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# Life cycle cost analysis of a floating wind farm in the Norwegian Sea

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# Life cycle cost analysis of a floating wind farm in the Norwegian Sea

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**Abstract**. The offshore wind energy industry has witnessed rapid growth in the past decade. Still, there is a lack of commercial floating wind projects due to the relatively high development costs and other factors. To facilitate the holistic evaluation of floating wind farms in Norway, this article investigates the levelized cost of energy of a floating offshore wind farm and its economic feasibility. The Troll field west of Bergen, Norway, is assumed to be the target offshore site, and a farm size of 50 wind turbines with a lifespan of 25 years are considered. Each floating wind turbine has a 15-megawatt turbine mounted on a semi-submersible floater. Based on detailed analysis, the levelized cost of energy of the wind farm is estimated to be approximately 100.7 \$/MWh. The capital expenditure is the most prominent cost and constitutes 63.1% of the total cost, and the operational expenditure constitutes the remaining 36.9%. Further, sensitivity analyses show the influence of the lifespan, capacity factor, and project discount rate on the levelized cost of energy. The present study contributes to techno-economic evaluation of floating wind projects at an early phase.

## 1. Introduction

The main advantage of offshore wind farms is their ability to bolster the effectiveness of renewable energy sources in alleviating the consequences of climate change [1]. With extensive maritime resources, industrial competence, and technical know-how from the petroleum sector, Norway may assume a prominent role in the production of floating offshore wind energy [2].

The levelized cost of energy (LCOE) is a concept employed to depict the average cost of generating electricity from an energy source over its entire lifespan [3]. In the case of floating wind farms (FWFs), the pricing of the electricity generated is influenced by numerous factors, such as the design of the support structure, grid connection, installation techniques [4], and operations and maintenance [5]. LCOE serves as a valuable metric for assessing the cost-effectiveness of different wind farm types.

The key obstacle to achieving commercial viability in floating wind power lies in the substantial initial capital investment, which significantly surpasses that of bottom-fixed turbines [6]. This underscores the challenge of addressing elevated costs, which is essential for facilitating the broad adoption of floating wind energy systems. Figure 1 illustrates a comparison of the estimated LCOE among different energy sources. Here, the global data are derived from [7-10] and the Norwegian data from [11]. As shown, the

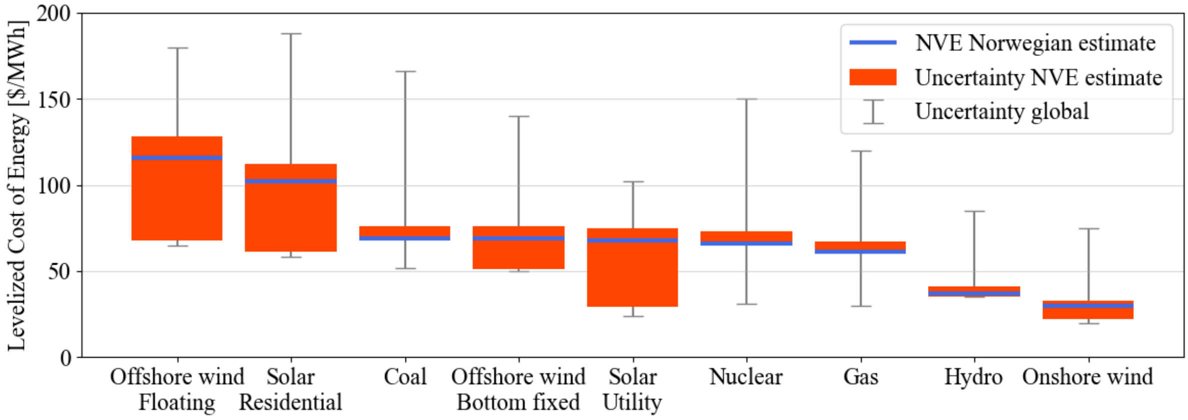


**Figure 1.** Comparison of the LCOE for different energy sources

costs linked to offshore floating wind energy are generally considered to be greater than those of other energy sources. Compared to the bottom-fixed offshore wind energy, the floating offshore wind energy has higher uncertainty in the LCOE estimated by either the Norwegian Water Resources and Energy Directorate (NVE) or by the global one. To reduce the uncertainties in the LCOE estimation, it is necessary to consider site-specific offshore conditions and turbine-specific technologies of the target offshore wind farm. To facilitate economic feasibility analysis of FWFs, we focus on a Norwegian offshore site and carry out a detailed LCOE analysis of an FWF consisting of 15-megawatt (MW) wind turbines for this site. The results of this paper contribute to an improved understanding of the cost elements for an offshore FWF and the key cost drivers of the LCOE.

