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Cost Analysis and Design Optimization for Floating Offshore Wind Platforms

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Abstract

In recent years, in Europe, there has been a great development of renewable energies, in order to reduce the emission of pollutants, increase the transition to cleaner energy sources and the decarbonization process. Of all the most promising renewable energy sources, wind energy is one of the most widespread (about 20% of total electricity generation) and the related electricity production is growing steadily. While onshore wind is already well developed and the major potential sites are already occupied by pre-existing power plants, the same cannot be said for offshore wind. The potential of the offshore wind resource, characterized by winds with higher productivity and availability than onshore ones, would make it possible to cover enormous energy needs by limiting further land use. Currently, the largest offshore wind farms are located in the North Sea and the Baltic Sea and exist in fixed structures that exploit sites with shallow waters.

To take advantage of deeper water sites such as the Mediterranean Sea and the Atlantic Ocean, floating structures have been introduced by some and have become the focus of offshore wind technology development. These systems consist of a floating platform that supports the wind turbine and is tied to the seabed through a system of moorings and anchors. Furthermore, these plants require an electrical system, consisting of electrical substations and array marine cables, to transfer the electrical energy to the mainland. However, the considerable size of these structures which require large quantities of steel and concrete, the difficulty in construction, the need to employ large ships and the lack of standardized structures imply very

high investment and maintenance costs and have slightly slowed down the development of such technologies. Today, the LCOE is much higher than for fossil fuels or other energy sources, although cost reductions are expected in the coming years due to the development of new technologies and industrial innovations.

The purpose of this thesis is to present the current floating structures, such as spar-buoy, semisubmersible and tension leg platform, to describe their most relevant characteristics, advantages and disadvantages. A small focus will be on tension leg platforms, which today are the structures on which less investments and research have been made, but which still have interesting characteristics. Subsequently, a hydrostatic tool, which allows to analyze the main hydrostatic parameters for four structure concepts (a spar-buoy, a semisubmersible and two TLPs), will be illustrated. This tool, implemented through the genetic algorithm of Matlab, allows to carry out an optimization of the main dimensional parameters of the structure, in order to minimize the economic parameters relating to the cost of the materials used to build the platform, respecting the stability and buoyancy constraints imposed by Standards.

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Chapter 1

Introduction

State of offshore wind power

In recent years, despite the efforts made to promote the transition to renewable sources and the decarbonization of the energy sector, the values of CO2 and other greenhouse gas emissions have reached critical values as reported in the "Offshore Wind Outlook 2019" [1]. To date, two-thirds of global energy is produced using fossil fuels, although efforts to switch to renewable energy sources have increased at the expense of fossil fuels, which are responsible for the climate and environmental problems that are being faced. In 2018, the offshore wind power had a total capacity of 23 GW (80% in Europe), and it covers the 0.3 % of global electricity supply. In the last years, offshore wind technology has improved rapidly by enlarging the physical dimensions of the turbines and their respective rated power capacities. In 2018, the amount of new offshore wind capacity was of 4.3 GW and the installed capacity passed from 1 GW in 2010 to 23 GW in 2018. The annual deployment has increased by nearly 30% per year and it is the higher value among all the renewable sources of electricity except the solar photovoltaic (PV). Policy has played a pivotal role in this growth, influencing progress, including offshore wind in maritime planning, financial support, and grid development through regulatory efforts. Stable policies and favorable offshore wind resource conditions supported nearly 17 GW of offshore wind capacity additions in Europe between 2010 and 2018. The United Kingdom, Germany, Belgium, Netherlands and Denmark together added 2.7 GW of capacity in 2018 alone. In the last few years, China has invested heavily in this sector, becoming the world leader in this market. In fact, in 2018, China increased its offshore wind power capacity by 1.6 GW, more than any other country.

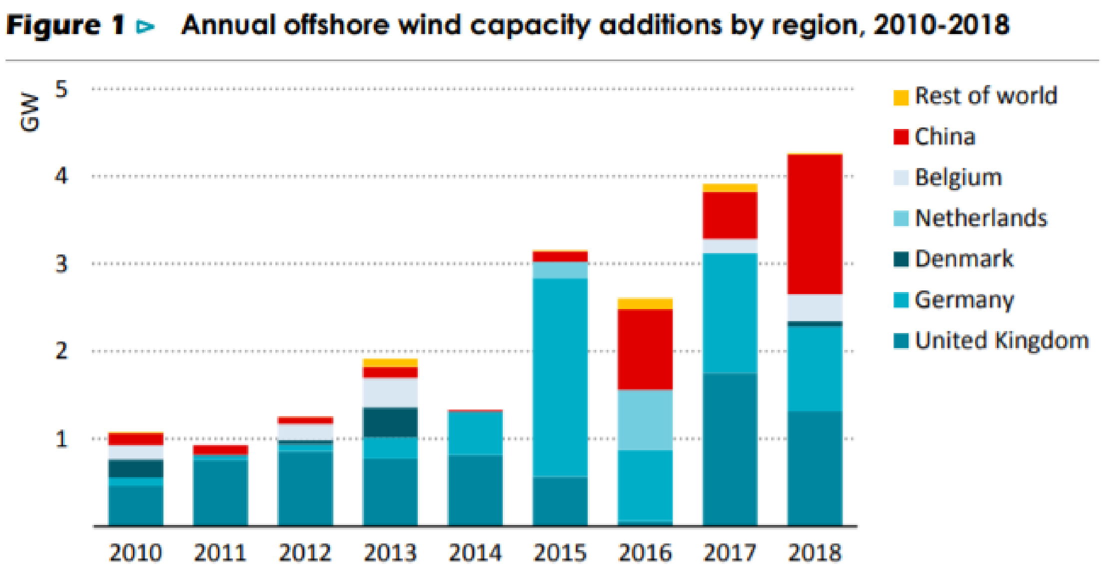
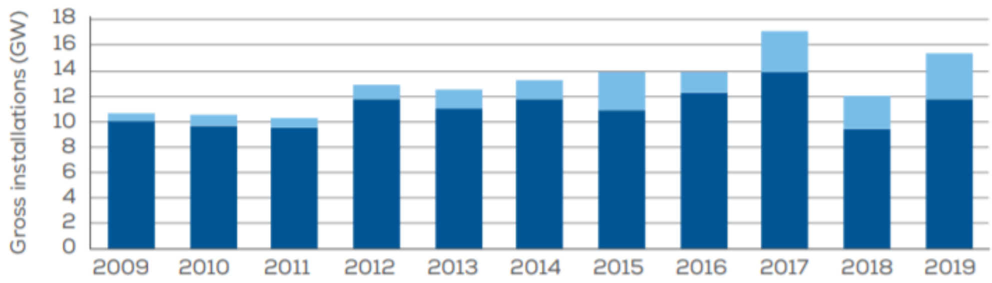


Figure 1.1 Annual increase in offshore wind capacity by region, 2010-2018 [1]

According to the IEA Wind Power [2] report of 2021, in 2020, offshore wind generation growth amounted to 25 TWh (+ 29%), reporting a 6 GW capacity increase, the same as in 2019. Furthermore, although offshore capacity additions remained concentrated in Europe and China in 2020, many new countries are expected to add their first large-scale offshore wind farms in the coming years (United States, Chinese Taipei and Japan above all).

State of offshore wind power in Europe

In 2019, the installed wind power capacity in Europe was 15.4 GW, of which 24% is offshore wind (3.6 GW). The total generated wind power amounts to 417 TWh and it corresponded to the 15% of the EU's electricity demand in 2019 [3]. In figure 1.2 the trend of new annual wind power capacity installations is reported showing that the trend is growing again after the 2017 peak.



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Offshore	0.6	0.9	0.8	1.2	1.5	1.5	3.0	1.6	3.2	2.7	3.6
Onshore	10.0	9.6	9.5	11.7	11.0	11.7	10.9	12.3	13.9	9.4	11.7
Total	**10.7**	**10.5**	**10.3**	**12.9**	**12.5**	**13.3**	**13.9**	**13.8**	**17.1**	**12.1**	**15.4**

Figure 1.2 New annual onshore and offshore wind capacity installations in Europe [3]

The new 3.6 GW offshore wind capacity in 2019 corresponds to 502 new offshore wind turbines connected to the grid. Hence, in 2019, Europe has a total installed offshore wind capacity of 22 GW that corresponds to 5047 wind turbines connected to the grid across 12 countries. The leader of the European countries in offshore wind is the UK with 1.76 GW of installed capacity, followed by Germany (1.1 GW), Denmark (374 MW), Belgium (370 MW) and Portugal (8 MW) [4]. In figure

1.3 it is reported the annual installed capacity by each country and the cumulative capacity.

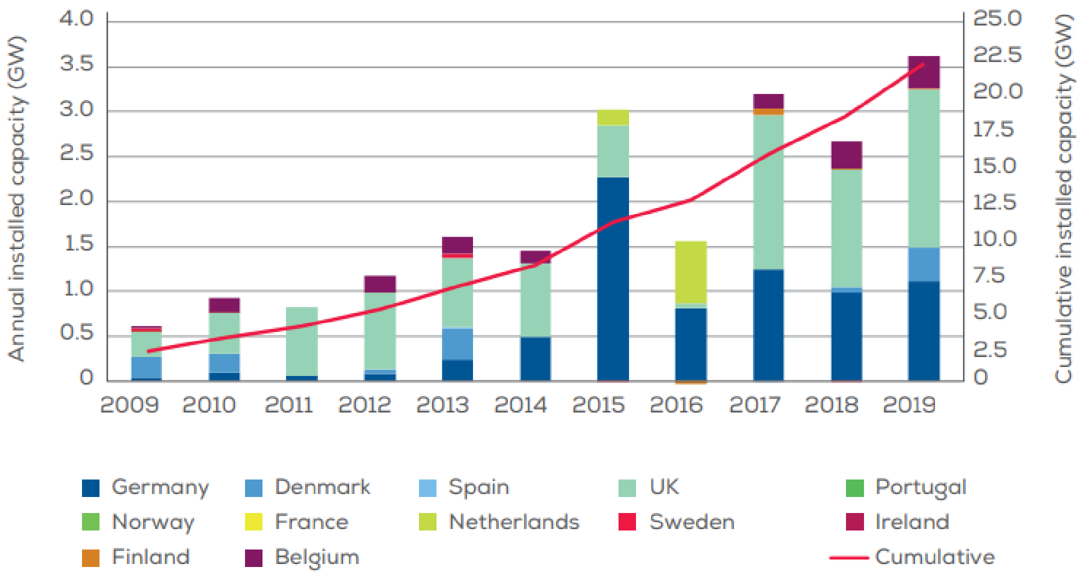


Figure 1.3 Annual offshore wind installation by country (left) and cumulative capacity (right) [4]

The offshore wind power will play an important role in the energy transition that the Europe is performing to reduce the level of carbonization and consequent CO2 emissions. The European Commission estimates that an installed capacity of between 230 and 450 GW could be needed by 2050, making it a crucial pillar in the energy mix together with onshore wind [5].

The main cause for this interest in the offshore wind resource from the European Commission is the abundance of sites that can be exploited in a feasible way. In fact, especially in the North Sea and Atlantic Ocean, where most of offshore turbines are installed, the European offshore wind resource is abundant, and the seabed is shallow enough to permit the installation of bottom fixed offshore turbine.

In figure 1.4 it is possible to evaluate the wind resource in Europe. In addition to northern Europe, also in the Mediterranean Sea there are location with good levels of productivity, for example in the South of France or along the Sicilian Channel. However, there are locations with goof level of productivity where the sea depth exceeds 100 m; in this case, it is necessary to exploit the floating structures.

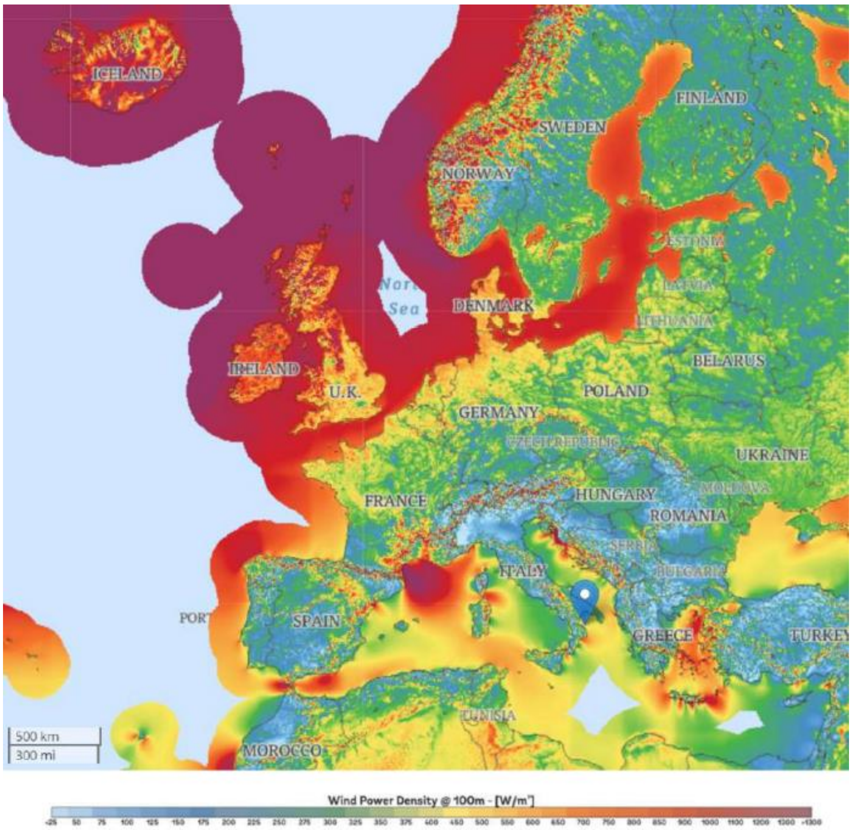


Figure 1.4 Wind Power density at 100 meters of altitude [6]

The floating offshore wind platforms are the most promising among the offshore structures, thanks to numerous features and benefits:

- They can be exploited in locations with a sea-depth larger than 100 m;

- They ease the turbine set-up and with time may offer a lower-cost alternative to bottom fixed structures.
- They are less invasive in an environmental point of view with respect to fixed platform.

The offshore wind power farm requires higher investment costs compared with the onshore one: the main cost drivers concern the construction of the substructure platform and the turbine, and their installation. The installation process may require the use of very large vessel; moreover, the laying phase of the anchors and moorings when present is an important cost driver, as well as the laying of electrical connections and substations. Furthermore, also the maintenance and control operations are more relevant since the marine environment can be very hostile, also the costs of these operations are higher than the ones required for onshore plant. Therefore, the current cost of offshore wind energy is higher than the onshore wind energy.

Moreover, a more accurate frame of the capital cost drivers is defined and reported in Figure 1.5. The turbine and platform construction costs constitute respectively the 30 ÷ 40 % and the 20 ÷ 25 % of the capital costs; obviously, these data are an average, so the cost of more complex platforms (floating structure with respect to bottom fixed) can constitute a higher percentage of the total cost. Offshore electrical connections, array and substation constitute the 20 ÷ 30 % of the capital cost and the cost of these transmission assets closely depends on the e regional regulations for connecting the project to the onshore grid. Finally, the installation makes up some 15 ÷ 20 % of the capital cost [1].

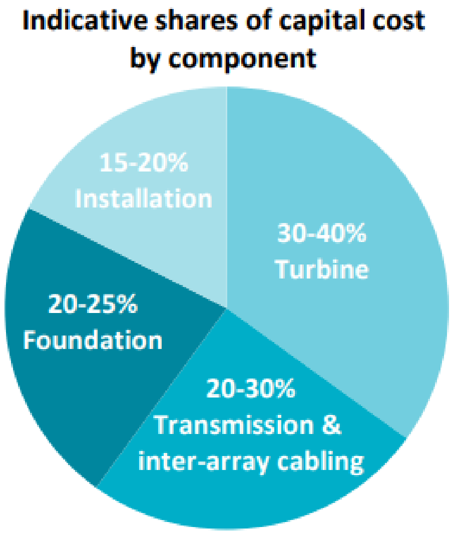


Figure 1.5 Indicative shares of capital cost for offshore wind projects in 2018 [1]

As stated in the Offshore Wind Outlook by IEA [1], for offshore wind projects completed in 2018, the Levelized Cost of Energy is equal to 140 $/MWh that is much higher than the average LCOE for onshore plant, evaluated at 60 $/MWh. However, the trend of the offshore wind LCOE is expected to decrease in the next year. These predictions are supported by the continuous improvements in the manufacturing of the turbine and by the increasing capacity factor of the new projects. In fact, larger turbines with greater swept area yield a greater capacity factor and so a greater output is possible to be obtained with the same resource. Moreover, a decrease in operation and maintenance costs as well as financial cost decrease, related to the declined project risk, may make the offshore wind LCOE drive down to reach the current onshore wind LCOE (60 $/MWh) in 2040.

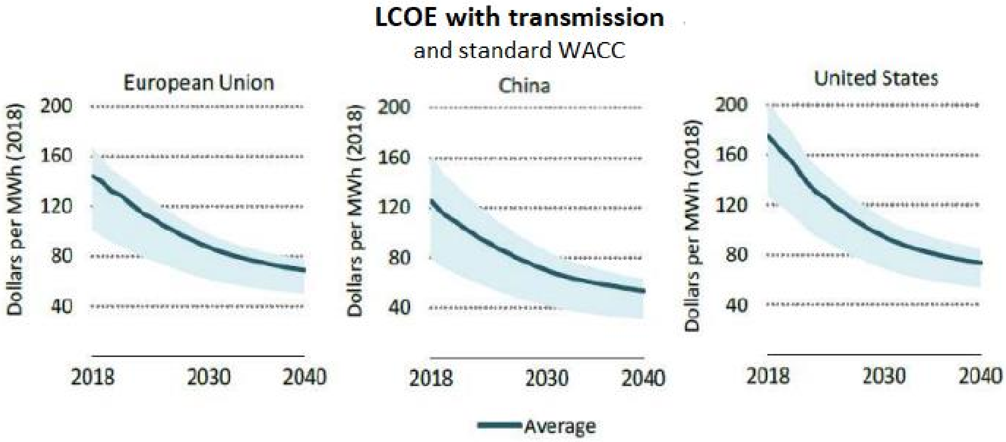


Figure 1.6 LCOE for new offshore wind project in Europe, China and USA in 2018-2040 period

Chapter 2

Offshore wind platform

This chapter deals with the offshore wind platform. First of all, the bottom fixed structures are described, which are currently the most widespread and used and are employed in shallow waters. Then, the floating structures and the main type of this technology are presented (spar-buoy, semisubmersible, tension leg platforms and barge), analyzing the relevant features and their advantages and disadvantages. Finally, a description of the projects already commercialized are presented.

2.1 Platform classification

The two main category of offshore wind turbine substructure are bottom fixed and floating type. Generally, the bottom fixed are employed in shallow or moderately deep waters, up to 50 meters depth, because they are more cost-effective.

