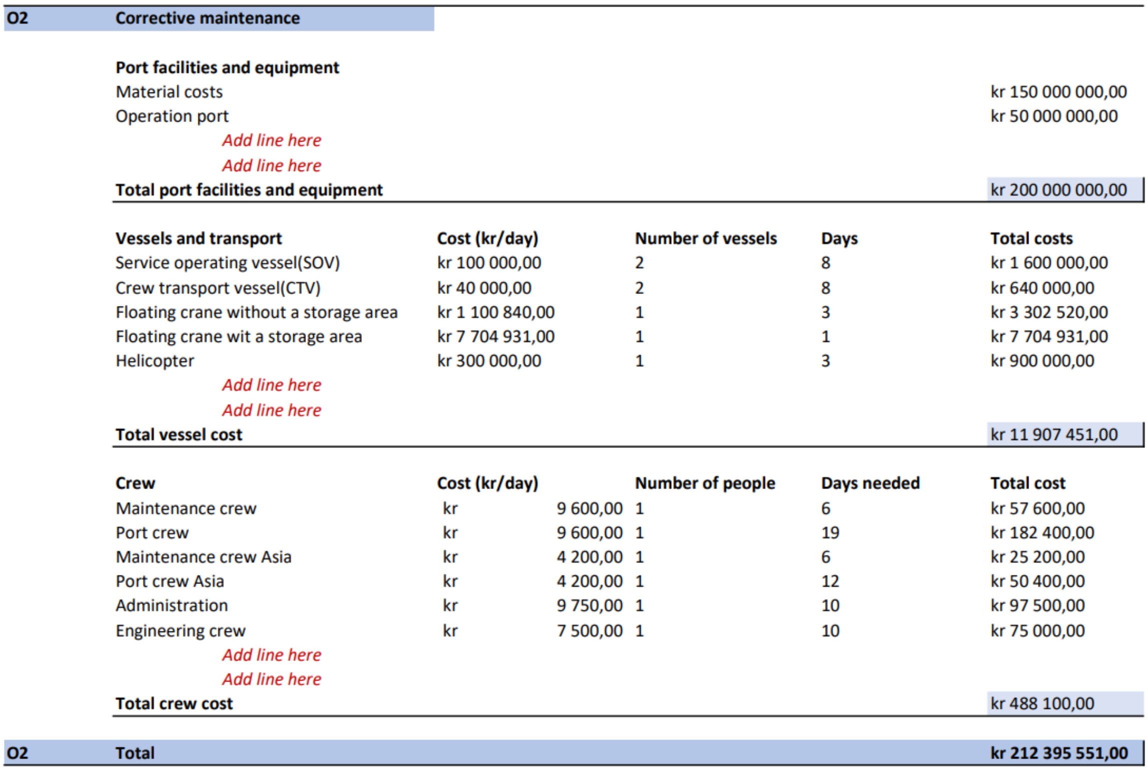
O1	**Planned maintenance**				
	Finances				
	Insurance				kr 4 500 000,00
	Annual lease				kr 3 000 000,00
	Annual property taxes				kr 21 000,00
	Transmission charges				kr 270 000 000,00
	Add line here				
	Add line here				
	Total finance cost				kr 277 521 000,00
	Vessels and transportation	**Cost (kr/day)**	**Number of vessels**	**Days needed**	**Total cost**
	Service operating vessel(SOV)	kr 1 000 000,00	1	8	kr 8 000 000,00
	Crew transport vessel(CTV)	kr 400 000,00	1	8	kr 3 200 000,00
	Floatel	kr 500 000,00	1	4	kr 2 000 000,00
	Helicopter cost	kr 2 000 000,00	1	2	kr 4 000 000,00
	Add line here				
	Add line here				
	Total vessel and transportation cost				kr 17 200 000,00
	Port facilities and equipment				
	Spare parts				kr 1 000 000,00
	Consumables				kr 500 000,00
	Port operation				kr 50 000 000,00
	Add line here				
	Add line here				
	Total cost for port facilities				kr 51 500 000,00
	Crew	**Cost (kr/day)**	**Number of people**	**Days needed**	**Total cost**
	Maintenance crew	kr 9 600,00	10	8	kr 768 000,00
	Port crew	kr 9 600,00	40	8	kr 3 072 000,00
	Maintenance crew Asia	kr 4 200,00	20	30	kr 2 520 000,00
	Port crew Asia	kr 4 200,00	30	30	kr 3 780 000,00
	Administration crew	kr 9 750,00	10	20	kr 1 950 000,00
	Engineering crew	kr 7 500,00	10	20	kr 1 500 000,00
	Add line here				
	Add line here				
	Total crew cost				kr 13 590 000,00
O1	**Total**				**kr 359 811 000,00**

Figure 8.6: Planned maintenance segment of the OPEX Excel sheet

The port facilities and equipment is divided into spare parts, consumables and port operation costs, summed to total cost for port facilities and equipment. There is also a crew cost related to O&M, where it is divided into maintenance crew, port crew, maintenance crew Asia, port crew Asia, administration crew and engineering crew. There is a different need for each type of personnel, which needs to be taken care of in the Excel tool. The crew cost is therefore the daily salary for a specific crew member times the number of personnel needed times the number of days needed. This gives a total cost for each of the specific crews, which then is summed up to a total crew cost. All of these calculations is shown in figure 8.6, and gives a total planned maintenance cost: O1.

Corrective maintenance

Figure 8.7 shows a segment of the *OPEX sheet*, visualising the decomposition of corrective maintenance. The subcategories for the port facilities and equipment is the same as in the planned maintenance. For the crew segment, the subcategories and calculations are the same, but the number of people and the days needed will of course differ from the planned maintenance due to being difference type of maintenance. The subcategories of vessel costs are more comprehensive due to the uncertainty of the needed maintenance when considering corrective maintenance and which component it concerns. As in planned maintenance each vessel cost is the cost per day times the number of vessels needed times the number of days needed. The number of people, number of vessels and number of days needed for each, are a sum throughout the year.



O2	**Corrective maintenance**				
	Port facilities and equipment				
	Material costs				kr 150 000 000,00
	Operation port				kr 50 000 000,00
	Add line here				
	Add line here				
	Total port facilities and equipment				kr 200 000 000,00
	Vessels and transport	**Cost (kr/day)**	**Number of vessels**	**Days**	**Total costs**
	Service operating vessel(SOV)	kr 100 000,00	2	8	kr 1 600 000,00
	Crew transport vessel(CTV)	kr 40 000,00	2	8	kr 640 000,00
	Floating crane without a storage area	kr 1 100 840,00	1	3	kr 3 302 520,00
	Floating crane wit a storage area	kr 7 704 931,00	1	1	kr 7 704 931,00
	Helicopter	kr 300 000,00	1	3	kr 900 000,00
	Add line here				
	Add line here				
	Total vessel cost				kr 11 907 451,00
	Crew	**Cost (kr/day)**	**Number of people**	**Days needed**	**Total cost**
	Maintenance crew	kr 9 600,00	1	6	kr 57 600,00
	Port crew	kr 9 600,00	1	19	kr 182 400,00
	Maintenance crew Asia	kr 4 200,00	1	6	kr 25 200,00
	Port crew Asia	kr 4 200,00	1	12	kr 50 400,00
	Administration	kr 9 750,00	1	10	kr 97 500,00
	Engineering crew	kr 7 500,00	1	10	kr 75 000,00
	Add line here				
	Add line here				
	Total crew cost				kr 488 100,00
O2	**Total**				**kr 212 395 551,00**

Figure 8.7: Corrective maintenance segment of the OPEX Excel sheet

8.6 Sensitivity analysis sheet

A sensitivity analysis identifies the uncertainty in an output parameter of a model by adjusting the inputs. The *Sensitivity sheet* is developed using the *What-If Analysis, Data table* tool in Excel, shown in figure 8.8. The total sensitivity analysis sheet is attached in appendix A.5.

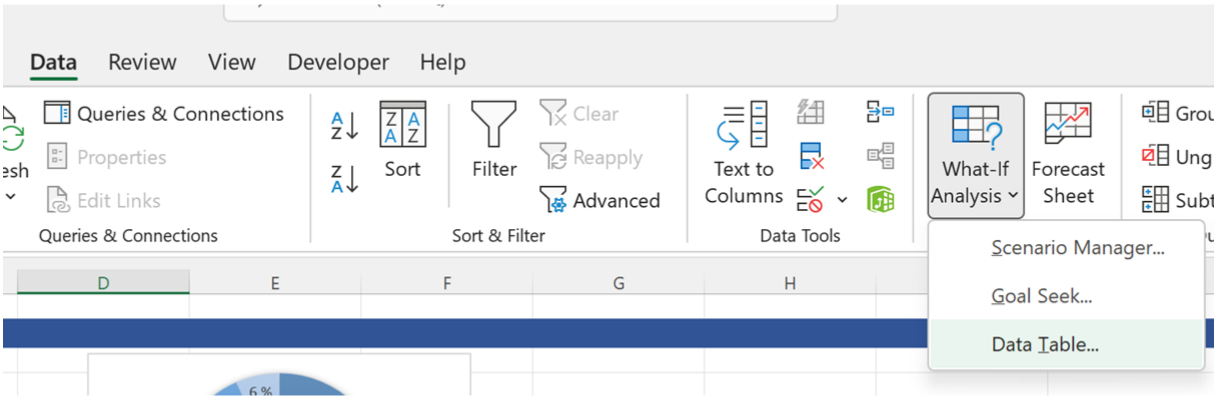


Figure 8.8: What-If Analysis tool in Excel

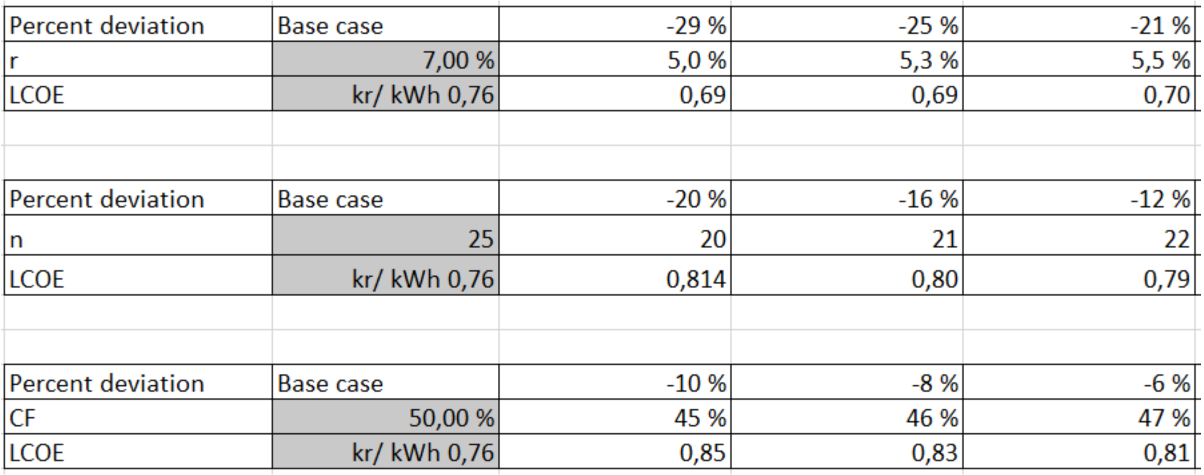
To be able to perform the sensitivity analysis, parameters from other sheets are brought in to the *Sensitivity sheet*. The *LCOE calculation sheet* is copied and changed to *Sensitivity sheet* due to lifetime, r and CF affecting the LCOE calculations to a greater extent than the other sensitivity parameters. The sensitivity analysis of parameters that originate from another sheet, is explained below. As explained above and shown in table 8.5, some of the sensitivity inputs are the same input parameters as in the *LCOE calculations sheet*. The input parameters can be adapted to the users preferences and objectives for the sensitivity analysis.

Table 8.5: Identical input variable box

CAPEX	NOK 10 784 548 766
OPEX	NOK 575 306 551
DECEX	NOK 800 000 000
Capacity factor (CF)	50,0 %
Installed capacity	450 000
Annual net electricity output [kWh]	1 971 000 000
Lifetime (n)	25
Discount rate (r)	7,0 %

In the *Sensitivity sheet* the green cells means that that they can be altered after the users needs. The grey cells means that these cells can only be altered in their respective sheets or cells. These sheets and cells becomes visible if one double clicks this cell.

To utilise the *What-If Analysis* function in Excel, a set up as shown in figure 8.9 is the most convenient. Here the different parameters shown in the grey cells are linked to their input cells (ref. figure 8.5), and will change accordingly.



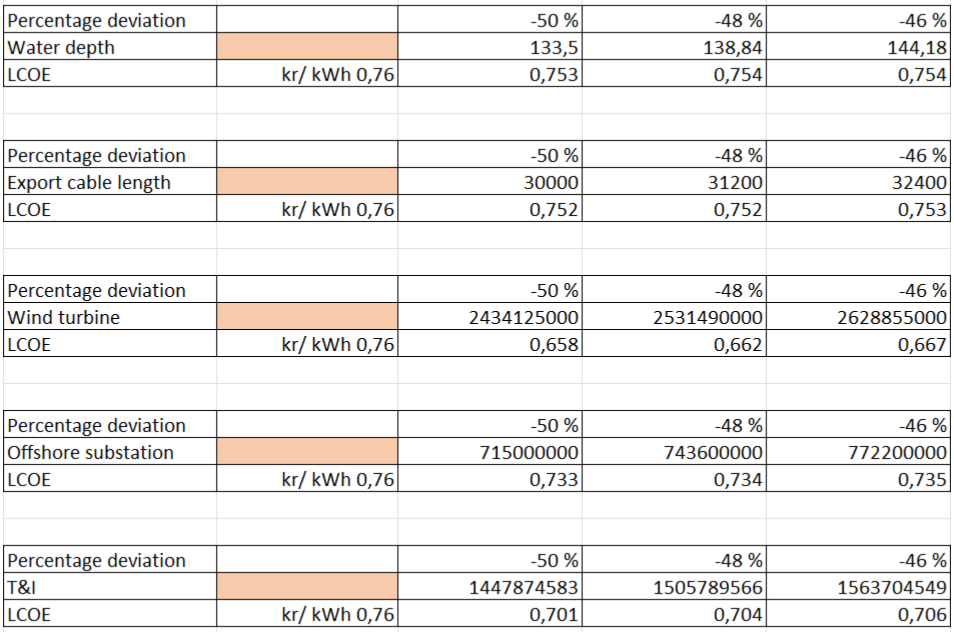
Percent deviation	Base case	-29 %	-25 %	-21 %
r	7,00 %	5,0 %	5,3 %	5,5 %
LCOE	kr/ kWh 0,76	0,69	0,69	0,70

Percent deviation	Base case	-20 %	-16 %	-12 %
n	25	20	21	22
LCOE	kr/ kWh 0,76	0,814	0,80	0,79

Percent deviation	Base case	-10 %	-8 %	-6 %
CF	50,00 %	45 %	46 %	47 %
LCOE	kr/ kWh 0,76	0,85	0,83	0,81

Figure 8.9: Set up for What-If Analysis for input variables in the same sheet

The orange cells, shown in figure 8.10, are created due to Excels limitation of only allowing one to do a *What-If Analysis* on the values in the same sheet. These orange cells in the *Sensitivity sheet* are linked to the respective sheets containing the value that the user wishes to preform a sensitivity on. The values needs to be changed in their respective sheets, where the orange cell contains a code linking the two sheets, enabling the possibility of a sensitivity analysis. The orange cells must not be edited, but still works if new lines are added in the *CAPEX sheet* or *OPEX sheet.*



Percentage deviation		-50 %	-48 %	-46 %
Water depth		133,5	138,84	144,18
LCOE	kr/ kWh 0,76	0,753	0,754	0,754

Percentage deviation		-50 %	-48 %	-46 %
Export cable length		30000	31200	32400
LCOE	kr/ kWh 0,76	0,752	0,752	0,753

Percentage deviation		-50 %	-48 %	-46 %
Wind turbine		2434125000	2531490000	2628855000
LCOE	kr/ kWh 0,76	0,658	0,662	0,667

Percentage deviation		-50 %	-48 %	-46 %
Offshore substation		715000000	743600000	772200000
LCOE	kr/ kWh 0,76	0,733	0,734	0,735

Percentage deviation		-50 %	-48 %	-46 %
T&I		1447874583	1505789566	1563704549
LCOE	kr/ kWh 0,76	0,701	0,704	0,706

Figure 8.10: Set up for What-If Analysis for input variables in a different sheet

In table 8.6 the values from other sheets are gathered to show the base case for the sensitivity of the desired parameters. They are linked to their respective sheets and are only used to calculate the percentage deviation from the base case. They are not an input in the data table like the parameters in table 8.5. To preform the sensitivity on the values from other sheets, the orange cell in the specific table, shown in figure 8.10, is used as input in the *What-If Analysis, Data table.*

Table 8.6: Other input variables

Water depth	267	[m]
Export cable lenght	60 000	[m]
Wind turbine	4 868 250 000	[NOK]
Offshore substation	2 034 400 000	[NOK]
T&I	2 912 749 166	[NOK]

8.6.1 Input parameters

The input parameters for the sensitivity analysis are chosen based on findings during preliminary literature studies and discussion between the group and the supervisors through weekly meetings. The sensitivity is preformed with a varying % deviation on each parameter, depending on realistic scenarios.

