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Assessment of Current Offshore Wind Support Structures Concepts – Challenges and Technological Requirements by 2020

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I got interested in the area of offshore wind energy in a conference during my last year of university, and it has been rewarding to work on what I believe is an issue for the future. I hope I can be able to work with wind power also in my professional career.

It was a long, challenging but one-of-a-kind journey. I would like to thank to those who made this project possible.

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Abstract

Offshore wind energy is one of the most promising technologies that the society has to provide an adequate response to our current energy demand. Within the cost drivers of this technology, support structures account for an important share of the total investments costs. Based mainly on technology from the oil & gas industry, there are currently in the market different support structure concepts which intent to achieve a satisfactory outcome to the changeable operational conditions and to help making this energy more cost effective.

Among these concepts, some have a higher representation in the market. In occasions, this difference is due to a longer application history, however, greater adaptability to varying conditions or simply a more advantageous technological solutions may be other causes. One way or another, the offshore wind support structure business continues to renew itself and new concepts and ideas keep on turning up. Thus, the question of which support structure is the most preferable to succeed in the future still remains in the air.

Through a method of technological assessment, this thesis introduces considerations for offshore wind support structures according to the challenges and technological requirements that will affect the development of the industry in the year 2020 and beyond. Applying a Delphi survey and throughout the opinion of independent experts, the thesis initially identify the most likely scenarios by that time and then, it compares the convenience of current offshore wind support structures to overcome them.

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Chapter 1

Introduction

1.1 Background

The increasing demand for energy is a consequence of various factors such as the growth of the world population, the continuous escalation of electricity consumption, the technological development and the impact of emerging economies particularly among Asian countries. A combination of these aspects has brought the necessity of a better exploitation of all our energy resources available.

Some of the technologies that for years were considered as conceptual projects have now turned into part of the solution to our current energy situation. We may not have reached a final solution yet, but step by step, we are creating an energy generation mix that, at least, is making our life not that dependent on fossil fuels.

In fact, our vulnerability to fossil fuels, the fluctuations of their prices or the diplomatic decisions of the fossil fuels producing countries are part of the reasons which led us to the necessity of creating a new energetic strategy. But in addition to these reasons, there is another one which can be considered the main trigger of this new energetic plan, the environmental deterioration and accelerated global warming. Global warming has become one of the greatest challenges our society has to face in the 21st century. The goal is not only to produce more energy but to produce it in the cleanest and most sustainable manner, minimizing, as much as possible, the effect on our environment. Wind energy is one of the most promising alternatives to face these problems. It is clean, there is plenty of it and it will never run out.

In the European Union, the targets set to increase renewable energy have been ambitious. In 2009, all members stated of European Union signed the *Renewable Energy Directive* by which the European Union aimed to boost the share of renewable energy in the European Union to 20% in 2020. According to

EUROSTAT, in 2010, the contribution of energy from renewable sources was estimate in 12.4 per cent of the gross final energy consumption, what reflects a good sign of success in the development of the European energy policies.

Wind power meets an important portion of this increase. In fact, globally, wind energy has seen the greatest capacity addition of any renewable technology [2]. In 2011, it grew at an impressive rate of 20 per cent to achieve, approximately, 238GW by year-end. In the particular case of the European Union, where probably the biggest investments have being made, the wind capacity at the end of 2011 was high enough to produce, considering a normal year, 6.3 per cent of the European's Union gross final consumption [3].

Currently wind energy is mainly produced by means of onshore wind installations. According to data from The European Wind Energy Association (EWEA), in 2011, offshore wind accounted only to approximately 4 per cent of total wind energy capacity installed in the European Union. However, this proportion will increase heavily to a range between 17 and 22 per cent in 2020[1]. In the report "*Pure Power - Wind energy targets for 2020 and 2030"* (2009) the EWEA defined a target between 140 and 190GW and of 40 GW for onshore and offshore wind power respectively [4].

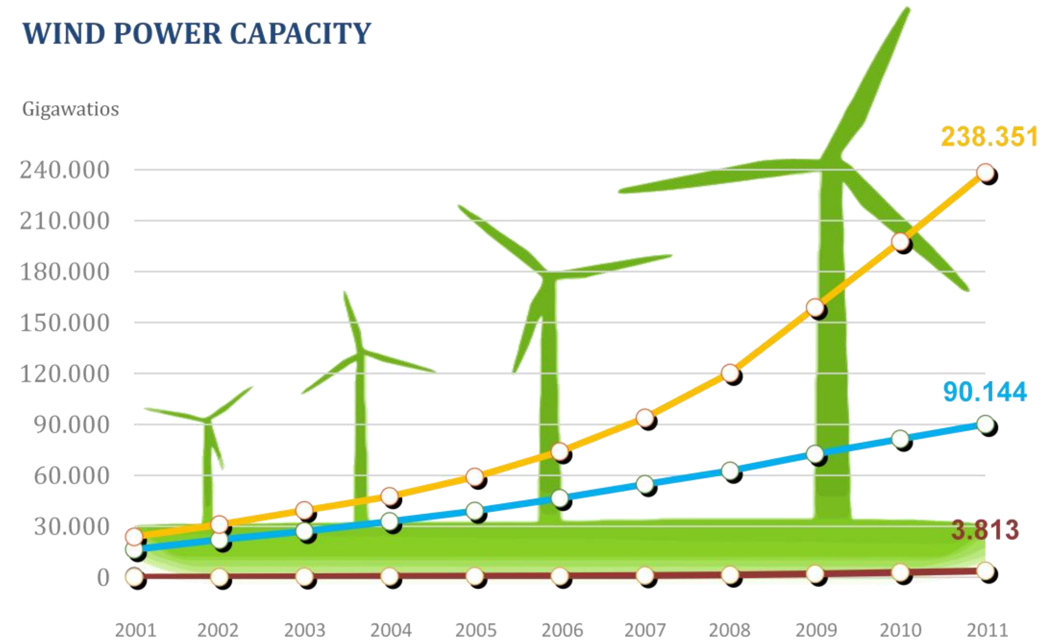

Figure 1. Orange line: global wind energy capacity - Blue line: EU wind energy capacity – Brown line: EU offshore wind energy capacity [1 - 2 - 3]

[1] Figures according to the low estimation of offshore wind energy with regard to the low and high estimation of the total wind energy by 2020

The main difference between onshore and offshore wind power lies in their respective backgrounds, being more complex from a design, construction and operation work point of view in the sea.

Regarding the advantages and disadvantages of these two technological solutions, offshore wind presents important advantages which make the development of its projects more attractive compared to onshore wind. The first advantage is the better quality that the wind has off the coastline. Usually, the further a wind park is from the shore, the faster and more uniform the wind is. As a consequence, the turbulences on wind towers are lower; they are subjected to less fatigue loads and achieve a longer life expectancy.

Other advantages of offshore wind have to do with the location. Some countries are finding problems finding suitable places on land for new wind parks. Offshore wind presents a larger availability of surface for developing projects of big scale than onshore wind. At the same time, it eliminates some of the drawbacks that have been associated to onshore wind, such as the visual impact on the landscape or the noise emissions. In addition to these benefits, it is necessary to add that as there are fewer limitations in the loads size to be transported, installation of bigger wind turbines is possible in offshore wind.

On the other hand, regarding offshore wind disadvantages, the tougher conditions of the sea result in more complex and demanding construction processes. The design and the resistance of the different wind turbine elements have to be selected to withstand the high humidity and corrosion caused by the sea conditions. This mixture of circumstances brings as a result an increase of costs. Currently, offshore wind cost ratios are not at the same level than onshore wind, the costs per megawatt in offshore wind is still too high and its reduction will play a major role in the success of offshore wind during the coming years

Plans to expand offshore wind power are very challenging, nevertheless, its development and expansion need to be led by technological concepts which can be deployed at reasonable costs and make this type of energy production economically viable.

