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ABSTRACT

This thesis investigates capital expenditure in floating offshore wind projects by analysing the main capital expenditure drivers, their potential for reduction, estimate and event uncertainty, and requirements for commercially viable floating offshore wind projects. A literature study and an analysis of capital expenditure estimations have been performed.

The main capital expenditure drivers for floating offshore wind farms are the turbine, substructure, electrical infrastructure, and mooring. The substructure has the highest variability in capital expenditure per MW, while the turbine has the lowest. Important measures for reduction of capital expenditure are improved infrastructure, economies of scale and standardization. Potential capital expenditure reducing measures for each subcategory have been identified.

Estimate uncertainty is partly caused by a lack of historical data and a rapid developing technology together with long project duration. Much of the event uncertainty is caused by the uncertainty about the market for floating offshore wind and the development of supply chain. A need for regulations to accelerate development was expressed by the industry.

To achieve commercially viable floating offshore wind projects, investments in projects and innovations that reduce capital expenditure are needed. These investments are not likely to happen if the technology is not expected to become profitable in the foreseeable future. Therefore, subsidies can be a key measure to stimulate the development needed.

PREFACE

This master thesis was written as a final thesis for the master's programme Industrial Economics at the University of Stavanger.

We want to thank our supervisor Tone Bruvoll for guidance throughout the period. We would also like to thank Knut Vassbotn from Aker Solutions and Anniken Ringnes from Equinor for helpful insights and confirmations on the floating offshore wind market potential and technology. Furthermore, we want to thank Erik Rijkers at Quest Floating Wind Energy for answering questions and helping us with their database. Through working with this thesis, we have attained a thorough understanding of the floating offshore wind turbine technology and its potential, and we look forward to following the development of it.

Stavanger, June 2020

Morten Loug Hansen and Håkon Landa Austbø

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ABBREVIATIONS

Abbreviation	Explanation
AC/DC	Alternating current / Direct current
CAPEX	Capital expenditure
EPCI	Engineering, procurement, construction, installation
EU	European Union
FOW	Floating offshore wind
HVDC/HVAC	High voltage direct/alternating current
IQR	Interquartile range
IRENA	International renewables energy agency
kW/MW/GW	Kilo/Mega/Giga watt
LCOE	Levelized cost of energy
MBOE	Million barrels of oil equivalent
NREL	National renewable energy laboratory
OPEX	Operational expenditure
QFWE	Quest Floating Wind Energy
R&D	Research and development
TLP	Tension leg platform

1 INTRODUCTION

1.1 Background

In 1991 Denmark installed the first offshore wind farm, Vindeby, and since then the potential for offshore wind turbines to generate electrical energy has been studied. One of the requirements for profitable offshore bottom-fixed wind farms is shallow waters. The depth limit is estimated to be around 60 m, and areas deeper than this are economically unviable for bottom fixed wind farms. Simultaneously, most of the total wind power potential lies further ashore where depths go deeper [1]. This means that there is a large energy potential that has not yet been utilised, but this also comes with a set of challenges that must be overcome before floating offshore wind is possible from an economic standpoint.

Based on this potential, floating offshore wind turbines have been proposed as a potential solution. This solves the problem of water depths but introduces a new set of challenges that needs to be solved. How these problems are solved, together with the general problems wind farms are facing, affects profitability and whether it can become commercially viable. There are currently 16 announced floating wind farm projects that are either online, under development or planned. These fall into the categories of commercial or pre-commercial, which means they consist of more than one turbine. The only operational project of scale is Hywind Scotland which was developed by Equinor and commissioned in 2017 [2].

Floating wind is still in an infant stage and subsidized projects are required to reduce cost for developers and developing competence and experience from these novel projects. In this thesis the main capital expenditure categories have been identified and analysed to reveal the challenges and the potential of floating offshore wind farms.

1.2 Problem definition

Many countries have decided to reduce their CO_2 footprint and part of that effort is to reduce consumption of oil and gas. One of the most ambitious goals is held by the European Union (EU), which have decided to reduce EU's energy generation from non-renewable sources and become carbon neutral by 2050. This means that most of the energy generated by fossil fuels today needs to be phased out and replaced by energy generated from non-carbon sources [3]. Energy must therefore be generated through alternative sources, which without subsidies or CO_2 taxes must be able to compete with traditional energy sources on price and availability.

Floating offshore wind farms can be part of the solution, but the technology still needs developing. The projects that have been carried out so far are more expensive than alternative renewable energy solutions and rely on subsidies to be realised. Due to a small number of completed projects there is big underlying uncertainty. This is related to the lifetime cost of the technology, which leads to an uncertainty about the profitability of this technology on a commercial scale. Without large scale investments in floating offshore technology, supply chain and infrastructure are not built to the scale that is needed to bring unit cost down. Secondly, the benefits of economies of scale and the increased efficiency through learning by doing does not occur. This creates a paradox: to become profitable, investments are needed, but no one wants to invest in something that is not profitable.

1.3 Purpose

The purpose of this thesis is therefore to identify capital expenditure drivers and the possibility for capital expenditure reduction in each category. This is done to highlight the potential of the technology and identify where more research and development is needed. Another purpose is to identify the uncertainty related to floating offshore wind projects.

The research questions this thesis tries to answer are:

- What are the main capital expenditure drivers of floating offshore wind farms?
- What are the possible measures for reduction in each capital expenditure category?
- What is the estimate and event uncertainty for a floating offshore wind project?
- What is required to make floating offshore wind farms commercially viable?

Based on the results of these findings the authors hope to create an overview of the current market for floating offshore wind technology and its potential, and shine light on challenges that needs to be overcome to create a commercially viable industry that can produce energy at a competitive price.

1.4 Limitations

When answering this thesis some limitations have been made. Firstly, this thesis is limited to capital expenditure. Capital expenditure is an important part of the investment decission but does not provide the whole picture. To do so, development expenditure, operational expenditure, financial expenditure, decommissioning expenditure and earnings (amongst others) must be included. This thesis is limited to capital expenditure to limit the scope.

Secondly, few projects have been developed. At the time of writing only one pre-commercial floating offshore wind farm is operational with five wind turbines for a total capacity of 30 MW. The true cost of commercial scale floating offshore wind farms is therefore unknown and based on estimates. The costs of the different components are also difficult to obtain, due to confidentiality. Therefore, the available data is mostly based on estimates and the accuracy of these estimates is not possible to verify before the projects are completed.

2 MARKET OVERVIEW AND TECHNOLOGY

This chapter begins with a brief overview of the history of wind turbine technology and the cost development of onshore- and bottom-fixed wind farms. Then comes an overview of the floating offshore wind (FOW) market, and the projects that are online, in development and under planning. Next, the cost of FOW farms are compare to other energy sources and some of the benefits and challenges with FOW is presented. Lastly, the FOW turbine is divided into capital expenditure (capex) categories to give an overview of the current technology.

2.1 The history of wind power

The first wind turbine used for generating electricity was built in 1888, and from then small wind turbine were used to generate electricity for personal use. The first wind turbine was built by Charles Brush, with a rotor of 17 m and capacity of 12 kW [4]. From 1888 and until the oil crisis in 1973, the wind turbines were used for private electricity generation, mostly as a way to power farms, pumps and machinery that was located off grid, as well as an alternative to centrally-generated electricity. Little was done to increase scale or power due to cheap energy from other sources. This changed during the oil crisis of 1973, when the price of oil increased by nearly 400% from $3 a barrel to nearly $12 a barrel [5].

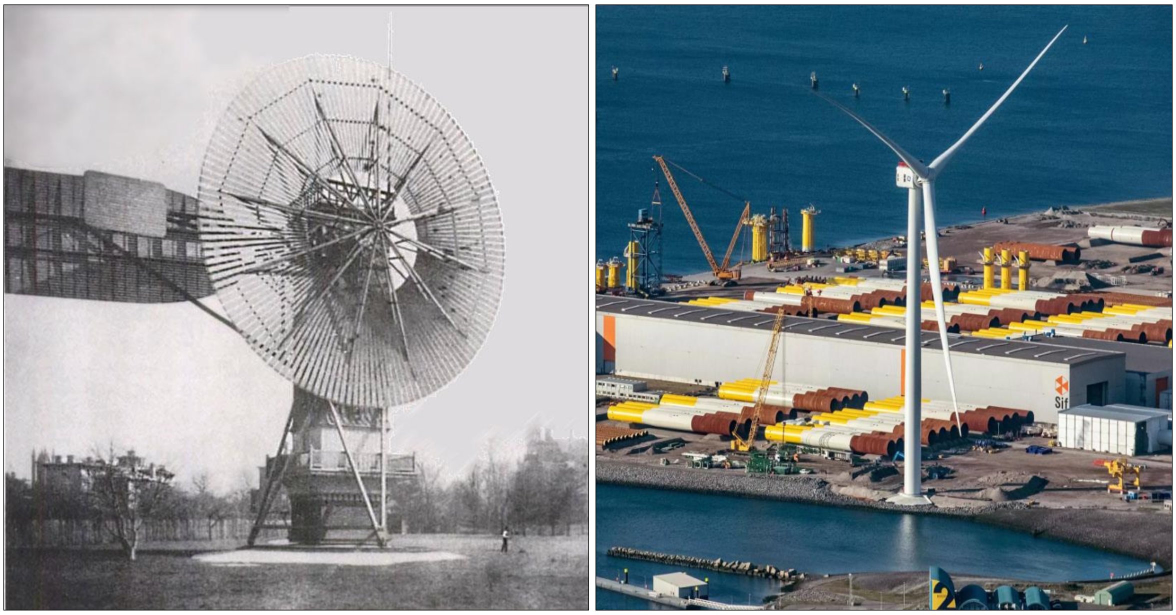

Figure 2.1 Left: The world's first wind turbine. 17 m rotor with a capacity of 12 kW built by Charles Brush in 1888 [5]. Right: Haliade-X, 220 m rotor with a capacity of 12 MW. Prototype in the port of Rotterdam [6].

The increase in oil price and the dependency on oil for energy lead to an increased incentive to develop alternative sources. Some of the important events that followed were:

1974 – The United States government initiates a program together with NASA to develop large commercial wind turbines. This program pioneered many of the technologies that are used in today's wind market, such as steel tube towers, variable speed generators and composite blade materials. One of the models developed was the MOD-5B, which at the time of completion in 1987, was the largest turbine in the world, with a rated power of 3,2 MW.

1978 – The world's first multi megawatt turbine was developed.

1980 – The first wind farm was completed and consisted of 20 turbines of 30 kW, with a total capacity of 600 kW [6].

1991 – The first offshore bottom-fixed wind farm was completed in Denmark, consisting of 11 wind turbines with a capacity of 450 kW.

2000 – The world's first commercial scale offshore wind farm, Middlegrunden, was constructed, consisting of 20 wind turbines of 2 MW each.

2009 – Equinor builds Hywind Demo, the first full-scale FOW turbine with a power capacity of 2,3 MW, utilising the spar buoy technique.

2011 – Principle Power's WindFloat prototype is commissioned in Portugal, utilising a semi-submersible substructure design with a 2 MW turbine, the first FOW turbine to be deployed without the use of offshore heavy lift vessels [7].

2014 – Over 240.000 wind turbines operate, producing 4% of the world's electricity, with a capacity of 336 GW [8].

2016 –In November, Vattenfall wins a contract for Danish Krieger Flak offshore wind project with a cost of €49,9/MWh.

2017 – EnBW and DONG Energy announces the first subsidy free bottom-fixed wind farm to be completed in 2025 [9].

2018 – GE reveals the 12 MW offshore wind turbine Haliade-X.

2020 – Siemens Gamesa launches a 14 MW offshore wind turbine. The first unit is expected to be installed in Denmark in 2021 [10].

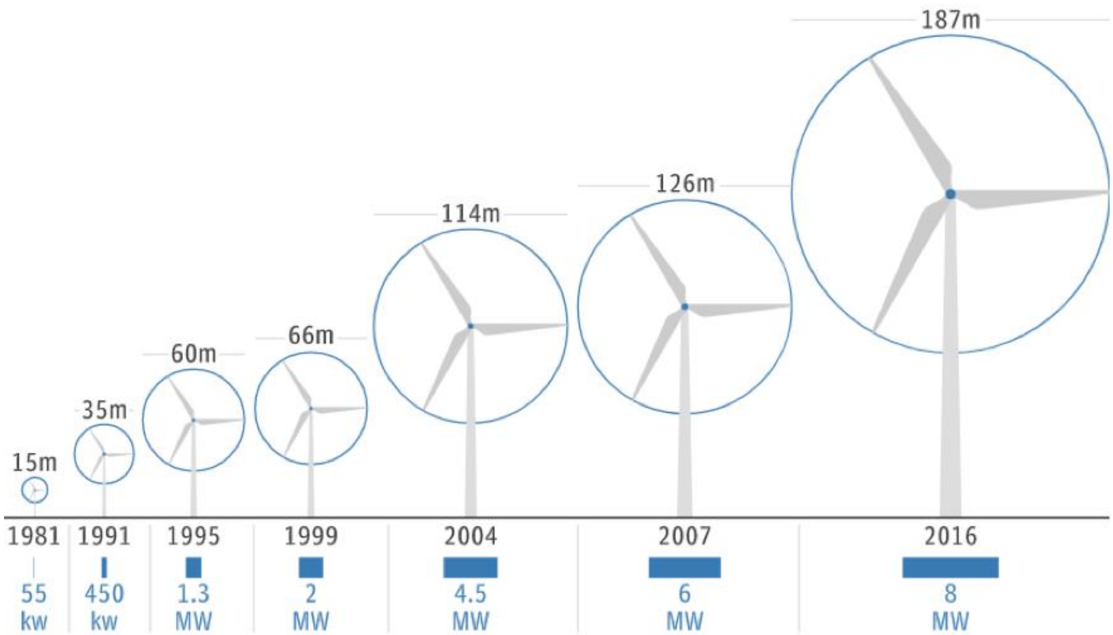

Figure 2.2 Evolution of wind turbine size and capacity [1].

The average operating turbine size increased from 4 MW to 4,8 MW over a four-year period between 2012 and 2016, with the largest turbine size increasing to 8 MW. The capacity of offshore wind turbines has increased by 62% over the past decade, and farm capacity has increased with 800% to an average of 379,5 MW in 2017. The largest offshore wind farm as of 2016 was Hornsea One with capacity of 1,2 GW. Offshore wind farms are moving further ashore, which is where the FOW turbine technology is introduced to solve the issue with increasing water depths [1]. The average rated capacity of offshore turbines installed in Europe in 2019 was 7,8 MW which is a 63% increase from the average in 2016. The average size of the wind farms has almost doubled and is now 621 MW. The cumulative power capacity in Europe in 2019 was 22.072 MW [11].

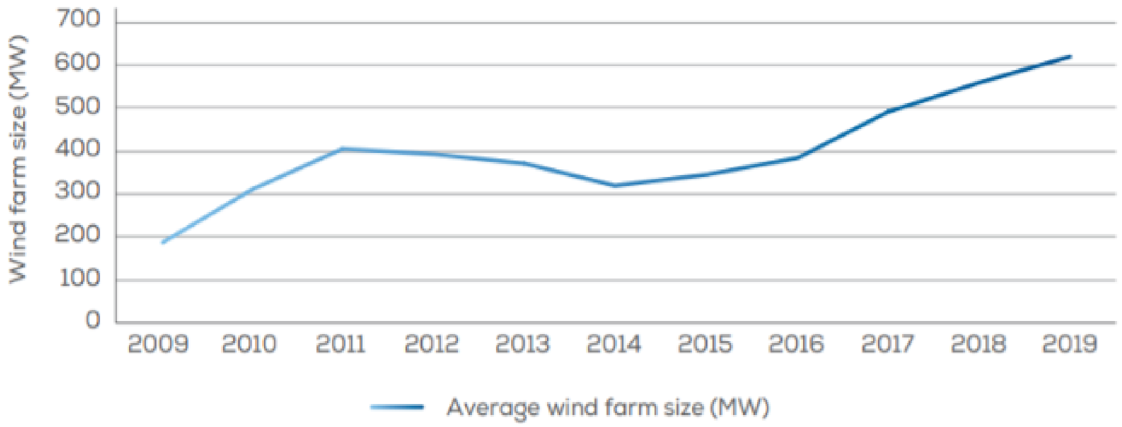

Figure 2.3 Average size of offshore wind farms each year [11].

2.2 Price development of onshore wind farms

Estimates show that levelized cost of energy (LCOE) dropped from \$150/MWh to around \$50/MWh between the 1980s and early 2000s for onshore wind farms as seen in figure 2.4 [12]. According to International Renewable Energy Agency (IRENA) the global weighted average LCOE for onshore wind projects commissioned in 2018 was \$56/MWh, which is a 35% reduction compared to 2010. This makes onshore wind competitive with the lower end of the fossil fuel cost range. The cost reduction is largely explained by a continuous reduction in installation cost, an increase in capacity factor and a more competitive global supply chain. In addition, IRENA's analysis found that some projects had an LCOE between \$30/MWh and

$40/MWh on sites with good wind conditions, which makes these projects cheaper than the cheapest fossil fuelled options [13].

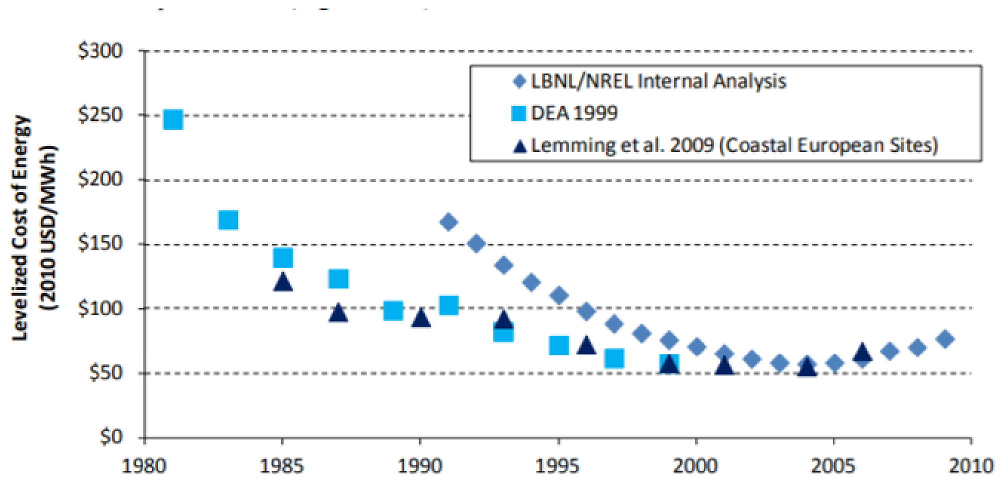

Figure 2.4 Estimated LCOE for onshore wind farms in the United states and Europe from 1980 to 2009 [12].

2.3 Cost estimates for bottom-fixed offshore wind farms

Estimates form a database by Quest Floating Wind Energy (QFWE) show LCOE development for bottom-fixed offshore wind farms. Although the LCOE varies between projects there is a downwards trend and the cost is expected to approach the cost observed in onshore wind farms. A study by IRENA found that total installed offshore capacity was 4,5 GW, and the global weighted average LCOE for offshore wind in 2018 was $127/MWh, which was 20% lower than the prices observed in 2010. The biggest contributors to cost reduction was found to be innovation in wind turbine technology, economies of scale and improved capacity factor due to higher hubs and larger rotor diameters. The cost reduction observed in offshore wind between 2010 and 2018 is smaller than the one observed for onshore wind, due to limited availability of shallow water sites, forcing new projects further into deeper waters. This increases cost and counteracts some of the progress made in other areas to reduce costs. The benefit of being located further from shore is often better and more stable wind conditions, which resulted in an increase in weighted average capacity factor from 38% in 2010 to 43% in 2018 [13].

2.4 Current floating offshore wind market

In 2019, total installed wind power capacity in Europe was 205 GW, where 183 GW were generated from onshore windfarms and 22 GW from offshore bottom-fixed windfarms, with 0,045 GW (45 MW) from FOW turbines. The 22 GW of offshore wind capacity is enough to power 2,3% of the EU's electricity demand. The average capacity factor was 24% for onshore turbines and 38% for offshore turbines [11]. According to Equinor's market outlook FOW farms could have a combined capacity of up to 12 GW in 2030, which is equivalent to a little more than half of the offshore capacity installed today. This would mean, assuming that EUs energy need is equal to that of today, that 1,25% of EUs electricity is created from FOW turbines in 2030 [14].