As shown in equation 2.5, CF is directly linked to the annual energy production, which has a direct affect on the LCOE through the NPV of energy production. Here the CF is scaled either up or down, between a CF of 45% and 65%.

Another parameter to consider is the wind farm lifetime. Even though many wind projects usually has a standard for a lifetime around 25-30 years, enabling a longer life time could affect the LCOE positively and the wind farm developer can consider if one can include a midlife upgrade, instead of decommissioning. The life time is scaled either up or down from the base case within a lifetime interval of 20 to 40 years.

The discount rate is one of the key factors of the LCOE result, as it affects both the NVP of costs and NVP of energy production. As explained in section 3.2.2, choosing this parameter is one of the most challenging things about LCOE analysis due to its risk rate. Henceforth, the discount factor is a key parameter to include in the sensitivity analysis.

The distance to shore and water depth are two important parameters that differentiates the floating wind turbine solution from the bottom fixed turbines. As mentioned in section 4.4, the distance to shore usually has a big impact on the total cost of the project. This is due to the influence of the export cable length and the duration of vessel and port operations. Furthermore, as mentioned in section 4.4, FOW constructed at water depths between 60 m and 300 m is economically feasible, but investigating the sensitivity of this parameter is interesting as these numbers are evolving.

Direct sensitivity results from the LCOE calculation tool are conveyed in section 9.2. Results from the completed sensitivity analysis are based on the base case illustrated in table 8.7, and results are further conveyed in the same section.

Table 8.7: Base case for sensitivity analysis parameters

Parameter	**Base case**
Lifetime [years]	25
Capacity factor	50%
Discount rate	7%
Water depth [m]	267
Export cable length [m]	60 000
Wind turbine cost [NOK]	4 868 250 000*
Offshore substation cost [NOK]	1 430 000 000*
T&I cost [NOK]	1 743 789 166*
LCOE [NOK/kWh]	0,76*

*Results from the LCOE calculation tool.

9 Results

The result of this bachelor thesis is the composed LCOE calculation tool. The whole LCOE tool is attached in appendix A. The tool is designed to cooperate between the different sheets. Most of the costs are found from research and sources, while some are a best guess due to lack of data. Some of the cost items was provided by Aibel. The main result is therefore not to determine the profitability of this wind projects base case, but to create a functioning tool. Section 8 explains thoroughly the structure of the constructed LCOE tool.

A sensitivity analysis with some of the input variables is preformed to examine what the main contributors to the LCOE results are. It is possible to use a higher discount rate to secure the project's risks when calculating LCOE. However, it will be implemented one risk assessment method of LCOE to considering the risk of the project.

9.1 Direct results from LCOE tool

Total CAPEX, DECEX and OPEX

Referred to equation 5.1 and 5.2 the total CAPEX and DECEX contribution are shown in table 9.1. Total CAPEX and DECEX is respectively, 10 784 548 766 NOK and 800 000 000 NOK. Total CAPEX has contribution from C0, C1, C2 and C3 all explained in section 5.

Table 9.1: CAPEX and DECEX total cost

C0	Project consent and development to FID	NOK 399 176 000
C1	Wind turbine structure	NOK 5 438 223 600
C2	Electrical infrastructure	NOK 2 034 400 000
C3	Transport and installation	NOK 2 912 749 166
C	**CAPEX total**	**NOK 10 784 548 766**
D1	**DECEX total**	**NOK 800 000 000**

The pie chart, figure 9.1, for the CAPEX distribution shows that the most influential cost item is the wind turbine, followed by the transport and installation. Even though the costs in the sheet are not fully reliable, this representation is meant to give an overview. Figure 9.1 show CAPEX costs in table 9.1. Light green is project consent and development to FID (C0) with 4% contribution. Blue is wind turbine structure (C1) with 50% contribution. Yellow is electrical infrastructure (C2) with 19% contribution. Dark green is transport and installation (C3) with 27% contribution.

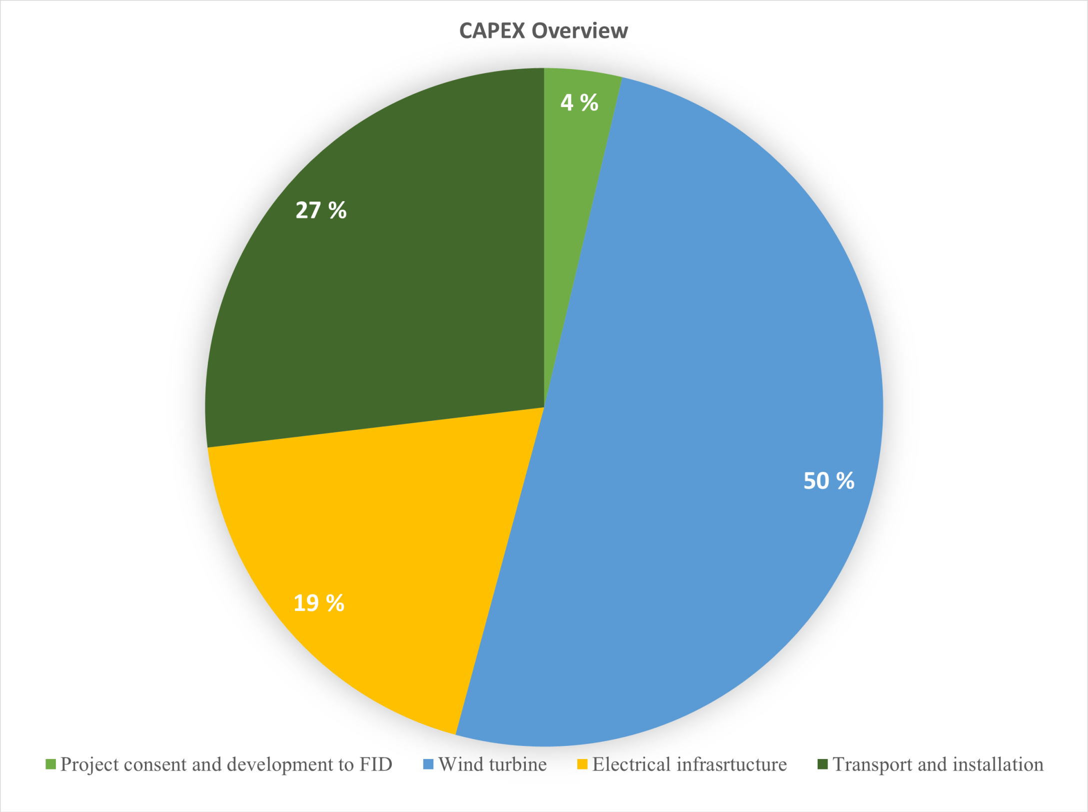


Figure 9.1: CAPEX overview

Equation 6.1 calculate the total OPEX. Table 9.2 shows the total OPEX contribution of 575 306 551 NOK. Planned maintenance has the highest cost value compared to corrective maintenance.

Table 9.2: OPEX total cost

C0	Project consent and development up to FID	NOK 399 176 000
O1	Planned maintenance	NOK 357 811 000
O2	Corrective maintenance	NOK 217 495 551
O	**OPEX total**	**NOK 575 306 551**

Total LCOE impact

With a discount rate, lifetime and capacity factor as shown in table 8.7 and already established CAPEX, OPEX and DECEX costs, the final LCOE was calculating with constructed LCOE calculating tool is equal to 0.76 NOK/kWh.

9.2 Sensitivity results

A sensitivity analysis is used to identify how outputs in a model reacts to variations in inputs in form of variables or parameters. In this bachelor thesis, output is the value of LCOE for a FOWF in NOK/kWh.

A sensitivity analysis was preformed with *What if analysis* tool in Excel creating sensitivity data tables. The sensitivity was preformed with several input parameters such as the lifetime, discount rate, capacity factor, water depth, export cable length, cost of wind turbine, cost of floating offshore substation and T&I cost. They are compared in different plots, shown in figures 9.2, 9.3, 9.4, 9.5, 9.6 and 9.7. The base case for all the parameters in the sensitivity analysis is located at 0%, and are shown in table 8.7.

Lifetime, CF and discount rate

The sensitivity analysis on the LCOE with varying discount rates is visualised in figure 9.2. The curve shows a linear trend, with the increasing discount rate from 5% to 10%. This is a interval ranging from -29% to +43% deviation from the base case of 7% discount rate. Within this interval the LCOE increases linearly from 0.69 NOK/kWh to 0.88 NOK/kWh. The LCOE as a function of discount rate curve shows an increasing LCOE in conjunction with higher discount rate.

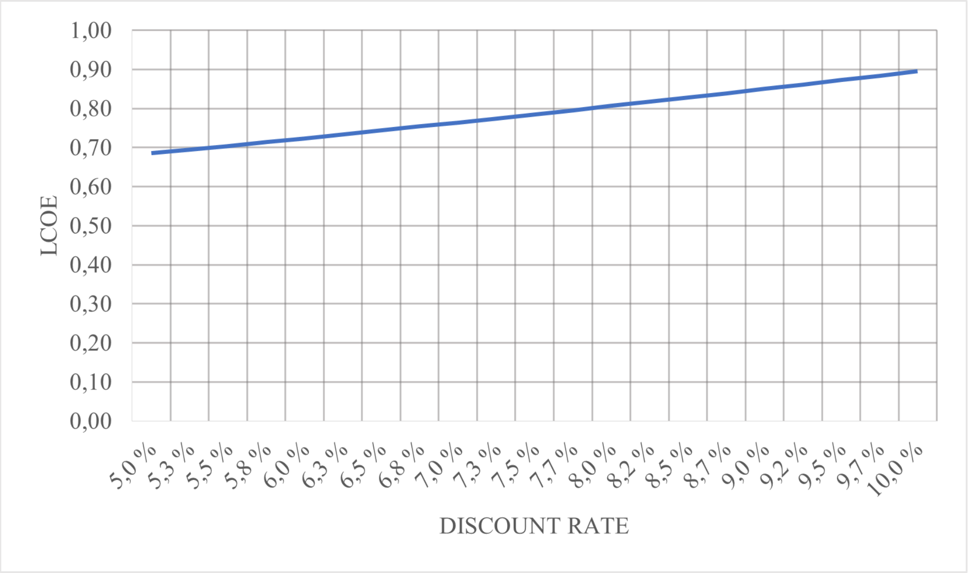


Figure 9.2: Sensitivity analysis of the discount rate

The LCOE as a function of lifetime, figure 9.3, shows a steep decreasing trend in the first 25 years, then hitting the lowest LCOE, before slowly increasing and showing a stagnating trend when increasing the lifetime. The LCOE is starting at 0.814 NOK/kWh with 20 years lifetime, then hitting the lowest LCOE, 0.76kr/kWh at the base case, and stagnating around 0.8 NOK/kWh. The LCOE is plotted with a lifetime interval ranging from - 20% to + 60% from the base case of 25 years, meaning an interval from 20 to 40 years.

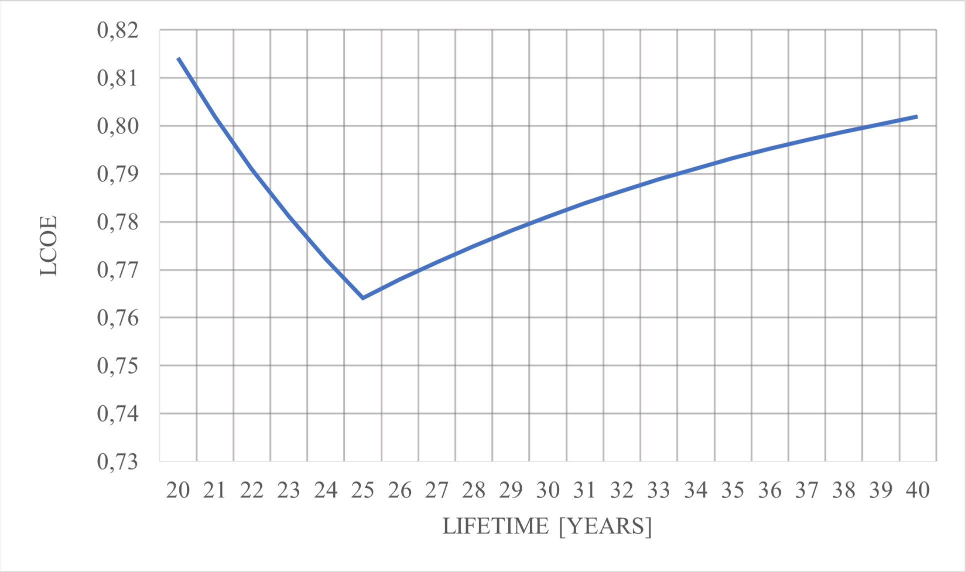


Figure 9.3: Sensitivity analysis of the lifetime

Figure 9.4 shows the LCOE curve, with a capacity factor varying from -10% to +30% from the base case of 50%. The LCOE decreases from 0.85 NOK/kWh to 0.59 NOK/kWh, with a capacity factor interval from 45% to 65%. The figure shows an approximate linear decreasing trend, conveying that a higher capacity factor results in lower LCOE.

