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Preliminary Techno-Economic Study of Optimized Floating Offshore Wind Turbine Substructure

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Abstract

Wild fires and excessive floodings have been seasonal climatic changes across the globe in the past decade. The need for clean energy to fight against the climate changes observed as a result of excessive green-house emission over the years is driving the development of the offshore wind sector. This drive is pushing the exploitation of rich wind resources in deep waters with water depth greater than 60 metres requiring a deviation from the commercialized fixed bottom foundation offshore wind technology. Resolving the issue of exploiting rich wind resources requires the use of floating foundation offshore wind technology satisfying stability and durability requirement in any environmental condition.
Floating offshore wind turbines (FOWTs) are still in the pre-commercial stage and although different concepts of FOWTS are being developed, cost is a main barrier to commercializing the FOWT system. This is evidence in the comparison of the CAPEX (capital expenditure) for a fixed bottom platform and a floating platform with the fixed bottom foundation CAPEX representing 13.5% of the total CAPEX of the system while the floating platform CAPEX represents about 29% of the total CAPEX of the system leading to an increasing cost.
This article aims to use a shape parameterization technique within a multidisciplinary design analysis and optimization framework to alter the shape of the FOWT platform with the objective of reducing cost. This cost reduction is then implemented in a 30 MW floating offshore wind farm (FOWF) designed based on the static pitch angle constraints (5 degrees, 7 degrees and 10 degrees) used within the optimization framework to estimate the reduction in the levelized cost of energy (LCOE) in comparison to a FOWT platform without any shape alteration – OC3 spar platform design. The optimal platform design variants and the OC3 platform are also deployed in a scaled up 60 MW farm to see the impact of platform geometric shape optimization in a scaled-up scenario.
Key finding in this work shows that an optimal shape alteration of the platform design that satisfies the design requirements, objectives and constraints set within the MDAO framework contributes to significantly reducing the CAPEX cost and the LCOE in the 30 MW floating wind farm. This is due to the reduction in the required platform mass for hydrostatic stability when the static pitch angle is increased. The FOWF designed with a 10 degrees static pitch angle constraint provided the lowest LCOE value while the FOWF designed with a 5 degrees static pitch angle constraint provided the largest LCOE value barring the FOWT designed with the OC3 dimension which is over designed and over dimensioned. The total cost and LCOE is further reduced in a scaled up 60 MW farm for each design assessed. This further reduction is due to combination of the geometric shape parameterization and optimization of the platform with the economics of scale of the wind farm.

Keywords: FOWT; MDAO; shape parameterization; CAPEX; fixed bottom

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Abbreviations

AEP	Annual Energy Production
B-Spline	Basis Spline
CAPEX	Capital Expenditure
DECEX	Decommissioning Expenditure
DPBP	Discounted Pay Back Period
DNV	Det Norske Veritas
GBP	Great British Pounds
GWh	Giga Watts Hour
FOWF	Floating Offshore Wind Farm
FOWT	Floating Offshore Wind Turbine
IRR	Internal Rate of Returns
LCOE	Levelized Cost of Energy
MDAO	Multidisciplinary Design Analysis and Optimization
MW	Mega Watts
MWh	Mega Watts Hour
NPV	Net Present Value
OC3	Offshore Code Comparison Collaboration
OPEX	Operating Expenditure
OWT	Offshore Wind Turbine
PSM	Pattern Search Model
TLP	Tension-Leg Platform
WACC	Weighted Average Capital Cost
WADAM	Wave Analysis by Diffraction and Morison Theory

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1. Introduction and Background

With more than three-quarter of the world's offshore wind resource potential available in waters deeper than 60m along the coastline of many countries, the potential for fixed bottom offshore wind system becomes limited (Gwec, 2022). This highlights the need for Floating Offshore Wind Turbine (FOWT) technology in order to see a true global growth of the clean technology (FOWT) to contribute to the reduction in green house emission.

Mega-Watts' (MW) scale floating technologies have only been tested in the last ten years through demonstration and pilot projects in both Europe and Asia. With the completion of the demonstration projects, deployment of floating offshore wind turbine system has not entered the commercial or industrial phase as development has just entered the pre-commercial stage with a shift in emphasis moving towards a larger first of a generation schemes(Gwec, 2022). It is anticipated that 2026 FOWT system deployment will move into the commercial phase with yearly installations surpassing 1 GW – a milestone achieved by fixed offshore wind in 2010 (Dnv-Gl, 2020).

The concept of floating offshore wind turbine has been conceived since the 1970s (Heronemus, 1972). Despite the early conception, FOWT is still in the pre-commercial stage leaving the fixed bottom foundation/platform in the dominant technology in the offshore wind turbine (OWT) sector (Zheng and Lei, 2018). The most efficient offshore foundations are floating offshore wind platforms because of all the advantages they offer. First and foremost, they enable the exploitation of huge sections of ocean that are deeper than 60 metres. Second, they make it easier to set up turbines, even in mid-depth circumstances (30–50 m), and they might eventually present a less expensive option than solid foundations. FOWT technology provides the capability to move further offshore to exploit better wind resources while also limiting visual impact from land and away from competing with other users of the sea (Kaldellis et al., 2016). Additionally, due to less invasive construction methods on the seabed than fixed-bottom designs, floating foundations typically provide environmental advantages over them. The world's forecast growth of floating offshore wind was 17MW in 2020 to 6.5GW by 2030. A review of the forecast was conducted in 2021 with the forecast increased to 16.5GW of floating offshore wind capacity by 2030 (Gwec, 2022) highlighting a significant interest in increasing the capacity of the FOWT technology in reducing the green-house emission. The floaters required for offshore wind must provide adequate buoyancy to support the weight of the wind turbines and also have the capability to constrain the motions within allowable limit (Butterfield et al., 2007).

Three main floating platform concepts (spar, semisubmersible, and tension leg platform) from the oil and gas industry are the early adapters (early to market floaters) in the FOWT sector. The stabilization mechanisms of the three platforms highlighted are: ballast, waterplane / buoyancy and mooring stabilization respectively. As highlighted in Leimeister et al. (2018), several floating solutions have currently been developed that are anticipated to be appropriate and considerably financially viable in depths more than 60 m. These new floating solutions still adapt the stability mechanisms used in the early adapters floaters from the oil and gas sector.

The ballast stabilized spar requires a large ballast that is deep at the bottom of the floater to move the center of gravity of the system below the center of buoyancy in order to provide a restoring moment or stabilizing righting moment which counteracts the inclining moments. In the waterplane area or buoyancy stabilized semi-submersible, a large second moment of waterplane area with respect to the rotational axis creates the restoring moment to counteract against the rotational displacement. The mooring stabilized TLP utilizes high tensioned mooring lines to generate the restoring moments to counteract the effect of any inclining moment on the structure. The benefits and challenges associated with the three types of platforms associated with the stability mechanism described are highlighted in Table 1 and Table 2 respectively. The choice of the platform used for a FOWT system will also depend on elements like water depth, localization potential, local infrastructure, and various turbine designs. As a result, the market will likely adjust to changing situations rather than rationalize around a single sort of floating platform (Gwec, 2022).

The average CAPEX of a floating platform is higher than that of a fixed bottom platform. The floating substructure of a reference wind power plant accounts for approximately 29.5% of the CAPEX for the project in contrast to 13.5% for a fixed-bottom reference project (Ioannou et al., 2020). These average values can be significantly higher or lower depending on the floater type employed and will significantly impact the profitability of the project. It is expected to see innovation in design, construction, operation and maintenance as the industry evolves to facilitate the build and operation of larger FOWT projects. The construction of FOWT system can be in ports or sheltered waters making use of specialized vessels. Major maintenance and repair activities might also be carried out away from the site using the innovative "tow-to-port" maintenance capability. Continuous innovation in design is expected to yield new technologies and products capable of supporting better mooring and anchor solutions, deep water substations and dynamic cabling, management of FOWT system's response to environmental conditions and sea-states and the design of floating platforms.

Bringing the cost of floaters/platform used in the FOWT system down to the level of fixed bottom platform needs extensive developmental process and ideas exploration. Some of the processes and ideas that can be explored in driving down the cost of FOWT systems are:

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1. Geometric shape parametric design, analysis and optimization of the FOWT platform (Clauss and Birk, 1996; Birk and Clauss, 2002; Birk, 2006; Ojo et al., 2022b);
2. Upscaling design platform to fit with larger and bigger turbines (Leimeister et al., 2016; Kikuchi and Ishihara, 2019; Papi and Bianchini, 2022);
3. Multidisciplinary design analysis and optimization of all components within the FOWT system (Turbine, tower, platforms, mooring lines and anchors) (Leimeister et al., 2020a; Karimi et al., 2017; Karimi, 2018);
4. Provision of government subsidy to floating wind projects in the precommercial stage to add economic value until the FOWT technology becomes cost competitive with the fixed-bottom OWTs (Markus Lerch, 2019).