For water depths greater than 60/70 meters, the bottom fixed design is no longer feasible, therefore the most suitable solution is that of floating turbines. The possibility of exploiting the wind resource at these depths allows to drastically increase the clean energy potential of the deeper Atlantic Ocean and North Sea, and of the Mediterranean Sea. At the moment the most used platforms in Europe are the bottom fixed, which also take advantage of the fact that many designs are inspired by the offshore oil industry such as gravity-based structures. The most employed bottom fixed design is the monopile one, because of its simplicity and cost-effectiveness. The distribution of the offshore wind foundation types in Europe is presented in Figure 2.1.

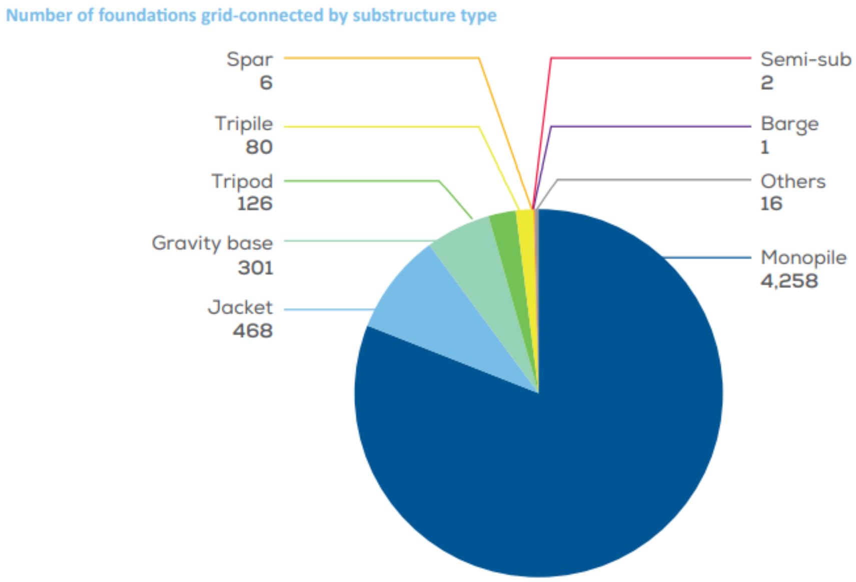


Figure 2.1 Distributions of offshore wind turbine substructures in Europe [4]

However, thanks to the enormous potential of the offshore resource, floating technology is closing the gap and is on the way to becoming a more economically competitive option. In fact, experimental and demonstration projects have already been developed and installed worldwide; in addition, the first commercial wind farms have been built, such as the Hywind Scotland project in the North Sea, and the WindFloat Atlantic project, in the Atlantic Ocean off the Portuguese coast.

2.2 Fixed Bottom Foundations

In this chapter a brief description of the most important and widespread bottom fixed structures is provided.

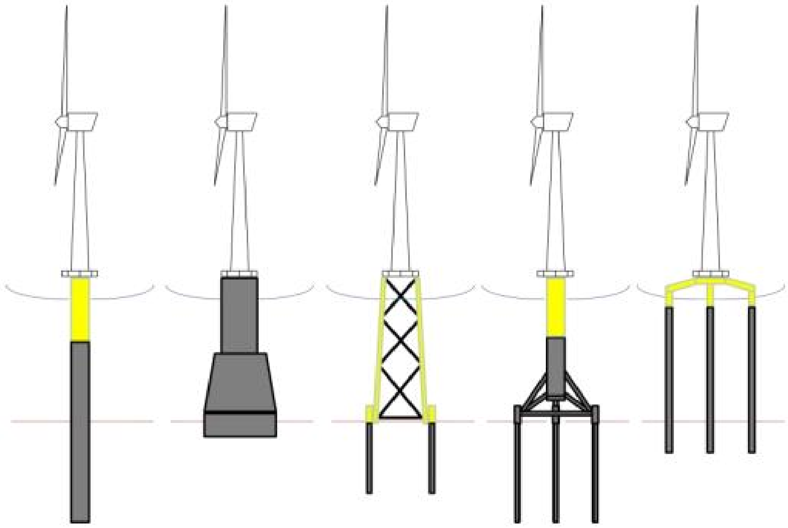


Figure 2.2 Types of bottom fixed concepts. From left to right: monopile, gravity-based, jacket, tripod and tripile [7].

Monopile foundation consists in a cylindrical steel tube piled into the seabed. This solution is the most dominant in the offshore wind market because of its simplicity. Its main feature is the capability to be adaptable to a wide range of seabed conditions, it is also considered the most cost-effective in case of depths up to 35 m but rarely is employed for water depth grater than 50 m [8].

Gravity based foundation are inspired from offshore oil industry, the main features of this technology are low environmental impact due to the absence in piling during installation and high durability and long lifetime [7].

Jacket foundation consists of a steel structure made of three or four legs connected by slender braces, the elements are all tubular, and the joints are welded. These structures are lightweight and stiff and have a better global load transmission compared to monopiles.

Alternative structures have been successively employed, even if in smaller numbers, such as tripod and tripile. For both jacket and monopile, it has been proved that their cost-effectiveness is strictly dependent on the water depths, these concepts are not convenient where the sea depth exceeds 50 meters.

2.3 Floating Foundations

A Floating wind turbine is a wind turbine mounted on a floating structure that allows to exploit the offshore wind resource and generate electric power in water depths where the bottom fixed concepts are not viable. The main difference between floating and bottom fixed foundations is that the floating concepts are moored, rather than fixed to the seabed. Although there are numerous concepts of floating structures, they can be classified into the following types:

- Spar-buoy;
- Semi-submersible;
- Barge;
- Tension leg platform (TLP).

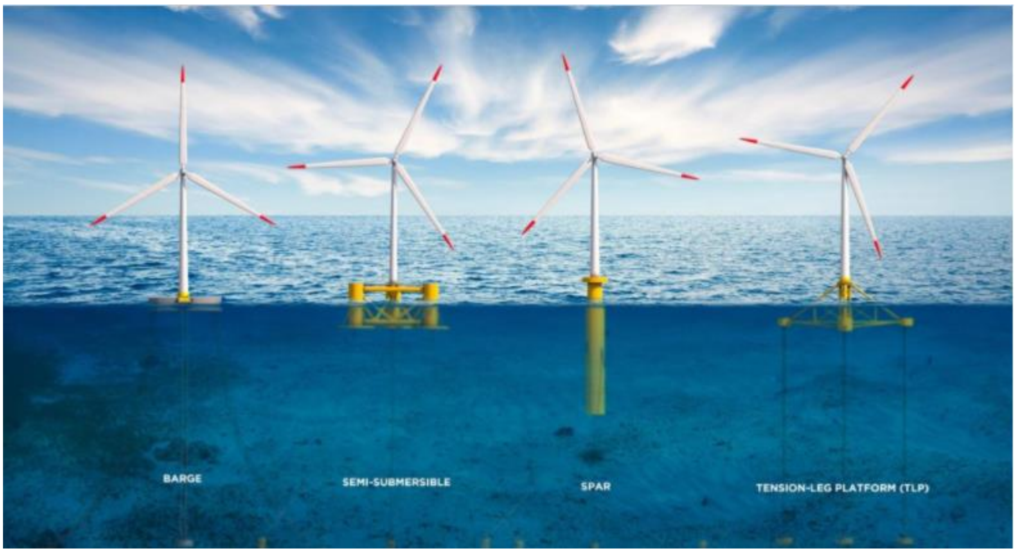


Figure 2.3 Floating structures classification

The strengths and weakness of each type of floating substructures are reported and analyzed in the following chapters. In fig 2.4 the European projects from 2007 to 2018 are reported and classified on the basis of the type of floating substructure. The majority of the projects are based on semi-submersible and spar buoy concepts. In particular, between 2017 and 2018, semi-submersible foundations had the upper hand, accounting for eight operational projects and 62% of the market, versus five spar projects (38%) [8]. Tension leg platform (TLP) projects are present from 2007 and 2009.

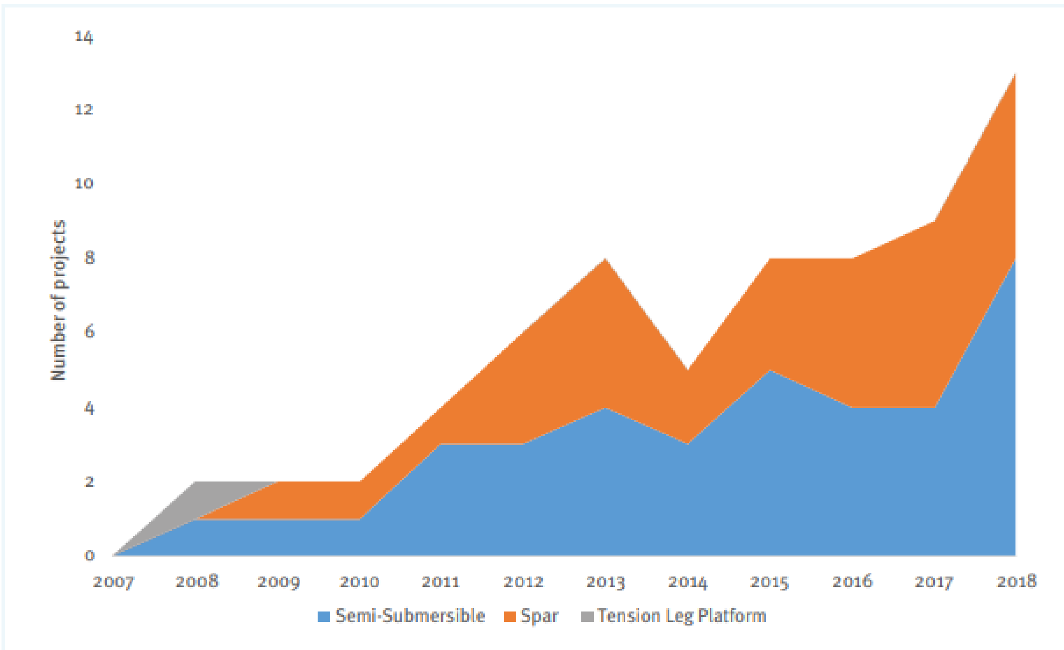


Figure 2.4 Cumulative number of European projects by structure concept type from 2007 to 2018 [8]

2.3.1 Spar-buoy concept

Spar-buoy design is based on a cylindrical body of steel and concrete, the structure is ballast-stabilized and the stability is gained from having the center of gravity lower in the water than the center of buoyancy. Thus, while the lower part is heavier (it is weighed down by ballast materials), the upper part is usually lighter, thereby raising the center of buoyancy [9].

Figure 2.5 Spar-buoy substructure concept

This type of floating foundations is usually characterized by low water plane area and are ballasted by means of concrete and sea water. Furthermore, the draft of these structures is quite large, and it provides high stability and minimizes heave motions. This technology is inspired by the offshore oil industry, where platforms based on spar-buoy design are used with water depths up to 1000 m.

The mooring system usually deployed with spar-buoy structures is the catenary that is usually made of steel chains and/or wires whose weight and curved shape holds the floating platform in place. The anchoring system most deployed with this type of concept is the drag-embedded. Spar-buoy design is usually deployed for water depth higher than 100 m because of large draft, and it implies a lower range of suitable site location. The large draft of the structure also implies precise methods of transport and installation. Indeed, it is necessary that the structure is towed to the site in a horizontal position, where a specialized vessel will carry out the installation in deep water, since the depth of the port is less than the draft. The use of specialized vessels, such as heavy lift vessels for the positioning of the structure, can increase the installation costs of the structure. However, the manufacturing costs are not excessive since the production processes are quite simple as the structure does not include complex parts. Also, the cost of materials and in particular of the metal is not excessive since the metal does not require particular properties in addition to good structural stability and resistance to corrosion.

The advantages of spar-buoy concept are well reported by the Floating Foundation report by IRENA [10]:

- Tendency for lower critical wave-induced motions, that overall provide a good stability;
- Simple design that makes this design suitable for serial fabrication process;
- Lower installed mooring cost.

On the other hand, the main disadvantages of these concepts are the following:

- Needs deeper water than other concepts (>100 meters), and so the range of suitable site location is limited;
- Offshore operations require heavy-lift vessels and currently can be done only in relatively sheltered, deep water.
- The installation of the wind turbine on the foundation can not be performed in port, but it must be done offshore.

2.3.2 Semi-submersible concept

The semi-submersible structures are composed of a number of large columns connected one another by connecting braces or submerged pontoons. The hydrostatic stability is provided by the columns, while the pontoons provide additional buoyancy.

Figure 2.6 Semi-submersible substructure concept

The wind turbine can be mounted on one of the columns or alternatively it can be positioned at the geometric center of the column tubes and supported by lateral bracing members. The semi-submersible design achieves the desired static stability thanks to the buoyancy force: when the platform is inclined, the leeward part of the platform has a larger submerged volume, and the windward a smaller submerged volume, with respect to the situation at equilibrium. This means that the leeward part experiences a larger buoyancy force. This creates the restoring moment necessary to counteract the wind inclining moment. In order to achieve this effect, the waterplane area needs to be large and/ or sufficiently spread and because of that these designs are defined as waterplane-stabilized structures [8].

In order to avoid the platform to drift away under the action of wind, wave and marine current forces, semi-submersible concepts are kept in position by mooring lines. These are composed of three or six catenary lines. In general, semisubmersible platforms, as well as the other floating wind turbine configurations that adopt a catenary mooring system, are characterized by larger oscillation when subject to wave loads. This is especially true when compared to TLP. An active ballast system can be used to counteract the average inclining moment caused by the aerodynamic thrust [9].

The construction of this type of foundation concepts can be performed onshore or in a dry dock. In this case, the construction process is more complex with respect the spar-buoy concept: the structure design implies welding joints that enhance the level of complexity of the fabrication process and have a shape that requires a lot of space, so the choice of a suitable port is important. Semi-submersible offshore wind turbine is relatively easier to install in the location site and they don't require specialized vessels since vessels are needed for towing only. Given these features, the fabrication cost is higher than other floating concepts, but the transport and installation costs are lower.

The advantages of semi-submersible concept are well reported by the Floating Foundation report by IRENA [10]:

- Constructed onshore or in a dry dock;
- Fully equipped platforms (including turbines) can float with drafts below 10 meters during transport;
- Transport to site using conventional tugs, so low transport cost;
- Can be used in water depths to about 40 meters, so high flexibility in the range of suitable locations related to sea depth;
- Lower installed mooring cost;

On the other hand, the main disadvantages of these concepts are the following:

- Tendency for higher critical wave-induced motions;
- Tends to use more material and larger structures in comparison to other concepts;
- Complex fabrication compared with other concepts, especially spar buoy.

2.3.3 Tension Leg Platform (TLP) concept

Tension leg platform (TLP) designs are characterized by high level of buoyancy and are composed of a central column and radial arms that are connected to tensioned tendons which secure the structure to suction or piled anchors. The higher tension in the windward leg compared with in the leeward leg creates a restoring moment, which counteracts the inclining moment due to the wind turbine aerodynamic thrust, providing a response to wind and wave loads [10]. It involves a shallow draft: smaller than a spar, but larger than a semi-submersible design. The anchors are typically gravity based, suction or pile driven and so they require certain seabed requirements making it more complex to install. However, TLPs have a good water-depth flexibility, as they can be installed in relatively shallow to very deep waters.

Figure 2.7 TLP structure design

Generally, TLP designs can be assembled onshore or in a dry dock, requiring the use of specialized vessels only to enable the necessary stability during the installation process.

The advantages of TLP concept are well reported by the Floating Foundation report by IRENA [10]:

- Can be used in water depths to 50-60 meters, depending on metocean conditions. As the sea depth increases, the mooring and installation costs increases;
- Low mass;
- Tendency for lower critical wave-induced motions;
- Can be assembled onshore or in a dry dock

On the other hand, the main disadvantages of these concepts are the following:

- Harder to keep stable during transport and installation
- Higher installed mooring cost compared to other floating structure designs;
- Depending on the design, a special purpose vessel may be required.

Compared to other platforms, TLP is the structure on which there have been fewer investments despite being one of the first structures to be used (in 2008, by Blue H Technologies in Brindisi, Italy). Despite this, it is a technology that can reserve very interesting aspects such as high stability and the low manufacturing cost of the structure itself. In fact, TLPs require less structural mass than other concepts such as semisubmersible. Obviously, the costs of transport and installation on site, especially the cost of mooring operations, must be taken into consideration and finding innovative solutions in this sense can lead to positive implications. For example, PelaStar cost of energy review by Glosten [11].

2.3.4 Barge

The barge platform is also called a waterplane-stabilized structure. This is a consequence of the fact that the hydrostatic stability of the barge is provided by the buoyancy force and to obtain this effect it is necessary to have a large waterplane. As for the advantages and disadvantages of using this type of structure, reference can be made to those of the semisubmersible structures described in Chapter 2.3.2.

The setback of the pontoon-type wind turbine is that it is susceptible to the roll and pitch motions in waves experienced by ocean-going ship-shaped vessels and may only be sited in calm seas, like in a harbor, sheltered cove or lagoon.

2.5 Main Commercial Wind Farm

Once the different types of substructures have been analyzed, the main commercial projects of floating offshore wind farms will be presented in the following paragraphs.

2.5.1 WindFloat Atlantic

The development and construction of WindFloat went through several stages and the construction and installation of the first full-scale prototype took place in 2011 near Aguçadoura, off the Portuguese coast. This was the WindFloat 1 Project, which included the design, construction and installation of a demonstration unit, mounting a 2 MW commercial turbine.

Figure 2.8 WindFloat Atlantic Project

The importance of this project is that it was the first multi-megawatt wind turbine mounted on a semisubmersible structure and it was the first offshore wind system installed in open Atlantic waters. WindFloat 1 remained in operation for 5 years with high efficiency: in the sea state with a significant wave height of 7 m and surviving waves up to 17 m, the productivity was higher than 17 GWh.

The next stage in the development of this technology was the pre-commercial phase: WindFloat Atlantic. This project consists of an offshore floating wind farm located 20 km off the coast of Viana do Castelo, also in Portugal. WindFloat Atlantic consists of three wind turbines installed on semi-submersible floating platforms, with a total capacity of 25 MW.

Once the economic competitiveness and technological validity of the platform had been verified, a new project was approved in France, with four WindFloat platforms that mount wind turbines with a rated power of 6 MW.

2.5.2 HyWind Scotland

Hywind Scotland was the first floating offshore wind farm ever built in the world; it is located 29 km off the coast of Peterhead, Scotland, at a sea depth of between 95 and 120 m. This project uses spar-buoy platforms and consists of 5 units supporting wind turbines with a power rating of 6 MW, for a total installed power of 30 MW. The mooring system implemented by Hywind consists of a ballasted catenary arrangement with three mooring cables weighing 60 t, hung at the midpoint of each mooring to add additional tension. The anchoring system consists of three suction tubes per substructure. Hywind Scotland was commissioned in October 2017 while the production of electricity began in 2019. Its realization required great efforts, especially for the installation phases of the turbines, which took place in the open sea and required the collaboration of the ship. Saipem 7000 crane.