The rest of the paper is structured as follows. Section 2 describes the approach for calculating the LCOE. Section 3 defines the floating wind turbine (FWT) system. Sections 4-5 specify the site conditions and the reference wind farm, and Section 6 present the results. Section 7 draws the concluding remarks.

## 2. Approach

*2.1 Components of LCOE*

The LCOE serves as a quantitative representation of the cost-efficiency of an energy project. LCOE can be computed by dividing the total project expenses by the total electricity production over the project's duration [3]. Equation (1) shows how the LCOE of an offshore wind farm is computed:

$$LCOE = \frac{(CapEx * FCR) + OpEx}{AEP_{net}} \tag{1}$$

where $CapEx$ is the investment expenditures, $OpEx$ is the operations and maintenance costs, $FCR$ is the fixed charge rate, and $AEP$ is the annual energy generation. Upon completing the LCOE calculation, the resulting figure is typically expressed in terms of dollars per MW hour [$/MWh].

*2.2 Estimation of CapEx and OpEx*

ORBIT [12] was applied to calculate the CapEx for all cost components of a wind farm except the wind turbine. ORBIT is an open-source Python tool designed to offer reasonably accurate estimates of component costs, sizes, and masses based on a limited set of user inputs. Given that ORBIT was initially introduced in 2017, subsequent developments have occurred. To ensure the precision of these estimates, it becomes imperative to source the wind turbine cost data from a current and up-to-date reference. Consequently, the wind turbine cost data is acquired from an analysis conducted by Rystad [13]. The costs provided by ORBIT are dollars from 2017, necessitating an adjustment for inflation up to 2023.

Two distinct inflation factors are employed to compute the adjusted CapEx. Specifically, the Producer Price Index (PPI) is used to modify general expenses, including production and installation costs, whereas steel prices are utilized to adjust costs associated with steel components, such as the material expenses for the substructure of an FWT. The calculation of these adjustment factors is presented in Table 1, and all the data values are sourced from the Organization for Economic Co-operation and Development [14].

**Table 1.** Calculation of CapEx inflation adjustment factors

| Description | Reference value | 2023 Value | Adjustment factor |
|---|---|---|---|
| PPI (general) | 108.9 (2017) | 147.8 | 1.35 |
| PPI (wind turbine) | 128.5 (2020) | 147.8 | 1.15 |
| Steel price index | 1060.7 (2017) | 1845.7 | 1.74 |

*2.3 Calculation of the financial cost ratio*

The financial cost ratio (FCR) represents the proportion of capital expenses required to cover capital-related costs [15]. The formula utilized to determine the FCR incorporates both the interest paid on debt and the return on equity. Consequently, when CapEx is multiplied by FCR, it yields a consistent annual annuity payment. The FCR is expressed in the following equation:

$$FCR = \frac{WACC}{1-(WACC+1)^{-n}} \tag{2}$$

where $WACC$ stands for the weighted average cost of capital and $n$ the economic lifespan of the system. As $WACC$ is calculated to be 4.73% [16], and the economic lifespan of the system is set to 25 years, the FCR for yields is as follows:

$$FCR = \frac{4.73\ \%}{1-(4.73\ \%+1)^{-25}} = 6.9\% \tag{3}$$

## 3. Description of the floating wind turbine

The characteristics of the semi-submersible FWT are determined using models created by Jonkman et al. [17] and Gaertner et al. [18]. These reference wind turbine models were established to assist in conceptual studies of offshore wind technology.

The chosen semi-submersible substructure is designed based on the work of Offshore Code Comparison Collaboration Continuation (OC4) coordinated by the National Renewable Energy Laboratory (NREL) [17]. This semi-submersible floater features three side columns and one central column. with all these columns interconnected by a series of diagonal steel members and pontoons. Figure 2 displays a top and side view of the semi-submersible substructure and Figure 3 shows the full system with a mooring system. As details of mass and size for substructures of 15-MW semi-submersible are missing, we scale up the steel costs from the NREL 5-MW semi-submersible floater by considering the power rating (15 MW) of the target FWT. The wind turbine characteristics are selected based on the NREL 15-MW wind turbine model proposed by Gaertner et al. [18]. This is a conventional three-bladed turbine with active blade pitch control. Table 2 lists the main parameters of the wind turbine.