The main aim of this study is to investigate the economic implication of use of bespoke geometric shape parameterization, design, analysis and optimization framework of spar platforms on a 30 MW floating wind farm and also the cumulative effect of this bespoke approach and economies of scale on a 60 MW floating wind farm. This investigation will be conducted with the use of some of the financial parameters highlighted in section 2 in conjunction with the methodology discussed in section 3. The tecno-economic study highlighting the impact on costing is detailed in in section 4 and adequate conclusion presented in section 5.

Table 1. Benefits of traditional platforms

Spar	Semi-submersible	TLP
Suitable for severe seastate	Broad weather window for installation	Small seabed footprint and short mooring lines
Inherent stability	Independent of water depth	High stability and low motions
Soil condition insensitivity	Soil condition insensitivity	Have a good water-depth flexibility
Simple fabrication process	Minimal risk to installation and operation	Possibility of onshore or dry dock assembly
Low operational risk	Heave plates for reducing heave response	Lower material cost due to minimal structural weight of the substructure
Little susceptibility to corrosion	Simple installation and decommissioning as specialised vessel required	Simple and light structure, easy for operation and maintenance
Cheap and simple mooring and anchoring system		

Table 2. Challenges of traditional platforms

Spar	Semi-submersible	TLP
Heavy weight with long draft and long mooring lines	Higher exposure to waves leads to lower stability that impacts turbine	High vertical load moorings
Deep drafts limit ports access and large seabed footprint	Labour intensive and long lead time	Unstable during assembly and will require the use of special vessels
Relatively large motions	Large and complex structure – difficult to fabricate	Mooring tendons present higher operational risk in case of mooring failure
Assembly in sheltered deep water is challenging and time consuming	Built in one piece requiring dry dock or special fabrication yard with skid facilities	Complex and costly mooring and anchoring system makes it the most expensive floater design type
High design manufacturing and installation cost.	Lateral movement presents potential problems for the export cables	Additional investigation of seabed condition to ensure it's fit for purpose of high tensioned mooring
High fatigue loads in tower base	Non-industrialized fabrication	
Specialised installation vessel required.		

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2. FOWT Techno-Economic Feasibility Review

2.1. Overview

At the turn of the millennium, the total installed costs for offshore wind farms were evaluated from those of existing shallow water and extrapolated to deeper waters for deep water offshore farms. The extrapolation resulted in increased costs of foundations, grid connection and installation. The new farms so designed had the effect of increasing the average cost of offshore wind installations from 2.300 €/kW in the year 2000 to a peak of 5.0 €/kW in the period between 2011 and 2014. However, from 2015 the total costs of FOWFs started to decreasing and in 2018, the decrease was down to 4.0 €/kW (Maienza et al., 2022; Irena, 2019a, b)

The predicted cost for FOWFs is also expected to decrease, according to recent study, primarily due to technological advancements. These allow capacity factors to rise while lowering overall installation and maintenance costs (Maienza et al., 2022). Additionally, the rise in this technology's competitiveness can also be efficiently improved by the following:

- Adequate use of shape parameterization technique within the multidisciplinary design analysis and optimization (MDAO) framework to optimize platforms in accordance to specified design objectives and constraints;
- Platform upscaling techniques to bigger and heavier turbines;
- Increase in designers' experience, which reduces project development costs and risks;
- The increase in the industry maturity, bringing lower capital cost and;
- Presence of economies of scale across the value chain.

The future development of floating wind technology will benefit from accurate financial analyses sustaining the economic and technical value of FOWTs. Some of the techno-economic study on FOWTs are detailed herein.

Shape parameterization study of the FOWT platform was conducted by Ojo et al. (2022a) to alter the shape of a spar platform coupled to a 5MW OC3 turbine, reduce the mass of the spar platform leading to a reduction in the required cost of steel for manufacturing the spar platform. This study used a B-spline parameterization technique within an MDAO framework with a metaheuristic pattern search optimization algorithm to explore the design space and produce an optimal design. The optimal design in the study is a spar variant platform with altered shape and lower mass than the standard OC3 platform. The limitation in this study is that only the cost of steel for the optimal spar was the only financial parameter to assess the economic feasibility of the FOWT system.

Ghigo et al. (2020) conducted a study on platform optimization and cost analysis in a floating offshore wind farm. This study focuses on the choice of a floating platform that minimizes the global weight, in order to reduce the material cost, but ensuring buoyancy and static stability. Subsequently, the optimized platform is used to define a wind farm located near the island of Pantelleria, Italy in order to meet the island's electricity needs. A sensitivity analysis to estimate the LCOE for different sites is presented, analyzing the parameters that influence it most, like Capacity Factor, Weighted Average Capital Cost (WACC) and number of wind turbines. The study concluded that the decrease of many Capex cost items and the evolution of the offshore wind market, will make this technology even more competitive in a few years.

Ioannou et al. (2020) conducted a preliminary parametric techno-economic study of offshore wind floater concepts. This study investigates through a parametric study the total mass and cost of three floater concepts: spar, barge and semi-submersible, particularly focusing on the material and manufacturing costs. A survey from floating offshore wind industry professionals was conducted to determine the manufacturing complexity factors' values, which were used to calculate the manufacturing cost. The main conclusion of this work is that, given the specified conditions, steel-based semi-sub structures proved to be the most expensive configuration followed by spar as spar prices fall with higher draught values due to the reduction in ballast mass. The barge solution is the least expensive option of the three configurations. Also, the study highlighted the risks and benefits of different configurations should also be considered alongside, as they could lead to savings throughout the service life of the asset.

Castro-Santos et al. (2016) presented an approach for evaluating the lifecycle costs of combined or a hybrid floating offshore renewable energy systems like a FOWT. Their methodology expressly takes into account, the life cycle stages amongst which are: concept generation and definition, design and development, manufacturing, installation, exploration, exploitation and decommissioning. It is a tool for strategic planning and decision-making, allowing for a better understanding of technical advancements and factors that could either expedite or slow down the growth of the FOWT sector. Their findings from two sites show that the exploitation, manufacturing and installation costs are the most important lifecycle costs on the LCOE but the important of the three costs could be site dependent.

Martinez and Iglesias (2022) conducted an extensive study that mapped the Levelized Cost of Energy (LCOE) for floating offshore wind in the European Atlantic. They emphasized the importance of understanding LCOE spatial variations to identify suitable areas for the development of Floating Offshore Wind Turbine (FOWT) technology. The study focused on floating semi-submersible platforms, presenting a comprehensive LCOE mapping across the European Atlantic. Accurate energy production estimates were obtained by combining hindcast wind data and an exemplary wind turbine's power curve. The study revealed the lowest LCOE values (around 95 €/MWh) in wind-rich regions like Great Britain, Ireland, the North Sea, and NW Spain. In contrast, higher LCOE values (approximately 125 €/MWh) were observed off Portugal and Norway, and significantly higher values exceeding 160 €/MWh were noted in the Gulf of Biscay and south of the Iberian Peninsula.

Filgueira-Vizoso et al. (2022) evaluated the technical and economic viability of floating offshore wind platforms. Their work defined an economic assessment approach for TLP platform-based offshore wind farms. Life-cycle costs were categorized into stages including conception, design, manufacturing, installation, exploitation, and dismantling. Economic indicators like IRR, NPV, DPBP, and LCOE were assessed based on cash flows. The study focused on a TLP platform designed by CENTEC, considering an 880 MW farm located along the European Atlantic Coast in the North-West region of Galicia, Spain. Eighteen case scenarios were analyzed, varying electric tariffs and capital costs. The study underscored the impact of electric tariffs on economic indicators. The optimal outcome emerged for a tariff of EUR 150/MWh and a 6% cost of capital, yielding an IRR of 18.34%, NPV of EUR 2636.45 million, and DPBP of 8 years. The farm's LCOE reached a minimum of EUR 54.33/MWh, rendering the platform economically feasible due to its IRR surpassing capital costs.

Pham and Shin (2019) introduced a novel conceptual design for a spar-type platform, intended to accommodate a 5 MW offshore wind turbine. This innovative concept effectively addresses challenges associated with the OC3-hywind model, notably the elevated nacelle acceleration and tower-base bending moment. This achievement is accomplished through the incorporation of an open moonpool positioned at the platform's center. By leveraging the water column within the moonpool, the mass and inertia of the entire wind system are augmented along the x and y axes. By appropriately sizing the moonpool diameter, it becomes possible to mitigate nacelle acceleration and tower-base bending moment concerns

Campos et al. (2016) presented a groundbreaking approach to achieving a cost-efficient offshore wind turbine floating platform. This novel concept revolves around a monolithic floating spar buoy design. The innovation lies in the integration of both the tower and floater components as a seamless, continuous concrete structure. This concept promises significant cost savings, not only during the construction phase but also throughout the platform's operational lifespan. The inherent design translates to minimal maintenance requirements. Comprehensive insights into the construction and installation processes are provided in Campos et al. (2016) considering the distinctive demands of the monolithic design. The authors conducted a comparative analysis of costs between steel and equivalent concrete platform designs and their findings underscore a material cost reduction exceeding 60% for the concrete design, reinforcing its economic viability.