The trend in FOW farms is the same as for bottom-fixed wind farms which is an increase in turbine capacity, and as seen from table 2.1 the online projects have smaller capacity than those who are planned for upcoming years, listed in table 2.2. By 2022, France is holding auctions for three FOW farms, each with a capacity of 250 MW. The target price of these farms is €120/MWh for the first park and € 110/MWh for the other two [11]. The cost for the pre-commercial projects online in Europe today is estimated to be between € 180-200/MWh [15].

The projects online today and those with planned completion in Europe before 2022 are pre-commercial projects. These projects are built to demonstrate their viability, study their performance in real life scenarios and develop a knowledge base through learning by doing.

Table 2.1 Online FOW projects [11].

Country	Project	Capacity (MW)	Year online
Norway	Hywind Demo	2,3	2009
Portugal	WindFloat	2	2011
UK	Hywind Scotland	30	2017
France	FloatGen	2	2018
UK	Kinkardine pilot	2	2018
Portugal	WindFloat Atlantic phase 1	25	2019

Table 2.2 lists the projects from the QFWE database, where some are under development and other are planned. The first four projects in the table are pre-commercial projects. From 2023 the capacity of the wind farms is approaching the capacity estimated to be necessary for commercially viable projects. This was further confirmed by conversations with experts within the field, where increase in turbine capacity, and increasing farm capacity to around 500 MW were identified as important factors towards achieving profitable FOW farms [16].

Table 2.2 FOW projects in the QFWE database.

Project	Country	Capacity (MW)	Year of completion
Kinkardine Tranche 2	UK	47,5	2020
Toda Sakiyama	Japan	20	2022
Hywind Tampen	Norway	88	2022
Lake Erie	USA	30	2023
W 1 N - Taouyuan	Taiwan	500	2023
Donghae 1	South Korea	200	2024
Hywind Scotland II	UK	250	2024
Donghae TwinWind	South Korea	200	2024
KFWind	South Korea	503,5	2024
Plambeck Floating Windfarm	Saudi Arabia	500	2025
Progression South	USA	598,5	2025
Humboldt Bay (Redwood)	USA	150	2026
Grey Whale	South Korea	200	2026
White Heron	South Korea	200	2026
Castle Wind	USA	1000	2028

2.5 Floating offshore wind compared to other energy technologies

The most important criteria for an energy technology, apart from practical possibility, is the LCOE. Table 2.3 gives an overview of the global weighted-average cost of electricity, the cost of electricity of the 5th and 95th percentiles (sorted by cost) and the change in the cost of electricity from 2017 to 2018 for various renewable energy technologies.

Table 2.3 Cost of various energy technologies [13].

	Global weighted-average cost of electricity (USD/MWh) 2018	**Cost of electricity: 5th and 95th percentiles (USD/MWh) 2018**	**Change in the cost of electricity 2017-2018**
Hydro	47	30-136	-11%
Onshore wind	56	44-100	-13%
Bioenergy	62	48-243	-14%
Geothermal	72	60-143	-1%
Solar photovoltaics	85	58-219	-13%
Offshore wind	127	102-198	-1%
Concentrating solar	185	109-272	-26%

Of the seven technologies, offshore bottom-fixed wind has the second highest global weighted-average cost of electricity, \$127/MWh. For FOW there are no precise data for the cost of the electricity. Cost from pilot projects are not comparable as they have not benefited from economies of scale. However, various experts have made predictions of LCOE for FOW farms. Investment bank HSBC estimates an LCOE of €120/MWh by 2025[11, 17].

2.6 Benefits and challenges with floating offshore wind

There are many advantages to FOW that makes it an alternative to onshore and bottom-fixed wind farms. Wind is stronger and more consistent further out to sea, which means that the turbines potentially can generate more energy at a more consistent rate than its onshore counterparts, increasing its capacity factor.

Bottom-fixed turbines are limited to depth of maximum 60 m to be economically viable. FOW turbines are not restricted to certain water depths like bottom-fixed turbines and can therefore be placed where wind conditions are best. Equinor estimates that 80% of the worlds offshore wind resource potential is located where water depths exceed 60 m [18]. Another benefit with placing the wind farms far from shore is that it is less intrusive to people and animals, and thus more likely to generate public support. It can also be less intrusive to ship traffic.

Since FOW turbines can be assembled at port and then towed to site, it is possible to assemble FOW turbines without heavy lift vessels, reducing the installation cost compared to bottom-fixed wind farms. Carbon Trust estimates that the capacity of delivering 50-100 turbines in a single summer campaign is necessary to make the technology cost competitive. To achieve this, port facilities need to be upgraded and expanded. It was further shown that turbine assembly and integration is a key cost driver. Some important priority needs identified was looking at feasibility of heavy offshore lift operations compared to tow to port maintenance jobs and develop efficient and cost-effective turbine integration procedures together with serial production methods for floating wind structures [19].

2.7 Components of a floating offshore wind farm

This chapter presents an overview of some of the biggest capex categories present in an FOW farm. The categories are turbine, substructure, mooring and electrical infrastructure.

2.7.1 Turbine

Wind turbines can be considered inverse fans: instead of consuming electricity to produces wind, it uses wind to produce electricity by converting kinetic energy to electrical energy. The kinetic energy turns the rotor of the turbine, which in turn makes a horizontal shaft run a generator, where the mechanical energy is converted into electrical energy. This is the concept of wind power in its most basic form. Other essential components include a gear system, the tower, the substructure, and the electrical infrastructure.

Wind's kinetic energy

The power of the wind that flows through a wind turbine can be calculated using the following formula:

$$P = \frac{1}{2} A \rho U^3 \tag{1}$$

Where P is power, A is the area of the turbine, ρ is the density of the air and U is the speed of the wind. As seen by the formula, power is proportional of the wind speed cubed. Precise data of the wind speeds at any potential wind farm site is therefore essential to make good estimates of the power production.

A wind turbine cannot harness 100% of the wind's energy. To calculate the maximum power a wind turbine can harness from wind, a highly idealized analysis must be done, including simplifications such as an infinite bladed rotor and ideal, uniform airflow. Despite simplifications, the estimate of the output is sufficient to gain an understanding of the principles of wind turbines.

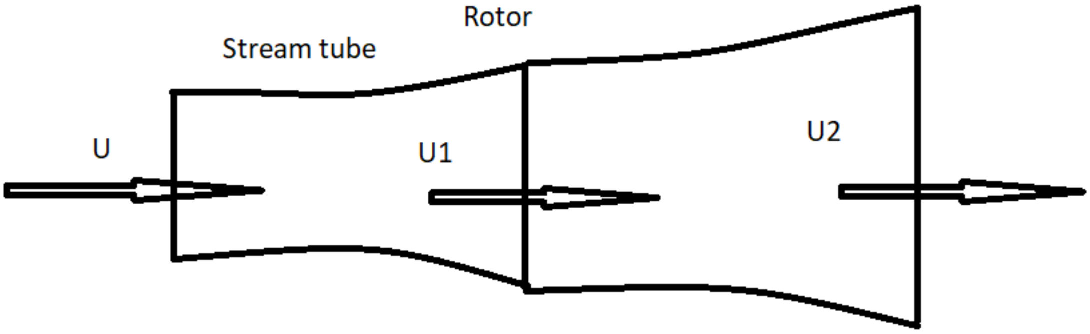

Figure 2.5 Airflow along rotor blade.

Figure 2.5 shows how wind flows through the rotor (shown in profile). The wind has an initial velocity, U, which is reduced to U1 as it flows through the rotor. As the speed is reduced, the volume of the air increases. This process is repeated after the rotor, reducing the velocity of the wind further, as well as air volume expanding to allow continued flow.

For the wind velocity to be reduced from U to U1 and U2, a force must work on it. This stems from the principle of conservation of linear momentum. The force on the wind is equal to and opposite the thrust, T, which is the force from the wind on the turbine. This stems from

Newton's third law. The change in momentum can be found by investigating the different velocities of the wind:

$$T = \frac{dm}{dt} * (U - U_2) = U(\rho AU) - U_2(\rho AU)_2 = \frac{1}{2}\rho A(U^2 - U_2^2) \quad \textbf{(2)}$$

Further algebra shows that the power extracted from the air is

$$P = \frac{1}{2}A\rho U^3 4a(1 - a)^2 \quad \textbf{(3)}$$

Where a new value, the axial induction factor *a*, has been defined as

$$a = \frac{(U - U_1)}{U} \quad \textbf{(4)}$$

The fractional decrease in the wind velocity once it has reached the rotor, due to a change in pressure.

From the axial induction factor *a*, the ratio of the power in the rotor to the power in the wind can be found. This ratio is known as the "performance power coefficient", C_p:

$$C_p = 4a(1 - a)^2 \quad \textbf{(5)}$$

This factor only accounts for the wind, and does not consider power drops from other sources, such as mechanical and electrical.

The maximum Cp can be found by taking the derivative of the power coefficient with respect to *a* and setting it equal to zero. Doing so will result in a factor *a* of 1/3. An *a* of 1/3 results in a C_p of 16/27, or approximately 59%. This was first found by physicist Albert Betz and is known as Betz' law: the maximum amount of power that can be extracted from the wind through a wind turbine is 16/27 of the kinetic power. As mentioned above, this does not account for power drops from mechanics, electronics, blades, and the wake effect, and is a theoretical maximal output.

To get as close as possible to the 59% stated by Betz' law, one must optimize the turbine to the highest possible degree. Since a solid rotor is not possible, a turbine with three rotor blades is the most common solution. This is a compromise between cost and practicality. More than three blades will return more power, but the additional cost has been shown not to be worth the extra power output. One or two blades is cheaper than three but is worse for symmetry and balancing of the turbine, as well as power output [20].

Blades

When the optimal number of blades is chosen, the shape of the blades needs to be optimized. To harness the kinetic energy in the wind the blades uses lift. The concept of lift is based on angling the blade so that the wind that passes on the upper side moves more quickly than on the lower side. When this occurs, the pressure on the upper side is lower than on the underside, which in turn lifts the blade upwards. As winds have unstable flow, both in terms of acceleration and velocity, the angle of the blade can be changed. This is done to keep the wind's angle of attack constant, which gives a more stable electricity production. The angle of attack can be changed either by "stall-controlled" or "pitch-controlled" blades [20].

Drivetrain

According to Nejad, "*the drivetrain is the heart of the wind turbine*" [21], because the drivetrain converts kinetic energy into electrical power. The drivetrain is a system that consist of all components necessary to convert the energy, including the main shaft, the gearbox and the generator.

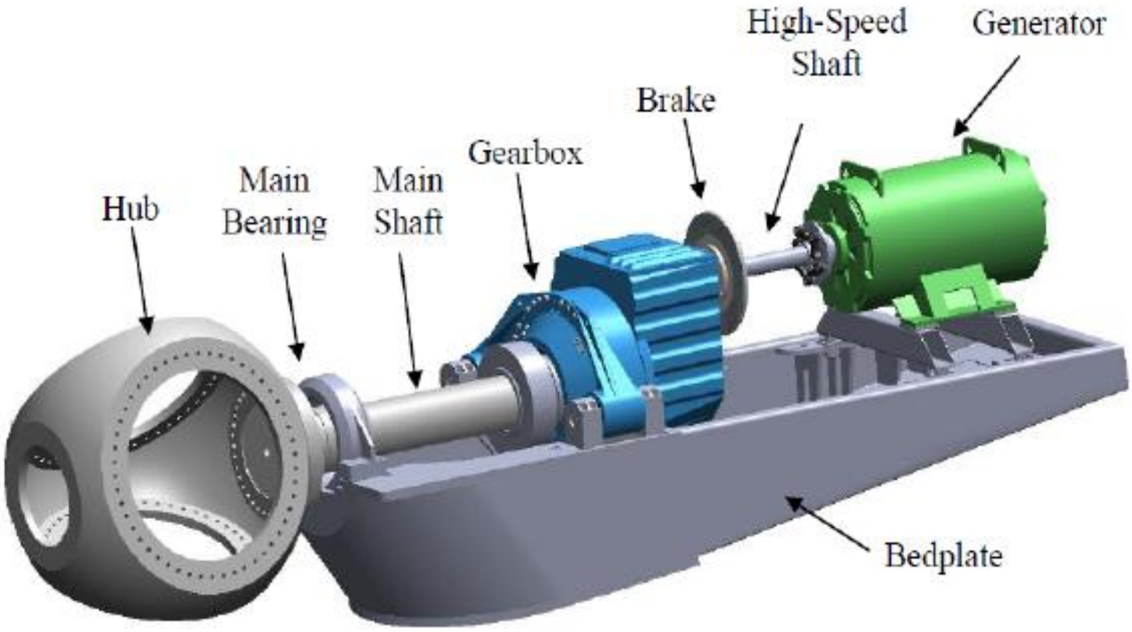

Figure 2.6 Drivetrain configuration for a wind turbine [22].

The most used drivetrains in wind turbines use gears. The gears are used to increase the number of rotations from the slow shaft to the fast shaft, to fit the high-speed generator. The main advantages of high-speed gearboxes are that it is a proven technology with a developed supply chain and good operational availability. The many components of a high-speed gearbox lead to a longer downtime when it has a fault compared to a gear-less drivetrain. In a gear-less drivetrain, the generator is directly driven by the turbine at the same rotation speed. This is compensated with a higher number of poles. The disadvantage of a gear-less system is a higher weight. According to Tavner the gearbox is the sixth most unreliable component in a wind turbine [23]. Despite this, it is one of the main sources for downtime. This is because when the drivetrain fails, it is difficult and time consuming to repair [21].

2.7.2 Substructure

The substructure's function is to keep the wind turbine floating, and together with the mooring system keep the turbine balanced and in place. Therefore, turbines will have different requirements mainly based on size and weight, but also wind and ocean conditions. The weight of the nacelle and the rotor has the highest impact as these are located at the top of the turbine and therefore generates the highest momentum once it is misaligned with centre of gravity. These forces need to be compensated for by the floating substructure. Wind and wave forces will act on the turbine, and depending on the direction cause roll, yaw or pitch motions as seen in figure 2.7.

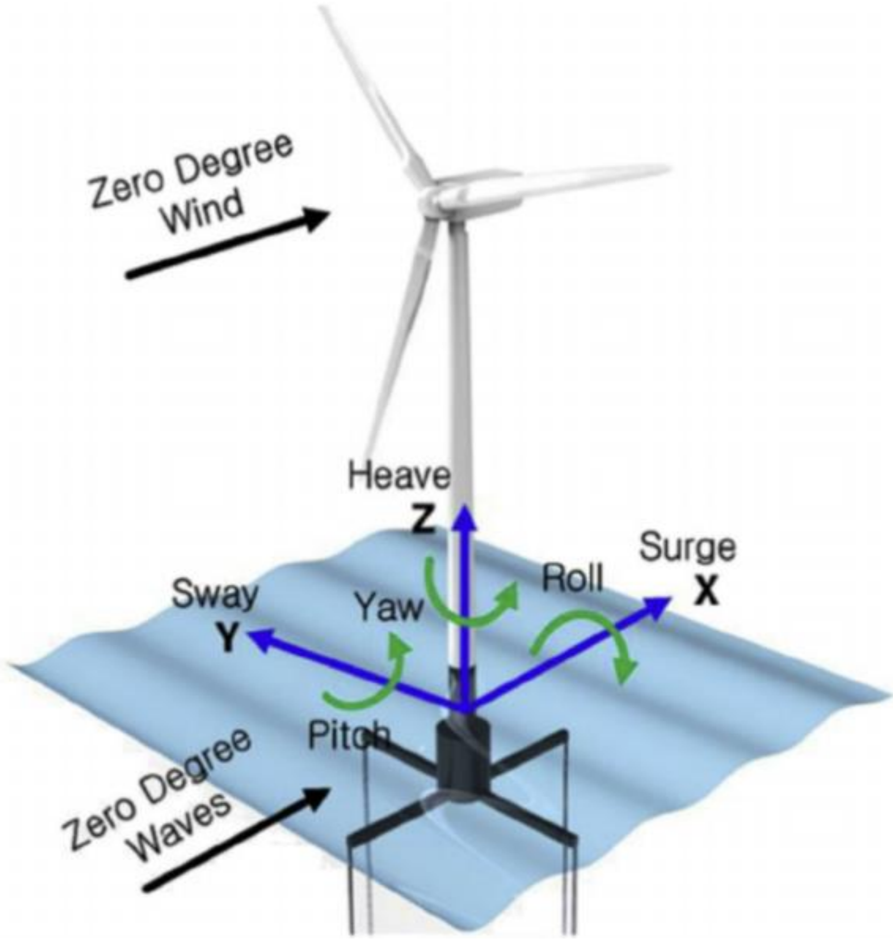

Figure 2.7 Degrees of freedom for an FOW turbine [24].

The four main categories of substructures are tension leg platform (TLP), spar, semi-submersible and barge. These four have different strengths and weaknesses and have all showed potential as a future design for commercial scale FOW farms. Many different designs exist, and some combine design elements from multiple categories. Figure 2.8 shows examples of each of the four substructure designs. BVG Associates analysed different substructure designs and concluded: “It is unlikely that any single floating foundation design concept will achieve market dominance. Instead a range of technology solutions will be deployed according to different site conditions, also influenced by local infrastructure and supply chain capabilities” [25].

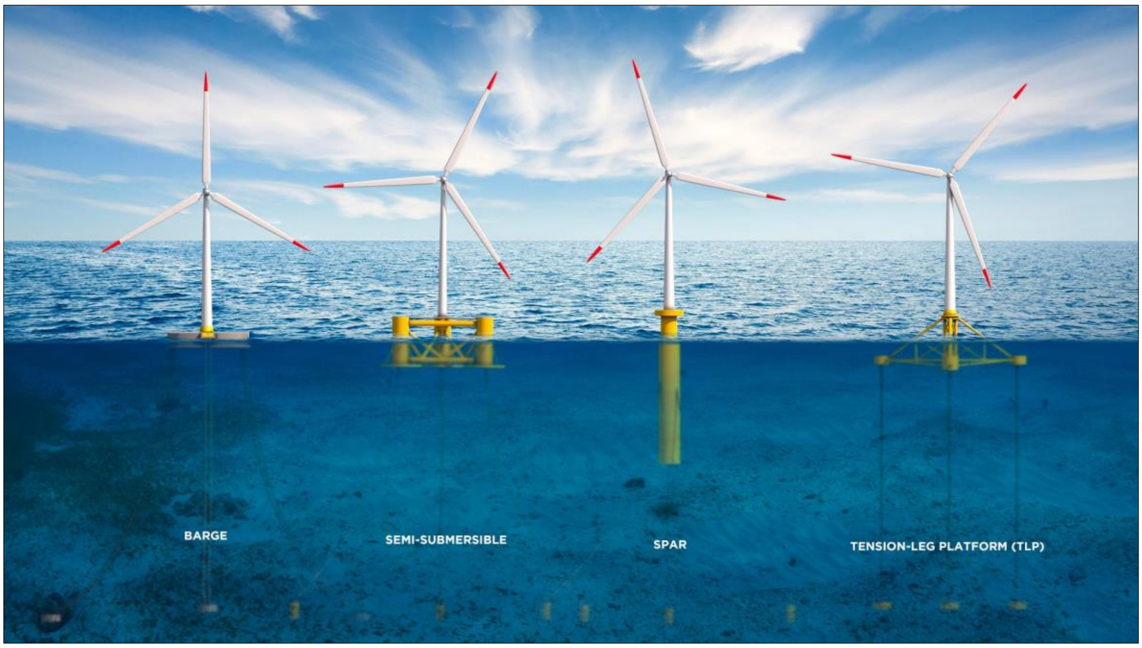

Figure 2.8 The four main floating substructure designs [26].

Tension leg platform

The tension leg platform (TLP) design has a large centre column which spreads out under the surface to several arms, usually three or four. These arms are connected to the mooring lines which are anchored to the seabed and are in a state of tension between the buoyancy of the wind turbine and the seabed anchors. Since the forces from the tension cables help keep the wind turbine stable, there are less requirements to the design and stability requirements of the substructure. This results in a simple design with low weight and small draft. Since the TLP is not stable without the tension cables, transporting the fully assembled wind turbine to location requires special vessels or special buoyance elements for towing. The TLP design leaves a small seabed footprint as the cables are anchored perpendicular to the seabed just below the substructure.