Hywind's previous project dates back to 2009, when the first full-scale prototype was installed in Norway, 10 km off the coast of Stavanger at a depth of 220 m, mounting a 2.3 MW offshore wind turbine. Based on the results and successes of the Hywind Scotland project, a new project called Hywind Tampen has been developed by Equinor. The new offshore wind farm will consist of 11 wind turbines, each with a rated power of 8 MW, for a total capacity of 88 MW. The project aims to provide electricity for Snorre and Gullfaks offshore field operations in the Norwegian North Sea. It will be the first floating wind farm in the world to power offshore oil and gas platforms. Construction will begin in 2022.

Figure 2.9 Hywind Scotland project

Chapter 3

Floating Offshore Wind Power System

In this chapter the Floating Offshore Wind Turbine (FOWT) is analyzed as a whole system composed by:

- Wind turbine;
- a floating platform;
- moorings;
- anchors.

Furthermore, from the perspective of a wind farm, it is convenient to discuss the electrical grid system which includes marine cables and substations. In this chapter, in addition to the properties of each component of the system, the economic aspect is taken into account.

3.1 Wind Turbine

The wind turbine is the most important part of the system. It is able to extract kinetic energy from the wind and convert it into electrical energy. the main components of the turbine are the rotor, the nacelle and the tower. The rotor extracts kinetic energy from the wind through the blades and converts it into rotational kinetic energy which is transmitted to the drive train. The nacelle converts the kinetic energy transmitted to the drive train into electrical energy through the generator and supports the rotor. Finally, the tower, which is usually a tubular structure made of steel, supports the nacelle and provides access to the turbine control systems and nacelle. Most turbine models have windward, variable pitch, variable speed rotors with three blades. The design life of an offshore turbine is typically 25 years. The largest turbine manufacturers are Vestas, Siemens-Gamesa and General Electric Renewable Energy.

In this work, the reference turbine is the NREL 5 MW. The reason why this turbine was used in this theoretical study is that, unlike other models whose data are secreted for industrial reasons, the data regarding this turbine are publicly available. Furthermore, in the theoretical studies concerning FOWT, at a theoretical level, turbines in the order of magnitude of 5/6 MW are the most used. At more advanced levels of development, the turbine cuts are slightly larger.

3.1.1 NREL 5 MW wind turbine

NREL 5 MW is an offshore wind turbine developed by the National Renewable Energy Laboratory (NREL) and the design is the result of specifications from several different previous prototypes, such as Multibrid M5000 and REPower 5M, and studies, such as RECOFF, WindPACT and DOWEC [12]. The rating is the result of considerations on offshore floater feasibility and the state of the art for wind turbines and the rating power of this turbine is 5 MW. Regarding the size of the turbine, the hub height is chosen equal to 90 m and the rotor radius is 63 m. The rule of thumb regarding the correlation between the rotor diameter (126 m in this case) and the hub height states that the hub height must be close to the turbine diameter. In this case, a value of 90 m was chosen to limit the overturning moment generated by the wind thrust on the turbine. Furthermore, a height of 90 m guarantees a 15 m clearance between the blade tips at their lowest point and an estimated extreme 50-year wave height of 30 m. The cut in speed of the wind, that is the minimum speed at which the tube begins to generate electricity, is equal to 3 m / s. While the cut-off speed of the turbine, that is the maximum wind speed at which the turbine stops producing electricity due to the excessive stress caused by the wind on the blades, is equal to 25 m / s. Finally, the nominal wind speed, ie when the power produced by the turbine reaches its maximum, is set at 11.4 m / s. As for the type of control, there is a conventional variable-speed, variable blade-pitch-to-feather configuration. The coordinates (x,y,z) of the overall center of mass (CM) location of the wind turbine are indicated in the table in a tower-base coordinate system, which originates along the tower centerline at ground or mean sea level (MSL). The x-axis of this coordinate system is directed nominally downwind, the y-axis is directed transverse to the nominal wind direction, and the z-axis is directed vertically from the tower base to the yaw bearing. The remaining data related to the chosen wind turbine are summarized in the following Table 3.1.

Rating	5 MW
Rotor orientation, configuration	Upwind, three blades
Control	Variable speed, collective pitch
Drivetrain	High speed, multiple-stage gearbox
Rotor, hub height	126 m, 3 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Overhang, shaft tilt, precone	5 m, 5°, 2.5°
Rotor mass (hub mass)	110 t (56.78 t)
Nacelle mass	240 t
Tower mass	250 t
Overall mass	600 t
Coordinate location of overall CM	(-0.2 m, 0.0 m, 64.0 m)
Hub inertia about rotor axis	115.96 kg m^2
Hub CM coordinates in shaft CS	(0 m, 0 m, -5.0191 m)
Nacelle CM coordinates in nacelle CS	(1.75 m, 0 m, 1.9 m)
Tower height	77.6 m
Distance from nacelle base to rotor axis	2 m
Distance from rotor axis to tower base	99 m

Table 3.1 NREL 5MW offshore wind turbine specifications

3.2 Floating platform

The platform is the most important part of the system and has the following functions:

- supports the wind turbine;
- guarantees the floatability of the FOWT, and an emerged height above sea level, for reasons of visibility and to avoid corrosion of the turbine tower;
- guarantees the stability of the system, in order to maximize wind productivity and to counteract the strength of the waves and currents.

The platforms, or substructures, are connected to the seabed through a system of moorings and anchors. The classification of the substructures takes place according to the method in which the stability is ensured. The wind acting on the turbine generates a thrust that causes the structure to tilt, the role of the floating platforms is to generate a moment that contrasts this effect, called restoring moment. The most important types of structures have been described in Chapter 2. The cost of the platforms will be dealt with in the following paragraph.

3.2.1 Platform cost

The cost of the platforms was defined following the methodologies described in the derivable D2.2 of life 50+ project [13]. In particular, the cost of a single C_{FS} platform is defined by the sum of the three main components:

$$C_{FS} = TC_{LC} + TC_{MC} + TC_{OC} \tag{3.1}$$

Where, TC_{LC} stands for the total labor cost, TC_{MC} is the total material cost and TC_{OC} is the total overhead cost. A single platform is made up of numerous (n) individual elements that need to be fabricated, such as several columns, pontoons, transition pieces, etc. The composition and quantity of components depend on the concept of floating platform considered. Therefore, the total labor cost for a single subtree is obtained from the sum of the labor costs for each of the components of a substructure as we can see in the following formula:

$$TC_{LC} = \sum_{i=1}^{n} t_{FSi} * c_{LCi} \tag{3.2}$$

Where, t_{FS} represents the manufacturing time in hours (h) and c_{LC} the hourly labor cost in (€/h).

The total material costs are the sum of material costs for each of the components of a substructure and is obtained as follow:

$$TC_{MC} = \sum_{i=1}^{n} \sum_{j=1}^{m} m_{ij} * c_{ij} \tag{3.3}$$

The material cost of a single component is obtained by the sum of the different materials (m) used in each phase of the processing. Hence, m is the quantity of the material express as mass (t) and c is the cost of the material in €/t. In this equation the cost of the material is calculated for each of the processing phases such as preparation, creation, painting and finishing. The total material cost will be then calculated considering the sum of all the components (n).

In this work, the cost of the platform is evaluated by assuming it equal to the cost of the mass of steel and concrete, since they are the most used materials for this type of structure.

Steel prices are volatile and vary greatly between countries, locations and other various factors. In 2020 in Europe, the cost of steel for naval applications, like S355 steel, is between €2500 and €3000 per ton, depending on the quality of the workmanship and structural properties. At the same time the price of concrete is in the range of €500 to €600 per metric ton.

Finally, overhead costs are not directly related to the manufacturing process but are necessary to run the business activity. For example, labor cost technicians, utilities, labor cost maintenance, rent, legal expenses, are overhead costs. In order to estimate overhead costs, that are difficult to determine, a general method applies a percentage for the overhead cost and a typical value is about 27% of the total manufacturing cost. In Figure 3.1 the steel weight and the cost of each type of floating platform (such as semi-submersble, spar buoy and TLP) are shown.

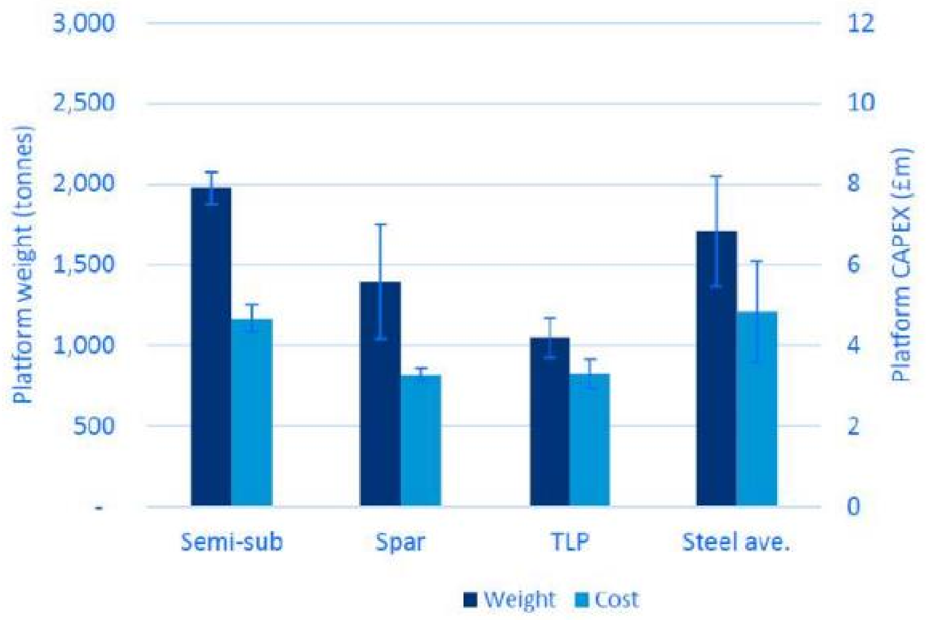


Figure 3.1 Platform weight vs cost (steel). Adapted from [9]

As can be seen from the figure, for the three main types of floating platforms, the relationship between the quantity of steel and the cost is not clear because it depends on the different grade of steel used in the single substructure. In fact, spar buoy structures appear to be the most cost-effective, attributed to the lower grade steel that can be used and the ease of fabricating simple structures. TLPs usually require smaller structural dimensions than semisubmersibles and this results in a smaller amount of material and therefore a less expensive structure.

Another important aspect is the choice of the material used to build the platform. Indeed, as can be deduced from the Carbon Trust study [9], floating structure concepts that use concrete as the primary material cost less. Today, the main floating structure concepts use steel as the primary material but concrete has advantages to consider. In fact, concrete also brings advantages in terms of increased local content and reduced maintenance, since it is less subject to the effects of corrosion than steel foundations. For example, concrete is already used as ballast by increasing the local content to give balance to structures as in the spar buoy concept developed by Hywind.

In this thesis work, one of the purposes is define a proper cost function for the platforms in floating offshore wind turbine systems. As stated in the thesis of C. Bjerkster and A. Agotines [14], the manufacturing cost of the substructure can be defined as function of the material cost, multiplying the material cost by a proper complexity factor that must be defined for each type of platform concept. The complexity factor depends mainly on two aspects:

- The first is the fabrication complexity; therefore, the cost of the work required to build the platform includes rolling, cutting, painting and corrosion treatments, and welding and miscellaneous assembly of materials into complete structures.
- The second aspect concerns a more economic discourse; that is, how suitable the considered structure concept is for mass production. Therefore, in this case the size and complexity of the structure are taken into consideration since large and complex platforms are difficult to mass produce.

Once the complexity factor is defined, the manufacturing cost is calculated using the following Equation:

$$TC_{man} = CF \cdot TC_{MC} \tag{3.4}$$

Where CF is the complexity factor and TC_{MC} is the total material cost of the structure. Finally, in order to calculate the cost of the floating foundation, including both materials and production cost, in this thesis work we consider the following Equation:

$$C_{sub} = TC_{MC} \cdot (1 + CF) \tag{3.5}$$

Where C_{PC} is the production cost, TC_{MC} is the total material cost and CF is the complexity factor.

In the following Table 3.2, are reported the values of complexity factor for different platform designs.

Floating Substructures	Complexity Factor
TLB B	110 %
TLB X3	130 %
Hywind II	120 %
WindFloat	200 %
SWAY	150 %
TLWT	130 %

Table 3.2 Complexity factor for different substructure concepts [14]

3.3 Moorings

The mooring system within the offshore wind turbine system plays an important role as it prevents the structure from drifting under the action of waves, currents or wind and increases rotational stability. Mooring configurations can be classified into three types: **catenary**, **taut-leg** and **semi-taut** system. The catenary configuration is used in the spar-buoy and semisubmersible floating platforms, while the taut-leg configuration is used in the TLP concepts. The semi-taut configuration is a mix of the previous two and is mainly used for semisubmersible platforms. However, mooring systems do not depend exclusively on the type of substructure but are also linked to the depth of the sea and the type of seabed. In Figure 3.2, a graphic representation of the three main types of mooring system is reported.

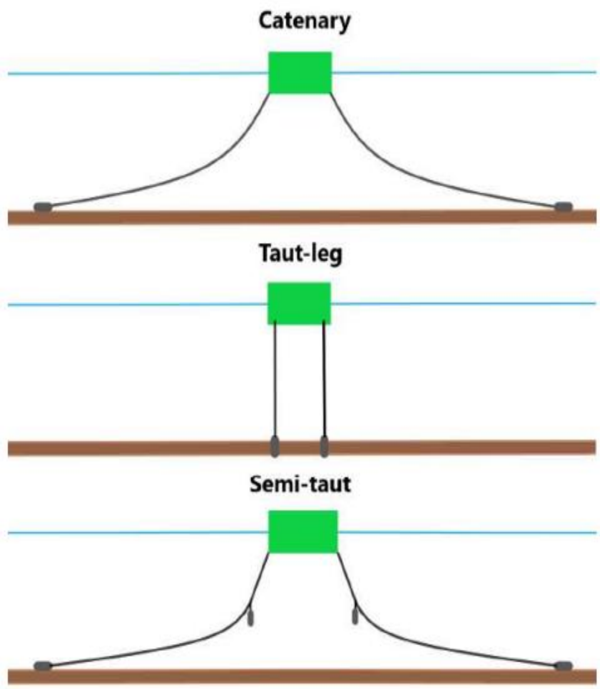


Figure 3.2 Mooring system classification

More specifically, as reported in the Carbon Trust [9], catenary consists in long steel chains and/or wires whose weight and curved shape holds the floating platform in place. Usually, lower section of mooring chain rests on the seafloor, supporting the anchor and acting as a counterweight in stormy conditions.

The taut-leg consists of synthetic fibers or wire which use the buoyancy of the floater and firm anchor to the seabed to maintain high tension for floater stability.

The semi-taut consist of synthetic fibers or wires usually incorporated with a turret system, where a single point on the floater is connected to a turret with several semi-taut mooring lines connecting to the seabed.

In Table 3.2 are reported the main features of the three type of mooring.

Moorings		
Catenary	*Taut-leg*	*Semi-taut*
• Horizontal loading at anchoring point	• Vertical loading at anchoring point	• Loading typically at 45 degrees to anchoring point
• Large footprint	• Small footprint	• Medium footprint
• Long mooring lines, partly resting on the seabed, reduce loads on the anchors	• Large loads placed on the anchors, requires anchors which can withstand large vertical forces	• Medium loads on the anchors
• Some degree of horizontal movement	• Very limited horizontal movement	• Limited horizontal movement, but full structure can swivel around the turret connection
• Weight of mooring lines limits floater motion, but greater freedom of movement than taut-leg	• High tension limits floater motion (pitch/roll/heave) to maintain excellent stability	• Single connection point makes the platform susceptible to wave induced motion
• Relatively simple installation procedure	• Challenging installation procedure	• Relatively simple installation procedure
• Lower section of chain rests on the seabed	• Minimal disruption to the seabed	• Low level of disruption

Table 3.3 Mooring classification and main features, from [9].

3.3.1 Mooring cost

The mooring cost accounts for 6 % of the CAPEX. In Figure 3.3, the cost per meter and cost per unit of each type of configuration are reported.

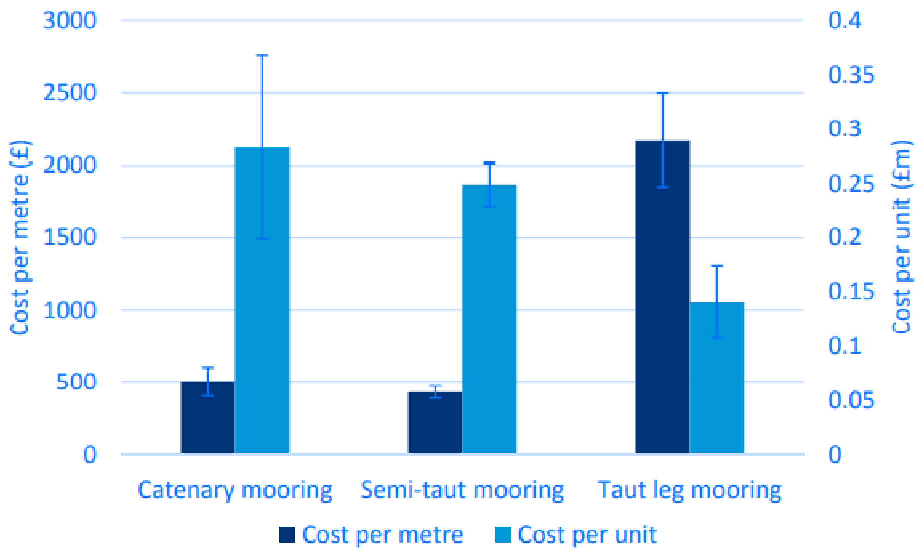


Figure 3.3 Moorings cost per meter and cost per unit [9]

From the previous graph, although the taut-legs are shorter in length, they have to sustain considerable vertical stresses, so the cost per meter is considerably higher than the other mooring configurations. Considering the type of platform related to the moorings classification it can be noted that the length of the lines is relevant for the cost per unit. In fact, semi-submersibles and spar-buoys have long mooring lines with a high unit cost, while TLP concepts have considerably shorter mooring lines which, despite a higher cost per meter, are still cheaper per turbine than the mooring lines used in the other typologies. It should be noted, however, that this does not include the cost of mooring installation, which is expected to be higher for taut-leg moorings as specific boats are required.

The mooring cost per unit considering the type of floating substructure is reported in the graph in Figure 3.4.

