Norwegian School of Economics
Bergen, Spring, 2023

From Idealism to Pragmatism: Exploring the Cost Realities of Offshore Wind Development in Norway

A Monte Carlo Approach with Emphasis on Cost Uncertainties

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Master Thesis in Economics and Business Administration

Major: Financial Economics & Energy, Natural Resources, and Sustainability

NORWEGIAN SCHOOL OF ECONOMICS

Acknowledgments

This thesis finalizes our master's degree in Economics and Business Administration with majors in Financial Economics & Energy, Natural Resources, and Sustainability at the Norwegian School of Economics (NHH). Writing this thesis has been both challenging and rewarding, allowing us to delve deep into a highly relevant research area.

We would like to express our heartfelt gratitude to our supervisor, Stein Ivar Steinshamn, for his invaluable support, guidance, and engaging discussions throughout the semester. Additionally, we extend a special thanks to Jan Emblemsvåg for his feedback and comments during the spring. We would also like to thank our friends and family for their contributions to making our five years at NHH memorable.

Norwegian School of Economics

Bergen, June 2023

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Abstract

This thesis addresses the inherent uncertainties associated with the cost of offshore wind deployment in Norway. The primary objective of this study is to provide a realistic estimation of the comprehensive cost involved in establishing and operating an offshore wind farm while investigating the influence of uncertainty in key cost variables. To achieve this objective, this study incorporates historical data from fully commissioned European offshore wind projects and employs Monte Carlo simulation to estimate the levelized cost of electricity. Furthermore, a sensitivity analysis is performed to explore the impact of fluctuations in key cost variables. The findings of this research unveil the potential for the LCOE of a Norwegian offshore wind farm to exceed previous assessments. This disparity may be attributed to the recent development of inflation and interest rates. Additionally, the analysis highlights the significant uncertainties inherent in cost estimation and emphasizes the substantial influence exerted by the variability in key cost variables. These observations emphasize the importance of considering the prevailing economic condition when evaluating offshore wind projects. Considering the Norwegian government's ambitious plans to allocate significant offshore areas for wind energy generation, this research highlights the necessity of conducting a comprehensive assessment before deploying plans.

Abbreviations

CAPEX	Capital Expenditure
CfD	Contracts for Difference
DECOM	Decommission Expenditure
DPB	Discounted Payback
EC	European Commission
FID	Final Investment Decision
HAWT	Horizontal Axis Wind Turbine
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IRR	Internal Rate of Return
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
MCDM	Multi-criteria decision-making
MCS	Monte Carlo Simulation
NPV	Net Present Value
OW	Offshore wind
OWF	Offshore Wind Park
OPEX	Operational Expenditure
PPA	Power Purchase Agreement
SPV	Special Purpose Vehicle
TSO	Transmission System Operator
VAWT	Vertical Axis Wind Turbine
WACC	Weighted Average Cost of Capital

Applied exchange rates[1]

EUR/NOK	11.548
EUR/USD	1.095
EUR/GBP	0.861

[1] The applied exchange rates are from the Norwegian central bank on May 10th 2023 (Norges Bank, 2023).

Contents

List of figures

List of tables

1. Introduction

Climate change is a global challenge that must be solved beyond national borders and requires international cooperation and coordinated solutions (UN, 2022a). The European Union (EU) is among the 196 parties that joined the Paris Agreement, a legally binding treaty, to address the issue. They set long-term goals and commitments to reduce their greenhouse gas (GHG) emissions and to prevent global warming to no more than 1.5°C. To do so, GHG emissions have to be reduced by 45% by 2030 and reach net zero by 2050 (UN, 2022b). The EU's Green Deal wants Europe to be the first climate-neutral continent by 2050, while Norway was among the first countries to submit an enhanced emission reduction target (EC, 2022a; UD, 2022). Both Norway and the EU want to cut their GHG emissions by at least 55% by 2030 compared to 1990 levels and will, if they succeed, have cut global emissions by less than 6%[2] (EEA, 2022b; Eurostat, 2022; SSB, 2022; Statista, 2023e).

Renewable[3] electricity emerges as the most critical driver to achieve net-zero emissions and will subsequently increase electricity demand (IEA, 2021). To reach its climate targets, the EU must fivefold its renewable electricity production by 2040 and install four times more wind and solar capacity annually than in the last decade (CAN, 2022). In Norway, a range of electrification initiatives anticipates driving up power consumption by as much as 23 TWh by 2040 (NVE, 2020). The increased demand expects to result in a power deficit in Southern Norway by 2025 and across the country by 2027 (Statnett, 2022).

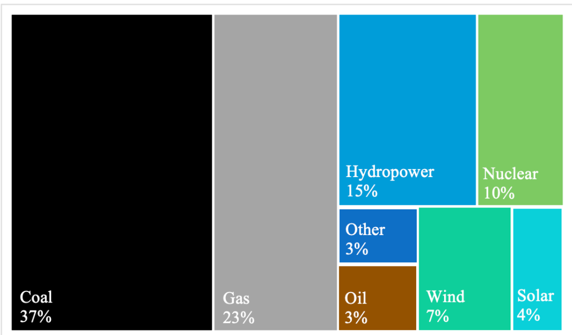

Figure 1.1: *Global electricity generation by source in 2021, data from Statista (2023c)*

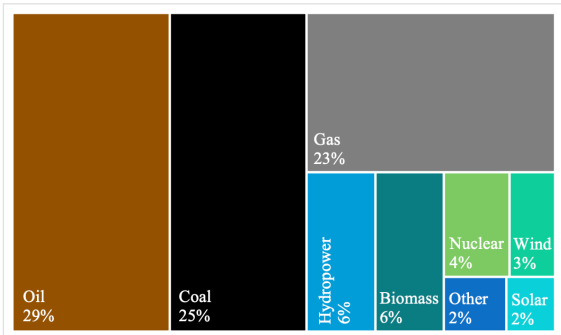

Figure 1.2: *Global primary energy by source in 2021, data from OWD (2023)*

Various geopolitical and economic factors have prompted a downward revision of European GDP projections for 2023 (IMF, 2023). These factors include the lingering effects of the COVID-19 pandemic, the Russian invasion of Ukraine, heightened inflation rates, and energy-related challenges, such as reduced nuclear production in France, closures in Germany, and

[2] If global emissions remain constant from 2022 levels.
[3] Include the following energy technologies: solar, wind, hydro, geothermal, ocean, and modern bioenergy.

decreased wind output in numerous Northern European wind farms. However, global electricity demand growth is expected to rebound in 2023 (IEA, 2023). By 2025, a 9% increase in electricity demand equivalent to 2 493 TWh will increase the overall global demand to 29 281 TWh. The increased demand is roughly equal to the total electricity consumption of the EU and has to be added in less than three years. According to IEA, renewables and nuclear energy will account for 2 450 TWh of added electricity production by 2025, equivalent to 98% of the increased global demand.

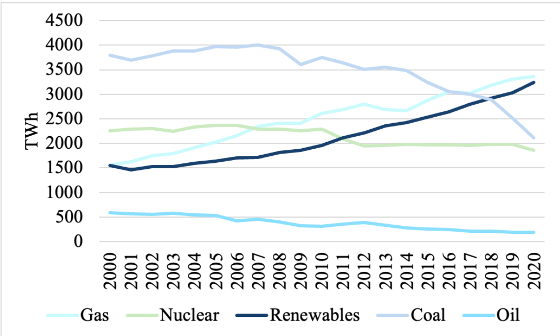

Figure 1.3: *Electricity generation in the OECD by source, 2000-2020, data from IEA (2022b)*

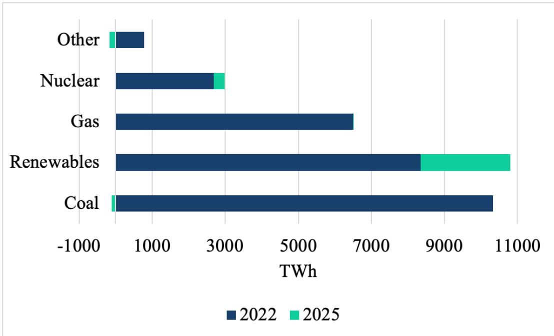

Figure 1.4: *Change in global electricity generation by source, 2022-2025, data from Ember (2023)*

The EU's Renewable Energy Directive (RED) from 2009 set a target of a 20% share of renewable energy sources by 2020 in the final energy consumption (EC, 2022d). The COVID pandemic reduced the final energy consumption in the EU by 8% and helped the EU reach this target, as renewables accounted for 22.1% of the share of consumed energy (CAN, 2022). The year after, renewables accounted for 22.2%, up 0.1% (EEA, 2022a). The EU revised the RED in 2018 and established a new binding renewable energy target for 2030 of 32%, which followed a proposal by the European Commission (EC) in 2021 to raise the target to 40% (EC, 2022d). In response to the Russian invasion of Ukraine and the disruption of global energy markets, the EC presented the REPowerEU Plan in 2022, with a further increased target of 45%. The EUs modest increase of 0.1% in the proportion of renewable energy sources within the final energy consumption between 2020 and 2021 highlights the challenge it faces in achieving its 2030 target of 45%. In order to surmount this challenge, the EU must embark on an accelerated expansion of renewable energy deployment.

Renewables represented 39% of the generated electricity production in the EU in 2020 and were, for the first time, bigger than fossil fuels, generating 36% (EC, 2022c). In 2022, 22% of the EU electricity came from wind and solar, for the first time overtaking gas, which generated 20% (Ember, 2022). During 2022, a 1-in-500-year drought across Europe resulted in the lowest hydro generation since 2000, together with reduced nuclear generation. Increased wind and solar generation and decreased electricity demand filled 83% of the gap, while increased use of coal fulfilled the remaining. The year's energy shocks resulted in an accelerated clean power transition, with the EU countries committed to phasing out coal and striving to replace gas. Despite Germany's plan to phase out coal by 2030, coal-fired power plants accounted for 36.3% of the country's electricity in Q3 2022, reflecting a year-on-year increase of 4.4%. Moreover, there was a significant rise of 13.3% in coal-to-power generation output. (Eckert & Sims, 2022). In 2023, hydro generation is expected to rebound together with French nuclear units, but the most peculiar change is the accelerated deployment of wind and solar (Ember, 2022).

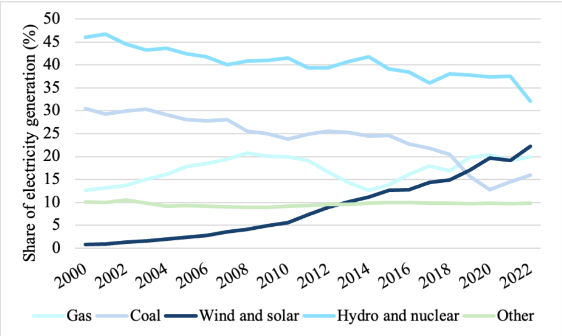

Figure 1.5: *Development in electricity generation in the EU by source, data from Ember (2023)*

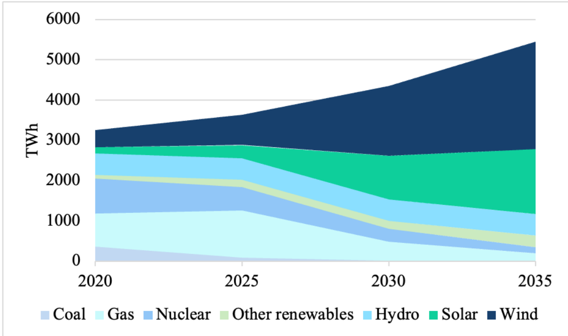

Figure 1.6: *1.5°C pathways to clean power by 2035 in Europe, data from Ember (2023)*

As of 2022, Europe has a total wind power capacity of 255 gigawatts (GW), representing slightly over 30% of the global capacity (WindEurope, 2023a). WindEurope anticipates that the EU will install 20 GW of new annual capacity between 2023 and 2027, which falls short of the estimated yearly average of 31 GW necessary to fulfill the REPowerEU target. In 2022 19 GW of new wind capacity was installed. The EC has acknowledged that it needs to increase the use of renewables in the electricity segment to 69% to reach its target[4] (IEA, 2022c). According to IEA, the average annual addition of wind power in a main and an accelerated case between 2022-2027 is 17 and 21 GW, respectively, which accumulated will result in a capacity of 290 or 316 GW in 2027. IEA further estimates that the EU's installed capacity by 2030 has to be 510 GW to reach the REPowerEU target. This requires an annual installed capacity of nearly 36 GW, or 19 GW of additional annual capacity, in addition to the predicted main case installation scenario. Given the disparity between the required and the projected realistic installed capacity by 2030, offshore wind has emerged as a potential solution.

[4] The transport segment must also reach a 32% share of renewables in 2027, in addition to an annual increase of 2.3% and 1.9% in the renewable share in the heating & cooling and industry segments, respectively.

1.1 Motivation for researching Offshore Wind

Offshore Wind (OW) has emerged as a vital resource for achieving net zero emissions by 2050, with a growing emphasis on its significance as part of the Green Deal (EC, 2022c). The EC's target of a 55% GHG emission reduction further highlights the importance of OW in mitigating climate change. The Russian invasion of Ukraine has raised the need to reduce Europe's gas dependence (IEA, 2022a). Simultaneously, the US Inflation Reduction Act (IRA) has set expectations for the EU's response to funding, programs, and incentives that may accelerate the transition to clean electricity production (IISS, 2023). Considering the IRA's significance as US history's most comprehensive climate legislation, renewable energy development, including OW, is expected to gain global momentum, particularly in Europe, through additional legislative measures (EP, 2022). However, China leads the market, having installed more OW in 2021 than the rest of the world during the past five years[5] (Statista, 2023c; Vetter, 2022). For instance, the city of Chaozhou plans an offshore wind farm (OWF) that will produce more energy than all Norwegian power plants combined (IEEFA, 2022).

OW was first mentioned in a Norwegian parliamentary notice in 2007 (St. Meld. 34 (2006-2007), p. 59). Sixteen years later, in 2023, Prime Minister Jonas Gahr Støre stated that the Norwegian OW development had commenced. Notably, the development and construction of an OWF is estimated to take 7-11 years[6] (Iberdrola, 2022; OED, 2022). Although the government's efforts towards OW have intensified since 2020, they have faced criticism for their lack of ambition, concrete action, and predicted cost overruns (Hustad, 2023; Piene, 2022). The government is currently conducting a competition for the first OW project areas in Norway, Southern North Sea II, and Utsira North, with expected allocation and auction scheduled for December 2023 (OED, 2022). A more significant allocation of areas is expected in 2025. The government operates with a target of 3 GW of OW by 2030 and an allocation of areas equivalent to 30 GW by 2040 (OED, 2023a).

The levelized cost of energy (LCOE) is a metric used to compare the cost of electricity generation from different sources over their lifetime (Holt et al., 1995). According to literature estimates, the general LCOE for OW decreased by over 40% from 2014 to 2019, and wind power analysts in 2020 expected a further 40-50% decline in the LCOE relative to 2019 by 2050 (Gilman et al., 2021; NREL, 2022). However, the cost of wind turbines, when measured in Norwegian Kroner, has increased by over 65% since 2020 (Hustad, 2023). Furthermore, three of the world's largest OW turbine manufacturers accumulated losses of almost €4 billion

[5] China increased the share of total wind power in its electricity generation from 1.5% in 2011 to 7.8% in 2022.
[6] 3-5 years development phase, 1-3 years pre-construction phase, and 2-4 years of construction.

in 2022[7] (Statista, 2023b; Woods, 2023). The prevailing notion is that the cost analyses associated with OWFs are highly uncertain, and the Norwegian Water Resources and Energy Directorate (NVE) has predicted that Norwegian OWFs will be among the most expensive in Europe (NVE, 2019).

1.2 Research question

Due to challenging sea conditions and the significant depths in the North Sea, the primary potential for OW in Norway is floating (NVE, 2019). However, floating OW is in its early stages and is considered a more expensive technology than the already mature development of bottom-fixed OW. While the costs of floating OW is anticipated to decrease with time, the analysis of its cost development is inherently uncertain, as it relies on global development rates and innovation (Meld. St. 36 (2020-2021), p. 85). Furthermore, only 113 megawatts (MW) of floating OW turbines are currently operational in Europe, with all installations being pilot or demo projects (WindEurope, 2022c). As a result, this thesis relies on the comprehensive data availability and established cost framework of fully commissioned bottom-fixed European OWFs to assess the potential development costs of OW in Norway.

To the best of our knowledge, only a limited number of studies have employed probabilistic cost analysis to evaluate the potential LCOE of a hypothetical Norwegian OWF while incorporating input variable uncertainties and cost data from fully commissioned projects. Hence, the objective of this thesis is to provide a comprehensive and realistic assessment of:

How do uncertainties in key cost drivers impact the overall cost of developing an offshore wind farm in Norway?

There has been a significant uptick in the debate regarding the development of OW in Norway, involving various stakeholders such as politicians, businesses, interest organizations, and academia. As the electrification of our society continues to increase, the public debate needs to encompass a realistic understanding of the challenges and costs associated with OW development. Therefore, we aim to offer new and insightful perspectives to contribute to the ongoing debate on the future of Norwegian energy production.

The next section provides a literature review, followed by a section focusing on OW. The methodology and data used for this study are presented in Sections 4 and 5, while the analysis and results are presented in Section 6. Section 7 provides a discussion of the study's findings and limitations, leading to the presentation of the conclusion in Section 8.

[7] Siemens Gamesa, General Electrics, and Vestas cumulatively installed 93% of OW turbines in Europe in 2020

2. Literature Review

Assessment of OWF costs has emerged as a significant research area, fueled by the growing emphasis of governments on secure and sustainable energy supply. The economic feasibility of OWFs requires careful evaluation due to the significant financial resources required. Ederer (2015) asserts that the OW industry's competitiveness depends on accurately evaluating the costs involved in development, installation, and operation. The author also raises his concern about the current cost analysis methodology that heavily relies on less resilient input data, which poses a challenge to reliable tracking of changes and identifying potential cost-reduction potentials. Aldersey-Williams et al. (2019) sought to address the issues of unreliable cost estimates by utilizing audited accounts to generate more accurate LCOE estimates. Their findings indicate that public domain cost estimates are unreliable, and the actual cost of OWFs is significantly higher than those implied by the UK's Contracts for Difference (CfD) auctions.

Various methods have been employed in the literature to evaluate OWF energy production's life-cycle cost. One such method is the Levelized Cost of Energy (LCOE), which measures the average lifetime cost of generating one unit of electricity (EIA, 2022). LCOE can be calculated in numerous ways. Levitt et al. (2011), the most frequently referenced study on the cost evaluation of OWFs since 2011, employed a cash-flow-based model to calculate the LCOE required for financial viability Pires et al. (2022). However, the study did not account for end-of-life scenarios such as decommissioning, resulting in an underestimation of the LCOE.

After assessing 341 articles regarding the economic feasibility of OWFs, Pires et al. (2022) found that approximately 60% did not include end-of-life costs. The cost of decommissioning is a significant aspect of OWF projects that should be considered from the design stage, as failure to do so can result in unexpected and severe cost overruns (Topham & McMillian, 2017). Pires et al. (2022) also identified the main methods and concepts applied in the studies. The most prominent methods include levelized cost of energy (LCOE), discounted payback (DPB), net present value (NPV), internal rate of return (IRR), and life cycle cost analysis (LCC). In addition, other approaches, such as Monte Carlo simulations (MCS) and multi-criteria decision-making (MDCM), have been applied, as illustrated in Figure 2.1 on the next page. It is important to differentiate between these concepts, as LCOE, DBP, LCC, and MCDM represent the end result of the analysis, while MCS is a supplementary tool used to obtain the final result. NPV and IRR are financial concepts that serve as underlying calculations during the analysis. As these concepts are not mutually exclusive, they can complement and be integrated.

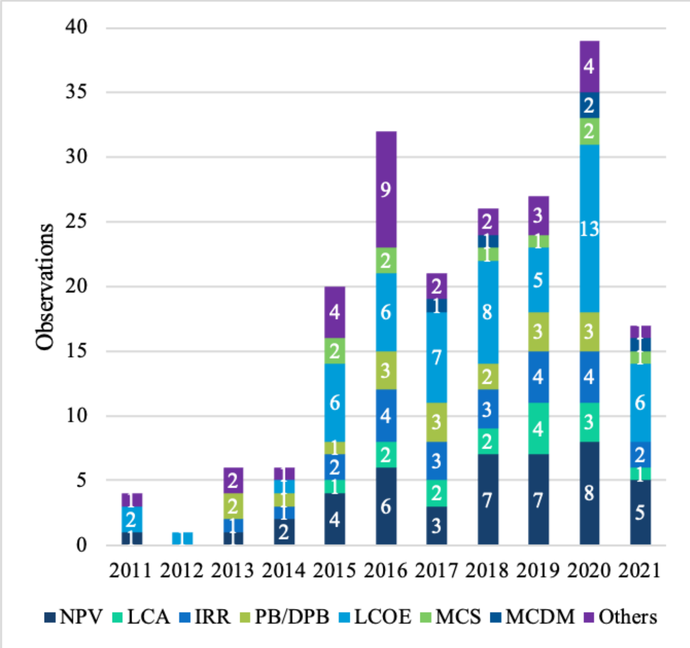

Figure 2.1: *Distribution by year of methods to aid investment decision-making, data from Pires et al. (2021)*

The LCOE, a popular metric among energy agencies, is typically based on fixed point values for all inputs, neglecting the uncertainty inherent in new electricity generation investment decisions. Heck et al. (2016) addressed this limitation by applying Monte Carlo simulations to compare the cost of electricity from different generation sources. This approach generates a probability distribution of possible LCOE outcomes, providing a more accurate representation than a single most likely value (Heck et al., 2016). The incorporation of probabilities facilitates more comprehensive scrutiny when two energy generation technologies exhibit overlapping probability distributions. Furthermore, the Monte Carlo simulation allows investors to decide based on their individual risk aversion.

When assessing the economic feasibility of OWFs, most studies rely on deterministic models and assumptions that may overlook the inherent uncertainties and risks associated with cost estimation. This study aims to offer a thorough and pragmatic assessment of the cost and uncertainties associated with establishing OWFs in Norway.

3. Offshore wind

The world's first OWF was launched off the coast of Vindeby in Denmark in 1991 (WindEurope, 2022a). Eleven wind turbines were raised in just as many days, giving power to around 2200 homes. The OWF had a capacity of 4.95 MW and was installed 2km from shore at a 4m water depth. The OW turbines commissioned today have an individual capacity of 10-13 MW, between 2-3 times Vindeby's total capacity. The world's largest installed OWF, Hornsea 2, entered full operation in 2022 (Ørsted, 2022). The 165 bottom-fixed OW turbines have a combined capacity of 1.3 GW, are located 89 km from shore, span an area of 462 km^2, and help power over 1.4 million homes.

The world's first floating OWF, Hywind Scotland, became operational in 2017; it consisted of five floating turbines with an installed capacity of 30 MW that power around 34 000 homes and was installed at up to 120m depth (Equinor, 2022). Considering floating OW is still maturing, it is first expected to surpass 1 GW of cumulative capacity in 2026[8] (4C Offshore, 2023). The technology development of bottom-fixed OW has matured and had a global cumulative capacity of 88 GW as we entered 2023. The total installed OW capacity is expected to reach 269 GW in 2030 and 428 GW in 2035. In comparison, the total installed capacity of onshore wind was 836 GW in 2022, twice as big as in 2015 (Statista, 2023d).

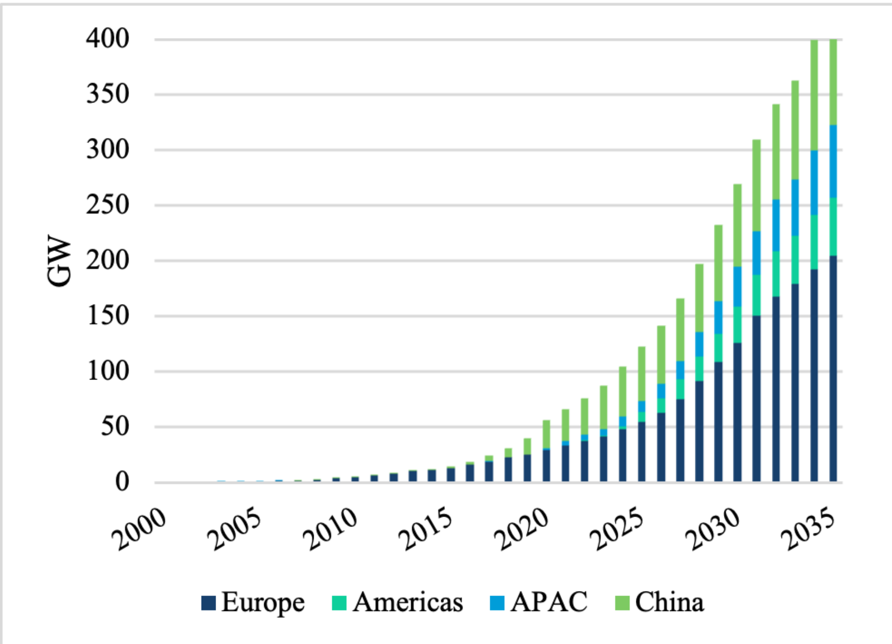

Figure 3.1: *The global cumulative capacity of offshore wind, data from 4C Offshore (2023)*

[8] The global cumulative capacity of floating OW is estimated to be 14 GW in 2030 and 58 GW in 2035.