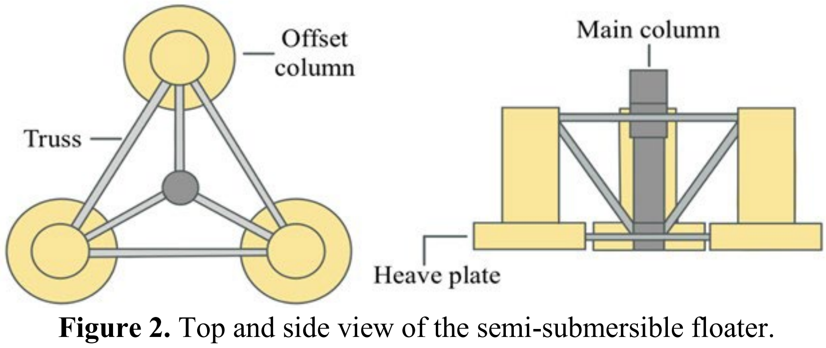


**Figure 2.** Top and side view of the semi-submersible floater.

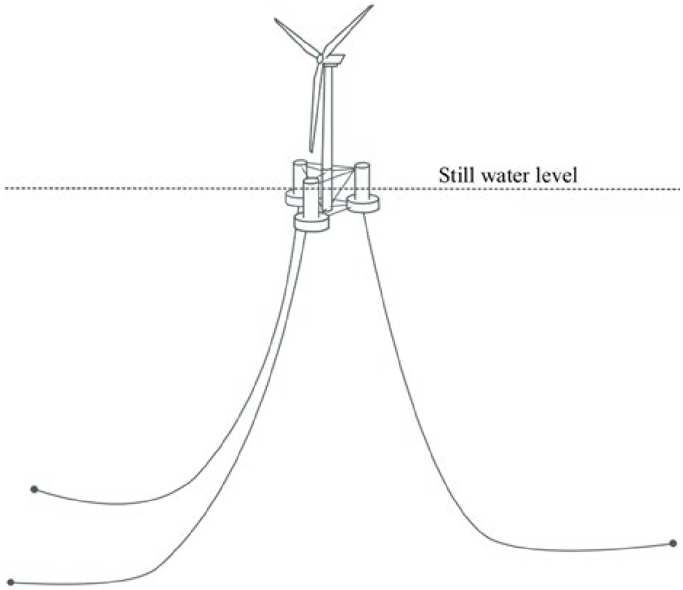


**Figure 3.** Illustration of the semi-submsersible FWT with moorings.

**Table 2.** Specifications of the wind turbine

| Description | | Value | Unit |
|---|---|---|---|
| General information | Power rating | 15 | MW |
| | Number of blades | 3 | - |
| | Rated wind speed | 10.59 | m/s |
| | Cut-in speed | 3 | m/s |
| | Cut-out speed | 25 | m/s |
| Tower | Length | 150 | m |
| | Mass | 480 | ton |
| Nacelle | Mass | 797 | ton |
| | Hub height | 150 | m |
| Blade | Length | 120 | m |
| | Mass | 72 | ton |
| | Rotor diameter | 240 | m |

## 4. Description of site conditions

### *4.1 Geographical conditions*

The target wind farm is located in the northern North Sea, along the Norwegian coast, where the water depth is approximately 325 m [19]. This particular area has not been previously explored for offshore wind projects. The only existing FWF in Norway, Hywind Tampen, is situated 128 km northwest of this site. The entire Troll field, which encompasses an area of 750 km$^2$, houses three operational oil platforms. As a result, the target wind farm has the potential to provide power to these existing oil field facilities. Figure 4 displays the geographical position of the Troll field.