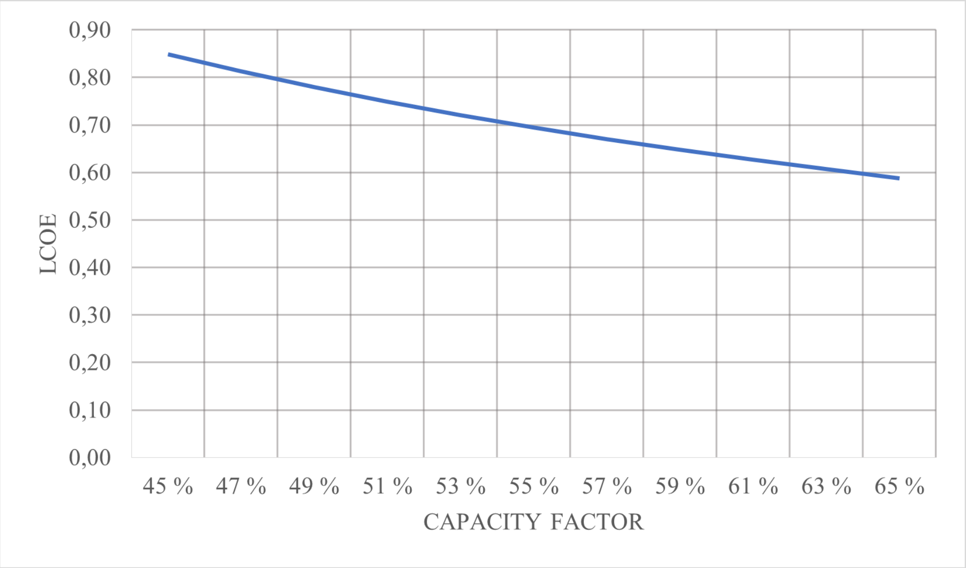


Figure 9.4: Sensitivity analysis of the capacity factor

Water depth and export cable length

Figure 9.5 shows the sensitivity on the LCOE in conjunction with increasing water depth. The water depth varies from 60 m to 300, giving an interval of - 78% to + 12% deviation from the base case of 267 m. The LCOE curve starts at 0.747 NOK/kWh and is linearly increasing to 0.767 NOK/kWh.

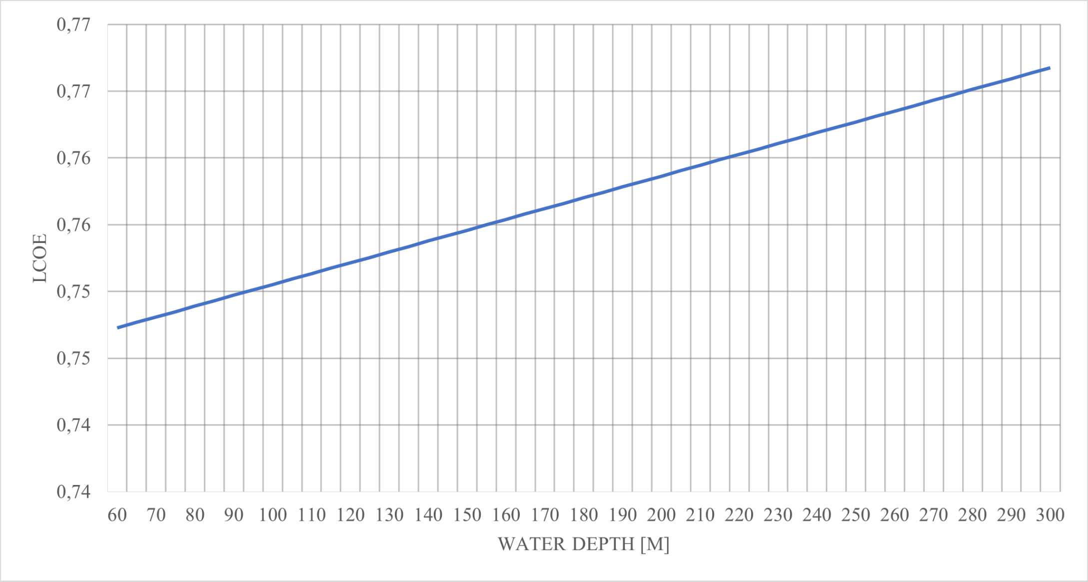


Figure 9.5: Sensitivity analysis on the water depth

Figure 9.6 shows the LCOE sensitivity of the export cable length. The sensitivity analysis is preformed with a ±50% deviation from the base case with an export cable length of 60 km. This gives a interval of 30 to 90 km, where the LCOE linearly increases from 0,752 NOK/kWh to 0,776 NOK/kWh.

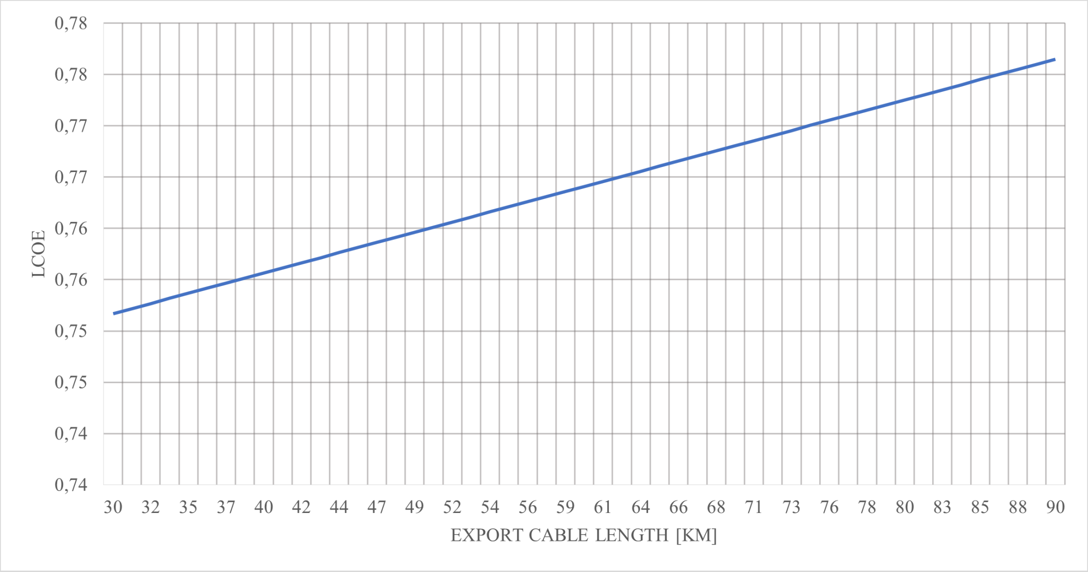


Figure 9.6: Sensitivity analysis on the export cable length

Substation-, wind turbine- and T&I costs

The substation cost is an interesting parameter for Aibel in a LCOE sensitivity analysis. In figure 9.7, the LCOE sensitivity of the LCOE in regards to the substation cost is compared to the wind turbine cost, as well as the T&I cost. The wind turbine cost has the highest impact on the LCOE, varying from 0.658 to 0.870. Regardless, the three parameters impact on the LCOE is notable. The LCOE for the varying substation cost ranges from 0.733 to 0.795, which is the parameter in this plot with the least impact on the LCOE.

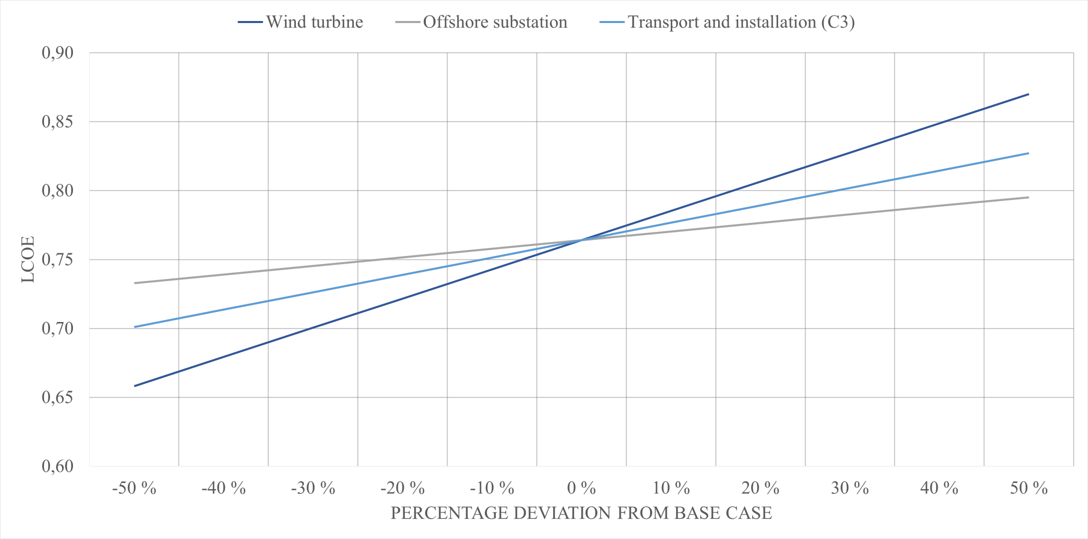


Figure 9.7: Sensitivity analysis comparison between cost of wind turbine, the floating offshore substation and T&I

10 Discussion

This chapter further comments and discuss the cost data, the LCOE calculation tool and the sensitivity analysis results. The discussion also includes the potential for LCOE reduction as well as further work for this thesis.

10.1 Cost data

The lack of correct data in terms of cost is definitely influential on the results. It is therefore important to keep in mind that the LCOE for this specific design basis will not be highly applicable for the reality. With this in mind, having the correct numbers will lead to a better LCOE result, and a more accurate sensitivity analysis.

Firstly, there is no standard around which costs that must be included in the calculation. This leads to some, and perhaps important, costs being excluded. Thus, it can be difficult to assess the real competitiveness of different energy projects. Therefore, in this LCOE tool it is possible to *add new lines* if there are cost items this tool has left aside. This makes it possible to adapt the LCOE tool to the current project. It will also make it possible to compare the LCOE in the market and choose which cost factors that are important for the company to analyse.

Furthermore, LCOE calculations are also known to be estimates due to uncertainty in the necessary data. This is because it is virtually impossible to collect costs values for investments expenses, since they are kept secret by the investors because of competitive reasons. Hence section 4.1.1 the investments cost will, based on experience, be greatly reduced in the coming years. At the same time, there is great uncertainty associated with the size of this reduction. From experience, cost reductions are often underestimated by the developers. In this LCOE tool most estimated expenses, except sourced costs, are over estimated to take this into account.

The tool's cost data sources has been extracted from NTNU Oria and Google Scholar, which are both NTNU approved search engine. Focusing on source criticism has been important for both the result and for Aibels' future use.

10.2 Excel tool

The Excel tool is constructed to calculate the LCOE based on the cost inputs and the specific project design basis. There are strengths and weaknesses to the structure and layout of the sheets. In terms of the tool, this will affect the LCOE result and users perception of the functionality.

10.2.1 Construction of the tool

The LCOE tool consists of separate sheets that has a decomposition and layout constructed to provide a user-friendly and comprehensible tool. Regardless, each sheets has its own specific characteristics and construction.

Introduction sheet
Giving the user the ability to change cells as the project's input varies, is an important part of designing this tool. The *Introduction sheet* states what type of cells are possible to alter within the specific sheet as well as what cells that needs to be altered in their respective sheets. This is done by colour coding. A green cell is probably the least problematic as it tells the user that this specific cell can be altered as desired and affect the all over results. The grey cells can be more confusing, at it requires the user clicking on the specific cell and comprehend the location of this linked number. The orange cells has a more complicated linking, making the tool somewhat less user-friendly. This is thoroughly explained in the *Introduction sheet*, though the probability for this function being confusing is unnecessarily present.

LCOE calculation sheet
The *LCOE calculation sheet* follows the BEIS method for LCOE calculations. The BEIS method discounts the energy as well as the cost since both costs and energy are expressed in net present value terms. Section 3.2.2 explains how the discount of energy is a conflicted solution. One can argue that energy produced will have the same value in terms of number of kWhs, regardless of year. However, the income value of this energy is dependent on the year, and this is why the project has chosen to discount the energy.

The LCOE tool treats energy production as a homogeneous product that is offered in the market at a constant price. The real market price for energy is not a fixed cost and varies a lot over a year. The LCOE tool gives a constant LCOE as a result and does not take into account these variations in the real market. LCOE can therefor be discussed to be a minimum price the company must take for the energy to invest, regardless of the real variations in the market. This constant price per kWh is based on the fact that AEP is assumed to be constant and discounted over the years. Again, in the energy production market the real AEP varies each year, and it is important that the user of the tool take this into account when calculating the LCOE for the wanted energy project.

The discount factor is held constant through-out the project, which is usual for a LCOE calculation as it is a difficult parameter to tackle. In reality the discount factor varies with the market, regardless the LCOE calculation tool operate with a constant discount rate explained in section 3.2.1. Several studies has pointed this out as a big flaw of the

LCOE method, and needs to be taken into account when analysing the LCOE impact.

The capacity factor of the wind farm is assumed constant throughout the LCOE calculations. This is not a realistic scenario, due to wind speed and maintenance (ref. section 2.2) varying each year. The assumption of this parameter being constant affects the LCOE by affecting the AEP. The correlation is shown in equation 2.5. Due to this unrealistic assumption, result from the LCOE tool is therefore only an estimate.

CAPEX and OPEX sheet
The *CAPEX sheet* and the *OPEX sheet* is decomposed into categories and subcategories. The current setup of these sheets allows the user to decompose each section further by adding new lines, but limits any further detailed decomposing. For example, the wind turbine is decomposed into two subcategories (ref. section 5), which both consists of an immense amount of steel. This deprives the user of the possibility to preform a sensitivity analysis on how the steel prices affect the LCOE, since steel is a material that is used in many of the components. If the user wishes to preform a sensitivity on this parameter, the current layout of the tool does not satisfy this requirement. This also applies for sensitivities on other materials or cost items and their impact on the LCOE.

The comment and source section of the two sheets, holds the benefit of utilising all the preparation research already done in advance of constructing the sheet. A lot of research hours and work lies behind each cost item, and the source section gives Aibel the opportunity to use these sources and costs in further work. This is also a benefit considering how new the field of floating offshore wind is, considering that the availability of costs are limited. The comment section provides the user comprehension about the cost and the basis behind it. These to sections gives the user the opportunity to choose to either use or dispose of the cost input.

A downside with the *OPEX sheet* is the decomposition choice of the crew costs. The crew cost is a category in both the planned and corrective maintenance section. In reality its most likely that the same crew preforms all of the maintenance, regardless of kind. The choice of structuring the sheet this way is because it gives a good overview over the ratio between the planned and corrective maintenance. When trying to reduce LCOE, this gives the opportunity to look at the sheet to see if the main cost contribution comes from planned or corrective maintenance, and look into the possibilities for reducing this cost. An advantage of combining the crew cost for O1 and O2, is that it would be easier to add up the total maintenance hours throughout the year, for type of crew personnel.

In both the *CAPEX sheet* and the *OPEX sheet* there are subcategories that are structured to fill in number of days the specific crew personnel, vessel or transportation is needed, as well as the corresponding number. This allows the user to let the cost per day be unchanged, but sets the days or number equal to zero. In the event of changes, the cost is already stated and only the concerning number can be changed to the desired value. The same applies for the cost per meter and cost per component. This structure can also complicate the functionality of the sheet if the stated cost the user holds is not in the same format as the layout of the sheet. For example, for the vessels or foatel there is a cost per day in the sheet, but the user might have a monthly cost instead. This can also be a complication for the cables, if the inter-array cable cost is obtained per turbine instead of meter.

It is difficult to generalise a setup and layout that works for all purposes the user prefers, especially considering how the field constantly evolves. Depending on the parameters that the user wishes to preform a sensitivity on, and the extent of costs they obtain, a completely generalised layout is exceedingly difficult. Therefore the LCOE tool is constructed with some limitations.

Sensitivity sheet

The sensitivity sheet utilises the *What-If* function in Excel, which is highly applicable for sensitivity analysis. The down side of this function is that it is not automatic. If the user wants to review other parameters for the sensitivity analysis, this requires more work. To accommodate this downside, an elaborate description on how to use this function is included in the introduction sheet.

The *What-If* function creates a data table for the sensitivity. If the user wishes to change the value of the input parameter for the data table, the output row needs to be deleted and the *What-If Analysis* needs to be run again with the new number, making it a manual sensitivity analysis. Another down side is that if the range of the interval for the input parameter is to be changed, this needs to be done manually, but the percentage deviation from base case will then be automatically updated.