3.1 Ambitious development plans

Increased development of OW is present globally, as countries with installed OW capacity will increase from 19 in 2023 to 35 in 2030 (4C Offshore, 2023; Ferris, 2022). China currently leads in installed capacity with 40 GW and may reach its 2030 renewable power targets by 2025[9], while the Biden administration aims to increase its capacity from less than 1 GW in 2023 to 30 GW by 2030 (Bloomberg, 2022; The White House, 2022). Similarly, the EU and the UK plan to increase their installed capacity from 23 GW and 19 GW, respectively, to at least 60 GW and 50 GW in 2030 (4C Offshore, 2023). The North Sea countries Belgium, Denmark, Germany, and the Netherlands, jointly announced a combined target of at least 65 GW installed capacity by 2030 and 150 GW by 2050 during a summit in 2022 (ECEEE, 2022). The year after, the remaining North Sea countries, France, Ireland, Luxembourg[10], the UK, and Norway, joined the quadruple at the Ostend Summit. Together with their heads of government and their energy ministers, they declared a collective target of 120 GW of OW in the North Sea by 2030 and 300 GW by 2050 (OED, 2023b).

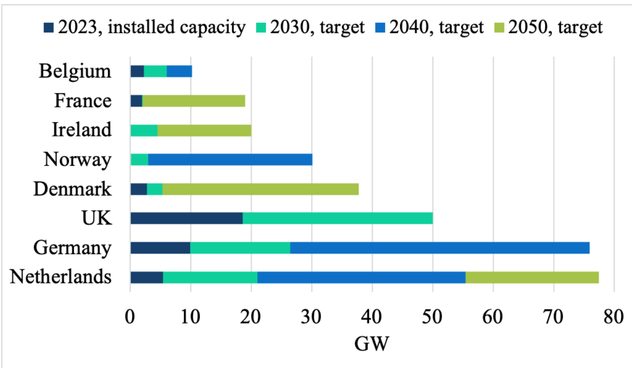

Figure 3.2: Current capacity and future targets[11], data from 4C Offshore (2023) & OED (2023b)

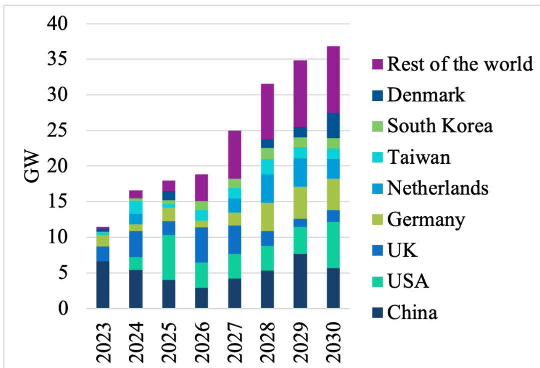

Figure 3.3: Annual OW capacity entering construction globally, data from 4C Offshore (2023)

Over 100 OW companies and industry groups issued a joint statement after the summit, acknowledging that the industry needs to expand to meet the ambitious targets without policy support and funding (ORID, 2023). The signatories[12] reported that the European industry could only produce 7 GW of OW annually, falling short of the 20 GW required to meet the countries' targets (Abnett, 2023). European investments in wind power in 2022 were the lowest since 2009, and the OW assets financed in 2022 only accounted for 2.4% and 1.4% of what was

[9] According to development plans of 22 of China's 34 local governments, the remaining 12 are yet to announce.
[10] Aims to contribute to the materialization of the combined OW targets by dedicated cooperation mechanisms.
[11] France aims at least 4.6-17 GW in 2050, Germany have a target of 66 GW by 2045, and the Netherlands targets for 2030 and 2050 depends on physical space, ecological impact and sufficient demand.
[12] Energy firms such as Ørsted, Shell, Equinor, Siemens Gamesa, BNG, and industry group WindEurope

financed in the two prior years (WindEurope, 2023b). The European industry faces challenges such as rising material costs and interest rates, competition from China, and the war in Ukraine, and is asking policymakers for greater use of qualitative criteria in project announcements and government support (Øvrebø, 2023). Achieving the visions of the Ostend Declaration will test Europe's ability to meet its energy policy goals of security, competitive prices, and sustainability simultaneously (Kurmayer, 2023).

Capital investments in OW are expected to increase from 6% of investments in offshore oil and gas in 2015 and 36% in 2020 to 62% by 2030, equivalent to USD88bn (McKinsey, 2022). Comparably, 4C Offshore expects global annual CAPEX spending to be USD108bn in 2030 (4C Offshore 2023). The North Sea areas have the highest OW development potential in Europe, estimated at 140-150 GW, representing half of the expected capacity in Europe by 2050 (McKinsey, 2022). Concurrently, Multiconsult estimates that it is possible to build 338 GW of OW in Norway in areas with a low level of conflict (Hovland, 2022; Multiconsult, 2023). McKinsey identifies OW as one of the ten most promising areas for Norway, with the potential to increase the country's GDP by €2.1 billion and create 36.000 new jobs by 2030 (McKinsey, 2022a). The Norwegian government pledged in the government platform, «Hurdasplatformen», to set a specific target for the production of OW power for 2030, and announced for the first time its 3 GW target at the Ostend Summit (Hurdalsplatformen, 2030; OED, 2023b). In 2023, the capacity stands at 0.1 GW, indicating that it needs to increase by almost 3000% over the next seven years (4C Offshore, 2023).

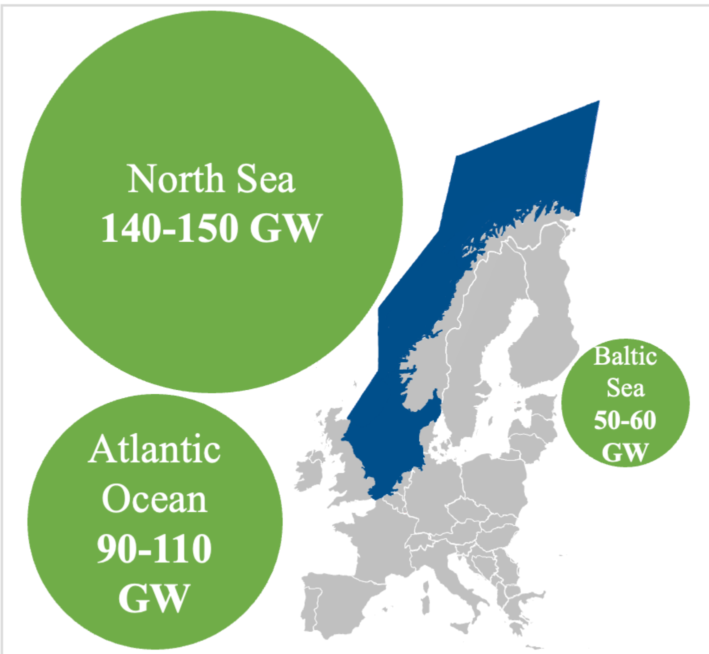

Figure 3.4: *European Sea's offshore wind potential, data from McKinsey (2022)*

3.2 Norwegian offshore wind initiative

The concept of offshore wind was initially introduced in a parliamentary notification on Norwegian climate policy in 2007 (St. Meld 34 (2006-2007), p. 59). The notification emphasized the necessity of establishing a national strategy for electricity production at sea, given the potential conflicts of interest related to natural interventions for wind power on land, making it relevant to move wind power projects offshore. It also highlighted the significance of developing and testing OW as one of the critical renewable energy sources due to better wind conditions offshore and the potential for large-scale OW development to significantly impact the global renewable energy landscape. In 2010, the Law of renewable energy production at sea, «Havenergilova», was implemented, establishing the legal framework for managing renewable energy production at sea (Havenergilova, 2010, §1). The Act applies to Norwegian maritime territory outside the baseline and on the continental shelf, stipulating that the right to utilize renewable energy resources at sea belongs to the state.

NVE conducted a comprehensive evaluation of Norwegian sea areas in the same year and identified 15 locations potentially suitable for deploying OW facilities (NVE, 2010). These areas span from the Southern North Sea to the north of Sørøya on the coast of Finnmark, with 11 of them situated at depths that allow for bottom-fixed OW installations. The remaining four areas possessing sea depths require floating solutions. However, given that the Norwegian coastal waters quickly transition to extreme depths, the opportunities for bottom-fixed OW are limited. Consequently, many of the suggested areas are situated close to the shore, differentiating Norway from other North Sea nations, which can establish bottom-fixed OW facilities several tens of kilometers offshore.

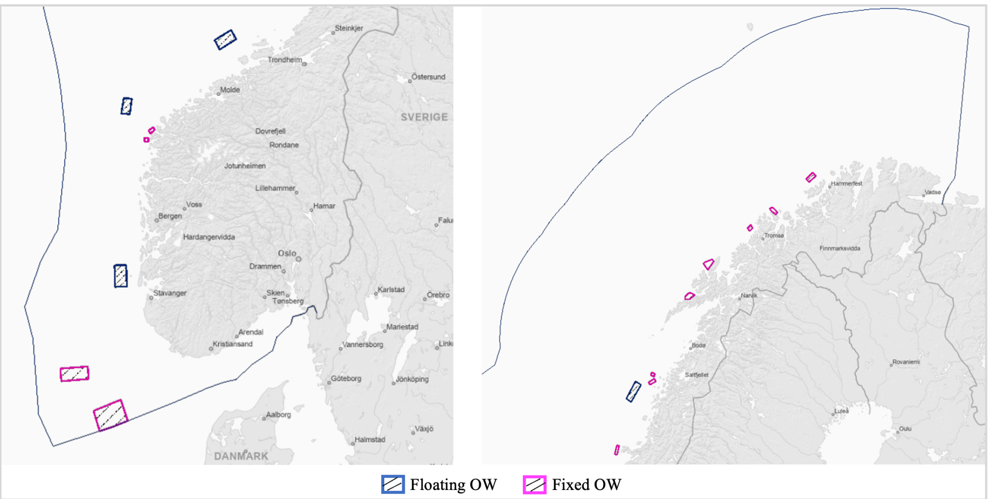

Figure 3.5: *Recommended OW facilities in 2012*
Source: NVE report 47/2012: Offshore wind – strategic impact assessment

The proposed area size determines whether it best suits bottom-fixed or floating OW, as bottom-fixed plants must connect to the regional grid onshore. The areas in the southern North Sea are larger, as the costs of grid connection here are more significant. Additionally, larger-scale floating OW development is proposed, given the higher costs of grid connection and the possibility of lower unit costs. The 15 proposed areas were the basis of a strategic impact assessment led by NVE in 2012/2013, at a time when global OW deployment was limited, and little was known about the potential effects on the natural environment or other users at sea (NVE, 2012). The Ministry of Petroleum and Energy commissioned NVE in 2017 to assess if significant changes had occurred since the last assessment. However, NVE concluded with no significant changes and that if two areas were opened for OW, the study areas Utsira North and either Southern North Sea I or II would be favorable (NVE, 2018).

In November 2020, the government decided to open up the areas of Southern North Sea II and Utsira North to produce renewable energy at sea (OED, 2020). As technology, project solutions, and the competitive landscape within OW had experienced rapid development, bottom-fixed wind turbines were already established and widespread technology in Europe (Meld. St.36, (2020-2021), p. 84). Conversely, floating turbines were still considered an emerging technology with higher associated costs. Nevertheless, the countries around the North Sea have ambitious plans to develop OW, which is a central part of the EC's efforts to advance Europe's green contribution. The EC estimated in 2020 that €800 billion is required in investments to integrate renewable ocean energy into the European energy system by 2050.

The development of OW is relatively unpracticed in Norway, both for authorities and companies, but it presents opportunities for Norway and its industries. However, the authorities must address various considerations, such as the impact of the power system on land, socioeconomic profitability, access to land areas, environmental consequences, and land conflicts. The Norwegian sea areas are five times larger than the land areas and have better wind resources, but large parts are only suitable for floating OW (Regjeringen, 2021; Meld. St.36, (2020-2021), p. 92). The Norwegian company, Equinor, has developed and operated the world's first floating and best-performing[13] OWF, Hywind Scotland, for five years (Equinor, 2022; Statista, 2023a). Its next floating OW project, Hywind Tampen, will be operational in 2023. Equinor will then operate around half the total global floating OW capacity.

[13] Hywind Scotland has averaged a capacity factor of 54% vs. the 40% average of OW between 2010-2021.

In June 2021, the government released a parliamentary notice that outlined how Norway should leverage its energy resources to generate growth and employment, and how it plans to further develop its position as an energy nation by investing in new industries such as OW (Meld. St.36, (2020-2021), p. 5-8). The notice mentions the ambition of a socioeconomically profitable development of bottom-fixed OW; even today, it also needs subsidies to be profitable, but it acknowledges that floating OW would need subsidies until the technology matures. Despite technological advancements, the cost of floating OW remains high (Blaker, 2023a). Therefore, technological development and cost reductions are necessary for long-term competitiveness, as government support is vital for immature technology projects in the early stages to realize (Meld. St.36, (2020-2021), p. 5-8). The notice further says it wants the Norwegian oil and gas supplier industries to participate in the growing market, given their decades of world-leading offshore expertise and experience. IEA estimates that 40% of the value chain for floating OW coincides with the value chain for offshore oil and gas, meaning that a competitive OW industry can be built in Norway because of the synergies of the two industries (IEA, 2019).

A year later, the government proposed an extensive development plan for OW energy to generate a similar amount of new power from OW as Norway currently produces (NFD, 2022a). Jonas Gahr Støre announced the intention to designate areas for producing 30 GW of OW in Norway by 2040, allocating sea areas in several stages and licenses for 5-6 times the size of the Southern North Sea II or about 1% of Norwegian sea territory. This objective entails the construction of over 1 500 OW turbines over the next two decades, a significant increase from the two currently in operation. To accommodate this growth, the government intends to support various network solutions, including two-way power flow cables, radials to Europe, and radials to Norway, which will be considered for each tender. However, the Norwegian power grid’s capacity is insufficient to handle the expected 30 GW of OW production, necessitating that a significant proportion of the power produced gets exported to other countries, presupposing that other countries would import Norwegian-produced OW power.

The month after, OW was identified as one of seven industries in the government initiative *«Roadmap for Green Industry»*, which aims to outline strategies for establishing new, environmentally friendly industries while bolstering existing industries in Norway (NFD, 2022a). The government stated that it would provide state risk relief for green industrial projects, with a contribution of €5.3 billion until 2025, in addition to government support schemes such as loans, guarantees, and equity, provided the projects meet specific criteria and have private investment interests.

Minister of Trade and Industry Jan Christian Vestre further announced that OW would be the initial export initiative in the government reform, *«The whole Norway Exports»,* in December 2022 (NFD, 2022b). The reform aims to increase Norwegian exports apart from oil and gas by 50% by 2030 while concurrently decreasing overall GHG emissions by at least 55%. To achieve this objective, the government has collaborated with the business sector and policy apparatus to make strategic moves abroad. As a component of this initiative, the government has created a National Export Council that includes representatives from businesses and parties in the work sector. The Council has suggested OW to be the first investment of the initiative, aiming to capture 10% of the global OW market by 2030, generating a turnover of €7.5 billion.

The Energy Commission released its findings in February 2023 after conducting an assessment to analyze Norway's energy requirements (NOU 2023:3). The Commission proposed enhancing energy production to ensure that Norway maintains a surplus of power and sustains its competitive advantage in renewable energy resources, which are abundantly available to support the country's industrial sector. The Commission recognized that Norway needs more of every power source faster, that the new era we are entering requires a comprehensive restructuring of the energy system, and that we are running out of time. As Norway transitions from a power surplus to a deficit in the coming years, the report underscores the need for a paradigm shift in the pace of action, accelerating efforts beyond previous levels. The Commission emphasized that Norwegian elected officials must make important choices, as there is room for action and a need for political governance. To succeed, a strategic orientation is needed and is possible by thinking holistically, as the time has come for politicians to take complex and vital path choices.

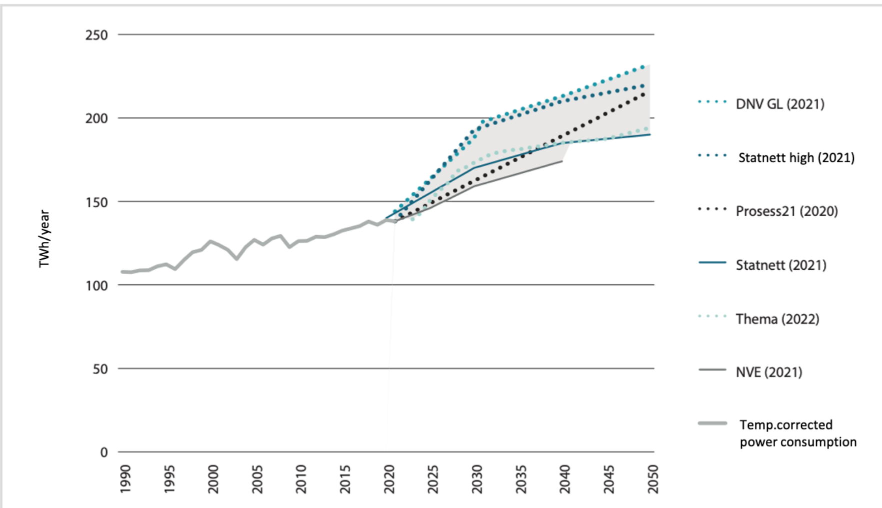

Figure 3.6: *Projected outcome range of power use, 2020-2050*
Source: NOU 2023:3: More of everything - faster

The Commission mentions OW as one of many solutions to solve a possible power deficit in the coming years. However, it highlights four areas where the authorities will have to play a more prominent role in the development of OW compared with onshore wind. The government has to (1) allocate land for OW development, (2) facilitate connections to grids that are built specifically for OW constructions, (3) play the role of the licensing authority that weighs the advantages and disadvantages of the developments, and determine mitigating measures, and (4) give support to OW developments. Therefore, the government has to play an active role in OW development for Norway to succeed. This requires clear goals for future investments, which, if quantified, will give directions to many more government decisions that then have to be made.

3.3 The starting point

Støre and Minister of Oil and Energy Terje Aasland announced the details for the first competitions for project areas for OW at Southern North Sea II and Utsira North in March 2023. Details regarding the project areas are illustrated in Figure 3.7 (OED, 2023a).

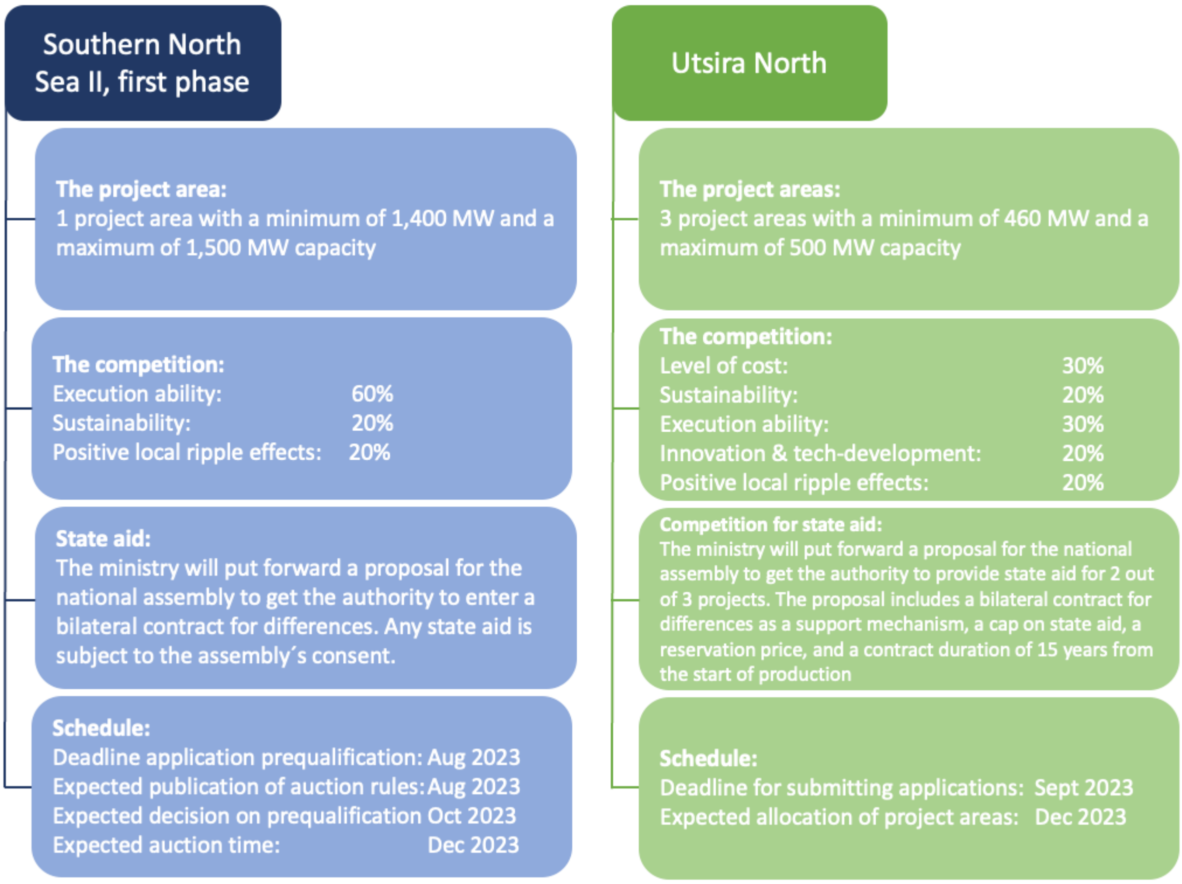

Figure 3.7: *Details about Southern North Sea II and Utsira North, input from OED (2023a)*

Less than a month later, a broadly composed directorate group[14] led by NVE identified 20 technically suitable areas based on known knowledge for OW along the Norwegian coast (NVE, 2023). The level of conflict is relatively low in the areas, but potential OW development will affect environmental, fishery, aquaculture, petroleum, and shipping interests. NVE says that these areas have to be further investigated in detail to find the most suited areas where there would be possible to develop projects that consider the value of the land areas and the possibility of coexisting with other interests. NVE director Kjetil Lund specified that additional studies on environmental and business interests, effects on the power system, the need for grid improvements, and the economics could result in some areas being reduced or eliminated. As an economic assessment of the development of OW was not a part of the assignment of NVE, the group of directorates has not specifically assessed the need for additional needed grid investments. Lund underlined during the submission of the report that OW is not profitable in Norway and that if a lot of OW is to be developed, there would be a need for extensive investments in grids, both offshore and onshore.

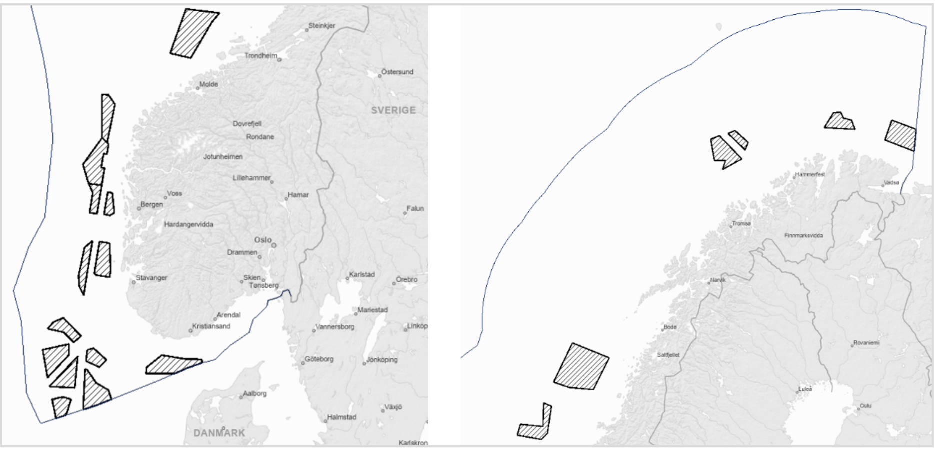

Figure 3.8: *The 20 technically suitable areas identified by the directorate group*
Source: NVEs identification of study areas for offshore wind (2023)

OW offers great opportunities but does require significant investments in production and grid development, as well as the possibility of storing power (Meld. St. 36 (2020-2021), p. 85). Many elements together decide if the production is profitable, as illustrated in Figure 3.9.