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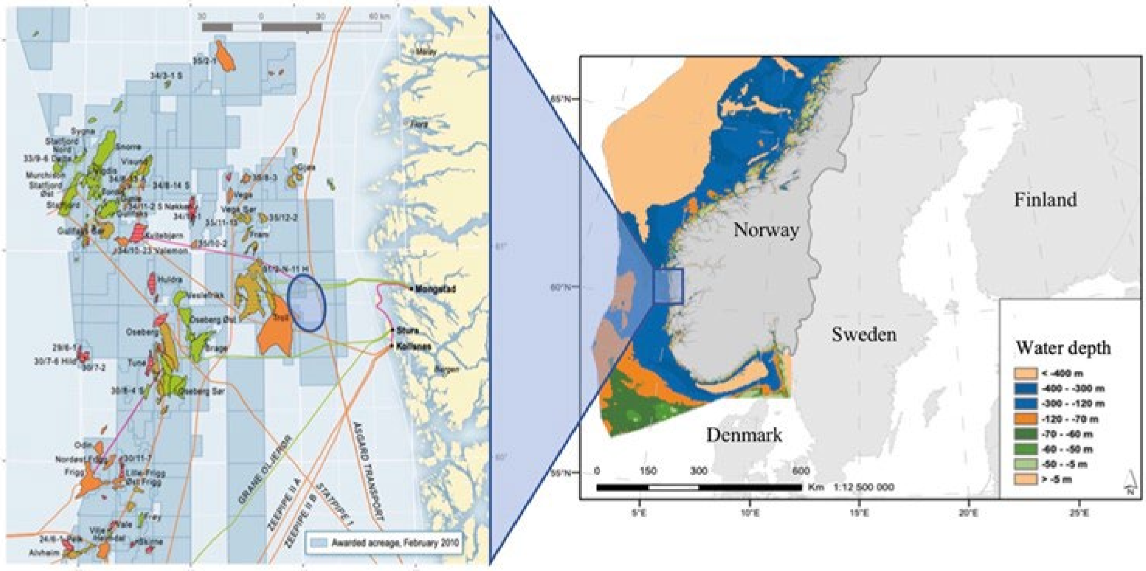
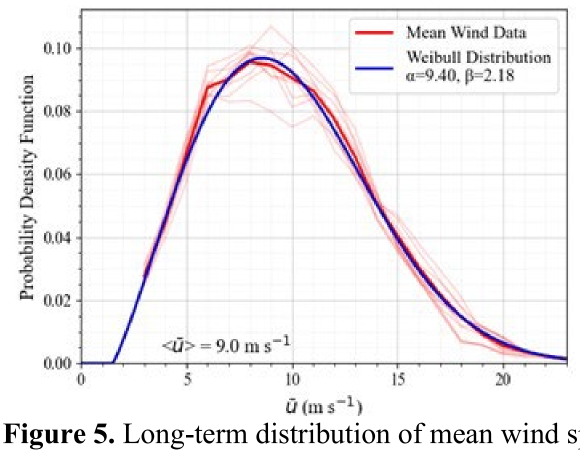


**Figure 4.** Geographical location of the Troll field.

*4.2 Metocean conditions*
To describe the long-term wind speed distribution at the Troll field, a two-parameter Weibull probability distribution model is used to fit the mean wind speed over 29 years. The fitted curve (blue) along with the scatter of mean wind speed is illustrated in Figure 5 where $\alpha$ and $\beta$ are respectively the shape and scale parameters of the Weibull distribution. Figure 6 presents a wind rose depicting the dominant wind direction for different wind speeds. The wind rose data have been sourced from the Norwegian Centre for Climate Services [20]. As indicated, the prevailing wind direction at this site is from the southeast.

## 5. Case study of a reference wind farm

*5.1 Wind farm layout*
The reference wind farm is designed with an assumed operational lifespan of 25 years, comprising 50 turbines, each with the rated power of 15 MW. Consequently, the FWF has a theoretical total capacity of 750 MW. Figure 7 illustrates the layout of this reference wind farm.