The *What-If* function also has the down side that the input parameter needs to be in the same sheet that the sensitivity is preformed. If the user wishes to preform a sensitivity on a new input parameter from another sheet, the user need to create the link between the sheets, as done in the orange cells. This makes it more complicated for the user to preform an analysis on other parameters than the ones already in the *Sensitivity sheet.*

These problems could be solved by using the Visual Basics for Applications tool in Excel, creating a code to automatically run the sensitivity analysis of a desired input parameter. This code could also contain a line specifying the interval for the sensitivity input parameter, reliving the user of this manual work.

10.2.2 CAPEX, OPEX and the LCOE

The total CAPEX has a value of approximately 11 billion NOK. There is uncertainty around if this is a realistic investment cost for this design basis. In C0, C1 and C3 are the cost values linked up to a reliable source. These sources are reliable due to comprehensive research behind each source. On the other hand, some of the cost in C2 and parts of C3 are a best guess or provided by Aibel, due to difficulties in finding relevant costs. Therefore these cost elements has higher uncertainty. The uncertainty in the T&I costs (C3) possibly derives from the best guess in the number of crew members and number of vessels, and the respective numbers.

The comparison between the constructed CAPEX distribution in figure 9.1 and the CAPEX distribution from *LIFES 50+* in figure 5.2, share some similarities. Although they are not fully accurate since this design basis and *LIFES 50+* do not follow the same decomposition. The greatest difference is between the substructure and turbine in *LIFES 50+* and the wind turbine structure in this design basis. They have respectively 75% and 50% contribution to the total CAPEX. Hence differences in decomposition in this section, this design basis has a lack of correct data at this category compared to *LIFES 50+*. At the same time, there is a resemblance in the impact of wind turbine cost, as it is the highest in both overviews.

Further on, electrical infrastructure is 6% higher in the design basis, which substantiates that these cost are within good estimation and good sources. The electrical infrastructure for a BFWF is estimated between 15% and 30% and is likely even higher for FOWFs. This corresponds to figure 9.1, where the CAPEX cost percentage of the electrical infrastructure is 19%. Development up to FID is approximately equal for both cases. The share of transport and installation is lower in *LIFES 50+*, with 6% compared to 27%. This can be due to different decomposition, different cost values and overestimation in the base case.

Further, the total OPEX and DECEX contribution is respectively 575 million NOK and 800 million NOK. Here the the lack of important cost data is the same as for CAPEX, and a big part off OPEX and the whole DECEX cost is a best guess referred to the costs of O1, O2 and D1. Since the FOWFs are relatively new, OPEX cost field is inexperienced and DECEX has yet to occur, giving these two costs especially high uncertainty. From section 5.5 costs of decommissioning an offshore wind project is estimated to around 2-3% of the CAPEX. The DECEX used in the LCOE calculation is around 7% of the CAPEX, this is most likely caused by the DECEX being a best guess estimation.

With the costs for CAPEX, OPEX and DECEX taken into account the final LCOE was calculated to be 0.76 NOK/kWh. To compare with typical LCOE for offshore wind farms which is in the range of 0.7-1.25 NOK/kWh (ref. section 3), LCOE for this base case is relative good, although one has to take uncertainty in the data into account.

10.3 Sensitivity analysis

Performing a sensitivity analysis captures the impact that an input parameter has on the output parameter, in this case the LCOE. Figures 9.2, 9.3, 9.4, 9.6, 9.5 and 9.7 shows how the different parameters from table 8.7 affect the LCOE, and which parameters the LCOE is most sensitive to.

10.3.1 Capacity factor

The sensitivity analysis was preformed with a capacity factor varying from 45% to 65%, covering all realistic events in the LCOE development. In this interval, the LCOE decreases from 0.85 NOK/kWh to 0.59 NOK/kWh with increasing CF. This substantial variation, shows how important the capacity factor of the wind farms is for the profitability. It also indicates that developing technology that increases the capacity factor for floating offshore wind farms will highly contribute to the competitiveness of floating offshore wind. The plot also shows that the capacity factor has the highest impact on the LCOE, compared to all the other parameters that was included in the sensitivity analysis.

The maximum possible capacity factor is 100%, although that is an unobtainable scenario. Equation 2.5 shows that the annual energy production is the capacity factor multiplied with installed capacity. With a decreasing annual energy production, due to discounting, the impact of CF will decrease resulting in a decreasing approximately linear curve for the LCOE.

10.3.2 Lifetime

The lifetime curve in the sensitivity analysis decreases unmistakably from 20 to 25 years, hits the lowest LCOE at 25 years and thereafter the curve increases and shows a stagnating trend towards an LCOE value at approximately 0.8 NOK/kWh, figure 9.3. The lowest LCOE occurs with a life time of 25 years, the base case, with a value of 0.76 NOK/kWh. These results shows that LCOE evidently will not be significantly affected after a certain number of years, and are most sensitive toward 25 years of lifetime.

Considering that renewable energy projects has a high investment cost and relatively low operational costs, the stagnation of the curve is reasonable, as well as it being most sensitive in the preliminary years. Regardless, a high investment cost would benefit from increasing the lifetime, because the capital expenditure and decommissioning cost would be divided on a greater number (ref. equation 3.1). A stagnating trend around 40 years of lifetime, means that the profitability of the wind farm will not increase if the lifetime increases further.

A lifetime of 25 years is a turning point for the LCOE. It is the point where the operational expenditures exceed the capital and decommissioning expenditures divided on the lifetime. If the operational expenditures are reduced, the the breaking point would occur toward a lower lifetime. Otherwise, if the the CAPEX and DECEX cost is increased or decreased, the breaking point would move respectively towards a higher or a lower lifetime. The LCOE at which the breaking point occurs, depends on both the value of CAPEX and OPEX.

10.3.3 Water depth and distance to shore

Figures 9.5 and 9.6 shows the impact that the water depth and export cable length has on the LCOE. The water depth directly influence the cost of the mooring line and the distance to shore affect the cost of export cable. Reports from the preliminary literature study argue that water depth and distance to shore are the two parameters that have the highest impact on the LCOE, hence section 4.4. This is due to export cable and mooring line being costly. From analysis it is possible to conclude that these two parameters are not particularly influential on the LCOE. The LCOE for the sensitivity with mooring line varies from 0.747 NOK/kWh to 0.767 NOK/kWh. The variation with the export cable is 0.752 NOK/kWh to 0.776 NOK/kWh. This is an exceedingly small influence considering the substantial interval of respectively -78% to +12% and ±50% of the sensitivity parameter. This may be caused by errors in the cost research. Some of the cost items in the Excel sheet is a best guess estimation, and is not collected from a source. The figures show that the water depth has a slightly higher impact on the LCOE, even though none of them have a significant influence.

10.3.4 Substation cost

Aibel has until now delivered substations to offshore wind projects, and it is therefore interesting to perform a sensitivity on the offshore substation cost. For some comparison, these numbers are plotted together with sensitivity of wind turbine cost and T&I costs. This is to portray the outcome from scaling up and down costs for different components of the wind farm. As the design basis states, the substation uses HVAC technology, but switching to a HVDC solution would be more expensive looking directly at costs for components and construction. However, the HVDC equipment is chosen to minimize loss and contribute to a better AEP, which eventually will lead to a more favourable LCOE.

Being able to adjust these parameters will be important for for Aibel's use of the tool.

Executing a sensitivity analysis that differs from -50% to 50% is quite substantial, but as seen in figure 9.7 the impact of the three parameters the is relatively small. The substation cost has the least impact on the LCOE. There is uncertainty connected to the cost of floating substations, due to the technology and experience being in the early stages, discussed in section 5.3.2. With increasing experience on the field, the cost will most likely decrease, resulting in an even less impact on the LCOE.

10.3.5 Discount rate

The influence of discount rate are prominent in these results and with background in financial theory, these results are highly viable. Section 3.2.1 explains how higher discount rate gives a higher discount factor, resulting in an increase in the present value of the cost in the specific year. A higher present value each year would naturally sum up to a higher total net present value of costs, resulting in a increase in the LCOE. This is supported by 9.2, visualising that an increasing the discount rate results in a increase in the LCOE. The analysis also shows that the LCOE is sensitive to the project's discount rate, and will vary from 0.69 NOK/kWh to 0.89 NOK/kWh together with the increase in discount factor from 5% to 10%. As it it is favourable with a low LCOE value, a low discount rate is complimentary, but this presupposes companies deliberately taking risk.

The discount rate curve has a linear development. This stems from the equations in section 3.2.1, showing that the discount factor is inverse proportional to the discount rate. The discount factor is proportional to the net present value of costs, resulting in a linear shape for discount rate curve in figure 9.2.

In the LCOE calculations performed in the Excel tool, a constant discount rate is used. In reality, the discount rate varies each year, but an accurate estimation of the discount rate's evolution ahead of time would be speculation. The discount rate consists of a risk free rate and a risk rate that are influenced by the economic climate, which will vary greatly over a project lifetime. Therefore setting a discount factor is challenging for the wind farm developer. It is advisable to set high discount rate if there is a high risk in the project, to secure the risk. On the other hand, it is difficult as a company to determine the uncertainty in the project, and also determine how uncertain the development of offshore wind are in the future. Wind is an renewable resource, and it has no delivery security. The discount rate must take into account the possible future changes in the market. Both concerning the electricity prices and the financial market.

10.4 LCOE reduction potential for floating offshore wind

As of now, the main challenges with floating offshore wind is technological challenges and inexperience in the field. Solving this will contribute to reducing investments and operational cost, which is important to enable a reduction of LCOE.

Reduction of CAPEX and OPEX
Technological development is important all over the supply chain, as is aims to streamline processes (ref. section 4.1.1) for manufacturing of equipment, port operation and T&I. The learning curve can contribute commercialisation of the field and decrease the risk for floating offshore wind projects. Furthermore, developing cost efficient wind turbines and electrical infrastructure with bigger capacity will also be favourable, if it improves the capacity factor and annual energy production.

The turbine cost has big impact on the total CAPEX. Good agreements with suppliers of wind turbines and buying in large quantum is a contributor to lower the total price of turbines. On the other hand, it is crucial to check with the turbine supplier that they have the capacity to deliver, given the current situation with material shortages due to global challenges and high demand of materials. It is also important to be able to understand the dynamics of a floating offshore wind system (ref. section 5.2.2) to help avoid exhaustion of the components, and reduce the LCOE for the project. This is closely related to experience on the field.

The operation costs can also be reduced by enabling more efficient logistics and management structure that will reduce costs in port operation, administrative development and research/engineering studies. This can potentially be made possible through initiating commercialisation of wind farms.

Experience in the floating offshore wind field will contribute largely to a reduction of costs, as well as risk. As already deliberated in this chapter, a lower discount rate will provide a notable potential to reduce the LCOE as it is design independent. The risk rate that contributes to the discount rate, has a reduction potential by initiating extensive commercialisation and technology development within FOWFs.

Subsidies
The Norwegian government has yet to conclude the subsidy scheme for floating offshore wind (ref. section 4.3). Although revenues from the sold electricity or the income from subsidies are not included in the LCOE calculation, the investors must have certainty that the investment will be profitable in the long run. A satisfactory LCOE and the security of being rewarded with subsidies for investing in green energy is a contributor to developing and investing in wind energy.

Designing well fitted subsidy schemes for floating offshore wind will be important to incentives development. Taking some risk away from the wind farm developer is one of the possibilities to enable this technology on a larger scale. This is feasible through for example CFD contracts which provides predictability. However, subsidies requires financial risk and investment from the state budget, so it depends if the government are willing to invest in offshore wind to make the future electricity cheaper and contribute to reach UNs climate goals.

10.5 Further work

To further develop this project, several suggestions have been discussed earlier in this chapter. This includes a further decomposition of CAPEX and OPEX, more accurate cost data and an automatic sensitivity analysis sheet. Further decomposition of CAPEX and OPEX can give an more accurate LCOE result. For example, by making it possible to adjust material amount, the price calculations will be more accurate.

Also looking at sensitivity of the wind farm installed capacity will be advantageous. This requires more substantial research on how much the different parameters change with a change in wind farm size. Naturally, an increase in capacity would either mean larger wind turbines or an increase in the number of wind turbines. Further on, parameters such as export cable price and substation cost would also have to increase as it needs to handle larger loads. The sensitivity analysis would therefore have to tackle a variation in a number of different parameters.

Creating a LCOE tool that can calculate the life extension costs of re-powering and refurbishment of a wind farm would be useful for future users, as this measure can prolong the life time and decrease the OPEX cost as well as the annual CAPEX. Experience from Aibel has shown that this has become a popular possible solution among wind farm developers, and will maybe be a standard practice in future years. The tool could also include the possibility of adding midlife upgrades as that is a highly relevant possibility in the future.

Conclusion

The LCOE calculation tool developed in this project has potential to assist LCOE calculations for a general floating offshore wind project within the addressed limitations. By using the well known software, Microsoft Office Excel, providing a thorough introduction sheet and well designed explanations in the report, it can be stated that the tool is made to be user-friendly. The tool has an inherent opportunity to be more advanced if desired, by further decomposing CAPEX, OPEX and DECEX. The tool is functional due to the validity of the LCOE results and the cost distribution.

For a relatively young technology, it can be challenging to calculate LCOE correctly, because of lack of cost data. The method is definitely most valuable to an analysts that has access to relevant cost data with associated decomposition of CAPEX, OPEX and DECEX. However, the obtained LCOE result from the tool, 0.76 NOK/kWh, is within a reasonable interval, which concludes that the costs are within a reasonable magnitude.

The results from the sensitivity analysis visualises the uncertainty in the numerical basis, that derive from lack of cost data. Based on the design basis, the three most influential parameters affecting the LCOE is the capacity factor, wind turbine cost and discount rate. Adjusting these parameters through increasing experience in the field, technological development and commercialisation can contribute to optimising the LCOE. The lifetime graph shows that the lifetime is highly influenced by the CAPEX and OPEX costs. The water depth and distance to shore had a lower impact on the LCOE than anticipated from preliminary research. The substation cost has a relatively small impact on the LCOE. Regardless, it gives Aibel the opportunity asses their products.

LCOE calculation tools can possibly contribute to launching FOWFs for commercialisation. With the given prerequisites, a LCOE calculation model has been developed, accommodated by a report thoroughly explaining the functions and structure of the tool. It gives the possibility to assess the feasibility of a potential FOWF and which cost items has the highest potential for improvement.

References

[1] UN. "Take Action for the Sustainable Development Goals". In: (). URL: `https://www.un.org/sustainabledevelopment/sustainable-development-goals/`.

[2] UN. *The Paris Agreement.* URL: `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement` (visited on 05/13/2022).

[3] European Wind Energy Association. *Wind energy scenarios for 2030.* Aug. 2015. URL: `https://www.ewea.org/fileadmin/files/library/publications/reports/EWEA-Wind-energy-scenarios-2030.pdf` (visited on 03/2022).

[4] Government og Norway. *Ambitious offshore wind initiative.* May 11, 2022. URL: `https://www.regjeringen.no/en/aktuelt/ambitious-offshore-wind-power-initiative/id2912297/` (visited on 05/21/2022).

[5] Equinor. *Flytende havvind i Equinor - equinor.com.* URL: `https://www.equinor.com/no/what-we-do/floating-wind.html` (visited on 02/18/2022).

[6] Utenriksdepartementet. *Kontinentalsokkelen: Spørsmål og svar.* Nov. 4, 2020. URL: `https://www.regjeringen.no/no/tema/utenrikssaker/folkerett/kontinentalsokkelen-sporsmal-og-svar/id448309/` (visited on 05/21/2022).