The trade-off between a structure with lower material requirements, and therefore lower weight and smaller cost, is greater operational risk as there is a possibility of total loss of the turbine if the mooring system fails [27]. The TLP design is the least developed of the four designs and is currently still in the developing phases as no full-scale unit have been built. An example of the TLP system is the GICON, by GICON GmbH. Their focus is to develop a modular substructure that can be assembled at most dry docs near installation site. The GICON design can be seen in figure 2.11.

Spar

The spar buoy design is a structure consisting of steel or concrete which stabilises itself by weight-buoyancy. This is achieved by designing the substructure as a deep column going down to a ballast which counteracts the forces from the turbine above sea level. This is because the centre of gravity is below the centre of buoyancy. The design is simple and uses a proven technology. The spar is moored to the seabed by chain, steel cable or fibre rope. Due to its inherently stable design (high inertia resistance) there are less requirements to the mooring and anchoring system compared to a TLP substructure.

The challenge of the spar buoy design is the large draft. This limits the areas where it can be used, ports where it can be assembled, and transport route. Alternatively, the spar can be transported horizontally but this will require additional crane vessels to lift the turbine in place [27].

The spar design that has reached the highest level of maturity is the Hywind concept developed by Equinor. A full-scale prototype was installed in 2009 outside of Karmøy, Norway. In October 2017, Hywind Scotland the world’s first pre-commercial offshore floating windfarm was commissioned, consisting of five turbines of 6 MW [3]. Equinor’s arguments for choosing the spar buoy design over the alternatives are: ”Most proven technology, conventional technology used in a new way, simple substructure construction with potential for standardisation and lower fabrication cost, beneficial motion characteristics, robust and suitable for harsh conditions and data and experience collected from ten years of successful operations" [18].

Figure 2.9 Transportation of a spar substructure used for Hywind Scotland [28].

Semi-submersible

The semi-submersible structure is a low draft structure that self-balances, which makes it versatile in terms of location and soil conditions. The minimum required water depth is around 10m. The design generally consists of several columns with ballast used for stabilization and buoyancy. The design requires a lot of material and if made in steel, multiple welds for connecting the subassemblies. The additional material and work hours required means that this is usually the most expensive of the four concepts. The semi-submersible experiences high wake motion in rough seas [27].

Figure 2.10 Loading of WindFloat semi-submersible substructure. July 2019 [29].

Barge

Barges are the substructures with the least draft, which make them easier to construct and assemble at existing ports. As a result of the low draft, the barge concept will be impacted more by the motion of waves compared to the other concepts. A method for reducing some of the motion is to design it with a moonpool, which will have dampening effect. An example of this design can be seen in figure 2.11, showing Ideol’s design. This design is also planned to be used for a commercial scale farm in Japan in 2023 [19].

The four design categories described above are simplifications of the different substructure concepts that have been proposed by various companies, research groups and universities. Within these groups there are different solutions and different materials are being utilized. This results in a lot of concepts with overlaps in design and function. Some of the design uses principles of two or more of the categories mentioned above like Flowocean which incorporates design elements from both TLP and semi-submersible design [30].

Table 2.4 Strengths and weaknesses of the four substructure designs [31].

Design	Companies/Designs	Strength	Weakness
Spar buoy	Equinor Hywind DeepWind SeaTwirl Windcrete	High inertia, tendency for less wave induced motion. Simple design. Lower mooring cost. Uses proven technology.	Fewer available sites due to deep draft. Requires deep ports for assembly or transporting sideways and assembled at site.
Semi-submersible	Principle Power (WindFloat) Fukushima Forward Hexicon	Low draft. Self-balancing. Fewer requirements for soil conditions.	Much material is required. Potential for higher wave critical wave motion. Complex construction compared to other solutions.
Tension leg platform (TLP)	GICON Glosten Associates (Pelastar)	Less material required. Low draft. Low mass. Assemble in dry dock or onshore.	Not self-balancing. Higher requirements to keep stable during transport. Higher mooring and anchoring costs. Higher requirements to mooring. Higher risk for loosing turbine in case of compromise of mooring lines or anchors.
Barge	Ideol – Floatgen	Lowest draft compared to other three designs. Same strengths as semi-submersible.	Large wave motions. Many of the same weaknesses as semi-submersible.

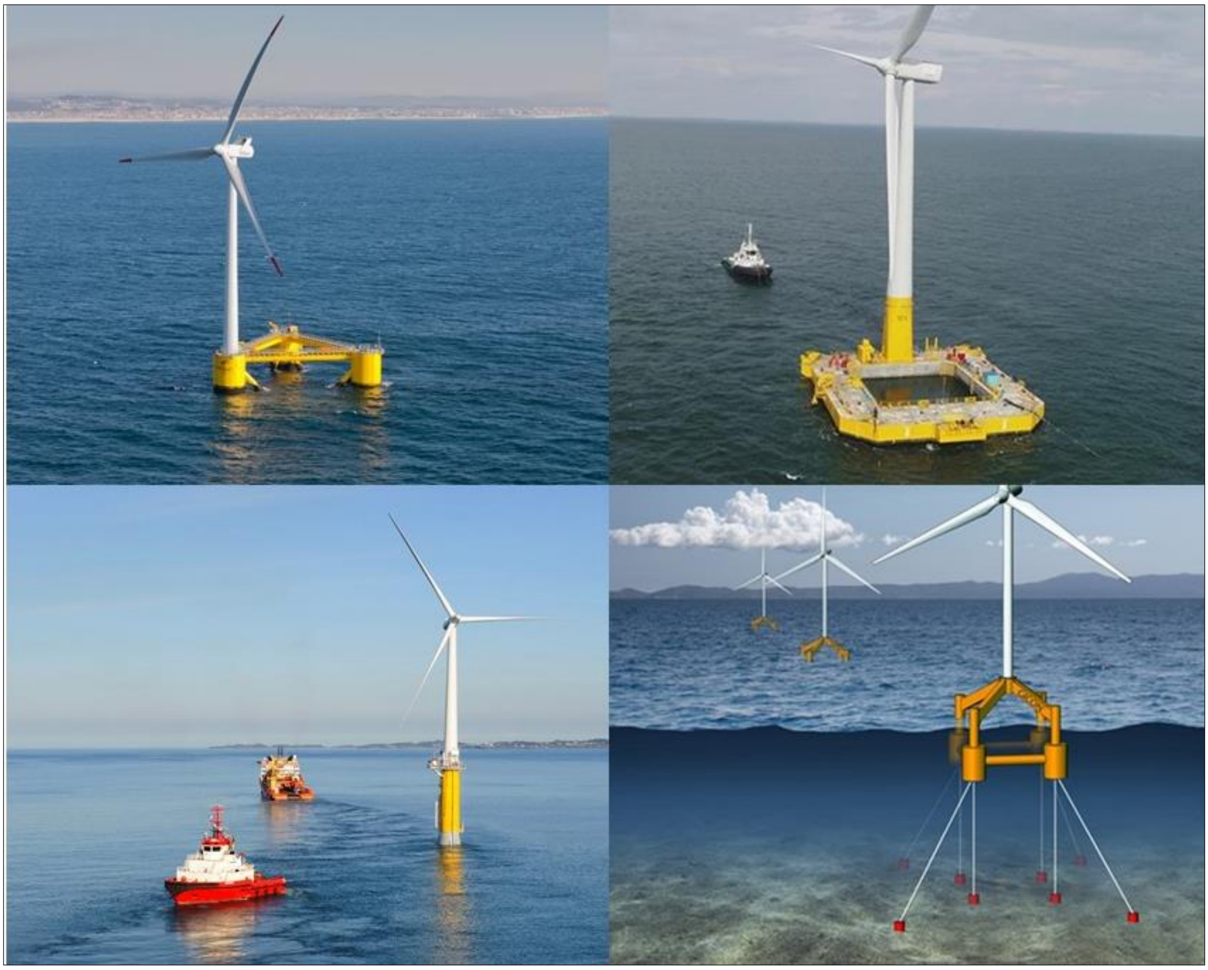

Figure 2.11 The most mature substructure solutions from each category. Top left: Principle Powers WindFloat [29]. Top right: Ideols barge [32]. Bottom left: Equinors Hywind spar [33]. Bottom right: Gicons tension leg platform [34].

2.7.3 Mooring

FOW turbines need to be anchored to the ocean floor to stay in position. There are three main mooring categories: Catenary mooring, vertical mooring, and taunt leg mooring. The categories are illustrated in figure 2.13. Catenary is the most proven method and is commonly used for FOW turbines with spar or semi-submersible substructures. Taunt leg mooring can withstand both horizontal and vertical forces, and the same for vertical mooring system, but to a lesser extent. The anchor points of the catenary mooring method only experience horizontal forces, as the lines are usually attached with clump weight or buoyancy elements to generate vertical forces to create system stiffness. Vertical mooring is used for FOW turbines with a TLP substructure. The catenary method uses far more line than the vertical mooring technique and has a bigger footprint [35].

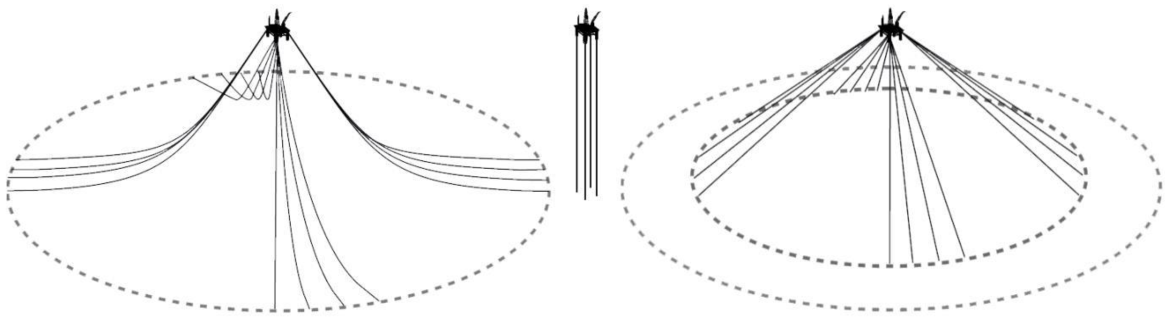

Figure 2.12 Different mooring systems. From left to right: Catenary, vertical and taunt leg [35].

Anchors

Based on mooring system and seafloor conditions, a variety of anchors are available. For the catenary mooring system, drag embedment anchors are commonly used, as these are design to hold large horizontal loads. Another anchor design is the suction pile anchor which is a large hollow cylinder which is forced into the soil. The friction of the soil makes this anchor well suited to withstand both vertical and horizontal forces, but it requires suitable soil conditions. These anchors can be used with the vertical mooring system. For the taunt leg mooring system, where the lines arrive at a 45° angle a vertical load anchor is suitable, this is an anchor that is installed deeper than the drag embedment anchor, and is therefore better at withstanding vertical forces [35].

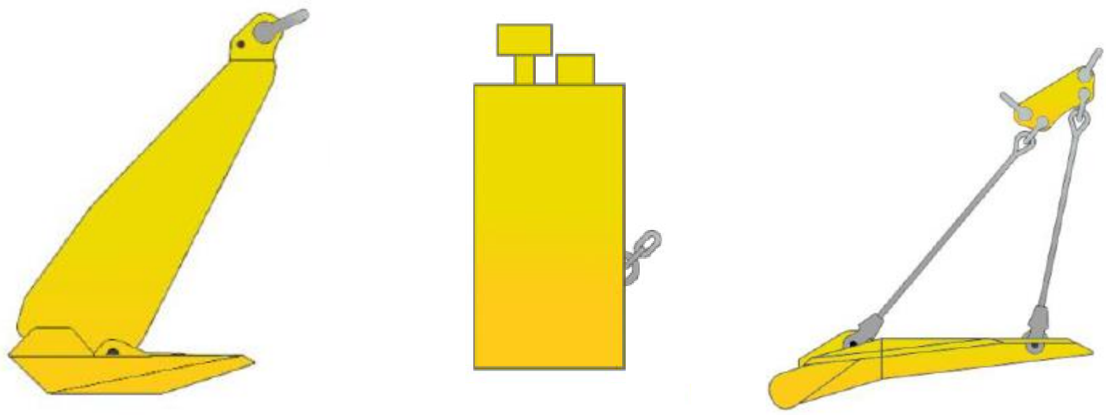

Figure 2.13 Anchors. From left to right: Drag embedment anchor, Suction pile anchor, Vertical load anchor [35].

Table 2.5 Pros and cons of different anchor technologies. Adapted from [36].

Anchor type	**Pros**	**Cons**
Drag Embedment Anchor	Proven technology. Well suited to resist large horizontal loads. Easy to retrieve.	Difficult to position exactly. Not as well suited for vertical loads.
Suction Pile Anchor	Exact anchor position. High holding power in right soil condition. Multiple lines for one anchor is possible. Can withstand both vertical and horizontal loads.	More costly to install compared to drag embedment anchor. Requires large vessel for installation and more equipment.
Vertical Load Anchor	Proven technology used for drilling rigs. Can withstand both vertical and horizontal loads	Exact anchor position is difficult to guarantee.

Mooring Lines

The mooring lines connect the anchors to the substructure. The three main categories for mooring lines are chain, wire rope and synthetic fibre rope. The synthetic lines are usually made from polyester or polyethylene, and the chain and wire ropes from steel. The choice of mooring line depends on multiple characteristic such as ocean depth, mooring system, excited loads, and motion characteristics of the substructure. Besides these categories, a mixed type mooring line is possible, for instance the part of the line which comes in contact with the seafloor is steel chain and the rest is synthetic fibre rope. This would increase resistance to wear and tear from contact with the seafloor and be lighter than an only chain mooring line, but come with increased complexity in the form of additional subsea activities during installation and connector devices [36].

Table 2.6 Pros and cons of different mooring lines. Adapted from [36].

Mooring line	**Pros**	**Cons**
Steel Wire Rope	Easy to install. Limited weight.	Reduced wear and tear resistance from contact with seafloor. Prone to material fatigue.
Steel Chain	Easy to install. Can withstand long term contact with seabed.	Heavy. Will not penetrate deep into soil.
Synthetic Fibre Rope	Easy to install. Low weight. No connection between different materials.	No resistance against wear and tear from contact with seafloor.

2.7.4 Electrical infrastructure

An FOW farm needs electrical infrastructure to transfer electrical energy from the farm to a grid. There are three main parts of the electrical infrastructure:

i) The array cables - Connects the turbines and collects electrical power from them. The array cables are also called "the collectors". The array cables typically have alternating current at 33 kV from the turbines.
ii) The substation - The array cables lead the power to the substation, where there are transformers increasing voltage. For FOW farms far from shore, the substations will convert the current from alternating to direct to reduce power losses during transmission.
iii) The transmission system - The transmission system consists of an external cable which is connected to the substation(s), transmitting the high voltage current to shore, where it is distributed to consumers.

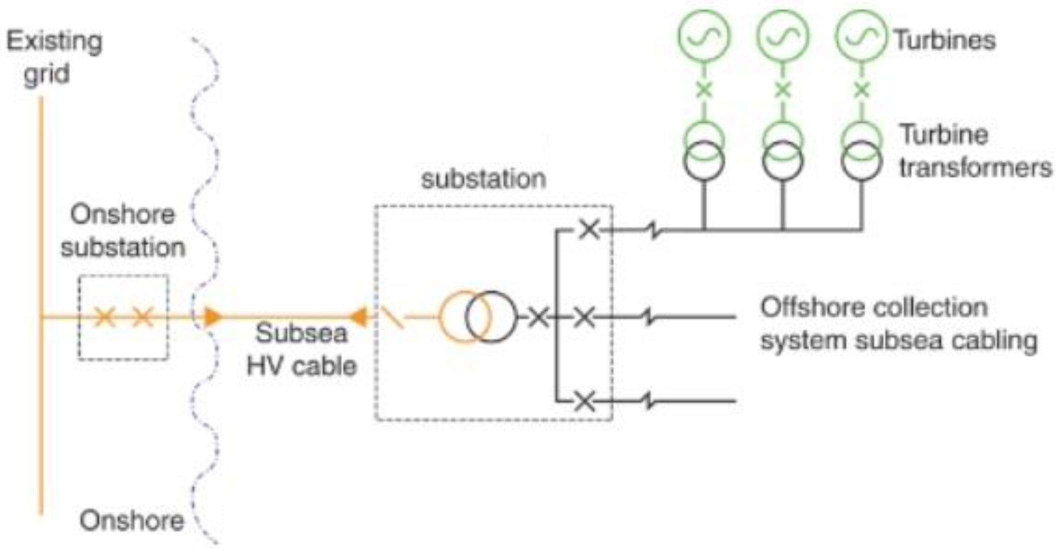

Figure 2.14 Typical electrical infrastructure layout for an offshore wind farm[37].

Array cables

In an FOW farm there is an internal collector system that transmits electrical energy from the turbines to the substation. From the generator in the turbine, electricity is usually transferred at a voltage of 22-66 kV to the transformer. To do this, there are several possible topology configurations. Common configurations include Single-sided Ring Clustered Topology, Double-Sided Ring Topology, Star Topology and Multiring topology, where the most used is the radial topology configuration [21]. The main difference between the configurations is related to investment cost and power loss. Table 2.7 shows how the configurations differ regarding cost and losses, relative to the radial configuration [38].

Table 2.7 Collector characteristics relative to the radial configuration [38].

	Investment cost (%)	**Losses (%)**
Radial	100	100
Single-sided ring	210	54
Double-sided ring	158	81
Star	97	101
Multi-ring	118	76

According to Multiconsult, the market for array cables is an international market dominated by established suppliers, and has more competition compared to export cables. However, in floating applications there is a need for dynamic cables, and this reduces the number of possible suppliers [39].

An obstacle to overcome for floating array cables is marine growth. The parts of the cable closest to the surface is expected to be more exposed to marine growth because the water is warmer and contains more oxygen. Marine growth has an impact on the cable because it adds weight which shifts buoyancy and the distribution of fatigue loads. Fatigue life of cables is important, and marine growth must be accounted for in the design phase.

Some feasible locations for floating wind farms exceed 800 meters depth, such as the western coast of USA. When depth reaches these levels, the amount of array cable needed to reach the seabed approaches an economically unviable length, and thus other options must be considered.

An option is to use mid-depth cable configurations, using buoyancy modules to keep the cable floating at a given depth instead of going down to the seabed. This is a common method used in the oil and gas industry, but not yet for FOW farms. Using this method can reduce costs in deep sea locations.

Substation

The electrical power generated from the turbines is collected by the substation. The components of an offshore substation are normally divided into three main categories:

- Electrical systems
- Facilities
- Structure

As the main purpose of the substation is to convert the power from the internal grid to a voltage suitable for long distance transmission, the electrical system is of high importance. The main components of the electrical system are:

- The transformer, usually transforming voltage from 33 kV to 132-800 kV.
- A switchgear, to isolate the export cables from the array cables.
- Converters to convert the alternating current from the turbines into direct current when the distance to shore exceeds the economically viable limit for AC transmission.
- Equipment to compensate reactive power (for AC transmission).

Historically, substations have been simple structures with basic modules on topside frames. As offshore wind farms deliver more power, the substations have evolved alongside. These days, the substations often function as the place where maintenance personnel arrive by boat or helicopter in addition to the main function of converting power.

As with offshore wind turbines, when depths exceed 60 meters, the substation needs to float. There are few suppliers who deliver floating substations. A collaboration between Ideol, Atlantique Offshore Energy and ABB have produced a concept floating substation that operates at depths from 40 m. Apart from this project there are few other alternatives. In smaller projects alternative solutions have been used. Hywind Scotland uses an onshore substation whereas Hywind Tampen and Donghae 1 will use substations installed on the platforms they supply electricity to. FOW farms that deliver electricity to an onshore grid will in most cases be dependent on floating substations.