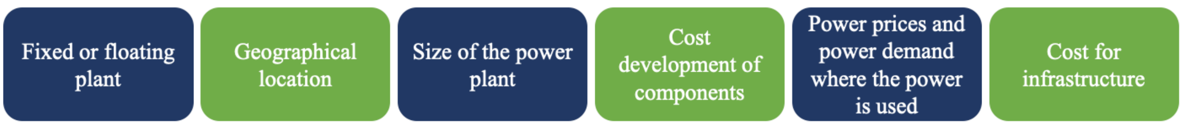

Figure 3.9: *Some profitability elements of OW, input from Meld. St. 36 (2020-2021)*

[14] Consisting of the Norwegian fishery, environmental, and petroleum directorates, in addition to sub-agencies from the industry & fishery and defense departments.

An additional part of the task of the directorate group was to create a timetable for a possible new allocation of OW areas in 2025 and to assess whether it is possible to increase the capacity of Southern North Sea II and Utsira North (NVE, 2023). The group believes that an allocation in 2025 has to be an extension of the already allocated areas, as both new areas and the possibility to expand the areas have been identified. However, the group admits that it needs to gain more knowledge of the other 18 identified areas and that they have to go through an ordinary process of strategic impact assessment to collect more extensive data and to involve the affected parties more heavily. The time it takes to carry out a sufficiently solid assessment with the necessary involvement means that the group believes it is not feasible to make any additional allocation by 2025 for the remaining 18 areas.

NVE reported[15] that a bottom-fixed OW power plant built in 2021 with a capacity of 1 400 MW in Southern North Sea II would have an LCOE of €68/MWh (Meld. St. 36 (2020-2021), p. 85). However, they expect the LCOE to decrease to €42-59/MWh by 2030. Floating OW, in contrast, is presently more expensive than bottom-fixed OW. While the costs of floating OW are expected to decrease with time, the analysis of its cost development is uncertain, given its dependence on global development rates and the degree of innovation realized. NVE posits that a floating OW power plant built in 2021 with a capacity of 500 MW at Utsira North would have an LCOE of €117/MWh. However, with the aforementioned uncertainties, the LCOE is projected to be between €62-95/MWh by 2030. On the other hand, the LCOE for onshore wind power was €26/MWh in 2021 but may decrease to €19/MWh by 2030. Nevertheless, the estimates provided by NVE, based on data from 2021, do not consider the recent upsurge in interest rates and the escalating costs of materials.

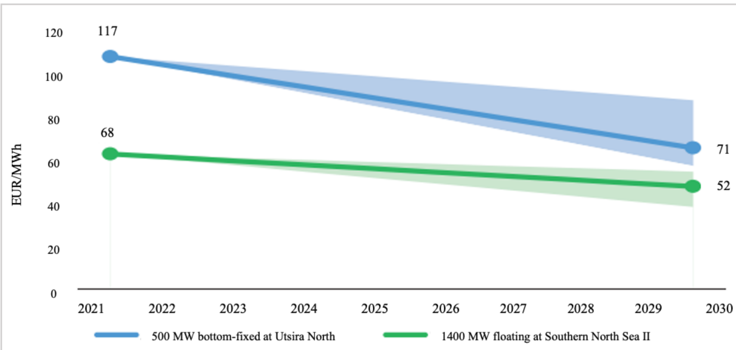

Figure 3.10: *LCOE predictions of floating and bottom-fixed OW by NVE*
Source: Meld. St. 36. (2020-2021). Climate plan for 2021-2030 - conversion to a low-emission society

[15] Superior assumptions: 3-year construction time, a 25-year lifetime for OW in 2021 and 30 years in 2030, 40-year grid lifetime, a discount rate of 6% for production and 4% for the grid, a degradation rate of 0.1%, and a quota price of EUR 30/ton CO2-equivalents in 2030.

The future outcome of the cost development of floating OW is uncertain. However, Equinor reduced its CAPEX/MW from its pilot project to Hywind Scotland by 70% and is expecting a further reduction of 40% for Hywind Tampen (Equinor, 2023a). DNV expects OW capacity to grow 56-fold by 2050, with LCOE reductions of bottom-fixed and floating OW by 39% and 84%, respectively (DNV, 2022).

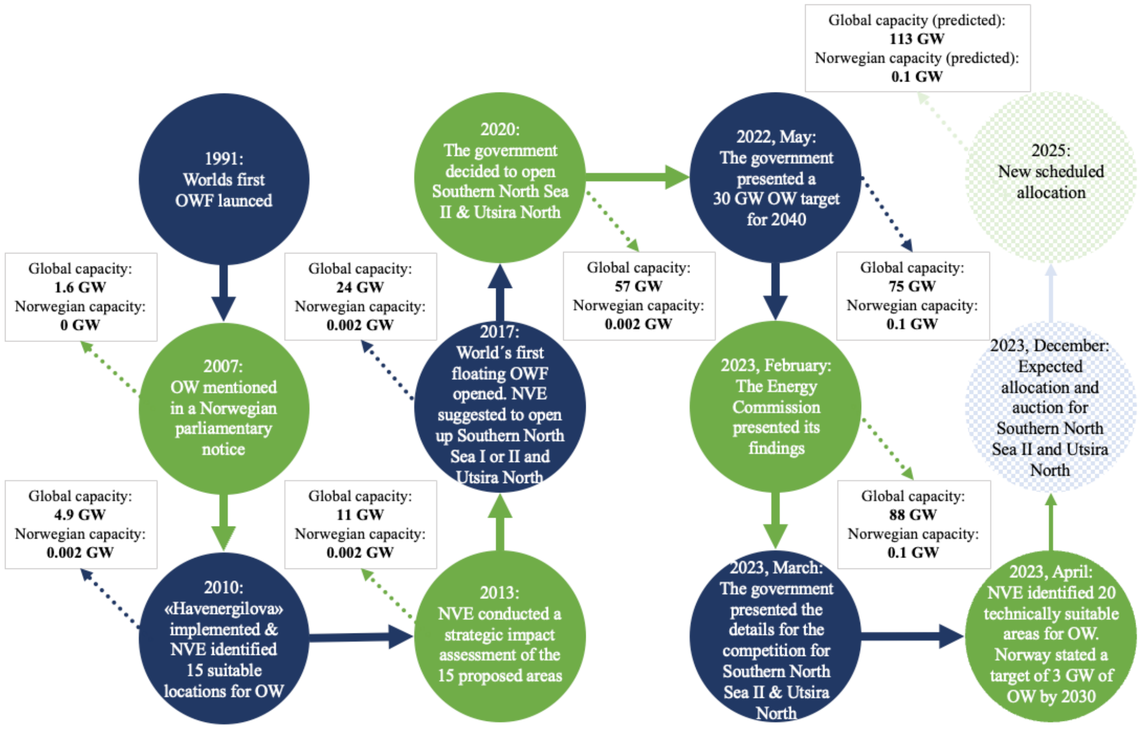

Figure 3.11: *Norwegian OW happenings, input/data from 4C Offshore (2023), NVE (2022), WindEurope (2022b), St. Meld 34 (2006-2007), Equinor (2023a), OED (2023a), NOU 2023:3*

Figure 3.11 reflects the most significant happenings regarding the development of OW in Norway since the world's first OWF was established in Denmark in 1991 (WindEurope, 2022a). The global cumulative OW capacity has surged from 1.6 GW in 2007 to 88 GW in 2023 and is projected to reach 113 GW by 2025 (4C Offshore, 2023). In contrast, Norway's initial OW capacity of 2 MW was established in 2010, but it took a span of 13 years to achieve a modest increase to 100 MW. The capacity is expected to remain stagnant until 2028, when it is anticipated to increase by 500 MW from Utsira North to a total of 0.6 GW.

Figure 3.11 highlights the concerns of the Energy Commission and their call for a pace of energy capacity expansion that is yet to be observed, as there still is potential for action (NOU 2023:3). The Commission also clarified that the authorities need to assume a more active role in the OW development. However, as the 20 technically suitable areas identified by NVE require further detailed investigation, coupled with the absence of an economic assessment of grid investments, the future progress of OW in Norway is difficult to predict (NVE, 2023).

3.4 Wind theory

3.4.1 The physics

According to Letcher (2017), the quantification of power generated by a wind turbine involves the evaluation of mass flow passing through a defined area, as expressed by the following equation:

$$\boldsymbol{P = \frac{1}{2} * \rho * A * U^3} \quad \textbf{(3.1)}$$

The power ($\boldsymbol{P}$) produced by a wind turbine is a function of three key variables: air mass ($\boldsymbol{\rho}$), the selected area ($\boldsymbol{A}$), and the wind speed ($\boldsymbol{U}$). With a constant air mass, the area of interest and wind speed become the primary determinants of power generation. Specifically, an increase in the area of interest results in a corresponding increase in power generation, reflecting a positive relationship between the two. Moreover, the relationship between wind speed and generated power is non-linear and cubic, implying that all else being equal, a doubling of wind speed results in an eightfold increase in power generation.

3.4.2 The power capture

It is crucial to recognize that not all energy generated by wind power is immediately usable. Letcher (2017) addresses this challenge by introducing another equation measuring the energy output of a wind turbine:

$$\boldsymbol{C_p = \frac{P_T}{P_{wind}} \Rightarrow P_T = \frac{1}{2} * \rho * A * U^3 * C_p} \quad \textbf{(3.2)}$$

The energy output of an OW turbine must be distinguished between the extracted power ($\boldsymbol{P_T}$) and the total wind power ($\boldsymbol{P_{wind}}$), and is a function of the variables: the mass of air ($\boldsymbol{\rho}$), the selected area ($\boldsymbol{A}$), wind speed ($\boldsymbol{U}$), and the power coefficient ($\boldsymbol{C_p}$). The selected area represents the swept area of each turbine, while the power coefficient reflects the turbine's efficiency in extracting power from the available wind resource. The Betz law sets a theoretical upper limit of the power coefficient at approximately 59% (Betz, 1920), implying that it is impossible for a wind turbine to capture more than 59% of the kinetic energy present in the wind (Letcher, 2017). Therefore, expanding the swept area represents the most efficacious approach, given the limited potential for enhancing the power coefficient. However, the feasible enlargement of the rotor blade length will hinge on the technological and economic viability of such an undertaking (IEA, 2013). Additionally, the cubic association with wind speed underscores the criticality of optimal wind speed conditions in wind energy production.

3.4.3 The power curve

The energy output of an OW turbine depends on various factors, including wind speed and the wind turbine (Letcher, 2017). Specifically, electricity generation commences only when wind speeds exceed a designated cut-in threshold (Manwell et al., 2009). In cases where wind speed falls below this level, the required torque to produce electricity cannot be achieved. The maximum power output of the turbine is achieved when wind speeds reach the rated value specified in the power curve. To prevent damaging the structure, the rotor is brought to a halt once wind speed exceeds the designated cut-out threshold (IRENA, 2017).

3.4.4 The theoretical vs. the annual energy production

Letcher (2017) further argues that the realistic operating conditions of an OW turbine result in lower power generation than the theoretical annual energy production. Different loss factors are:

Figure 3.12: *Loss factors of an OW turbine, input from Letcher (2017)*

3.4.5 The degradation rate

The degradation rate refers to the yearly decrease in energy output that occurs over the lifespan of an energy plant (NVE, 2015). A decrease in energy output can be caused by various factors, such as plant performance loss, which can be due to site unavailability, wind hysteresis, and material fatigue (Staffell & Green, 2014). According to a study by Matthew et al. (2022), the efficiency index of a 2 MW wind turbine operating in a Norwegian environment decreased by 0.64% annually (Matthew et al., 2022). Through personal communication with NVE[16], we were provided with a model indicating a degradation rate of 0.1% for the decline in turbine performance. However, no additional explanation was given regarding this specific rate. The lack of studies regarding turbine deterioration was surprising, with most of the literature focusing on increased failure rates as a function of age.

3.4.6 The capacity factor

According to Letcher (2017), the capacity factor of an OW turbine is the percentage of actual energy produced ($\boldsymbol{E_{actual}}$) relative to the theoretical maximum ($\boldsymbol{E_{ideal}}$). The equation below illustrates the concept:

$$\boldsymbol{Capacity\ factor} = \frac{E_{actual}}{E_{ideal}} = \frac{Time*\overline{P}}{Time*P_N} = \frac{Annual\ Energy\ Production_{actual}}{Time*P_N} \quad \textbf{(3.3)}$$

The nominator outlines the actual annual energy production of an OW turbine by multiplying the actual energy production by the number of hours in a year ($\boldsymbol{Time * \overline{P}}$). The denominator illustrates an OW turbine´s theoretical maximum energy production by multiplying the theoretical maximum energy production by the number of hours in a year ($\boldsymbol{Time * P_N}$). As the wind does not always blow, the production of an OW turbine will vary.

The capacity factor is an effective and commonly used metric to measure a wind turbine's overall performance and efficiency (Cooney et al., 2017). Improvement in technology and the location of the turbines has resulted in major improvements in the capacity factor of OW, increasing by 56% from 1983 to 2017 (IRENA, 2018). The average capacity factor for OW was 42%-43% in 2020, but with large variations depending on location. With a capacity factor of 43%, four wind farms with completely uncorrelated weather systems would be required to guarantee the output of one wind farm and, on average, only produce the output equivalent to less than two wind farms (Emblemsvåg, 2020). In 2021, the average capacity factor in the EU and the UK was 35%, a 7% decrease from 2020 due to the high concentration of bigger OWFs in some European regions (WindEurope, 2022b). The average numbers for new OWFs are higher, ranging between 42%-55%. As the wind does not always blow, uncorrelated weather systems are crucial but require enormous geographical areas.

[16] Received through personal communication (e-mail) on 24. February 2023.

3.5 An offshore wind farm

There are many ways of building and operating an OWF, as the specific conditions at a specific site differ (BVG Associates, 2019). The process of development, installation, and operation of an OWF is complex and is dependent on many components to be able to generate, transport, and deliver electricity to a national grid connection on the mainland. Figure 3.13 illustrates the needed generic infrastructure for an OWF (Bauer et al., 2016), consisting of **(a)** wind turbines; **(b)** array cables; **(c)** export cables; **(d)** transformer station; **(e)** offshore substation converter; **(f)** meteorological mast; **(g)** onshore substation.

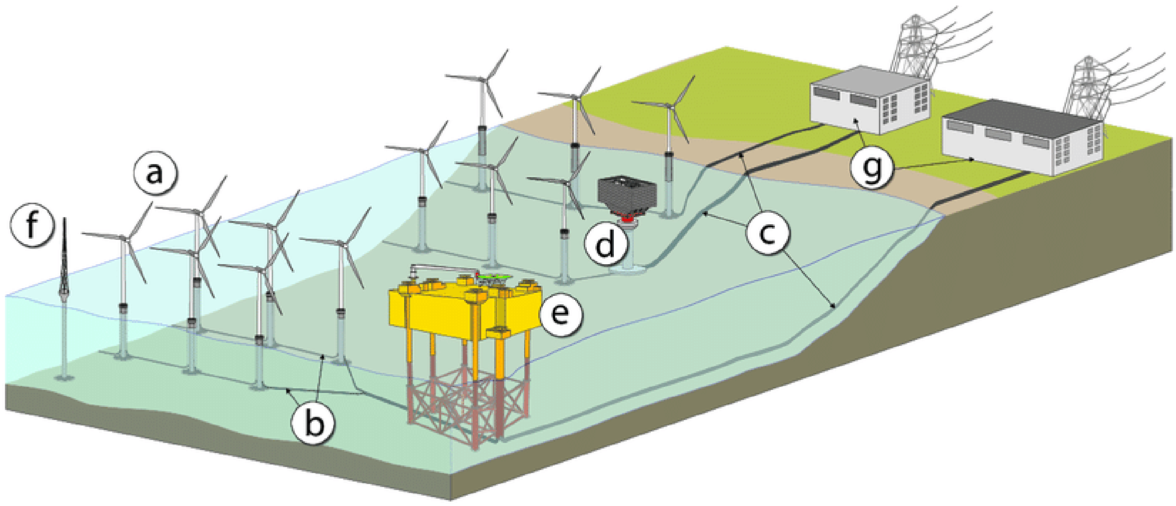

Figure 3.13: *Main components of an OWF*
Source: Bauer et al. (2016)

The development of OWFs in Europe has undergone substantial changes, as presented in Table 3.1 (IRENA, 2022). On average, European OWFs that start construction in 2023 have a total project size of 532 MW, a turbine size of 9 MW, and are developed at 62 m water depth, 34 km from shore (4C Offshore, 2023).

	2010	2015	2020
Water Depth (m)	21	29	37
Distance from shore (km)	18	49	40
Project Size (MW)	155	270	336
Hub Height (m)	83	87	97
Rotor Diameter	112	119	163
Turbine Size (MW)	3.1	4.2	8.0
Foundation	Monopile/Gravity	Monopile/Jacket	Monopile/Jacket

Table 3.1: *Development of OWFs in Europe, 2010-2020, data from IRENA (2022)*

3.5.1 The wind turbine

The two main OW turbine designs consist of either horizontal axis wind turbines (HAWT) or vertical axis wind turbines (VAWT) (IRENA, 2019). The HAWTs dominate the wind industry, as their main advantage is the ability of their blades to move perpendicular to the wind flow so there can be generated energy through the whole rotation of the blades. Thus, they have a disadvantage, as they must be pointed in the wind direction to work efficiently (Johari, 2018). VAWTS are less common as they are less effective but have the potential to outperform the HAWTs in urban environments, as they are omnidirectional and can benefit incoming wind from all directions (Winslow, 2017). The HAWTs are more consistent and efficient than the VAWTs during consistent wind conditions and are the preferred choice. The HAWTs are complex, with the rotor, nacelle, and tower as the main components.

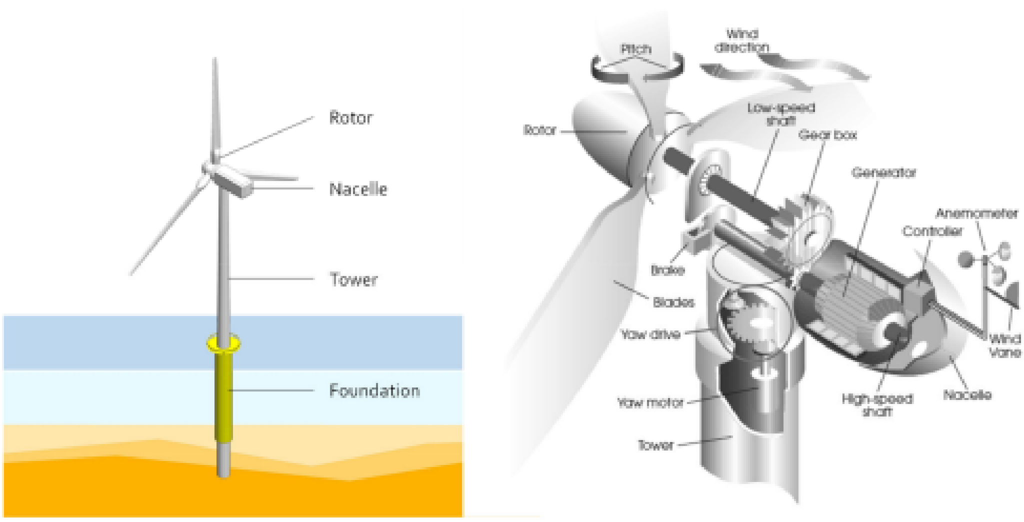

Figure 3.14: *Components of a HAWT*
Source: Jiang et al. (2022)

The rotor consists of various parts that extract and convert kinetic energy from the air into rotational energy (BVG Associates, 2019). The blades are connected to a turbine drive train through a central hub and mounted on bearings to adjust each blade's pitch angle. In September 2022, the Chinese company LZ Blades presented a 123-meter-long blade they claimed is the longest in the world, with the single mass of the blade being over 50 tons and a surface area exceeding 1000 m^2 (OER, 2022). The nacelle supports the rotor by converting the rotational energy from the rotor into three-phase alternating current electrical energy (BVG Associates, 2019). The nacelle offers high levels of remote monitoring, control, and health checking. The tower is a steel structure that provides access to the nacelle, houses electrical and control equipment, and shelters and storage for safety equipment (BVG Associates, 2019). Each tower is about 100m long, weighs over 600 tons, and is typically as low as necessary to comply with maritime safety regulations for blade clearance above the water. Integrated design of substructures and towers is becoming more popular, but the tower remains a discrete component. The OW turbines have developed rapidly over the last 30 years and are expected to become both bigger and more powerful in the upcoming years (Bauer et al., 2016). The current most powerful turbine commissioned has a capacity of 13 MW[17], while some projects with expected construction start in 2025 have a capacity of up to 15 MW (4C Offshore, 2023).

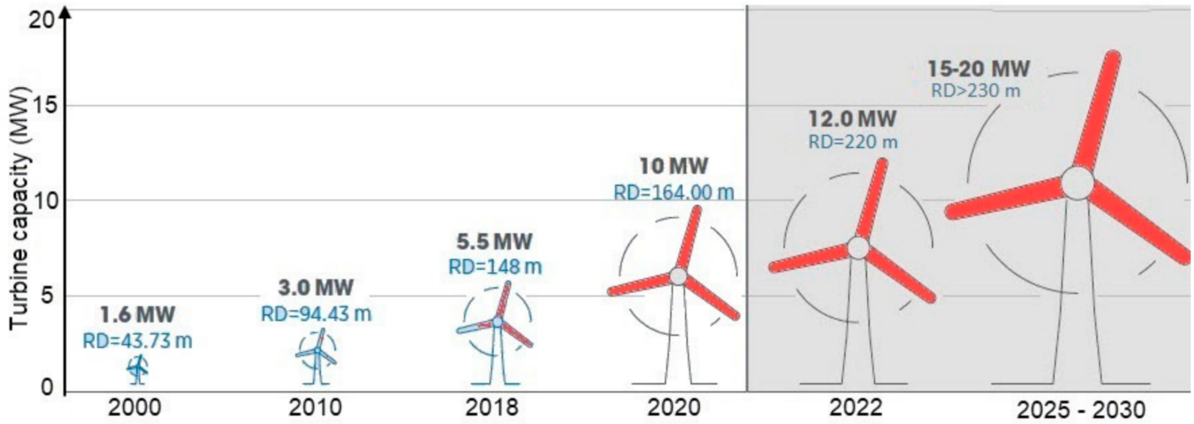

Figure 3.15: *Development of wind turbine power and rotor diameter*
Source: Bošnjakovic et al. (2022)

3.5.2 The turbine foundation

The turbine foundation supports the OW turbine by transferring loads from the turbine to the seabed, where the loads are reacted, in addition to providing conduits for electrical cables and access for personnel from vessels (BVG Associated, 2019). Designing the turbine foundation is a complex engineering task, as the design requirements must include gravity load, thrust and associated overturning moment, natural frequency, fatigue strength, verticality (over time), personnel access, cable entry, and support. In addition, the design must also protect against both wind and wave loading and earthquakes, typhoons, and sea ice. Most OWFs are located on the continental shelf less than 10 km off the coast in water depths of about 10m (Liao et al., 2019). However, countries like Norway, Japan, and the United States have limited coastal territorial waters with depths of less than 50m. As the average distance of an OWF from shore has increased from 18 km in 2010 to 40 km in 2020, the kind of turbine foundations has thus evolved.

[17] GE Energy's Haliade-X 13 MW turbines

Bottom-fixed and floating foundations are the main types. Bottom-fixed foundations can further be divided into several different subcategories. Gravity-based foundations were used at early OWFs in less than 10m water depths and are the least common (BVG Associates, 2019). Their design is primarily according to their self-weight and consists of a concrete caisson structure (Liao et al., 2019). Monopiles are the most common bottom-fixed turbine foundations, accounting for over 80% of the installed capacity (BVG Associates, 2019). They require a lot of steel but are easy to manufacture and install in volume. The geology of the North and Baltic Seas are best suited for monopiles, but their cost rises substantially for larger turbines and deeper waters and are thus usually used in water depths of between 20-40m (Liao et al., 2019). Jackets represent around 15% of the installed capacity worldwide and have become cost competitive at around 35m water depth. They are easier to design for 10 MW and above turbines and are relatively economical in steel consumption compared to monopiles. However, they are more expensive regarding storage, logistics, and installation costs. They are mainly used in intermediate water depths up to 50m.