1.2 Target of the research

The aim of this thesis is to study current concepts of offshore wind support structures and decide which ones are the most likely to succeed according to the challenges and technological requirements that the offshore wind industry will have to face in the year 2020 and beyond. The thesis also aims to get a glimpse of how the environment and the properties of the support structures would look like by that time.

The different concepts of offshore wind support structures are described and analyzed attending to their most important characteristics. These support structures are classified as monopiles, gravity base structures, jackets, tripods, tripiles, spar bouyance monopiles and semisubmersible platforms. The first five concepts belong to the group of bottom-mounted structures, while the latter two refer to flouting support structures.

The challenges and technological requirements predicted for the year 2020 and beyond are selected and listed by means of a consensus reached by a group of experts in the field who participate in a Delphi survey.

1.3 Research Methodology

Companies devoted to the development of offshore wind support structures are undertaking a period of extensive research. The industry is moving into new limits, like for instance distance from the shore and water depth, and these firms need to adapt themselves to the new environment so that they can keep up with the current tendency. They are constantly performing their own analysis and studies about current concepts of support structures and comparing them with new solutions or alternatives which may give a better response to the demands of the business.

The goal of this thesis is to predict the future about the types of support structures, their characteristics and properties, which will be a reference beyond the year 2020. It makes this study to be in line with an environment of uncertainty where there is an incomplete knowledge about a specific phenomenon. In this context, it is necessary to undergo a research methodology that can give a satisfactory and precise answer about the future. Besides, it is also relevant to keep in mind that, due to the numerous alternatives and solutions presented in the industry of offshore wind support structures, a tool that can analyze all the different possibilities of decision should be a must.

Within the range of prospective research methods the followings can be highlighted:

- Methods based on the opinion of individuals with a noticeable know-how on the topic to study who share their beliefs in order to reach a consensus.
- Methods based on extrapolating historical data into the future.
- Methods based on the correlation among the different aspects involved in the problem and their grade of influence.

Among these methods, and for the particular case of this study, extrapolation of data is not feasible. As some concepts of support structures are founded on “new” technology, forecasting their historical data is not available. Thus, the number of paths which could be followed to undergo this research is reduced to two.

Methods based on the correlation among the different factors that involved a problem represent a useful solution in order to quantify the relevance of those factors. Nonetheless, the main obstacle here lies in how to measure that relevance, how to score the grades of influence. For example, in the case of offshore wind support structures, scoring the effect of water depth on the structures is out of the reach of non- experts. In fact, even among professionals, different points of view may be identified. As a consequence, the method applied in this thesis cannot rely exclusively on correlation methods but it must be completed with methodologies based on expert’s opinions.

In the case of the latter methodologies, the first challenge that has to be overcome is the selection of a group of experts with knowledge on diverse backgrounds. That is, according to the targets of the thesis, the participation of individuals with expertise on the different types of offshore wind support structures. This will promote the exchange of opinions and will lead to productive discussions. At the same time, attention should also be put in the selection of a representative number of experts to each technology. If possible, equally distributed. The next question to deal with is the way experts are going to interact with themselves. In this case, an important inconvenient is the fact that offshore wind support structure experts are distributed all over the world. Keeping an eye to the list of operational offshore wind projects in Europe (Annex 1), it can be observed that, depending on the country selected, there will be one or another type of predominant support structure. Therefore, direct contact such as interviews, company visits, discussion groups or even international calls, becomes really difficult within the resources and limits of this research.

Given all these considerations, the methodology used in this thesis follows an approach that combines the advantages of methods based on expert's opinions as well as the ones based on correlations. The methodology chosen is the Delphi method, a technique that fits perfectly with these characteristics. It is able to give response to both qualitative and quantitative aspects. In addition, its process also allows to be administered remotely and without direct participant interaction.

Delphi method is a flexible research procedure that has given successfully results on studies where forecasting the future of different technological solutions is a must, suiting really well the targets of this thesis.

1.4 Organization of the Report

Chapter II starts with an overlook to offshore wind power key drivers in terms of investment costs and explains the particular importance of the support structures among them. Following, the chapter gives an overview of current support structures concepts for offshore wind turbines. For each concept it is presented a definition of the support structure design, its manufacturing and installation process and an evaluation of its advantages and disadvantages.

Chapter III introduces the Delphi method that has been used to compare and analyzed the offshore wind support structure concepts presented in chapter II. The chapter begins by defining the basis and principles of the method and follows with a description of the different steps taken during its implementation. The chapter aims to provide sufficient understanding on the method, its assessment and the way it is carried out.

Chapter IV contains the discussion where the results and findings from the Delphi survey are evaluated.

Chapter V is the conclusion where the main accomplishments are presented, and the final evaluation of the report is made.

Chapter 2

State of Art

2.1 Key Drivers

Over the last decades, the wind energy industry has experienced a remarkable transition from the plains and mountains of the earth's crust to new limits beyond our cost lines. The basis of this change is mainly under the better quality of wind which allows a better exploitation of this resource in terms of energy generation. While in the early stage of this transformation wind parks used to be placed near the shore, as the technology developed and improved, the newer facilities were located at more remote areas, giving shape to the current offshore wind industry.

Onshore and offshore wind are two technologies of energy generation that share the same production source but, at the same time, include two opposite backgrounds; land and sea. These different environments affect the approach used in the construction of each type of wind park. For instance, onshore parks, set on land, imply locations with a relatively high accessibility, while on the other hand, offshore wind is surrounded by more hostile and challenging conditions, the sea. As a consequence, it results in a cost increase. If the equivalent to the current available and extensive road network were presented in the sea, the offshore wind installation costs would not raise that sharply compared to onshore wind.

When it comes to costs comparison, offshore wind generation is significantly higher than onshore wind farms. It seems obvious that, a priori, the construction of offshore wind parks will be more expensive and in general more complex than the onshore ones, even though the development of new technological improvement may potentially narrow this gap. In the recent years, however, offshore wind costs have increased rather than dropping, in part due to the rise of material prices (especially steel) and in part by the rapidly increasing demand in terms of supply chain capacity [1].

In 2009, Risø published the report "*The economics of wind power*", highlighting the capacity costs of onshore and offshore wind parks taking into account data from European wind turbine installations. According to the results presented by the report, the average investment cost for an onshore wind farm typically varies from around €1 million/MW to €1.35 million/MW, compared to offshore wind parks which costs can increase up to €2.7 million/MW (*Robin Rigg* wind park data), almost twice as expensive [2].

These figures are also comparable to the estimates stated in McDonald (2010) and Blanco (2009). The former one provides a summary and support documentation of current and future wind power generation costs in the UK, giving onshore investment costs that range between £1.3 million/MW to £1.68 million/MW and £2.32 million/MW to £3.35 million/MW for offshore wind parks [3]. On its side, in 2009, Blanco carries out calculations for new onshore wind projects based on turbine's capacity of 2MW and for 22 offshore wind projects plus 3 near-shore projects put into operation at that time. The estimating capital investment costs for the onshore and offshore projects are around €1.1 million/MW and €1.4 million/MW, and €1.8 million/MW and €2.5 million/MW respectively [4].

A summary of the different report's assumptions is represented in Table 1.

Cost estimates for onshore and offshore wind parks

	Mott MacDonald [(1)]		M. I. Blanco		Riso	
	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore
Low	1.335	2.320	1.100	1.800	1.000	1.200
High	1.680	3.350	1.400	2.500	1.350	2.700

[(1)] For Nth of a kind offshore wind turbine

Data in € million/kW

Table 1. Costs estimation for onshore and offshore wind parks [2 - 3 - 4]

These cost differences between offshore and onshore wind facilities are often attributed to the larger structures as well as to the more complex installation logistic model of offshore wind elements [2]. Table 2 shows an overview of cost breakdown for both onshore and offshore wind. The table gathers data from different sources and represents the value that the different elements have on the total investment costs. Thus, these figures help to identify the cost drivers of each wind energy solution. Several conclusions can be drawn from this table.