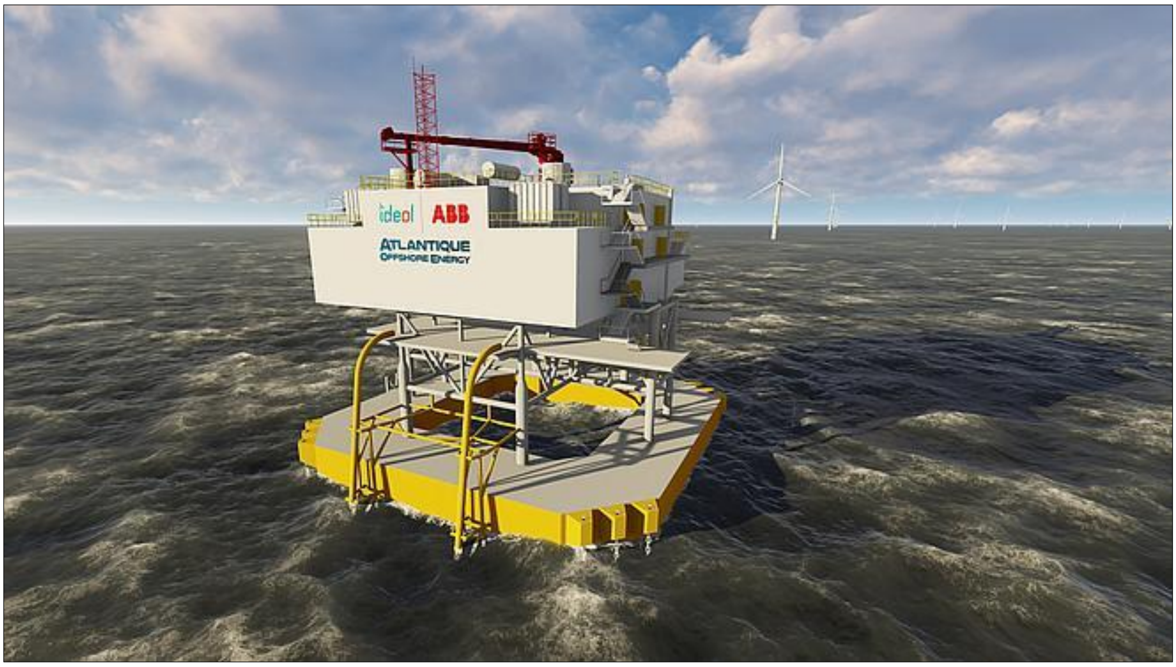

Figure 2.15 Ideol and ABBs floating substructure concept [40].

Transmission system

Connected to the substation, the transmission system transmits high voltage current to shore. Depending on the size of the wind farm and the distance to shore, the electricity is transmitted using alternating current or direct current. In general, a wind farm can transfer either HVDC or HVAC to transmit electrical energy to an onshore grid. However, each technology has ranges where it is the most viable solution. HVAC transmission requires a lower investment cost compared to HVDC, because DC-transmission requires a converter onshore before electricity is fed into the grid [41]. Compared to HVAC, the power loss during transmission using HVDC is substantially lower, and the difference in power loss increases as power and distance increases. This is due to the reactive power losses, reducing the real power. For a 1000 MW wind farm, the distance when the annual costs of AC surpasses DC is between 120 km and 160 km, and for a wind farm of 500 MW, the distance where DC becomes beneficial is at approximately 200 km [41]. Compared to bottom-fixed wind farms, FOW farms have the potential to be situated further from shore, and often need to produce more power to be economically viable. Therefore, HVDC transmission is the likely solution for future FOW farms.

A key technology gap for FOW farms is high voltage dynamic cables for long distance transmission. When voltage requirements exceed 130 kV, cables need to be “dry” designs, which in turn requires a large cross-sectional area of the cable. This makes it difficult to maintain both a stable water barrier, while minimizing fatigue. Currently, the most widespread material is a lead sheth which has unsatisfying fatigue life when used in dynamic applications [21].

Cable installation

The internal cable system between the turbines can either be laid in a single process using a plow or in a process where first a vessel lays the cables, followed by another vessel which buries it, usually by a remotely operated vehicle. After the cable is laid, it is pulled through a J-tube and then connected to the turbine foundation. This process usually takes around 24 hours per cable and is commonly known as a cause of delays and need for rework [42].

As opposed to the array system, export cables are installed in a single length. The vessels performing these operations also operate in the oil & gas and telecommunications markets and are thus not specialized for the task. The companies Jan de Nul and Van Oord have two vessels, Isaac Newton and Nexus respectively, that are specialized vessels with dynamic positioning and large carousels. Compared to the non-specialized vessels that also operate in other markets, these vessels significantly reduce cable installation time and capital expenditures [42].

3 METHOD

This thesis is based on two methods: a literature study of FOW technology, and an analysis of a capex database from Quest Floating Wind Energy. This chapter explains how the two methods are used.

3.1 Literature study

A literature study has been carried out to gather data on FOW capex and to investigate the potential for capex reduction. This method was chosen to get enough data because FOW is in an infant stage there is little data on real cost. Emphasis has been put on information from publications from credible journals such as ScienceDirect and ResearchGate, the University of Stavanger’s online library and Google Scholar. Common for these are that there is a peer-review filter. This ensures that credible sources are used. Governmental and intergovernmental reports have also been used. Examples are IRENA and NREL. For the theory, textbooks from the University of Stavanger’s library has been used, as well as peer-reviewed reports from ScienceDirect and ResearchGate and reports from consulting agencies, such as BVG Associates and Multiconsult. As FOW is in an early stage, a focus on publishing date has been important throughout the literature study. Emphasis has been put on newer publications where available to avoid outdated information.

3.2 About the Quest Floating Wind Energy database

The QFWE database has been used to analyse the FOW project's capex. The database consists of six different capex categories:

- Substructure – substructure materials and fabrication.
- Turbine – turbine fabrication and floating turbine installation.
- Mooring – mooring components fabrication and installation.
- Cabling – export and array cabling fabrication and installation, offshore substation (if applicable) + onshore AC/DC conversion substation.
- Installation – substructure, piles and fixed turbine installation.
- Other – project management, construction insurance and contingency.

The values are sourced from public industry press or industry relationships whenever possible. In absence of these number a cost model is applied, which is a bottom up summation of project costs. All numbers are in current USD, with no inflation adjustments. QFWE finds their accuracy to be within ±15-25% of real cost according to conversations with Erik Rijkers of QFWE [2].

The projects of interest are those that fall within the category of pre-commercial and commercial, as the demo and pilot projects are more expensive and does not give a good indication of costs at a commercial level. The projects in the database are divided into four categories: Online, under development, planned and possible. The "possible" category has been excluded because it is too uncertain. There is currently one online project, six are under development and nine are under planning. Due to the projects being in different stages of development, the available information varies. This makes it difficult to compare the projects while controlling for variables such as ocean depths or anchoring method.

3.2.1 How the data was prepared for the analysis

For each project, the capex categories are multiplied by capex/MW to obtain capex/MW of each category. These values are then plotted according to categories to reveal the category variation across projects. The categories "other" and "installation" have the smallest total variation as these represent a small portion of total capex. “Other” and “installation” have therefore been excluded for the rest of this analysis to limit the scope.

The data has then been sorted to show each category’s capex/MW so costs can be compared on a more equal basis.

3.3 Criticism of method

A qualitative method was chosen as the main approach to answer the research questions due to a lack of empirical data on FOW projects. Normally, a regression analysis would be useful to investigate the questions in this thesis and control for variations, but in the case of FOW, this was not possible due to small sample size. To provide more information, the QFWE database was included in addition to the findings from the literature study. The variation in cost estimates from the literature indicates a high uncertainty. With the access to more empirical data, and a quantitative approach, the future costs of FOW farms could be better understood and more accurate predictions could be made. The QFWE database was included as a quantitative part of the analysis. Since the values in the QFWE database are mainly estimates this introduces estimate uncertainty. It is assumed that the cost estimations from the QFWE database fall within acceptable range as these are the “best guesses” the authors could find of the true costs. The estimate accuracy of the capex costs found in the database will not be known until the true cost of these projects are disclosed.

3.4 Criticism of sources

Reports and books covering rapidly changing technologies such as FOW are potentially outdated. Therefore, an attempt has been made towards using the newest possible reports throughout the literature study. It is difficult to know when a source is outdated, so there is a possibility that some sources contain outdated information. Consulting agencies such as IRENA and NREL publish many reports relevant for this thesis and is cited several times. These consulting agencies are targeting renewable energy, and thus there is a risk for a positive bias. Before such sources are used, a focus has been to reveal any form of bias.

3.5 Theoretical framework

This sub chapter explains key concepts and assumptions needed for the readers to better understand the content of this thesis.

3.5.1 Capital expenditure

Capex can be divided into several sub-categories. As an example, soft costs can be divided into insurance during construction, construction finance, contingency, decommissioning, plant commissioning and lease price. However, each sub-category under soft finance will account for such a small part of total sum of capex that it will not be expedient to investigate all. Instead, the main cost drivers are analysed. As illustrated by the figure below, the main cost drivers are the turbine and balance of system. The category balance of system is further divided into substructure, electrical infrastructure, and mooring [43].

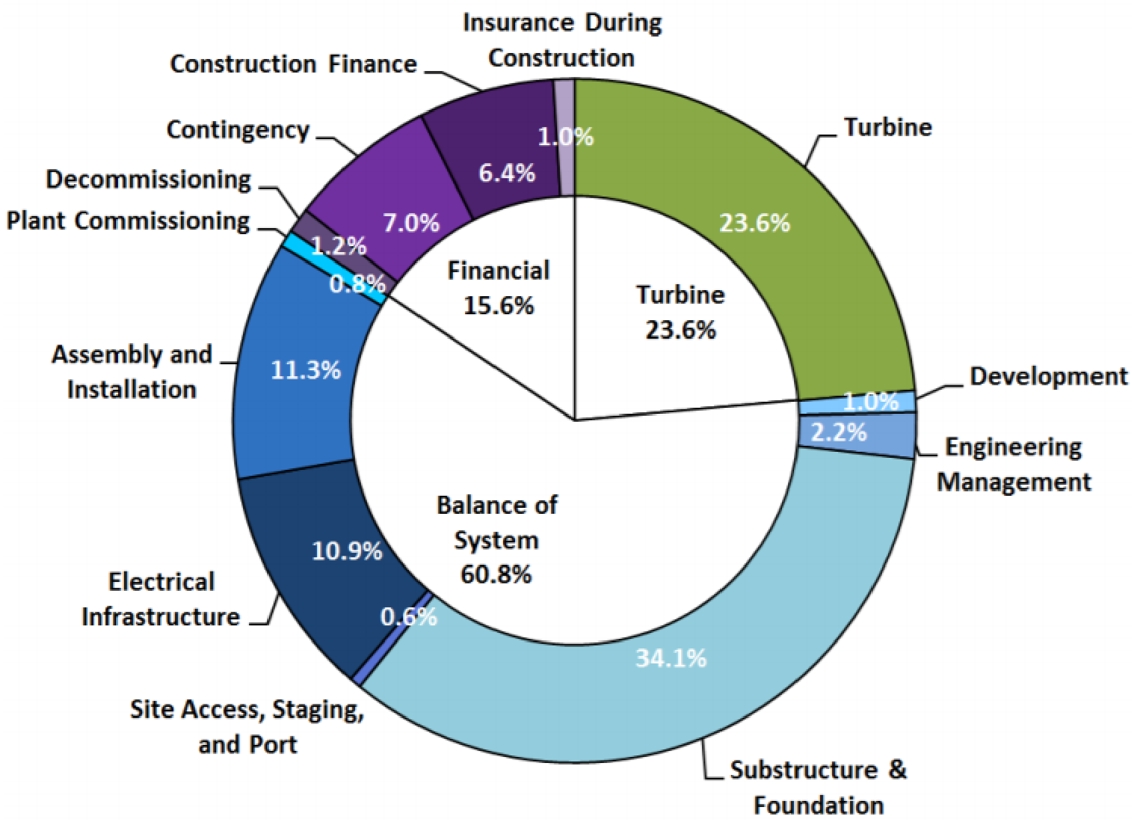

Figure 3.1 Example of FOW project capex breakdown [44].

3.5.2 LCOE

When reviewing energy generating systems, it is necessary to have a standardised unit to measure costs in a way that makes it easy to compare to other investment opportunities. One of the methods is to calculate LCOE. This calculation considers the full lifetime cost and the time value of money, expressed as a discount rate, and outputs the cost in today's money. When comparing projects, it is common to divide by energy generated, i.e. MWh to get cost per unit of energy generated. The dictionary of energy describes LCOE as:

> *"capital and operating expenses occur in different amounts at different points in time, economists employ a "time value of money" – expressed as an interest rate, discount rate or rate of return – to determine the "net present value" of all lifetime costs. This is the total amount needed to acquire, operate and maintain the plant over its useful life as well as paying all interest(or make a profit) on funds used to finance the project[…]The levelized cost can also be expressed as cost per unit of electricity generated by dividing the total annual cost by the total annual KWh generated. "*[45]

LCOE is calculated with the following formula:

$$LCOE = \frac{Capital\ Investment + \sum_{n=1}^{N} \frac{O\&M\ Costs}{(1+DR)^n}}{\sum_{n=1}^{N} \frac{Net\ Annual\ Energy\ Generated * (1_{DR})^n}{(1+DR)^n}} \qquad \textbf{(6)}$$

The capital investment plus the sum of operation and maintenance costs (discounted) is divided by the net annual energy generated (i.e MWh) (discounted). What is included in the different categories is shown in figure 3.2.

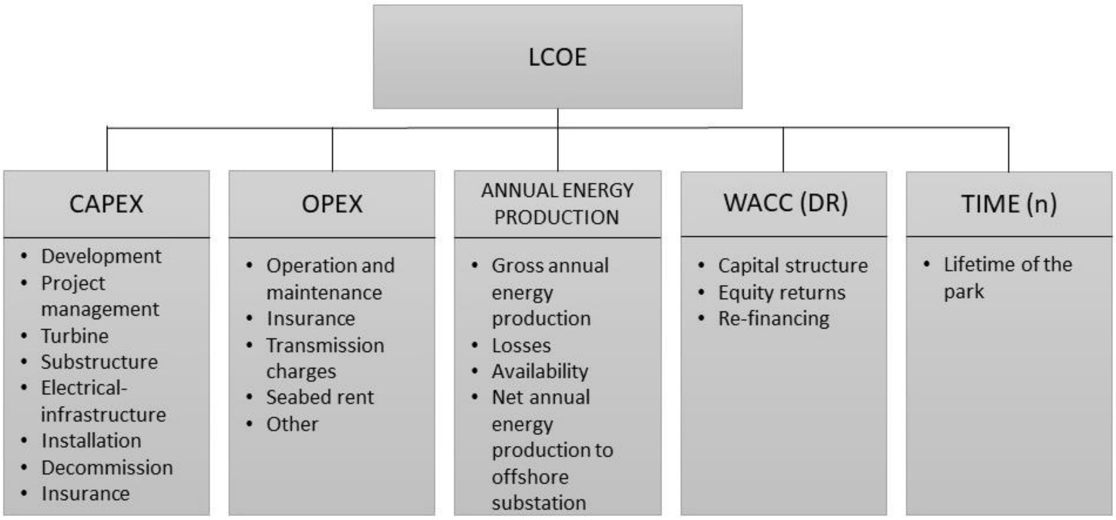

Figure 3.2 LCOE for offshore floating wind. Adapted from [46].

LCOE is a way of comparing different energy generating projects based on total cost of the project. A weakness of LCOE is that it does not distinguish between energy quality and when it is being generated. LCOE is therefore a good starting point for comparison but does not provide a complete picture, as energy generated during peak usage is more valuable. Energy generated at peak periods are more valuable because it allows for a greater reduction in energy from fossil fuels, as increased demand is often supplied by increasing fossil fuel energy production [47].

3.5.3 The difference between LCOE and capex/MW

Capex/MW is derived from dividing capex by total capacity. This number is useful to compare capex of projects with different capacity as it provides a simple way of comparing cost while controlling for size of projects. LCOE gives a more complete picture of the cost of energy because it includes aspects like total lifetime costs and earnings. A measure that increases the amount of energy produced but increases the initial investment cost could therefore increase capex/MW but reduce the LCOE. An example of this is locations further ashore but with better wind conditions. The capex/MW will increase due to increased cost for cable and vessels, but due to better wind conditions the capacity factor would increase and potentially reduce the LCOE.

3.5.4 Definition of project maturity stages

FOW projects can be divided into three categories. Pilot/demo project, pre-commercial project, and commercial projects. The definitions used in this thesis are the following:

i. Pilot/demo projects are projects with one or two turbines. These projects are built to validate design and study the behaviour of the turbine. The unit cost of such projects is high, and the projects are not profitable.

ii. Pre-commercial projects fall between pilot/demo and commercial projects. These projects consist of more turbines than the pilot/demo projects but are not profitable without subsidies. Like pilot/demo projects, these are built for research purpose, but are intended to operate at location for the whole lifetime of the equipment. Hywind Scotland is an example of a pre-commercial project.

iii. Commercial projects are usually defined as making or intended to make a profit. For simplicity, all projects over 200 MW are defined as commercial projects in this thesis.

3.5.5 Uncertainty

Uncertainty is defined in economic terms by the works of J. K. Galbraith as: “the difference between the information needed to make the decision in certainty and the information available at the time of making the decision” [48]. Uncertainty is divided into two categories, which are estimate uncertainty and event uncertainty. Subcategories of these have been identified as:

Estimate uncertainty

i. Model Error – T. Aven defines model error as: “Model error: the difference, $\Delta G(x)$, between the model prediction $G(X)$ and the true future value Z, i.e. $\Delta G(X)=G(X)-Z$.” and “Model output uncertainty: Uncertainty about the magnitude of the model error.” [49].
ii. Input uncertainty – Uncertainty regarding the input values, their distribution and accuracy.

Event uncertainty

i. Technology uncertainty – Uncertainty regarding which technology will be available in the future and how will it affect costs.
ii. Market/supplier uncertainty – Uncertainty regarding demand. How many suppliers will compete for contracts, and how it will this affect costs.
iii. Funding/regulation uncertainty –The possible to get subsidies from governmental institutions and how will regulations affect the technology.

4 RESULTS

The first part of this chapter presents estimated capex/MW and LCOE for the different projects, and the cost development for the different capex categories. The second part presents potential technology and cost reducing measures within each capex category and a list of FOW industry key innovation needs to reduce costs.

4.1 Capex variation

To get an understanding of the variation in capex for FOW farms, capex/MW in the six different categories are compared project wise. In this analysis, the pre-commercial projects have been excluded as they do not give an accurate picture of cost for a commercial FOW farm. The projects excluded are Toda Sakiyama, Hywind Scotland, Lake Erie and Kinkardine Tranche 2. The remaining projects have capacities ranging from 88 MW to 1000 MW, and total capex ranging from $390M to $3355M.

Figure 4.1 shows the distribution of data in quartiles and highlights the average and outliers in each category. The cross in each box represents the average, and the line represents the median. Above and below the line are the first and the third quartile. The vertical lines above/below the boxes are maximums/minimums outside the first and third quartile. The dots above the boxes represent outliers. A data point is considered an outlier if the value exceeds 1,5 times interquartile range (IQR) below/above the first/third quartile. IQR is the distance between the first and third quartile.

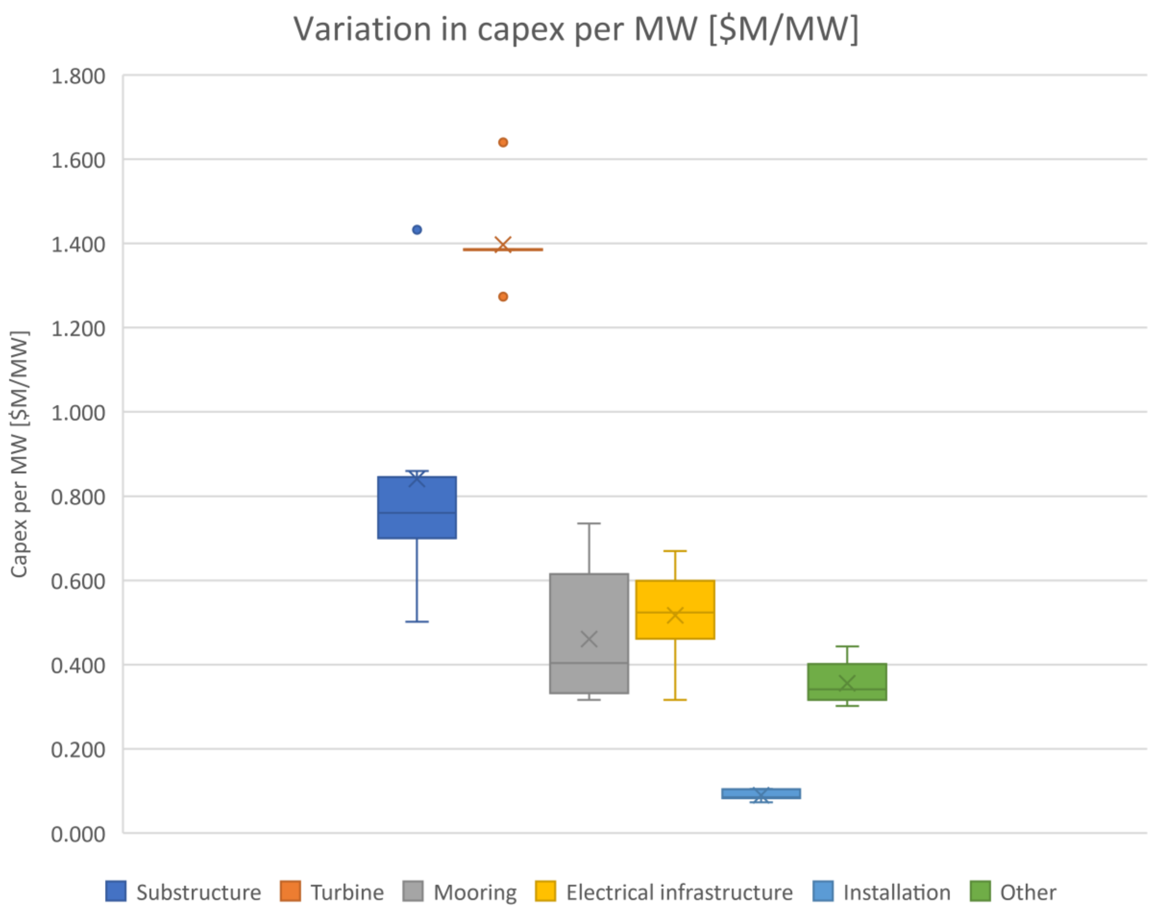

Figure 4.1 Variation in capex per MW for the categories.