(Lerch et al., 2018) conducted a study exploring three platform concepts (spar, semi-submersible and TLP) for floating offshore wind turbines (FOWTs), situated across different locations and comprising a 500 MW floating offshore wind farm. Their findings underscore the competitiveness of FOWTs, demonstrating their capacity to generate energy at an equivalent or lower Levelized Cost of Energy (LCOE) compared to bottom-fixed offshore wind technologies. They identified significant parameters influencing the LCOE FOWF with potential for substantial cost reductions. Notably amongst these parameters are manufacturing-related costs, including those of the wind turbine, substructure, and mooring system. These parameters are key factors driving LCOE variations across all concepts and offshore sites. They also highlighted innovative ideas such as dedicated construction and assembly facilities tailored for floating wind can further contribute to cost reduction, particularly during the manufacturing phase of a FOWF components.

Castro-Santos et al. (2020a)Castro et al. developed a method to assess the economic viability of deep-water offshore wind farms by considering their economic factors. This procedure involves the use of various economic parameters, including internal rate of return, net present value, and levelized cost of energy. Notably, the research indicated that among the considered platform types, the semisubmersible platform exhibited the most favourable levelized cost of energy (LCOE) value, followed by the spar platform and the TLP platform.

Some innovative studies to improve the design and optimization of floaters also contributes to the process of maturing the FOWT technology and making it as economically competitive as the fixed bottom foundation counterpart. Some of the innovative technical and optimization studies are highlighted herein: -

Hall et al. (2013) focused on optimizing the hull shape and mooring lines of FOWTS across various substructure categories. This optimization was carried out using a Genetic Algorithm (GA) and a frequency domain model based on FAST software. Their model is a linear representation of hydrodynamic viscous damping and did not include a representation of wind turbine control. The GA was employed for both single and multi-objective optimization. The study's outcomes revealed an un-conventional design, highlighting the need for further refinement of cost functions in the optimization process.

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Karimi et al. (2017) enhanced the research conducted by Hall et al. (2013) by implementing a new optimization algorithm and a linearized dynamic model, leading to improved optimal solutions. In their study, Karimi et al. (2017) introduced a fully coupled frequency domain dynamic model and a design parameterization approach. This allowed for the evaluation of system motions and forces in scenarios involving turbulent winds and irregular waves. Furthermore, they employed the Kriging-Bat optimization algorithm, a surrogate-based evolutionary approach, to facilitate the exploration and exploitation of optimal designs across three stability classes of platforms: MIT/NREL TLP, OC3-Hywind Spar, and OC4-DeepCwind semi-submersible platforms. This optimization primarily aimed to assess the cost implications of platform stability, as reflected by the nacelle acceleration objective function, across these three categories of Floating Offshore Wind Turbines (FOWT) platform stability. This study shows an enhanced correlation between cost and substructure design compared to the previous work by Hall et al. (2013).

Hegseth et al. (2020) conducted a comprehensive design optimization for an integrated system including the platform, tower, mooring system, and blade pitch controller for a 10 MW spar-type floating wind turbine. The study involved optimizing various design parameters for the spar, including its diameter and wall thickness along ten distinct sections. These dimensions, along with the configuration of stiffeners, were represented using a B-spline curve, utilizing four control points. The study's findings revealed that the optimized platform exhibits a relatively small diameter within the wave zone and assumes an hourglass shape beneath the waterline. This particular design serves to minimize wave-induced loads on the structure. Additionally, the distinctive shape enhances the system's restoring moment and natural frequency in pitch, resulting in an enhanced dynamic response within the low-frequency spectrum.

Dou et al. (2020) introduced an optimization framework tailored for the support structure of floating wind turbines, specifically the spar-buoy floater, which also includes the mooring system. This framework is developed from frequency domain modelling, and it extends its analytical capabilities to provide design sensitivities for various design criteria. This unique capability facilitates rapid optimization by leveraging on the Sequential Quadratic Programming (SQP) optimization algorithm.

The optimization techniques discussed in Hall et al. (2013); Karimi et al. (2017); Hegseth et al. (2020) and Dou et al. (2020) also reviewed above have the capability of reducing the computational time for the design and analysis of FOWTs. The reduction in time to search a large design space and identify optimal solutions allows stakeholders in making informed decisions that can potentially help in driving down the cost of FOWT to the levels of cost in fixed bottom foundation turbines.

This study aims to further reduce computational time for design of bespoke FOWTs and also reduce the LCOE of a FOWF by integrating shape parameterization techniques using B-spline parametric curve to model a spar. The design and analysis process of the spar is integrated with a gradient free optimizer to search the design and analysis space and select the optimal design in a quick duration.

2.2. Financial Parameters

2.2.1. Net Present Value

The Net Present Value (NPV), corresponds to the net value of the cash flows of the floating offshore wind farm, taking into account its discount from the beginning of the investment (Castro-Santos et al., 2016; Castro-Santos et al., 2020b). It is dependent on the cash flow in year t, CF_t, the discount rate (r) and the initial investment G_0, as highlighted in Eq. (1).

$$NPV = -G_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{1}$$

The discount rate (r) considered for a project is the WACC (weighted average cost of capital) (Filgueira-Vizoso et al., 2022). Investment decisions made from the NPV's are highlighted herein.

- NPV > 0. The investment will generate earnings above the required return (r). This will imply that the acceptance of the project is recommended
- NPV < 0. The investment produces returns below the required minimum return (r). It is not recommended to accept the project.
- NPV = 0. The project does not add monetary value above the required profitability (r).

The decision must be based on other criteria such as obtaining a better position in the market.

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2.2.2. Internal Rate of Return

The internal rate of return (IRR) is the interest generated by the project throughout its useful life. This is defined as the discount rate that cancels the NPV. It is the interest rate that makes the future flow of funds financially equivalent to the initial outlay (Filgueira-Vizoso et al., 2022). The IRR is highlighted in Eq. (2).

$$-G_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} = 0 \quad (2)$$

The economic feasibility of the project will depend on the IRR and profitability can be defined from the three conditions highlighted herein.

- IRR < k. The profitability obtained from the project is less than the required minimum. This shows the investment is not recommended.
- IRR > k. The profitability of the project is above the required minimum, therefore, it is recommended to invest in the project.
- IRR = k. The profitability is the same as that required minimum, the same happens as in the case where the NPV = 0. The decision in this kind of scenario is conditioned by other factors

2.2.3. Discounted Pay-Back Period

The discounted pay-back period (DPBP), in years, comprises the cash flow of each year with the respective discount rate and adds it to all the previous cash flows with their respective discount rate, accumulating its NPV (Filgueira-Vizoso et al., 2022). When this sum is equal to or greater than the initial investment, this is the year of the DPBP, as highlighted in Eq. (3). The best DPBP is as low as possible.

$$\sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \geq G_0 \quad (3)$$

The feasibility of the project is assessed by the conditions highlighted herein.

- DPBP <<< t. The initial outlay takes less time to recover than the life of the project (t). It is recommended to accept the project in this scenario.
- DPBP = t. The initial outlay takes to recover the same as the life of the project (t). This highlights the project is indifferent or no changes in project.
- DPBP > t. The initial outlay takes longer to recover than the life of the project (t). It is recommended to reject the project in this scenario.

2.2.4. LCOE

The levelized cost of energy (LCOE) is theoretically the price at which the electricity would have to be sold to reach the break-even point. It is therefore a fundamental parameter in analysing the economic viability of an energy project and serves as a standardised approach to compare costs of different energy sources (Martinez and Iglesias, 2022) – onshore/offshore wind, solar, coal, hydro. The LCOE can be defined as the ratio of the costs of an energy project to the electricity production over its lifetime, which is usually expressed as highlighted in Eq. (4).

$$LCOE = \frac{\sum_{t=1}^{n} (CAPEX_t + OPEX_t)(1+r)^{-t}}{\sum_{t=1}^{n} (AEP_t)(1+r)^{-t}} \quad (4)$$

where the costs are subdivided into CAPEX (capital expenditures), i.e., the costs spent prior to the operation of the project, and OPEX (operational expenditures), i.e., the costs of the electricity production and maintenance of the energy farm. AEP represents the annual energy production of the project, which constitutes the main source of income. The variable t represents the lifetime of the project in years and *r* denotes the discount rate.