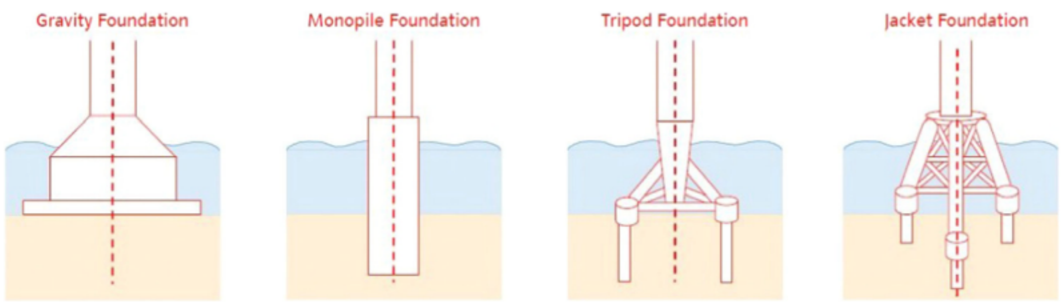

Figure 3.16: *Some bottom-fixed OW foundations*
Source: Liao et al. (2019)

Floating turbine solutions are the best option for OW turbines in water depths exceeding 60m, but they are far more expensive solutions (Liao et al., 2019). In comparison, the foundation supply and installation costs for bottom-fixed OW account for 16% of the total CAPEX, while it accounts for 32% for floating OW (4C Offshore, 2023).

3.5.3 The electricity transmission

Cabling systems integrate OWFs into the national grid or electricity transmission networks, conveying electricity over longer distances to thousands of homes (Srinil, 2016). The cabling systems consist mainly of array and export cables. Depending on the turbine size and the spacing between each OW turbine, there is around 1km of array cables on each side of an OW turbine, connecting all of the turbines to the offshore substation (BVG Associates, 2019). The cables are laid up with insulation and armor coating around the conductors, as they must be tensile, abrasion, and have high chemical resistance, in addition, to being able to withstand both tidal and wave loading.

The offshore substation reduces the electrical losses by changing the electrical voltage from the array cables before it is exported through export cables to an onshore substation (BVG Associates, 2019). The offshore substation uses two transmission systems to get the electricity onshore, High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC). First, electricity gets transported through AC cables to the offshore substation, where it gets converted to DC and then transported onshore. At the onshore substation, it then gets converted back to AC. Many factors are used in choosing between the use of HVAC or HVDC technology, such as the distance from the shore and the power capacity required (Ergun et al., 2019). HVAC is typically used for shorter distances, up to 80 km, and lower power capacities, while HVDC is more suitable for longer distances and higher power capacities (IEC, 2015). At the onshore substation, the power then gets transformed to the grid voltage. It is normally located close to the offshore export cable landfall to limit the distance of the cables onshore, but it can be as far as 60km from the cable landfall (BVG Associates, 2019).

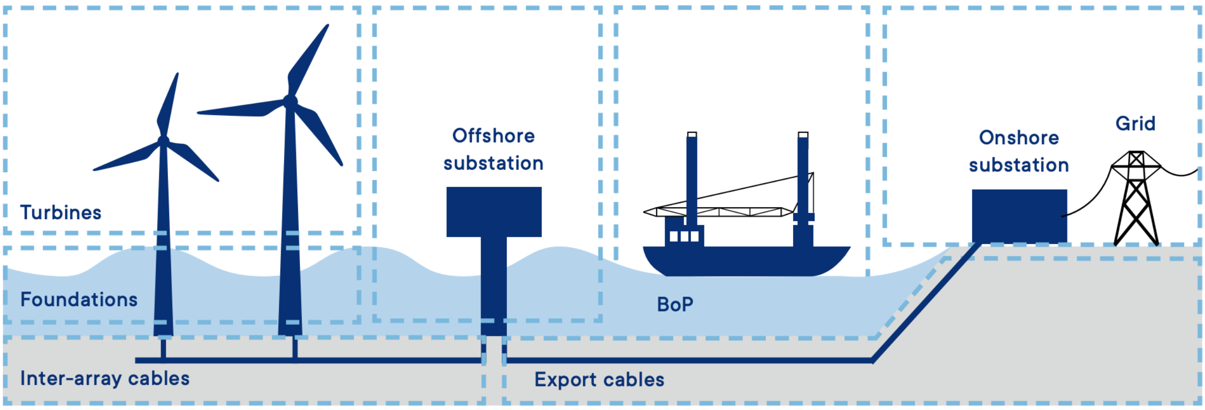

Figure 3.17: *Trivialized electricity transmission system of an OWF*
Source: World Forum Offshore Wind (2022)

3.6 Cost Drivers

The main cost drivers of an OWF can be divided into capital expenditure (CAPEX), operational expenditures (OPEX), and decommission expenditure (DECOM) (Bosch et al., 2019). Substantial upfront costs are needed to realize OW projects, and almost half of the total costs, including financing costs, are related to CAPEX (Ioannou et al., 2018). In addition, due to considerable costs related to the foundations, the adaption of the projects to demanding offshore environments, and deployment far from shore in deep waters, OW will naturally be more costly than if the projects were realized onshore (BVG Associates, 2022).

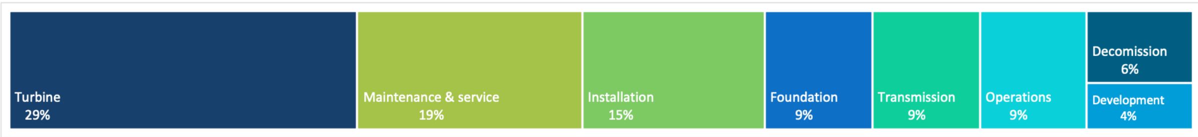

Figure 3.18: *The cost distribution of OWFs, data from BVG Associates (2022) & 4C Offshore (2023)*

OWF projects exhibit a substantial disparity in cost composition compared to non-renewable fossil fuels like natural gas (EWEA, 2009). Excluding financing costs, approximately 70% of the total cost of OW projects consists of CAPEX, while OPEX represents around 28% **(**BVG Associates, 2022). In contrast, natural gas projects can have a fuel and OPEX share of 40-70% (EWEA, 2009). Figure 3.19 illustrates a summary of the life cycle costs of an OWF (Bosch et al., 2019). According to the figure, DECOM appears at the end of the life cycle of an OWF, but in reality, it is financed upfront as a part of the CAPEX.

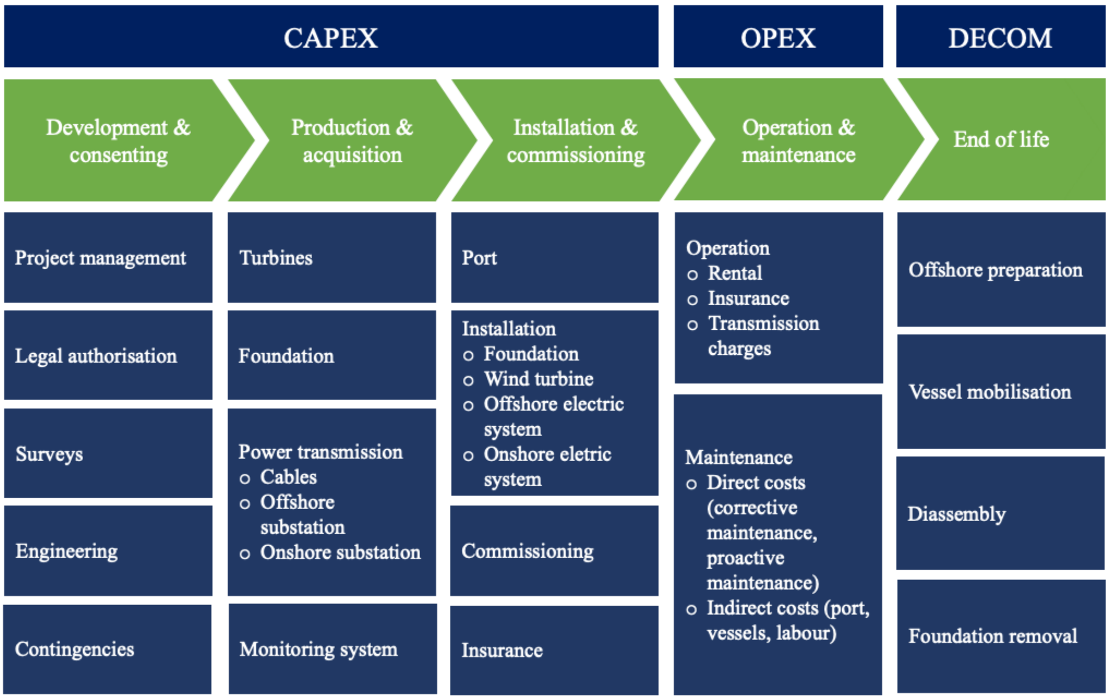

Figure 3.19: *Summary breakdown of the life cycle cost of a wind farm, input from Bosch et al. (2019)*

3.6.1 CAPEX

As per Figure 3.19, the CAPEX of an OWF is divided into several stages: development & consenting, production & acquisition, and installation & commissioning (Bosch et al., 2019). Wind farms cannot always produce energy because of calm winds, so the value of a megawatt-hour of electricity from OW could be 20-50% lower if compared with the value demanded by a consumer for one megawatt of electricity (Edenhofer et al., 2019). The industry standard is, however, to refer to CAPEX on a per-megawatt basis for installed capacity, as illustrated in the equation below (Bosch et al., 2019).

$$\boldsymbol{CAPEX_i\left(\frac{1}{MW}\right) = C_{dev.i} + C_{turb.i} + C_{found.i}(d) + C_{trans.i}(D) + C_{inst.i}(D) + C_{decom.i}} \quad \textbf{(3.4)}$$

The development costs ($C_{dev.i}$) and turbine costs ($C_{dev.i}$) are dependent on the capacity of the wind farm, while the foundation costs ($C_{found.i}$) depend on the water depth (d), and the transmission costs ($C_{trans.i}$) and installation costs ($C_{inst.i}$) depend on the distance (D) from the OWF to the coastline. Decommissioning costs ($C_{decom.i}$) are normally preconceived as a part of the installation costs, even though it appears at the end of the life cycle of the OWF. The different components of the equation will depend heavily on the specific site conditions of each OWF, such as seabed characteristics, depth, and distance to shore, but also technology and supply chain development (BVG Associates, 2022). In this thesis, we exclude DECOM from the CAPEX-equation above and elaborate on its challenges in a separate subsection because of its particular importance.

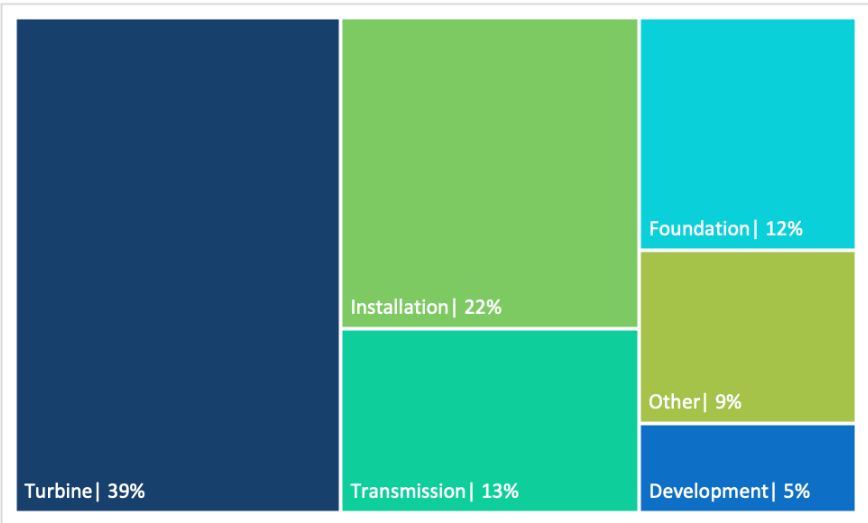

Figure 3.20: *The CAPEX distribution[18] of bottom-fixed OW, data from 4C Offshore (2023)*

[18] 4C Offshore have excluded decommission costs in their estimates.

3.6.1.1 Development costs

Development and project management costs occur before the financial close or before the orders to proceed with the construction materialize (BVG Associates, 2019). This makes up 5% of the CAPEX, according to 4C Offshore and BVG Associates, and includes many different required activities such as environmental research and impact assessments, consultancy, consenting services, and engineering (BVG Associates, 2022; 4C Offshore, 2023). The activities are many and complex and are often outsourced to specialized firms. BVG Associates (2019) estimate the development costs for a 1 GW wind farm to be €140 million.

3.6.1.2 Turbine costs

The OW turbine is the most vital component of an OWF and the most significant contributor to the CAPEX, with approximately a share of 39% for the turbine supply, excluding installation costs of the turbine (4C Offshore, 2023). According to BVG Associates (2022), the nacelle, rotor, tower, and other turbine supplies comprise 42% of the CAPEX. The two estimates are consistent with the IEA calculations of a CAPEX share between 30-40% (IEA, 2019). Globally, the size of OW turbines has increased and is expected to increase further, resulting in the share of turbine costs as a part of the CAPEX increasing more than the total CAPEX decreases (Meissner, 2021). Five turbine manufacturers stood for over 99% of European OW installations in 2020[19], as the barriers to entering the market are significant (Statista, 2023b).

3.6.1.3 Foundation costs

OW turbines depend on solid foundations to cope with the strong winds and wave loads in the harsh marine environments at deep sea levels far from shore (BVG Associates, 2019). The foundation costs are a significant part of the CAPEX, accounting for between 12-13%, excluding installation costs of the foundation (BVG Associates, 2022; 4C Offshore, 2023). However, the foundation costs can be significantly higher as the cost for foundations at 40-50m is 1.9 times higher than that at a water depth of 10-20m (Ki-Yong et al., 2018). The specific conditions at a site, such as the depth and the seabed, can result in the CAPEX share of the foundation cost being as high as 20-25% (IEA, 2019).

3.6.1.4 Transmission costs

Transmission costs have an approximately similar share of the CAPEX as the foundation costs, with a share of 12-13% when the supply of array cables, export cables, and the offshore

[19] Siemens Gamesa, Vestas, Senvion, Bard Engineering, and GE Renewable Energy installed 68%, 23.9%, 4.4%, 1.5%, and 1.4 %, respectively.

substations are included and installation costs excluded (BVG Associates, 2022; 4C Offshore, 2023). The IEA estimates the share of the CAPEX to be as high as 20-30%, depending on regional regulations when it comes to grid connection and the distance to shore, and that the share is expected to increase as the total CAPEX will decrease in the coming decades (IEA, 2019). If IEA's estimates entail correctness, the transmission costs may increase to over 50% of the CAPEX but are uncertain and dependent on innovation and technology development that make OW significantly cheaper over the next decades.

The significant difference in the estimates of BVG Associates and 4C Offshore compared with IEA could result from different approaches toward the transmission assets, as there are different models[20] in the ownership and development of transmission costs in Europe (IEA, 2019). The transmission costs also depend on the chosen technology (Bosch et al., 2019). For bigger OW projects with several hundreds of MW capacity, HVAC cables are only used up to a certain distance, as electrical losses may result in HVDC cables being economically more beneficial.

3.6.1.5 Installation costs

Installation costs hold the second most significant share of the CAPEX with a share of 19-22%, as there are substantial costs linked to the installation of the turbine, foundation, and transmission system, in addition to insurance (BVG Associates, 2022; 4C Offshore, 2023). The costs distribute themselves between the installation of the turbine (1.5-2.5%), the foundation (3-4%), the transmission system (12-15%), and insurance (~1%). The installation period for a 1 GW OWF is typically three years, and one of the most substantial cost drivers is weather downtime (BVG Associates, 2019). A third of the time is usually lost on waiting for better weather, as wave height and its periodicity, direction, persistence, wind speed, and tidal flows define the workable and non-workable days for offshore crews.

The weather downtime will become more relevant as OWFs move to deeper waters further from shore, which is associated with increased weather downtime due to unfavorable weather conditions (BVG Associates, 2019). Furthermore, with the increase in turbine size, there is a heightened demand for larger vessels, resulting in additional costs due to the need for bigger vessels to install more intricate offshore structures.

[20] It can be developed and owned by a transmission system operator (TSO), the government, or a project developer.

3.6.2 OPEX

OPEX is OW's second biggest cost driver, representing around 28% of total costs (BVG Associates, 2022). The share is significant, as in comparison, onshore wind only accounts for 5% (Jiang et al., 2021). Once the construction of the OWF is finished and production commences, the combined operations, maintenance, and service activities account for the OPEX expenses (BVG Associates, 2019). According to BVG, the annual OPEX for an OWF commissioned in UK waters in 2022 is estimated at €66 975/MW. In contrast, Stehly et al. (2019) provide a different estimate of €140 909/MW. The total OPEX of a project can vary due to various factors, including port costs, project site characteristics and conditions, local labor expenses, weather conditions, and distance from the shore, as Bosch et al. (2019) noted. Based on publicly available accounts, Peak Wind's analysis of 60 operational European OWFs shows a market average of €135 000/MW in 2020 (Peak Wind, 2022). The activity's primary purpose is to optimes electricity generation and thus maximize the financial return by finding a balance between the operational expenditures and the turbine yield. Typically, downtime for wind turbines is scheduled during the summer and periods of lower wind speeds, ensuring their availability during winter and periods characterized by higher wind speeds. Onshore turbines have a technical availability of 98%, while OW turbines, due to logistics planning and other restrictions, are around 95-98%.

3.6.2.1 Maintenance & service

The maintenance & service share of the OPEX represents around 19% of total costs and ensures the ongoing operational integrity of the turbines, foundations, and cables, with both scheduled and unscheduled responses to faults (BVG Associates, 2022; BVG Associates, 2019). Maintenance results in downtime of electricity production and is a vital contributor to the profitability of an OWF (Jiang et al., 2021). The maintenance involves correcting failures, replacing components, and regular inspections, which differ with both the location and the foundation of an OW site. The costs are estimated to be 2-3 times higher than the maintenance costs of onshore wind and are an important factor in developing OWFs. Efficient maintenance strategies can decrease downtime, as the efficiency degrades as equipment ages.

3.6.2.2 Operations

The operation share of the OPEX represents 9% of total costs and involves activities such as management of the asset, electricity sales, administration tasks, operating the infrastructure, back-office tasks, and remote and environmental monitoring (BVG Associates, 2022; BVG Associates, 2019). A special-purpose vehicle is normally created to operate a project, and the site gets monitored through an onshore control room, where there is access to historical and real-time data for the turbines and the surrounding infrastructure.

3.6.3 DECOM

The first OWF to be decommissioned was in Sweden in 2016 (McMillan & Topham, 2017). When the lifetime of an OWF is by its ends, the operator has to decide between repowering, a lifetime extension, or decommissioning the site (Luengo & Kolios, 2015). The technical, economic, regulatory, and environmental aspects have to be considered when a site gets repowered or extended, but still, every site will be decommissioned at some point. The DECOM includes all costs of returning the site to its original state after revenue from the residual value of scrap materials and is estimated to be between 1.2-4.0% of the total project cost (Bosch et al., 2019; Kaiser & Snyder, 2012). As there are just a few sites that have been decommissioned, both the cost and the methods differ. BVG Associates estimates the cost to be around 2.5% of CAPEX but mentions that it can increase to 14%, excluding the potential residual value of components (BVG Associates, 2022). Decommissioning funds have provided security against environmental and decommissioning liabilities with annual payments based on OWF revenues (CCP, 2010).

Historically, the focus has been on planning and constructing new projects, giving the decommissioning phase little to no attention (McMillan & Topham, 2017). The unique marine environment at each site, the technical limitations of vessels, and the lack of specific regulations make the decommissioning process challenging. In addition, each OW site has unique characteristics that involve different solutions. As over 30% of the total installed OW capacity was older than 17 years in 2022, the challenges will be further addressed when the sites reach the end of their lifetime (Topham et al., 2019).

The volatility in scrap metal prices is further decisive in deciding when an OW gets commissioned, as recycling OW components could cover up to 20% of the DECOM if the monopile foundations also get recycled (Topham et al., 2019). Components of the nacelle and tower are today established recycling practices, but the composite materials from the turbine blades have been challenging to recycle (Siemens, 2021). It is demanding to recycle the blades, as they are designed to be durable and withstand harsh weather for 20-30 years. In addition, the chemical structure of the blades makes it challenging to separate the used materials from each other (Jacoby, 2022). As a result, when wind turbine blades reach the end of their service lives, they usually end up in landfills. As tens of thousands of blades will be retired annually between 2030 and 2040, some countries will start to ban landfilling of blades from 2025. Recyclable blades may be a solution, and Siemens Gamesa recently announced the world's first recyclable blade ready for commercial use (Siemens, 2023).

3.6.4 Cost of financing

Project finance is common for OW projects, as debt is directly provided to a project and only repaid by its revenue without any guarantee from its owner's balance sheet (PWC, 2020; WFOF, 2022). To manage the financial risks and complexities of the project, a special purpose vehicle (SPV) is typically established (PWC, 2019). The SPV acts as a dedicated legal entity, effectively isolating the project's assets and liabilities from the balance sheet of the project sponsors (BVG Associates, 2019). The SPV makes it easier to attract investors and lenders, provides tax advantages, simplifies regulatory compliance, and reduces the risk, thus increasing the transparency, efficiency, and accountability of the financing process of OW projects. Investors determine the market value of a project by calculating the project's cash flow with a discount factor (Ezzell & Miles, 1980). As they may be risk-averse, they would require compensation for funding risky projects. The weighted average cost of capital (WACC) is regularly used for renewable energy projects to compensate investors for the risk of funding projects (Tagliapetra et al., 2019). The WACC formula below reflects the project's sources of financing, debt ($\boldsymbol{D}$) and equity ($\boldsymbol{E}$). It calculates a weighted average based on the proportion of each source, cost of equity ($\boldsymbol{R_E}$) and cost of debt ($\boldsymbol{R_D}$), in the project's capital structure, after-tax ($\boldsymbol{T}$).

$$\boldsymbol{WACC = \frac{E}{E+D} * R_E + \frac{D}{E+D} * R_D * (1 - T)} \quad \textbf{(3.5)}$$

The different life-cycle phases of an OWF result in different profiles of each phase in terms of time, invested capital, and risk (WFOF, 2022). As OW is capital-intensive, substantial upfront costs are needed, but once its operational, the repayment of the initial investment is the main cost, either as interest on loans or as dividends to equity providers (Ioannou et al., 2018; WFOF, 2022). The cost base is thus relatively fixed and dependent on the cost of capital, and the lower the cost of capital, the more affordable it will be to allocate the initial investment over the years of production.

3.6.5 Economic risk

Pure developers usually focus on a project's early phases, a relatively little capital-intensive but time-consuming and risky phase, with potentially high sunk costs if the project does not proceed (PWC, 2020; WFOF, 2022). These tend to reduce their share in the project once it is fully permitted or financially closed. Financial investors are involved through all the development stages, while industrial players focus on late development and construction, selling their shares after completion. When a project is built and operational, the most risk-averse investors come in, as a minority stake in an OWF with a fixed price tariff is a safe investment.

Figure 3.21 outlines three risk categories associated with OW projects (WFOF, 2022). The first category is common for all infrastructure projects and involves risks such as if regulators change the rules if the prices for copper or steel increase or if a third-party stakeholder goes bankrupt. Political risk is a critical risk factor carefully assessed by lenders and investors. Commodity price risks are a key risk closely assessed by financiers, while lenders and investors must carefully monitor the counterparty risks. The second category of risks is specific to wind projects and involves the risks of calm winds or less innovation. Electricity production estimates or wind estimates are critical, as wrong estimates affect the economies of a project substantially. Wind turbine technology is decisive, as developers want to use the biggest and most recent turbine models, often untested and without long track records. For example, Equinor recently had to postpone the project Trollvind due to the unavailability of technology that was the basis for the project (Equinor, 2023b). The third risk category is unique for OW and involves the that arise during the construction and operations of the project (WFOF 2022). The construction risk is critical, as lenders bear it and must understand the project and price it accurately. Operational risk combines unexpected losses, the project's performance at sea, and the required operations and maintenance work.

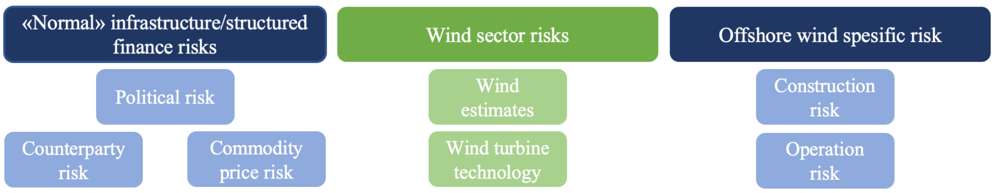

Figure 3.21: *Three risk categories associated with OW development, input from WFOW (2022)*

3.6.6 Learning curve

Learning curve approaches are well-established cost trajectories, but there are few such assessments of OW technologies to date (Wiser et al. 2016). A learning rate indicates the fractional reduction in the cost for each doubling of cumulative capacity (Rubin et al., 2015). The estimated learning rates for OW tend to differ between 3%-31% (NREL, 2022). For OW plants between 2001 to 2022, a learning rate of between 26.8% and 31.2% has been found, but with huge fluctuations from past OW costs, making it challenging to develop a helpful learning rate that could help predict future costs accurately (Juninger & Louwen, 2020). A multifactor approach to learning curves that considers factors such as the cost of raw materials, location-specific properties, and financing costs may offer greater potential for accurately predicting future costs. However, it is necessary to collect more data to determine how effective these models will be in making such projections.