[7] Microsoft 365. *Microsoft Excel Spreadsheet Software.* URL: `https://www.microsoft.com/en-us/microsoft-365/excel` (visited on 05/13/2022).

[8] Utsira gir energi. *Utsira Nord – Utsira.* URL: `https://www.utsira.no/en/utsira-nord/` (visited on 05/03/2022).

[9] Anthony L. Rogers James F. Manwell Jon G. McGowan. *Wind Energy Explained: Theory, Design and Application.* 2010. URL: `https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781119994367`.

[10] Yiannis Katsigiannis and G. Stavrakakis. "Estimation of wind energy production in various sites in Australia for different wind turbine classes: a comparative technical and economic". In: (Jan. 2013). URL: `https://www.researchgate.net/figure/Typical-wind-turbine-power-curve_fig3_312786418`.

[11] Z. R. Shu and Mike Jesson. *Estimation of Weibull Parameters for Wind Energy Analysis across the UK.* Jan. 27, 2021. URL: `https://doi.org/10.1063/5.0038001`.

[12] Jiale Li and Xiong Yu. *Assessment of fresh water wind resources on Lake Erie.* 2019. URL: `https://journals.sagepub.com/doi/pdf/10.1177/0309524X18821029` (visited on 05/05/2022).

[13] Christoph Wolter Henrik Klinge Jacobsen Pablo Hevia-Koch. *Nearshore and offshore wind development: Costs and competitive advantage exemplified by*

nearshore wind in Denmark. Accessed: 21-2-2022. Mar. 30, 2019. URL: `https://www.sciencedirect.com/science/article/pii/S0973082618315047`.

[14] Walter Musial et al. "Offshore Wind Market Report: 2021 Edition". In: (2021). URL: `https://www.energy.gov/sites/default/files/2021-08/Offshore%20Wind%20Market%20Report%202021%20Edition_Final.pdf`.

[15] Andrew Angus, Feargal Brennan, and Anastasia Ioannou. *Stochastic Prediction of Offshore Wind Farm LCOE through an Integrated Cost Model*. In: Sept. 11, 2016. URL: `https://www.sciencedirect.com/science/article/pii/S1876610216317696`.

[16] Wind Europe. *Floating Offshore Wind Vision Statement*. June 2017. URL: `https://questfwe.com/wp-content/uploads/2018/02/WindEurope-2017-Floating-wind-statement.pdf`.

[17] Alexandra Eide Hvidevold and Malin Karlsen. *Økonomiske utsikter for utbygging av Utsira Nord*. Accessed: 22-2-2022. 2020. URL: `https://openaccess.nhh.no/nhh-xmlui/handle/11250/2682373`.

[18] C. Maienza et al. *A life cycle cost model for floating offshore wind farms*. Feb. 21, 2020. URL: `https://www.sciencedirect.com/science/article/pii/S0306261920302282` (visited on 02/22/2022).

[19] Ângelo P. Teixeira Fernando P. Santos and Carlos Guedes Soares. *Operation and Maintenance of Floating Offshore Wind Turbines*. 2016. URL: `https://link.springer.com/content/pdf/10.1007/978-3-319-27972-5_10.pdf`.

[20] BVG associate. *Guide to an offshore wind farm*. Accessed: 2022-01-24. Apr. 2019. URL: `https://bvgassociates.com/wp-content/uploads/2019/04/BVGA-Guide-to-an-offshore-wind-farm-r2.pdf`.

[21] CFI. *Levelized Cost of Energy (LCOE)*. URL: `https://corporatefinanceinstitute.com/resources/knowledge/finance/levelized-cost-of-energy-lcoe` (visited on 02/25/2022).

[22] Daniel J. Packey Walter Short and Thomas Holt. *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*. URL: `https://www.nrel.gov/docs/legosti/old/5173.pdf`.

[23] CFI. *Discount Rate*. URL: `https://corporatefinanceinstitute.com/resources/knowledge/finance/discount-rate/` (visited on 02/25/2022).

[24] Victoria Collin. *Discount Factor*. Mar. 1, 2022. URL: `https://www.fe.training/free-resources/financial-modeling/discount-factor/` (visited on 09/17/2021).

[25] J. Aldersey-Williams and T. Rubert. *Levelised cost of energy – A theoretical justification and critical assessment*. Oct. 7, 2018. URL: `https://www.sciencedirect.com/science/article/pii/S0301421518306645` (visited on 02/25/2022).

[26] Kåre P Hagen. *Verdsetting av fremtiden. Tidshorisont og diskonteringsrenter*. In: Sept. 27, 2011. URL: `https://www.ntnu.no/documents/1261860271/1262010703/CONSEPT_27_web.pdf`.

[27] Laura Malaguzzi Valeri. "INSIDER: Not All Electricity Is Equal— Uses and Misuses of Levelized Cost of Electricity (LCOE)". In: (Aug. 1, 2019). URL: `https://www.wri.org/insights/insider-not-all-electricity-equal-uses-and-misuses-levelized-cost-electricity-lcoe` (visited on 03/2022).

[28] Sergei Manzhous. *On the Choice of the Discount Rate and the Role of Financial Variables and Physical Parameters in Estimating the Levelized Cost of Energy*. In: MDPI, July 18, 2013. URL: `https://www.mdpi.com/2227-7072/1/3/54/htm`.

[29] Equinor. *Hywind Tampen*. URL: `https://www.equinor.com/no/energi/hywind-tampen` (visited on 05/01/2022).

[30] Anders Ågotnes Anders Myhr Catho Bjerkseter and Tor A. Nygaard. *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective*. Accessed: 18-2-2022. Jan. 18, 2014. URL: `https://www.sciencedirect.com/science/article/pii/S0960148114000469`.

[31] Castro-Santos Laura and Diaz-Casas Vicente. *Life-cycle cost analysis of floating offshore wind farms*. June 2014. URL: `https://www.sciencedirect.com/science/article/pii/S0960148113006642` (visited on 05/11/2022).

[32] European comission. *FLOATING OFFSHORE WIND ENERGY*. URL: `https://windeurope.org/wp-content/uploads/files/policy/position-papers/Floating-offshore-wind-energy-a-policy-blueprint-for-Europe.pdf`.

[33] MODEC. *Floating Production Systems Business*. URL: `https://www.modec.com/business/floater/index.html` (visited on 05/11/2022).

[34] Markus Lerch. *Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m*. June 1, 2015. URL: `https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c3ac71f4%5C&appId=PPGMS` (visited on 01/24/2022).

[35] Jiahao Chen Zhiqiang Hu Peng Chen. "Review of Experimental-Numerical Methodologies and Challenges for Floating Offshore Wind Turbines". In: (Sept. 2020). URL: `https://link.springer.com/10.1007/s11804-020-00165-z` (visited on 03/16/2022).

[36] Daniel Micallefa and Abdolrahim Rezaeihabc. *Floating offshore wind turbine aerodynamics: Trends and future challenges*. Sept. 14, 2021. URL: `https://www`

.sciencedirect.com/science/article/pii/S1364032121009709 (visited on 03/11/2022).

[37] Anna J. Wieczorek et al. “A review of the European offshore wind innovation system”. In: (Oct. 1, 2013). URL: https://www.sciencedirect.com/science/article/pii/S1364032113003481 (visited on 05/01/2022).

[38] Electric power research institute. *An Insider’s Guide to the Calculation and Use of LCOEs*. Feb. 2020. URL: https://esca.epri.com/pdf/Back-Pocket-Insights/EPRI-P201-LCOE-Brief.pdf.

[39] E&T editorial staff. *Energy subsidies offered to cover floating offshore wind and tidal power*. Sept. 13, 2021. URL: https://eandt.theiet.org/content/articles/2021/09/energy-subsidies-to-cover-floating-offshore-wind-and-tidal-power/ (visited on 02/25/2022).

[40] Office of the Prime Minister. *Major initiative to promote offshore wind power*. Feb. 12, 2022. URL: https://www.regjeringen.no/en/aktuelt/major-initiative-to-promote-offshore-wind-power/id2900436/ (visited on 02/25/2022).

[41] Olje-og energidepartementet. *Styrkjer satsinga på havvind*. Nov. 8, 2021. URL: https://www.regjeringen.no/nn/aktuelt/regjerina-styrkar-arbeidet-med-havvind-i-olje-og-energidepartementet/id2884658/ (visited on 03/01/2022).

[42] Enova. *Enova-støtte til Hywind Tampen*. URL: https://www.enova.no/bedrift/energisystem/historier/derfor-stotter-vi-hywind-tampen/ (visited on 08/22/2019).

[43] Elizabeth Nyman Rachel Tiller. *To manage or own the Svalbard Fisheries Protection Zone*. Oct. 2015. URL: https://www.sciencedirect.com/science/article/pii/S0308597X15001700 (visited on 05/11/2022).

[44] International seafood sustainability foundation. *Exclusive economic zone*. URL: https://www.iss-foundation.org/glossary/exclusive-economic-zone/ (visited on 04/30/2022).

[45] Adnan Durakovic. *Fixed Bottom Offshore Wind Farms 90 Metres Deep? Offshoretronic Says Yes*. Nov. 29, 2021. URL: https://www.offshorewind.biz/2021/11/29/fixed-bottom-offshore-wind-farms-90-metres-deep-offshoretronic-says-yes/ (visited on 05/01/2022).

[46] IBERDROLA CORPORATIVA. *Floating offshore wind power: a milestone to boost renewables through innovation*. URL: https://www.iberdrola.com/innovation/floating-offshore-wind (visited on 04/30/2022).

[47] Nes Fircroft. *Offshore and Onshore Wind Farms: What Are the Pros and Cons?* Sept. 7, 2021. URL: https://www.nesfircroft.com/blog/2021/09/offshore-and-onshore-wind-farms (visited on 05/01/2022).

[48] Orsted. *Our energy infrastructure: from wind farm to Grid.* URL: `https://orsted.co.uk/energy-solutions/offshore-wind/how-we-work-onshore` (visited on 04/30/2022).

[49] Rhona Fairgrieve, Kath Wellard, and Colin Trigg. *Floating offshore wind development and consenting process - Risks and opportunities.* July 22, 2021. URL: `https://ore.catapult.org.uk/wp-content/uploads/2021/09/FOW-CoE-FOW-Development-and-Consenting-Process-Risks-and-Opportunities-Public-Summary.pdf`.

[50] Laura Comay and Corrie Clark. *Offshore Wind Energy: Federal leasing, Permitting, Deployment and Revenues.* Dec. 7, 2021. URL: `https://sgp.fas.org/crs/misc/R46970.pdf`.

[51] Schjødt. *Ny veileder om havvind-konsesjoner.* June 11, 2021. URL: `https://www.schjodt.no/en/news--events/newsletters/ny-veileder-om-havvind-konsesjoner/` (visited on 04/21/2022).

[52] Olje- og energidepartementet. *Lov om fornybar energiproduksjon til havs (havenergilova).* June 4, 2010. URL: `https://lovdata.no/dokument/NL/lov/2010-06-04-21` (visited on 05/14/2022).

[53] Regjeringen. *Veileder for arealtildeling, konsesjonsprosess og søknader for vindkraft til havs.* June 11, 2022. URL: `https://www.regjeringen.no/contentassets/5a7268e3397b4f4ea6eb4fa84897808e/veileder-for-arealtildeling-konsesjonsprosess-og-soknader-for-vindkraft-til-havs-l1244319.pdf`.

[54] BVG Assosiates. *Wind farm costs – Guide to an offshore wind farm.* URL: `https://guidetoanoffshorewindfarm.com/wind-farm-costs` (visited on 04/18/2022).

[55] K. Herklotz. "Oceanographic results of two years operation of the first offshore wind research platform in the German Bight". In: (Feb. 15, 2007). URL: `https://www.osti.gov/etdeweb/biblio/20902946` (visited on 05/14/2022).

[56] *EPC Projects (Engineering, Procurement and Construction) - PMPC.* URL: `https://pmpconsulting.ro/portfolio/epc-engineering-procurement-construction-projects/` (visited on 05/14/2022).

[57] POSCO. *Steel Solutions in Wind Power.* URL: `https://newsroom.posco.com/en/steel-solutions-in-wind-power` (visited on 05/12/2022).

[58] Norsk staal. *Markedsrapport fra Norsk Stål.* Oct. 12, 2020. URL: `https://www.norskstaal.no/Default.aspx?ID=6966` (visited on 05/01/2022).

[59] Jan Weinzettel et al. "Life cycle assessment of a floating offshore wind turbine". In: (Mar. 1, 2009). URL: `https://www.sciencedirect.com/science/article/pii/S0960148108001754` (visited on 02/18/2022).

[60] Qian Yi Yichao Liu Sunwei Li and Daoyi Chen. *Developments in Semi-Submersible Floating Foundations Supporting Wind Turbines: A Comprehensive Review*. June 2016. URL: `https://www.sciencedirect.com/science/article/pii/S1364032116001398` (visited on 04/21/2022).

[61] N.Y.Sergiienko L.S.P.Silva B.Cazzolato and B.Ding. "Nonlinear dynamics of a floating offshore wind turbine platform via statistical quadratization — Mooring, wave and current interaction". In: (Sept. 15, 2021). URL: `https://www.sciencedirect.com/science/article/pii/S0029801821008738` (visited on 02/22/2022).

[62] G.Iglesias S.Astariz. *The economics of wave energy: A review*. May 2015. URL: `https://www.sciencedirect.com/science/article/pii/S1364032115000714` (visited on 04/21/2022).

[63] Intermoor. *How do suction piles work?* May 25, 2016. URL: `https://intermoor.com/press-releases/how-suction-piles-work/` (visited on 05/04/2022).

[64] Kristine Ekeli Klingan. *Automated Optimization and Design of Mooring Systems for Deep Water*. June 2016. URL: `https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2409562`.

[65] Tobias Bjørshol Roksvaag Torbjørn Herberg Lunde and Sondre Solheim. *Mooring of Floating Offshore Wind Turbines*. June 2021. URL: `https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2782239`.

[66] The carbon trust. *Floating offshore wind market technology review*. June 2015. URL: `https://questfwe.com/wp-content/uploads/2018/02/The-Carbon-Trust-2015-floating-offshore-wind-market-technology-review.pdf`.

[67] Mikel De-Prada-Gilb Markus Lercha and Climent Molinsa. *A metaheuristic optimization model for the inter-array layout planning of floating offshore wind farms*. Apr. 18, 2021. URL: `https://www.sciencedirect.com/science/article/pii/S0142061521003677` (visited on 04/07/2022).

[68] Maria Ikhennicheu et al. *D3.1 Review of the state of the art of dynamic cable system design*. Feb. 2020. URL: `https://corewind.eu/wp-content/uploads/files/publications/COREWIND-D3.1-Review-of-the-state-of-the-art-of-dynamic-cable-system-design.pdf`.

[69] Peng Hou et al. "A review of offshore wind farm layout optimization and electrical system design methods". In: (Sept. 2019). URL: `https://link.springer.com/article/10.1007/s40565-019-0550-5`.

[70] Markus Lerch. *Technical-economic analysis, modeling and optimization of floating off shore wind farms*. Feb. 2020. URL: `https://upcommons.upc.edu/handle/2117/183150`.

[71] *Offshore wind*. 2022. URL: `https://aibel.com/our-business/offshore-wind` (visited on 05/01/2022).

[72] ABB. *HVDC technology for offshore wind is maturing*. Oct. 24, 2018. URL: `https://new.abb.com/news/detail/8270/hvdc-technology-for-offshore-wind-is-maturing` (visited on 05/01/2022).