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3. Methodology and LCOE

3.1. Overview

The majority of wind turbines are rated according to their power output (Ramachandran et al., 2013), and each rated turbine has a unique rotor nacelle assembly design. To effect quick optimization changes on the FOWT system for economic feasibility purposes is best done on the substructures - platform, mooring and anchor designs. As highlighted in section 1, the cost of a FOWT platform is substantially more than the fixed-bottom design configuration. It has been shown that the mass of steel used in the design of ship hull and FOWT platforms can be reduced in Birk and Clauss (2002) and Ojo et al. (2022a) respectively using shape parameterization techniques like NURBS and B-spline within an optimization framework. This reduction in the mass of steel material used in manufacturing the hull/platform substantially reduces the cost of the structure. For mooring optimization, Munir et al. (2021) showed that Floating wind turbines (FWTs) with shared mooring systems can be one of the most cost-effective solutions in reducing mooring costs and also mooring footprint on the seabed which invariably minimized the disruption or total loss of the Ocean biodiversity.
The methodological approach selected in this study is to estimate the LCOE of a 30MW and 60MW wind farms using an optimized platform distinguished by applying static pitch angle constraints in the optimization process. The optimal platforms based on the constraints are utilized in hypothetical wind farms to compare the economic feasibility using the LCOE financial parameter.
The process adopted is similar to the approach used in Ojo et al. (2022a) with an additional task of preliminary LCOE estimation added to the framework. The proposed methodology for the exploration, exploitation and preliminary LCOE estimation of a FOWT farm is to firstly define a parameterization scheme with a robust design space configuration using the B-spline / NURBS parameterization technique. This is followed by assessing the design models within the design space with frequency domain analysis tools - Sesam suite by DNV (Genie and HydroD/Wadam). The next stage is to integrate the analysis with the optimizer for optimal design selection for the 5 degrees, 7.5 degrees and 10 degrees static pitch angle. The last stage involves estimating the LCOE for a 10MW Floating Offshore Wind Farm (FOWF) – 2 platforms for each optimal design selected with each static pitch angle constraint. For this preliminary assessment, the hydrostatic analysis is sufficient to estimate the mass of the optimal platform. The described methodological process is shown in Figure *1*. The schematic configuration of the FOWF estimated is shown in Fig2abc.

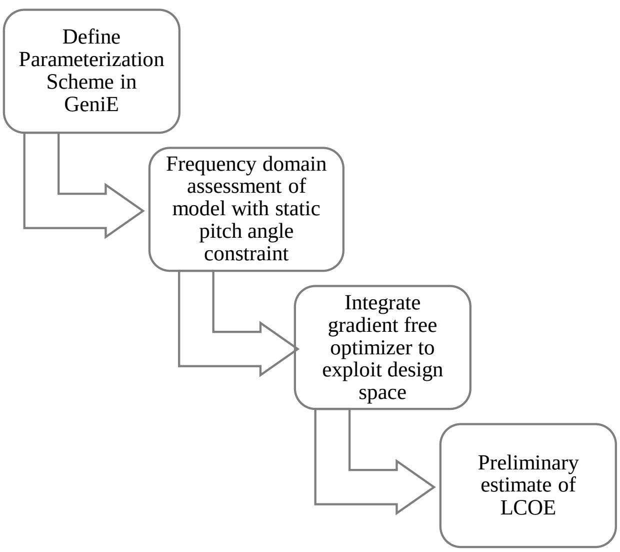

Figure 1: Platform shape optimization and LCOE estimation of a FOWF

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3.2. Hydrostatics for mass estimation

The design and optimization of any type pf floating offshore wind system must satisfy the stability requirement. This needs a detailed hydrostatic assessment to ensure the floater provides enough buoyancy to support the turbine, tower and mooring lines while also restraining the heave, roll and pitch motions within allowable limits. The hydrostatic equations in pitch for the available stability mechanisms based on ballast, waterplane area and mooring systems are represented with the buoyancy equations and the restoring equation highlighted in Eqns. (5) and (6) respectively.

$$M_{Total} = \rho_w V \tag{5}$$

$$(\rho_w g I_y + F_b z_{CB} - F_w z_{CG} + C_{55,moor})\theta = F_T(z_{hub} - z_{CB}) \tag{6}$$

Where M_{Total} is the total mass of the FOWT system which consists of the substructure components (platform, mooring lines, ballast and anchors) and the superstructure components (tower and turbine), ρ_w is the water density and V is the volume of the displaced fluid, g is the acceleration due to gravity, I_y is the second moment of area of the initial waterplane area (within the approximation of small angle of inclination, the waterplane area remains constant) with regards to the X axis, F_b is the buoyancy force, Z_{CB} is the center of buoyancy (point at which the resultant buoyancy forces on the body acts), F_w is the system's weight force, z_{CG} is the system's center of gravity (Point at which the total systems weight $C_{55,moor}$ is the contribution of the mooring stiffness to the pitch stiffness, θ is the pitch inclination angle, F_T is the thrust force from the wind speed and z_{hub} is the hub height.
The expressions on the left-hand side of Eqn. (6) highlights the stability mechanisms within the FOWT system. The first expressions highlight the water plane stability mechanism, the second and third expression represents the ballast stability mechanism (Ioannou et al., 2020) while the fourth expression represents the mooring stability mechanism (Collu and Borg, 2016). A schematic highlighting all the forces and reference points mentioned for a representative spar FOWT system is shown in Fig*ure 2*.

3.3. Floatability and maximum inclination angle requirements

The floatability requirement is satisfied with Eqn. (5) which highlights the equality of the buoyancy force of the platform and the total mass of the substructure. With regards to the maximum angle of inclination, it is equivalent to imposing a minimum pitch stiffness derived from Eqn. (6) and highlighted in Eqn.(7) (Ioannou et al., 2020).

$$\frac{F_T(z_{hub} - z_{CB})}{(\rho_w g I_y + F_b z_{CB} - F_w z_{CG} + C_{55,moor})} \leq \theta_{max} \tag{7}$$

Where $(\rho_w g I_y + F_b z_{CB} - F_w z_{CG} + C_{55,moor})$ is the minimum total stiffness resulting in the maximum angle of inclination.

The expression in Eqn. (7) is very important in the early stages of design as a constraint for exploring the design space based on the allowable static pitch angle required for the FOWT system prior to conducting detailed analysis on the design.

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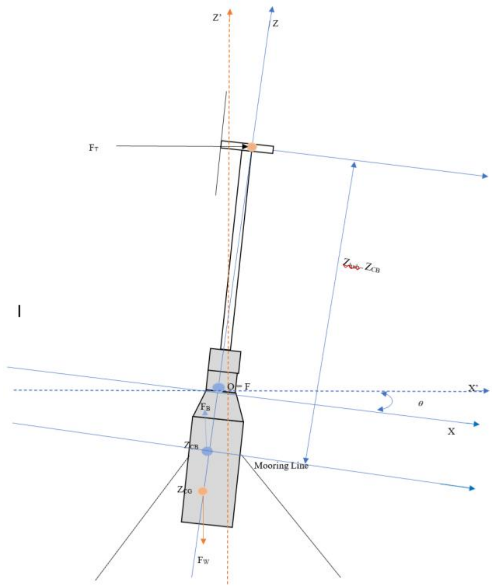

Figure 2: Sketch of forces and reference points of a representative spar FOWT.

4. Techno-economic analysis, results and discussion

4.1. Overview

As highlighted in section 2, the LCOE is an essential financial parameter for assessing any energy generating project – wind farms inclusive as it is the ratio of the costs of an energy project to the electricity production over its lifetime. A host of factors can reduce the LCOE amongst which are listed below and detailed in Markus Lerch (2019).

- CAPEX reduction due to optimization
- Cost reduction potential through industrialization
- Cost reduction due to economies of scale
- Cost reduction due to discount rate.

Exploring the four factors listed above will ensure the commercial viability of the FOWT concept and bring the LCOE cost for FOWT concepts down to what obtains in the fixed bottom offshore wind turbines. For the purpose of this study, the preliminary techno-economic assessment is based on the CAPEX reduction due to optimization. The CAPEX cost this study influences is the cost of the platform which makes up about 30% of the total CAPEX cost of a floating wind project (Shields et al., 2021). The shape of the platform is geometrically optimized with the objective of reducing the mass of steel used which invariably should reduce the cost of steel. The technicality involved in the shape optimization is highlighted in section 4.2. The effect of mass reduction of steel for platform development is highlighted in section 4.3.

4.2. Technical Assessment

A high-level numerical simulation from a reference FOWT model (NREL OC3 spar platform) is assessed within a multidisciplinary design analysis and optimization framework to explore, exploit and select optimal design variants from the design space. The optimal design variants are then assessed with a preliminary economic feasibility study using a representative wind farm with material and cost assumptions from literature.

4.2.1. Reference Design

The reference design for this study is the OC3 spar platform supporting a conventional three-bladed, upwind variable-speed 5MW baseline horizontal axis wind turbine. The geometric and structural properties of the OC3 spar platform is highlighted in Table 3 and Table 4 respectively.