3.7 Revenue

With an increasing share of renewables in Europe, weather conditions will play a growing role in influencing electricity production, subsequently impacting the power price (Statkraft, 2023). This heightened dependence on weather patterns will result in volatile electricity prices, giving rise to the occurrence of both extremely low and high price levels. There are limitations related to the storage of electricity production that arises from renewables, resulting in them having to be used when produced (Evans et al., 2012). In addition, global power grid connections are not developed to efficiently transfer and utilize capacity from areas with an electricity surplus to areas with a deficit (Statkraft, 2023). As a result of limitations in the Norwegian transmission capacity, the power grid is divided into five geographical areas with individual prices (Blaker, 2022). During the summer of 2022, the area’s price differences were historically high, as spot prices in Northern Norway could be between 26-35 cents higher per kWh than in Southern Norway. On some days, the spot price difference resulted in several hundred times higher prices in the South compared with the North.

Figure 3.22 on the next page illustrates the merit order curve and the rising marginal cost of electricity production from different energy sources (Evans, 2012). In European electricity markets, buyers must submit their demand before sellers submit their supply and required price. Renewables with the lowest price begin production first, followed by higher-priced producers until the demand is met. The market price, set by the most expensive producer, typically gas producers, is the price all buyers must pay.

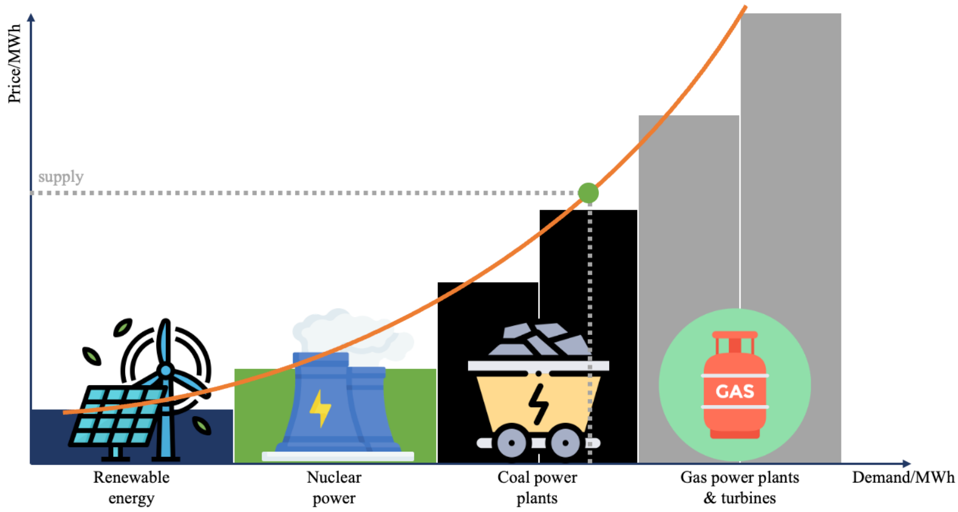

Figure 3.22: *The merit order curve*

Renewable electricity production will thus occur when the facilities are physically able to do so; they cannot operate flexible production and are referred to as «price takers» (Heptonstall, 2010). Furthermore, the weather dependency could result in significant volatile electricity prices, as the prices would be very low when the wind conditions are good and comparably very high when there are calm winds (Statkraft, 2023). The merchant electricity price exposure is thus a severe risk factor for OW producers, resulting in full market exposure to volatile electricity prices (McKinsey, 2018). The exposure has resulted in subsidies to renewable projects to cope with the risk and attractiveness of investing in renewables. Power purchase agreements (PPA) may be a solution to reduce the risk, in addition to government subsidies like sliding feed-in premiums such as CfDs (Dahroug et al., 2018; Poudineh & Welisch, 2020). Auctions for CfDs are increasingly common and are proposed to be the subsidizing tool for the first phase of Southern North Sea II (Regjeringen, 2022).

An initiative from the Transmission System Operators (TSO's) from Belgium, Denmark, Germany, and the Netherlands to develop a high-level strategic integrated offshore network was highlighted at the Ostend Summit, inviting the TSOs from the remaining countries around the North Sea to join the initiative (OED, 2023b). Such an integrated system could increase the utilization of OW further from shore at deeper seas, as the need for individual offshore substations for each OWF would no longer be necessary. In addition, initiatives like this would reduce the overall costs of developing OW, decrease the necessity of subsidies such as CfDs, and reduce bottlenecks between the countries' grids. To illustrate, over the past two years, Germany has compensated Danish wind turbine owners with nearly €70 million to deactivate their turbines (Ghaderi, 2022). This arrangement arises from the limitations in the capacity of the German power grid to effectively transmit Danish electricity further into the country

4. Methodology

Given the considerable uncertainties surrounding the cost of establishing and operating an OWF, it is necessary to introduce methods that allow quantifying uncertain cost parameters. Uncertainty quantification techniques have a crucial role in minimizing the impact of uncertainties in the decision-making process and have been effectively utilized to address a diverse range of real-world problems (Abdar et al., 2021).

To assess the cost associated with establishing and operating an OWF in Norway, the LCOE metric is utilized. The LCOE metric is a deterministic approach that produces identical outcomes given the same set of input parameters. To account for uncertainties of specific parameters, a stochastic methodology is necessary. In this study, the Monte Carlo method is therefore applied.

4.1 LCOE

The levelized cost of energy is a widely used metric for comparing the cost of generating electricity from different energy sources (Aznar, 2015). It represents the revenue from selling electricity required for an energy project to break even (Chalise et al., 2015). By considering a project's lifecycle costs and lifetime energy production, this metric estimates the cost-effectiveness of energy generation, expressed as a price per unit of energy generated. For the electricity generated,

$$\boldsymbol{E_T = E_{TGross} * l_{performance}} \quad \textbf{(4.1)}$$

$L_{performance}$ is the annual production degradation due to falling availability, aerodynamic performance, and conversion efficiency (Staffell & Green, 2014). LCOE is given by the function in Equation 4.2, where the net present value of total cost is divided by the net present value of the total electricity generated.

$$\boldsymbol{LCOE = \frac{\sum_{t=1}^{n} \frac{CapEx_t + OPEX_t + V_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}} \quad \textbf{(4.2)}$$

Where:

- CAPEX = Capital expenditures
- OPEX = Operational expenditure
- V = Decommissioning
- r = Discount rate
- E = Electricity production

The LCOE estimation employed in this thesis represents a project's power price threshold to encompass its expenses, settle its debts, and fulfill the expected return on investment for its equity shareholders.

4.2 Monte Carlo simulations

Monte Carlo simulation (MCS) is a method used for uncertainty quantification. MCS computes outcomes as functions of multiple uncertain inputs, each expressed as a probability distribution (Spinney & Watkins, 1996). The probability distribution provides more realistic information about risk and uncertainties within the LCOE parameters than deterministic point values. A simple sensitivity analysis for estimating the LCOE with high-low values is limited as they do not provide a likelihood of the outcomes.

The MCS produces a random number from the probabilistic input variables' respective distributions (Brandimarte, 2014). The expected value of interest computed can be written as follows:

$$\boldsymbol{E[g(X)] = \int_{x \in X} g(x) P_x(x) dx} \tag{4.3}$$

Where the probability variable X has a probability density function $\rho_x(X)$ and assumes an arbitrary function g(x). The integral encompasses the entire range of possible X values, at which X's probability density function is evaluated to derive the expected value of g(x). The MC method employs probability space sampling of the associated random variable to evaluate the integral in equation X. To estimate the expected value of g(x), a distribution of the probability function X is sampled to obtain n number of samples ($x_1, \dots, x_n$), and the average of g(x) is then calculated as follows:

$$\boldsymbol{\tilde{g}n(X) = \frac{1}{N} \sum_{i=1}^{N} g(x_i) \overset{a.s}{\rightarrow} E[g(x)]} \tag{4.4}$$

$\tilde{g}n(X)$ is the MC estimator of E[g(x)], based on the law of large numbers. In essence, the function implies that as the limit is approached, the methods converge to a constant value for the mean and variance of the variable of interest. A procedure flow chart is illustrated in Figure 4.1 on the next page.

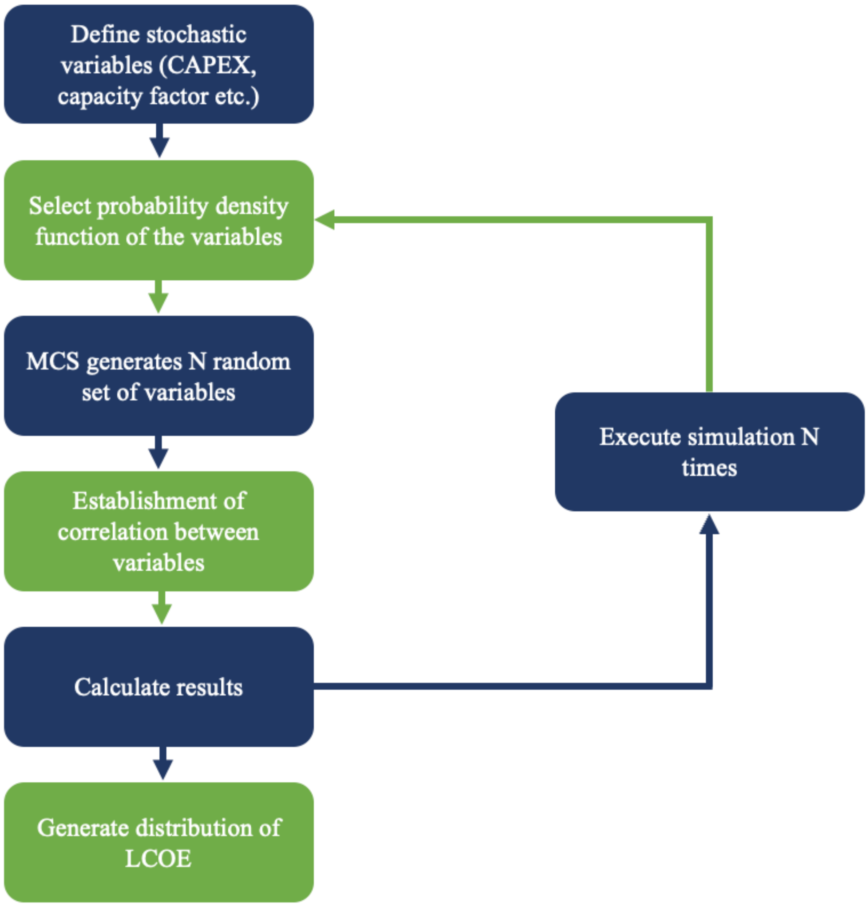

Figure 4.1: *Procedure of MCS*

Following the execution of numerous simulations, the resulting LCOE can be represented as a probability distribution encompassing various possible LCOE values. Due to the comprehensiveness of generating random numbers for the sampling process and running the simulations, the R programming language has been employed for the analysis.

4.3 Limitations with LCOE through MCS

LCOE is a widely adopted metric for comparing the cost of producing electricity across different generating technologies over the lifetime of a power plant. However, the validity of this comparison is predicated on the assumption that electricity is a homogenous good. For example, this assumption implies that one MWh of electricity generated by a wind turbine would be a perfect substitute for one MWh generated by a nuclear plant; nonetheless, the heterogeneity of electricity caused by its fluctuating prices challenges this assumption (Hirth et al., 2016). This can lead to imprecision in the correlation between production and revenue and non-dispatchable sources' unpredictable production compared to dispatchable generation technologies (Joskow, 2011).

When assessing the LCOE of an OWF, wind conditions are vital. Variability in wind supply varies with the capacity factor, production, and consequently, the LCOE. This is not included in the LCOE as it operates with a static energy production over the energy technology's lifetime. Another issue is LCOE's sensitivity toward the project's discount rate. Changes in discount rates can make the comparison to other technologies or OWF sites less relevant. This is especially a problem when the discount rates vary across countries, strengthened by currency fluctuations and differences in inflation- and interest rates.

Another weakness of the model is that the LCOE is affected by different treatment of costs for its calculation. These are particular costs related to transmission, decommissioning, and grid balance. In addition, the lack of a standard definition for the cost variables included in the LCOE calculation can lead to differences in how it is calculated from one energy-generating site to another. This could result in an inefficient comparison of different energy-generating projects.

To mitigate some of these uncertainties, Monte Carlo simulations have been employed to calculate the LCOE. However, MCS is only as accurate as the input data used to generate them. The availability and quality of data can therefore affect the accuracy of the results. Additionally, MCS assumes that the input parameters adhere to specific probability distributions. However, identifying the appropriate distribution for certain variables can be challenging. These assumptions failing to capture real-world conditions, may lead to biased results. Moreover, the sensitivity of MCS to model parameters may present difficulties in isolating the effects of individual inputs on the LCOE. This is especially true when specific parameters exhibit a high degree of variability.

5. Data

This section presents the data selected for further analysis of the actual cost of an OWF located on the Norwegian continental shelf. The uncertain stochastic variables influencing the LCOE are presented together with their respective distributions. The cost data were acquired from developers and subjected to cross-verification using publicly audited accounts whenever feasible. In cases where direct access to developer data was unavailable, data was obtained from wind project consultants to supplement the information.

5.1 Project Selection

As Norway is in the early stages of OWF development, we had to look abroad for cost data on fully developed projects. The initial database collected includes 2888 OWF projects all over the globe. The projects are classified based on status, such as fully commissioned, under construction, or in early planning stages. The data had to be sorted to ensure our sample could be used as an accurate benchmark for an OWF established in Norwegian waters. Consequently, projects in the final dataset fulfill the following requirements: 1) they are either fully commissioned or have partial generation, 2) they are situated in Northern- or Western Europe, and 3) they have a modeled capacity exceeding 5 MW.

To gather a proper selection of OWFs for analysis, we compiled data on Northern- and Western European OW projects from 2000 to 2022, including the dates of final investment decision (FID), construction start, first generation, and full commissioning. It should be noted that project costs are usually locked or hedged at the time of FID, making it the relevant cost year. The choice of georegion for our observations is based on the significant variation in cost profiles across different markets. For instance, emerging markets typically have higher expected CAPEX due to higher financing costs and a lack of local supply chains (Dutton et al., 2019). Since our thesis focuses on the cost of establishing OWFs in Norway, European OWF projects provide a more accurate representation.

After applying the selection criteria, 108 operational bottom-fixed OWF projects were identified. Figure 5.1 and Table 5.1 on the next page illustrate the geographical distribution of the OFW projects selected for the analysis and present summary statistics, respectively.

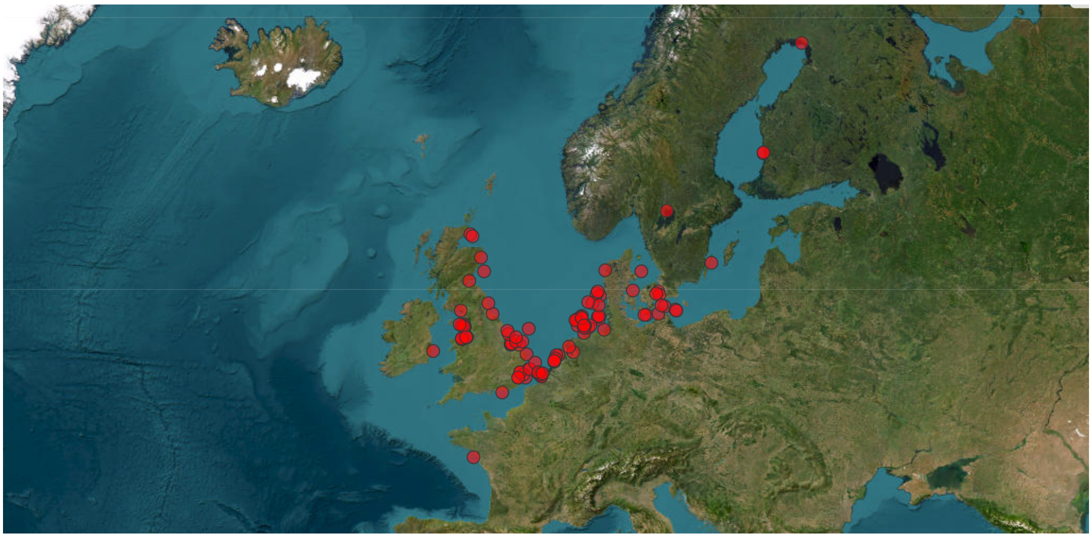

Figure 5.1: *Geographical location of the OWF projects*

Variable	Mean	Median
CAPEX (million €/MW)	4.71	4.90
Distance from Shore (km)	27.85	19.50
Modelled Capacity	285.05	217.50
Water Depth (m)	24.15	23.00
Wind Speed (100m) (m/s)	9.46	9.57
Year Constructed	2012.96	2013.00
Turbine Size (MW)	5.04	4.00
Expected Life	23.35	25.00

Table 5.1: *Summary statistics of the OWF projects*

5.2 Inflation and currency adjustments

Considering the inclusion of various projects from multiple countries commissioned at different points in time, the data in this thesis encompasses CAPEX and OPEX figures reported in different currencies and from multiple years. The values were standardized to euros using the currency exchange rate at the time of FID or the reported year to facilitate cross-currency comparisons. Additionally, the standardized values were further adjusted for inflation. In the case of CAPEX, the Producer Price Index (PPI)[21] was utilized. Unlike the consumer price index (CPI), PPI tracks the price change received by industrial and service businesses for their goods and services, making it a more suitable indicator of developers' underlying capital expenditure trend. Conversely, OPEX was adjusted for inflation using the CPI[22] index. This divergence is due to the nature of OPEX, which reflects consumer-oriented expenses. Inflation was quantified with 2015 prices as the baseline, and the values were subsequently adjusted to reflect 2022 prices.

[21] PPI 2022 = 141.00
[22] CPI 2022 = 116.82

5.3 Uncertain variables

Several uncertain variables influencing the LCOE have been identified and will be applied in the MCS for the analysis. These variables can be divided into two categories: internal and external factors. The internal factors include cost and facility characteristics, while the external factor includes the WACC.

5.3.1 CAPEX

CAPEX was sourced from the developers or other primary sources and includes transmission costs. The obtained values were reported in the original currency at the time of FID. Numerous factors can contribute to fluctuations in CAPEX values. Existing literature indicates that longer distances to shore and deeper water typically correspond to higher material use, thereby resulting in elevated costs. When calculating the CAPEX for our reference project, it is important to step carefully due to the inherent fluctuations associated with project characteristics. Considering the learning curve, it is observed that CAPEX generally diminishes over time as experience accumulates. However, as depicted in Figure 5.2, CAPEX exhibited a fundamental upward shift around 2010, followed by a decline that persisted until 2020.

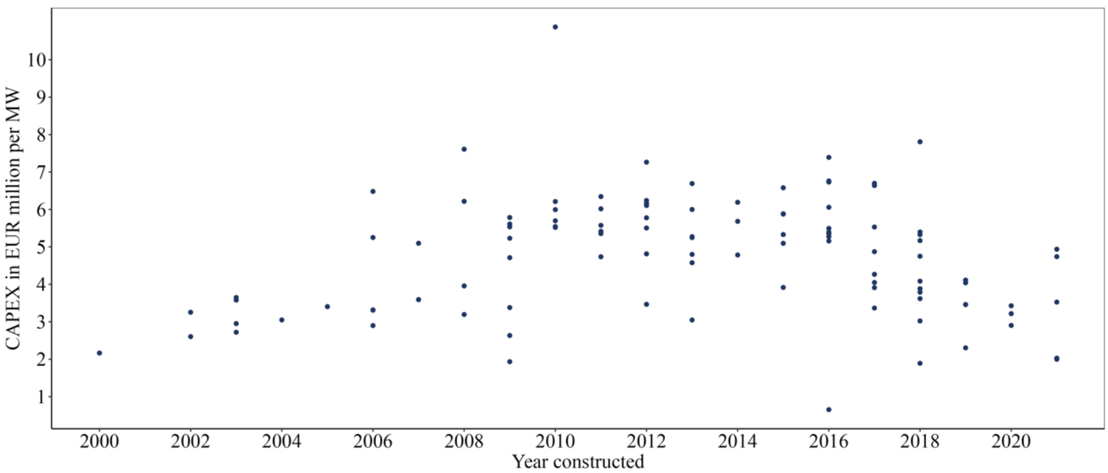

Figure 5.2: *Overview of CAPEX per MW by year of construction*

The learning curve effect may be mitigated by longer distances to shore and deeper waters. Upon analyzing the data, it becomes evident that projects situated in shallower water and closer to the shore demonstrate lower capital costs. This observation is illustrated in Figures 5.3 and 5.4 on the next page, which depicts notably lower average CAPEX for projects close to land and with very shallow waters, respectively. Additionally, CAPEX has a slight upward trend as projects move deeper and farther away from the shore. Although not as pronounced as in the case of projects very close to the shore.

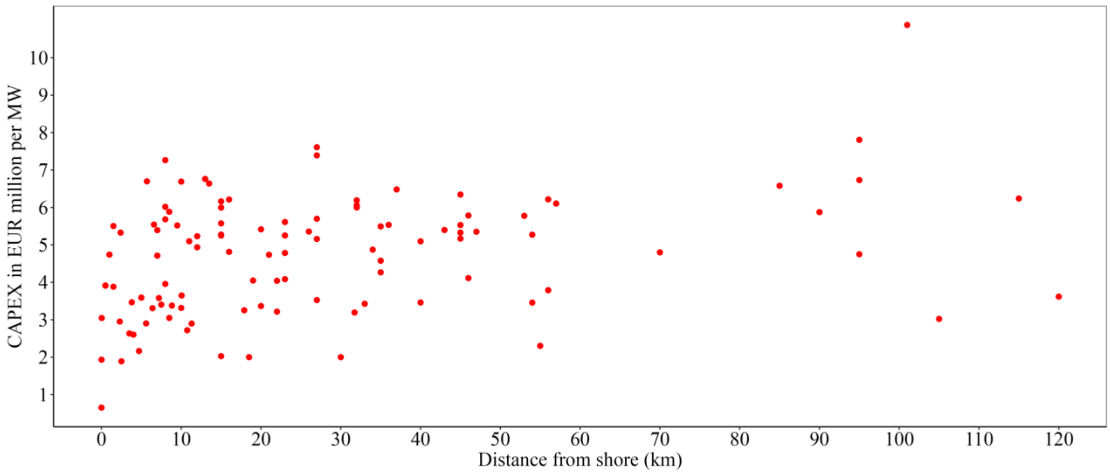

Figure 5.3: *Overview of CAPEX per MW by distance to mainland*

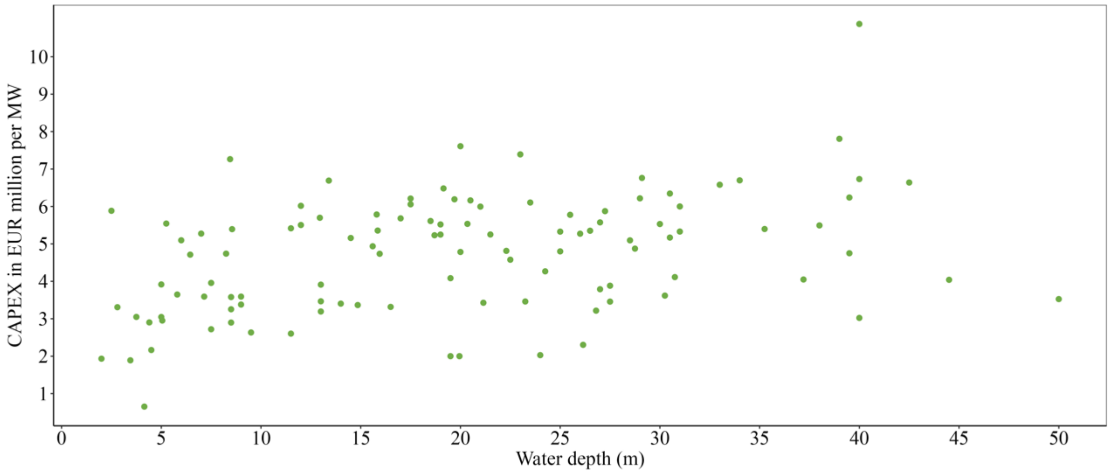

Figure 5.4: *Overview of CAPEX per MW by water depth at the project site*

5.3.2 OPEX

Estimating O&M costs can be challenging due to the uncertainty associated with the lifetimes of significant components. In addition, the evaluation is further complicated by the need to consider future advancements and account for site-specific conditions. Existing literature reveals a notable variation in cost estimates, as discussed in section 3.6.3. Additionally, extracting accurate O&M costs is further complicated by the involvement of separate entities responsible for their management and developers' hesitation to disclose such information.