First of all, it seems clear that onshore wind is dominated by the cost of the wind turbine itself. According to the figures calculated by Risø, the cost share of turbines represents 75 per cent of total investment cost. On the other hand, this share falls considerably in offshore wind, with percentages that go from 40 per cent, according to RenewableUK report, to 49 per cent in the EEA publication. In general, the design process of offshore wind turbines follows similar trends to the ones onshore, with little modifications to ensure high power performances. These modifications could include larger generators (note that the turbine capacity of the wind parks in the report *Horns Rev* and *Nysted* is 2.3MW but at the moment performances up to 5MW to 10MW are being considered), higher instrumentation specifications, and component redundancy [1].

Secondly, installation procedures are more expensive in offshore wind projects than onshore. As it has already been mentioned, onshore wind locations have a relatively high accessibility, while on the other hand, offshore wind, where transportation and erection are made at sea, presents a more restricted access during construction. Sea conditions are more challenging than on land and furthermore, weather conditions have a higher influence in the installation process.

Another difference between onshore and offshore investment costs has to do with the electrical cable connection which, like in the case of the installation, sees its percentage increased in offshore wind. Connections between turbines and between the farm and the onshore grid generate substantial additional costs compared to onshore wind projects [2]. For the projects built in 2011 in the UK, RenewableUK forecasts figures of 14 per cent, what means an increment of more than 50 per cent compared to onshore wind. This difference is even bigger compared to the EWEA data, but in this case, it is important to highlight that installation costs are also included.

Finally, the support structure costs are heavily more expensive for offshore projects. For a standard turbine placed on land, the support struture's share of the total investment cost is usually around 6 per cent, contrary to the offshore wind in which this proportion ranges between 19 percent and 21 percent. In this case, the reason to such a gap lies in the different design approach that offshore wind support structures require. While onshore wind has basically one type of support structure configuration, in offshore wind they vary from bottom fixed support structures to floating platforms. Besides, their costs depend on other aspects like, for instance, water depth, soil properties, wave loads and currents.

Investment cost breakdown for onshore and offshore wind parks

	Risø [(1)] (2009)	EEA [(2)] (2009)	EWEA [(3)] (2009)	RenewableUK (2011)
	Onshore	Offshore	Offshore	Offshore
Turbine	75	43	49	40
Support structure	6	20	21	19
Installation	2	26		23
Grid connection	9	7	21	14
Project	3	4	9	4
Land infrastruture	5			

[(1)] Costs relative to Financial Costs and Consultancy have been gathered as Project. Costs relative to Road Construction and Land have been gathered as Land Infrastructure.

[(2)] The cost split refers to the EEA (2009) base scenario of € 1.8 million/MW.

[(3)] Installation costs are distributed among the other four elements.

Table 2. **Costs breakdown for onshore and offshore wind [2 - 12 - 4 - 26]**

To sum up, contrary to onshore wind cost breakdown, offshore wind projects are not dominated by turbine costs, but by other main drivers like the electrical or the support structure. The latter one represents the biggest increase, with its proportion being multiplied by almost four times. Support structures become one of the main cost drivers in offshore wind and a matter of enormous interest in order to make the industry more economically efficient. Hence it is of a great importance to select or design the most effective support structure.

2.2 Function

The basic function of a support structure is to maintain the wind turbine in position and to confront the loads caused by the wind, waves and sea current. Besides, the support structure has secondary functions like transferring the energy produced by the turbine or like facilitating the maintenance activities required during the lifetime of the offshore wind farm.

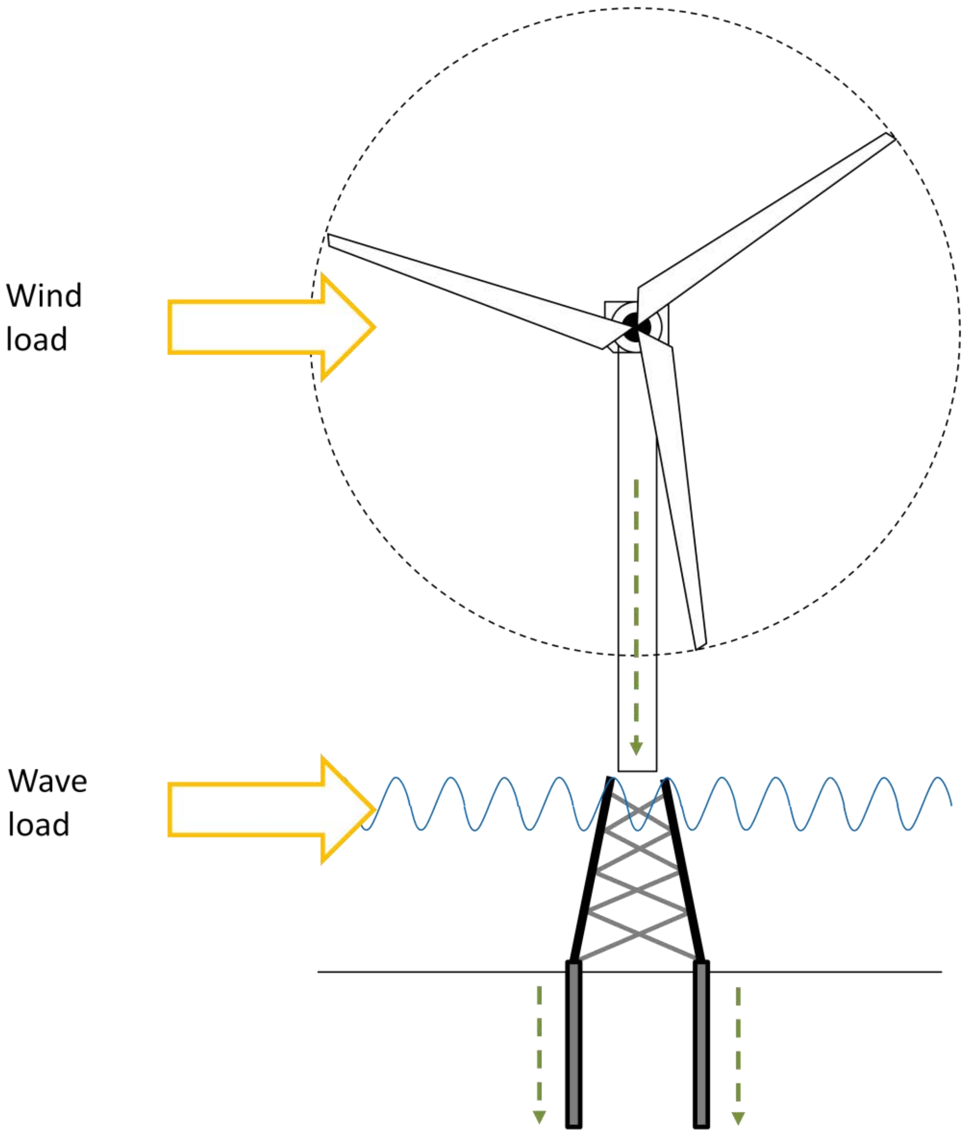

Figure 2. **Loads affecting an offshore wind support structure**

2.3 Definition and components

Definition

Several definitions of offshore wind support structure can be found among different literature references. Sometimes this term is referred as the whole structure below the turbine, as shown in the Figure 3 (A). Other references don't consider the tower and refer to it just as the part above the seabed and below the tower. This definition is represented as the Figure 3 (B). However, for the purpose of this thesis, the support structure will be defined as the whole part below the tower, including the structure under the soil. This interpretation is characterized as the Figure 3 (C).

For its part, the support structure is divided in two main parts, the foundation and the substructure. These components, as well as the other parts of an offshore wind turbine, are described as following:

- **Turbine**: usually made up of two elements, the blades which capture the wind energy, and the nacelle, where the generator and gearbox are set.
- **Tower**: used to support the turbine is usually provided by the turbine manufacturer. Its most common design is a steel cylinder.
- **Substructure**: is the upper part of the support structure, extending from the seabed[1] to the lower part of the tower.
- **Foundation**: is the lower part of the support structure, located in direct contact with the soil. It transfers the loads from the wind turbine into the seabed.
- **Mooring**: is the system employed by the offshore floating wind turbines to connect the floating structure to the seabed.