Table 3: Geometric parameters for OC3 Spar (Jonkman, 2010)

Parameters	**Dimensions (m)**
Top cylinder diameter	6.5
Height of top cylinder	4
Diameter at top of transition area	6.5
Diameter at base of transition area	9.4
Height of transition area	8
Bottom cylinder diameter	9.4
Bottom cylinder height	108
Distance of platform keel to still water level (Draft)	120

Table 4: Floating platform structural properties (Jonkman, 2010)

Parameters	**Values per Literature**
Platform mass (including ballast) - (kg)	7,466,330
Center of mass below Sea water level (SWL) – (m)	89.9155
Platform roll inertia- about center of mass – kgm^2	4,229,230,000
Platform pitch inertia- about center of mass – kgm^2	4,229,230,000
Platform yaw inertia- about central axis – kgm^2	164,230,000

4.2.2. Technical Selection of optimal variants within an MDAO framework

This study assesses a high-level hydrostatic study of a spar substructure discipline in a FOWT system. The design is conducted using the B-Spline shape parameterization technique to enable the exploration of a rich design space for optimal variant selection. B-spline is utilized due to its capability to alter the shape of the design locally when the control point values are changed. This gives the designer an effective control of the shape with the capability of exploring a richer design space. A metaheuristic pattern search optimization algorithm is used to select the optimal design satisfying the specified objective function and constraints provided within the optimization framework. The specified objective function in this study is minimizing the mass of the platform. This objective is estimated by conducting a hydrostatic analysis using DNV suite – GeniE and WADAM stability software. The process involved in the technical selection within the MDAO framework are detailed herein:

4.2.2.1. B-Spline design of Spar.

B-spline parameterization technique is selected for this study due to its many suitable properties amongst which are: it has local propagation property for effective control of shape of a design, its capability to explore large and rich design space, its invariance property under affine transformation and its quick simulation turnaround time.

Samareh (2001) showed that several low-degree Bezier segments can be used to represent a complex curve rather than using a high degree Bezier curve. The resulting composite curve from this low degree representation is a spline more accurately referred to as B-spline. A multisegmented B-spline is described in Eq. (8) (Samareh, 2001).

$$\bar{R}_{(U)} = \sum_{i=1}^{n} \bar{\boldsymbol{P}}_i N_{i,p}(u) \quad (8)$$

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Where $\bar{P}_i$ are the B-spline control points, p is the order/degree, $N_{i,p}(u)$ is the *I th* B-spline basis function of degree p. B-spline form can represent complex curves more efficiently and accurately than other curve representation like the Bezier, cubic Hermite spline, cubic spline and polycurves.

This multi-segmented curve in Eqn. (8) is used in modelling the curve defining surface of the spar platform used for the hydrostatic analysis of the FOWT system's substructure. Modelling was conducted with the B-spline tool in DNV Sesam GeniE software.

4.2.2.2. Hydrostatics and Optimization.

The high-level hydrostatic and optimization assessment in this study is conducted synchronously to obtain the optimal design. The hydrostatic assessment is based on the stability Eqns. (5) and (6) highlighted in section 3 in which the buoyancy force of the spar from the volume of liquid it displaces is equivalent to the total mass of the system while also considering the contribution of the stability mechanisms. Eqn. (6) is also evolved into Eqn. (7) which is an assessment of the maximum static pitch angle of the system. This is an important parameter which is used as a constraint in the optimization assessment of the optimal design variant.

The optimization algorithm used in this study is the pattern search method. Pattern search is a relatively inexpensive but rather effective optimization technique (Findler et al., 1987). It is based on the heuristic of repeating the best search direction in exploratory moves as long as the response function improves. It also has the capability adequately dispersed and appropriate number of starting points – multi-start ability to overcome noise and the danger of getting trapped in local optima.

The optimization problem for this study is represented with the Eqn. (9).

$$\min_{x \in \mathbb{R}} J(x)$$

$$subject\ to \begin{cases} xlower \leq x \leq xupper \\ h_i(x) = 0; i = 1\ to\ m \\ g_i(x) \leq 0; j = 1\ to\ p \end{cases} \tag{9}$$

Where x is a k-dimensional vector of design variables with lower and upper bounds, $J(x)$ is a single objective function, m is the number of equality constraints and p is the number of inequality constraints. The main objective for this optimization study is to minimize the mass of steel and invariantly, cost of the steel material used for the spa platform. The two main constraints considered for all the parametric free-form curves considered in this study are highlighted below:

1. Three maximum static pitch angles of inclination of the system set at 5 degrees, 7 degrees and 10 degrees respectively.
2. A positive ballast mass to ensure floatability requirement.

The control points on the B-spline curve in Sesam GeniE are interfaced with the optimization algorithm with python codes to ensure that design variables within the specified boundary conditions in the optimizer are passed into Sesam Genie Java Script without human intervention. This ensure the static pitch angle constraint highlighted in Eqn. (7) is coded into the optimization framework to integrate the hydrostatic analysis and the optimization algorithm for feasible optimal design selection.

The optimal design variables obtained for the 12 segmented spar with 13 control points and a modelled OC3 spar with its dimension from literature are highlighted in Table 5 . The optimal variants in Table 5 based on the static pitch constraints of 5 degrees, 7 degrees and 10 degrees are named case A, case B and case C respectively. The model visuals from Sesam GeniE are presented in Figure 3 and it can be seen that the each of the three optimized spars shows distinct geometric changes in comparison to the OC3 spar.

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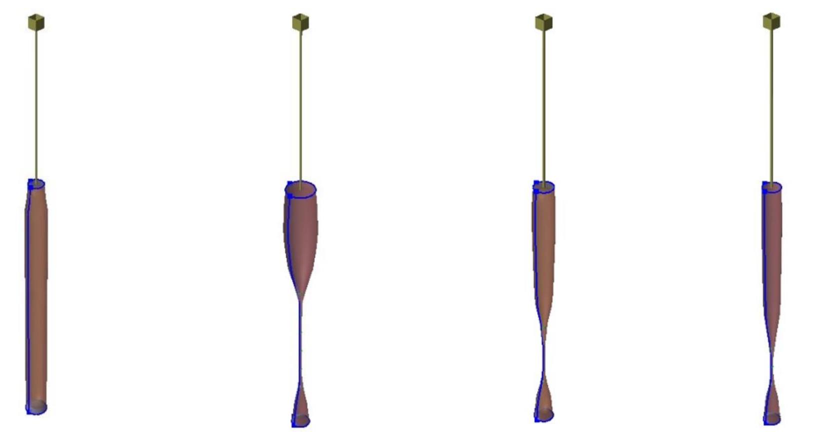
Table 5. Design data for selected models and OC3 spar

OC3 (m)	Height	0	4	12	30	40	50	60	70	80	90	100	110	120
	Radius	3.25	3.25	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Case A (m)	Height	0	10	20	30	40	50	60	70	80	90	100	110	120
	Radius	6.91	6.86	7.22	6.04	5.00	0.55	0.50	0.50	0.50	0.50	0.53	3.38	3.92
Case B (m)	Height	0	10	20	30	40	50	60	70	80	90	100	110	120
	Radius	4.13	4.92	4.69	4.42	4.18	3.95	3.48	0.72	0.50	0.50	0.50	4.05	4.18
Case C (m)	Height	0	10	20	30	40	50	60	70	80	90	100	110	120
	Radius	3.72	4.13	4.01	3.89	3.77	3.65	3.54	2.64	0.50	0.50	0.50	3.65	3.71



OC3 Spar **Case A** **Case B** **Case C**

Figure 3: Optimal models from pattern search optimization algorithm and OC3 spar

For each case in Figure 3, the models are constructed using B-Spline curves, and a material density of 7850 kg/m3 (Steel) is used. A wall thickness of 0.0418 m is determined by utilizing the ratio of steel mass to buoyancy mass of 0.13, as highlighted in Anaya-Lara et al. (2018); Bachynski and Collu (2019). This wall thickness is selected based on the buoyancy mass of the NREL OC3 platform as a target value. Once the model is completed, Sesam Genie is utilized to generate finite element mesh (FEM) files to be used for their hydrostatic assessment.

Hydrodynamic analyses for the four cases are carried out using the Wave Analysis by Diffraction and Morison theory (Wadam) tool within the HydroD software of the DNV Sesam suite. The total mass of the system (including wind turbine, support platform, and ballast) and the system's center of gravity are determined through the Wadam analysis.

4.2.2.3. Optimal Variants and Hydrodynamic Response

This section focuses on the inherent design characteristics of the model, specifically the system's responses. These responses are assessed with WADAM within DNV Sesam HydroD software. The assessment was conducted in a wave height of 2 meters (1 meter wave amplitude) and a time period of 5 seconds to 200 seconds in steps of 1 second. These responses are evaluated for all three cases and are compared to the OC3 NREL 5MW FOWT system. Figure 4 shows the Response Amplitude Operators (RAOs) in surge, heave, pitch, and horizontal nacelle displacement motion for the three design variant cases and the OC3 spar-buoy. The RAOs in Figure 4 shows the frequencies of the peak motion response of the system. This is a very important tool for subsequent design of the system in different environmental conditions to ensure the system's response avoid these peak motion response frequencies.