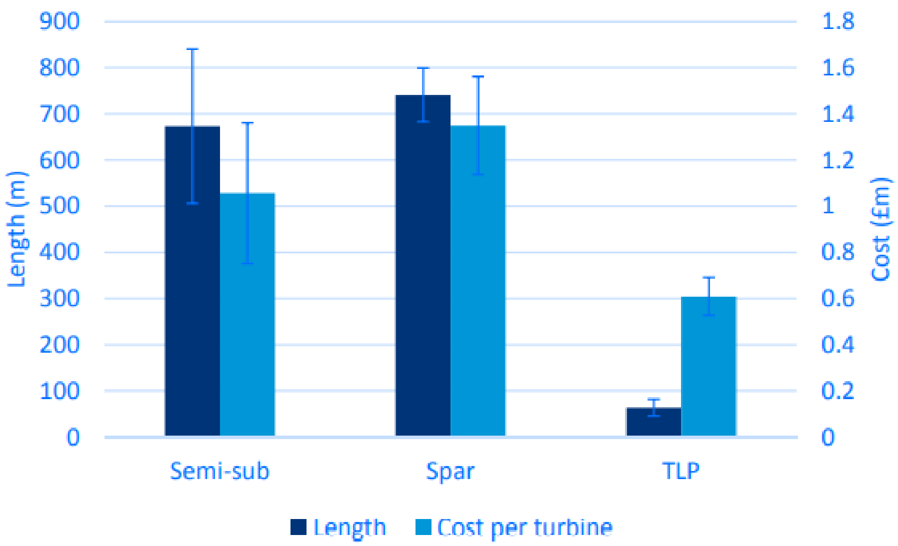


Figure 3.4 Mooring length and cost per turbine, by floater typology [9]

3.4 Anchors

The anchoring system of the FOWT systems have the important task of keeping the structure in position, counteracting the effect of waves, currents and wind. There are different types of anchors and these are chosen according to the type of mooring and the state of the seabed. Catenary mooring configurations often use **drag-embedded** anchors to handle the horizontal load, while taut-leg moorings usually use either **drive piles**, **suction piles**, or **gravity anchors** to cope with the large vertical loads placed on the mooring and anchoring system.

Ultimately, the choice of the type of anchor strictly depends on the installation site of the FOWT, as it is closely linked to the conditions of the seabed. Higher holding capacities are usually generated in sands and hard clays than in soft clays, although where penetration is difficult in firm soils, gravity base or piled solutions might be required. Table 3.3 summarizes in detail the main characteristics of the different types of anchors.

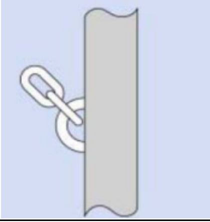
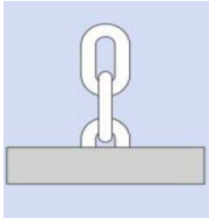
Anchors			
Drag-embedded	*Drive pile*	*Suction pile*	*Gravity anchor*
			
• Best suited to cohesive sediments, though not too stiff to impede penetration	• Applicable in a wide range of seabed conditions	• Application constrained by appropriate seabed conditions	• Requires medium to hard soil conditions
• Horizontal loading	• Vertical or horizontal loading	• Vertical or horizontal loading	• Usually vertical loading, but horizontal also applicable
• Simple installation process	• Noise impact during installation	• Relatively simple installation, less invasive than other methods	• Large size and weight can increase installation costs
• Recoverable during decommission-ing	• Difficult to remove upon decommission-ing	• Easy removal during decommission-ing	• Difficult to remove upon decommission-ing

Table 3.4 Anchors classification and main properties [9]

3.4.1 Anchors cost

The anchors cost account for a 3% of the CAPEX. In Figure 3.5 the weight and the cost of each type of anchor are reported. Anchor cost is closely tied to weight, and therefore the amount of steel used. Drag-embedded anchors are considerably lighter and cheaper than the heavier and more expensive driven and suction piles. Gravity anchors are extremely heavy, but the availability of cheap concrete means that the cost is fairly modest. However, it should be noted that this does not include the cost of anchor installation: consequently, for example, gravity anchors may incur higher costs if an additional vessel is needed to install the ballast.

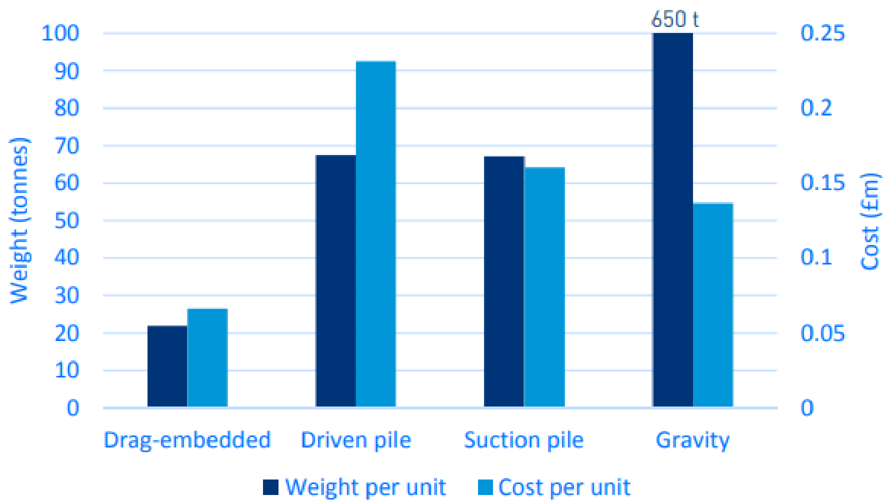


Figure 3.5 Anchor weight and cost per unit, by anchor type [9]

Anchor costs are generally higher for TLPs, both on a per unit and per turbine basis, largely attributed to the need to withstand high vertical loading and maintain platform stability. Conversely, the drag embedded anchors used in semi-submersible and multi/hybrid concepts are demonstrably cheaper than other alternatives. Anchor costs for spar-buoys would be expected to be in line with this, but the driven, suction, and gravity anchors assessed in this analysis derive higher costs.

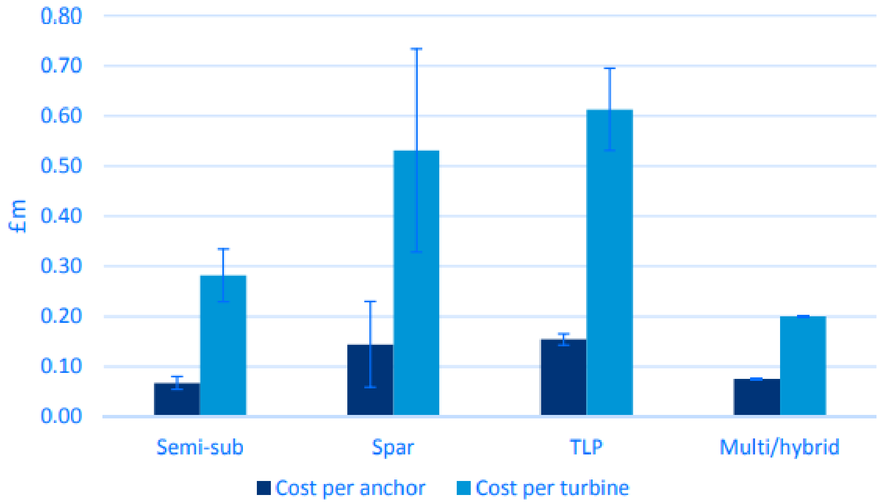


Figure 3.6 Anchor cost per unit and per turbine, by floater typology [9]

3.5 Electrical system

A challenging aspect of the design of a FOWT park is the transport of the electricity produced to the shore. To do this, it is necessary to use some components that make up the electrical part of the plant and are usually marine cables, offshore and onshore substations and grid connections.

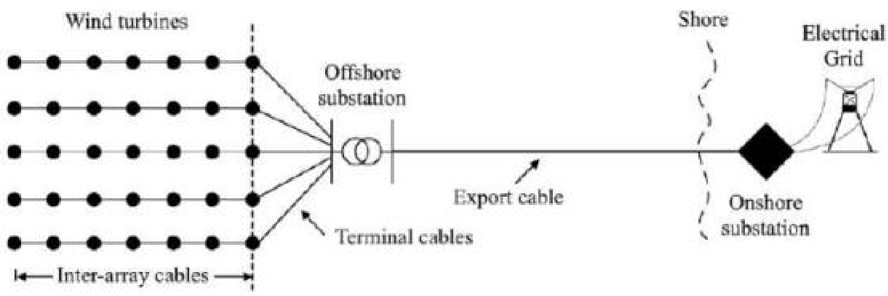


Figure 3.7 Electrical power transmission system of an offshore wind farm in top view [15]

In an offshore wind farm, the turbine generator transforms the kinetic energy extracted from the wind into electrical energy, after which it is fed down along the tower, where a converter converts the direct current into alternating current and the transformer increases its voltage to transport it through the wind farm. Thereafter, the energy is transported through the wind farm to the offshore substation via inter-array cables buried under the seabed. Currently, an inter-array voltage of 33 kV AC is considered a standard electrical specification for the collection system of an offshore wind farm. However, efforts have been made in recent years to set a new 66 kV AC standard aimed at further cost reductions for large farms.

The offshore substation reduces electricity losses and improves the efficiency of the entire wind farm, by increasing the voltage up to 150 kV, before it is transported to the shore. In the substation, there are various electronic components, electrical and auxiliary equipment and control systems. Finally, electricity is transmitted from the substation by export cables which come to shore, where the onshore substation provides to raise further the voltage, so that it can be connected to the national electricity grid.

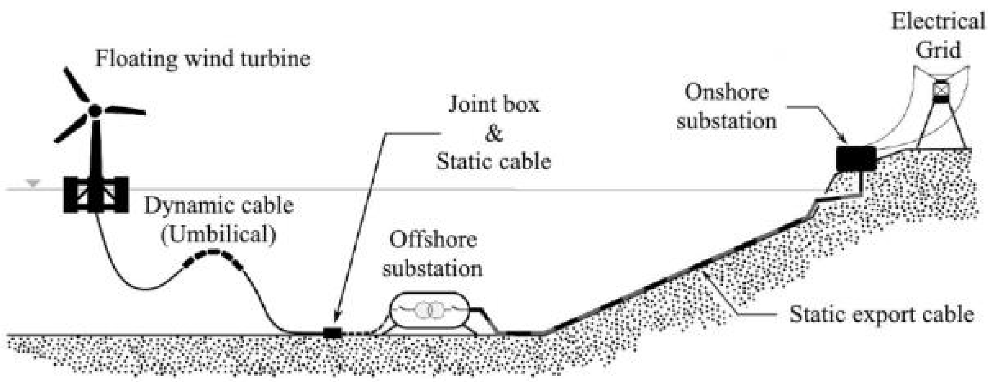


Figure 3.8 Power transmission system of a floating offshore wind [15]

This setup is valid for the transmission system of bottom-fixed and floating wind farms alike [16]. The difference between the inter-array cables in the case of a bottom fixed wind farm and a floating one, is that in the first case the cables are entirely buried under the seabed, while in the second case the cable is traversing a column of water moving freely, as can be seen in the Figure 3.8. Only fixed at its end points, the cable is exposed to the motion of the floating platform, to wave excitation and currents. This type of dynamic cable is also further referred to as "umbilical."

Because floating platforms are a very recent addition to the offshore renewables sector, field experience with dynamic cables in this area is still scarce and a lot of research problems remain to be investigated.

3.6 Installation

The installation process for FOWT plant projects is very important as it is one of the most complex life cycle processes of these plants, mainly due to marine conditions [9]. Regarding semi-submersibles and TLPs, it is able to assemble the turbine at port, removing the need to charter expensive heavy lift vessels. Semi-submersibles have the lowest vessel constraints, requiring only simple tugboats to tow the fully assembled structure to site for hook-up, in addition to the obligatory anchor handling tugs and cable lay vessels. TLPs are slightly more constrained, often requiring a bespoke barge for optimal installation procedures, although standard barges can be used in the intermediary. Spar-buoys must be transported to a sheltered deep-water location for erection and turbine assembly, using heavy-lift vessels. Spar-buoys have the greatest vessel requirements, often needing a barge to float the structure to a deep-water location (wet-tow also possible) and a heavy-lift vessel for turbine assembly, like Saipem 7000 semi-submersible crane vessel.

Installation process, which depends on the vessels availability and port infrastructure, can be different for each platform design. However, general guidelines of the installation process for floating wind offshore are summarized below:

1. Load-out of the platform from port is conducted by either flooding the dry-dock, or using a slipway or heavy lift vessel to place the structure in the water;

2. Turbine is assembled on the platform port-side using onshore cranes (not applicable for spar-buoys);
3. Anchors and moorings are pre-installed using an anchor handling tug (AHT) and a remotely operated underwater vehicle (ROV);
4. Electrical cables are pre-installed using a cable lay vessel;
5. Structure is towed to site using simple tugs or on a barge; however, Spar-buoys will be towed to a sheltered location for ballasting and turbine assembly, using a crane vessel, before final transit to site;
6. Fully assembled structure is hooked up to the mooring lines and electrical cables;
7. Ballast is added to stabilise the platform;
8. Mooring lines are tensioned appropriately;
9. Final commissioning.

The two main drivers affecting installation cost are installation time and vessel availability. Regarding installation time, complex and weather-constrained installation procedure for TLPs results in a significantly slower installation process than other concepts, with up to ~40 hours required even during commercial application. This is due to the fact that the installation of the mooring takes more time, since taut-legs mooring are used which must be installed taut in order to provide stability to the structure. Installation time for semi-submersible and spar concepts is shorter, at ~20-24 hours, as the moorings serve to prevent the platform from being dragged by the waves and do not affect the stability of the system. Consequently, the installation cost strictly depends on the installation time and on the type of vessels required: spar-buoys entail higher installation costs, largely driven by the greater vessel requirements and met-ocean limitations during turbine assembly. Installation costs are also high for TLPs due to the met-ocean limitations and extended installation time. Finally, the simplicity and flexibility of semi-submersibles results in a lower installation cost. In Figure 3.9, a graph of the installation time and cost for each type of floating platform is reported.

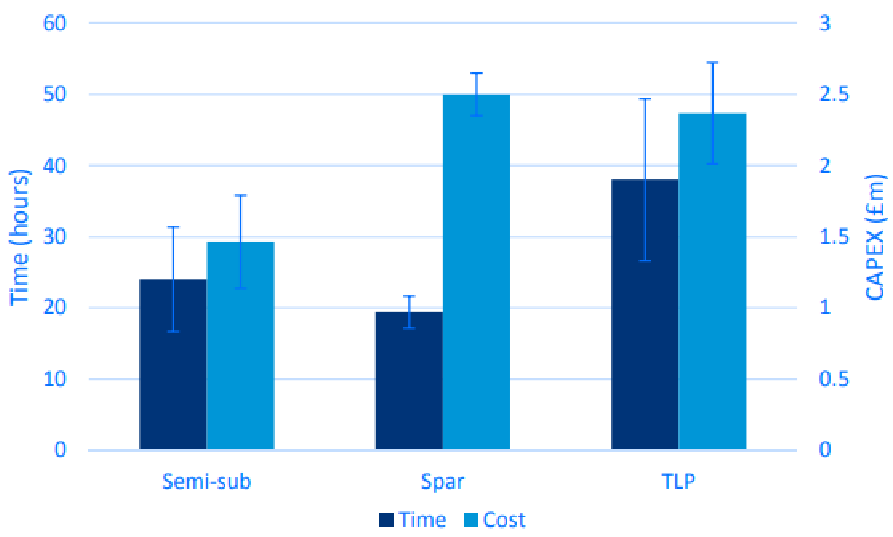


Figure 3.9 Installation time and cost for each type of floating platform [9]

Semi-submersible concept presents lower time and cost installation. The long installation time for TLP concepts drives up costs compared to semisubmersible platforms, despite both concepts using low cost vessels. Conversely, for spar-buoys, installation costs are considerably higher than the other typologies due to the added expense of heavy lift crane vessels for turbine assembly.

3.6.1 Offshore Installation Vessels

The main possibility of saving when it comes to floating offshore wind turbines is the installation phase which accounts for 20% of the total cost of the structure. Indeed, one of the main problems is the need to contract out the largest installation vessels in the world, which have large lifting capacity and hook height for a large wind turbine. For offshore installation the typical installation vessels utilized fall into the following categories: heavy lift vessels and jack-up vessels [17]:

- Heavy Lift Vessel (HLV) — A HVL is a heavy lift crane vessel which utilizes dynamic positioning rather than an anchoring system to hold its position during installation.
- Jack Up vessel — A Jack Up rig or a self-elevating unit is a mobile platform that consists of a buoyant hull fitted with a number of movable legs, capable of raising its hull over the surface of the sea. The buoyant hull enables transportation of the unit and all attached machinery to a desired location. Once the vessel is in place, it jacks its legs up to the required elevation above the sea surface supported by the sea bed.

The vessel operability characteristics also vary between HLVs and jack-ups. The Jack-up will likely be less sensitive to wave climate conditions due the vessel's ability to jack up out of the splash-zone but will usually have a smaller crane in comparison to HLVs.

Using these ships is very expensive and their cost can be as high as € 500k per day. In addition, there are very few laying ships of this type, and this only adds to the cost. For this reason, the ability to assemble the turbine on shore and tow the fully assembled structure on site primarily using simple tugboats eliminates the need for this expensive heavy duty and dynamically positioned vessel jack, both for foundation installation and for l assembly of offshore turbines.

Figure 3.10 Heavy Lift Vessel (left) and Jack-Up Rig (right).

Offshore Support Vessels (OSV) can offer a different range of services, and some may have firefighting and medical support facilities, but usually they are less specialized. Primarily these vessels are used as:

- Platform supply vessels, for example to transport the barges and to change the crew;
- Construction Support vessels, such as anchor handling tug, trenching vessel and rock dumping vessel;
- Survey Vessel.

To conclude, in Table 3.4 the approximate cost per day of the different class of vessels are reported:

Floating wind installation vessel	
Vessel	*Cost per day*
Heavy lift vessel (foundation installation)	€ 150k-500k
Jack-up vessel (turbine installation)	€ 150k-200k
Standard tug boat (tow out and hook up)	€ 30k-60k
Anchor handling tug (mooring installation)	€ 20k-50k

Table 3.5 Typical charter day rates for installation vessels [9]

3.7 CAPEX

In the previous chapters the main properties and characteristics of the components of the FOWT system have been analyzed. The characteristics of the turbine were analyzed and in chapter 2 the types of floating platforms were presented in detail. Subsequently, the other components such as mooring, anchors and electrical parts of the FOWT system were also considered. In addition, the economic aspects of the aforementioned components and other cost items that appear in the CAPEX such as the cost of installation and the cost of transporting the structure were analyzed.

It is therefore understood that the construction of a wind farm requires a large capital effort to meet all the costs that have been presented. Indeed, despite the enormous potential of offshore wind, the main obstacles to the spread of floating wind turbines are high capital and operating costs (CAPEX, OPEX). The reason is that the construction of the turbine and the platform are major works that require high capital. In addition, they require expensive production, transport and installation vessels, due to the hostile environment, characterized by strong winds and currents, in which it is difficult to operate. In Figure 3.11 the pie chart shows the cost items that make up the CAPEX and the respective percentages.

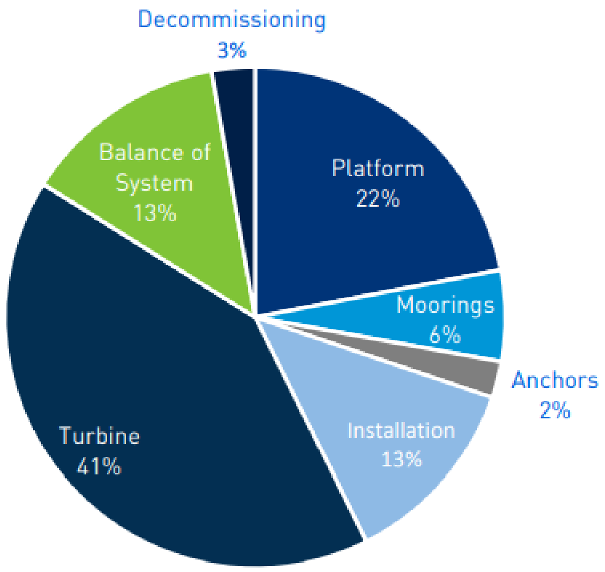


Figure 3.11 CAPEX breakdown for a commercial scale floating wind farm [9]

The greatest share of the overall Capex comes from the turbine (41%) followed by the platform (22%) and balance of system (13%), which includes the costs of the electrical infrastructure, like substation, cables and grid connection. Installation costs are also significant, representing 13% of Capex, the combined cost of the moorings and anchors makes up 8% of the total Capex. Finally, decommissioning costs are relatively minor, at just 3% of capital expenditure, at the end of the plant's life cycle, usually estimated at 25 years.