[1] Note that not all types of substructures concepts are covered by these definitions. For instance, for a gravity base structure the base slab standing out the seabed can be considered part of the foundation.

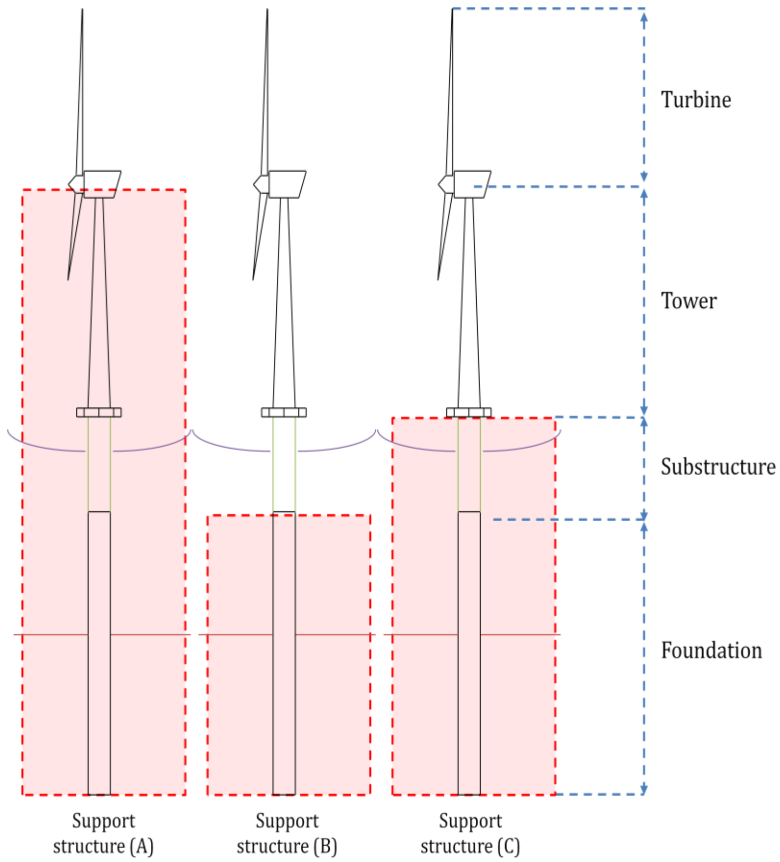

Figure 3. **Support structure definitions and components.**

Components

In 1991 *Vindeby WindPark* became the world's first offshore wind park. Built in Denmark and with a total output of 4,95MW the park consists of 11 wind turbines of 0,45MW each. These turbines stand on robust and heavy gravity base foundations made of concrete. These structures, based on the accumulated experience of the oil & gas industry in the North Sea, were very stiff and heavy compared to the slender turbine. The design showed several advantages and contributed to the construction of the next offshore wind farm, *Tunø Knøb*, five years later. In general terms, this learning process from old projects to new ones, has continued step by step until the current days, with an important number of lections already learnt.

In the search of costs optimization, the offshore wind industry started to use other types of foundation and substructures. At the moment several are the types of support structures that have already been used in the construction of offshore wind parks, monopiles, gravity base, tripods or jackets are some examples. In fact, the number of combinations and variations of both foundations and substructures are numerous. In 2009, a competition carried out by the UK fund Carbon Trust, attracted 104 types of support structures around the world aiming to reduce the costs of these structures by developing new foundations and installation techniques [6].

The current state of art in the offshore wind support structure industry can be classified within two groups, bottom mounted-fixed support structures and floating platforms. The difference between them lies on the way the wind turbine is attached to the seabed. While bottom mounted-fixed support structures come from the seabed, in the case of the floating support structures they come from the water and are in contact to the seabed through mooring cables.

The support structures belonging to the bottom mounted-fixed group can be categorized by the type of foundation used in the construction. These alternatives basically consist of:

- Pile foundation
- Gravity base foundation
- Suction bucket foundation

The common solutions used by the offshore floating support structures to connect the mooring systems to the soil are:

- Anchors
- Piles
- Suction bucket

With regard to the structural configuration, bottom mounted-fixed support structures can be categorized into five basic types:

- Monopile structures
- Gravity structures
- Tripod structures
- Jacket / Lattice structures
- Tripile structures

For floating support structures, three types with high potential for offshore wind applications are:

- Spar floater structures
- Semisubmersible structures
- Tension leg platforms

The different categories and subcategories for both bottom mounted-fixed and floating structures have been represented in the Table 3.

Offshore Wind Support Structures			
Bottom-Mounted Fixed Support Structures		Floating Support Structures	
Structure	**Foundation**	**Structure**	**Foundation**
Monopile	Pile	Spar Floater	Anchor
Gravity	Gravity Base	Semisubmersible	Pile
Jacket	Suction Bucket	Tension Leg Platform	Suction Bucket
Tripod			
Tripile			

Table 3. **Different types of foundations and substructures of offshore wind support structures**

Foundation

Within the whole picture of support structures, different concepts of foundations can be identified. These solutions usually come from the oil & gas industry. For bottom mounted-fixed support structures the most common solutions are piles, suction buckets and gravity base foundations.

- **Pile foundation**: is by far the most popular form of foundation used for offshore wind. It is basically an open-ended tubular element which is installed by drilling or driving the structure into the soil in order to transfer the loads from the turbine. A pile can be installed in a vertical position or at an inclination, producing a permanent and precise location. Currently the largest pile yet installed is at *London Array* wind park and has a length of approximately 60m, a diameter of 5.7m and penetrates around 25 into the seabed [36].
- **Gravity Base foundation**: is the most common alternative to the pile foundation, but contrary to this, the gravity base is not driven into the soil, but rather rests on the seabed. It relies on its dead weight to retain the structure's stability. Sometimes, if necessary, once in position on the seabed, the gravity base weight can be increased by adding supplementary ballast such as sand, concrete, rock or iron.
- **Suction Bucket foundation**: lighter than the gravity base foundation, the bucket foundation is a large diameter cylinder with a closed top. After it is placed on the seabed a pump is activated to remove water from within the bucket, and thus, creating a pressure difference with respect to the ambient pressure, resulting in a downward force. As a consequence, the bucket foundation is pressed down into the seabed. Once the pump is deactivated skin friction and end bearing will keep the foundation in place and provide the required bearing capacity.

In the case of floating support structures, piles and suction cans are also used to attach the mooring system of the structures. In addition, anchors are another solution used for this purpose.

- **Anchor**: is a device which connects the offshore wind turbine to the seabed so that it can hold its position. There are four types of different seafloor anchors: gravity-base, driven pile anchor, suction anchor and drag-embedded anchor. The first three systems rely on the same principles as their respective foundation concept. On its side, the drag-Embedded Anchor is a structure dropped to the seabed and dragged so that it can achieve deep embedment. When pulling horizontally the anchor mobilizes the shear strength of the soil to resist the pulling force. The project *Hywind*, a full scale floating offshore wind project, uses drag anchors as foundations.

Secondary steel

Secondary steel items are attached on the substructure to facilitate the access to the wind turbine as well as the transference of electricity and the protection of the structure itself. Depending on the structure type, several or all of the following items represented in Figure 4 can be presented:

- **Boat landings platform**: manufactured in steel, the boat landing platform is located at the base of the tower and allows vessel to moor. Personnel and equipment can access to the substructure to check for faults and make possible repairs.
- **Access ladder**: communicates the boat landing platform with the main platform. The ladder must fulfill some security requirements in order to guarantee the personnel safety.
- **Main platform**: represents the safe working area for personnel who need to work on the structure. In occasions the platform is equipped with a foundation crane that improves and makes easier the maintenance operations. Usually is made up of steel though in some projects concrete has been the material used for its manufactured. For instance, the platforms of *Horns Rev 2* in Denmark are an example of the concrete solution. The advantages presented on concrete platforms compared to a steel platform relates with its resistance to corrosion and its lifetime maintenance.
- **J-tubes**: tubes made of steel that aim to protect and guide the electrical cable going to the support structure. The name comes from the shape that the tubes make as they curve near the ground, allowing the cable to go from its underground trench to the turbine.