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From an operational perspective, case C is projected to display the highest motion across all considered degrees of freedom (DOFs), except for the heave DOF where case A exhibits the greatest motion. In addition, the peak frequencies of the platform variants are all outside the first order wave excitation frequency range of 0.05Hz to 0.2Hz (5-25 Seconds) in the surge, pitch and nacelle displacement responses. However, all the variants peak periods are slightly within the first order wave excitation frequency range in the Heave degree of freedom. This observation necessitates structural assessment for future work. While increasing the static pitch angle can potentially reduce the steel material used for manufacturing, it can have consequences for the fatigue loads in the tower as detailed in Souza and Bachynski-Polić (2022). The authors conducted fatigue assessment on three 20MW spar FOWTs with static pitch angles of 6, 8 and 10 degrees. They concluded that for a 20MW FOWT, the largest fatigue damage at the still waterline was observed on the platform with 10 degrees static pitch angle. However, for the tower, the design with the 6 degrees static pitch angle resulted in increased fatigue damage.

In addition, to the need for structural assessment, manufacturing can also be a challenge. However, technologies like Metal 3D printing and concrete slip-forming can potentially resolve manufacturing issues of the bespoke shaped spar.

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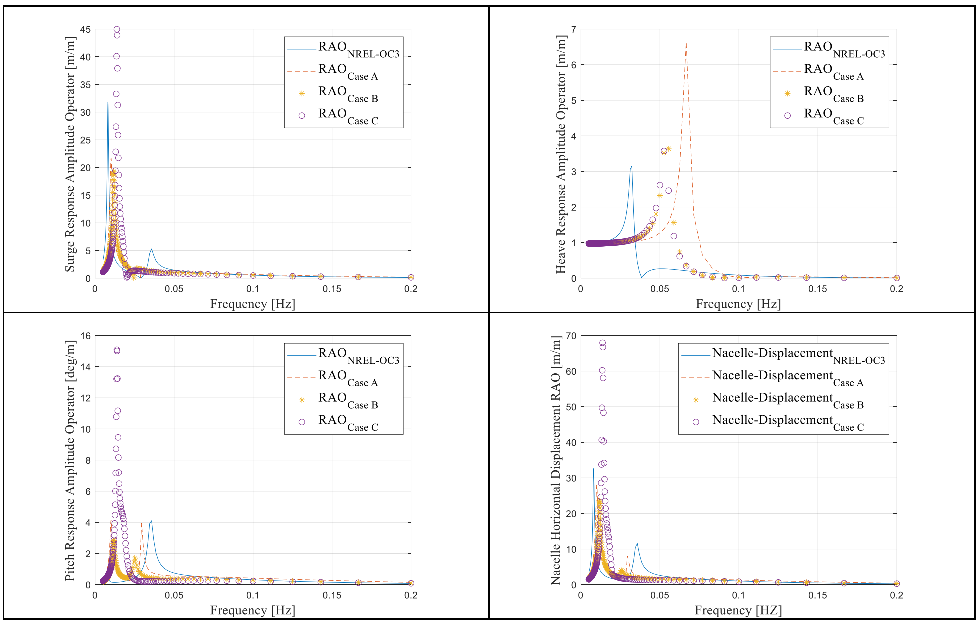

Fig*ure* 4. Surge, Heave, Pitch and Nacelle displacement RAO

4.3. Economic Feasibility study

Some of the financial parameters used in assessing various projects in literature are highlighted in section 2. However, for the purpose of this study, the financial parameter chosen to assess the economic feasibility of the project to assess in this study is the LCOE.

The wind farm site used to assess the LCOE for this study is the Hywind wind park with a hypothetical water depth of 320m. It is essential to utilize measured data for the annual energy production (AEP) estimation of the project site. For this article, the AEP estimate of the Hywind site is taken from Saenz-Aguirre et al. (2022) where they have used the conventional Weibull distribution based calculation for the estimated energy generation at the site during a studied climate period between 1991 and 2020. Their calculations are summarized as a fitting of the shape parameter ‘k’ and scale parameter ‘c’ related to the Weibull distribution to match the 30-year wind speed

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data, and a latter implementation of the power curve of the FOWT on the fitted histogram to estimate its energy production. Based on the work done in Saenz-Aguirre et al. (2022), the AEP value for the study is 139.8 GWh. Based on the AEP value of 23.2 GWh for a FOWT, the capacity factor worked out from a name-plate wind farm of 30 MW is 52.97%. The capacity factor of 52.97% estimated from this study is much more conservative than the AEP capacity factor of 65% recorded for the HyWind Scotland floating wind farm site in Aldersey-Williams et al. (2020).

4.3.1. CAPEX OPEX and DECEX Estimation

Due to the large number of cost components and frequent difficulty and complexity of the FOWT system, the Capital Expenditure (CAPEX) for a Floating offshore wind farm (FOWF) is challenging to quantify. According to studies done like the Carbon Trust in 2015 (James, 2015) and projects completed and some currently under construction like HyWind Scotland, Kincardine Offshore wind farm, Windfloat Atlantic and HyWind Tampen, the main cost items are related to turbines, towers, platforms, moorings, anchors and the balance of the system, amongst which are the cost of installation of the components that makes up the holistic system, cost of the electrical grid and connections to shore.

As highlighted in Maienza et al. (2020), CAPEX contributions are mostly determined analytically and /or as a function of the wind farm's installed power. The costs for components and installations are taken into account separately, in part because the former is moderately dependent on the site of installation while the latter heavily depends on the site of installation. The CAPEX is the largest cost and it includes all investment costs to be faced before the commercial operation date (Maienza et al., 2022). The contributions to OPEX are also calculated analytically and /or as a function of the installed power of the wind farm while contributions to DECEX (decommissioning and clearance) are calculated as a percentage of the installation procedures cost (Maienza et al., 2020).

For this study, the CAPEX costs are going to be taken from literature and in cases where they are not available, assumptions are made. The percentage split of a spar FOWF's CAPEX, OPEX and DECEX for this study is 77%, 19% and 4% respectively as specified for a spar FOWF in Maienza et al. (2020).

The masses of the spar platform and corresponding estimated costs based on the platforms masses is shown in Table 6. The mass of the optimal design variant tends to reduce as the static pitch angle is increased as highlighted in Table 6 where the static pitch angle 5 degrees – Case A, 7 degrees – Case B and 10 degrees – Case C yielded reduced platform masses respectively. The reduction in the platform's mass based on the design and optimization constraints leads to a reduction in total cost of the wind farm as subsequently discussed in this section.

The estimation of the costs and assumptions made based on references from literature are presented in Table 7 while the total cost estimate for the hypothetical 30MW Hywind site based on the variation in cost of the platform due to the static pitch angles are presented in Table 8 to Table 11. Similarly, a sensitivity study is conducted for a larger FOWF site – 60 MW farm to assess the total cost estimate for the OC3 platform and the optimal design variants based on the selected constraints and data presented in Table 14 to Table 17 in Appendix A.

A clear trend of results from Table 8 to Table 11 shows that the Hywind farm with the OC3 platform has the largest total cost and this is partly due to the observation made in Leimeister et al. (2020b) that the OC3 spar floater is highly over-dimensioned for safety reason; hence, more material cost for the platform, which impacts the total cost of the wind farm as highlighted in Table 8. The total cost estimates of the wind farms in Table 9 to Table 11 shows the static pitch angle constraint used within the design and optimization framework highlighted in section 4.2 has the capability of reducing or increasing the mass of the optimal design variant. The increase or decrease in the mass of the optimal platform's design variant is proportional to an increase or decrease in the cost of steel material for the platform and a cumulative effect of the cost increase or decrease is seen in a sample windfarm as highlighted in Table 8 to Table 11. The same observation is made on a larger FOWF i.e., the larger the static pitch angle, the smaller the mass of the platform and hence the total cost of material which significantly contributes to the total cost of the farm. The impact of the static pitch angle design constraint on the LCOE of the farm is discussed in section 4.3.2.