Currently, floating offshore wind technology is still expensive. Over the next few years, new developments at both academic and industrial levels will aim to reduce costs in terms of capital expenditure and in terms of the cost of operations and maintenance. The floating offshore technology will pass from the prototype development phase to the commercial one and substantial cost reductions are expected with regard to the various cost items, as can be seen from Figure 3.12.

The component that would allow the greatest cost saving is the floating platform. The optimization of the platform in terms of overall weight and dimensions would allow the use of smaller quantities of steel or concrete, the use of smaller vessels for transport from the dry-dock to the site as well as the use of existing port infrastructures.

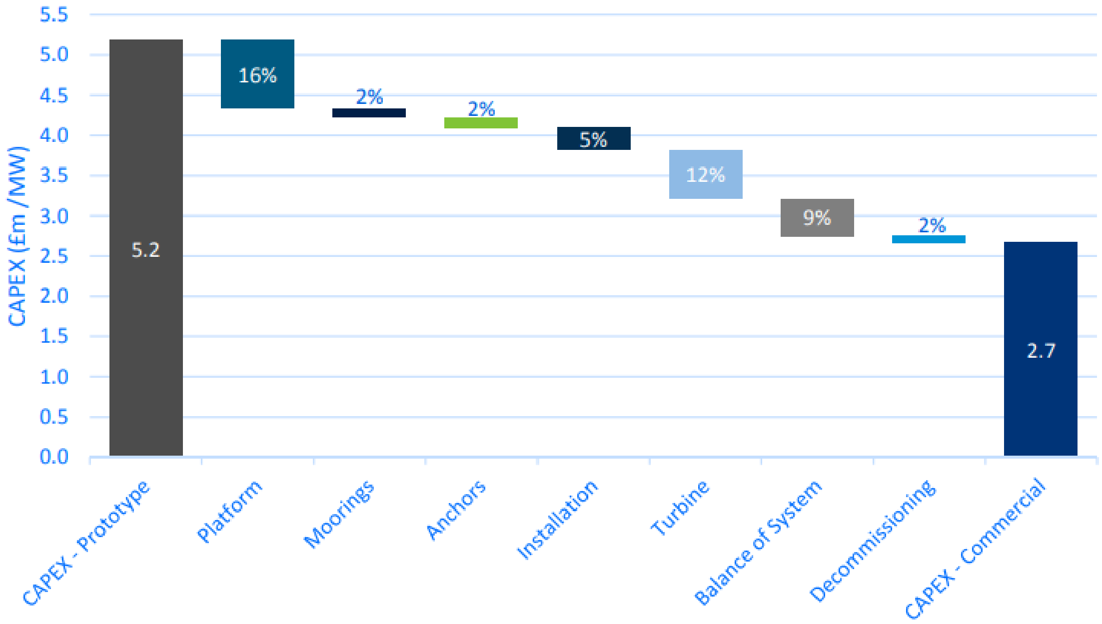


Figure 3.12 Reduction in capital expenditure from prototype to commercial deployments [9]

Furthermore, the type of platform conditions the choice of moorings and anchors, as well as the installation costs, particularly for TLP and spar-buoy concepts.

The purpose of this thesis work is to investigate, among the available concepts for semisubmersible, spar-buoy and even TLP, the one that allows the greatest material savings, while guaranteeing stability and buoyancy performance.

In addition, further CAPEX reductions can be achieved by developing advanced electrical and control systems, such as floating transformers, and improved mooring and anchoring systems. Another important aspect to make FOWT more cost-competitive is the reduction of the OPEX, achieved by developing robust procedures for port-side major repairs, for which the technical feasibility and cost benefit is currently poorly understood.

Chapter 4

Floating platform stability

In this chapter, the design process for a floating offshore wind turbine is introduced. First of all, a brief introduction will be made on the most used methodology and on the standards found in the literature and then the static analysis of the floating platform will be presented. In this chapter, five concepts of floating structures will be presented, two of which have already been developed commercially (Hywind and WindFloat) and two TLPs, which are the least developed type of structure but which can reserve important potential. The aim is to define a hydrostatic tool for the definition and estimation of the main hydrostatic parameters: metacentric height, hydrostatic stiffness and maximum pitch angle.

4.1 Design process

This section focuses on the design process and its application for the floating offshore wind turbine, considering the most common guidelines. Usually, it is possible to consider three main design steps:

- Pre-sizing design;
- Static analysis;
- Dynamic analysis.

An overview of the main key design step for a FOWT substructures is reported in the deliverable 7.4 of LIFES50+ project [18].

The first step of the design process is typically a pre-sizing or spreadsheet design considering only a basic representation of the FOWT platform and of the wind turbine. Typically, at this stage of the design process the environmental conditions at site and metocean data, like wave height, wind velocity and water depth in the site location, are not known. The objective of this simple design step is to evaluate the dimensions of the structure and the characteristic quantities of the floater and mooring lines in order to ensure the stability and the floatability of the FOWT. In this stage it is important to estimate the cost of the structure, mainly based on the kind of the material chosen and their quantities, in order to minimize it during the next stages.

After the pre-sizing step, a static analysis is performed in order to evaluate the stability of the structure and the hydrostatic parameters, like minimum required draught, maximum inclination in roll and pitch and the metacentric height.

Afterwards, motion characteristics are determined through consideration of frequency responses of the system that focus on stability and mooring lines. Hydrodynamic tools like Orcaflex Software or Nemoh can be used for dynamic analysis because they permit to simulate both wind and waves effects on the structure.

Also, once a basic internal structural layout is determined, a structural analysis is performed by applying pressure mapping in combination with finite element analysis. At this design stage, the wind turbine system and the floating platform are considered as rigid body with a very simple representation of wind loads acting on the rotor. A first design of the wind turbine controller needs to be defined in order to ensure the overall stability and to determine the dynamic response of the system. Also, the design of the mooring lines can be performed independently from the rest of the structure by application of higher-level numerical models at each design stage.

Once the conceptual design of floater, mooring lines and controller are defined an iteration loop repeating previous design steps should be defined in order to tune the simpler models and arrive at an improved conceptual design.

Finally, the last step is the validation of the loads through experimental procedures in wave tank. Figure 4.1 shows the main steps in order to find an optimal design.

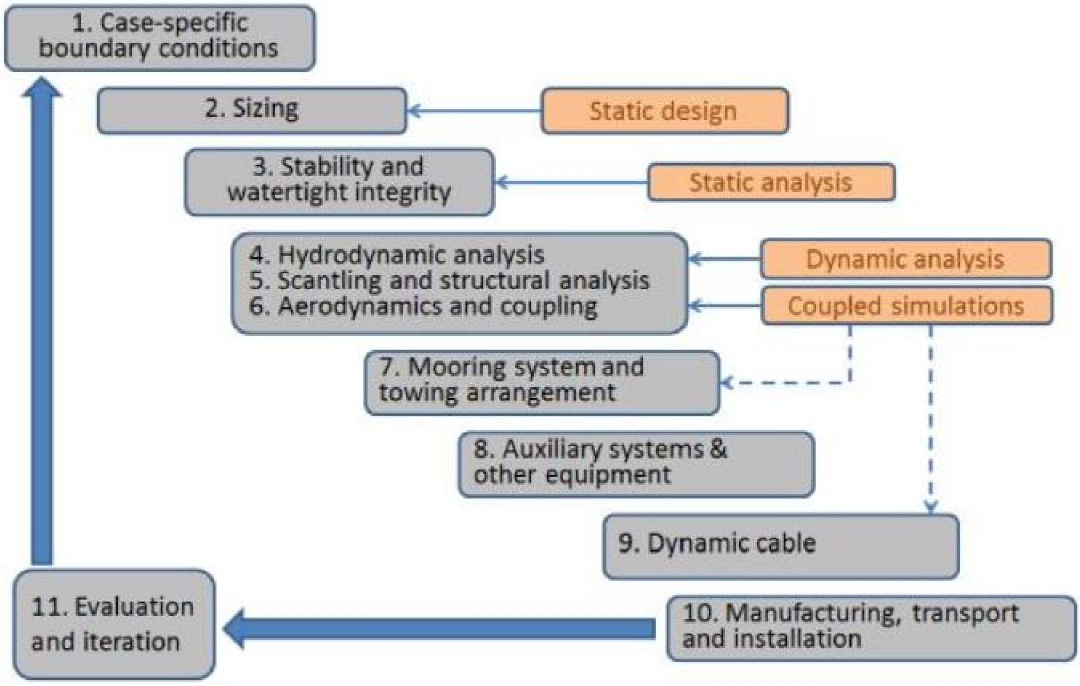


Figure 4.1 Design procedure for a floating offshore wind turbine system [18]

For concepts with low TRL, usually with TRL lower than three, the main analysis are the static and the hydrodynamic ones. The following phases of the design procedure are investigated later with more developed concept with an higher TRL.

4.2 Main design parameters

This section focuses on the most important aspects considered in the design phase of floating offshore wind turbine. The following four key design parameters have been defined because they constitute the elements with the most impact with regard to the design:

- Stability;
- Dimensions;
- Mass;
- Cost.

4.2.1 Stability

The structure must have sufficient stability to remain upright, this condition is defined as stable equilibrium. Therefore, when the structure is subjected to an external disturbance, such as exciting forces or moments from wind and waves, it must be able to return to equilibrium once the excitation ends. Stability requirements for floating offshore wind turbines are defined in the design standard DNV-OS-J103 [19]. This standard states that the floating structure shall be capable of maintaining stability during operation of the wind turbine at the wind speed that produces the largest rotor thrust. It must also be capable of maintaining stable during standstill during severe storm condition, and it requires sufficient stable condition during temporary phases such as assembly, installation and tow-out stages.

The stability of FOWT is closely connected with its efficiency since the power produced by a wind turbine is related to the inclination between the incoming wind flow and the rotor plane. If an excitation produces a variation in this angle, the power produced by the wind turbine decreases with the cosine of the angle [20]. Hence, the restoring stiffness related to the y-axis of the platform should be as large as possible in order to minimize the rotation about this axis. During the initial stages of the design process, it is possible to assume a single direction of origin for wind and waves. It can be realistic for those locations particularly close to the shoreline. However, when the location is far from the coast the wind can come from any direction, so the FOWT structure must be designed to bear moments and forces caused by the wind from every direction.

4.2.2 Dimensions

The overall dimension of the structures must be defined for manufacturing issue, to adapt to existing infrastructures and for economic reasons. The existing shipyards or production facilities can be used for the construction of these platforms only if the dimensions of the structure are somewhat limited. In Re's thesis work [21], the main ports characterized by dry-docks in Italy are considered and their dimensions are reported. The docks are adapted for platforms with a draught between 3 m and 11.5 m, while, considering the width, the maximum allowable dimensions are ranging from 38 m to 56 m. Considering that the docks are designed for the ships, these infrastructures are long enough for floating substructures. Hence, the construction or assembly of different structures can be performed within the length of one dock.

4.2.3 Mass

The main cost driver for floating offshore wind substructures is the structural mass. Mass drives the material cost as well as manufacturing infrastructures, manufacturing manhours, the size of required lifting equipment and the costs of transportation and installation. Lowering the mass allow to reduce the costs, the environmental impact and to increase the competitiveness in the offshore wind framework. Finally, the structures must be as light as possible and also scalable in order to easily adapt the substructures to different size of wind turbine.

4.2.4 Cost

The high investment costs are the main issue in the diffusion of the floating offshore wind systems. The costs include the cost for substructure, mooring system, electrical connection, transport and installation process, maintenance, etc. In order to make the offshore wind power economically profitable the costs must be low and the energy output as high as possible. New technological innovations have the objective of reducing the costs and making it more competitive with respect to the traditional energy sources, like fossils.

4.2.5 Standards

The following standards have been used:

- DNV-OS-J103;
- DNV-OS-C105;
- DNVGL-ST-0119.

The floating stability should be considered in the design stages, and it is defined for different states: towing, positioning, ballasting, installation and in-service condition. In particular, the stability requirements are described in DNV-OS-J103 section 10. For the static floating stability, the following information shall be considered:

- Steel or concrete weight and ballast material;
- Centre of buoyancy (COB) and center of gravity (COG);
- Draught and submerged volume;
- Loading conditions;
- Metacentric height (GM);
- Hydrostatic stiffness matrix;
- Maximum inclination angle in pitch;
- Righting arm curve (GZ);

4.3 Hydrostatic tool

This work is based on the use of an in-house hydrostatic tool that, once four different substructures are chosen, allow to calculate the main hydrostatic parameters, in order to easily verify the platform static stability.

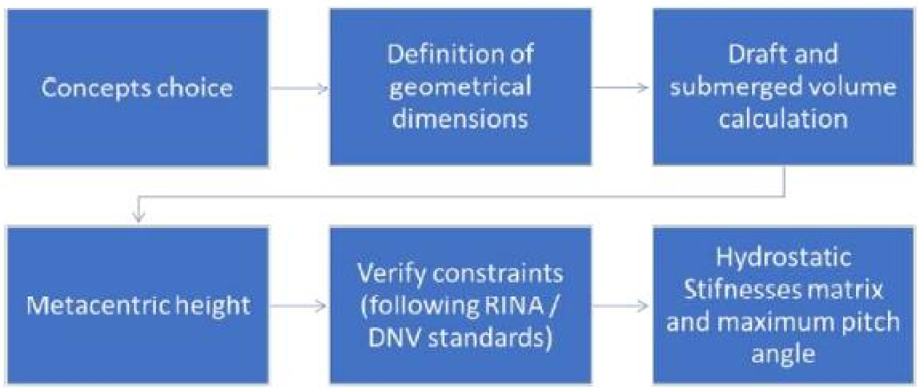


Figure 4.2 Operating scheme of hydrostatic tool

According to the objective of this work, the approaches are slightly different between the semisubmersible or spar buoy platforms and the tension leg platforms. For each platform concept, that has been defined by literature documents or commercial project data, the tool calculates weights and volumes. Then, applying the Archimedes' principle, the submerged volume and the draught are determined and, after implementing the data of the turbine (NREL 5MW), the tool estimates the coordinate of the center of gravity (COG) and the center of balance (COB). Hence, the metacentric height (GM), that is the first hydrostatic parameter of great relevance, is obtained: if this value is major than zero the system can be considered stable, otherwise the platform is unstable, and the geometry and weight distribution must be modified. At this point the process slightly changes for TLP with respect to the other floating structure. In fact, as already explained in the previous paragraph the stability of the TLP is not provided by the buoyancy but by the tension of the mooring. So, being our purpose to obtain an optimized structure and having the TLP serious stability issue during transport and installation phases, the platform is considered as a semisubmersible structure and the excitation is assumed smaller than the case of maximum thrust at the turbine. Hence, applying the right thrust force at the turbine and coupling it with the hydrostatic stiffness the tool estimates the maximum inclination angle in pitch. Finally, once the main material costs have been estimated, for each concept has been defined a material cost function, in order to minimize the platform cost through a genetic algorithm optimization, that will be explained in the following chapter.

4.4 Platform study

In this work four platforms have been investigated: two of them are technologically mature and commercial wind farm has already been developed (Hywind's spar-buoy and Windfloat's semi-submersible), both with a Technology Readiness Level (TRL) of 7; the other two concept are tension leg platforms, the first one has been developed at demonstration state with a 6 MW turbine (Pelastar), the second one is only at experimental state (Windstar platform).

In the next paraphs the concepts will be analyzed, and the most interesting features will be described.

4.4.1 Hywind spar-buoys

Hywind is a platform developed by Equinor (Statoil), as part of the Hywind Scotland project. The structure is a spar-buoy consisting of a cylindrical shaped column. It is a hollow structure made of steel and it contains ballast made by concrete and sea water in order to guarantee stability and low inclination angle in pitch. The total weight of the structure, after being ballasted, is of 12000 ton and it is coupled with a three-line mooring system with suction anchor [22]. Main geometrical sizes are summarized in the next table

Figure 4.3 Hywind spar-buoys concept representation

(Table 4.1). All geometrical parameters have been obtained from Equinor's documents, except for the concrete and sea-water height, that has been hypothesized. The complexity factor is reported from the Table 3.2.

HyWind spar-buoy	
Dimension	*Value*
Platform diameter	14.5 m
Platform height	91 m
Concrete height	10 m
Sea-water height	5 m
Density	7850 Kg/m^3
Complexity Factor	120 %

Table 4.1 Hywind spar-buoy concept parameters

4.4.2 WindFloat

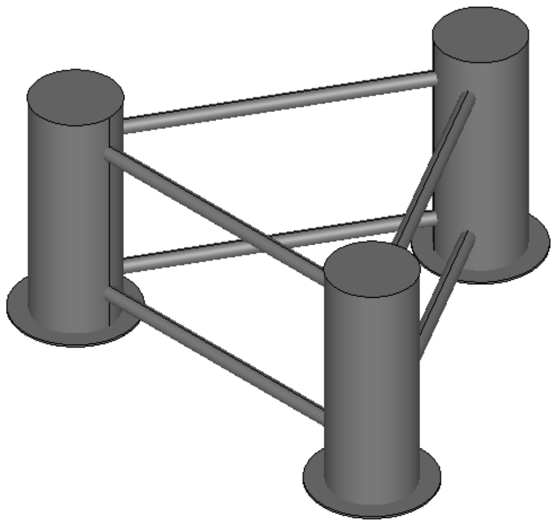


Figure 4.4 WindFloat concept represantation

The second concept is the WindFloat semisubmersible platform developed by Principle Power, as part of the WindFloat Atlantic project [23]. The semisubmersible is composed of three cylindrical columns connected to form a triangular alignment. The columns are connected by horizontal bracing beams and each column is equipped with horizontal heavy plates at the bottom of the columns. The heavy plates are very useful in terms of stability because they increase the added mass of the structure and reduce the overall motions. WindFloat is ballasted by seawater and perform an active system to control the ballast moving the water between the columns in order to compensate for the mean wind loading on a turbine. The turbine tower is placed on one of the three columns. Hence, the tower base diameter should be close to the column diameter in order to avoid discontinuities and to reduce stress concentration. Main geometrical sizes are reported in Table 4.2 All geometrical features have been obtained from Principle Power’s documents, except for the heavy plates dimensions that have been hypothesized. The complexity factor is reportef by Table 3.2.