- **Sacrificial anodes**: to minimize corrosion, the support structure is supplied with cathodic protection both outside and inside. That is, nodes made of aluminum are used as the sacrificial material.

Figure 4. **Secondary steel items [39]**

2.4 Review of Concepts

As mentioned on the previous section, the possible combination of existing substructures and foundations is numerous. Besides, in terms of support structure development, the offshore wind industry is in a constant search of becoming more competitive, launching periodically new updates or concepts. A study of all these alternatives would be out of the reach for the purpose of this thesis. Therefore, in this point, a selection of the most established solutions has been made:

- **Monopile structure**
- **Gravity structure**
- **Jacket structure**
- **Tripod structure**
- **Tripile structure**
- **Spar bouyance monopile structure**
- **Semisubmersible structure**

Each technology has been described attending to its principal basis of design, current situation on the market, as well as steps or requirement during the manufacturing or installation process. For some concepts existing alternatives during these stages has also been presented.

Figure 5 represents a sketch of the different support structure concepts.

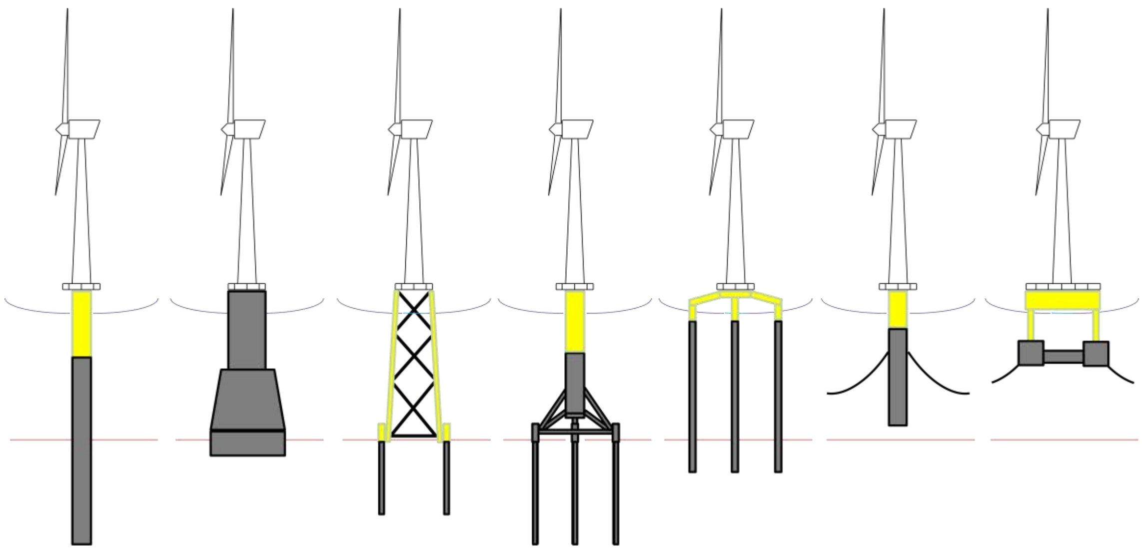

Figure 5. Types of support structure concepts. From left to right: monopile, gravity base, jacket, tripod, tripile, spar and semisubmersible platform

2.4.1. Monopiles

Monopiles are by far the most common offshore wind support structure. Only in the UK 13 offshore wind farms, out of the 15 fully commissioned at the end of 2011, are based on monopiles [Annex 1]. Besides, this solution has been used in other countries such as Denmark, Belgium, the Netherlands, Ireland or Germany. Within the European offshore wind picture, more than 50 percent of all the projects are built on this support structure solution.

The roots of this monopiles come from the North Sea oil & gas industry, a sector where monopiles have been used for decades. This has allowed their implementation in the offshore wind business at a low risk and with a wide range of existing practices.

The design of the monopile is quite simple, consisting of a cylindrical foundation pile and a transition piece (transitional section between tower and monopile) which together could be identified like a continuation of the turbine tower. The support structure transfers easily the vertical loads into the soil, being more exposed to the action of lateral loads. This loading together with the maximum water depth and seabed conditions determine the diameter of the structure to provide enough stiffness.

Depending on the sea bed conditions, there are basically two ways for the foundation pile to be installed. If the seabed presents a rocky structure, previous to the foundation pile installation, a drilling process is required. Otherwise, the foundation pile can be driven and placed firmly in the seabed with the use of a vibrating hammer.

An important aspect to consider during the monopile installation process has to do with the erosion that water currents produce on the pile at the seabed level. As water flows, the layer of soil covering the pile has a tendency to be reduced and therefore, the length of the pile exposed to hydrodynamic loads increases. To avoid this effect score protection is provided. This protection is constituted by layers of stones placed around the pile. A first layer of small stones is dumped on the seabed acting as a filter so that the sand keeps in place around the pile. Consequently, a second layer of larger stones is deposited over the first one to maintain the set steady.

After the foundation pile is set, the transition piece is mounted onto it using a specialized grouted joint. This grouting eliminates the tolerances existing between the pile and the transition piece during the installation and helps to transfer the loads from the wind turbine tower down to the seabed. The problem with this type of connection is that over the time, due to the forces of wind and waves, the grouting crumbles, resulting in the need of refilling operations. In order to solve this grouting problem, conical design concepts for the transition piece have been launched. This is for instance the case of the support structures in offshore wind park *Walney 2* in the UK [37]. Figure 5 represents the differences between the old grouting method and the solution used in the conical concept.

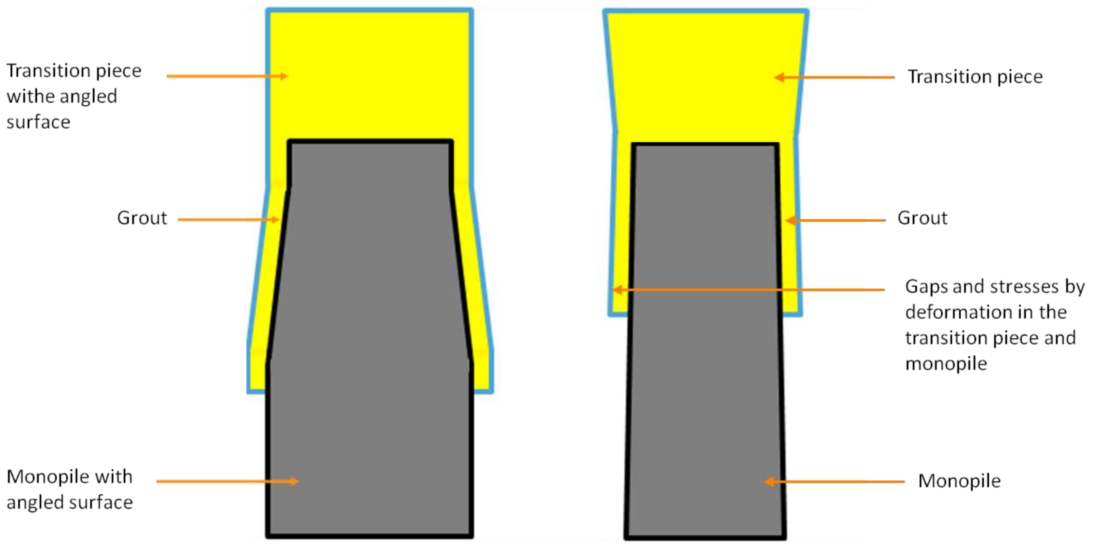

Figure 6. [1] **Grouting connection. Left side the new conical design and right side the old method [36]**

In general terms, the relatively simple fabrication and installation process have made monopiles the most widely used support structure. Nevertheless, they present some limitations in terms of water depth. According to a survey deployed by KPMG on the offshore wind in Europe [5], monopile support structures are not feasible for waters deeper than 40m. At the moment, the offshore wind park located at the deepest water depth corresponds to *Belwind Phase I* at 37m [Annex 1].