[73] Justin Jones and Ian Childs. *Floating Substations: the next challenge on the path to commercial scale floating windfarms*. 2021. URL: `https://www.dnv.com/article/floating-substations-the-next-challenge-on-the-path-to-commercial-scale-floating-windfarms-199213` (visited on 05/01/2022).

[74] Fukushima Offshore Wind Consortium. *Fukushima Floating Offshore Wind Farm Demonstration Project*. Feb. 2020. URL: `http://www.fukushima-forward.jp/pdf/pamphlet4en.pdf`.

[75] Axel Norman Aibel. *Data collection*. E-mail and digital meetings. 2022.

[76] AP Crowle and PR Thesis. *Floating offshore wind turbines port requirements for construction*. Jan. 19, 2022. URL: `https://journals.sagepub.com/doi/pdf/10.1177/14750902221078425`.

[77] Bartolomej Tomic. *PHOTO: Boskalis Tows First of Five 9.5MW Turbines for Kincardine Floating Wind Farm*. Dec. 9, 2020. URL: `https://www.oedigital.com/news/483774-photo-boskalis-tows-first-of-five-9-5mw-turbines-for-kincardine-floating-wind-farm` (visited on 04/05/2022).

[78] Adnan Durakovic. *First Floating-to-Fixed Wind Turbine Connection Completed Offshore China*. Sept. 2, 2021. URL: `https://www.offshorewind.biz/2021/09/02/first-floating-to-fixed-wind-turbine-connection-completed-offshore-china/` (visited on 04/18/2022).

[79] Norsk Industri. *LEVERANSEMODELLER FOR HAVVIND*. URL: `https://www.norskindustri.no/siteassets/dokumenter/rapporter-og-brosjyrer/leveransemodeller-havvind/leveransemodeller-havvind_marine-operasjoner.pdf`.

[80] *Semi-submersible heavy transport vessels*. URL: `https://boskalis.com/about-us/fleet-and-equipment/offshore-vessels/semi-submersible-heavy-transport-vessels.html` (visited on 05/14/2022).

[81] Xavier Turc Castellà. *OPERATIONS AND MAINTENANCE COSTS FOR OFFSHORE WIND FARM*. June 2020. URL: `https://upcommons.upc.edu/bitstream/handle/2117/329731/master-thesis-xavier-turc-castell-.pdf`.

[82] Yuna Zhao et al. “Numerical study on the feasibility of offshore single blade installation by floating crane vessels”. In: (Mar. 1, 2019). URL: `https://www`

.sciencedirect.com/science/article/pii/S0951833918302272 (visited on 05/12/2022).

[83] Adrijana Buljan. *Floatel International Wins First Offshore Wind Contract.* May 27, 2021. URL: https://www.offshorewind.biz/2021/05/27/floatel-international-wins-first-offshore-wind-contract/ (visited on 05/12/2022).

[84] Mario Pierobon. *Windfarm Support Boosts Offshore Helicopter Work.* URL: https://www.ainonline.com/aviation-news/general-aviation/2020-01-24/windfarm-support-boosts-offshore-helicopter-work (visited on 05/12/2022).

[85] Kurt Thomesen. *Offshore Wind - A Comprehensive Guide to Successful Offshore Wind Farm.* 2014. URL: https://books.google.no/books?hl=en&lr=&id=tONuAwAAQBAJ&oi=fnd&pg=PP1&dq=installation+of+offshore+wind+farm&ots=pnKXf8AayJ&sig=HMlNCnAT51UMQkrqHhW8gwDhHNU&redir_esc=y#v=onepage&q&f=false.

[86] Silja Bergitte Nordvik. *Installation of Anchors for Mooring System of Floating Wind Turbines.* June 2019. URL: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2622952/no.ntnu%5C%3Ainspera%5C%3A2526111.pdf?sequence=1%5C&isAllowed=y.

[87] Yichao Liu et al. *Developments in semi-submersible floating foundations supporting wind turbines: A comprehensive review.* July 2016. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032116001398.

[88] DNV. *GUIDELINES FOR OFFSHORE WIND FARM INFRASTRUCTURE INSTALLATION.* July 28, 2016. URL: https://rules.dnv.com/docs/pdf/gl/nobledenton/0035-nd%20rev%201.1%2028-jun-16%20guidelines%20for%20offshore%20wind%20farm%20infrastructure%20installation.pdf.

[89] Constantine Michailides Vasileios A. Mamatsopoulos and Efstathios E. Theotokoglou. “An Analysis Tool for the Installation of Submarine Cables in an S-Lay Configuration Including “In and Out of Water” Cable Segments”. In: (Jan. 16, 2020). URL: https://www.mdpi.com/2077-1312/8/1/48 (visited on 05/01/2022).

[90] James Hamilton and Drew Liming. *Careers in Wind Energy : U.S. Bureau of Labor Statistics.* URL: https://www.bls.gov/green/wind_energy/ (visited on 05/14/2022).

[91] Hamish Roberts and Daniel Gumsley. *Offshore windfarms: Project insurability can make or break a bid.* URL: https://www.marsh.com/tn/industries/energy-and-power/insights/offshore-windfarms-project-insurability-can-make-or-break-a-bid.html (visited on 05/14/2022).

[92] Yalcin Dalgic et al. *Optimum CTV Fleet Selection for Offshore Wind Farm O&M Activities*. URL: `https://strathprints.strath.ac.uk/49631/1/Optimum_CTV_fleet_selection_for_offshore_wind_farm_O_M_activities.pdf`.

[93] Eva Topham and David McMillan. *Sustainable decommissioning of an offshore wind farm*. Oct. 30, 2016. URL: `https://www.sciencedirect.com/science/article/pii/S0960148116309430` (visited on 04/07/2022).

[94] O. Mauricio Hernandez et al. *Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil*. June 2021. URL: `https://www.sciencedirect.com/science/article/pii/S1364032121002859` (visited on 04/18/2022).

[95] Adnan Durakovic. *Decommissioning the Last Option for Offshore Wind Farms - Analysis*. June 10, 2021. URL: `https://www.offshorewind.biz/2021/06/10/decommissioning-the-last-option-for-offshore-wind-farms-analysis/` (visited on 04/07/2022).

[96] James. *Decommissioning of Offshore Renewables – Blackfish Engineering*. Sept. 3, 2018. URL: `https://blackfishengineering.com/2018/09/03/decommissioning-of-offshore-renewables/` (visited on 04/07/2022).

[97] Benjamin Pakenham, Anna Ermakova, and Ali Mehmanparast. *A Review of Life Extension Strategies for Offshore Wind Farms Using Techno-Economic Assessments*. In: *Energies*. Mar. 31, 2021. URL: `https://www.mdpi.com/1996-1073/14/7/1936` (visited on 05/08/2022).

[98] IRENA. *RENEWABLE POWER GENERATION COSTS IN 2019*. Accessed: 24-2-2022. 2020. URL: `https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf`.

[99] PEAK Wind. *OPEX Benchmark – An insight into operational expenditures of European offshore wind farms*. URL: `https://peak-wind.com/insights/opex-benchmark-an-insight-into-operational-expenditures-of-european-offshore-wind-farms/` (visited on 02/24/2022).

[100] Waseem Khodabux, Paul Causon, and Feargal Brennan. *Profiling Corrosion Rates for Offshore Wind Turbines with Depth in the North Sea*. In: May 15, 2020. URL: `https://www.mdpi.com/1996-1073/13/10/2518`.

[101] Windustry. *Chapter 8: Costs*. Dec. 5, 2007. URL: `https://www.windustry.org/community_wind_toolbox_8_costs` (visited on 05/08/2022).

[102] *Executed Lease OCS*. Oct. 1, 2013. URL: `https://www.boem.gov/sites/default/files/renewable-energy-program/State-Activities/RI/Executed-Lease-OCS-A-0487.pdf`.

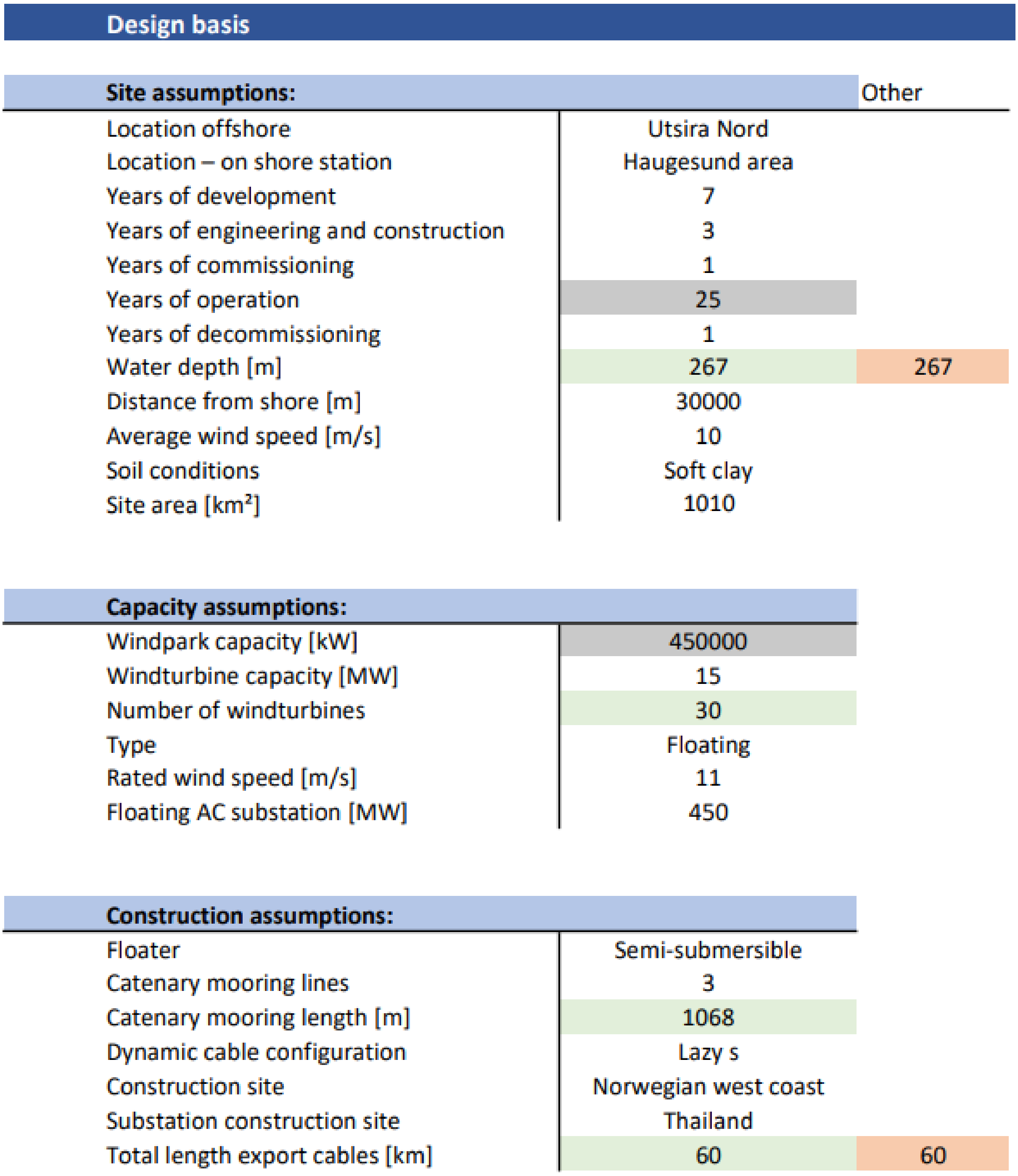
[103] KPMG. "The power of nature". In: (Dec. 2020). URL: `https://assets.kpmg/content/dam/kpmg/no/pdf/2020/12/The_Power_Of_Nature_Taxation_Of_Wind_Power_2020.pdf`.

[104] Scottish Hydro Electric Transmission. *Offshore Wind Transmission Charges*. Sept. 2021. URL: `https://www.ssen-transmission.co.uk/media/5764/ssen-transmission-offshore-tnuos-addendum_.pdf`.

[105] Zhengru Ren et al. *Offshore wind turbine operations and maintenance: A state-of-the-art review*. July 2021. URL: `https://www.sciencedirect.com/science/article/abs/pii/S1364032121001805` (visited on 05/01/2022).

A LCOE Calculations tool

A.1 Design basis sheet



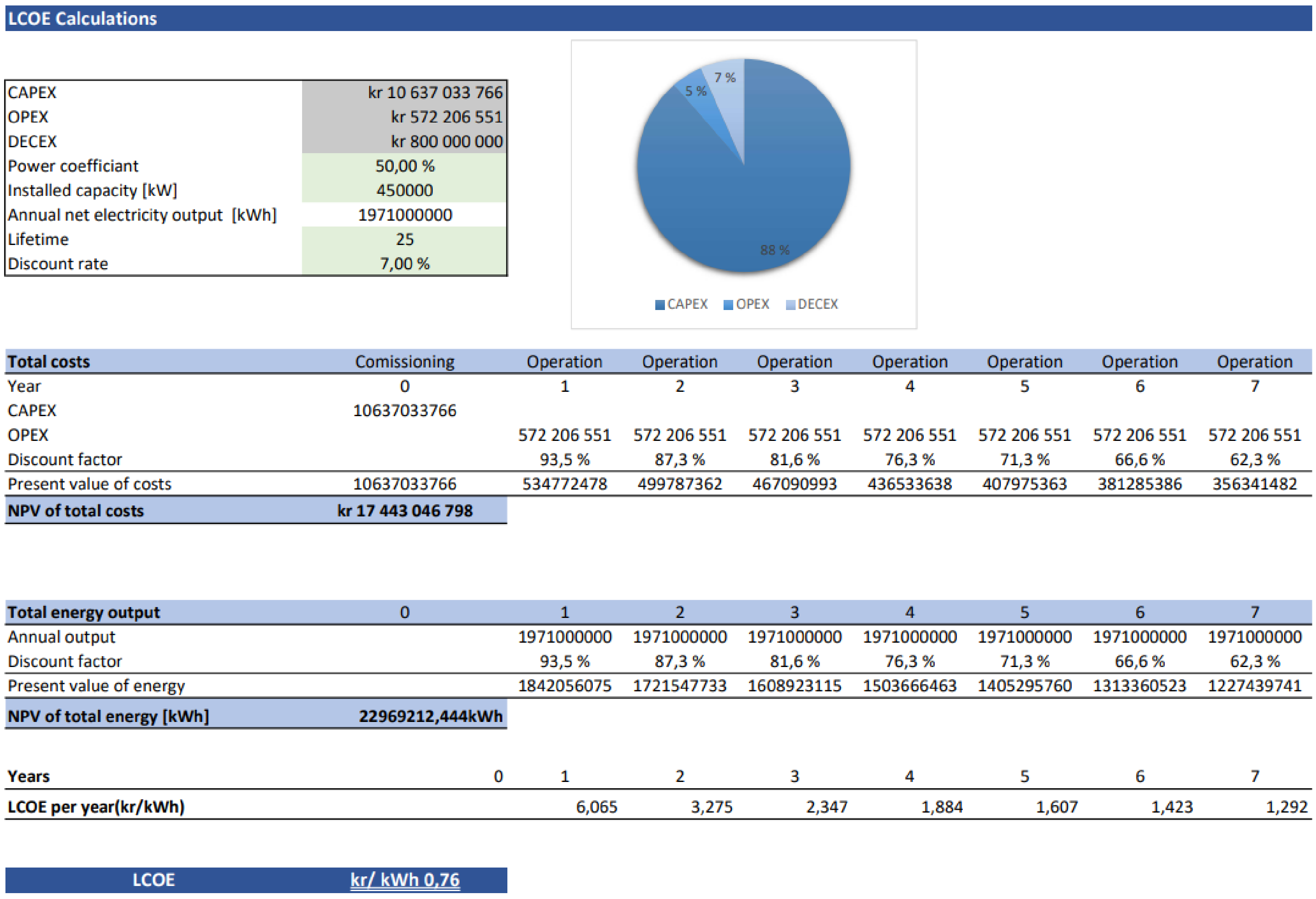
Design basis

Site assumptions:		Other
Location offshore	Utsira Nord	
Location – on shore station	Haugesund area	
Years of development	7	
Years of engineering and construction	3	
Years of commissioning	1	
Years of operation	25	
Years of decommissioning	1	
Water depth [m]	267	267
Distance from shore [m]	30000	
Average wind speed [m/s]	10	
Soil conditions	Soft clay	
Site area [km^2]	1010	