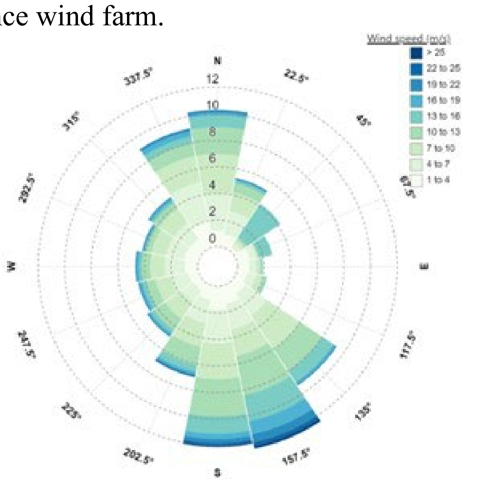




**Figure 5.** Long-term distribution of mean wind speed at Troll. **Figure 6**. Wind rose at Troll.

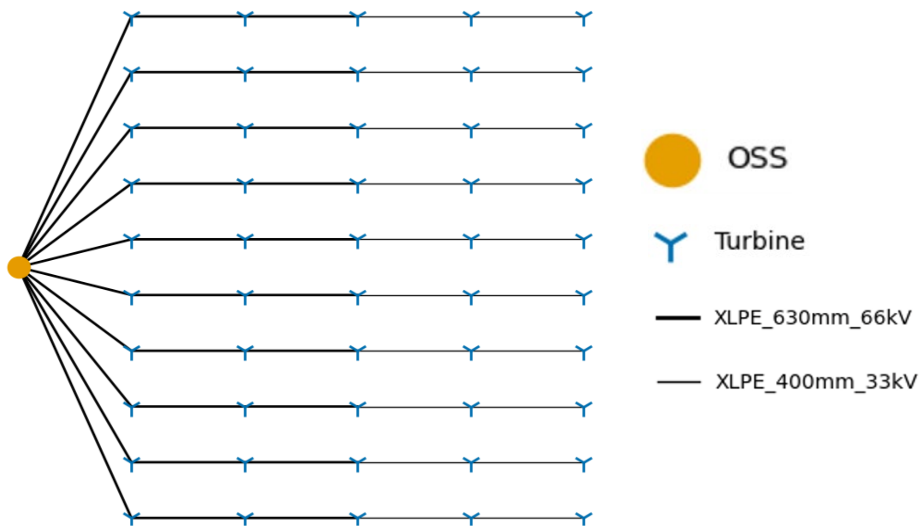



**Figure 7.** Layout of the studied FWF.

As depicted, the wind turbines are organized in a grid pattern with a layout of 5 turbines in a row and 10 rows. There are a total of 10 cables connected to the offshore substation (OSS), and these cables progressively increase in voltage and radius as they approach the OSS to sufficiently transmit electricity with minimal losses during transportation. To minimize the loss caused by aerodynamic wake effects, the spacing between the turbines is set to 8 times the rotor diameter in the dominant wind direction and 4 times the rotor diameter in the direction perpendicular to the dominant wind direction. As FWTs are in motion, these spacings are expected to be larger than those of bottom-fixed wind turbines. This layout is chosen for the sake of simplicity and no layout optimization is carried out in this work.

*5.2 Capacity factor of the reference wind farm*

To determine the capacity factor for the reference wind farm, statistical techniques are employed. The approach utilized is grounded in the Weibull distribution of wind speeds, combined with the specific power curve of the 15-MW wind turbines. Figure 8 illustrates the idealized power curve, sourced from [18], in conjunction with the probability distribution of the long-term wind speed.

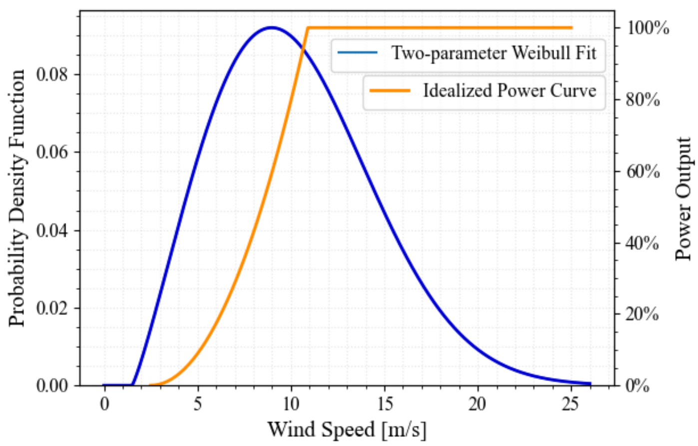



**Figure 8.** Power output curve and probability distribution of the mean wind speed.

The capacity factor for the 15-MW wind turbine at the Troll site is determined by integrating the Weibull distribution with the power curve as the upper limit. This process yields an approximate capacity factor of 57.75%. To consider grid or array losses and potential downtime, a 5% deduction has been applied to the calculated capacity factor. Therefore, the capacity factor used for the reference wind farm is set at 52.75%.To account for grid or array losses, as well as potential downtime, 5% has been subtracted from the calculated capacity factor; thus, the capacity factor used for the reference wind farm is set to 52.75%. Larger fluctuations are expected in the wind speed and power output in turbulent wind, and FWF control will play an important role in the power quality.

*5.3 Cost categories for the wind farm*

To assess the cost breakdown, various subcategories have been established. These subcategories cover different aspects within both the design and installation phases, encompassing electrical components, turbines, and substructures. During the installation phase, the turbine and substructure are combined due to onshore assembly and the subsequent towing process. Similarly, mooring design and installation costs have been consolidated into one section since they represent a relatively small portion of the CapEx. Additionally, other sub-costs encompass all soft costs, project-related expenses, and OpEx. Table 3 provides an overview of the cost subcategories, outlining the components included in each sub-cost section.

**Table 3.** Cost elements included in the different cost categories

| Cost category | Cost elements | | | |
|---|---|---|---|---|
| Electrical grid | Inter-array cables | Export cable | Offshore substation | Substation foundation |
| Turbine | Tower | Nacelle | Rotor blades | Hub |
| Substructure | Stiffened column | Truss | Heave plate | Secondary steel |
| Mooring line | Steel chain | Anchor | | |
| Soft | Insurance | Financing | Commissioning | Decommissioning |
| Project | Site auction | Site assessment | Construction plan | Installation plan |
| OpEx | Operation | Maintenance | | |

## 6. Results and discussion

*6.1 Initial calculation for the LCOE*

According to the method outlined in Section 2, there are certain components that are not assessed in ORBIT but are essential for the calculation of the LCOE. These components are computed as follows:

$$OpEx_{annual} = \$\,118\,000/MW/yr * 15MW * 1yr * 50\ turbines = \$\,88.5M \tag{4}$$

$$AEP = 15MW * 50\ turbines * 52.75\,\% * 8760hr/yr = 3\,465\,675\ MWh \tag{5}$$

*6.2 Total LCOE estimation and cost description for the reference wind farm*

Table 4 displays the breakdown of CapEx for the reference FWF. The cost categories and specific cost elements are described in Table 3. According to Table 4, the overall investment for the construction and installation of the reference wind farm, consisting of 50 wind turbines, amounts to $3772572000. This results in a cost of $75451440 for each installed turbine, encompassing all associated components.