Table 6. Platform mass and corresponding cost estimate

Platform Type	**Mass (Tonnes)**	**Cost- Steel (GBP)**
OC3	1069.86	1.50E+06
Case A	811.29	1.14E+06
Case B	781.84	1.09E+06
Case C	736.55	1.03E+06

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Table 7. Assumptions for hypothetical Hywind wind farm (30 MW – 6 Turbines)

CAPEX Components	Assumption	Unit	Reference
Turbine	1.3	[million GBP/MW]	(Ghigo et al., 2020)
Platform	Material cost.f	[million GBP]	(Maienza et al., 2020; Ghigo et al., 2020)
Anchors	80000/ Anchor	[GBP]	(James, 2015)
Moorings	500	[GBP/m]	(Myhr et al., 2014)
Export marine cables	400	[GBP/m]	(Ghigo et al., 2020)
Array marine cables	600	[GBP/m]	(Ghigo et al., 2020; Maienza et al., 2020)
Installation	1.5	[m GBP/MW]	(James, 2015)
Offshore electrical substation	3312000	[million GBP]	Scaled from Maienza et al. (2020)
Onshore electrical substation	1653600	[million GBP]	Scaled from Maienza et al. (2020)
OPEX			
Operating Expenditure	19% of Total Expenditure		(Maienza et al., 2020)
DECEX			
Decommissioning and clearing	4% of Total Expenditure		(Maienza et al., 2020)

Table 8. Total cost for hypothetical Hywind wind farm (30 MW – 6 Turbines) – OC3 Platform

CAPEX Estimate (GBP)	171063720
OPEX Estimate (GBP)	42210528.31
DECEX Estimate (GBP)	8886427.013
Total Cost (GBP)	222160675.3

Table 9. Total cost for hypothetical Hywind wind farm (30 MW – 6 Turbines) – 5^0 static pitch angle platform - CaseA

CAPEX Estimate (GBP)	160203780
OPEX Estimate (GBP)	39530802.86
DECEX Estimate (GBP)	8322274.286
Total Cost (GBP)	208056857.1

Table 10. Total cost for hypothetical Hywind wind farm (30 MW – 6 Turbines) – 7^0 static pitch angle platform - CaseB

CAPEX Estimate (GBP)	158966880
OPEX Estimate (GBP)	39225593.77
DECEX Estimate (GBP)	8258019.74
Total Cost (GBP)	206450493.5

Table 11. Total cost for hypothetical Hywind wind farm (30 MW – 6 Turbines) – 10^0 static pitch angle platform - CaseC

CAPEX Estimate (GBP)	157,084,700
OPEX Estimate (GBP)	38,756,225
DECEX Estimate (GBP)	8,159,205
Total Cost (GBP)	203,980,130

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4.3.2. LCOE Estimation

The levelized cost of energy (LCOE) calculation is the ratio of the net present value of total cost to the net present value of electricity generation. It is a method used to obtain the cost of one unit energy produced and is typically applied to compare the cost competitiveness of different power generation technologies and concepts (Markus Lerch, 2019). LCOE's results are based on the discounted values of CAPEX, OPEX and DECEX before being distributed relative to the energy generation (Myhr et al., 2014). LCOE returns the constant real energy price required to generate the return equal to the discount rate used over the full life of the project (Aldersey-Williams and Rubert, 2019).

The discount rate is a critical criterion in estimating the LCOE as the higher the discount rate, the larger the range of LCOE in the future and the lower the discount rate, the lower the LCOE in the future(Aldersey-Williams and Rubert, 2019). The discount rate typically presents values in the range of 8 % - 12 % for offshore wind investments (Martinez and Iglesias, 2022). For conservative purpose, this study is adopting a discount rate of 10% and the lifetime of the project is set to be 20 years.

For the purpose of this study, the CAPEX values are distributed as per the values in Table 8 to Table 11 for the 30 MW demonstration wind farm for the four varying optimal platform designs considered and in Table 14 to Table 17 in Appendix A for the 60 MW demonstration project considered for the different optimal platform designs considered. The OPEX costs are assumed to be evenly distributed over the 20 years of operation. The DECEX cost is assumed to be a one-off distribution process after the operation phase.

The mass of the designed platform tends to vary based on the design constraint specified as shown in Figure 5 and highlighted in Table 6 where the mass of the optimal platform variants reduces as the static pitch angle constraint is increased. The cumulative effect of the reduction in mass due to the design constraint on the total cost of the farm is discussed in section 4.3.1. However, the cumulative effect of the reduction in mass due to design constraint on the platform cost for 30 MW farm and 60 MW farm are highlighted in Table 12 and shown in Figure 6 and Figure 8 respectively. Table 12 shows that for both the 30 MW and 60 MW FOWFs, the total mass of the platforms used in both sides reduces as the static pitch angles are increased from 5 degrees to 7 degrees and 10 degrees respectively for both farms. This reduction in the mass of material – Steel used in manufacturing the designed platforms also culminates in the reduction in the cost of the materials used in manufacturing the platforms as detailed in Table 12 for both FOWFs. This occurrence (reduction in total mass of platform due to increase in static pitch angle) is also shown in Figure 6 and Figure 8 for the 30 MW and 60 MW FOWFs respectively.

The LCOE for the 30 MW site and the 60 MW site is developed based on the site's total costs for each optimal design highlighted in section 4.3.1 and Appendix A respectively. This study investigates the LCOE result from two fronts highlighted below:

1. The impact of the design constraint on the estimated LCOE of the FOWF.
2. The effect of scaling up a FOWF on the LCOE of the project.

The impact of the design constraint – mainly the static pitch angle on the LCOE is demonstrated on a 30 MW FOWF as highlighted in Table 13 and shown in Figure 7 where the LCOE for the 30 MW OC3 FOWF is the largest with a value of 197 £/MWh.

The LCOE values for the 30 MW FOWFs based on static pitch constraints of 5 degrees, 7 degrees and 10 degrees are 185 £/MWh, 183 £/MWh and 181 £/MWh respectively. The reduction in the LCOE is due to a cumulative effect of the mass reduction from optimizing a single platform on the six platforms carrying 5 MW NREL turbines that make up the floating wind farm. Although, the difference is not very significant, this result shows that the design optimization of a FOWT platform which is a component of the FOWT system contributes to the reduction in the LCOE of a FOWF.

The study on the effect of scaling up the 30 MW FOWF is conducted by doubling its capacity to 60 MW. The LCOE result for the 60 MW FOWF is highlighted in Table 13 and shown in Figure *9*. Just like the 30 MW FOWF, the LCOE for the 60 MW FOWF is the largest with a value of 185 £/MWh. The LCOE for the 60 MW OC3 platform FOWF is 6.23 % lower than the LCOE of the 30 MW OC3 platform FOWF.

The LCOE values for the 60 MW FOWFs based on static pitch constraints of 5 degrees, 7 degrees and 10 degrees are 176 £/MWh, 175 £/MWh and 173 £/MWh respectively. Table 13 shows the difference between 5 degrees, 7 degrees and 10 degrees static pitch angle constraint design variants of the 60 MW FOWF is 4.68 %, 4.72 % and 4.78 % lower than the corresponding optimal design variants for the 30 MW FOWF.

This significant reduction in LCOE values between the 60 MW FOWF and the 30 MW FOWF is a cumulative effect of the mass optimization of the platform as detailed in section 4.2 and the concept of scaling up the floating wind size (economies of scale). The concept of increasing the farm size is detailed in Myhr et al. (2014) where they showed that by increasing the number of turbines from 100 to 200 would lower the LCOE by approximately 10 % and that by increasing the turbines to 600 results in an LCOE reduction of up to 15 %. The reduction in the

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LCOE value for the optimal design variants between the 60 MW and 30 MW FOWFs considered in this study is less than 5 %. The 5 % reduction in LCOE value is not as significant as the 10 % to 15 % reduction in LCOE value recorded in Myhr et al. (2014). However, comparing the number of turbines - 200 it took Myhr et al. (2014) to attain 10 % reduction in LCOE value with the 12 turbines we have used to attain about 5 % reduction in LCOE value in this study, the approach adopted using platform mass optimization in combination with scaling up the floating wind farm is a much more effective approach to reducing the value of the LCOE in comparison to just scaling up the farm size or conducting platform mass optimization alone.

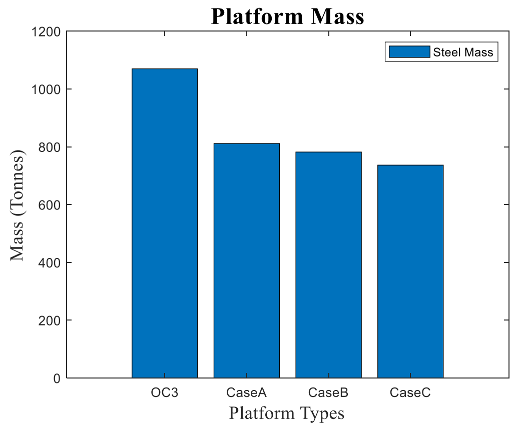

Figure 5: Mass of platform types

Table 12. Estimated total platform mass and total platform material cost for 30 MW and 60 MW FOWF

Design Variants	30 MW FOWF Platform mass (Tonnes)	60 MW FOWF Platform mass (Tonnes)	30 MW FOWF Platform cost (£)	60 MW FOWF Platform cost (£)
OC3 Design	6419.16	12838.32	8.99E+06	1.80E+07
Case A- 5^0 Static Pitch angle	4867.74	9735.48	6.81E+06	1.36E+07
Case B- 7^0 Static Pitch angle	4691.04	9382.08	6.57E+06	1.31E+07
Case C- 10^0 Static Pitch angle	4419.3	8838.6	6.19E+06	1.24E+07