This study extracted the OPEX costs from audited accounts and other projects obliged to publish operational reports. To enhance the dataset, literature estimates were also incorporated. The detailed OPEX data used in the analysis can be found in Appendix 3. It is important to highlight that, for computational purposes, OPEX is assumed to be a fixed annual amount despite its tendency to fluctuate in reality.

5.3.3 Capacity Factor

To calculate the energy output for a turbine, windspeed is a crucial input. To obtain the required data, we retrieved hourly wind speed from the offshore platform Ekofisk from 2007-2013 (NK, 2023). The Ekofisk oil field is adjacent to Southern North Sea II, our reference location. As discussed in section 3.4.3, the power curve plays a critical role in determining the energy output of a turbine. Therefore, we utilized the power curve provided by IEA for a 15 MW reference turbine, with a cut-in speed at 3 m/s and a cut-out speed of 25 m/s (IEA, 2020).

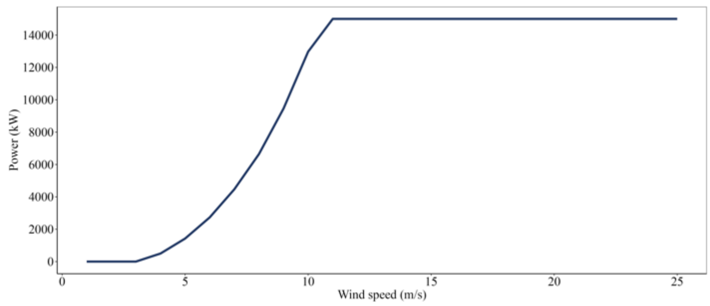

Figure 5.5: *Power Curve for the 15MW_240D reference turbine (IEA, 2020)*

To ensure accurate measurements, it was necessary to extrapolate the wind speeds measured at 58 meters to the hub height of our turbines at 150 meters above sea level. This was accomplished by applying the following wind power law equation:

Where:

$$\frac{V(H)}{V(Z)} = \frac{\log\left(\frac{H}{R_0}\right)}{\log\left(\frac{Z}{R_0}\right)} \tag{5.1}$$

- V = velocity
- H = Height we want our velocity
- Z = Height (we have measured wind speed)
- Ro = Roughness length[23]

The daily variation in wind speed from our observations after adjusting to the turbine's hub height is presented in Figure 5.6.

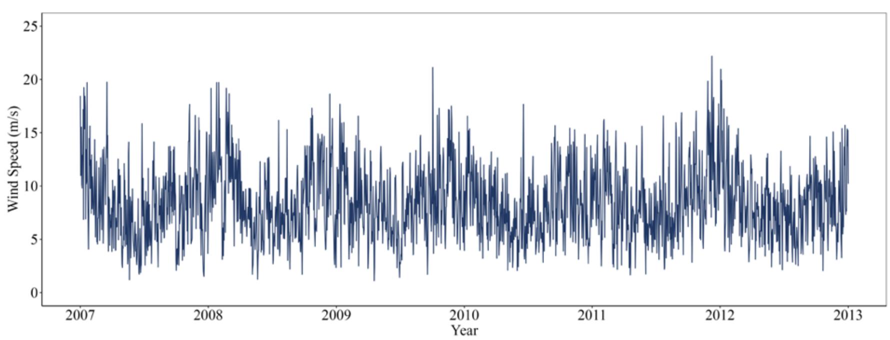

Figure 5.6: *Daily average wind speed from 2007 to 2013 at turbine hub height*

[23] Depends on the roughness class, OW is characterized with roughness class 0.

We obtained a gross capacity factor of 59% by creating a function for energy output based on hourly wind speeds at hub height, the power curve, and the laws of wind turbine physics through the interpolation of hourly wind speed data. When estimating the total net energy output, we need to account for loss factors, effectively decreasing the output. After applying the loss factors retrieved from NVE[24], we obtained a net capacity factor of 49,15%. The loss factors are described in Table 5.2.

Gross Capacity Factor	59.60%	
	Loss	% Loss of full
Wake Effects	7.00%	93.00%
Blockage	1.00%	99.00%
Turbine availability	4.84%	95.16%
Electrical transmission efficiency	2.00%	98.00%
Environmental	2.00%	98.00%
Electrical losses	2.00%	98.00%
Total factor	82.46%	
Net capacity factor	49.15%	(-17.54%)

Table 5.2: *Capacity loss factors*

5.3.4 WACC

Estimating an accurate discount rate is challenging due to the variation in project risk and interest rates. In addition, the weighted average cost of capital has a considerable impact on the lifetime costs of the project as it determines the annual debt and equity repayments. According to Thema Consulting Group (2020), the discount rate for a typical renewable energy utility in Europe is around 6% before tax, while Aures II (2021) estimated a WACC between 3.5-9% for European countries. Given the higher inflation and interest rates observed in the past year, attributed to macroeconomic and geopolitical developments, WACC has been chosen carefully based on literature estimates.

5.3.5 Project lifetime

Project life is a critical parameter affecting the LCOE, impacting O&M and energy production. Different project lifetimes can lead to significant variations in the LCOE. For example, while NREL (2019) uses a 25-year lifetime in their analysis, BVG (2019) estimates a 27-years lifespan for a UK OWF commissioned in 2022. However, older fully commissioned UK wind farms are estimated to have a 20-25 years lifespan, which can be extended if their operations are profitable and safe (Adedipe & Shafiee, 2021). Project life could have been set to a fixed value through the analysis, but incorporating it as a stochastic variable allows for considering its potential variation and impact on the LCOE.

[24] Received through personal communication (e-mail) on 24. February 2023.

5.4 Summary of stochastic variables

Table 5.3 summarizes the input variables necessary for the LCOE computation and their respective distributions. As they are based on real-world data with known standard deviations, a normal distribution has been selected for CAPEX and OPEX. Although the capacity factor is also derived from real-world data, its high uncertainty and variability over the OWF's lifetime make it more suitable for a triangular distribution. On the other hand, WACC, project life, decommissioning, and degrading rate are based on literature estimates without an actual mean or apparent standard deviation. Hence, a triangular distribution is more suitable for these variables as it accommodates a minimum, most likely, and maximum value.

The PDF of the normal distribution can be written as,

$$f(x) = \frac{e^{-(x-\mu)^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}} \quad \textbf{(5.2)}$$

where μ refers to the average and σ represents the standard deviation. The formulation of the triangular distribution involves the specification of three parameters: a, b, and c, representing the lower limit, upper limit, and mode. The distribution can be expressed mathematically as follows:

$$f(x) = \frac{2(x-a)}{(b-a)(c-a)} \; for\ a \leq x \leq c \quad \textbf{(5.3)}$$

&

$$f(x) = \frac{2(b-x)}{(b-a)(b-c)} \; for\ c \leq x \leq b \quad \textbf{(5.4)}$$

Inputs	Distribution	Mean (million €/MW)	σ	Mode	Upper	Lower
CAPEX	Normal	4.7111	1.5769			
O&M Cost (annual)	Normal	0.0859	0.0086			
Project life	Triangular			25	30	20
WACC	Triangular			0.06	0.08	0.04
Degrading rate	Triangular			0.002	0,003	0.001
Capacity factor	Triangular			0.49	0,54	0.45
DECOM	Triangular			70.000.000	90.000.000	50.000.000

Table 5.3: *Overview of stochastic variables*

6. Results & Analysis

This section presents the results and analysis of the cost and uncertainties associated with establishing and operating a bottom-fixed OWF on the Norwegian continental shelf. The probability distributions of the input variables were established using the stochastic simulation technique discussed in Section 4.2 and illustrated in Section 5.4. Then, a random sample was drawn from the distribution of each variable, and the corresponding LCOE was calculated through 10 000 iterations.

The input parameters are presented in Table 5.3, while the project characteristics and additional parameters are provided in Table 6.1. As such, the analysis pertains to an OWF with a total installed capacity of 1500 MW, comprising 100 turbines, each with a capacity of 15 MW.

Description	
Project characteristics	
Foundation	Bottom-fixed
Electricity type	DC
Capacity (MW)	1500
Number of turbines	100
Distance to shore (km)	150
Water depth (max)	70
Water depth (min)	53
Turbine specifications	
Turbine (MW)	15
Rotor diameter (m)	240
Hub height (m)	150
Cut-In WS (m/s)	3
Cut-out WS (m/s)	25

Table 6.1: *OWF project characteristics*

6.1 Probability density functions of the stochastic variables

The MCS generates a large number of random samples from the variable's respective probability density functions. The following section will go through each stochastic variable probability distribution.

6.1.1 CAPEX

Figure 6.1 on the next page displays the normal distribution of CAPEX. The average CAPEX for the OFW is €4.71 million/MW, with a standard deviation of 1.57. With a capacity of 1 500 MW, the total CAPEX amounts to around €7 billion. Considering the one standard deviation

(1SD) range, the CAPEX for the project falls between €4.7 billion and €9.4 billion[25]. Compared to the projects in our dataset, Hornsea I, which has a capacity of 1 200 MW, had a CAPEX of €4.4 billion (Appendix 1). The relatively high standard deviation highlights the inherent uncertainty in estimating CAPEX for the OWF. Important factors behind the variation may be related to differences in distance to shore, water depth, and construction year, as examined in section 5.3.

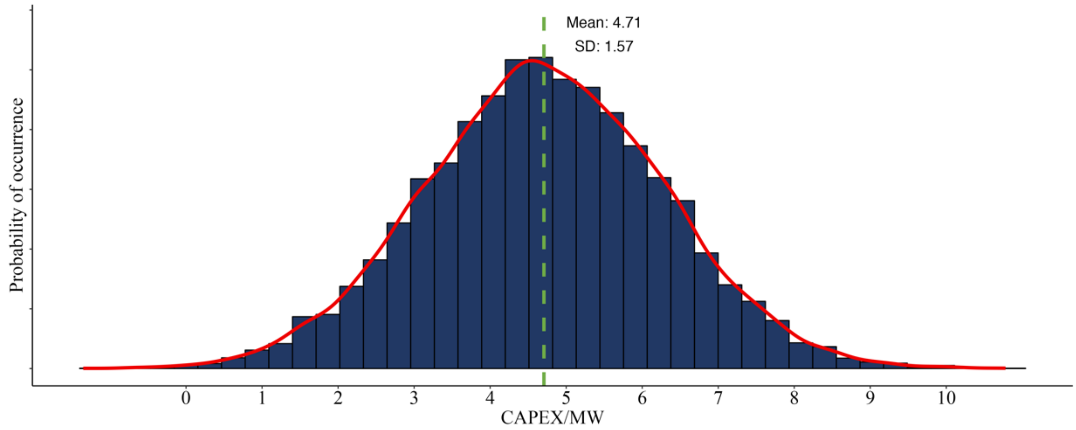

Figure 6.1: *Probability density function for CAPEX in million €/MW*

6.1.2 OPEX

As previously discussed, OPEX was modeled with a normal distribution. Figure 6.2 illustrate that the generated distribution has an annual average of €86 000/MW with a standard deviation of 0.1. Similarly to CAPEX, distance to shore is an important factor driving variability in O&M cost estimates, alongside weather conditions and new technologies. The estimation of OPEX is characterized by considerable uncertainty due to the necessity of predicting failure rates and corresponding maintenance needs.

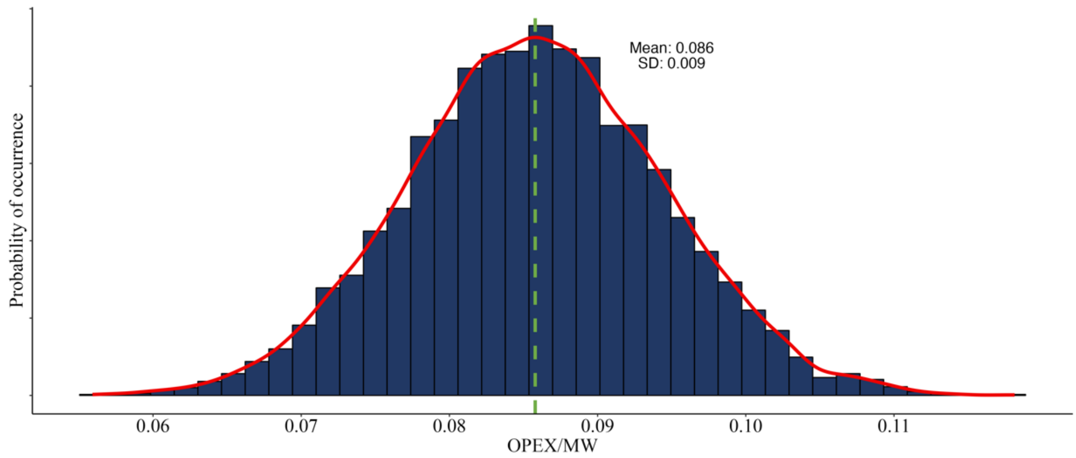

Figure 6.2: *Probability density function for OPEX in million €/MW*

[25] Assuming that the standard deviation remains constant across different capacity levels.

6.1.3 Capacity factor

A triangular distribution was employed to account for the inherent uncertainties arising from long-term predictions, measurement inaccuracies, and the non-static nature of the capacity factor. The estimated capacity factor, calculated in Section 5.3.3, serves as the mean, while the minimum and maximum values were set at 45% and 54%, respectively. By applying the triangular distribution, we can effectively manage the risks associated with wake effects, wind direction, and other factors contributing to the variability of the net capacity factor. Figure 6.3 illustrates the probability distribution of the capacity factor, reflecting the assumptions outlined above.

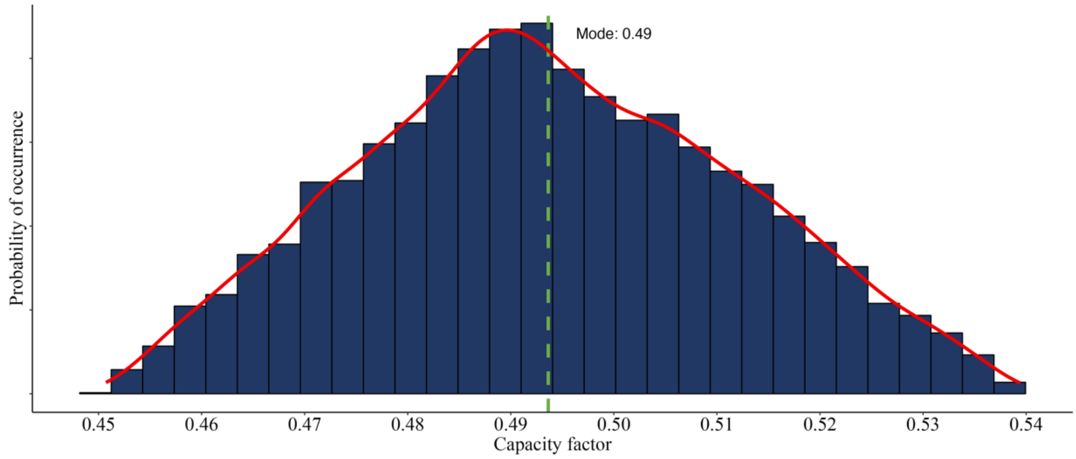

Figure 6.3: *Probability density function for net capacity factor*

6.1.4 Project life, WACC, degrading rate, and DECOM

The remaining stochastic variables were modeled using a triangular distribution. The average value for decommissioning an OWF was €70 million, while the lower and upper bound was €50 million and €90 million, respectively. It is important to note that these values are the present value of decommissioning the OWF in the future.

Regarding the WACC, the authors determined 6% as a sensible mode, with lower and upper bounds of 4% and 8%. The degrading rate is based on NVE's estimate at 0.1% as the lower bound, 0.2% as the mode, and 0.3% as the maximum rate. However, due to insufficient scientific literature about turbine deterioration with age, the degrading rate distribution is highly uncertain. Project life was estimated with a most-likely value of 25 years, with lower and upper bounds of 20 and 30 years in relation to literature estimates. Figure 6.4 on the next page summarizes the stochastic variables' probability distributions.

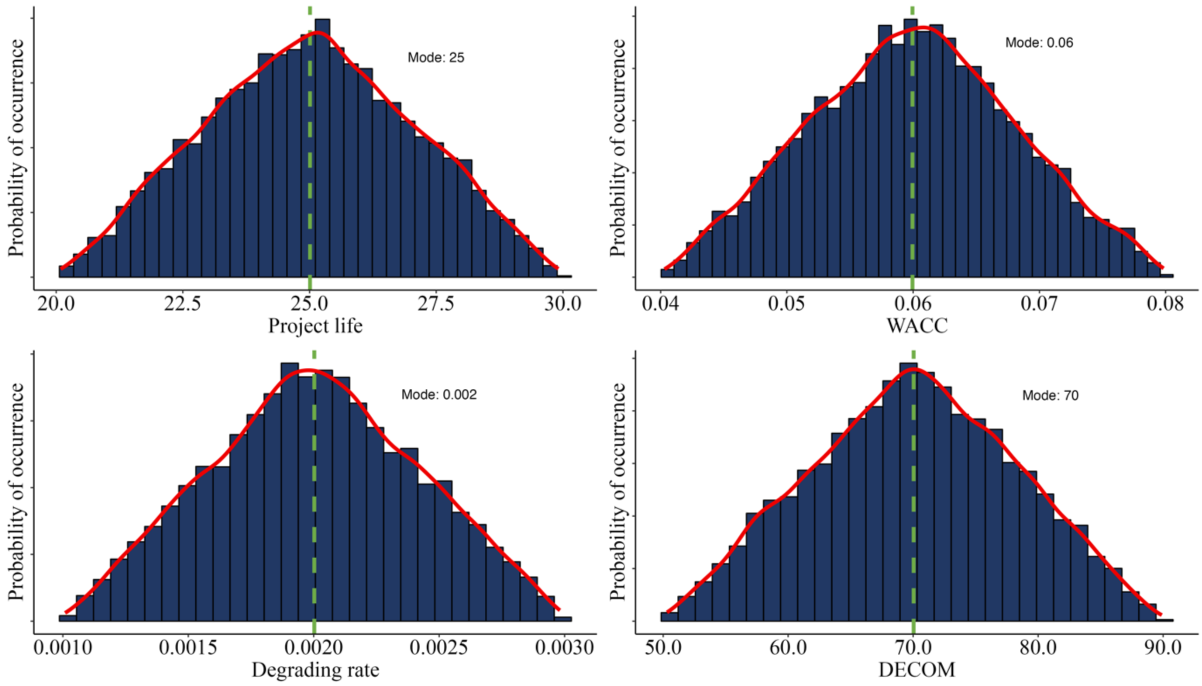

Figure 6.4: *Probability density function of project life (years), WACC (%), degrading rate (%), and DECOM (million EUR)*

6.2 Total produced energy

Figure 6.5 presents the MCS results and distribution of total produced energy. Total produced energy is the discounted value of the annual energy production over the OWF's lifecycle. The cumulative energy production of the OWF is estimated at 81.6 TWh with a standard deviation of 7.6. This translates to a 68% probability that the estimated value of the cumulative energy production falls between 74 TWh and 89 TWh. In comparison, the Norwegian government projected an annual production of 7 TWh for Southern North Sea II (Regjeringen, 2022). When considering the application of our study's most likely degrading rate and WACC, this projection corresponds to 87 TWh and a capacity factor of 53%.

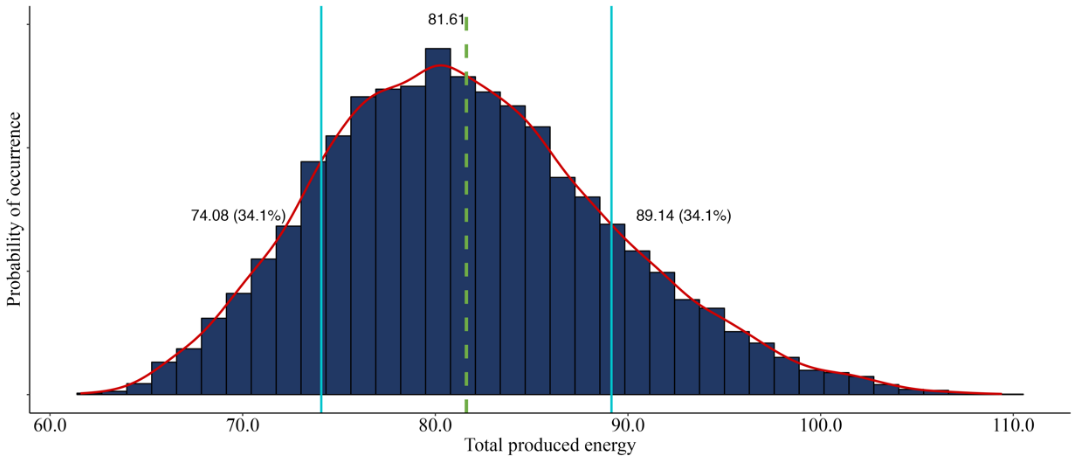

Figure 6.5: *Discounted produced energy distribution for the OWF in TWh*

6.3 Total cost

Based on the probability distributions of the cost variables, the combined expenses associated with the OWF's construction, operation, and decommissioning are projected to be €8.78 billion. Moreover, the estimated total cost demonstrates a 68% probability range between €6.40 billion to €11.15 billion, indicating the level of uncertainty associated with the cost estimation.

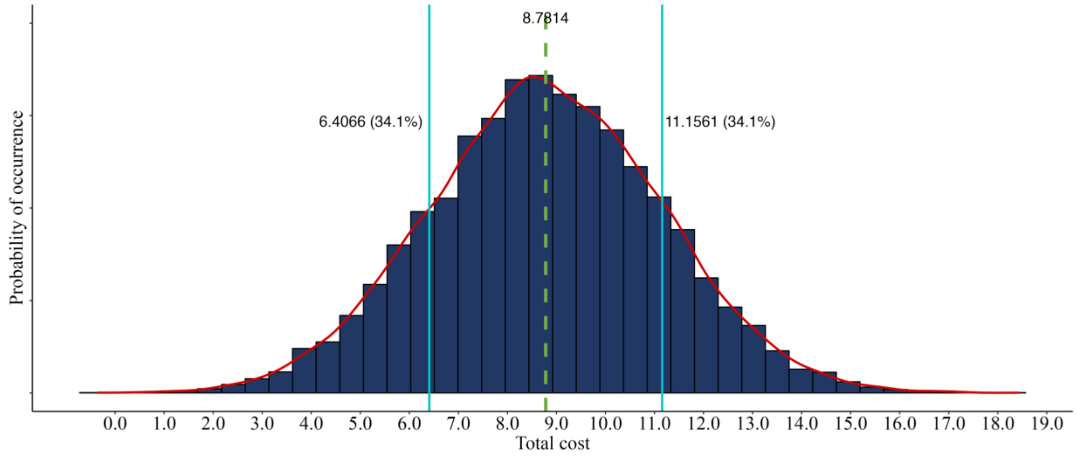

Figure 6.6: *Total cost distribution of the OWF project in billion EUR*

6.4 Levelized Cost Of Electricity

Through Monte Carlo simulation, we generated 10 000 sets of randomly sampled numbers based on the probability density distributions of the uncertain variables. Figure 6.7 shows that this analysis yielded a most likely LCOE of €108/MWh. Additionally, with a 95% confidence level, the estimated LCOE is projected to fall within a range of €50/MWh to €170/MWh. The standard deviation 30.4 indicates that approximately 68% of the LCOE observations are between €77.6/MWh and €138.4/MWh.

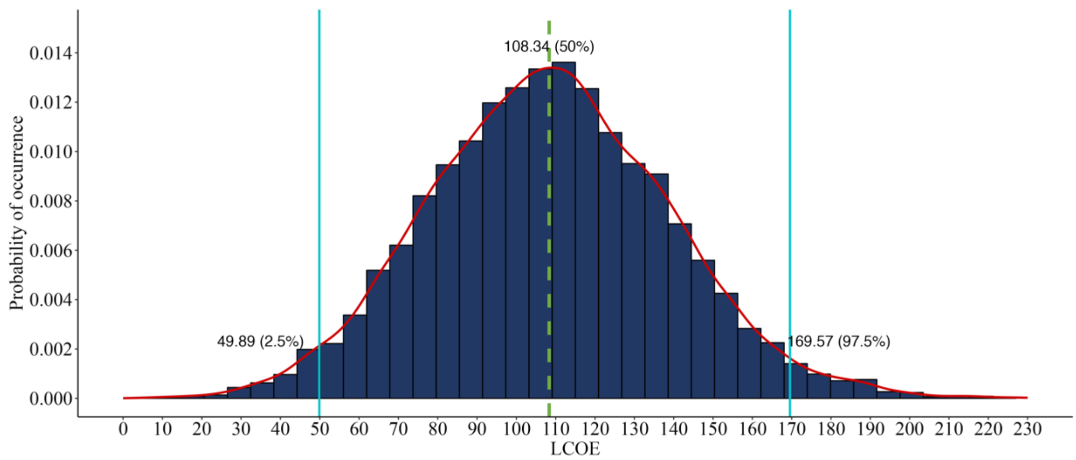

Figure 6.7: *LCOE of the OWF project*

6.5 Sensitivity analysis

In order to assess the influence of input variables on the LCOE, a sensitivity analysis was conducted following the MCS. Figure 6.8 illustrates the changes in LCOE when the input variables are modified by +/- 20% relative to their most-likely values. Notably, the capacity factor significantly impacts the LCOE for the OWF, emphasizing the importance of parameters such as wind speed, loss factors, and generation availability in assessing feasibility. On the cost side, CAPEX is the most influential contributor to the LCOE. Consequently, aside from project site characteristics, fluctuations in steel prices, supply chain constraints, and new technology may influence the total cost significantly.