**Table 4.** Cost breakdown of CapEx

| Cost category | Cost | Percentage of CapEx |
|---|---|---|
| Electrical Grid | $ 384363000 | 10.2% |
| Electrical Grid Installation | $ 221400000 | 5.9% |
| Turbine | $ 759000000 | 20.1% |
| Substructure | $ 1275740000 | 33.8% |
| Substructure Installation | $ 56700000 | 1.5% |
| Mooring Line (Inc. Installation) | $ 218120000 | 5.8% |
| Soft | $ 653400000 | 17.3% |
| Project | $ 203850000 | 5.4% |
| Total | $ 3772572000 | 100% |

Table 5 displays the key parameters applied during the LCOE calculations, along with the computed LCOE for the reference wind farm. In the table, FCR, OpEx and AEP are calculated using Eqs. (3)-(5), respectively, and the estimated annual cost per MW is from [5]. The table shows that the LCOE of the reference wind farm is estimated to be 100.69 $/MWh.

**Table 5.** Parameters for the LCOE calculation

| Description | Reference Wind Farm |
|---|---|
| CapEx | $ 3772572 000 |
| OpEx (annual) | $ 88500 000 |
| AEP | 3 465575 MWh |
| FCR | 6.9% |
| Lifespan | 25 years |
| LCOE | 100.69 $/MWh |

To evaluate the most influential components on LCOE, all costs related to energy production are displayed in Figure 9.

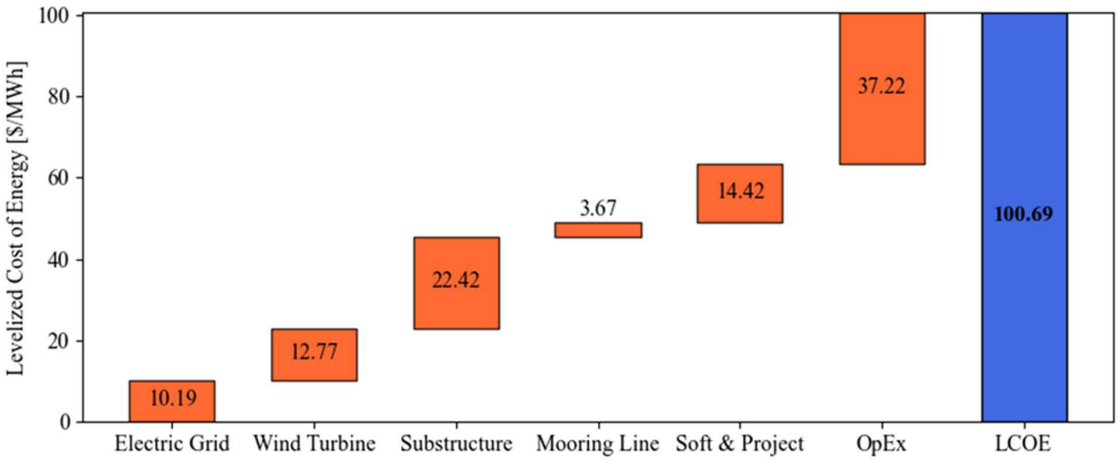



**Figure 9.** Total LCOE and its cost distribution.

Figure 9 integrates the installation costs within the total component costs. Among the components, the mooring line represents the smallest cost, totaling 3.67 $/MWh. On the other hand, OpEx is the most substantial contributor to the LCOE, amounting to 37.22 $/MWh. Notably, the costs associated with operation and maintenance make up approximately 37% of the LCOE throughout the 25-year production

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period. Despite the combined CapEx being higher in total, OpEx emerges as the most significant individual cost driver.

*6.3 Sensitivity analysis of the reference wind farm*
To analyze how LCOE varies with different input parameters, several sensitivity analyses have been performed. This will provide insights into factors that impact the LCOE for the reference FWF.

*6.3.1 Key cost drivers of LCOE.* Figure 10 illustrates the primary cost drivers affecting the LCOE. It reveals which factors exert the most significant influence on the LCOE and how they impact the LCOE when these cost drivers change. The baseline LCOE, set at 100.69 $/MWh, serves as the reference point. The diagram displays the extent to which the LCOE is affected by various cost drivers. Notably, it demonstrates that the lifespan, capacity factor, and project discount rate have the most substantial impact on the LCOE. These factors, when adjusted from the baseline, can significantly alter the LCOE.