WindFloat	
Dimension	*Value*
Column diameter	10.5 m
Column height	27.5 m
Pontoon length	50 m
Pontoon diameter	1.8 m
Heavy plates diameter	15 m
Heavy plates height	0.25 m
Density	7850 Kg/m^3
Complexity factor	200 %

Table 4.2 WindFloat concept parameters

4.4.3 Pelastar

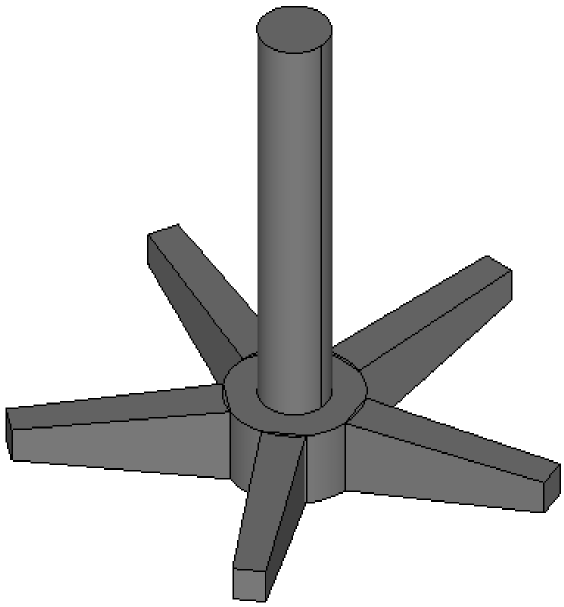


Figure 4.5 Pelastar concept representation

This concept is the Pelastar tension leg platform developed by The Glosten Associates, as part of the Carbon Trust Offshore Wind Accelerator Program [24]. The platform composed of an upper column and a lower hull. The hull is composed of a central body and 5 arms that provide redundancy avoiding any single point failure. In order to obtain a minimum stability during the transport and installation the weight must be well distributed in order to moving the center of gravity toward the bottom. Finally, the platform stability is given by five fiber ropes tendons connecting each arm tip to the anchors. Given the complexity of the structure due to the rounded connection of the arm to the hull, for the in-house tool the geometry assumed describe the hull as five arms connected to a central cylindrical body. The dimensions of the Pelastar platform are summarized in Table 4.2 and all the geometrical values are obtained from Glosten's documents [11]. The complexity factor is defined by a hypothesis comparing the ones of other concept defined by [14].

Pelastar tension leg platform	
Dimensions	*Values*
Column diameter	7 m
Column height (below sea level)	22 m
Hull diameter	18 m
Hull depth	8.5 m
Arm radius	30 m
Arm root width	4 m
Arm tip width	3m
Complexity factor	150 %

Table 4.3 Pelastar concept parameters

4.4.4 Windstar

The last concept is the Windstar tension leg platform proposed by the State Key Laboratory of Ocean Engineering (SKLOE) at Shanghai Jiao Tong University [25]. The platform is composed of a central column and three radiating corner columns and pontoons. These columns and pontoons are disposed in order to create a frame that is supported by the central column. More

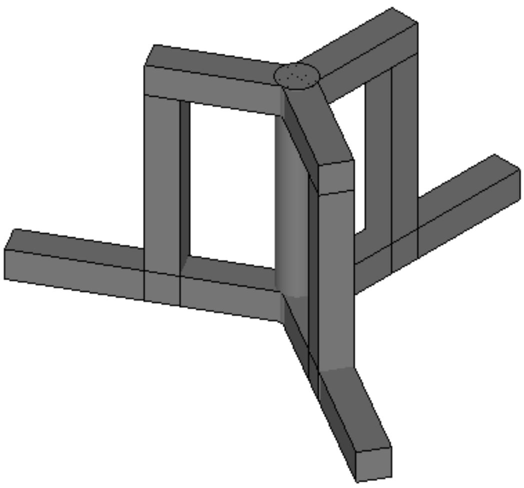


Figure 4.6 Windstar concept representation

specifically, the lower pontoons are longer than the upper one and is where the tendons are connected to the platform. The upper pontoons are used as support to connect the corner columns to the central column. The section of the upper pontoons and corner columns is squared. One of the most interesting features of this platform is that can be integrated at the fabrication yard and towed to the installation site with specially designed temporary buoyancy modules (TBM). In Figure 4.6 can be observed the structure slightly simplified for the in-house tool. In Table 4.4 the geometrical dimensions are reported as described in the State Key Laboratory of Ocean Engineering's study [25]. The complexity factor is defined by a hypothesis comparing the ones of other concept defined by [14].

Windstar tension le platform	
Dimensions	*Values*
Column height	37.8 m
Column diameter	6 m
Lower pontoons radius	39 m
Lower pontoons depth	5 m
Upper pontoons radius	20 m
Pontoons and columns square section	4.8 x 4.8 m
Complexity factor	170 %

Table 4.4 Windstar concept parameters

4.5 Hydrostatic Analysis

Once the main concept features have been defined and discussed, the tool focuses on the floatability and stability of the FOWT system, consisting of both the platform and the turbine. Hence, in the following paragraph the forces acting on the system and the min hydrostatic parameters will be presented.

4.5.1 Gravitational and buoyancy forces

The floatability and the equilibrium are given by the balance between the gravitational force of the system and the buoyancy forces. The first is simply give by the weight of the entire system. The second one is given by the Archimedes' principle, saying that any object partially or entirely immerged in a fluid is lifted up by a force equal to the weight of the fluid that the body displaces. The buoyancy force is calculated by the multiplication between the submerged volume and the fluid density and the gravitation acceleration. At this preliminary stage, the mooring forces are not considered. Equation 4.1 shows the relation between the gravitational forces F_G and the buoyancy force F_B, acting on opposite directions:

$$F_B - F_G = \rho g V - mg = 0 \tag{4.1}$$

m is the weight of the system, comprising the substructure, including steel and ballast material such as concrete or water, and the turbine. Hence, knowing that the water density is 1025 kg/m^3 and the mass of system, we can calculate the submerged volume.

The next step is the calculation of the center of gravity (COG), more precisely the coordinate of the COG. The overall COG is determined considering the structure divide in smaller masses, then the sum of every little mass times their position is divided by the overall mass. All the concepts are symmetric, so only the vertical position along z axis of the COG has been estimated. Equation 4.2 represents the calculation methodology for the center of gravity:

$$COG = \frac{\sum_{i=1}^{n} z_i dm_i}{\sum_{i=1}^{n} z_i} \tag{4.2}$$

where z_i is the position of the COG of the i-th part of the system and dm_i is the mass of the i-th part.

The next step consists in the calculation of the center of buoyancy COB. The center of balance is determined by the center of gravity of the displaced fluid. The coordinate of the COB is calculated by the sum of the volumetric center of each submerged part time the submerged volume, divide by the total submerged volume. Equation 4.3 shows how the COB coordinate is calculated:

$$COB = \frac{\sum_{i=1}^{n} z_{bi} dV_i}{\sum_{i=1}^{n} dV_i} \tag{4.3}$$

where z_{bi} is the volumetric center position of the i-th part of submerged volume and dV_i is the volume of the i-th part.

4.5.2 Metacentric height

Stability is defined as the ability of a structure to manage external excitation and disturbances like waves, currents and wind. The main parameter for static stability analysis is the metacentric height GM, that is defined as the distance between the center of gravity and the metacenter of the system [26]. The Figure 4.7 reports the transversal section of a floating body with the parameters needed to define the metacentric height. In particular, G is the center of gravity, B is the center of buoyancy, M is the metacenter and K is the keel of the structure. The metacenter is defined as a fictive point that is the intersection of the line of action of the buoyancy forces when the body rolls through different angles [26].

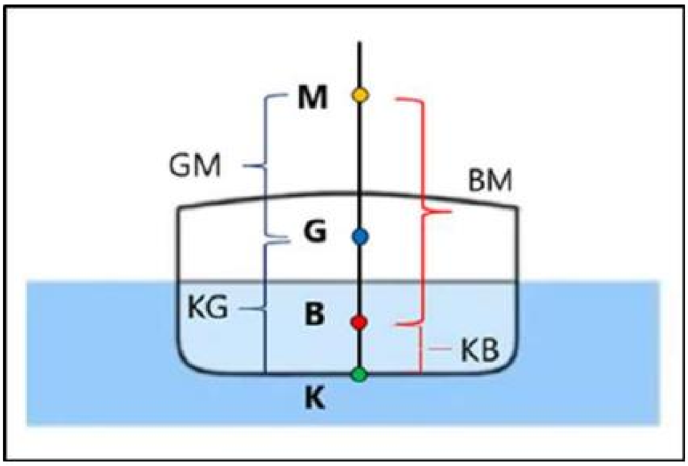


Figure 4.7 Representation of metacentric height

When the metacentric height is major than zero, the structure is considered stable and able to return to the equilibrium position when disturbing forces occur. Instead, when the metacentric height is negative the structure is not able to recover the original position: the structure is not stable and must be modified. In order to guarantee sufficient level of stability, a safe value for the metacentric height is one meter. In this case, assuming small heel angle (less than 10°), the GM can be assumed constant and can be calculated by the Equation 4.4:

$$GM = BM + KB - KG \tag{4.4}$$

where BM is the metacenter radius, that is the distance from the metacenter to the COB, KB is the distance from the COB to the keel and KG is the distance from the COG to keel. Furthermore, the metacenter can be calculated by the Equation 4.5:

$$BM = \frac{I}{V} \tag{4.5}$$

where I is the second moment of area of the water plane area and V is the submerged volume. The second moment of area, commonly called area of inertia, is calculated by the Equation 4.6:

$$I = \int_A x^2 dA = I_0 + d^2 A \tag{4.6}$$

Where I_0 represents the area of inertia of the element calculated with the reference axis in its centroid; the second term is the Steiner's contribution comes from the offset between the actual center point and the part considered.

4.5.3 Hydrostatic stiffness

The following stage of the static analysis is the definition of the hydrostatic matrix, in particular the most significant parameters: heave, roll and pitch stiffness. The calculation methods of these parameters depend on the type of the structure and on the way the structure is stabilized. Hence, the methods to calculate the hydrostatic matrix changes between semisubmersible or spar-buoy and TLP because the stability is related to different factors.

Hydrostatic stiffness for semisubmersible and spar buoy concept.

During the static analysis of floating structures such as semisubmersible and spar-buoy concepts, the stability is given by the buoyancy of the structure. Hence, in this case, we take into account the waterplane area, the submerged volume and the metacentric height.

Therefore, the hydrostatic stiffness in heave is given by Equation 4.7:

$$C_{33} = \rho g A_{wp} \tag{4.7}$$

where ρ is the water density, assumed 1025 kg/m^3, g is the gravity acceleration and A_{wp} is the waterplane area of the structure.

The hydrostatic stiffness in roll is calculated from Equation 4.8:

$$C_{44} = \rho g V G M \tag{4.8}$$

where ρ is the water density, g is the gravity acceleration, V is the submerged volume and GM is the metacentric height.

The hydrostatic stiffness in pitch is calculated from Equation 4.9:

$$C_{55} = \rho g V G M \tag{4.9}$$

where ρ is the water density, g is the gravity acceleration, V is the submerged volume and GM is the metacentric height. In case of axi-symmetric platform, the hydrostatic stiffness in roll and pitch is the same since the metacentric height is the same.

Hydrostatic stiffness for TLP.

The hydrostatic parameters calculations for tension leg platform differs from the other platform like spar-buoy or semi-submersible since the stability is provided by the tendons. For TLP, the methodology for the calculation of the hydrostatic stiffness in heave, roll and pitch is obtained by the re-elaboration of the equations presented in the Withee's thesis [27]. The Equation 4.10 shows the calculation for the hydrostatic stiffness in heave:

$$C_{33} = \frac{3 \cdot n_{tend} E_{tend} A_{tend}}{L_{tend}} + \rho g A_{wp} \tag{4.10}$$

where n_{tend} is the number of tendons, E_{tend} is the Young modulus of the tendon, A_{tend} is the of the tendons and L_{tend} is the length of the tendons.

The hydrostatic stiffness in pitch and roll in the cases analyzed in this work are equal since the platform are symmetric and they are given by Equation 4.11:

$$C_{44} = C_{55} = \frac{3 \cdot n_{tend} E_{tend} A_{tend}}{2 \cdot L_{tend}} \cdot \left(L_{fairlead}\right) + F_{buoy} \cdot z_{cob} + m_{tot} \cdot g \cdot \left(z_{cog}\right) \tag{4.11}$$

where n_{tend} is the number of tendons, E_{tend} is the Young modulus of the tendon, A_{tend} is the of the tendons, L_{tend} is the length of the tendons and $L_{fairlead}$ is the distance from the fairlead to the center of the platform (in the cases analyzed it is the center of the column). F_{buoy} is the buoyancy force given by the product of the submerged volume, the gravity acceleration and water density; z_{cob} and z_{cog} are the z coordinate of the center of buoyancy and center of gravity respectively with respect the z quote of the attachment of the tendons and m_{tot} is the total mass of the system, including the mass of the structure and the mass of the turbine system. In this analysis, the values presented in the previous equations are taken from the study of the Windstar TLP [25], the length of tendons has been hypothesized equal to 100 m.

The hydrostatic stiffness in surge, sway and yaw are ignored since they do not affect the static stability analysis. Furthermore, the hydrostatic stiffness in pitch is very important since the rotation of the platform along the y axis must be absolutely limited. In fact, the pitch motion of the platform involves an inclination of the turbine and consequently a reduction of power production.

4.5.4 Pitch angle

Another important features that must be considered is the effect of the wind on the turbine, that produce an inclination of the turbine tower and a reduction of the energy produced. When a simple one-dimensional model for an ideal rotor is considered, the aerodynamic thrust is the force acting perpendicularly on the rotor plane as result of the pressure drop on the rotor and can be expressed as:

$$T = \frac{1}{2}\rho v^2 A c_t \tag{4.12}$$

where ρ is the air density, v is the wind speed, $A = \pi R^2$ is the area of the rotor and c_t is the thrust coefficient. Through the data available on the site, that provides the thrust coefficient for each wind speed it is possible to obtain the thrust and power curve for the NREL 5 MW wind turbine.

The thrust force, acting on the rotor, produce an overturning moment acting in the center of buoyancy that the system must be able to counter.

Hence, the thrust moment can be calculated as:

$$M_{thrust} = T \cdot d \tag{4.13}$$

where T is the thrust force and d is the distance from the center of the rotor to the COB. In the tool the thrust force considered is the maximum thrust the turbine undergoes in working conditions.

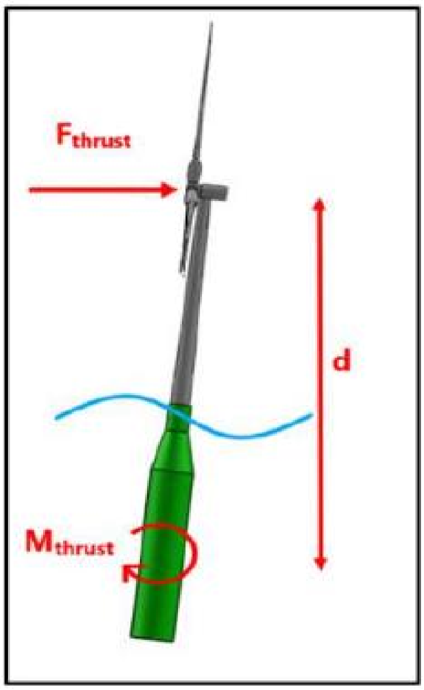


Figure 4.8 Thrust force and moment acting on a FOWT

Finally, the maximum static pitch angle is calculated by dividing the thrust moment by the hydrostatic stiffness in pitch C_{55}:

$$\alpha_{\max pitch} = \frac{M_{thrust}}{C_{55}} \tag{4.14}$$

As defined by the DNV-OS-J103 standard the maximum pitch angle must be limited to 6° and 12° for operating conditions and survival conditions, respectively [19]. To maintain the efficiency as high as possible, the static pitch angle must be limited to 5° in this work.

4.5.5 Natural periods

The natural periods are very important in the design process for FOWT because they are related to the waves. If the system eigen period is similar to the waves period, it will oscillate causing structural and operative problems.

Hydrostatic stiffness and structure inertia strongly affects the formula of eigen periods. Hence, the heave eigen period is defined by the following equation:

$$T_{eigen\,33} = \frac{2\pi}{\sqrt{\frac{C_{33}}{m_{33}}}} \tag{4.15}$$

Where C_{33} is the heave hydrostatic stiffness and m_{33} is the sum of the mass of the structure and the added mass.

Roll and pitch eigen periods are defined by the following equation:

$$T_{eigen\,55} = \frac{2\pi}{\sqrt{\frac{C_{55}}{I_{55}}}} \tag{4.16}$$

Where C_{55} is the pitch hydrostatic stiffness and I_{55} is the moment of inertia.

The Table 4.4 reports the common value of eigen periods for spar, semi-submersible and tension leg platforms, adapted from [28].

	Spar	Semi-submersible	TLP
Surge	>100 s	>100 s	>100 s
Heave	20 ÷ 35 s	20 ÷ 50 s	1 ÷ 2 s
Roll	50 ÷ 90 s	30 ÷ 60 s	<5 s
Pitch	50 ÷ 90 s	30 ÷ 60 s	<5 s
Yaw	>100 s	>100 s	>100 s

Table 4.5 Eigenperiods for different platform designs.

For the final purpose of this preliminary design phase the heave roll and pitch eigen periods are considered, while the others are neglected. Moreover, the pitch and roll periods are the same since the structure are symmetric.

The spar platform presents intermediate values of period in heave, and the largest periods in roll and pitch because of little stiffness in these degrees of freedom. The semi-submersible structures present the lowest value of yaw due to the small inertia in this degree of freedom, and long period in heave due to the large volume displaced. Finally, the TLP are characterized from the lowest periods in heave, roll and pitch with respect to the other type of structure. It means that these platforms have high natural frequencies, which is due to the tension of the tendons that keep the platform stable and safe.

As the standard recommends [19] the natural periods of the platforms should lay out of the energy rich part of wave spectra from 5 s to 25s. Most of the natural periods are above this range except for the tension leg platforms motion in heave, pitch and roll. By the way, the natural periods stay well below the critical periods.

4.5.6 GZ Curve and Restoring Moment

The metacentric height is a parameter for the floating stability of the platform valid only for small inclination angle and so it is defined as initial stability. Hence, as already explained in the previous paragraph, the greater the GM value, the better the platform's stability. When the body suffers a heel, that can be caused by the wind, the gravitational force and the buoyancy force acts on two different vertical lines and the system assumes a condition of imbalance. As can be seen in Figure 4.9, there is a distance between the vertical lines on which the gravitational force and the buoyancy force acts is called. This horizontal distance is called righting arm GZ. The dimension of the righting arm is very important for the stability of the platform since the higher the value, the better the ability to straighten up and recover the stable state. The restoring moment is function of the trim angle η and it can be expressed by the following equation:

$$M_{restoring}(\eta) = -F_B \cdot GZ(\eta) = -\rho g V \cdot GZ(\eta) \tag{4.16}$$

The minus sign in the equation is because of the counteracting effect of the moment for positive values of GZ which is dependent on the trim angle.