The WACC emerges as the third most influential parameter affecting the LCOE. In assessing the economic feasibility of the OWF, factors such as inflation and interest rates, which impact the cost of capital, can introduce fluctuations in cost projections. Additionally, the project's lifespan plays a significant role in determining the electricity generation from the OWF and the duration of O&M costs. Unexpected earlier decommissioning negatively impacts the unit cost of electricity, whereas an extended lifetime may decrease the unit cost. Furthermore, variations in OPEX exert a meaningful influence on the unit cost of electricity. Therefore, accurately predicting maintenance failure rates is important when evaluating the cost of the OWF.

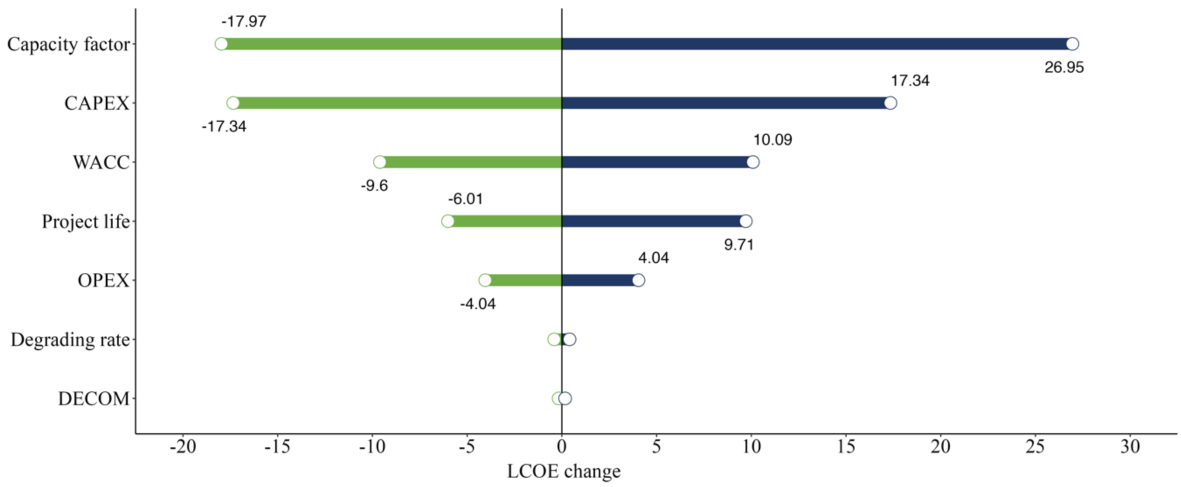

Figure 6.8: *Change in LCOE by adjusting variables by +/-20%*

7. Discussion

Norway and the EU have ambitious plans to develop OW projects in the North Sea to reduce dependence on Russian fossil fuels and achieve climate targets (IEA, 2022a; UD, 2022). The Energy Commission's report highlights the need for Norwegian authorities and policymakers to make complex and crucial path choices, as Norway is transitioning from a power surplus to a deficit within a few years (NOU 2023:3). The Commission identifies a necessity to accelerate the deployment of various energy sources beyond previous levels. However, it is worth noting that the report did not include consultation from Statnett, Statkraft, or NVE. In response, Kjetil Lund, the director of NVE, expressed reservations regarding the Commission's unwarranted optimism and raised concerns about potential misconceptions of the figures used to reach their conclusion (Blaker, 2023b).

Furthermore, Lars Sørgard, the leader of the Energy Commission, recently acknowledged that Norway should refrain from establishing goals that may quickly deviate from the desired outcomes or realistic possibilities (Sørgard, 2023). He further concedes that the expenses associated with OW development are considerably higher than what was assumed just six months ago. The government previously operated with the assumption of a maximum price of NOK 0.66/kWh and subsidies amounting to NOK 15 billion. However, it is now suggested that these figures should be revised upwards to NOK 0.90/kWh, accompanied by a proportional subsidy increase. In contrast, the Norwegian OWF analyzed in this thesis was projected to have a most probable electricity unit cost of NOK 1.24/kWh.

The government appears to have decided that OW is a preferred solution for future Norwegian energy production. However, there is still an absence of a comprehensive economic assessment of OW and its necessary grid investments (NVE, 2023). Over the past years, alternative energy sources have been proposed alongside the government's OW initiatives as potentially more economically feasible and reliable options for Norway (Emblemsvåg & Grønneberg, 2023). The ongoing energy debate is witnessing increased engagement from academia, politics, interest organizations, and businesses, which will be highly affected by the government's path choices. Referring once again to the Energy Commission's report, it is evident that the complex and critical path choices made by the government today will have far-reaching implications for Norwegian energy production over an extended period.

7.1 Summary of findings

In order to examine the cost implications of a prospective OWF located on the Norwegian continental shelf, a Monte Carlo simulation was employed with emphasis on the LCOE. Our analysis yielded a most-likely LCOE of €108/MWh, with a 95% probability range of €50/MWh to €170/MWh. Furthermore, the sensitivity analysis identified capacity factor and CAPEX as the most influential variables, followed by WACC, project life, and OPEX, in the specified order.

7.2 Interpretation of results

LCOE represents the per-unit cost of electricity generated by the OWF. The LCOE of €108/MWh, equivalent to NOK 1.24/kWh, within this research, indicates the average power price required for the project to break even. However, it is important to acknowledge that notable uncertainty exists surrounding the LCOE, as demonstrated by the one standard deviation range of €77.6/MWh to €138.4/MWh.

The estimated LCOE can be compared with existing literature estimates. For instance, NVE[26] reported a notable different LCOE of €68/MWh for the Southern North Sea II project, which is projected to decrease to €52/MWh by 2030 under a base scenario (Meld. St. 36 (2020-2021), p. 86). However, it should be noted that the authors are unaware of the specific adjustments made by NVE to account for inflation. Additionally, WindEurope (2019) estimated an LCOE between €65/MWh and €80/MWh for OWFs established in the area surrounding Southern North Sea II by 2030. Finally, a more recent estimate from Lazard (2023) suggested a general LCOE range for OW between €66/MWh and €128/MWh.

Before delving into potential reasons for the disparities in the estimates, it is pertinent to examine the key variables that influence the unit cost of electricity. The sensitivity analysis conducted in this study unveiled the capacity factor as the most significant driver of the LCOE. However, enhancing the capacity factor without additional investment in research and development, leading to higher overall costs, poses challenges. Therefore, the precise estimation of the capacity factor becomes pivotal when incorporating it in evaluating the unit cost of electricity, as inaccurate estimations can have significant implications for the LCOE and subsequent project assessments.

[26] NVE applied a total capacity of 1 400 MW in their analysis and an applied rate of GBP/NOK = 11.61.

Regarding direct cost, CAPEX emerges as the predominant factor exerting influence. Thus, understanding the interplay between CAPEX and LCOE is essential for evaluating the cost of an OWF. However, in addition to the significance of project-specific characteristics in determining CAPEX, there is a notable uncertainty surrounding the trajectory of commodity prices, particularly steel prices. Additionally, accurately quantifying the amount of material required for OWF development is a vital consideration. The implications of this uncertainty are elucidated by the findings of this thesis, revealing that a 20% estimated error in CAPEX can increase the LCOE by €17/MWh.

Considering the significant changes in the financial landscape over the recent year, WACC emerges as a particularly relevant and compelling variable in assessing the cost uncertainties associated with an OWF. Moreover, the findings of the sensitivity analysis underscore the influence of WACC, positioning it as the third most influential variable contributing to the sensitivity of the LCOE.

Previous investigations into the cost assessments of an OWF were conducted within a different economic environment characterized by historically low interest rates and lower inflation. However, since 2022, European interest rates have risen rapidly, reaching levels unprecedented since the 2008 financial crisis. This surge in interest rates signifies an upward shift in the cost of capital. Schmidt et al. (2019) investigated the effect of higher interest rates on the LCOE for renewable energy. The findings revealed that the recovery of interest rates to 2008 levels would increase the LCOE of onshore wind by 25%. These results demonstrate the significant influence of a changing economic landscape on the evaluations of OWF development projects.

7.3 Implications

There is no doubt that uncertainties in key cost drivers have a significant impact on the overall cost of developing an OWF. Hence, it is imperative that decision-makers undertake a meticulous cost analysis that reflects the underlying economic landscape. Furthermore, incorporating the inherent uncertainty of variables through stochastic modeling or similar methodologies become crucial in quantifying and analyzing risks. This comprehensive approach offers valuable insights for policy decisions pertaining to feed-in tariffs and the Norwegian government's proposed CfD scheme and assists prospective developers in effectively evaluating strike prices.

7.4 Limitations

This thesis is subject to several limitations that have the potential to influence the outcomes and the overall validity of the findings. For instance, Monte Carlo simulations are only as accurate as the input data incorporated. Thus, when modeling the unit cost of electricity for OWFs, the collected data must be accurate and reliable. To mitigate this risk, we collected as much data as possible from the developers, audited accounts, and other projects required to publish annual reports. However, in cases where direct data collection was not feasible, reliance on estimates from consultants, OW analysts, and literature became necessary. It is important to note that these estimates may introduce additional uncertainty. Furthermore, it should be noted that the dataset used for analysis encompassed OWF projects across 11 European countries. Therefore, it is crucial to recognize that transmission cost policies can vary significantly among countries, potentially impacting the accuracy of the cost estimates presented in this thesis.

The cost estimation of establishing an OWF in this study primarily relies on historical data, which introduces inherent uncertainty if the market environment changes. Since 2022, interest rate levels and inflation have substantially increased, influencing the cost of capital for OWF projects. Therefore, we adjusted all costs to reflect 2022 prices, with 2015 as the index baseline for the increased inflation. While this approach allows for comparability of cost data across different time periods, it is important to acknowledge a potential limitation by reflecting the prices in a year that may have experienced abnormal inflation and interest levels. In addition, different approaches to price adjustments can introduce confusion for readers. For instance, UK CfD auctions are commonly expressed in 2012 prices. Reflected in 2015 prices, the most-likely LCOE of our OWF is around €80/MWh. Therefore, when interpreting cost and LCOE across different projects or studies, it is important to exercise caution due to the variations in price adjustments.

In this study, we examine an OFW with a total capacity of 1 500 MW, consisting of 100 turbines with a capacity of 15 MW each. It is important to note that there is no prior operational history for turbines with this capacity. As a result, the potential impact of larger turbines on both CAPEX and OPEX is associated with uncertainty. Moreover, the current dimensioning fault in the Nordic power system is set at 1 400 MW. Therefore, it is necessary to increase the limit to accommodate an OWF with a capacity of 1 500 MW. This will entail increased costs for all Nordic countries and may have implications for the total cost of the OWF, which falls outside the scope of this thesis.

7.5 Recommendations for future research

A predictable and renewable power grid comprising OW energy necessitates integrating balancing power to ensure a consistent electricity supply during periods of wind intermittency (Emblemsvåg & Nøland, 2022). Over the past 20 years, the installed wind capacity in Germany has increased by 80%, whereas electricity production has only grown by 5%. This discrepancy has led to higher coal and gas consumption to meet the electricity demand (Smil, 2020). The increased dependence on weather conditions represents a significant vulnerability, potentially leading to rolling disconnections and severe consequences (Buchele, 2023). Thus, it is strongly advised to undertake a comprehensive examination of the ramifications associated with an augmented reliance on weather-dependent energy sources.

If the countries surrounding the North Sea achieve their ambitious targets from the Ostend Summit, several hundred GW of OW capacity would depend on a correlated weather system. This interdependency can give rise to significant volatility in electricity prices, whereby prices would be markedly low during periods of favorable wind conditions and comparably high during periods of calm winds across all the facilities. The potential implications of such volatile electricity prices for the economies and populations of Europe are of utmost importance. Therefore, we strongly advocate for further research to investigate the consequences of the intensified development of OWFs within a single, correlated weather system.

Given the Norwegian government's ambitious target of allocating areas equivalent to 30 GW for OW by 2040, it is evident that substantial grid investments are necessary to facilitate increased electricity generation. Consequently, conducting an economic assessment specifically focused on extensive grid investments becomes an area of research with significant relevance.

OWF developers depend on a stable and predictable economic framework when analyzing the feasibility of a project. However, the financial landscape for such development is susceptible to fluctuations in interest rates, inflation, and commodity prices. Therefore, it is recommended that future research thoroughly investigate these impacts when assessing the overall cost of an OWF.

8. Conclusion

In the pursuit of achieving climate goals through the development of sustainable energy-generating power plants, it is essential to possess a comprehensive understanding of the cost determinants behind the project. Within the context of the Norwegian government's development plans for offshore wind, this thesis contributes to a realistic cost analysis of developing and operating a Norwegian offshore wind farm with a capacity of 1 500 MW. To accomplish this, an extensive compilation of data was collected from fully commissioned European projects. The analysis employed stochastic modeling techniques to incorporate risk and assess the uncertainty associated with key cost variables, ultimately calculating the Levelized Cost of Electricity for the project.

The analysis revealed a most-likely LCOE of €108/MWh, accompanied by a 95% confidence interval ranging from €50/MWh to €170/MWh. Notably, this estimate deviates significantly from literature estimates, which can be attributed to its alignment with the recent price and interest rate developments. Furthermore, the relatively high standard deviation observed for the LCOE highlights the substantial uncertainty and variability in estimating the cost of the offshore wind farm. Among the uncertain variables analyzed, the capacity factor, capital cost, and the weighted average cost of capital emerged as the most influential drivers of the LCOE. For instance, an estimation error of 20% in the capital cost led to a €17/MWh increase in the unit cost of electricity.

The findings of this thesis offer compelling evidence of the significant influence that uncertainties in key cost variables have on the overall cost of offshore wind farms. The estimated LCOE derived from this research underscores the necessity of conducting an assessment that reflects the current economic landscape and incorporates the uncertainty in variables for offshore wind. Consequently, it is of utmost importance for the Norwegian government to conduct a thorough evaluation aligned with the present reality before embarking on development and allocating subsidies. Research of this nature can play a vital role in guiding policy decisions related to the energy transition toward more sustainable energy sources.

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Appendix

A1: CAPEX database overview

Wind Farm Id	Wind Farm	Country	Year Constructed	Modelled Capacity (MW)	Turbine MW	Num Turbines	CAPEX	CAPEXmill	Water Depth Min (m)	Water Depth Max (m)	Distance From Shore Quoted (km)	EUR_Multiplier	CAPEX_EUR	CAPEX_MW	PPI	CAPEX_MW2015PPI	CAPEX_MW22
DK08	Middelgrunden	Denmark	2000	40	2,0	20	EUR 44.89 million	44,9	3,0	6,0	4,7	1,0000	44,8900	1,1223	0,731	1,5352	2,1647
DK03	Horns Rev 1	Denmark	2002	160	2,0	80	EUR 278 million	278,0	6,0	11,0	17,9	1,0000	278,0000	1,7375	0,753	2,3074	3,2535
DK01	Samsø	Denmark	2002	23	2,3	10	EUR 31.97 million	32,0	10,0	13,0	4,0	1,0000	31,9700	1,3900	0,753	1,8459	2,6028
IE01	Arklow Bank - phase 1	Ireland	2003	25,2	3,6	7	EUR 50 million	50,0	1,6	10,0	10,1	1,0000	50,0000	1,9841	0,767	2,5869	3,6475
UK16	North Hoyle	United Kingdom	2003	60	2,0	30	GBP 81 million	81,0	5,0	12,0	7,2	0,6933	116,8325	1,9472	0,767	2,5387	3,5796
UK23	Scroby Sands	United Kingdom	2003	60	2,0	30	GBP 66.8 million	66,8	0,0	10,1	2,3	0,6933	96,3508	1,6058	0,767	2,0937	2,9521
DK07	Nysted	Denmark	2003	165,6	2,3	72	EUR 245 million	245,0	6,0	9,0	10,8	1,0000	245,0000	1,4795	0,767	1,9289	2,7198
UK12	Kentish Flats	United Kingdom	2004	90	3,0	30	GBP 105 million	105,0	3,0	4,5	8,5	0,6787	154,7075	1,7190	0,795	2,1622	3,0487
UK01	Barrow	United Kingdom	2005	90	3,0	30	GBP 123 million	123,0	12,0	16,0	7,5	0,6845	179,6932	1,9966	0,827	2,4143	3,4041
BE02	Northwind	Belgium	2006	216	3,0	72	EUR 851 million	851,0	15,3	23,0	37,0	1,0000	851,0000	3,9398	0,857	4,5972	6,4821
NL01	Prinses Amaliawindpark	Netherlands	2006	120	2,0	60	EUR 383 million	383,0	19,0	24,0	23,0	1,0000	383,0000	3,1917	0,857	3,7242	5,2512
NL02	Egmond aan Zee	Netherlands	2006	108	3,0	36	EUR 217.7 million	217,7	15,0	18,0	10,0	1,0000	217,7000	2,0157	0,857	2,3521	3,3164
UK02	Burbo Bank	United Kingdom	2006	90	3,6	25	EUR 181 million	181,0	0,2	5,4	6,4	1,0000	181,0000	2,0111	0,857	2,3467	3,3088
SE05	Lillgrund	Sweden	2006	110,4	2,3	48	SEK 1800 million	1800,0	4,0	13,0	11,3	9,2562	194,4643	1,7615	0,857	2,0554	2,8981
UK20	Robin Rigg	United Kingdom	2007	174	3,0	58	GBP 381 million	381,0	0,0	12,0	11,0	0,6845	556,6107	3,1989	0,885	3,6146	5,0966
UK15	Lynn	United Kingdom	2007	97,2	3,6	27	GBP 150 million	150,0	7,0	11,0	5,0	0,6845	219,1381	2,2545	0,885	2,5475	3,5919
UK11	Inner Dowsing	United Kingdom	2007	97,2	3,6	27	GBP 150 million	150,0	6,4	7,9	5,0	0,6845	219,1381	2,2545	0,885	2,5475	3,5919
BE01	Thornton Bank - phase I	Belgium	2008	30	5,1	6	EUR 153 million	153,0	20,0	20,0	27,0	1,0000	153,0000	5,1000	0,945	5,3968	7,6095
DE01	Alpha Ventus	Germany	2008	60	5,0	12	EUR 250 million	250,0	28,0	30,0	56,0	1,0000	250,0000	4,1667	0,945	4,4092	6,2169
UK19	Rhyl Flats	United Kingdom	2008	90	3,6	25	GBP 190 million	190,0	4,0	11,0	8,0	0,7960	238,6935	2,6521	0,945	2,8065	3,9572
DK10	Horns Rev 2	Denmark	2008	209,3	2,3	91	EUR 448 million	448,0	9,0	17,0	31,7	1,0000	448,0000	2,1405	0,945	2,2650	3,1937
BE03	Belwind	Belgium	2009	165	3,0	55	EUR 614 million	614,0	11,6	20,0	46,0	1,0000	614,0000	3,7212	0,907	4,1028	5,7849
UK27	Sheringham Shoal	United Kingdom	2009	316,8	3,6	88	NOK 10000 million	10000,0	14,0	23,0	23,0	8,7453	1143,4714	3,6094	0,907	3,9795	5,6112
UK05	Greater Gabbard	United Kingdom	2009	504	3,6	140	GBP 1600 million	1600,0	3,7	37,0	36,0	0,8916	1794,5267	3,5606	0,907	3,9257	5,5352
UK29	Thanet	United Kingdom	2009	300	3,0	100	GBP 900 million	900,0	14,4	23,0	12,0	0,8916	1009,4213	3,3647	0,907	3,7097	5,2307
UK07	Gunfleet Sands	United Kingdom	2009	172,8	3,6	48	DKK 3900 million	3900,0	0,0	12,9	7,0	7,4455	523,8063	3,0313	0,907	3,3421	4,7124
DK11	Rødsand 2	Denmark	2009	207	2,3	90	EUR 450 million	450,0	6,0	12,0	8,8	1,0000	450,0000	2,1739	0,907	2,3968	3,3795
SE06	Vindpark Vänern	Sweden	2009	30	3,0	10	SEK 540 million	540,0	1,0	18,0	3,5	10,6258	50,8197	1,6940	0,907	1,8677	2,6334
DK15	Avedøre Holme	Denmark	2009	10,8	3,6	3	DKK 100 million	100,0	2,0	2,0	0,0	7,4455	13,4309	1,2436	0,907	1,3711	1,9333
DE23	BARD Offshore 1	Germany	2010	400	5,0	80	EUR 2900 million	2900,0	39,0	41,0	101,0	1,0000	2900,0000	7,2500	0,940	7,7128	10,8750
DE78	EnBW Baltic 1	Germany	2010	48,3	2,3	21	EUR 200 million	200,0	16,0	19,0	16,0	1,0000	200,0000	4,1408	0,940	4,4051	6,2112
UK31	Walney - phase 1	United Kingdom	2010	183,6	3,6	51	GBP 630 million	630,0	19,0	23,0	15,0	0,8585	733,8381	3,9969	0,940	4,2521	5,9954
BE09	Thornton Bank - phase II	Belgium	2010	184,5	6,2	30	EUR 700.89 million	700,9	5,9	20,0	27,0	1,0000	700,8900	3,7989	0,940	4,0413	5,6983
FI02	Reposaaren tuulipuisto	Finland	2010	2,3	2,3	1	EUR 8.5 million	8,5	0,5	10,0	6,6	1,0000	8,5000	3,6957	0,940	3,9315	5,5435
UK17	Ormonde	United Kingdom	2010	150	5,1	30	EUR 552 million	552,0	17,0	21,0	9,5	1,0000	552,0000	3,6800	0,940	3,9149	5,5200
DE27	Trianel Windpark Borkum I	Germany	2011	200	5,0	40	EUR 900 million	900,0	28,0	33,0	45,0	1,0000	900,0000	4,5000	1,000	4,5000	6,3450
UK13	Lincs	United Kingdom	2011	270	3,6	75	GBP 1000 million	1000,0	7,6	16,4	8,0	0,8679	1152,2065	4,2674	1,000	4,2674	6,0171
UK32	Walney - phase 2	United Kingdom	2011	183,6	3,6	51	GBP 630 million	630,0	24,0	30,0	15,0	0,8679	725,8901	3,9536	1,000	3,9536	5,5746
UK14	London Array	United Kingdom	2011	630	3,6	175	EUR 2420 million	2420,0	0,0	23,0	20,0	1,0000	2420,0000	3,8413	1,000	3,8413	5,4162
BE10	Thornton Bank - phase III	Belgium	2011	110,7	6,2	18	EUR 420.53 million	420,5	10,2	21,5	26,0	1,0000	420,5300	3,7988	1,000	3,7988	5,3563
DK13	Anholt	Denmark	2011	399,6	3,6	111	DKK 10000 million	10000,0	12,5	19,4	21,0	7,4506	1342,1738	3,3588	1,000	3,3588	4,7359
UK73	Gunfleet Sands 3 - Demonstration Project	United Kingdom	2012	12	6,0	2	GBP 51 million	51,0	5,0	11,9	8,0	0,8112	62,8698	5,2392	1,017	5,1516	7,2637
DE09	Global Tech I	Germany	2012	400	5,0	80	EUR 1800 million	1800,0	38,0	41,0	115,0	1,0000	1800,0000	4,5000	1,017	4,4248	6,2389
DE21	Riffgat	Germany	2012	108	3,6	30	EUR 480 million	480,0	18,0	23,0	15,0	1,0000	480,0000	4,4444	1,017	4,3702	6,1619
DE06	Nordsee Ost	Germany	2012	295,2	6,2	48	EUR 1300 million	1300,0	22,0	25,0	57,0	1,0000	1300,0000	4,4038	1,017	4,3302	6,1056
DE07	Meerwind Süd/Ost	Germany	2012	288	3,6	80	EUR 1200 million	1200,0	24,0	27,0	53,0	1,0000	1200,0000	4,1667	1,017	4,0970	5,7768
UK28	Teesside	United Kingdom	2012	62,1	2,3	27	GBP 200 million	200,0	6,0	18,0	1,5	0,8112	246,5483	3,9702	1,017	3,9038	5,5044
UK09	Gwynt y Môr	United Kingdom	2012	576	3,6	160	EUR 2000 million	2000,0	12,6	32,0	16,0	1,0000	2000,0000	3,4722	1,017	3,4142	4,8140
SE08	Kårehamn	Sweden	2012	48	3,0	16	EUR 120 million	120,0	6,0	20,0	3,8	1,0000	120,0000	2,5000	1,017	2,4582	3,4661
UK10	Humber Gateway	United Kingdom	2013	219	3,0	73	GBP 900 million	900,0	10,6	16,2	10,0	0,8490	1060,0707	4,8405	1,020	4,7456	6,6913
DE52	EnBW Baltic 2	Germany	2013	288	3,6	80	EUR 1250 million	1250,0	20,0	42,0	32,0	1,0000	1250,0000	4,3403	1,020	4,2552	5,9998
DE04	Borkum Riffgrund 1	Germany	2013	312	4,0	78	EUR 1190 million	1190,0	23,0	29,0	54,0	1,0000	1190,0000	3,8141	1,020	3,7393	5,2724
UK33	West of Duddon Sands	United Kingdom	2013	389	3,6	108	GBP 1254 million	1254,0	17,0	21,0	15,0	0,8490	1477,0318	3,7970	1,020	3,7225	5,2488
DE02	DanTysk	Germany	2013	288	3,6	80	EUR 1000 million	1000,0	21,0	29,0	70,0	1,0000	1000,0000	3,4722	1,020	3,4041	4,7998