[1] The deformation and gap sizes have been significantly enlarged for illustration purposes only and are not true to scale to actual events.

Monopile Structures

Advantages	Disadvantages
Simple and quick fabrication process	Limitations of fabrication and handling from certain sizes
Proven concept	Limitations due to heavy installation equipment (hammers)
No seabed preparation required	Large scour protection required
Low price per ton of steel	Flexible at water depths
High serial production	Limited to large water depth
	Difficult to remove after design life

Tabla 4. Monopile - advantages and disadvantages

2.4.2 Gravity base

Gravity base was the support structure of the world's first offshore wind park in 1991. At that time, 11 concrete structures weighted over 900ton each and were placed in Danish waters. In fact, gravity base represents the majority of the support structures used in that country. The last of these offshore wind parks is *Nysted 2*, built in 2009 locates 90 structures weighting from 1,200 to 1,800ton each excluding the ballast [Annex 1].

Gravity base support structures relay on their weight and ballast to retain the tower and turbine in place. The base structures are made of steel reinforced concrete on which the tower is placed. There are different designs with regard to the base structure. The first models had circular designs but since some shapes are difficult to process in concrete the design changed toward rectangular forms.

An advantage of the gravity base is that the structure can be extended to the platform level and thus, since there is no need to install the transition piece, the number of offshore installation activities is reduced.

Regarding the transportation, in the most common case, the structures are driven on a barge to the location site. In other cases, the support structure is floated and towed to the installation site. This latter possibility produces an important reduction of costs.

During the installation stage nor drilling or hammering is required. Nonetheless, the gravity based support structure needs the seabed to be horizontal and prepared with a layer of crushed stones, what in the end, increases the total cost. Besides, the total cost is generally in line with the water depth, being levels over 20m difficult to reach an economical feasibility. Once the gravity base is placed on the seabed, ballast is filled or layed on its base. The ballast used consists of sand, iron ore or rock, and its weight increment represents up to two thirds of the final weight.

Once the whole installation process is finished, a final advantage of this support structure has to do with its long lifetime, exceeding over 100 years with little maintenance.

Gravity Base Structures

Advantages	Disadvantages
Reduced fatigue sensitivity compared to other concepts	Limitations of transportation and installation due to the high weight
Low environmental impact due to the absence of piling during the installation	High production cost
No transition piece installation	Challenging logistical requirements
Low levels of corrosion protection	Require seabed preparation
Posibility to be internally J-tubed	Not suitable on soft seabed surfaces
The structure can be floated	Requires special operations on deep waters
Long lifetime	

Table 5. **Gravity base - advantages and disadvantages**

2.4.3 Jackets

Jackets have been more recently accepted in the offshore wind industry for projects such as *Alpha Ventus* in Germany, *Beatrice Demonstration* and *Ormonde Park* in the UK, appearing to gain acceptance in deeper waters. Until 2007, other support structures like monopiles or gravity base were only able to put wind turbines in water depth up to 20m, but the *Beatric Demonstration* wind park established water depth from 20 to 45m.

Jackets were among the very first structures to be used in the offshore oil & gas industry. A jacket is a structure made up of three or four legs connected by slender braces. All the elements are tubular and they are joined by welding. Each of the joints has to be specially fabricated, taking a lot of time to complete the whole structure.

Like monopiles, jackets need a transition piece to support the wind turbine tower. Melting the transition piece with the jacket substructure becomes one of the key activities during the jacket manufacturing. The transition piece is designed to ensure that the forces acting on the wind turbine and tower are distributed to the four legs of the jacket and into the seabed.

Once the substructure is fully assembled, it is transported on a barge to the installation site where it meets with the installation vessel. There are two procedures when it comes to install a jacket: pre-pilling and post-pilling. Post-pilling is the more traditional way and this method was used during the construction of *Beatrice Demonstration*. During the post-pilling the structure is usually attached into the seabed using piles driven through sleeves at the bottom of each jacket leg and then hammered or vibrated in the soil. On the other hand, pre-pilling installs the piles before the jacket is lowered to the seabed. A template is used to drive the piles at an exactly distance from each other. Afterwards, the gap between the sleeves and the piles is secured by filling a special grouting material. The pre-pilling option allows spending less time during the installation of the jacket and consequently saving costs. Pre-piling was done for the first time ever on the installation of the German project *Alpha Ventus*.

In the near future it may be possible to see variations or new concepts of jackets where, for instance, the transition piece weight is reduced, the jacket and the tower are integrated in a unique element or a new design of a twisted jacket will be used instead of the conventional method.

Jacket Structures

Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopiles	Large number of joints required compared to other latticed structures
Economically viable on transitional/deep waters	Logistical issues due to the templates (prepiling case)
No scour proteccion required	Complex connection to transition pieces
Structural redundancy	
Low soil dependency	
Good response to wave loads	

Table 6. Jacket - advantages and disadvantages

2.4.4 Tripod

Even though this support structure is known in the oil & gas industry, so far, there is only one offshore wind project supported on this solution, *Alpha Ventus* in Germany. By 2015 another project, also in Germany, will be add to this list, *Borkum Phase 1*, where 40 wind turbines will be installed on tripods of approximately 700ton of weight each [40].

A tripod is a standard three leg structure made of cylindrical steel tubes. These legs are connected to the main tubular, in the center of the structure, making the transition to the wind turbine tower. The substructure is driven into the seabed using foundation piles through sleeves at the end of each leg.

The standard installation procedure is to load several tripods onto a barge and tow them to the location site where the support structures are lifted by a crane and guided to the final position. At this stage, piles are driven into the seabed through each sleeve and connections between piles and sleeves are filled with concrete or grouting. It does not require any seabed preparation.

Although tripods have been used only in one offshore wind park so far, they present several benefits compared to other types of support structures. For instance, with respect to monopiles, tripods transfer loads to the soil in a different way. From the main join downwards the three legs, as well as the piles, tripods are loaded axially, allowing the structure to be shallower and lighter than monopiles. Besides, tripods also have the potential for sites far away from the coast line and thus for deeper water. Manufacturing at great distances from the location site are not considered to be a problem since tripods has a light weight structure. Nonetheless, problems may arise when they are installed at waters below 6 to 7 meters due to the requirement for sufficient water depth for service vessels.

Jacket Structures

Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopiles	Limitations of transportation due to the width
No seabed preparation required	Limitations of storage due to large sizes
No scour protecction required	Slow fabrication process
Posibility to be internally J-tubed	Impractical in shallow waters
Easy to remove after design life	Main join susceptible to fatigue

Table 7. **Tripod - advantages and disadvantages**

2.4.5 Tripile

The tripile is a relatively new interpretation of the traditional monopile. This support structure patented by BARD Engineering was first tested in the *Hooksiel* (a single support structure) in Germany, containing about 1,100ton of steel and holding a wind turbine of 5MW capacity. In 2008, BARD Engineering started the construction of *BARD Offshore I*, a 400MW wind park distributed in 40 turbines all of them standing on triples. Currently, there are four offshore wind plants planned to be installed making used of Bard tripile support structures, amounted to a total of 260 wind turbines.

A tripile is made of three individual tubular steel piles and a three-legged transition piece placed on top of them and connecting with the turbine tower. The transition piece is welded from flat steel elements and weights around 490ton. The joins between the piles and the transition piece are grouted permanently.

An advantage presented in this support structure is that it can easily be adjusted to accommodate water depth variations. While the transition piece dimensions can be maintained, the pile dimensions can be adjusted to suit the site.

During the installation the piles are first driven into the seabed. Afterwards, with the top of the piles rising above the water, the transition piece is placed on top, with each leg-end aimed into a pile. This stage of the installation process requires high accuracy, making sure that the transition piece fits inside the piles. For this purpose, a piling template is employed ensuring the good positioning of all the elements.