Table 4.1 Standard deviation, third quartile minus first quartile (Q3-Q3) and max-min for the different capex categories. The different shades of red to green illustrates the values from highest to lowest.

Data/Capex category	Substructure	Turbine	Mooring	Electrical infrastructure	Installation	Other
Standard deviation	0,297	0,083	0,155	0,102	0,011	0,047
Difference Q3 - Q1	0,195	0,002	0,282	0,138	0,021	0,085
Difference max - min	0,948	0,367	0,419	0,354	0,032	0,141

Table 4.1 lists standard deviation size, Q3-Q1 and Max-Min. The biggest variability is in substructure and mooring, with electrical infrastructure having the third most variability. Based on these results installation and other have been excluded from further analysis as these are the categories with the smallest variation. The small variation is an indication of low uncertainty regarding costs. The low variation observed in installation is a result of the cost model from QFWE, where the installation cost is just added as a percentage of total cost.

4.2 Project capex development

The graph below shows the estimated capex/MW and LCOE for the different projects. The projects are sorted in the order of planned completion date, from earliest to latest. The estimated capex' are behaving like predicted by the literature, with rapid reduction before levelling off and stabilising at an LCOE of roughly $100/MWh and capex of $4M/MW. Hywind Scotland and Kinkardine Tranche 2 have larger LCOE and capex/MW than the other projects, with almost twice the LCOE and capex/MW.

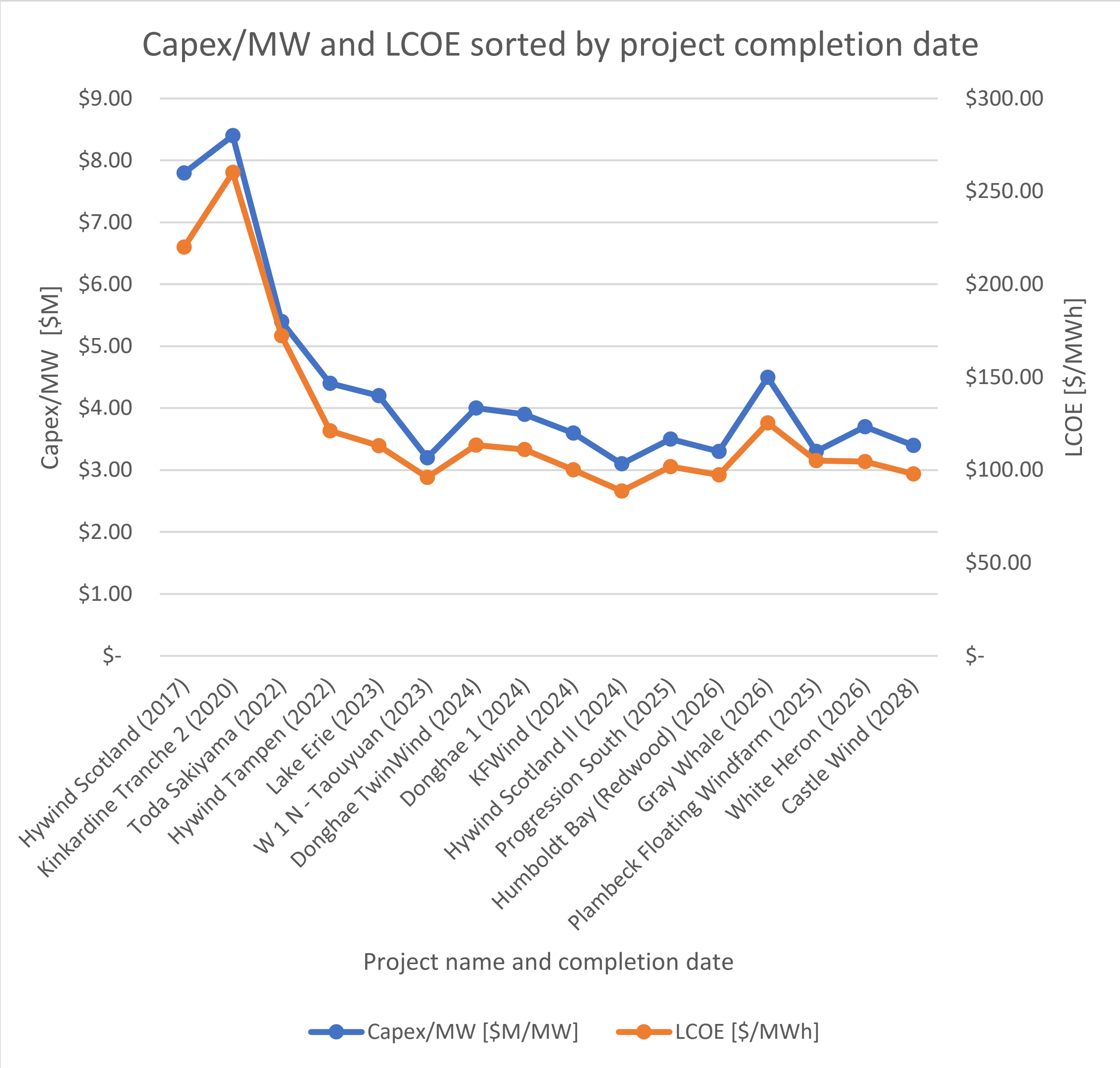

Figure 4.2 Capex/MW and LCOE for each project.

Figure 4.3 shows the relationship between capex/MW of each project and capex sorted by capex from lowest to highest. As capex reaches $500M, capex/MW seems to stabilise between $3M-$4M. Hywind Scotland and Kinkardine Tranche 2 are outliers with capex per MW of around $8M.

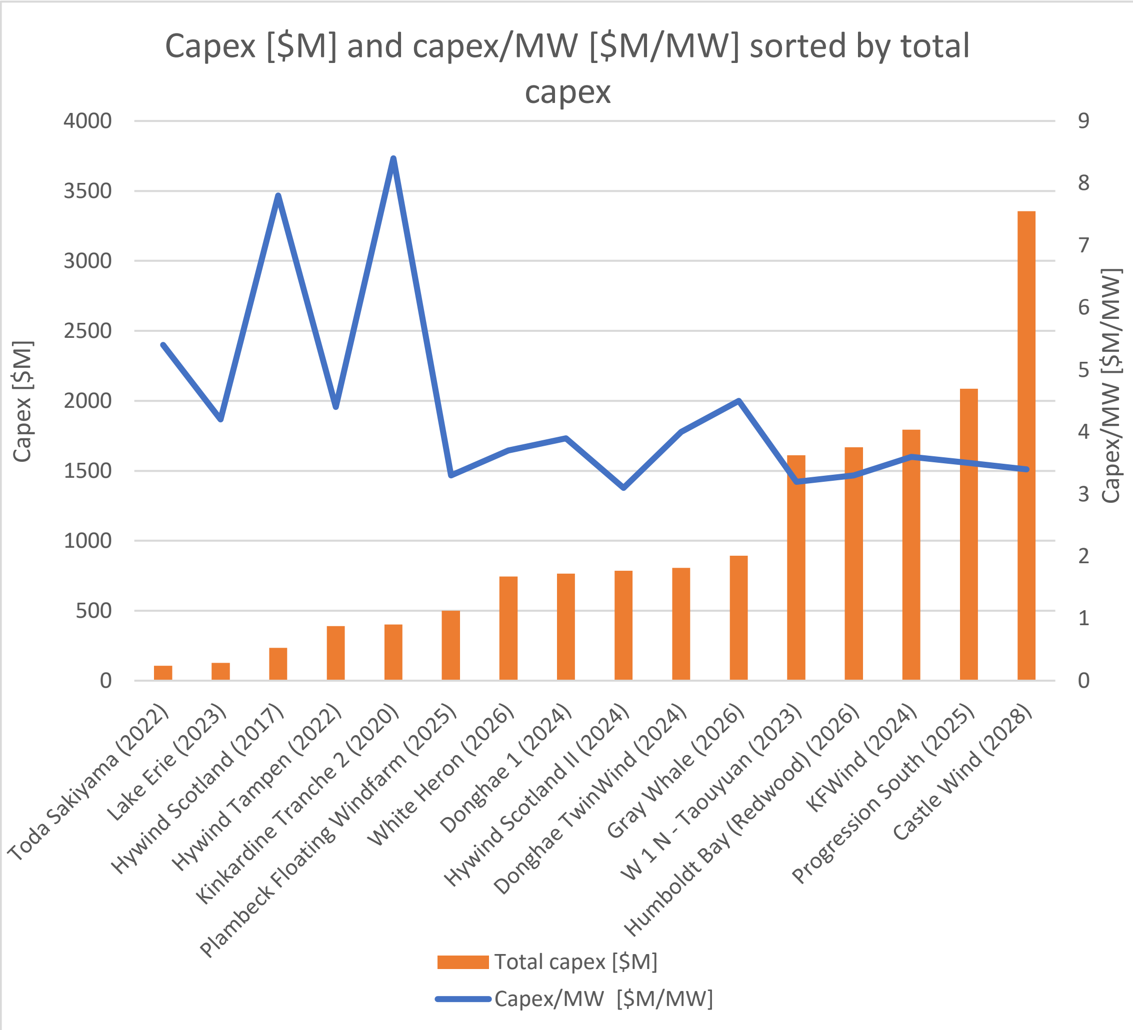

Figure 4.3 Relationship between capex size and capex/MW.

4.3 Sub-project capex development

This chapter looks at the estimated capex development of the turbine, substructure, mooring and electrical infrastructure.

4.3.1 Turbine

The turbine accounts for a large part of capex. When looking at the projects in the QFWE database, one can get an understanding of how the cost of the wind turbine varies. A varying cost contribution leads to uncertainty. Variation in turbine contribution to capex is shown in table in appendix. This gives an average capex contribution of 37,8% and a standard deviation of 4,2%. Toda Sakiyama has the lowest contribution to capex from the turbines, 30,84%, utilising the smallest turbines of 4 MW. On the other hand, the highest contribution is in Hywind Scotland II with 44%, using 10 MW turbines.

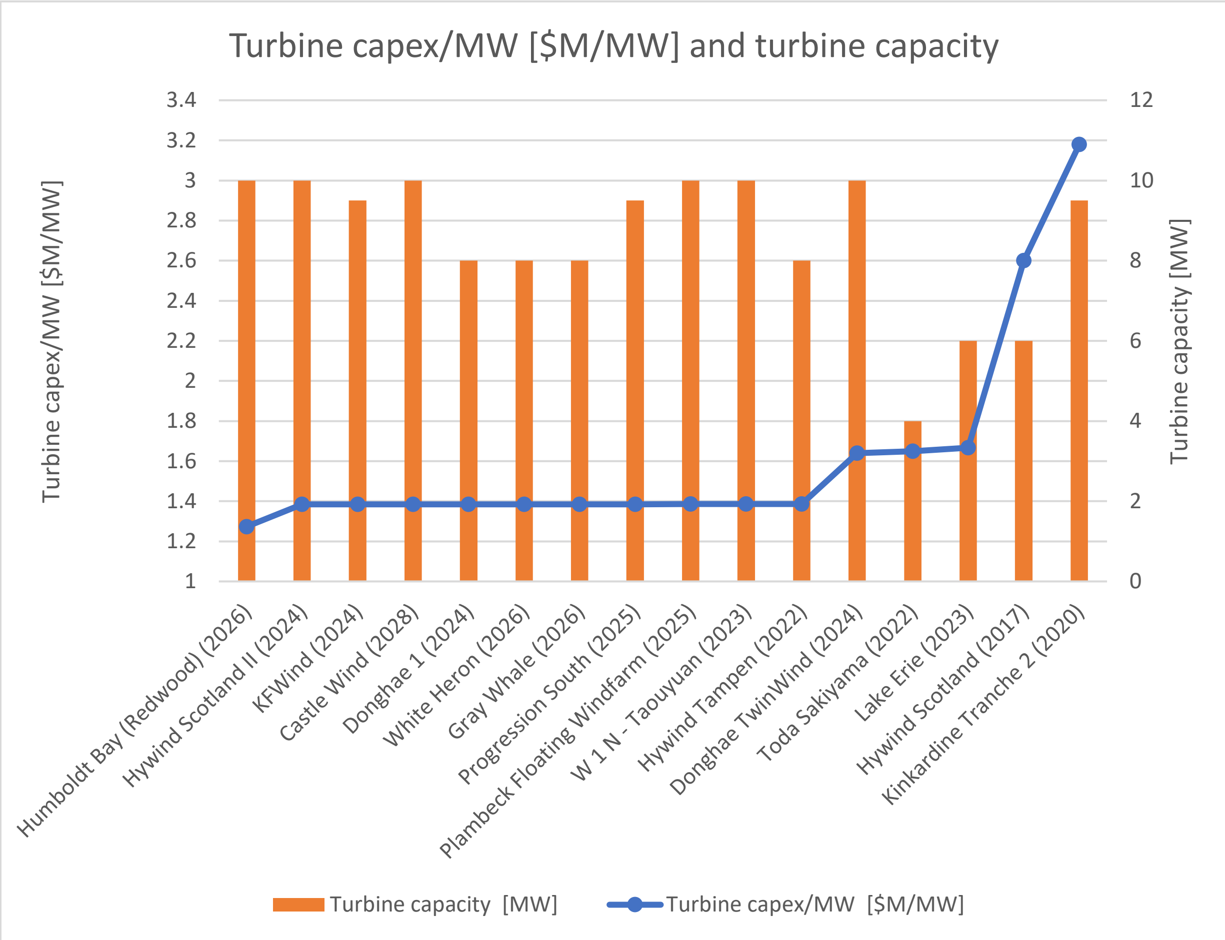

Figure 4.4 Relationship between turbine capacity and turbine capex/MW.

Figure 4.4 shows a tendency of increase in turbine capex/MW as turbine capacity decreases. Compared to the other projects, Hywind Scotland and Kinkardine Tranche 2 have a considerable larger turbine capex/MW. Figure 4.5 shows that the smaller projects tend to have a larger turbine capex/MW. Still, Hywind Scotland and Kinkardine Tranche 2 stand out from the other projects in regard to turbine capex/MW.

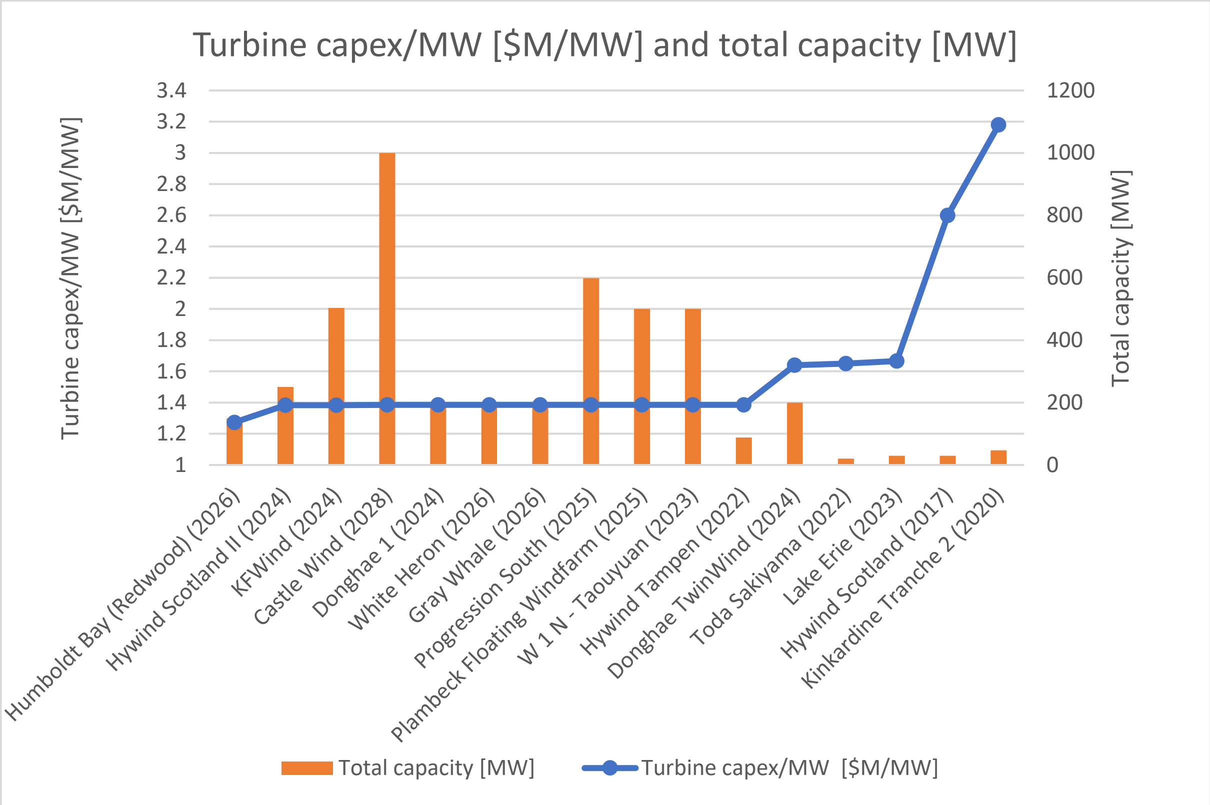

Figure 4.5 Relationship between total capacity and turbine capex/MW

Turbine capex/MW is somewhat related to turbine capacity and farm capacity. The larger the turbines capacity are, the bigger share of capex the turbines will have, but the cost of turbines per MW will be reduced. Projects with a larger total capacity (200MW+) tend to have a smaller turbine capex per MW and costs are estimated to decrease with time. Hywind Scotland and Kinkardine Tranche 2 have the costliest turbines per MW, with respectively $2,6M/MW and $3,2M/MW. Hywind Scotland started producing electricity in 2017, and Kinkardine Tranche 2 will start in 2020, while the median start of production of all projects is 2024, the latest being in 2028. Regarding variability in turbine capex/MW it is small, especially if excluding the two oldest projects. The cheapest turbines/MW are at project Humboldt Bay at a cost of $1,27M/MW, while the most expensive is at Lake Erie at a cost of $1,67M/MW. This is a difference of $0,40M/MW with project capacities ranging from 20MW to 1000MW, and turbine capacity ranging from 4 MW to 10 MW. The average turbine capex/MW is $1,61M/MW and the standard deviation is $0,51M/MW.

4.3.2 Substructure

The substructure is the second biggest capex category, after turbine. The average substructure capex/MW is $1,07M/MW and the standard deviation is $0,54M/MW. For the projects included in this analysis, three different substructure designs are used. Barge, semi-submersible, and spar. The substructure represents on average 23,82% of a windfarm's capex, with a median value of 22,87%. The project where substructure makes up the biggest share of capex is Gray Whale, with a share of 32,47%. The project where substructure make up the smallest share of capex is W 1 N – Taouyuan with 15,57%.