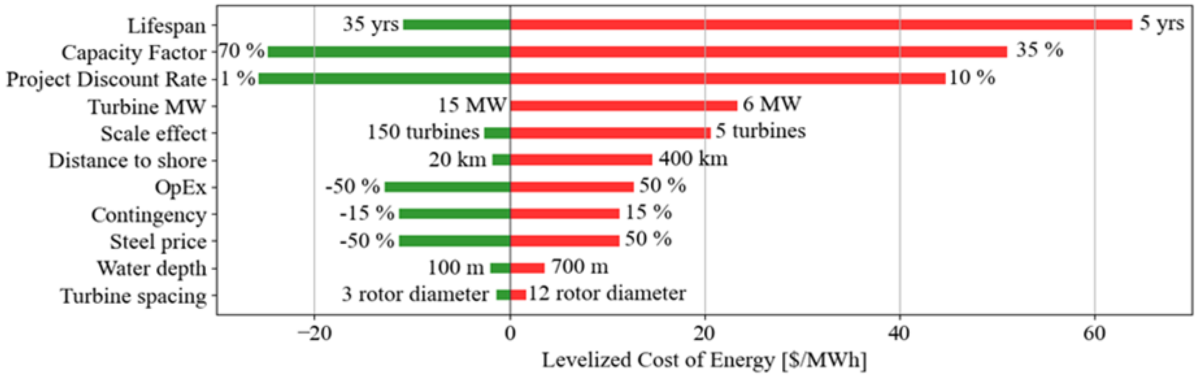


**Figure 10.** Key parameters affecting LCOE.

*6.3.2 Effect of project lifespan and capacity factor.* As the project lifespan and the capacity factor are two important factors in the cost of the LCOE, their influences are highlighted in Figure 11 and Figure 12.

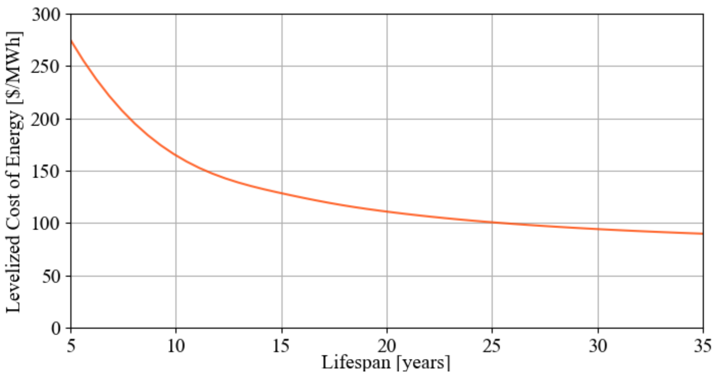


**Figure 11.** Variation of LCOE with project lifespan.

Figure 11 demonstrates that the LCOE decreases as the project's lifespan increases. For instance, at a five-year lifespan, the LCOE is 275.1 $/MWh, but it decreases significantly to 89.8 $/MWh for a 35-year lifespan, representing a reduction of 67.3%. Notably, this reduction in LCOE is more pronounced at the beginning of the project's lifespan, indicating that the benefits of longer project lifespans have a more substantial impact initially. It is important to acknowledge that the model does not account for adjustments in CapEx based on different lifespans. In practice, materials and installation for an FWF with an extended lifespan may be more time-consuming and costly, and the present model has not considered these factors.

Figure 12 illustrates that higher capacity factor leads to a reduced LCOE. Thus, it is of high importance to choose wind farm sites with the best wind resources to achieve a capacity factor. On the other hand, as most waves are wind-driven, such sites are often associated with large waves and higher material costs for mooring systems and substructures are expected.