Table 13. LCOE comparison for 30 MW and 60 MW FOWF with 10% discount rate

Design Variants	LCOE – 30 MW FOWF (£/MWh)	LCOE – 60 MW FOWF (£/MWh)	Percentage Difference (%)
OC3 Design	197	185	6.23
Case A- 5^0 Static Pitch angle	185	176	4.68
Case B- 7^0 Static Pitch angle	183	175	4.72
Case C- 10^0 Static Pitch angle	181	173	4.78

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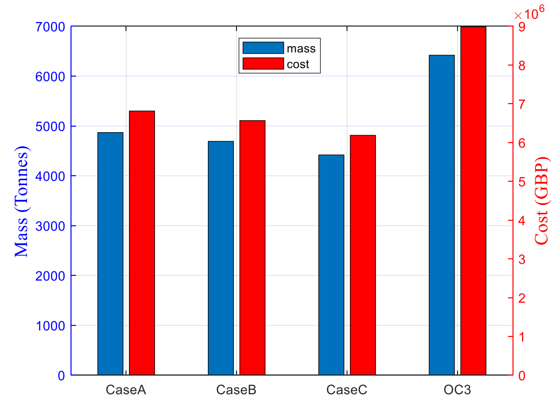

Figure 6: 30MW Farm Total Platform Mass and Total Platforms Material Cost

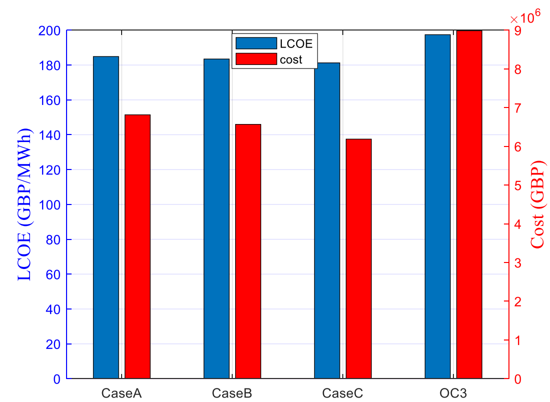

Figure 7: 30MW Farm LCOE and Total Platforms Steel Cost

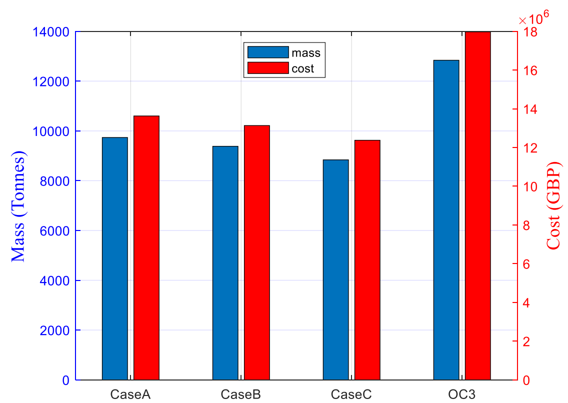

Figure 8: 60MW Farm Total Platform Mass and Total Platforms Material Cost

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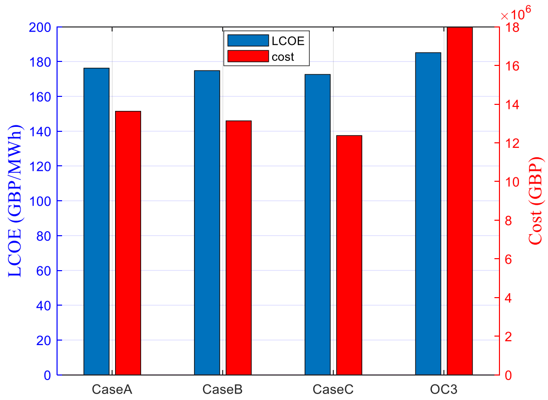

Figure 9: 60MW Farm LCOE and Total Platforms Steel Cost

5. Conclusion and recommendation

This study investigates the economic implication of use of bespoke geometric shape parameterization, design, analysis and optimization framework of spar platforms on a 30 MW floating wind farm and also the cumulative effect of this bespoke approach and economies of scale on a 60 MW floating wind farm. The bespoke technical assessment was conducted using the B-spline shape parameterization technique within an MDAO frame work to design analyze and optimize the concept. The shape parameterization and alteration of the design was conducted with Sesam Genie using B-Spline parameterization technique, analyses of the design was conducted using the hydrostatic capability of the Hydro D tools and optimization of the frame work was executed with the Pattern search (derivative free) optimization method. The main design constraint within the optimizer to facilitate the shape alteration within the MDAO framework is the static pitch angle. This study considered there static pitch angles of 5 degrees, 7 degrees and 10 degrees respectively and the OC3 NREL model. As highlighted in literature, the OC3 model is over-dimensioned for safety reasons; hence, it has the largest mass of all the optimal models considered. It is followed by the 5 degrees static pitch angled optimal model then the 7 degrees and 10 degrees static pitch angled optimal model respectively. This shows that as the static pitch angle is increased, the mass of the optimal platform model reduces. The mass reduction of the platform as a result of the constraints used in the design contributes to a reduction in material cost – a vital component of the total CAPEX cost for a FOWF.

The ratio of the net present value of total cost to the net present value of electricity generation which translates to the LCOE are the financial parameters used in assessing the different scenarios considered in this study (30 MW FOWFs and 60 MW FOWFs for OC3 NREL platforms, 5 degrees, 7 degrees and 10 degrees static pitch constrained platforms). The LCOE values for the 30 MW FOWFs based on the OC3 platform model and static pitch constraints platform models of 5 degrees, 7 degrees and 10 degrees are 197 £/MWh, 185 £/MWh, 183 £/MWh and 181 £/MWh respectively. On scaling up the farm size to 60 MW, the estimated LCOE values for the 30 MW FOWFs based on the OC3 platform model and static pitch constraints platform models of 5 degrees, 7 degrees and 10 degrees are 185 £/MWh, 176 £/MWh, 175 £/MWh and 173 £/MWh respectively - which is 6.23 %, 4.68 %, 4.72 % and 4.78 % lower than the corresponding optimal design variants for the 30 MW FOWF. This is due to a combination of design shape parameterization and optimization framework utilized in this study and economy of scale.

Recommended future work from this study is the structural assessment of the bespoke shaped optimized spar subject to different environmental conditions as it has been highlighted in some work that increasing the static pitch angle tends to have consequences for the fatigue life of the tower. Manufacturing of bespoke shaped spar is a constraint that must not be overlooked. However, ongoing research in the advancement of wire arc additive manufacturing (WAAM), particularly in the 3D printing of metals, and the development of concrete slip-forming techniques are expected to potentially provide valuable solutions for overcoming this constraint.

This preliminary study shows that in addition to other means of ensuring FOWT technology is as economically and technically viable as the fixed-bottom counterpart (platform upscaling, government subsidy, holistic system MDAO), geometric shape design and optimization of FOWT platform is an effective method that can be used in reducing the cost of floating wind farms.

6. Competing Interest

The contact author declared that none of the authors has any competing interests.

Author Contributions: Article structure and conceptualization, A.O, M.C and A.C; Design and shape alteration Software A.O; Data curation, A.O; Optimization framework, A.O, M.C and A.C; Analyses and Investigation, A.O and M.C; Writing – Original draft preparation, A.O; Writing, review and editing, M.C and A.C; Project Supervision, MC and AC.

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Appendix A

This appendix provides total estimated cost for the scaled up Hywind wind farm from 30 MW to 60 MW highlighting the variation in total costs due to the design constraint as discussed in section 4.

Table 14. Total cost for scaled up Hywind wind farm (60 MW – 12 Turbines) – OC3 Platform

CAPEX Estimate (GBP)	320,827,440
OPEX Estimate (GBP)	79,165,212.47
DECEX Estimate (GBP)	16,666,360.52
Total Cost (GBP)	416,659,013

Table 15. Total cost for scaled up Hywind wind farm (60 MW – 12 Turbines)– 5^0 static pitch angle platform - CaseA

CAPEX Estimate (GBP)	305,407,560
OPEX Estimate (GBP)	75,360,307.01
DECEX Estimate (GBP)	15,865,327.79
Total Cost (GBP)	396,633,194.8

Table 16. Total cost for scaled up Hywind wind farm (60 MW – 12 Turbines) – 7^0 static pitch angle platform - CaseB

CAPEX Estimate (GBP)	302,933,760
OPEX Estimate (GBP)	74,749,888.83
DECEX Estimate (GBP)	15,736,818.7
Total Cost (GBP)	393,420,467.5

Table 17. Total cost for scaled up Hywind wind farm (60 MW – 12 Turbines) – 10^0 static pitch angle platform - CaseC

CAPEX Estimate (GBP)	299,129,400
OPEX Estimate (GBP)	73,811,150.65
DECEX Estimate (GBP)	15,539,189.61
Total Cost (GBP)	388,479,740.3

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