Figure 4.6 and 4.7 show the relationship between substructure capex/MW and capex for each project. As the projects increase in size, the substructure capex/MW decreases. Sorting the projects by completion date, the substructure capex/MW is reduced before stabilising at around $0,5M/MW-$1,0M/MW. The capex of the substructure per MW decreases from above $2M/MW in the period from 2017 to 2020, and stabilises in the range of $0,5M/MW-$1,0M/MW. Gray Whale (yellow bar) is more expensive than similar projects. This is the first project utilising the barge substructure technology at a large scale.

Based on median and average the barge substrucutre design is the most expensive followed by spar and semi-submersibl as seen in table 4.3.

Table 4.2 Average and median capex/MW for the three substructure designs.

Substructure design	Average capex/MW	Median capex/MW
Semi-submersible	$ 0,93 M	$ 0,77 M
Barge	$ 1,46 M	$ 1,46 M
Spar	$ 1,22 M	$ 1,15 M

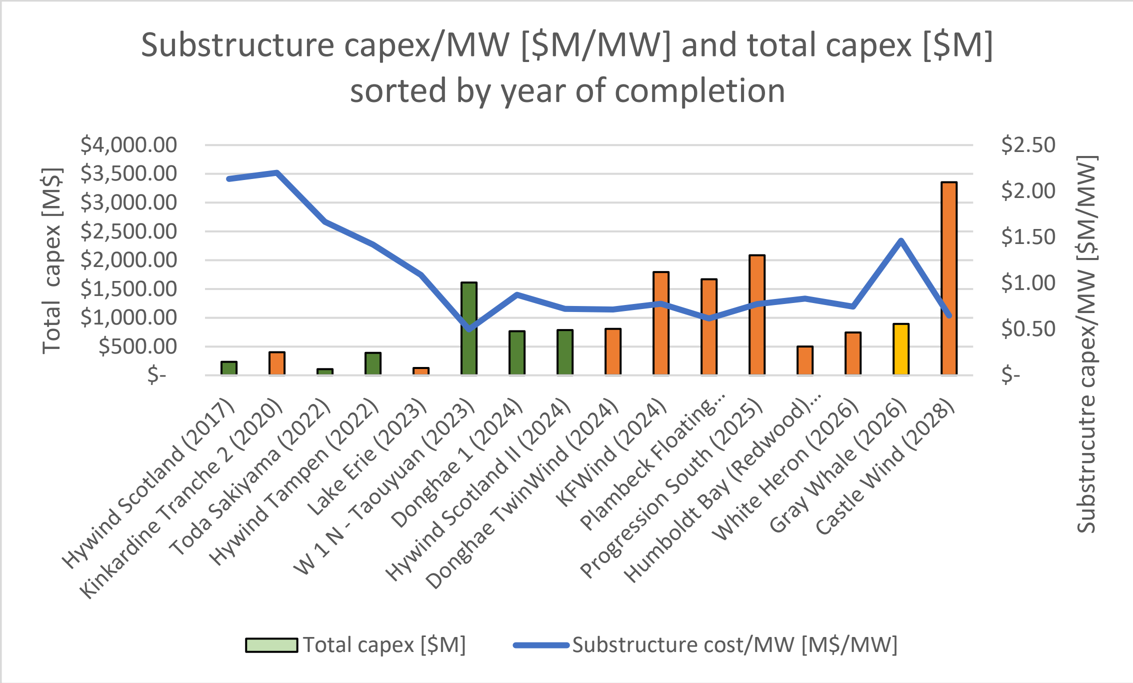

Figure 4.6 Relationship between substructure capex/MW and total capex. Green columns are utilising the spar design, orange the semi-submersible and yellow the barge design.

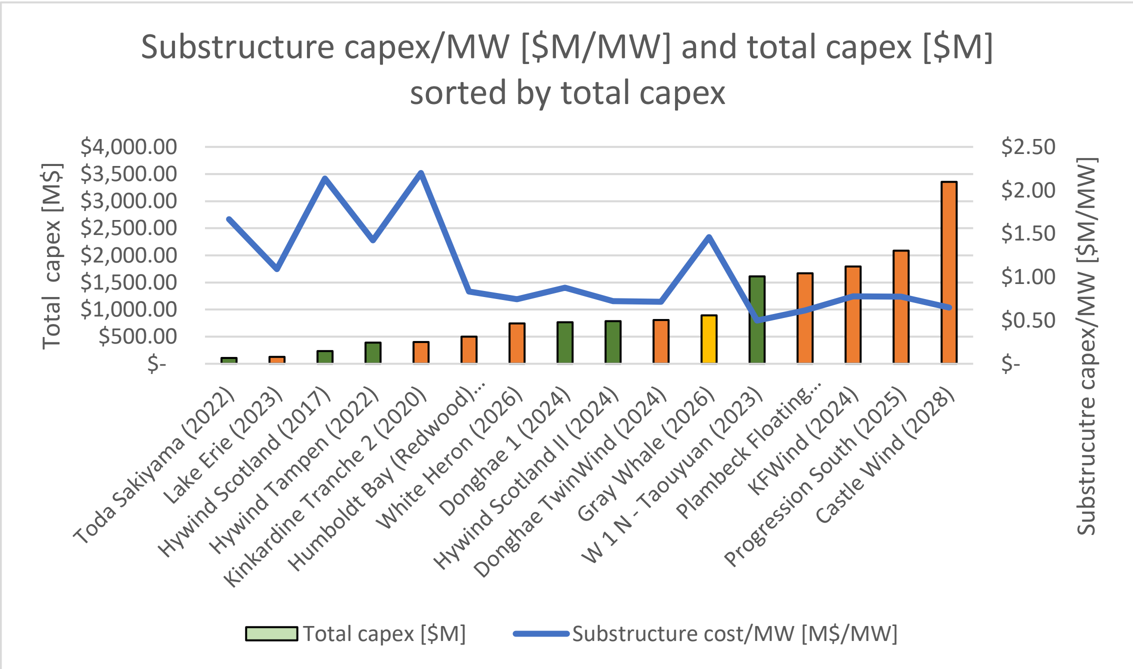

Figure 4.7 Relationship between substructure capex/MW and total capex. Green columns utilise the spar design, orange the semi-submersible and yellow the barge design.

4.3.3 Mooring

Mooring is the fourth largest capex category with an average contribution to capex of 12,08%. The project where mooring contributes the least to capex is Kinkardine Tranche 2 with a contribution of 7,98%. The project with the highest contribution to capex from mooring is Donghae TwinWind with 18,22%. When sorting the projects by completion date and capex size as seen in figure 4.8 there seems to be a trend of reduction in mooring capex per MW as total capex increases. Hywind Scotland has the largest mooring capex of $0,83M/MW and Hywind Scotland 2 the smallest with a capex of $0,31M/MW. The average mooring capex for FOW parks utilising semi-submersible, spar and barge substructure is $0,47M/MW, $0,58M/MW and $0,62M/MW, respectively. The total average capex per MW is $0,52M/MW and the standard deviation is $0,18M/MW.

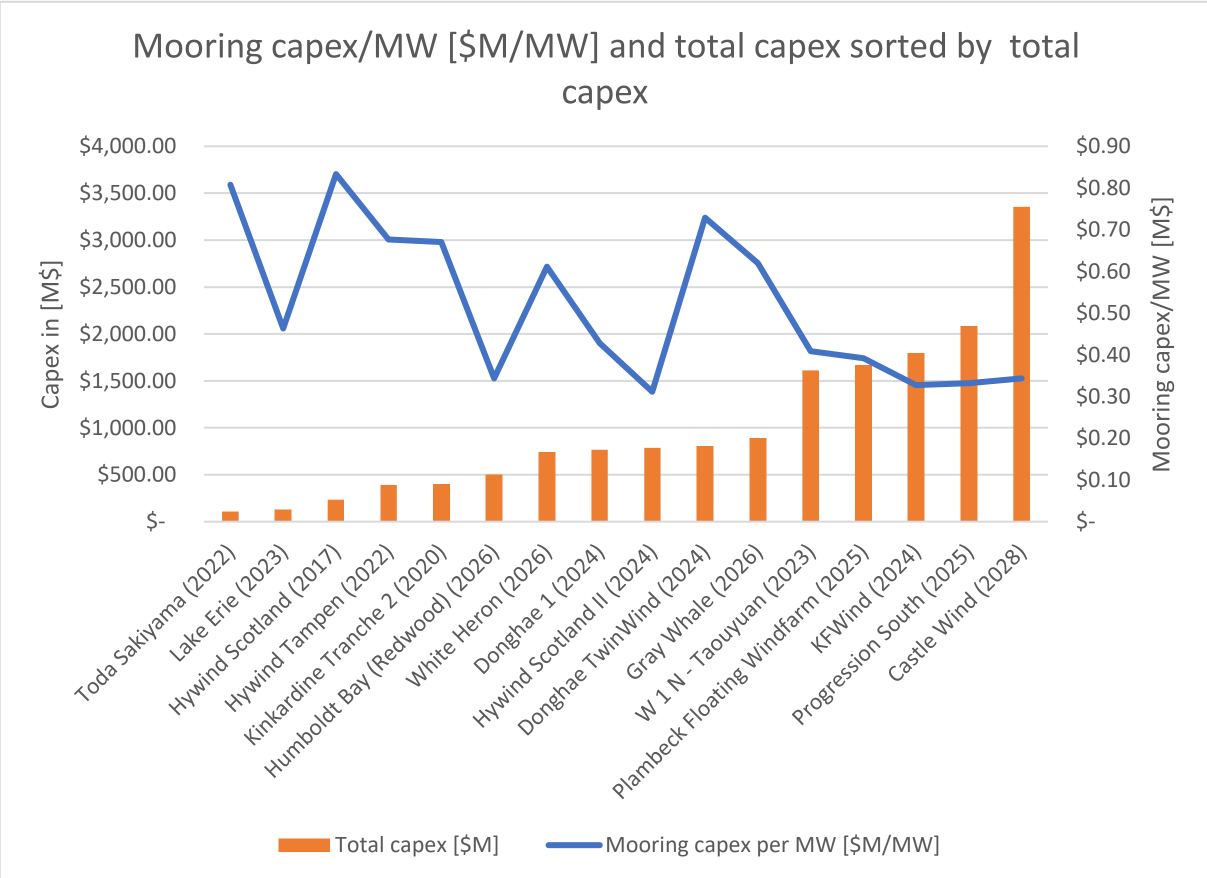

Figure 4.8 Relationship between capex/MW and total capex.

4.3.4 Electrical infrastructure

The capex of the electrical infrastructure includes export cable and array cable fabrication, installation, and substation(s). Some projects have floating substations at location while other projects have onshore substations. The average capex contribution from electrical infrastructure is 13,97%.

Export cable voltage ranges from 33 kV to 155 kV between the projects. Seven out of sixteen projects have disclosed export cable voltage. All projects utilize alternating current due to the relative short distances from shore. Distance from shore ranges from 8 km at Toda Sakiyama to 53 km at both Castle Wind and Lake Erie. Hywind Tampen is located 140 km ashore but will not be connected to an onshore power grid. Figure 4.9 shows electrical infrastructure share of capex and distance to shore.

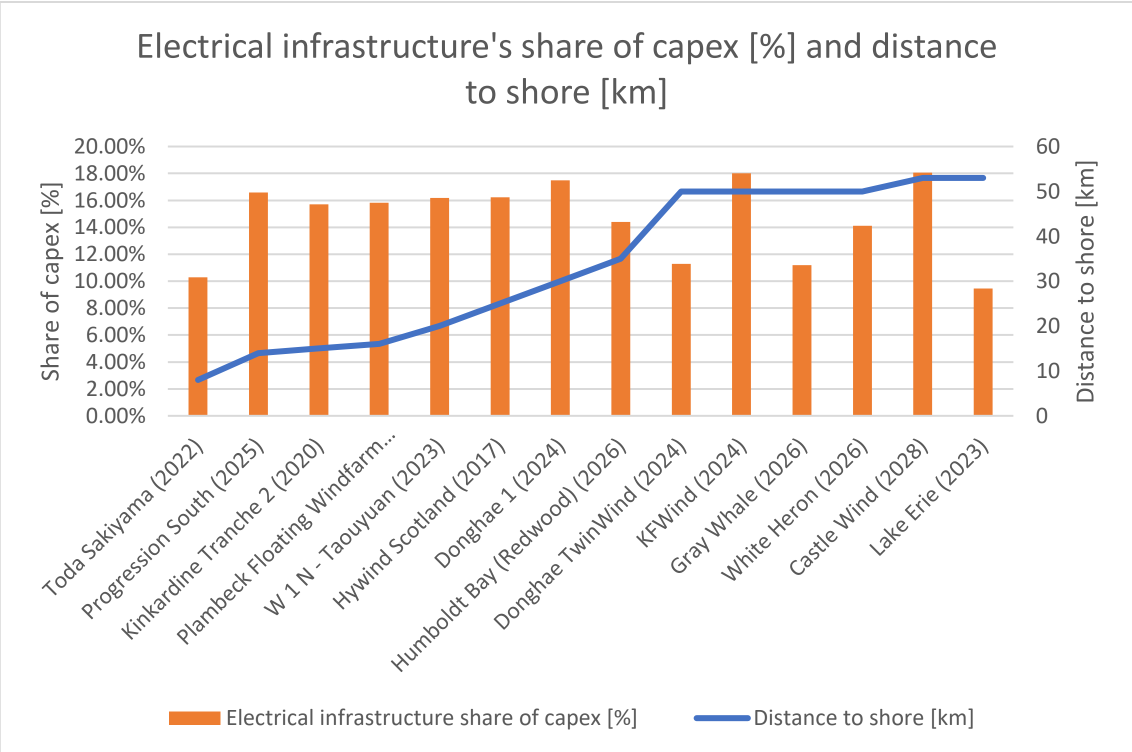

Figure 4.9 Relationship between electrical infrastructure's share of capex and distance to shore.

As seen in figure 4.9, Toda Sakiyama (8 km) and Lake Erie (53 km) have approximately the same electrical infrastrucutre share of capex (10,3% and 9,4%, respectively). Furthermore, Progression South, Kinkardine Tranche 2, Plambeck, W 1 N, Hywind Scotland, Donghae 1, Humboldt Bay, KFWind and Castle Wind have similar electrical infrastrucutre % of capex, ranging from 14,4% at Humboldt Bay to 18,1% at Castle Wind, while distance to shore ranges from 14 km at Progression South to 53 km at Castle Wind. In the graph, Hywind Tampen and Hywind Scotland II are excluded. Hywind Tampen's distance to shore is not relevant because it is not connected to shore, and the distance at Hywind Scotland II has not been disclosed.

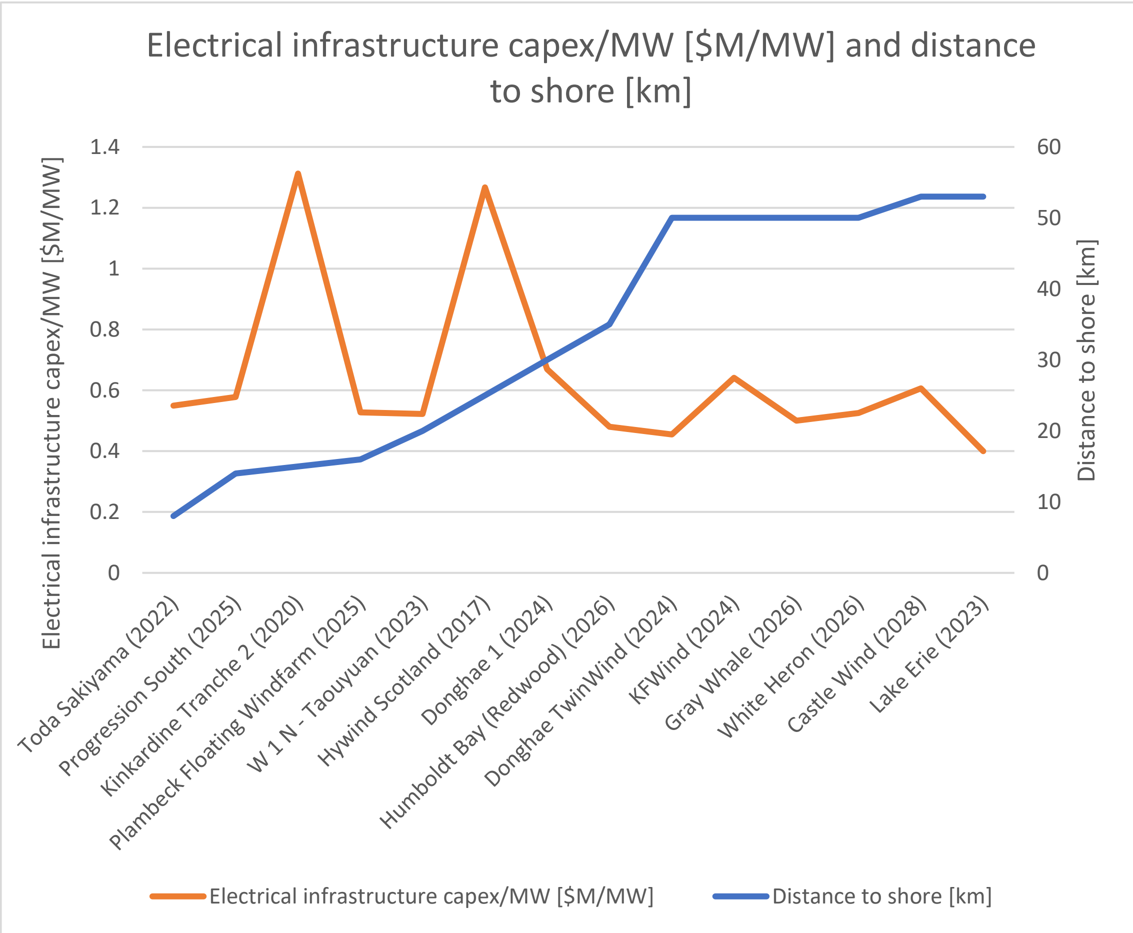

Figure 4.10 Relationship between electrical infrastructure and distance to shore.

Plotting capex per MW of electrical infrastructure against distance to shore gives two outliers: Kinkardine Tranche 2 and Hywind Scotland, the earliest completed projects. Apart from these there is little variation between the projects despite large variations in total capacity and distance to shore. The electrical infrastructure cost per MW ranges from $0,4M/MW at Lake Erie to $0,67M/MW at Donghae 1.

Despite literature pointing to distance to shore being a major contribution to cable capex, the projects in the QFWE database does not point to the same, however, it is impossible to ignore the fact that longer lengths of cable will come at a higher cost. The projects at hand show that the two earliesst projects, Kinkardine Tranche 2 and Hywind Scotland have higher electrical infrastructure capex than what is anticipated by the remaining projects, which are yet to be initiated.