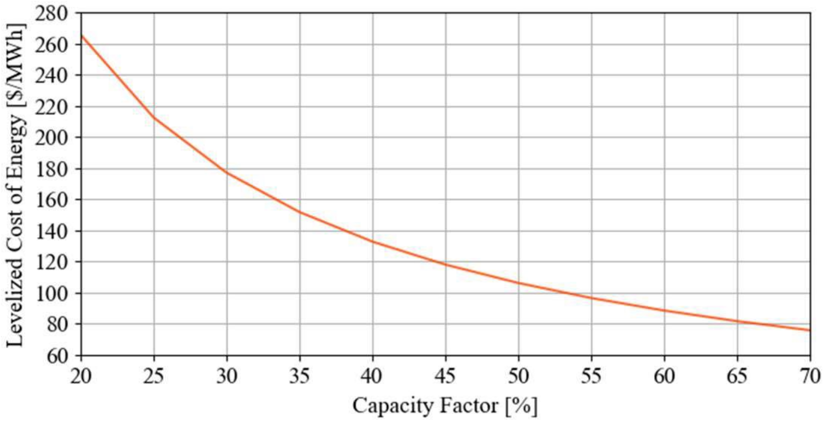


**Figure 12.** Variation of LCOE with capacity factor.

*6.4 Financial modeling*

To assess the economic viability of the wind farm, specific financial analyses have been performed, including the calculation of the Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP). These calculations are derived from a discounted cash flow analysis, where the project discount rate is equivalent to the pre-tax WACC, set at 5.46%. Table 6 provides an overview of the cash flows for the initial five years and the final five years of the project, along with the resulting NPV, IRR, and PP values. These financial metrics serve as the basis for evaluating the project's economic feasibility and potential return on investment.

**Table 6.** Calculation of NPV, IRR, and PP

| *USDm* | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2046 | 2047 | 2048 | 2049 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total Revenue** | **-** | **333.2** | **333.2** | **333.2** | **333.2** | **333.2** | **333.2** | **333.2** | **333.2** | **333.2** | **-** |
| (-) CapEx | 3 571.0 | - | - | - | - | - | - | - | - | - | - |
| (-) OpEx | - | 88.5 | 88.5 | 88.5 | 88.5 | 88.5 | 88.5 | 88.5 | 88.5 | 88.5 | - |
| (-) Decommisioning | - | - | - | - | - | - | - | - | - | - | 36.0 |
| (+) Depreciation | - | 142.8 | 142.8 | 142.8 | 142.8 | 142.8 | 142.8 | 142.8 | 142.8 | 142.8 | |
| (-) Principal Payment | - | 166.6 | 166.6 | 166.6 | 166.6 | 166.6 | - | - | - | - | |
| (-) Interest Payment | - | 118.0 | 110.1 | 102.3 | 94.4 | 86.5 | - | - | - | - | - |
| (+) Interest Tax Deduction | - | 26.0 | 24.2 | 22.5 | 20.8 | 19.0 | - | - | - | - | - |
| **Cash Flow** | **- 3 571.0** | **128.9** | **135.0** | **141.2** | **147.3** | **153.4** | **387.6** | **387.6** | **387.6** | **387.6** | **- 36.0** |
| Cumulative Cash Flow | - 3 571.0 | - 3 442.1 | 3 307.1 | - 3 165.9 | - 3 018.6 | - 2 865.1 | 1 719.8 | 2 107.4 | 2 494.9 | 2 882.5 | 2 846.5 |
| **Disc. Rate 5.46 %** | | **NPV** | **-561.9** | ***USDm*** | | **IRR** | **4.0 %** | | **PP** | **18 years, 30 weeks** | |

Given that the reference FWF exhibits a negative NPV exceeding $500000000, it suggests that the project is not financially viable without government subsidies. The high cost of manufacturing and installing an FWF leads to a substantial initial investment and a significant debt burden. An IRR of 4.0% is not inherently an unattractive return, but since this rate is lower than the WACC, it implies that the investment may warrant reassessment. An IRR lower than the WACC suggests that the cost of opportunity for this project may be higher than that of other alternative investments, making it potentially less profitable in comparison. Hence, it is crucial to explore alternative strategies or investment opportunities that might offer a more favorable return given the financial constraints and performance metrics of the reference FWF project.

## 7. Concluding remarks

This paper provides a comprehensive examination of an offshore floating wind farm situated in the Norwegian Sea. The research model involves the utilization of semi-submersible floaters, each supporting a 15-MW wind turbine, and the wind farm under investigation comprises 50 such turbines with a projected operational lifespan of 25 years. The calculated levelized cost of energy (LCOE) amounts to $100.69 per megawatt-hour, with capital expenditure accounting for 63.1% of the overall expenses. This highlights a significant challenge associated with floating offshore wind, which is the substantial upfront capital investment required for such projects.

A sensitivity analysis reveals that the most influential factors affecting the LCOE are the lifespan, capacity factor, and project discount rate. Furthermore, the financial analyses indicate that the reference wind farm is not economically viable due to a negative Net Present Value (NPV) and an Internal Rate of Return (IRR) lower than the Weighted Average Cost of Capital (WACC). This suggests that the project may not be financially feasible without government subsidies or alternative measures to address its financial challenges.

As this study is limited to a wind farm layout, idealized power curve for the wind turbines and simplified OPEX estimates, future work can address the motion characteristics of floating wind turbines, wind farm with multiple-rated wind turbines, and advanced operation and maintenance strategies. All these elements will influence the economic analysis.

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