Capacity assumptions:	
Windpark capacity [kW]	450000
Windturbine capacity [MW]	15
Number of windturbines	30
Type	Floating
Rated wind speed [m/s]	11
Floating AC substation [MW]	450

Construction assumptions:		
Floater	Semi-submersible	
Catenary mooring lines	3	
Catenary mooring length [m]	1068	
Dynamic cable configuration	Lazy s	
Construction site	Norwegian west coast	
Substation construction site	Thailand	
Total length export cables [km]	60	60

A.2 LCOE calculation sheet



LCOE Calculations

CAPEX	kr 10 637 033 766
OPEX	kr 572 206 551
DECEX	kr 800 000 000
Power coefficiant	50,00 %
Installed capacity [kW]	450000
Annual net electricity output [kWh]	1971000000
Lifetime	25
Discount rate	7,00 %

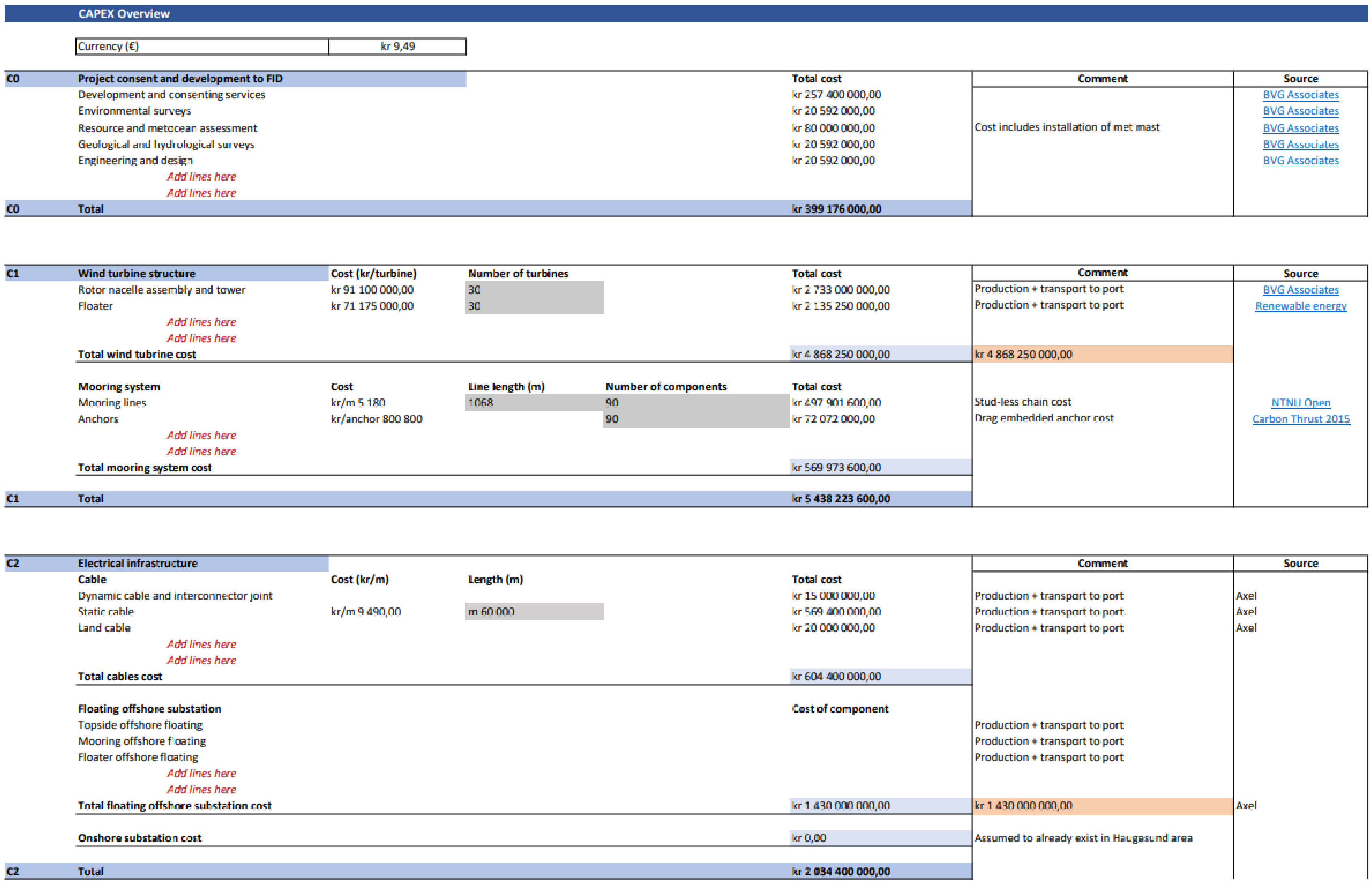
Total costs	Comissioning	Operation	Operation	Operation	Operation	Operation	Operation	Operation
Year	0	1	2	3	4	5	6	7
CAPEX	10637033766							
OPEX		572 206 551	572 206 551	572 206 551	572 206 551	572 206 551	572 206 551	572 206 551
Discount factor		93,5 %	87,3 %	81,6 %	76,3 %	71,3 %	66,6 %	62,3 %
Present value of costs	10637033766	534772478	499787362	467090993	436533638	407975363	381285386	356341482
NPV of total costs	**kr 17 443 046 798**							

Total energy output	0	1	2	3	4	5	6	7
Annual output		1971000000	1971000000	1971000000	1971000000	1971000000	1971000000	1971000000
Discount factor		93,5 %	87,3 %	81,6 %	76,3 %	71,3 %	66,6 %	62,3 %
Present value of energy		1842056075	1721547733	1608923115	1503666463	1405295760	1313360523	1227439741
NPV of total energy [kWh]	**22969212,444kWh**							

Years	0	1	2	3	4	5	6	7
LCOE per year(kr/kWh)		6,065	3,275	2,347	1,884	1,607	1,423	1,292

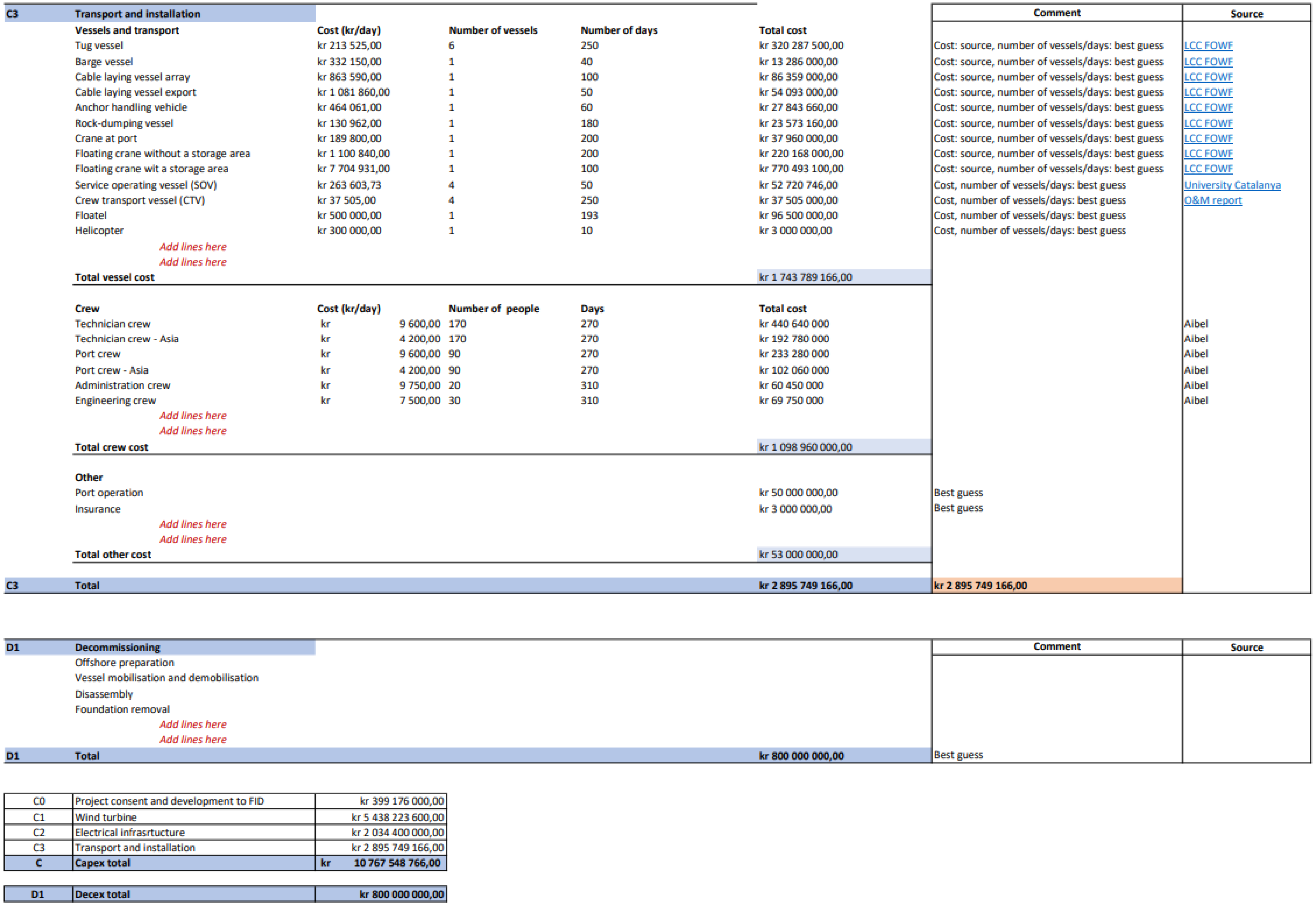
LCOE	**kr/ kWh 0,76**

A.3 CAPEX sheet



CAPEX Overview

	Currency (€)	kr 9,49					
C0	**Project consent and development to FID**				**Total cost**	**Comment**	**Source**
	Development and consenting services				kr 257 400 000,00		BVG Associates
	Environmental surveys				kr 20 592 000,00		BVG Associates
	Resource and metocean assessment				kr 80 000 000,00	Cost includes installation of met mast	BVG Associates
	Geological and hydrological surveys				kr 20 592 000,00		BVG Associates
	Engineering and design				kr 20 592 000,00		BVG Associates
	Add lines here						
	Add lines here						
C0	**Total**				**kr 399 176 000,00**		
C1	**Wind turbine structure**	**Cost (kr/turbine)**	**Number of turbines**		**Total cost**	**Comment**	**Source**
	Rotor nacelle assembly and tower	kr 91 100 000,00	30		kr 2 733 000 000,00	Production + transport to port	BVG Associates
	Floater	kr 71 175 000,00	30		kr 2 135 250 000,00	Production + transport to port	Renewable energy
	Add lines here						
	Add lines here						
	Total wind tubrine cost				kr 4 868 250 000,00	kr 4 868 250 000,00	
	Mooring system	**Cost**	**Line length (m)**	**Number of components**	**Total cost**		
	Mooring lines	kr/m 5 180	1068	90	kr 497 901 600,00	Stud-less chain cost	NTNU Open
	Anchors	kr/anchor 800 800		90	kr 72 072 000,00	Drag embedded anchor cost	Carbon Thrust 2015
	Add lines here						
	Add lines here						
	Total mooring system cost				kr 569 973 600,00		
C1	**Total**				**kr 5 438 223 600,00**		
C2	**Electrical infrastructure**					**Comment**	**Source**
	Cable	**Cost (kr/m)**	**Length (m)**		**Total cost**		
	Dynamic cable and interconnector joint				kr 15 000 000,00	Production + transport to port	Axel
	Static cable	kr/m 9 490,00	m 60 000		kr 569 400 000,00	Production + transport to port.	Axel
	Land cable				kr 20 000 000,00	Production + transport to port	Axel
	Add lines here						
	Add lines here						
	Total cables cost				kr 604 400 000,00		
	Floating offshore substation				**Cost of component**		
	Topside offshore floating					Production + transport to port	
	Mooring offshore floating					Production + transport to port	
	Floater offshore floating					Production + transport to port	
	Add lines here						
	Add lines here						
	Total floating offshore substation cost				kr 1 430 000 000,00	kr 1 430 000 000,00	Axel
	Onshore substation cost				kr 0,00	Assumed to already exist in Haugesund area	
C2	**Total**				**kr 2 034 400 000,00**		