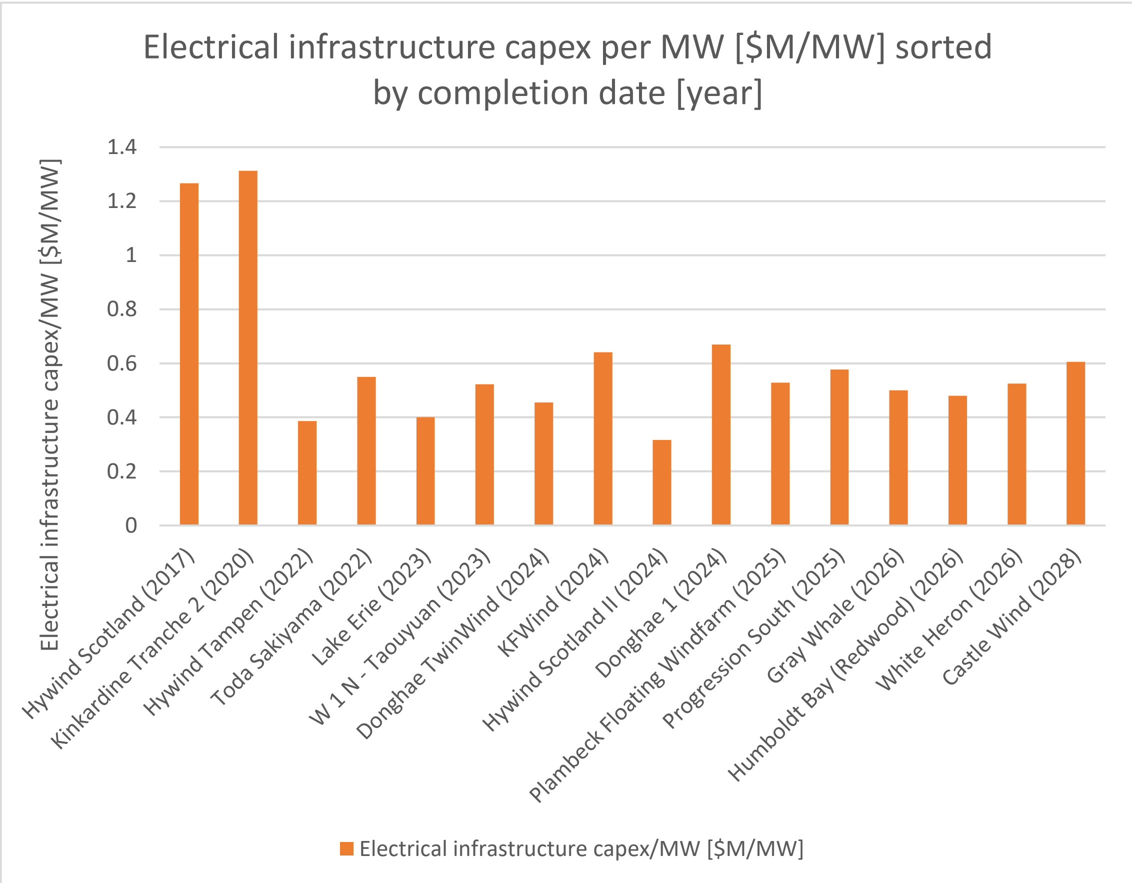

Figure 4.11 Electrical infrastructure capex/MW sorted by completion date.

Sorting the projects by completion date, the two first projects are outliers. The variation between the other projects is small compared to the differences in project size, export cable voltage and distance to shore. The total average capex per MW is $0,61M/MW and the standard deviation is $0,28M/MW.

4.4 Potential for innovation and cost reduction

This chapter presents the findings from the literature study and includes potential capex reducing measures for FOW projects.

4.4.1 Turbine

The turbines used in FOW farms are not unique. To a large extent, the same turbines used in onshore and bottom-fixed applications can be used for floating applications, and thus, the turbines come from a mature market of developers [50]. Examples of large producers are Siemens Gamesa, MHI Vestas and GE. These companies have delivered wind turbines of commercial scale for years. This heavily reduces uncertainty regarding procurement, both in terms of time of delivery and cost.

Increasing the rated turbine output is a focus for innovation. In 2018, most offshore bottom-fixed turbines were rated 6 MW [50]. Many producers are developing bigger turbines, with GE's Haliade-X currently being the most powerful turbine. To further develop this turbine, and to make it more suitable for FOW applications, GE has been awarded $3M from Advanced Research Projects Agency-Energy (ARPA-E), a US government agency. The focus of this work is to reduce the weight of the turbine by replacing mass with cheaper control systems. Currently, floating turbines are designed to be heavy to maintain stability. This work is based on the Haliade-X rotor and has a reported potential of reducing the mass by 35%, leading to capex reductions [51].

Most innovations to improve the turbine do not reduce the capex contribution from the turbine but improves its efficiency or power output. This reduces LCOE, the most important figure for an investment decision. Innovations in the nacelle can reduce LCOE up to 4,7%, while innovations in the turbine rotor can reduce LCOE by 4,8% in projects with investment decisions by 2030 [50].

Table 4.3 Turbine improvement measures with the biggest impact on capex and LCOE [50].

	Capex / LCOE impact by financial investment decision in 2030.	
Improvement measure	Capex	LCOE
Introduction of continuously variable transmission drive trains.	-2,0%	-2,4%
Development in blade construction and materials.	-1,6%	-1,4%
Introduction of advanced turbine optimisation tools.	-1,5%	-1,1%

Introduction to continuously variable transmission drive trains

By implementing continuously variable transmission drive trains there is no need for a power converter. This is because the drive train can control the generator speed. By avoiding the power converter, capex will be reduced, and reliability will increase. However, a small reduction in power production is expected due to lower efficiency. A reduction in capex of 2,0% is expected from this innovation [50].

Development in blade construction materials

Wind turbine blades are massive components. At Hywind Tampen, where 8 MW Siemens turbines will be utilized, each blade is 81,5 m long. The most common material used in turbine blades is glass fibre, but carbon fibre can also be used to reduce weight and increase stiffness. To reduce cost and improve performance, research is done to develop both material and manufacturing of the blades, which to some extent is inspired by the aerospace industry. This can lead to a reduction of capex by 1,6% on projects with financial investment decision by 2030 [50].

Introduction of advanced turbine optimisation tools

Currently the optimisation of turbines is performed at an individual component level. By developing more advanced analysis software and optimisation tools, a more holistic approach to optimisation can be utilized. This is estimated to potentially reduce capex by 1,5% [50].

4.4.2 Substructure

A report published by DNV GL estimates that the percentage capex of the substructure is higher for FOW projects than for bottom-fixed projects. It is estimated that 25% of capex comes from the substructure, compared to 15% for bottom-fixed concepts [27]. Similarly, Multiconsult estimated that the substructure represents 24% of total capex [9]. From the QFWE database, the substructure contributes on average with 23,82% of capex. Looking for ways to reduce the capex of the substructure is therefore important for reducing the total investment.

Multiconsult have divided the supply of substructure into cost categories. 35% of total cost is from construction work, 30% for fabricated metal products, 5% for basic metal and 15% for other non-metallic materials [39]. According to these estimates this means that 50% of the cost of the substructure come from purchasing of materials. An important measure for reducing the capex of the substructure is therefore to reduce material costs. This can be achieved by reducing amount of material needed, from volume discount or by using cheaper materials like concrete instead of steel. Ideol claims that concrete is substantially more cost-efficient in most geographies compared to steel [15].

Kværner's VP of business development of renewables Niklas Indrevær talks about how Kværner tries to reduce cost and lead time for the Hywind Tampen project by being involved through the whole lifetime of the project and being responsible from planning to installation. By using an EPCI (engineering, procurement, construction hook-up, installation) approach Kværner estimates that they can reduce lead time by 10-25%. Secondly, the EPCI approach, facilitates industrialization through the whole value chain. Examples being employing standards, repetition, monitoring current process and employing best practice, systematic learning and upgrading current practices. This also leads to innovation and creating of systems that are designed for each other. By using practices from the oil and gas industry and employing EPCI contracts, the contractors can reduce risk of delay between the different phases and consider the whole cycle of the project, not just their part of the contract. Kværner also focuses on simplification and “good enough.” Implementing these methods together with increase in scale has the potential to industrialize the production of the substructures and reduce the capex substantially [52].

Another way of reducing the capex of the substructure indirectly is to increase the turbine capacity. The increased capacity of the turbine will reduce the capex/MW for the substructure. All else being equal larger turbines means fewer units are required to achieve the same total capacity, which means fewer substructures, mooring lines, anchors, and electrical infrastructure.

Carbon Trust reported that a bottle neck in the supply chain was producing and installing 50 units in a single summer campaign (200 days). 50 units is an estimation of the number of units needed for a large scale FOW park. This would require a construction time of four days per substructure. This could be achieved by producing several substructures in parallel and/or create designs more suitable for serial production. A solution could be to use more than one facility to make sure the project is delivered in a timely manner [19].

Another potential way of reducing the capex of the substructure is optimizing the design and allow for technology convergence. This way there will be fewer substructure designs and the standardization process and industrialization would be simpler. M. Lerch et al. looked at the cost of three different FOW projects. They showed that manufacturing cost was highest for the semi-submersible concrete substructure, followed by TLP steel and lowest on the concrete spar. The concrete spar design uses a cheap material and a simple manufacturing process to achieve lower costs. It is well suited for mass production. In the same study the TLP had the lowest cost overall, which was a consequence of a light structure combined with tense mooring lines. This design is not self-stabilising during towing and would need additional vessels or buoyancy collars. Further research into self-stabilising TLP designs could potentially lower capex [53].

4.4.3 Mooring

As seen in figure 4.8 the mooring capex per MW is relatively stable, with a slight downwards trend. This is likely the result of increased experience with mooring, better infrastructure, and specially designed mooring solutions for FOW parks. The possible capex reduction is therefore small compared to the capex reduction expected to happen with the substructure or turbine. Some of the measures to reduce capex is refining the technology and adapt it to FOW farms.

Mooring systems have been used in the oil and gas industry for decades. These methods have been tested and improved upon and have a proven track record, but the mooring system for FOW farms is yet to be optimized. Rambøll carried out a study on the current state of mooring technology and identified key innovation needs to improve the technology. Some of the findings that have the biggest impact on cost is that mooring line failures in an FOW farm are quite likely to occur which mean that redundancy is needed. Another finding was that shallow water (<100m) is more challenging than deep water for mooring, due to the mechanical properties and dynamic loading which can increase fatigue loads. This in turn needs to be compensated for with more robust systems, which would potentially increase capex [19].

The same study found that capex reduction for mooring is likely to happen because of better understanding of fatigue mechanics, alternative mooring line materials and improved installation methods. Synthetic mooring lines could reduce capex, due to lower mass and higher fatigue performance but further research and development is needed for the long-term application of such lines. Another way of reducing capex is to connect multiple mooring lines from different wind turbines to the same anchor. This can be difficult to implement successfully as it puts restrictions on positioning of the turbines and array layout. Another obstacle is strict requirements of accuracy for anchor placements which could create increased complexity due to seabed infrastructure and seabed topology and excludes some of the cheaper anchoring solutions like drag embedment anchors [19].

Mooring is the fourth biggest capex category based on average value. Multiconsult estimates that 50% of the mooring capex are from fabricated material products, 30% from repair and installation services of equipment and 5% for transportation [39]. Important factors that influence the capex of mooring is ocean depth and seabed conditions. There seem to be little expectation of the capex of mooring equipment to drop substantially, but reduced installation time through optimizing of design and reducing the number of mooring lines and anchors needed are potential areas for reducing costs.

4.4.4 Electrical infrastructure

Compared to bottom-fixed wind farms, there are additional factors that must be included in the electrical infrastructure for FOW farms. Due to the motions of waves, FOW farms need dynamic export cables. Companies such as Aker Solutions and Nexans are suppliers of this, but the technology is still in an infant stage, and is therefore associated with cost uncertainty and reduction potential. According to Multiconsult, the market for array cables is an international market dominated by established suppliers, and has more competition compared to export cables [39]. However, for dynamic cables there is a limited number of suppliers. The case is similar for floating substations. The substations used for bottom-fixed farms have shown to be sufficiently solid to withstand the accelerations caused by wave motion, but more testing is needed before these can be utilized at a commercial level.

According to NREL, electrical infrastructure makes up 18,7% of total capex for a reference project of 600 MW. For the electrical infrastructure, distance to shore is the most important factor influencing capex. Distance to shore is difficult to change, and therefore other capex reducing measures must be focused on. Below follows some potential capex reducing measures [15].

Reduction of cable burial depth

Export cables are buried under the seabed for protection from the environment and the fishing industry. The deeper the cable is buried, the higher the cost. When burying cables, it is uncommon to consider what the seafloor consists of, despite this being a major factor in the real protection of the cable. For instance, sand offers less protection compared to clay. By modifying the cable burial depth according to what the seafloor is made of, capex can be reduced.

Floating substation

FOW farms will in many cases require floating substations. The electrical equipment of the substation must be dimensioned to withstand the accelerations of the ocean, and the structure must be designed to minimize the motions.

Carbon Trust analysed how a substation on different floating technologies, namely the semi-submersible, spar-buoy and TLP, would behave in different ocean conditions, in the North Sea, the Mediterranean, coast of Japan and the coast of California. Examination of motion characteristics showed that all three technologies gave suitable fatigue lives, both for cables and for hull. The conclusion was that floating substations are achievable with small modifications. These modifications as well as testing and qualification is required for future commercial wind farms [19].

To reduce capex, Siemens is working on an innovation to avoid using independent substations, by dividing the substations into smaller units, for example two substations with a capacity of 250 MW as opposed to one with a capacity of 500 MW. Doing so allows for the substation to be mounted on the turbine jacket, reducing the complexity of switchgears. This technology was intended for bottom-fixed turbines, but as technology progresses, it is likely that it can be translated onto floating systems as well, reducing substation capex by 40% [31].

Another key area for capex reductions in substations is standardization. Usually, substations are custom designed, but some suppliers, such as Ørsted, are working on standardised modules on the substations.

Introduction of DC power take-off

By switching to DC power collection in the array system and DC power transmission to shore, a power converter can be removed from the system. DC collection requires only two cable cores, while AC requires three. This reduces the material needed in the electrical infrastructure, and thus capex is reduced. An expected capex reduction of 1,2% is reported [50]. This would also lead to a potential 30% material reduction as array cable cores are reduced from three to two [42]. Currently, each core in the cable is connected to the offshore substation. This is a time-consuming and costly process with potential for cost reductions. According to IRENA, a large capex saving potential will be from reduction of personnel used in installation, which can be reduced to 25% of 2016 levels [54].

Upgrading from 33 kV to 66 kV array cables

The norm of array cables today is 33 kV three-core AC cables in the array system. In the QFWE database, the projects where array cable voltage is disclosed, all cables have a voltage of 33 kV, and therefore it is likely that this is the case for the rest of the projects. All cables have a limited power capacity. Depending on turbine size, a 33 kV cable can usually handle five to six turbines. Upgrading the array cables to 66 kV has two main advantages. A smaller conductor diameter to transfer an equal amount of power reduces capex. Higher voltage reduces power losses during transmission. As an example, a 33 kV cable of 630 mm^2 copper can transmit 40

MW, which would be equal to five of the Hywind Tampen turbines. With a 66 kV cable, the capacity would double to 80 MW [42].

Array cable material

Copper is the main material used in array cables. Compared to alternative materials, the price of copper has increased over the years which impacts cable capex. An alternative to copper is aluminium. Aluminium in cables are more expensive to install, but this is outweighed by the overall reduction in material costs [55].

4.5 Key capex reducing measures.

Table 4.5 lists important cost reducing measures that affects the whole project.This information is gathered from 168 wind energy experts for private wind industry, public R&D institutes, academia, and other organizations. The table presents these experts' rating of how impactful the cost reducing measures will be on LCOE.

Table 4.4 Key cost reducing measures. Results from questionnaire of 168 wind energy experts. Adapted from [56].

Cost reducing measure	Percentage of experts rating item "Large expected impact"	Mean rating 3 – Large impact 2 – Median impact 1 – Small impact 0 – No impact
Installation process efficiencies	78%	2,7
Economies of scale through increased project size	65%	2,6
Installation and transportation equipment advancements	63%	2,5
Improved component durability and reliability	58%	2,5
Reduced financing costs and project contingencies	46%	2,3
Increased competition among suppliers	46%	2,2

5 Discussion

This chapter discusses the limitations of the thesis and the results. The purpose of this chapter is to critically assess the thesis' method and results and to discuss contexts and relations of the results.

5.1 Limitations

This thesis seeks to identify capex drivers and the possibility for capex reductions. To do so, a data collection of capital expenditure from 16 FOW projects was performed. Only one of these projects has been completed, while the remaining are either under development or planned. The true capex of a project is unknow until all invoices are paid. Therefore, there is an unavoidable uncertainty related to the capex' in this thesis. However, to indicate the order of which capex drivers have the biggest contribution to total capex should still be credible, considering the large differences between the capex of each category.

The data collection of capex performed in this thesis uses a selection of sources. These sources operate with various currencies and various dates for the given currency. Currencies have not been adjusted to inflation due to most costs occuring in recent years.

Similarly to currency, different reports operate with different capex categories. A common example is to include electrical infrastructure with substructure into a category called "balance of system." Hywind Tampen is divided into the following contracts: turbine, turbine maintenance, substructure, mooring, cable, and cable installation. Different methods of reporting capex make it difficult to compare projects on an equal basis. This, in addition to the small number of completed projects, reduces the available amount of data, and affects the accuracy of the analysis. More data would open the possibility to use econometric methods such as regression analysis and controll for project parameters. This would allow for results that could show statistical significance and increase the credibility of the thesis. Unfortunately, the FOW market lacks maturity for such amount of data to be available. As there is scarce data material to examine, this thesis relies on cost models from various sources. All such models are associated with some degree of uncertainty which is difficult to verify. A cost model is only as reliable as the input information.

Another limitation is that this thesis is confined to capex. The most informative measure of an energy technology's economic viability is LCOE, where capex is part of the equation. This is important to be aware of when discussing capex reducing measures. A capex reducing measure does not necessarily reduce the LCOE of a project, because the measure can lead to increase in opex, a reduced project lifetime, reduced annual energy production, or other effects that increases LCOE.

5.2 The future of floating offshore wind farms

The future of FOW projects will depend on multiple factors. Two likely scenarios are: FOW projects become economically viable and an economical incentive exists to drive development, or economically viable FOW parks are not possible, and development must be motivated by factors that are not profit oriented.

This thesis investigates the potential for economically viable FOW projects, mainly through the potential for capex reduction. This reduction will happen through innovation and development of the different subcategories of an FOW turbine, and the development of infrastructure and supply chain so that upscaling is possible. In the event of economically profitable FOW projects the market will be responsible for development.

In the second scenario where FOW projects are not expected to become economically viable it is likely that governments will have to facilitate this development through direct involvement or incentives. In this scenario FOW farms will likely be used in special situations, where there are limited alternatives. An example is to replace electricity from gas with wind like seen in the Hywind Tampen project.

At the time of writing, FOW farms exists in an early stage, and both scenarios are possible outcomes. Private companies develop pilot and pre-commercial farms, which rely on subsidies to be able to compete economically. Governments, like the French and South Korean have plans for tenders of large FOW farms, and governmental subsidiary schemes are available in certain markets. There are multiple commercial scale farms planned or in development, but the total cost of these project will not be known before completion. The future looks promising, but to get to the point of maturity needed, challenges must be overcome. If and how these challenges are solved will determine which of the two scenarios will play out.

The prevalence of FOW farms is also dependent on the development of other renewable energy technologies, and how these compete on price. But FOW energy can be attractive in some scenarios regardless of the development of the other renewable energy sources. At the same time as FOW energy can be beneficial compared to other sources, the fact that the power output varies with the wind makes it difficult to rely on FOW as the sole energy source.

5.3 Estimated capex development for floating offshore wind projects

Figure 4.2 shows the estimated capex/MW and LCOE for the projects included in this thesis. These projects have been sorted by completion date and the graph shows that capex is falling. The projects with completion after 2023 have an estimated LCOE ranging between \$80/MWh and \$140/MWh which is in the range of LCOE for offshore bottom-fixed wind farms completed in the last two years. Bottom-fixed wind farms have seen a substantial cost reduction, but there is a limited supply of sites with shallow water and good wind conditions and therefore some of the cost reducing efforts made are countered by the increased distance from shore and water depths. It is possible that floating wind will be able to compete with bottom-fixed on LCOE in the long run, but FOW farms are more likely to co-exist with bottom-fixed wind farms rather than replace them. FOW is also benefiting from the development and learning experienced in the other wind energy sectors which might help drive down cost.

One argument that supports the capex reduction estimated in figure 4.2 is the expectation of turbines with larger capacity in the future. As the turbine capacity increases, fewer are needed to achieve the same combined capacity. This results in a capex reduction per MW in some of the other capex categories because fewer substructures, mooring lines and anchors are needed. Larger turbines will require bigger dimensioned substructures, mooring lines, and anchors. The unit cost will increase with the turbine capacity, but capex/MW will decrease if everything else is kept equal.

A second argument supporting the estimated capex reduction in capex/MW is savings through economies of scale. This can only happen if infrastructure and supply-chain is developed. The scaling of FOW projects could have a big impact on procurement costs, and unit cost for installation and fabrication [19]. This is to some extent the essence of the paradox mentioned in the problem definition. Due to the current cost of FOW projects investments are not happening at the scale that is needed to drive development of infrastructure and supply chain. It is possible that the uncertainty regarding the cost reduction from economics of scale, together with the uncertainty related to the development of turbine technology and cost reducing measures, keeps investors from investing in FOW projects, infrastructure, and suppliers.

5.4 The main capex drivers

The main capex drivers have been identified with an average percentage contribution to capex as: turbine (37,76%), substructure (23,82%), electrical infrastructure (13,97%), and mooring (12,08%). Below is a discussion about the potential capex reducing measures within each category.