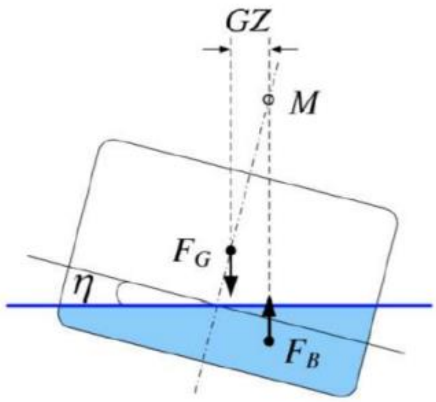


Figure 4.9 Floating structure in heeled condition

The GZ curve and the restoring moment are important parameters especially in the case of semi-submersible platforms. The DNVGL-OS-C301 Standard [29] establishes two conditions that must be verified:

- The area under the righting moment curve to the second intercept or downflooding angle, whichever is less, shall be not less than 30% more than the area under the wind heeling moment curve to the same limiting angle.
- The righting moment curve shall be positive over the entire range of angles from upright to the second intercept.

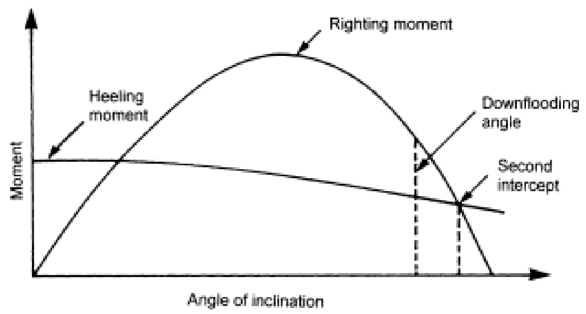


Figure 4.10 Righting moment and heeling moment curves [29]

Chapter 5

Optimization process through Genetic Algorithm

In this chapter the hydrostatic tool previously described has been implemented with a genetic algorithm by Matlab. The purpose for each type of platform for FOWT is to obtain the best concept in terms of weight and cost considering the constraints in terms of stability parameters imposed by Standards.

5.1 Working principle of the Genetic algorithm

Genetic algorithm (GA) is a method for solving constrained and unconstrained optimization problems based on a natural selection process inspired by the mechanisms of biological genetics.

The algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm randomly selects individuals from the current population and uses them as parents to produce the next generation of individuals. Over successive generations, the population "evolves" toward an optimal solution.

According to Matlab guide [30], the syntax for the generic genetic algorithm is written in the following form:

x = ga(fun,nvars)

where ga find a local unconstrained minimum x, for the fitness function fun, and nvars is the number of variables of fun. In this work, the syntax changes in the following form:

[x,fval] = ga(fun,nvars,[ ],[ ],[ ],[ ],lb,ub, nonlcon)

Where fun defines the fitness function, nvars is the number of design variables, lb and ub represents a set of lower and upper boundaries of the design variables x, so that the solution is found in the range of value $lb \leq x \leq ub$ and nonlcon is a Matlab function that contains nonlinear constraints. The nonlcon function accepts x and returns C and Ceq, that represents respectively nonlinear inequalities and equalities. Hence, ga minimizes the fitness function fun such that $C(x) \leq 0$ and $Ceq(x) = 0$. Finally, with this syntax the solver returns the value of the fitness function, fval, at x. In order to obtain the minimum of the function through the genetic algorithm, the following steps are required:

- Variables identification;
- Problem definition;
- Definition and coding of the fitness function;
- Definition and coding of the constraint function;
- Finding the minimum of the fitness function using ga.

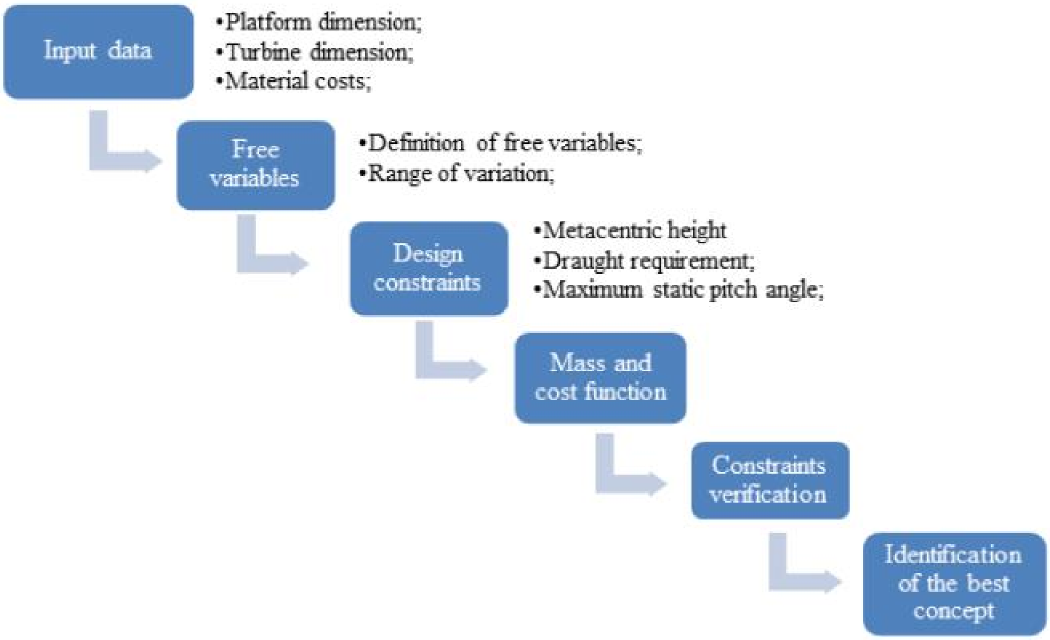


Figure 5.1 Design optimization process through genetic algorithm

In this study the purpose is to use the genetic algorithm to minimize the material cost function for each floating concept presented in the paragraph 4.4 and to find the lightest and least expensive structure.

The first step is the identification of free variables for each type of structure: the free variables are those quantities that characterize the concept, for example column radius, column height or arm radius. Moreover, for each free variable lower and upper boundaries are defined in order to avoid out-of-scale or unfounded solutions. Subsequently, the constraint function is defined and the constraints in terms of stability and buoyancy are imposed, according to the standards. Finally, the cost and mass function are defined and coded, the cost function is then used as fitness function of the genetic algorithm. For each cycle, the solver provides to minimize the fitness function in order to satisfy the constraints, the process is repeated and it last until the value of cost function no longer decrease. The process described is applied for each type of substructure and, at the end, the optimized concepts are compared and the best one in term of material cost is defined.

5.2 Free variable definition

For each type of platform, the free variables are defined among the dimensions that mainly describe the structure. The range of variation of these variables has been also defined, so that the algorithm is able to cycle and to find the optimum structure within that range. The upper and lower limits were chosen through hypotheses, starting from the basic values the most suitable ranges were defined considering common sense and design aspects. In fact, a careful choice of these parameters avoids obtaining from the optimization a structure that differs excessively from the initial design.

5.2.1 HyWind spar buoy

In the HyWind structure, four variables are defined as reported in Figure 5.2:

- Platform diameter;
- Platform height;
- Seawater height;
- Ballast height.

In order to obtain an acceptable concept lower and upper limits have been imposed, as can be seen in Table 5.1:

Free variables	Lower limit	Upper limit
Column diameter	8 m	16 m
Column height	60 m	120 m
Seawater height	0 m	30 m
Ballast height	0 m	30 m

Table 5.1 Free variables upper and lower limits

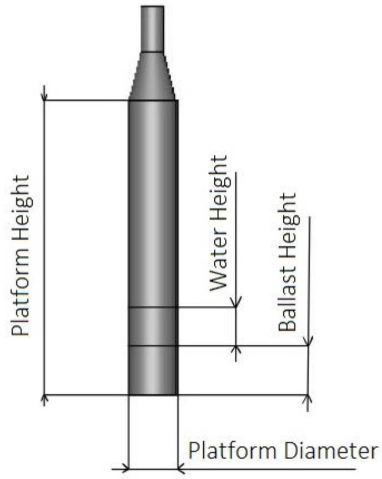


Figure 5.2 Hywind free variables

5.2.2 Windfloat

In the Windfloat design, four free variables have been defined as reported in Figure 5.3:

- Column diameter;
- Column height;
- Pontoon length;
- Heavy plates height.

Moreover, in order to obtain an acceptable concept, the lower and upper limits of these dimensions have been imposed and reported in Table 5.2:

Free variables	Lower limit	Upper limit
Column diameter	6 m	20 m
Column height	10 m	40 m
Pontoon length	20 m	60 m
Heavy plates height	0.25 m	2 m

Table 5.2 Free variables upper and lower limits

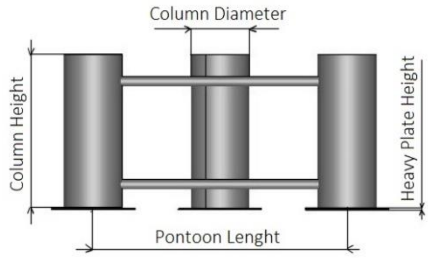


Figure 5.3 WindFloat free variables

5.2.3 Pelastar

In the Pelastar design, six free variables have been defined and they are reported in Figure 5.4:

- Column height;
- Column diameter;
- Hull diameter;
- Hull depth;
- Arm radius;
- Concrete volume.

Moreover, in order to obtain an acceptable concept, the lower and upper limits of these dimensions have been imposed and reported in the following table:

Free variables	Lower limit	Upper limit
Column height	20 m	50 m
Column diameter	6 m	10 m
Hull diameter	12 m	30 m
Hull depth	6 m	20 m
Arm radius	25 m	40 m
Ballast volume	100 m^3	1000 m^3

Table 5.3 Free variables upper and lower limits

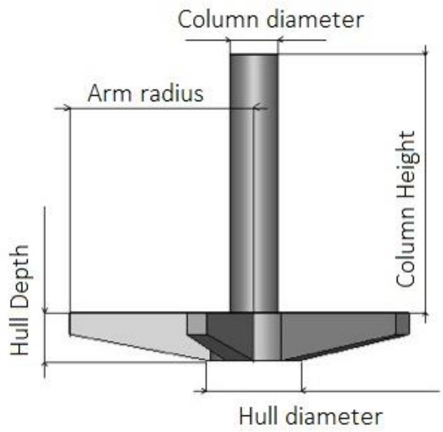


Figure 5.4 Pelastar free variables

5.2.4 Windstar

In the Windstar concept, five free variables have been defined, as reported in Figure 5.5:

- Column height;
- Column diameter;
- Arm radius;
- Arm depth;
- Support radius;

Moreover, the lower and upper limits for these dimensions have been imposed, as reported in the following table:

Free variables	Lower limit	Upper limit
Column height	15 m	45 m
Column diameter	6 m	10 m
Arm radius	20 m	50 m
Arm depth	4 m	10 m
Support radius	10 m	25 m

Table 5.4 Free variables upper and lower limits

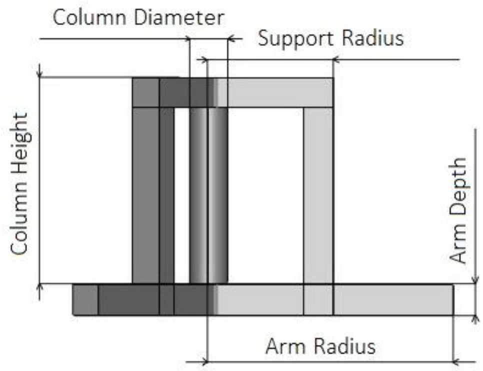


Figure 5.5 Windstar Free Variable

5.3 Material cost

A very important aspect in a floating platform design is the cost of materials; since the size of the structure is imposing, this cost item must necessarily be considered. Modern platforms are generally made by naval steel or concrete. In the platforms considered in this work the materials used are only naval steel and ballast material. In the following table, the density and the specific cost of steel and ballast is reported:

Material	Density	Cost	Source
	[kg/m^3]	[€/ton]	
S355 steel	8500	3000	InnWind.Eu D4.3.3 [20]
Generic ballast	2500	70	InnWind.Eu D4.3.3 [20]

Table 5.5 Materials density and cost

Actually, the density of naval steel S355 is 7850 kg/m^3, but in order to consider the welds and flanges the density has been incremented to 8500 kg/m^3.

5.3.1 Material cost function

The material cost function assumes great importance for the purpose of this work, since this is the fitness function considered by Matlab genetic algorithm. Hence, the algorithm provides to minimize a material cost function subject to nonlinear inequality constraints. The cost function results as the sum of different material weight multiplied by their respective specific costs:

$$f_{cost} = m_{steel}c_{steel} + m_{ballast}c_{ballast} \tag{5.1}$$

Where m is the mass and c is the specific cost for each type of material of the considered platform.

Finally, once the material cost has been calculated, using the Equation 3.2, the production cost of each platform concept has been calculated.

5.4 Design constraints

For the preliminary design of the structure, a set of requirements are defined in order to achieve acceptable value for floating equilibrium, static stability and in order to obtain a structure with acceptable dimensions and proportions.

The methodology for the design constraints definition slightly differs between semi-submersible or spar-buoy and tension leg platform. In fact, while the stability of semi-submersible and spar-buoy stability is determined by the geometrical and physical parameters of the platform itself, for TLP the stability is mainly defined by tendon tension and mechanical properties. So, for TLP platforms the stability analysis is performed for temporary free-floating conditions, like during construction, tow-out and installation, as stated by DNVGL-OS-0119's standard [31]. From a practical point of view TLP's center of gravity, center of buoyancy and metacentric are analyzed as reported in paragraphs 4.5.1 and 4.5.2 while for the hydrostatic stiffness analysis some assumption must be defined. Finally, TLP platforms in free-floating condition shall satisfy the requirements applicable for semi-submersibles and spar-buoys [31]. The design constraints are listed below:

- Metacentric height must be larger than 1 meter;
- The draught must be larger than 10 m;
- Freeboard height must be larger than 5 m;
- Maximum pitch angle should be lower than 5°.

Metacentric height is required to be larger than 1 meter for deep draught floaters as defined by DNV-OS-J103 standard [19], and it is then used as a requirement for the other platforms in this project as well. The draught must be larger than 10 m in order to avoid slamming loads [32]. The freeboard height minimum requirement is defined in order to prevent the turbine tower being at sea level to avoid corrosion phenomena. Finally, DNV-OS-C301 standard [29] states that the intact inclination angle should be limited to 6° and 12° for normal conditions and survival conditions, respectively.

5.5 Results

Matlab genetic algorithm has performed the iteration at least 100 times, the optimized structure obtained from the algorithm may require a little re-elaboration. Each optimization was carried considering the NREL 5 MW wind turbine. The iterations, in which free variables and total cost were larger than the constraints, haven't been considered by the Matlab program itself and haven't been reported.

In this paragraph, the optimized structures are reported with their free variables and the main hydrostatic parameters obtained through the algorithm. For TLP platforms, once the optimized structure is defined by the algorithm, the hydrostatic stiffnesses and the maximum pitch angle are calculated in operating condition using the Equations 4.10 and 4.11 and the maximum thrust of the turbine in working conditions. The mechanical properties of the tendons are provided by the study of the SKLOE about the Windstar platform [25]. So, for the TLP concepts it is reported the hydrostatic stiffnesses values and the pitch angle for both free-floating condition and operating condition. Moreover, for each optimized concept the point cloud crated by the genetic algorithm is reported: it is possible to observe the minimization process of the fitness function through the iterations of the genetic algorithm. Finally, a comparison is performed between the optimized platforms in terms of steel weight and cost.

5.5.1 HyWind

As for the HyWind spar-buoy platform from Equinor, the optimized free variables and the most significant hydrostatic parameters are reported in the Table 1.6:

HyWind	**Optimized value**
Platform diameter	13,75 m
Platform height	93,48 m
Seawater height	20,95 m
Ballast height	16,34 m
Steel mass	2,32 x 10^6 kg
Material cost	7,37 x 10^6 €
Draught	87,28 m
Metacentric height	11,44 m
Stiffness in pitch	1,36 x 10^9 Nm/rad
Pitch angle	4,97°

Table 5.6 Parameters of the optimized structure

In Figure 5.6, the representation of the point cloud obtained by the genetic algorithm is reported.

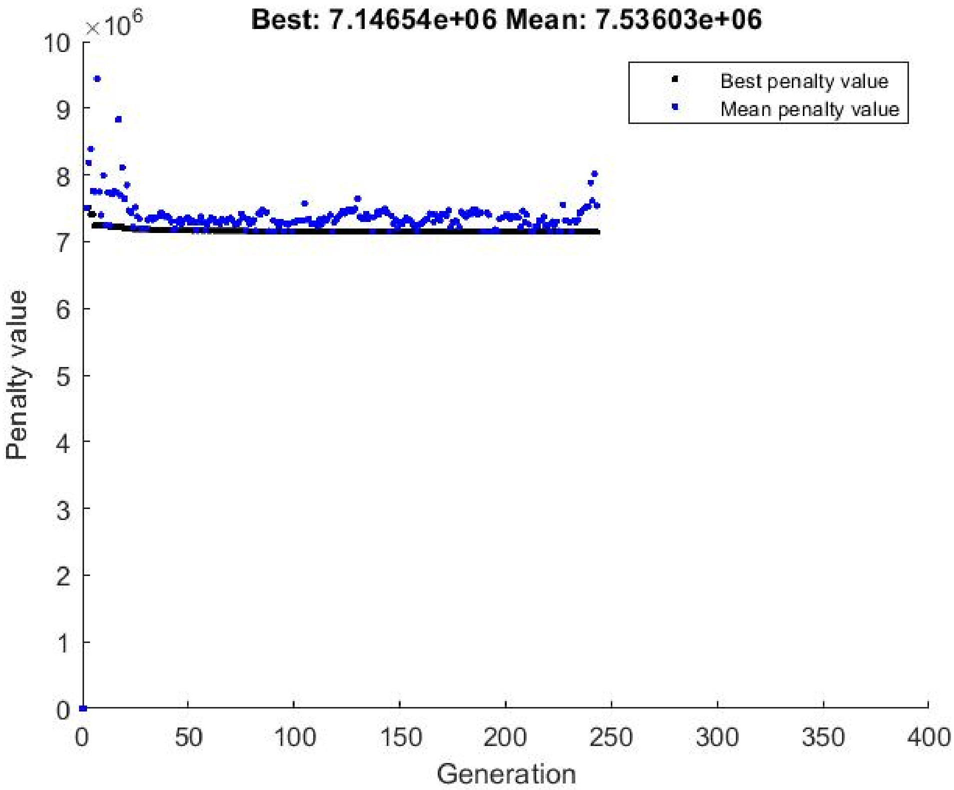


Figure 5.6 Points cloud of the genetic algorithm iterations for the platform HyWind from Equinor

5.5.2 WindFloat

As for the WindFloat semi-submersible platform from Principle Power, the optimized free variables and the most significant hydrostatic parameters are reported in Table 5.7:

WindFloat	**Optimized value**
Column diameter	13,50 m
Column height	19,138 m
Pontoon length	42,00 m
Heavy plates height	0,25 m
Steel mass	$3{,}27 \times 10^6$ kg
Material cost	$9{,}81 \times 10^6$ €
Draught	14,07 m
Metacentric height	14,05 m
Stiffness in pitch	$8{,}88 \times 10^8$ Nm/rad
Pitch angle	5,42°