Tripile Structures

Advantages	Disadvantages
No bolted or welded connection between piles and transition pieces	Complexity of transition piece manufacturing
Easily adjustable to water depths	Complexity of transition piece installation
Loads transferred by the grout alone	Only one test facility to date
Compact construction relatively cost-effective	
All connections above the water surface	
Less dependency on weather conditions	

Tabla 8. **Tripile - advantages and disadvantages**

2.4.6 Floating support structures

Floating support structures have appeared in the offshore wind market as a consequence of the tendency within this industry to move into deeper waters. Since the first gravity base installed, going through monopiles, jackets or tripods, offshore wind parks have gone, step by step, into deeper and deeper waters. The main reason behind this transition yields on the better quality that wind presents at those locations.

But for some countries going deeper is not only a matter of a better wind resource but a requirement of the morphology of their seabed. Countries like Japan, Norway or Spain present the majority of their offshore wind resource over deep waters. This counters with some European countries, such as the United Kingdom, Germany, Denmark and the Netherlands, where shallow water sites appear to be abundant, and therefore, the installation of wind parks at those water depth levels should still proliferate.

Another example of the need to develop technologies, like floating support structures, for deep waters is the case of the United States. In the United States approximately 500 MW of shallow water development is underway, but up to date, because some legal obstacles, no installations have been permitted. On the other hand, deep waters are not affected by those terms. The National Renewable Energy Laboratory operated for the United States department of energy estimated the offshore resource to be greater than 1000 GW. Only about 100 GW are over shallow waters, the remaining of offshore wind resource is over deep waters. It represents another sample of the importance of this market niche [27].

Floating offshore wind has been in the works for a while. Consortiums of companies, academic institutions and research organizations have developed different projects of offshore wind floating foundations [28]. However, at the moment, three main types of floating foundations, each one based on a different solution, can be identified:

- **Spar bouyance monopile**
- **Semisubmersible platform**
- **Tension leg platform (TLP)**

All these solutions have their origin in the oil & gas industry, but modifications and hybrids are beginning to emerge in their use for wind turbines.

Up to now, there is just a couple of full scale projects of offshore wind turbines standing on floating support structures, *Hywind* in Norway and *Windfloat* installed off the coast of Portugal. Furthermore, there are other two scale models, the *Blue H*, near Italy, and *Sway*, a prototype in the waters of Norway.

The following paragraphs describe the details of these support structure concepts as well as projects based on those technological solutions.

Floating Support Structures

Advantages	Disadvantages
Inexpensive manufacturing	High mooring and platform costs
Less sensitive to water depth	Excludes fishing, recreation and navigation from most areas of the farm
Lower sensitivity to wave loads	Increase in design complexity
Access to superior wind resources further offshore.	Lack of mass production
Ability to reduce visual effect	Little experience
Ability to locate further offshore	
Simplified offshore installation procedures	

Tabla 9. **Floating support structures - advantages and disadvantages**

Figure 7. **Floating support structures Hywind (spar) - Sway (spar) - WindFloat (semisubmersible) - Blue H (TLP) [44 - 45 - 46 - 47]**

Spar bouyance monopile

The spar is the simplest design regarding floating support structures. It is basically a large tube that floats due to the air in the top of the structure and stays in a vertical position due to the big amount of ballast at the bottom, that is, moving its center of mass as low as possible. Its elongated shape also serves to minimize heave motion due to wave action.

The turbine is placed on top of the spar which is attached to the sea bed by means of anchors. Because the center of mass of a horizontal-axis wind turbine is quite high, a massive structure is necessary to support a wind turbine.

- **Hywind**

Hywind was the first full scaled floating wind turbine in the world, a project undertook by StatoilHydro, a Norwegian oil & gas company. It is located around 10km off the southwest coast of Norway, in Stavanger, at a water depth that extends until 220m beneath the sea´s surface.

The origin of this concept was born in 1999 when engineers from the oil & gas industry though about a new use for the floating structures already used in that business, so that, these structures could also be applied on the offshore wind energy field. The purpose behind this project was to develop a floating support structure intended to sustain stable enough conditions on deep water so that wind energy could be generated. Unlike other floating foundations prototypes, instead of developing a new technology, *Hywind* was meant to use existing offshore technology. The project cost around € 55 million and was operating in 2009.

Several leading companies were involved during its construction. Siemens was the firm in charge of the wind turbine, developing a unit of 2.3 MW capacity. Technip, a Finnish engineering company from the oil and gas industry, was responsible for the floating structure. The manufacturing work took place in Finland where the transition piece was also assembled. The support structure has a diameter of 8.3m in the submerged body, a diameter of 6m in the body at water level, a length around 90m and weights 1500tons before the ballast is added. Regarding the cabling, Nexans Norway was the firm responsible to facilitate the submarine power line.

The installation of the spar floater was done is several stages. During the first stage the support structure was towed horizontally from the coast of Finland and up to Norway. Secondly, when the desire location was reached, the foundation was straightened up by pumping water to an end of the structure. Once the foundation was made vertical more water was added to sink the foundation in. Consequently, and with the help of a big barge used to reduce the differential motion from the tower, a crane lifted up the tower, the turbine and blades. Therefore all the different parts were assembled. Finally, three anchors were dropped out to sea and the turbine was connected to the cable line.

Currently, Statoil is already working in the *HyWind II*, a new project that expects to reduce the amount of steel required in the manufacture of the floating foundation searching for a lighter structure and therefore a drop of its costs.

- **Sway**

The *Sway* tower is a unique floating wind turbine system developed from the experience of the Norwegian offshore industry. The company responsible of its production installed in 2011 its 1:6 model to be tested in real conditions outside Bergen.

In November of that year the tower sank due to severe wave conditions for a scale model. Water entered the J-Tube for the cable connection which caused the system to tilt. Wave and storm surge then increased the water level on the turbine. According to the company the tested prototype was able to withstand waves of only 4m but the full scale project is design for maximum waves of 26m.

The tower consists of a floating pole with ballast on the lower end, similar to a floating bottle. The pole is anchored to the seabed with a single pipe and a suction anchor. When the wind hits the rotor, the tower tilts some 5 to 8 degrees. By tilting the rotor the opposite way, which is made possible by placing the rotor downwind of the tower, the rotor is perfectly aligned with the wind. When the wind changes direction, the entire tower turns around a subsea swivel. This in turn, makes possible to reinforce the tower with the tension rod system. Due to the resulting reduction of stresses in the tower, the tower is capable of carrying a much larger turbine which greatly enhances the total economy.

Unlike a conventional windmill, the rotor is placed on the leeward side of the tower. The rotor has a diameter of about 120m and if wind speeds exceed 25, per second the rotor is automatically turned off. Access is possible by either helicopter or boat. Due to its simple contraction the capital expenditure of the floating Sway system is competitive to bottom mounted near shore wind parks [45].

Semisubmersinble platforms

A semisubmersible platform is a structure usually movable by towing and with the principal characteristic of remaining in a substantially stable position with small movements when they experience environmental forces such as wind, wanes and currents.

The structure is comprised of hulls fabricated from large horizontal pontoons onto which vertical steel columns are welded. The columns and horizontal pontoons are interconnected and braced by a lattice of tubular steel supports. The platform is held to the seabed by anchors, whose chains are maintained in a catenary mooring mode by winches situated on the main deck.

- **WindFloat**

WindFloat is a project developed by Principal Power in partnered with the Portuguese utility EDP. The concept is a semisubmersible platform put partially under water, with more water inside the platform as a ballast to weight it down and provide stability. The system utilizes drag embedment anchors and conventional catenary mooring and is designed to accommodate any multi-megawatt offshore turbine.

The project started in 2009 and in 2011the first full-scale prototype, a Vestas – 2.0MW turbine, was deployed off the coast of Portugal. Grid-connected in Aguçadura, the unit is being tested for over a year focusing specially on performance validation of the WindFloat and turbine integration, as well as commissioning and O&M studies.