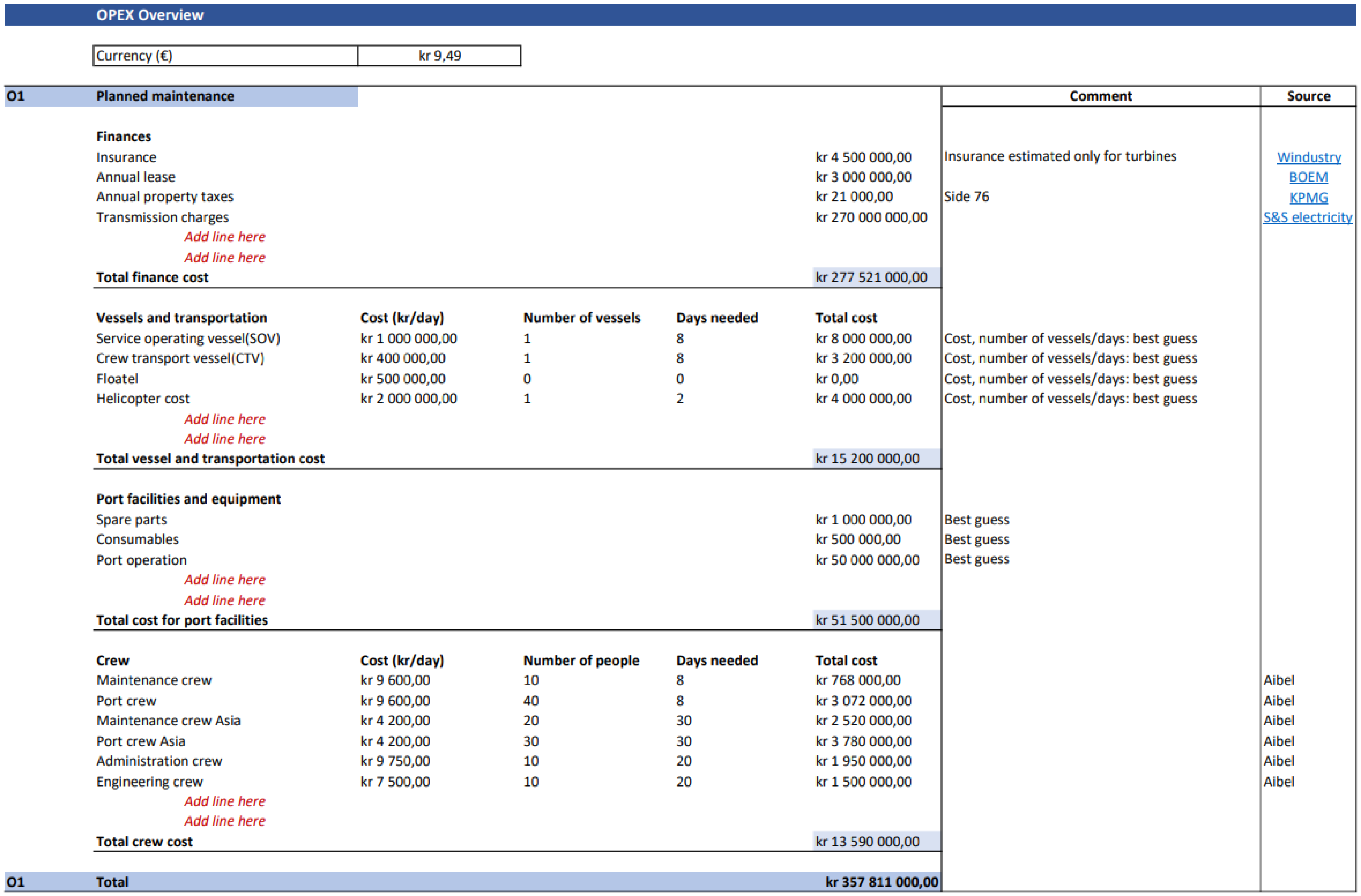


C3	Transport and installation					Comment	Source
	Vessels and transport	**Cost (kr/day)**	**Number of vessels**	**Number of days**	**Total cost**		
	Tug vessel	kr 213 525,00	6	250	kr 320 287 500,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Barge vessel	kr 332 150,00	1	40	kr 13 286 000,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Cable laying vessel array	kr 863 590,00	1	100	kr 86 359 000,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Cable laying vessel export	kr 1 081 860,00	1	50	kr 54 093 000,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Anchor handling vehicle	kr 464 061,00	1	60	kr 27 843 660,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Rock-dumping vessel	kr 130 962,00	1	180	kr 23 573 160,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Crane at port	kr 189 800,00	1	200	kr 37 960 000,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Floating crane without a storage area	kr 1 100 840,00	1	200	kr 220 168 000,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Floating crane wit a storage area	kr 7 704 931,00	1	100	kr 770 493 100,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Service operating vessel (SOV)	kr 263 603,73	4	50	kr 52 720 746,00	Cost, number of vessels/days: best guess	University Catalanya
	Crew transport vessel (CTV)	kr 37 505,00	4	250	kr 37 505 000,00	Cost, number of vessels/days: best guess	O&M report
	Floatel	kr 500 000,00	1	193	kr 96 500 000,00	Cost, number of vessels/days: best guess	
	Helicopter	kr 300 000,00	1	10	kr 3 000 000,00	Cost, number of vessels/days: best guess	
	Add lines here						
	Add lines here						
	Total vessel cost				kr 1 743 789 166,00		
	Crew	**Cost (kr/day)**	**Number of people**	**Days**	**Total cost**		
	Technician crew	kr 9 600,00	170	270	kr 440 640 000		Aibel
	Technician crew - Asia	kr 4 200,00	170	270	kr 192 780 000		Aibel
	Port crew	kr 9 600,00	90	270	kr 233 280 000		Aibel
	Port crew - Asia	kr 4 200,00	90	270	kr 102 060 000		Aibel
	Administration crew	kr 9 750,00	20	310	kr 60 450 000		Aibel
	Engineering crew	kr 7 500,00	30	310	kr 69 750 000		Aibel
	Add lines here						
	Add lines here						
	Total crew cost				kr 1 098 960 000,00		
	Other						
	Port operation				kr 50 000 000,00	Best guess	
	Insurance				kr 3 000 000,00	Best guess	
	Add lines here						
	Add lines here						
	Total other cost				kr 53 000 000,00		
C3	**Total**				**kr 2 895 749 166,00**	**kr 2 895 749 166,00**	

D1	Decommissioning		Comment	Source
	Offshore preparation			
	Vessel mobilisation and demobilisation			
	Disassembly			
	Foundation removal			
	Add lines here			
	Add lines here			
D1	**Total**	**kr 800 000 000,00**	Best guess	

C0	Project consent and development to FID	kr 399 176 000,00
C1	Wind turbine	kr 5 438 223 600,00
C2	Electrical infrasrtucture	kr 2 034 400 000,00
C3	Transport and installation	kr 2 895 749 166,00
C	**Capex total**	**kr 10 767 548 766,00**
D1	**Decex total**	**kr 800 000 000,00**

A.4 OPEX sheet



OPEX Overview

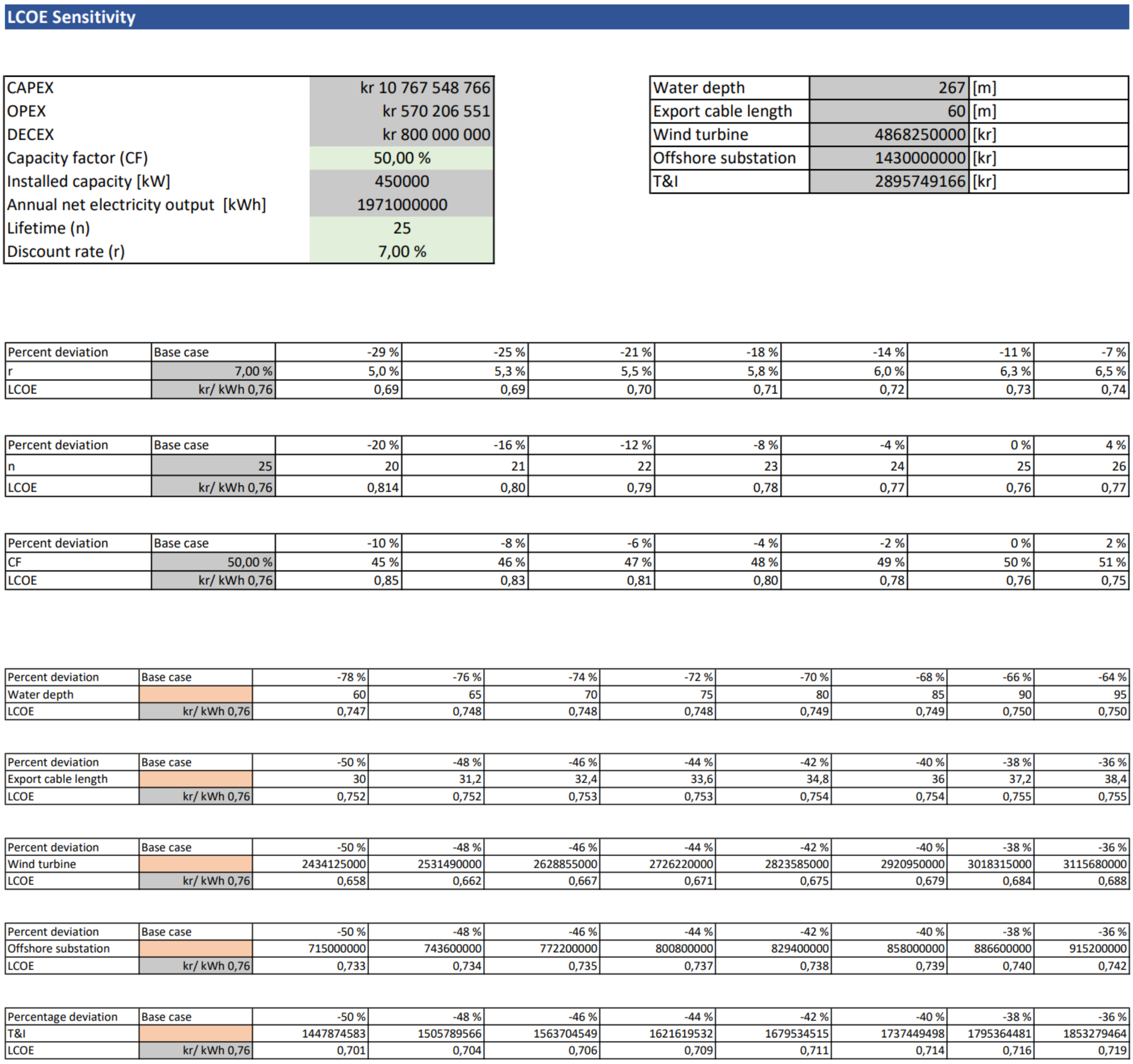
Currency (€)	kr 9,49

O1	**Planned maintenance**					**Comment**	**Source**
	Finances						
	Insurance				kr 4 500 000,00	Insurance estimated only for turbines	Windustry
	Annual lease				kr 3 000 000,00		BOEM
	Annual property taxes				kr 21 000,00	Side 76	KPMG
	Transmission charges				kr 270 000 000,00		S&S electricity
	Add line here						
	Add line here						
	Total finance cost				kr 277 521 000,00		
	Vessels and transportation	**Cost (kr/day)**	**Number of vessels**	**Days needed**	**Total cost**		
	Service operating vessel(SOV)	kr 1 000 000,00	1	8	kr 8 000 000,00	Cost, number of vessels/days: best guess	
	Crew transport vessel(CTV)	kr 400 000,00	1	8	kr 3 200 000,00	Cost, number of vessels/days: best guess	
	Floatel	kr 500 000,00	0	0	kr 0,00	Cost, number of vessels/days: best guess	
	Helicopter cost	kr 2 000 000,00	1	2	kr 4 000 000,00	Cost, number of vessels/days: best guess	
	Add line here						
	Add line here						
	Total vessel and transportation cost				kr 15 200 000,00		
	Port facilities and equipment						
	Spare parts				kr 1 000 000,00	Best guess	
	Consumables				kr 500 000,00	Best guess	
	Port operation				kr 50 000 000,00	Best guess	
	Add line here						
	Add line here						
	Total cost for port facilities				kr 51 500 000,00		
	Crew	**Cost (kr/day)**	**Number of people**	**Days needed**	**Total cost**		
	Maintenance crew	kr 9 600,00	10	8	kr 768 000,00		Aibel
	Port crew	kr 9 600,00	40	8	kr 3 072 000,00		Aibel
	Maintenance crew Asia	kr 4 200,00	20	30	kr 2 520 000,00		Aibel
	Port crew Asia	kr 4 200,00	30	30	kr 3 780 000,00		Aibel
	Administration crew	kr 9 750,00	10	20	kr 1 950 000,00		Aibel
	Engineering crew	kr 7 500,00	10	20	kr 1 500 000,00		Aibel
	Add line here						
	Add line here						
	Total crew cost				kr 13 590 000,00		
O1	**Total**				**kr 357 811 000,00**		

O2	**Corrective maintenance**					**Comment**	**Source**
	Port facilities and equipment						
	Material costs				kr 150 000 000,00	Best guess	
	Operation port				kr 50 000 000,00	Best guess	
	Add line here						
	Add line here						
	Total port facilities and equipment				kr 200 000 000,00		
	Vessels and transport	**Cost (kr/day)**	**Number of vessels**	**Days**	**Total costs**		
	Service operating vessel(SOV)	kr 100 000,00	2	8	kr 1 600 000,00	Cost, number of vessels/days: best guess	
	Crew transport vessel(CTV)	kr 40 000,00	2	8	kr 640 000,00	Cost, number of vessels/days: best guess	
	Floating crane without a storage area	kr 1 100 840,00	1	3	kr 3 302 520,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Floating crane wit a storage area	kr 7 704 931,00	1	1	kr 7 704 931,00	Cost: source, number of vessels/days: best guess	LCC FOWF
	Helicopter	kr 300 000,00	1	3	kr 900 000,00	Cost, number of vessels/days: best guess	
	Add line here						
	Add line here						
	Total vessel cost				kr 11 907 451,00		
	Crew	**Cost (kr/day)**	**Number of people**	**Days needed**	**Total cost**		
	Maintenance crew	kr 9 600,00	1	6	kr 57 600,00		Aibel
	Port crew	kr 9 600,00	1	19	kr 182 400,00		Aibel
	Maintenance crew Asia	kr 4 200,00	1	6	kr 25 200,00		Aibel
	Port crew Asia	kr 4 200,00	1	12	kr 50 400,00		Aibel
	Administration	kr 9 750,00	1	10	kr 97 500,00		Aibel
	Engineering crew	kr 7 500,00	1	10	kr 75 000,00		Aibel
	Add line here						
	Add line here						
	Total crew cost				kr 488 100,00		
O2	**Total**				**kr 212 395 551,00**		

O1	Planned maintenance	kr 357 811 000,00
O2	Corrective maintenance	kr 212 395 551,00
O	**Opex total**	**kr 570 206 551,00**

A.5 Sensitivity sheet



LCOE Sensitivity

CAPEX	kr 10 767 548 766
OPEX	kr 570 206 551
DECEX	kr 800 000 000
Capacity factor (CF)	50,00 %
Installed capacity [kW]	450000
Annual net electricity output [kWh]	1971000000
Lifetime (n)	25
Discount rate (r)	7,00 %

Water depth	267	[m]
Export cable length	60	[m]
Wind turbine	4868250000	[kr]
Offshore substation	1430000000	[kr]
T&I	2895749166	[kr]

Percent deviation	Base case	-29 %	-25 %	-21 %	-18 %	-14 %	-11 %	-7 %
r	7,00 %	5,0 %	5,3 %	5,5 %	5,8 %	6,0 %	6,3 %	6,5 %
LCOE	kr/ kWh 0,76	0,69	0,69	0,70	0,71	0,72	0,73	0,74

Percent deviation	Base case	-20 %	-16 %	-12 %	-8 %	-4 %	0 %	4 %
n	25	20	21	22	23	24	25	26
LCOE	kr/ kWh 0,76	0,814	0,80	0,79	0,78	0,77	0,76	0,77

Percent deviation	Base case	-10 %	-8 %	-6 %	-4 %	-2 %	0 %	2 %
CF	50,00 %	45 %	46 %	47 %	48 %	49 %	50 %	51 %
LCOE	kr/ kWh 0,76	0,85	0,83	0,81	0,80	0,78	0,76	0,75

Percent deviation	Base case	-78 %	-76 %	-74 %	-72 %	-70 %	-68 %	-66 %	-64 %
Water depth		60	65	70	75	80	85	90	95
LCOE	kr/ kWh 0,76	0,747	0,748	0,748	0,748	0,749	0,749	0,750	0,750

Percent deviation	Base case	-50 %	-48 %	-46 %	-44 %	-42 %	-40 %	-38 %	-36 %
Export cable length		30	31,2	32,4	33,6	34,8	36	37,2	38,4
LCOE	kr/ kWh 0,76	0,752	0,752	0,753	0,753	0,754	0,754	0,755	0,755

Percent deviation	Base case	-50 %	-48 %	-46 %	-44 %	-42 %	-40 %	-38 %	-36 %
Wind turbine		2434125000	2531490000	2628855000	2726220000	2823585000	2920950000	3018315000	3115680000
LCOE	kr/ kWh 0,76	0,658	0,662	0,667	0,671	0,675	0,679	0,684	0,688

Percent deviation	Base case	-50 %	-48 %	-46 %	-44 %	-42 %	-40 %	-38 %	-36 %
Offshore substation		715000000	743600000	772200000	800800000	829400000	858000000	886600000	915200000
LCOE	kr/ kWh 0,76	0,733	0,734	0,735	0,737	0,738	0,739	0,740	0,742

Percentage deviation	Base case	-50 %	-48 %	-46 %	-44 %	-42 %	-40 %	-38 %	-36 %
T&I		1447874583	1505789566	1563704549	1621619532	1679534515	1737449498	1795364481	1853279464
LCOE	kr/ kWh 0,76	0,701	0,704	0,706	0,709	0,711	0,714	0,716	0,719

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