DE05	Amrumbank West	Germany	2013	302	3,8	80	EUR 1000 million	1000,0	20,0	25,0	35,0	1,0000	1000,0000	3,3113	1,020	3,2463	4,5773
UK1E	Levenmouth demonstration turbine	United Kingdom	2013	7	7,0	1	GBP 13.1 million	13,1	5,0	5,0	0,0	0,8490	15,4299	2,2043	1,020	2,1611	3,0471
DE08	Butendiek	Germany	2014	288	3,6	80	EUR 1300 million	1300,0	18,4	21,0	32,0	1,0000	1300,0000	4,5139	1,028	4,3909	6,1912
UK34	Westermost Rough	United Kingdom	2014	210	6,0	35	EUR 870 million	870,0	12,0	22,0	8,0	1,0000	870,0000	4,1429	1,028	4,0300	5,6823
NL32	Eneco Luchterduinen	Netherlands	2014	129	3,0	43	EUR 450 million	450,0	18,0	22,0	23,0	1,0000	450,0000	3,4884	1,028	3,3934	4,7846
NL18	Gemini	Netherlands	2015	600	4,0	150	EUR 2800 million	2800,0	32,0	34,0	85,0	1,0000	2800,0000	4,6667	1,000	4,6667	6,5800
UK60	Kentish Flats Extension	United Kingdom	2015	49,5	3,3	15	GBP 150 million	150,0	1,0	4,0	8,5	0,7261	206,5831	4,1734	1,000	4,1734	5,8845
DE12	Sandbank	Germany	2015	288	4,0	72	EUR 1200 million	1200,0	25,5	29,0	90,0	1,0000	1200,0000	4,1667	1,000	4,1667	5,8750
DE13	Gode Wind 1 and 2	Germany	2015	582	6,3	97	EUR 2200 million	2200,0	28,0	34,0	45,0	1,0000	2200,0000	3,7801	1,000	3,7801	5,3299
DE28	Nordsee One	Germany	2015	332,1	6,2	54	EUR 1200 million	1200,0	28,0	29,0	40,0	1,0000	1200,0000	3,6134	1,000	3,6134	5,0949
NL85	Westermeerwind	Netherlands	2015	144	3,0	48	EUR 400 million	400,0	3,0	7,0	0,5	1,0000	400,0000	2,7778	1,000	2,7778	3,9167
UK62	Galloper	United Kingdom	2016	353	6,0	56	GBP 1500 million	1500,0	6,0	40,0	27,0	0,8188	1831,9492	5,1897	0,990	5,2421	7,3913
UK36	Rampion	United Kingdom	2016	400,2	3,5	116	EUR 1900 million	1900,0	19,2	39,0	13,0	1,0000	1900,0000	4,7476	0,990	4,7956	6,7618
DE36	Veja Mate	Germany	2016	402	6,0	67	EUR 1900 million	1900,0	39,0	41,0	95,0	1,0000	1900,0000	4,7264	0,990	4,7741	6,7315
UK04	Dudgeon	United Kingdom	2016	402	6,0	67	GBP 1400 million	1400,0	11,5	23,5	32,0	0,8188	1709,8192	4,2533	0,990	4,2962	6,0577
DE47	Wikinger	Germany	2016	350	5,0	70	EUR 1350 million	1350,0	36,0	40,0	35,0	1,0000	1350,0000	3,8571	0,990	3,8961	5,4935
UK59	Burbo Bank Extension	United Kingdom	2016	258	8,0	32	GBP 800 million	800,0	3,2	13,9	7,0	0,8188	977,0396	3,7870	0,990	3,8252	5,3936
BE08	Nobelwind	Belgium	2016	165	3,3	50	EUR 620 million	620,0	20,0	33,0	47,0	1,0000	620,0000	3,7576	0,990	3,7955	5,3517
DE20	Nordergründe	Germany	2016	110,7	6,2	18	EUR 410 million	410,0	3,0	11,0	15,0	1,0000	410,0000	3,7037	0,990	3,7411	5,2750
UK18	Race Bank	United Kingdom	2016	573,3	6,3	91	GBP 1700 million	1700,0	6,0	23,0	27,0	0,8188	2076,2091	3,6215	0,990	3,6581	5,1579
FI25	Ajos	Finland	2016	26,4	3,3	8	EUR 12.1 million	12,1	0,0	8,3	0,0	1,0000	12,1000	0,4583	0,990	0,4630	0,6528
UK70	Blyth Offshore Demonstrator - phase 1	United Kingdom	2017	41,5	8,3	5	GBP 178 million	178,0	29,0	39,0	5,7	0,8766	203,0573	4,8929	1,030	4,7504	6,6981
UK53	Beatrice	United Kingdom	2017	588	7,0	84	GBP 2500 million	2500,0	35,0	50,0	13,5	0,8766	2851,9279	4,8502	1,030	4,7089	6,6396
DE26	Merkur	Germany	2017	396	6,0	66	EUR 1600 million	1600,0	27,0	33,0	45,0	1,0000	1600,0000	4,0404	1,030	3,9227	5,5310
BE05	Rentel	Belgium	2017	309	7,0	42	EUR 1100 million	1100,0	23,5	34,0	34,0	1,0000	1100,0000	3,5599	1,030	3,4562	4,8732
DE46	Arkona	Germany	2017	385	6,4	60	EUR 1200 million	1200,0	21,0	27,5	35,0	1,0000	1200,0000	3,1169	1,030	3,0261	4,2668
UK63	Walney Extension	United Kingdom	2017	659	8,3	87	DKK 14498 million	14498,0	20,4	54,0	19,0	7,4387	1948,9965	2,9575	1,030	2,8714	4,0486
FI03	Tahkoluoto	Finland	2017	42	4,0	10	EUR 120 million	120,0	0,0	26,0	0,5	1,0000	120,0000	2,8571	1,030	2,7739	3,9112
DK19	Horns Rev 3	Denmark	2017	406,7	8,3	49	EUR 1000 million	1000,0	10,6	19,1	20,0	1,0000	1000,0000	2,4588	1,030	2,3872	3,3660
DE24	Deutsche Bucht	Germany	2018	252	8,4	31	EUR 1500 million	1500,0	38,0	40,0	95,0	1,0000	1500,0000	5,9524	1,075	5,5371	7,8073
UK64	East Anglia ONE	United Kingdom	2018	714	7,0	102	GBP 2600 million	2600,0	29,5	41,0	43,0	0,8849	2938,1851	4,1151	1,075	3,8280	5,3975
UK47	Aberdeen (EOWDC)	United Kingdom	2018	93,2	8,8	11	GBP 335 million	335,0	20,0	30,0	2,4	0,8849	378,5739	4,0620	1,075	3,7786	5,3278
DE0K	Trianel Windpark Borkum II	Germany	2018	203	6,3	32	EUR 800 million	800,0	28,0	33,0	45,0	1,0000	800,0000	3,9409	1,075	3,6659	5,1690
DE11	Hohe See	Germany	2018	497	7,0	71	EUR 1800 million	1800,0	39,0	40,0	95,0	1,0000	1800,0000	3,6217	1,075	3,3691	4,7504
BE04	Norther	Belgium	2018	369,6	8,4	44	JPY 150000 million	150000,0	13,0	26,0	23,0	130,3510	1150,7392	3,1135	1,075	2,8963	4,0837
ES61	ELISA/ELICAN - Mario Luis Romero Torrent (PLOCAN site)	Spain	2018	5	5,0	1	EUR 14.8 million	14,8	25,0	30,0	1,5	1,0000	14,8000	2,9600	1,075	2,7535	3,8824
DE30	Borkum Riffgrund 2	Germany	2018	450	8,3	56	EUR 1300 million	1300,0	25,0	29,0	56,0	1,0000	1300,0000	2,8889	1,075	2,6873	3,7891
UK81	Hornsea Project One	United Kingdom	2018	1218	7,0	174	EUR 3360 million	3360,0	23,5	37,0	120,0	1,0000	3360,0000	2,7586	1,075	2,5662	3,6183
DE39	Albatros	Germany	2018	112	7,0	16	CAD 395 million	395,0	40,0	40,0	105,0	1,5305	258,0788	2,3043	1,075	2,1435	3,0224
DK44	Nissum Bredning Vind	Denmark	2018	28	7,0	4	DKK 300 million	300,0	0,9	6,0	2,5	7,4350	40,3497	1,4411	1,075	1,3405	1,8901
BE12	Northwester 2	Belgium	2019	219	9,5	23	EUR 695 million	695,0	24,5	37,0	46,0	1,0000	695,0000	3,1735	1,088	2,9168	4,1127
UK40	Moray East	United Kingdom	2019	950	9,5	100	GBP 2600 million	2600,0	39,0	50,0	22,0	0,8778	2961,9503	3,1178	1,088	2,8657	4,0406
BE06	Seamade (SeaStar)	Belgium	2019	252	8,4	30	EUR 673 million	673,0	20,0	26,5	40,0	1,0000	673,0000	2,6706	1,088	2,4546	3,4610
BE07	Seamade (Mermaid)	Belgium	2019	235	8,4	28	EUR 627 million	627,0	25,0	30,0	54,0	1,0000	627,0000	2,6681	1,088	2,4523	3,4577
NL0J	Borssele 3 and 4 - Blauwwind	Netherlands	2019	731,5	9,5	77	EUR 1300 million	1300,0	14,3	38,0	55,0	1,0000	1300,0000	1,7772	1,088	1,6334	2,3031
UK30	Triton Knoll	United Kingdom	2020	857	9,5	90	GBP 2000 million	2000,0	12,3	30,0	33,0	0,8898	2247,6961	2,6227	1,079	2,4307	3,4273
NL0B	Borssele 1 and 2	Netherlands	2020	752	8,0	94	EUR 1851 million	1851,0	15,6	38,0	22,0	1,0000	1851,0000	2,4614	1,079	2,2812	3,2165
NL0G	Windpark Fryslân	Netherlands	2020	382,7	4,3	89	EUR 850 million	850,0	2,7	6,1	5,6	1,0000	850,0000	2,2211	1,079	2,0584	2,9024
FR37	Saint-Nazaire	France	2021	480	6,0	80	EUR 2000 million	2000,0	10,4	20,8	12,0	1,0000	2000,0000	4,1667	1,190	3,5014	4,9370
IT31	Taranto	Italy	2021	30	3,0	10	EUR 120 million	120,0	3,0	13,5	1,0	1,0000	120,0000	4,0000	1,190	3,3613	4,7395
UK44	Seagreen	United Kingdom	2021	1140	10,0	114	GBP 3000 million	3000,0	39,0	61,0	27,0	0,8845	3391,7467	2,9752	1,190	2,5002	3,5253
DK37	Kriegers Flak	Denmark	2021	605	8,4	72	DKK 7700 million	7700,0	18,0	30,0	15,0	7,4371	1035,3498	1,7113	1,190	1,4381	2,0277
NL0D	Hollandse Kust Zuid Holland I and II	Netherlands	2021	770	11,0	70	EUR 1300 million	1300,0	17,9	22,0	30,0	1,0000	1300,0000	1,6883	1,190	1,4187	2,0004
NL0E	Hollandse Kust Zuid Holland III and IV	Netherlands	2021	770	11,0	70	EUR 1300 million	1300,0	17,0	22,0	18,5	1,0000	1300,0000	1,6883	1,190	1,4187	2,0004

A2: CAPEX literature overview

Wind Farm ID	CAPEX source
DK08	4C Offshore (2023)
DK03	http://www.businessgreen.com/bg/news/2168137/dong-gears-install-worlds-siemens-6mw-offshore-wind-turbines-near-essex
DK01	4C Offshore (2023)
IE01	https://www.iberdrola.com/about-us/what-we-do/offshore-wind-energy%E2%80%A8/east-anglia-one-offshore-wind-farm
UK16	https://www.marketscreener.com/ORSTED-AS-28607554/pdf/809241/Orsted%20AS_3rd-quarter-forecast-results.pdf
UK23	https://www.sumitomocorp.com/en/jp/news/release/2016/group/20160729
DK07	4C Offshore (2023)
UK12	http://ec.europa.eu/competition/state_aid/cases/253211/253211_1583612_84_2.pdf
UK01	https://www.beatricewind.com/
BE02	https://group.vattenfall.com/se/siteassets/sverige/om-oss/finans/delarsrapporter/2016/q4_2016_rapport.pdf
NL01	4C Offshore (2023)
NL02	https://twitter.com/ENGIE_UK/status/1071020555262930944
UK02	4C Offshore (2023)
SE05	4C Offshore (2023)
UK20	https://www.iberdrola.com/sala-comunicacion/noticias/detalle/iberdrola-inaugura-en-reino-unido-el-parque-de-west-of-duddon-sands-su-primera-instalacion-eolica-marina-4193346320141030
UK15	4C Offshore (2023)
UK11	4C Offshore (2023)
BE01	https://www.nsenergybusiness.com/news/innogy-financial-close-triton-knoll-offshore-wind/
DE01	http://www.guardian.co.uk/environment/2010/sep/23/british-firms-worlds-biggest-windfarm
UK19	http://www.windfarmbrazil.com/uploadedFiles/Upcoming-Wind-Farms.pdf

DK10	http://www.windfarmbrazil.com/uploadedFiles/Upcoming-Wind-Farms.pdf
BE03	https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=3d23f162a64c4cb44792957416ed6c16f7258c5c
UK27	http://www.eon-uk.com/E.ON_Robin_Rigg_UK_content_report_October_2011.pdf
UK05	https://www.graham.co.uk/media/projects/Civils/Case-Study/Case-Study-Samsung.pdf
UK29	https://gov.wales/sites/default/files/publications/2019-07/future-potential-for-offshore-wind.pdf
UK07	http://cleantechnica.com/2015/07/07/siemens-awarded-possible-1-2-billion-wind-turbine-order/
DK11	http://www.power-technology.com/projects/ormonde-offshore-wind-farm/ormonde-offshore-wind-farm4.html
SE06	http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file41542.pdf
DK15	https://www.power-technology.com/projects/lynnandinnerdowsing/
DE23	4C Offshore (2023)
DE78	https://www.bloomberg.com/news/articles/2012-06-07/centrica-siemens-dong-receive-660-million-for-u-k-wind-park
UK31	https://group.vattenfall.com/uk/what-we-do/our-projects/vattenfall-in-kent
BE09	https://www.power-technology.com/projects/lynnandinnerdowsing/
FI02	https://www.eon.com/content/dam/eon-com/ueber-uns/publications/Facts_and_Figures_2014.pdf
UK17	https://www.rwe.com/-/media/archive/ir-archiv/investoren-und-analystenkonferenzen/offshore-wind-capital-market-day-2012/Gwynt-y-Mor-Offshore-Wind-Farm.pdf
DE27	http://mhk.pnnl.gov/wiki/images/c/cb/Kaiser_%26_Snyder_2012.pdf
UK13	https://www.sse.com/media/0bklm0gx/fifteenyearsofoffshorewind.pdf
UK32	https://dudgeonoffshorewind.co.uk/
UK14	http://www.wind-energy-the-facts.org/en/part-3-economics-of-wind-power/chapter-2-offshore-developments/
BE10	http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file50163.pdf
DK13	http://www.eon.com/content/eon-com/en/media/news/press-releases/2013/10/1/eon-to-open-k-rehamn-offshore-wind-farm-in-sweden.html?t_camp=rssen&chan6=rss&t_var=eon-to-open-k-rehamn-offshore-wind-farm-in-sweden
UK73	https://sverigesradio.se/artikel/5321217
DE09	http://mhk.pnnl.gov/wiki/images/c/cb/Kaiser_%26_Snyder_2012.pdf

DE21	http://www.consultancy.uk/news/12373/mott-macdonald-advised-on-westermeerwind-project-now-open
DE06	https://news.eneco.com/eneco-luchterduinen-wind-farm-increases-dutch-offshore-wind-power-by-56/
DE07	https://www.northlandpower.com/en/about-northland/resources/Northland%20Power%20Investor%20Presentation%20Sept%202021.pdf
UK28	https://www.vanoord.com/news/2018-blauwwind-consortium-reaches-financial-close-borssele-iiiiv
UK09	https://windparkfryslan.nl/provincie-aandeelhouder-windpark-fryslan-2/
SE08	4C Offshore (2023)
UK10	4C Offshore (2023)
DE52	https://orsted.com/-/media/Aarsrapport2017/Orsted_Annual_Report_2017_Final.pdf
DE04	https://www.shell.nl/energy-and-innovation/wind/noordzeewind/reports/_jcr_content/par/expandablelist_451882206/expandablesection.stream/1554282176475/334aa72f20805ebcbe44c1bdfc2cae19539d1e59/owez-r-141-general-report.pdf
UK33	http://mhk.pnnl.gov/wiki/images/c/cb/Kaiser_%26_Snyder_2012.pdf
DE02	https://www.linkedin.com/pulse/taranto-italy-renexia-acquires-first-offshore-wind-farm-salvo-vitale/
DE05	http://www.offshorecenter.dk/offshorewindfarms_detail.asp?id=37016&t=Arklow%20Bank
UK1E	https://www.edf.fr/sites/default/files/contrib/groupe-edf/espaces-dedies/espace-finance-en/financial-data/investors-analysts/events/investor-day-workshops/edf-renewables-march-2021.pdf
DE08	https://www.pohjolanvoima.fi/wp-content/uploads/2020/09/Pohjolan-Voima-Annual-Report-2010.pdf
UK34	http://hyotytuuli.fi/en/suomen-hyotytuuli-to-build-an-offshore-wind-farm-in-pori/
NL32	http://ec.europa.eu/energy/res/publications/doc2/EN/PORI_EN.PDF
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DE12	https://group.vattenfall.com/siteassets/corporate/investors/annual-reports/2019/vattenfall-annual-and-sustainability-report-2019.pdf
DE13	http://mb.cision.com/Main/865/2021812/523885.pdf
DE28	http://www.hvidovrevindmollelaug.dk/wp-content/uploads/2013/05/facts.pdf
NL85	http://dise.org.pl/dania2019/AnholtOffshoreWindFarm.pdf

UK62	http://www.eon.se/upload/eon-se-2-0/dokument/broschyrarkiv/in-english/Energy%20for%20the%20future%20-%20R%C3%B6dsand%202%20Wind%20Farm.pdf
UK36	https://www.nib.int/who_we_are/news_and_media/articles/133/where_the_wind_blows
DE36	http://www.offshorecenter.dk/log/bibliotek/Middelgrunden%2040%20MW.PDF
UK04	https://offshorewindhub.org/sites/default/files/resources/njdivratecontrol_2-3-2012_fishermensenergydismukespresentation_0.pdf
DE47	http://mhk.pnnl.gov/wiki/images/c/cb/Kaiser_%26_Snyder_2012.pdf
UK59	http://wind.nrel.gov/public/SeaCon/Proceedings/Copenhagen.Offshore.Wind.2005/documents/papers/Cases/H.Bjerregaard_Samsoe_offshore_wind_park_2_years_status.pdf
BE08	https://www.enbw.com/company/press/enbw-baltic-1-structured-and-completed.html
DE20	https://www.nesfircroft.com/candidates/projects/enbw-baltic-2
UK18	https://www.iberdrola.com/wcorp/gc/prod/en_US/inversores/docs/Perspectivas16_5.pdf
FI25	http://www.c-power.be/index.php/project-phase-2-3/investment
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UK53	http://www.power-technology.com/projects/ormonde-offshore-wind-farm/ormonde-offshore-wind-farm4.html
DE26	https://www.enbw.com/company/press/enbw-baltic-1-structured-and-completed.html
BE05	http://ec.europa.eu/energy/res/publications/doc2/EN/PORI_EN.PDF
DE46	https://www.sse.com/media/0bklm0gx/fifteenyearsofoffshorewind.pdf
UK63	http://www.windfarmbrazil.com/uploadedFiles/Upcoming-Wind-Farms.pdf
FI03	http://www.guardian.co.uk/environment/2010/sep/23/british-firms-worlds-biggest-windfarm
DK19	http://www.eon.se/upload/eon-se-2-0/dokument/broschyrarkiv/in-english/Energy%20for%20the%20future%20-%20R%C3%B6dsand%202%20Wind%20Farm.pdf
DE24	http://mhk.pnnl.gov/wiki/images/c/cb/Kaiser_%26_Snyder_2012.pdf
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UK47	https://sverigesradio.se/artikel/5321217
DE0K	http://www.mpi-offshore.com/workboats-projects/lynn-and-inner-dowsing-offshore-wind-farm/

DE11	https://www.nib.int/who_we_are/news_and_media/articles/133/where_the_wind_blows
BE04	https://gov.wales/sites/default/files/publications/2019-07/future-potential-for-offshore-wind.pdf
ES61	https://web.archive.org/web/20090830001558/http://www.alpha-ventus.de/index.php?id=80
DE30	http://www.c-power.be/index.php/project-phase-1/overview
UK81	http://www.eon-uk.com/E.ON_Robin_Rigg_UK_content_report_October_2011.pdf
DE39	http://www.mpi-offshore.com/workboats-projects/lynn-and-inner-dowsing-offshore-wind-farm/
DK44	http://www.mpi-offshore.com/workboats-projects/lynn-and-inner-dowsing-offshore-wind-farm/
BE12	https://green-giraffe.eu/project/northwind-2/
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BE06	http://mhk.pnnl.gov/wiki/images/c/cb/Kaiser_%26_Snyder_2012.pdf
BE07	https://www.shell.nl/energy-and-innovation/wind/noordzeewind/reports/_jcr_content/par/expandablelist_451882206/expandablesection.stream/1554282176475/334aa72f20805ebcbe44c1bdfc2cae19539d1e59/owez-r-141-general-report.pdf
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UK30	http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file50163.pdf
NL0B	https://group.vattenfall.com/uk/what-we-do/our-projects/vattenfall-in-kent
NL0G	https://offshorewindhub.org/sites/default/files/resources/njdivratecontrol_2-3-2012_fishermensenergydismukespresentation_0.pdf
FR37	http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file41542.pdf
IT31	http://s3.amazonaws.com/windaction/attachments/547/Capital_grant_scheme_for_offshore_wind.pdf
UK44	http://www.offshorecenter.dk/offshorewindfarms_detail.asp?id=37016&t=Arklow%20Bank
DK37	http://mhk.pnnl.gov/wiki/images/c/cb/Kaiser_%26_Snyder_2012.pdf
NL0D	http://wind.nrel.gov/public/SeaCon/Proceedings/Copenhagen.Offshore.Wind.2005/documents/papers/Cases/H.Bjerregaard_Samsoe_offshore_wind_park_2_years_status.pdf
NL0E	http://www.offshorecenter.dk/log/bibliotek/Middelgrunden%2040%20MW.PDF

A3: OPEX literature

Name	Price year	Capacity (MW)	Cost/MW	Currency	EURMultiplier	EUR/MW	2015CPI Cost	COST/MW22
Scroby Sands	2007	60	27 379	GBP	0,682	40 147	45 298	52 917
Gunfleet Sands	2010	172,8	45 139	GBP	0,862	52 390	56 164	65 611
Kentish Flats	2006	90	26 111	GBP	0,681	38 331	44 175	51 606
North Hoyle	2007	60	46 667	GBP	0,682	68 430	77 209	90 195
Barrow	2007	90	44 267	GBP	0,682	64 911	73 238	85 557
BVG (2019)	2019	1000	76 000	GBP	0,877	86 637	82 669	96 574
Ederer (2014)	2014		63 490	EUR	1,000	63 490	63 509	74 191
Aldersey-Williams (2019)	2012		37 000	GBP	0,810	45 707	46 540	54 368
Hughes (2020)	2018		192 000	GBP	0,884	217 116	209 673	244 940
4C (2023)	2023		42 705	EUR	1,000	42 705	36 556	42 705