Table 5.7 Main variables of the optimized structure

The representation of the point cloud obtained by the genetic algorithm is reported in Figure. 5.7

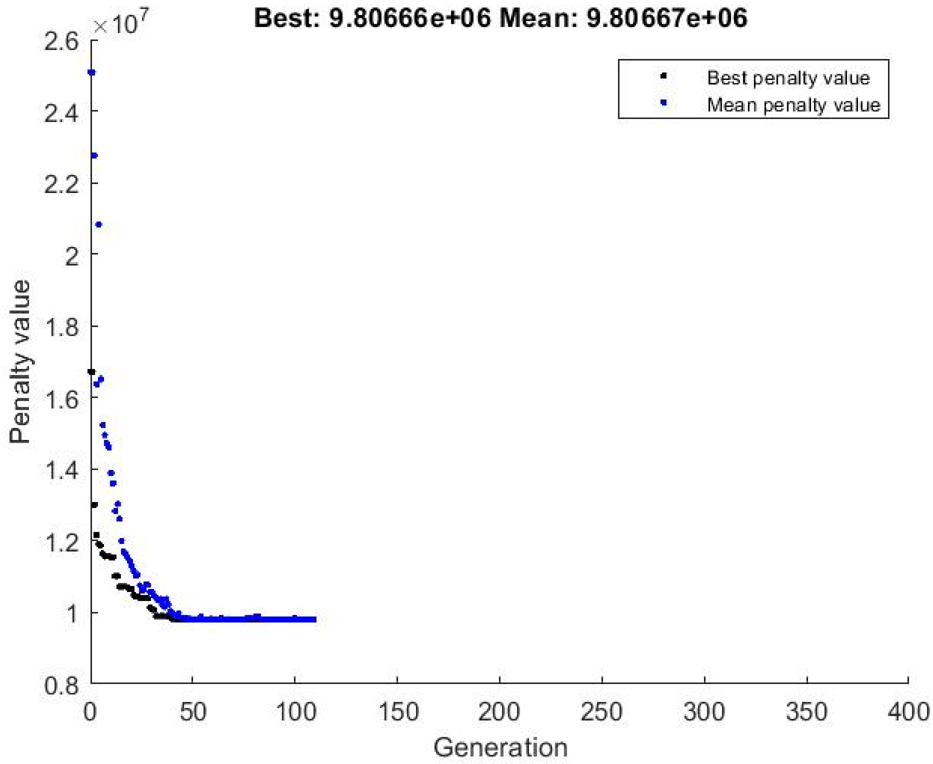


Figure 5.7 Points cloud of the genetic algorithm iterations for the platform WindFloat from Principle Power

5.5.3 Pelastar

As for the Pelastar tension leg platform from The Glosten Associates, the optimized free variables and the most significant hydrostatic parameters are reported in Table 5.8:

Pelastar	**Optimized value**
Column height	25.00m
Column diameter	6.18 m
Hull diameter	12.39 m
Hull depth	6.04 m
Arm radius	25.00 m
Concrete mass	6.73×10^{5} kg
Steel mass	1.60×10^{6} kg
Material cost	4.85×10^{6} €
Draught	25.03 m
Stiffness in pitch	2.28×10^{10} Nm/rad
Pitch angle	0.24°

Table 5.8 Main variables of the optimized structure

The representation of the point cloud obtained by the genetic algorithm is reported in Figure. 5.8.

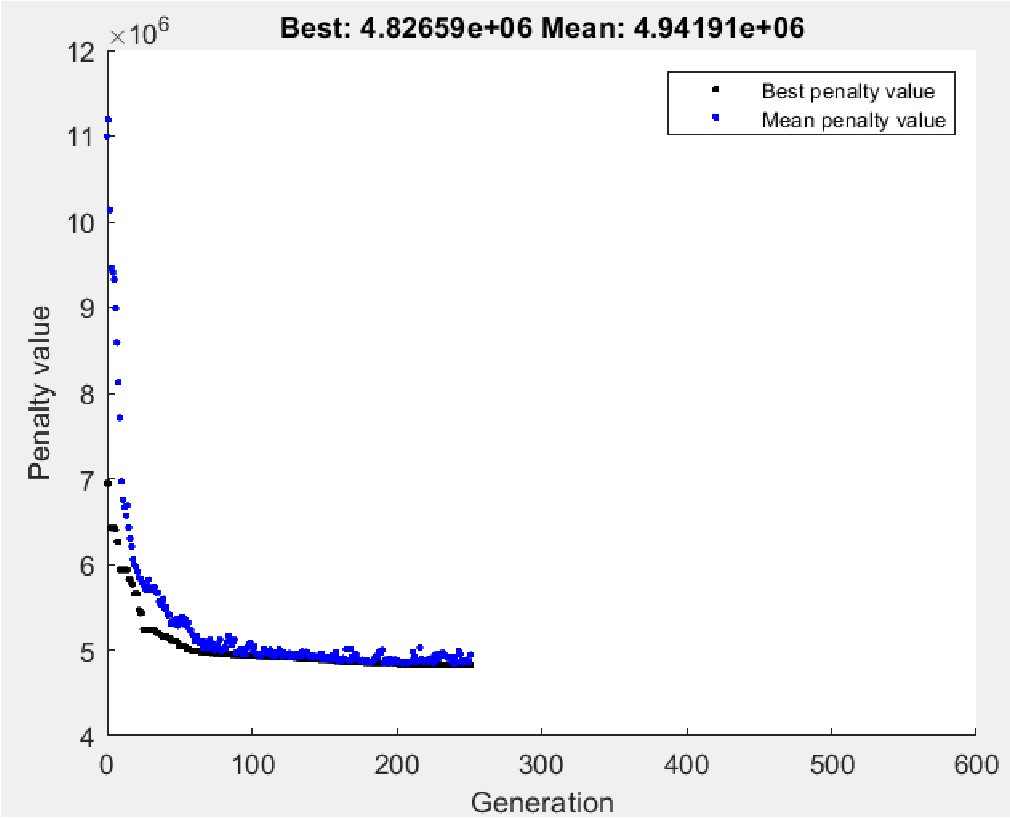


Figure 5.8 Points cloud of the genetic algorithm iterations for the platform Pelastar from The Glosten Associates

5.5.4 Windstar

As for the Windstar tension leg platform from State Key Laboratory of Ocean Engineering (SKLOE), the optimized free variables and the most significant hydrostatic parameters are reported in Table 5.9.

Windstar	**Optimized value**
Column height	15.00 m
Column diameter	6.35 m
Arm radius	28.85 m
Arm depth	4.03 m
Support radius	15.87 m
Steel mass	1.86×10^6 kg
Material cost	5.58×10^6 €
Draught	11.72 m
Stiffness in pitch	1.84×10^{10} Nm/rad
Pitch angle	0.26°

Table 5.9 Main variables of the optimized structure

The representation of the point cloud obtained by the genetic algorithm is reported in Figure 5.9

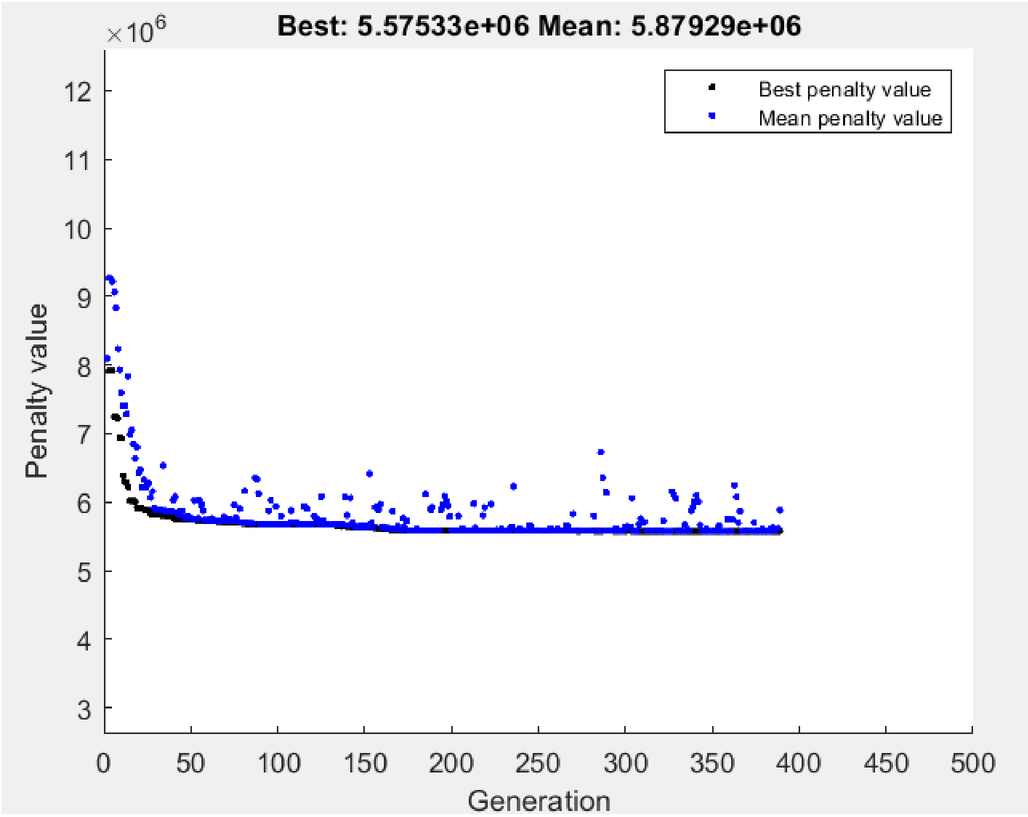


Figure 5.9 Points cloud of the genetic algorithm iterations for the platform Windstar from SKLOE

5.6 Concepts comparison

As stated before, the main driver of the deployment of the FOWT are the mass and the cost of the platforms. Hence, the main results for each substructure are the mass of steel and the material cost and they are reported in the following graphs Fig 5.10 and 5.11.

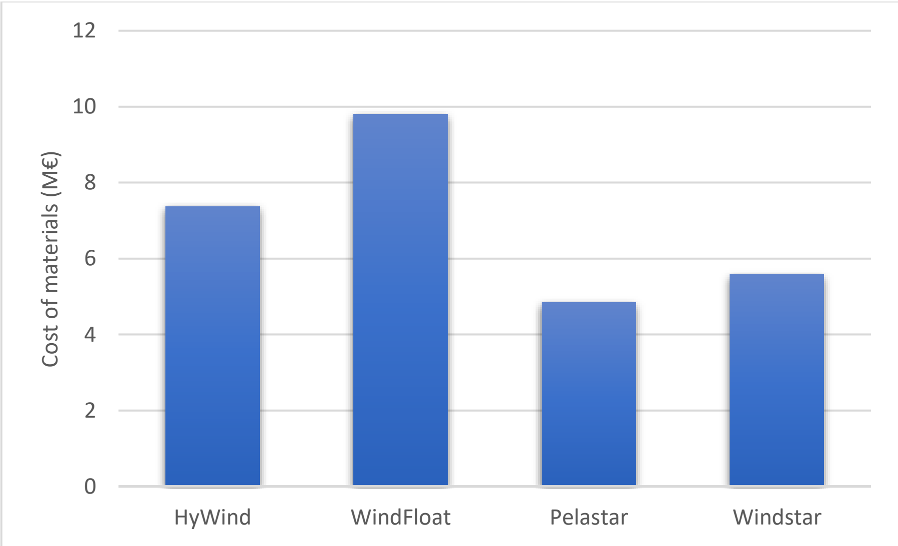


Figure 5.10 Comparison of the structure design based on the cost of materials

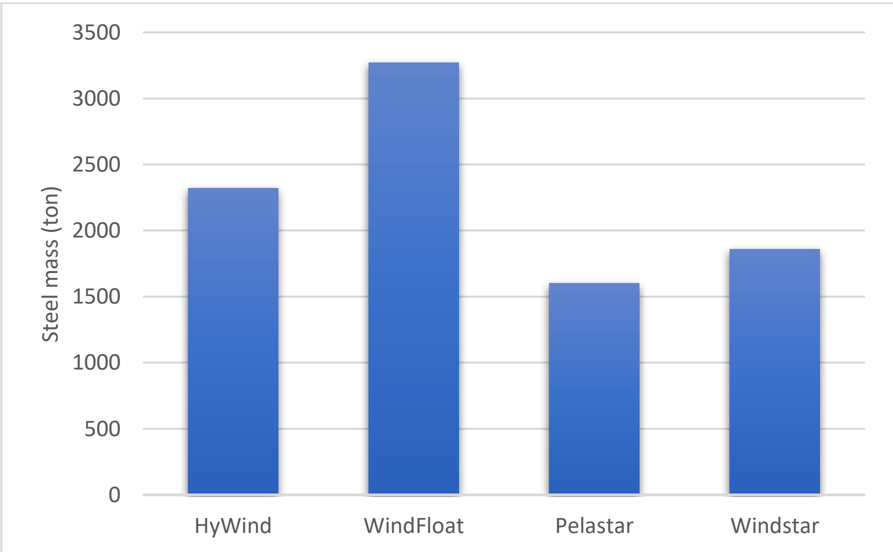


Figure 5.11 Comparison of the structure deign based on the steel mass

Finally, applying the methodology for the calculation of the production cost seen in the paragraph 3.2.1, we can define the production cost for each substructure concept using the complexity factor.

Table 5.10 shows the total cost of each platform design, considering the material and production costs.

Platform concept	***Production cost***
Hywind	16.95 M€
WindFloat	29.43 M€
Pelastar	12.12 M€
Windstar	15.07 M€

Table 5.10 Material and production cost of the platforms

Chapter 6

Conclusions

The purpose of this thesis is to analyze the platforms of offshore floating wind systems and to optimize their structure. In the first part of this work, the state of the art of floating platforms was presented. For each type of substructure, i.e. semisubmersible, spar-buoy and TLP, their main characteristics and properties have been listed. Above all, the way to achieve stability was analyzed and the respective advantages and disadvantages were analyzed. Subsequently, in Chapter 3, the various parts of the floating offshore wind system and the related cost items that make up the CAPEX were analyzed from the literature. In particular, it was analyzed how the cost items relating to moorings and anchors vary according to the different types. A brief mention was made of the electrical system that is used in offshore wind farms.

In the second part of the thesis, the operating principle of the hydrostatic tool and the subsequent optimization algorithm was analyzed. The hydrostatic tool was used to define the main hydrostatic stability parameters for four floating platform concepts: HyWind, WindFloat, Pelastar and Windstar. In this work we have therefore analyzed a spar buoy structure, a semisubmersible structure and two TLP structures since the latter are the least developed and on which the state of the art is not yet at the level of the others. The main hydrostatic parameters are the metacentric height, stiffnesses in roll, pitch and heave and the maximum static pitch angle. Subsequently, the hydrostatic tool is integrated in the optimization process and more precisely in the genetic algorithm of Matlab, obtaining the best structure in terms of weight and cost of the materials. The optimization process using the genetic algorithm consists mainly of three phases.

The first phase involves the definition of the free variables for the different platform concepts, or the definition of the physical quantities that intrinsically characterize the structure and which are modified during optimization. The complexity factor, that will be used for the estimation of the total production cost, is also defined by the literature or by hypothesis. Furthermore, limit values have been defined for each of these variables to avoid structures with out-of-scale dimensions.

The second phase of the process involves the definition of the constraints of the hydrostatic parameters which are defined according to the Standards found in the literature.

Finally, the mass and cost values of the materials are defined through the relative functions. In particular, the cost function is used as a fitness function in the genetic algorithm: at each cycle, the genetic algorithm tries to minimize the cost function in order to satisfy all constraints. The process develops until the algorithm is no longer able to further minimize the fitness function, as a minimum has been reached. The process described above is repeated for each substructure concept, at the end the platforms can be compared based on the mass and cost of the materials to evaluate the convenience of the structures.

6.1 Main results

The main results of this work on the stability of floating platforms, on the estimation of the cost of the substructures and on the optimization of the structure are the following:

- The definition of the most important hydrostatic parameters, such as metacentric height, hydrostatic stiffness and maximum pitch angle provide a preliminary assessment, but further analysis are necessary.
- The cost of manufacturing the structure, which includes both the cost of materials and manufacturing processes, was assessed with the use of multiplying factors, such as the complexity factor. According to the purpose of this thesis, the cost of materials is the only driver that changes the total cost of the structure. Again, this work provides a preliminary assessment of the cost of the structure and further analysis is needed to obtain more accurate cost functions.
- The use of the genetic algorithm is a good solution because it allows to perform the optimization of the structures by minimizing complex functions with many variables. The main disadvantage of using the genetic code is that increasing the free variables requires more computing power and processing time.

As for the results of the optimization process, it can be said that:

- The spar-buoy and semi-submersible structures (such as the Hywind and WindFloat concepts) are already developed and used in commercial projects, so their technology is already well developed. Nevertheless, due to their properties and their principles of stability, they are structures of considerable size that require special infrastructures to carry out their construction, such as dry-docks and ports. In addition, the considerable size increases the amount of material required and this leads to an increase in the price of the structure.

- The TLPs (such as Pelastar and Windstar) are much lighter structures since their stability is guaranteed by the tension of the moorings. The small size and their lightness allow to have fewer restrictions on the construction site compared to the structures but require higher costs in the installation phase due to the requirements that the moorings must respect. Nonetheless, their total cost is lower than structures since less material is required.
- The overall cost of the platform, considering both the cost of the material and the cost of production, is a preliminary assessment since the complexity factor is an estimate that may not be accurate. As for the Hywind and WindFloat concepts, the complexity factors were estimated in 2013 and therefore technological development may have reduced these values. As regards the concepts of TLP (Pelastar and Hywind) these factors have been hypothesized and therefore may have been underestimated.

6.2 Future works

Floating offshore wind turbine technology is still relatively young with much untapped potential. The main factor limiting its further diffusion is the still high investment cost. However, there are ample possibilities for cost reduction in the coming years: floating offshore wind systems are composed of several components that can be optimized to increase energy productivity and improve performance. Furthermore, the development of scientific research and new industrial techniques can lead to a decrease in costs. In this thesis work some topics have not been dealt with, but the conclusion of this work can highlight some possibilities for future developments:

- First, a good development of this work is to create a model closer to the real behavior of the offshore wind system, implementing a dynamic analysis of the structure that takes into account the actions of winds, waves and currents.
- Furthermore, in an optimization discourse, it would be appropriate to also consider the electrical performance, the energy productivity and the type of control of the turbine.

Also at the level of economic analysis there are interesting ideas for future developments:

- It would be useful to deepen the discussion and the analysis of the cost function. At the moment, the analysis concerning production costs has been introduced with the complexity factor, but it is possible to deepen this aspect by investigating the manufacturing processes more precisely. The best thing would be an industrial collaboration to understand in more detail the processes and production costs of the various components of the structure.

- Additionally, an economic analysis that extends to the rest of the floating offshore wind system components, such as mooring and anchoring, can allow for a more accurate assessment of substructures. In fact, as regards some platforms, such as TLPs, the installation cost of the structure, which mainly concerns the type of mooring and anchoring, is a fundamental cost item.

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