5.4.1 Turbine

When measuring capex/MW, the turbine is the part of the FOW farm that has the least variability. A likely reason for this is that the turbine is one of the most mature technologies of the FOW farm. This is because the same turbines used in onshore and bottom-fixed can be used in floating applications, with small adjustments [57]. Looking at the variation in the turbine's contribution as a percentage gives more variation. The trend is that bigger turbines make up a larger share of capex. Bigger turbines are commonly pointed as the most important technology development to reduce the total cost of FOW projects. This is simply because bigger turbines allow for fewer turbines that can deliver the same power output, and thus less material is needed for the other parts, as mentioned earlier. This is particularly the case in projects that are extra far from shore, or in challenging environments, as this leads to an increased installation cost. Then, bigger turbine allows for less effort spent on installation.

5.4.2 Substructure

The substructure is identified as one of the areas with the biggest potential of reducing capex. The capex reducing measures mainly fall into two categories: industrialisation and innovation. The industrialisation category includes all processes for constructing the substructures, and the innovation category includes improvement in design, by simplifying installation, using less and using alternative materials. From table 4.5 substructure design advancement was identified as the area that experts believed had the biggest expected impact for reducing LCOE. Manufacturing standardization, efficiency and volume was expected to have the third biggest impact on LCOE reduction. Another key focus should be on localization, so that the substructure can be manufactured as close to location as possible. Scaling up production of the substructures together with building of infrastructure will reduce unit costs. Design choices and supply chain is where key innovations are expected [25].

An estimate from Multiconsult shows that material capex make up 50% of total capex of a substructure. One capex reducing measure is to reduce the material needed by optimizing the design. Different substructure designs have been presented and the TLP design is the design which is likely to have the smallest material cost, but this results in more difficult transportation and more complex mooring [39].

A key area for capex reduction for all parts of FOW projects is standardization. The potential for standardization has been one of Equinor's arguments for using the spar technology for substructure , and is also a key focus for Ørsted in the development of floating substations [18]. An obstacle for FOW farms is the different characteristics from project to project, such as depth or port facilities. This affects the possibilities of a standardised substructure concept. Additionally, leading companies have their own patented concepts, such as Equinor’s Hywind or Principle Power’s WindFloat. Managing to standardise the different components of FOW, especially the substructure, would be an important step towards reducing capex. Another issue with companies owning intellectual property is that they have invested interests in using their technology. Instead of evaluating the best substructure design for each project, developers are locked to a certain design. This can be a hindrance to technology convergence and optimization of the substructure design, where the best and cheapest solution for each project are not chosen because of proprietary designs. This is a contrast to bottom-fixed turbines where project designs have mainly been driven by cost, developers or EPCI contractors [25].

The figures in chapter 4.3.2 show that there is a relationship between year of completion, total capex, and substructure capex per MW. The most important challenges to overcome is material reduction and designs that meet all requirements but at the same time is easy to manufacture. The spar design is easy to manufacture and can use cheap material like concrete, but the drawback is the deep draft which limits potential sites and ports. The semi-submersible and spar solution is more costly to construct but have less draft.

5.4.3 Mooring

Mooring capex is dependent on water depths, amount of lines required and seabed conditions. Ocean depth and soil condition for the parks analysed in this thesis are not disclosed. Therefore, it is difficult to control for water depths and soil condition when comparing capex.

The figure in chapter 4.3.3 shows a trend for reduction in mooring capex when sorted by completing date. This is partly due to an increase in turbine size, which results in less capex per MW for mooring. The development of low-cost installation methods is going to be important for reducing overall capex. A commercial scale FOW farm will consist of hundreds of mooring lines. Efficient top connectors and anchors with improved stability will be a key factor. Like substructure, component standardisation to unlock economies of scale is needed. In other words, greater design consolidation in the industry could potentially lower capex [19].

Mooring technology is a mature technology which has been used in the oil and gas industry for a long time. The mooring systems must retain the best features of the current low-cost mooring solution but be adapted to the needs of FOW farms. Design that allows for simple, safe, and fast connection and disconnection for the mooring lines to the substructure is needed. Design innovation and anti-corrosion innovation is expected to reduce maintenance and service cost for mooring lines which would impact LCOE, but not capex [25].

5.4.4 Electrical infrastructure

As FOW farms are placed further ashore, the capex of export cables will increase due to the increased length. For the projects in this thesis there is little variation in capex of electrical infrastructure per MW, except for at Kinkardine Tranche 2 and Hywind Scotland. The two projects likely have higher costs due to being completed earlier than the rest, not benefiting from learning rate and other potential capex reducing measures. The remaining projects have a capex of electrical infrastructure ranging from \$0,4M/MW - \$0,67M/MW and a distance to shore ranging from 8 km – 53 km. Hywind Tampen is excluded from this range because the project's distance to shore is irrelevant as it is connected to the oilfields Snorre and Gullfaks. The distance to these fields is not disclosed.

Intuitively one would expect a bigger variation in the capex of electrical infrastructure when distance varies this much. There can be different reasons to why this is not the case. Different project characteristics can lead to varying cost. This is mentioned in the section about the thesis' limitations. Four projects have floating substations, three do not, and the remaining have not disclosed this. A floating substation will lead to increase cost, as opposed to projects that for instance use already existing substations at platforms. Additionally, the projects have varying export cable voltage, ranging from 33kV-155kV. Variations like this make it difficult to compare the real cost of electrical infrastructure from project to project.

5.5 Externalities

Externalities do not directly affect a project's LCOE, but more than LCOE should be assessed when determining whether an FOW farm is a viable option as an energy source. Some of them are discussed below.

A common issue with big projects is the "not in my backyard" problem, also known as "NIMBY" or nimbyism. Nimbyism is opposition towards a project from those who live close to the project, despite it being beneficial to society. Onshore wind farms have frequently met opposition due to locations being close to homes or being in previously untouched nature. Tellenes Wind farm in Egersund, Norway and Frøya Wind farm in Frøya, Norway are examples [58] [59]. FOW farms solve this problem to some degree. By being placed out of sight offshore, there are less opposition compared to onshore farms. Yet, it is common to meet opposition from fishers and animal welfare activists. Unfortunately, some form of opposition is unavoidable.

Oil companies are including renewable technology in their investment portfolios. Equinor's Hywind Tampen is a common example. An argument for including renewables in a usually highly profitable oil production portfolio is to prepare for the future where the world attempts to be less reliant on fossil energy. Another aspect of these investments is the intangible public relations effect. With the increased focus on climate change, "green washing" has risen as a term. Oil companies are accused of shifting the focus of their core business to their new renewable energy focus and using this as a "licence to operate".

No company will admit to "greenwashing", as this would diminish the positive public relations effects from such investments, but there is an imbalance between the focus on core business versus renewables, and the energy production from the two. Despite this, greenwashing can be a driving force for the development of renewables, regardless of intentions.

Another benefit of FOW farms is the benefit of producing electricity without emitting pollutants. In areas where the main source of electricity stems from technologies such as coal power plants or diesel generators, a positive externality is an improved local air quality. This is difficult to include in an LCOE calculation but is a large benefit of the technology.

5.6 Uncertainty

A part of the purpose was to identify the uncertainty that the FOW market is facing to make investments in the market more attractive. Quantifying this uncertainty in any meaningful way has proven to be difficult, and what follows in this chapter is an identification of the different types of uncertainty present in FOW projects, together with a discussion of potential ways to reduce the uncertainty in each category.

5.6.1 Estimate uncertainty: model and input uncertainty

One of the challenges when trying to quantify cost uncertainty is the uncertainty which relates to the accuracy of the cost predictions, i.e. how accurate these estimations are compared to the actual cost. This is defined as model error and is present in all cost estimations. Due to only one project being completed and a few in development, as well as companies not revealing their contracts, there is limited availability of true costs in FOW projects. This makes it difficult to verify the accuracy of these cost predictions, both from the QFWE database and other sources. Their own estimates of accuracy must be used, which introduces more uncertainty. By comparing multiple sources of cost estimations some of this uncertainty could be reduced.

Hywind Scotland should have the lowest uncertainty, where the reason for uncertainty mainly is a result of access to accurate costs. Secondly, the projects under development should have lower uncertainty compared to projects in the planning phase because the further away the completion dates are the more difficult it is to make predictions. This is often referred to as the cone of uncertainty. Uncertainty of the cost estimate is large in the concept phase and as the project progresses the uncertainty is reduced, up until completion when the capex of the project is known. Even if the cost estimation does not change as the project progresses the underlying uncertainty of the cost estimation will, because more information becomes available.

The project costs from the QFWE database that are derived from the cost model have greater uncertainty compared to those who are sourced from industry relations, because these are based on assumptions. These assumptions are defined as input uncertainty. How good the model estimate is, is unknown until the projects are complete. This means that the model output, which is defined as the uncertainty about the magnitude of the model error, is high.

5.6.2 Event uncertainty: Technology, markets, and regulations

Event uncertainty is the uncertainty about an event happening and the consequence of this [60]. The outcome of these events affect the possibility of FOW to become commercially viable.

There is a recognition that it is necessary with regulations for FOW *ex ante* to accelerate the development and make it more attractive as an investment. The regulations include regulations for sea activities, permitting and licencing, grid connection and standards [61]. If governments get involved a country could capitalize on the first mover advantage, to establish supply chain and generate jobs, and at the same time make sure that cost reduction continues through economies of scale, by having low financing costs through "green loans" or subsidise and funding of research and innovation [25].

A questionnaire distributed to the relevant actors within the industry in the UK found some of the similar industry needs regarding policy making. These findings were availability of seabed rights for developing of floating wind sites, revenue support for pre-commercial parks up to 100 MW, public co-investment with private investors in assets such as port and fabrication facilities [57].

Based on this, government regulations are identified as a key factor for reducing uncertainty. Defined goals for FOW capacity and supporting policies from government can stimulate the growth of the current FOW market, and act as driver for development of new technology and supply chain.

Another uncertainty reducing measure is joint ventures. By seeking alliances with others and collaborate, instead of competing, the risk is shared and some of the uncertainty regarding the availability and price of technology is reduced. An example of this kind of alliance is Aker Solution investing in Principle Power which is a technology and service provider for FOW, and the developer of the WindFloat substructure technology [62].

6 CONCLUSION

This chapter will summarize the findings which are based on capex estimations from the FOW database and a comprehensive literature study by answering the four research questions

What are the main capital expenditure drivers of floating offshore wind farms?

The main capital expenditure drivers in an FOW farm have been identified. The biggest capex drivers are the turbine, the substructure, the electrical infrastructure, and the mooring system, sorted by biggest capex driver. The total capex/MW seems to stabilise at $4M/MW. Each subcategory has the following average capex/MW:

- Turbine: $1,61M/MW
- Substructure: $1,07M/MW
- Electrical infrastructure: $0,61M/MW
- Mooring: $0,52M/MW

The average share of capex is the following:

- Turbine: 37,8%
- Substructure: 23,82%
- Electrical infrastructure: 13,97%
- Mooring: 12,08%

What are the possible measures for reduction in each capital expenditure category?

Some capex reducing measures are common for all categories. Achieving economies of scale, standardization and weight reduction will be important measures to reduce capex. The most effective measures for reducing capex in each category is presented below.

Turbine - Cost reductions can be achieved by replacing buoyancy-improving mass with cheaper turbine control systems. Furthermore, implementing continuously variable transmission drive trains will make the power converter redundant.

Substructure - Some of the important cost reducing measures for the substructure is to optimize the design for mass production and reduce material costs. Standardization of the substructure and simplifying the manufacturing process are other important measures.

Mooring - For mooring, optimizing the amount of mooring lines and anchors, and standardising the equipment for a simpler installation process is going to reduce costs. The use of alternative mooring line materials is likely to reduce costs but better understanding off the fatigue mechanics is needed.

Electrical infrastructure - An effective cost reducing measure would be to consider the seafloor when laying cables. In some conditions, for example under clay, it is not necessary to bury the cable a full meter beneath the seafloor. Currently, this is not considered, and all seafloors are treated equally, leading to an unnecessary cable burying depth at some locations. By optimizing this, installation cost of electrical infrastructure could be reduced.

What is estimate and event uncertainty for a floating offshore wind project?

Quantifying the uncertainty for an FOW farm proved to be difficult, but the event and estimate uncertainty was divided into subcategories and discussed. The estimate uncertainty was divided into input uncertainty and model error. Both categories contribute to uncertainty in cost estimations for FOW farms. Lack of historical data and a rapid developing technology together with long project duration creates most of this uncertainty. Event uncertainty has been divided into technology uncertainty, market and supply uncertainty and funding and regulation uncertainty. Much of the event uncertainty is caused by the uncertainty about the market for FOW wind and the development of supply chain. A need for regulations for FOW to accelerate development was expressed by the industry. Government regulations was identified as a key factor for reducing event uncertainty.

What is required to make floating offshore wind farms commercially viable?

The simple answer to this question is to reduce costs and/or increase earnings so that earnings are greater than costs. A more nuanced answer is that there are multiple factors that influences both the costs and earnings of FOW farms and improving upon each of these factors would move FOW farms towards becoming commercially viable. The potential for cost reduction has been discussed, and costs are expected to decrease. The estimations show that LCOE for the commercial sized FOW farms, planned from 2022, is approaching the LCOE for bottom-fixed wind farms built today. However, the LCOE for FOW is still higher than other energy technologies.

Reducing capex through innovation and cost reducing measures within each of the main capex categories is an important step. In addition, increasing scale and a develop supply chain is identified as important measures. With today’s market and technology maturity, government involvement through subsidization and regulations is identified as an important measure for stimulating growth and reducing uncertainty.

Even with costs expected to fall substantially it is still unknown if FOW farms will ever become commercially viable. Two likely scenarios were presented in the discussion. One where the technology becomes commercially viable and development is mostly driven by the market and the second where the technology is not expected to become commercially viable in the foreseeable future and development is driven by factors other than profit. Few investors are willing to make investments which are not expected to generate profits and therefore the driving force for FOW development will likely be the positive externalities. This means governments involvement will be a key factor for development and the future of FOW farms.

6.1 Future work

For future work on this topic it would be interesting to look at both operational expenditure and annual electricity production. Optimising these are important steps towards achieving commercially viable FOW projects and there is a big focus on developing bigger turbines that generate more power as well as preventative maintenance strategies which can reduce opex.

Currently, there is very little data available on the true costs of FOW projects, especially of a size that can reap the benefits of economies of scale. When there are more completed projects and exact cost data, a regression analysis to show which factors are most effective to reduce costs would be beneficial as it would provide a more accurate answer on which measures and concepts to further develop.

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Appendix

Project	Substructure share of capex [%]	Turbine share of capex [%]	Mooring share of capex [%]	Electrical infrastructure share of capex [%]	Installation share of capex [%]	Other share of capex [%]
Toda Sakiyama	30,84 %	30,84 %	14,95 %	10,28 %	3,74 %	9,35 %
Lake Erie	25,98 %	39,37 %	11,02 %	9,45 %	3,15 %	10,24 %
Hywind Scotland	27,35 %	33,33 %	10,68 %	16,24 %	2,56 %	9,83 %
Hywind Tampen	32,31 %	31,28 %	15,38 %	8,72 %	2,31 %	10,00 %
Kinkardine Tranche 2	26,18 %	37,66 %	7,98 %	15,71 %	2,49 %	9,98 %
Humboldt Bay (Redwood)	25,20 %	38,20 %	10,40 %	14,40 %	2,20 %	9,40 %
White Heron	20,16 %	37,23 %	16,53 %	14,11 %	2,82 %	9,41 %
Donghae 1	22,45 %	36,16 %	10,97 %	17,49 %	2,74 %	10,18 %
Hywind Scotland II	23,28 %	44,02 %	10,05 %	10,05 %	2,67 %	10,05 %
Donghae TwinWind	17,84 %	40,64 %	18,22 %	11,28 %	1,98 %	10,04 %
Gray Whale	32,47 %	31,02 %	13,77 %	11,20 %	2,35 %	9,41 %
W 1 N - Taouyuan	15,57 %	42,99 %	12,78 %	16,19 %	2,61 %	9,99 %
Plambeck Floating Windfarm	18,69 %	41,52 %	11,86 %	15,82 %	2,52 %	9,53 %
KFWind	21,63 %	38,85 %	9,09 %	18,00 %	2,45 %	9,98 %
Progression South	22,10 %	39,74 %	9,49 %	16,59 %	2,49 %	9,54 %
Castle Wind	19,08 %	41,28 %	10,10 %	18,06 %	2,47 %	9,00 %

Figure 7.1 Data from the QFWE database - category share of capex

Project	Total capex [$M]	Capex/MW [$M/MW]	LCOE [$/MWh]	Completion date [year]	Substructure type	Material of substructure
Toda Sakiyama	107	5,4	172,3	2022	spar	concrete
Lake Erie	127	4,2	113,1	2023	semi spar	steel
Hywind Scotland	234	7,8	220,1	2017	spar	steel
Hywind Tampen	390	4,4	121,1	2022	spar	concrete
Kinkardine Tranche 2	401	8,4	260,2	2020	semi sub	steel
Humboldt Bay (Redwood)	500	3,3	105,1	2026	semi sub	steel
White Heron	744	3,7	104,5	2026	semi spar	steel
Donghae 1	766	3,9	111	2024	spar	steel
Hywind Scotland II	786	3,1	88,7	2024	spar	steel
Donghae TwinWind	807	4	113,4	2024	semi sub	steel
Gray Whale	893	4,5	125,4	2026	barge	concrete
W 1 N - Taouyuan	1612	3,2	96	2023	spar	concrete
Plambeck Floating Windfarm	1669	3,3	97,5	2025	semi spar	steel
KFWind	1794	3,6	100,1	2024	semi sub	steel
Progression South	2086	3,5	101,8	2025	semi sub	steel
Castle Wind	3355	3,4	98	2028	semi sub	steel

Figure 7.2 Data from the QFWE database - miscelleanous facts.

Project	Distance to shore [km]	Turbine capacity [MW]	Number of units [#]
Toda Sakiyama	8	4	5
Lake Erie	10	6	5
Hywind Scotland	25	6	5
Hywind Tampen	140	8	11
Kinkardine Tranche 2	15	9,5	5
Humboldt Bay (Redwood)	35	10	15
White Heron	50	8	25
Donghae 1	30	8	25
Hywind Scotland II	-	10	25
Donghae TwinWind	50	10	20
Gray Whale	50	8	25
W 1 N - Taouyuan	20	10	50
Plambeck Floating Windfarm	16	10	50
KFWind	50	9,5	53
Progression South	14	9,5	63
Castle Wind	53	10	100

Figure 7.3 Data from the QFWE database - miscelleanous facts.

Project	Export cable [kV]	Array cable [kV]	Floating substation [Yes/no]	Connected to shore [Yes/No]
Toda Sakiyama	N/A	N/A	No	Yes
Lake Erie	N/A	N/A	N/A	N/A
Hywind Scotland	33	33	No	Yes
Hywind Tampen	66	33	Yes	No
Kinkardine Tranche 2	33	33	No	Yes
Humboldt Bay (Redwood)	N/A	N/A	Yes	Yes
White Heron	110	N/A	N/A	Yes
Donghae 1	66	33	N/A	N/A
Hywind Scotland II	N/A	N/A	N/A	N/A
Donghae TwinWind	155	N/A	Yes	N/A
Gray Whale	N/A	N/A	N/A	N/A
W 1 N - Taouyuan	N/A	N/A	N/A	N/A
Plambeck Floating Windfarm	N/A	N/A	N/A	N/A
KFWind	155	N/A	Yes	N/A
Progression South	N/A	N/A	N/A	N/A
Castle Wind	N/A	N/A	N/A	N/A

Figure 7.4 Data from the QFWE database - miscelleanous facts.

Table 7.1 Turbine contribution to capex and turbine capacity for each project.

Project	Turbine contribution to capex [%]	Turbine capacity [MW]
Toda Sakiyama	30,84	4
Gray Whale	31,02	8
Hywind Tampen	31,28	8
Hywind Scotland	33,33	6
Donghae 1	36,16	8
White Heron	37,23	8
Kinkardine Tranche 2	37,66	9,5
Humboldt Bay (Redwood)	38,20	10
KFWind	38,85	9,5
Lake Erie	39,37	6
Progression South	39,74	9,5
Donghae TwinWind	40,64	10
Castle Wind	41,28	10
Plambeck Floating Windfarm	41,52	10
W 1 N Taouyuan	42,99	10
Hywind Scotland II	44,02	10