WindFloat provides acceptable static and dynamic motions for the operation of large wind turbines and in deep waters. Besides, due to its design efficiency and size, *WindFloat* can be assembled onshore, contributing to limit expensive offshore installation and maintenance procedures. Fabrication, installation, and commissioning of the floating support structure should be in line with other current fixed installations methods for deeper water sites.

The next step of Principal Power, Phase I, is to deploy two floating WindFloat platforms, anchored to the seabed about 15km far from the shore of the coast of Netarts, Oregon. Each structure will be outfitted with a 5MW turbine reaching a total capacity of 10MW for the project. The technology is expected to be commercially available between 2015 and 2020.

Tension-Leg Platform (TLP)

A tension-leg platform is a floating platform which allows a wind turbine to be motionless in spite of wind, waves and currents loads. The principle of the tension leg platform is to create an underwater platform with buoyancy instead of the large amount of ballast to keep the structure stable. The buoyancy exceeds the weight of the platform and hence causes a pretension in the vertical cables which keep the platform on location.

The legs can either be secured to a template at the seabed, by individual piles or by suction anchors. The platform is kept underwater to create a small cross-section at the waterline. This limits the amount of hydrodynamic loads from waves. Tension-leg platforms are usually restricted to areas without an intense tidal fluctuation and current.

- **Tricase - Blue H**

Blue H is a Dutch company that commenced its activities in the offshore wind market by adapting the concept of submerged TLPs, originally developed by the oil & gas industry and designed a platform large and stable enough to support a tower and a wind turbine in all foreseeable weather conditions. Additionally, other important design considerations were the cost of construction, installation and maintenance, with an emphasis on these expenses being kept at economical levels [47].

In 2008 Blue H started testing a 3:4 prototype located off the coast of Italy. After a six months period, the platform was decommissioned in the early 2009. Afterwards, in the phase II, a second platform with a 2MW turbine began to be developed with the aim to be finished before the end of 2012. In the phase III, the 2MW turbine will be follow by a pre-concept in 2014, combining Blue H technology with a third party to provide the offshore turbine.

Chapter 3

Methodology

3.1Delphi Method

Delphi survey is one of the most traditional methods to technological foresight. This technique was originated in the early 1950's by the RAND Corporation as a spinoff of Air Force-sponsored research on the use of expert opinion. This first study included a number of questionnaires with controlled feedback in order to establish the opinion of a group of experts on the U.S. industrial systems most likely to be targeted by Soviet strategic planners. Since then, Delphi method has been applied by numerous firms, universities and organizations for foresighting and planning technical and strategic activities.

The core of the method is a multy-round survey. During the first round the experts receive a questionnaire to be filled out. In following rounds, besides the respective questionnaire of the round, the group of experts also receives the results from the previous round. At this point, the experts are asked to reconsider or even modified their responses on the base of the group opinion. The basis of this method is that an expert in an area of study has an individual opinion in his head on how future developments may progress, but asking a large number of experts, possible individual misperception are balanced out. By applying feedback during a number of iterations the strongest perceptions become perceivable.

An important characteristic of this method is anonymity. Anonymity is achieved by using questionnaires through several iterations which allow to know others individuals' visions without the need to meet them. Therefore, the method introduces discussion between individuals but, at the same time, makes sure that the perceptions of influential individuals do not control the final result. Instead, the most likely or convincing developments are identified based on rational arguments. The iterative process can be replicated as many times as it is considered necessary.

In addition, the formalization of the methodology, the amount of data gathered, the number of experts involved and the fact that diverging opinions are partially hidden behind the main covering one, are all factors that contribute to the Delphi method being considered a popular and credible research technique [5].

Delphi method is well suited to assess long-term prospection and scenarios where no hard data is available. The method is aimed to identify topics that are relevant for the future and it has been considered most effective when the best available information is the judgment of knowledgeable individuals. These judgments allow for analyses, ranking and priority- settings. The degree of uncertainty dealt by the method is high and, at the same time, the issues or topics are usually complex.

It should however be noted that some disadvantages exist when applying this technique. Delphi method is very time-consuming as well as labour-intensive. Therefore, it is difficult to convince experts to take part in this type of research and achieve a high level of participant commitment. In occasions, some participants quit after some iterations, especially after the first round. The participants abandon rate tends to increase with the number of rounds what makes that the majority of studies are limited to no more than three rounds. A solution to this problem consists of, somehow, incentivizing the experts' participation with, for instance, the provision of the study results.

3.2 Survey Steps

The survey on “Offshore wind support structures - Challenges and technological requirements in the year 2020 and beyond” has been created to identify the challenges that the offshore wind industry will have to face by that time, to determine the technological progresses or improvements needed to overcome those challenges and to foresight the behavior of current concepts of offshore wind support structures in adapting to those new conditions.

The different steps that have been implemented during the course of the Delphi survey are defined by:

- Design of questionnaires.
- Search of companies involved in the whole lifetime development of offshore wind support structures and selection of possible candidates within the companies identified.
- Beginning of round one.
    - Launch of the first questionnaire.
    - Recompilation and analysis of the responses to the first questionnaire.
- Beginning of round two.
    - Launch of the second questionnaire.
    - Recompilation and analysis of the responses to the second questionnaire.

Design of questionnaires

Delphi method is considered a multi-round survey. In the case of the survey carried out in this thesis, two were the number of round selected. For each round a questionnaire was created and launched to experts of the offshore wind community.

The purpose of the first questionnaire was to bring out the perception of what the experts in offshore wind support structures foreseen as the potential scenario for the year 2020 and beyond (Question 1), the characteristics of support structures by that time (Question 2), the challenges that would be needed to face by current concepts of offshore wind support structures (Question 3) and the technological requirements that would allow these offshore wind support structures to overcome the challenges they would be forced to meet (Question 4).

In order to stimulate creative and insight thought from the participants open-ended questions were chosen as the best type to accomplished this target.

Otherwise experts thinking would have been limited and the range of responses narrowed. An example of the first questionnaire is presented in the Annex 2.

Regarding the second questionnaire, a different approach was given. First of all, together with the second questionnaire, feedback from the first is provided to the participants. The purpose of the second questionnaire was to ask respondents about their opinion on the most important challenges among (Question 5) and most important technological requirements (Question 6) both from a list of responses that collects the opinion of all the experts as a whole. In addition to these questions, two more were added. The aim of these last questions was to know the most optimal offshore wind support structures to achieve successfully the most important challenges (Question 7) and the most important technological requirements identified for the year 2020 (Question 8). The questions from the second questionnaire were formulated based on close-ended type. An example of the second questionnaire is presented in the Annex 2.

A draft of the first and second questionnaire was first discussed with the tutor of the thesis, and after getting her acceptance about its content and length, they were delivered into the offshore wind community.

Search of companies and selection of candidates

The search of companies and potential candidates for the survey was divided into two stages. The first stage included companies related to the construction of offshore wind projects which were identified at the time of writing the list of current offshore wind parks in Europe (Annex 1). The range of services provided by these companies covers the whole cycle of offshore wind support structures. There are companies specialized in the designing, manufacturing, transportation and installation processes, as well as in consultancy services.

These companies were first contacted and asked about their willing to participate in the survey. In the majority of cases the requests were sent to the information email published in the company's web site, but in other occasions, personal emails were found. In those latter situations, recommendations for colleagues with knowledge in the field of the survey were also requested.

After a period of few days it was clear that the rate of successful answers from the requests sent to personal email addresses compared to the company's information emails was significantly higher. This outcome determined the line to follow in order to increase the number of participants in the second stage. Table 10 shows the list of companies identified and contacted in the first stage

List of companies identified and contacted during the first stage

Company	Services	No.of messages sent
[1] AARSLEFF	Manufacturing	2
[1] ABJV	Manufacturing	1
BALLAS NEDAM	Manufacturing	1
[1] BIFAB	Design Manufacturing	4
[1] BLADT	Manufacturing	1
[1] CIVIL BILFINGER	Manufacturing	1
COWI	Consultancy	4
[1] CUXHAVEN STEEL	Manufacturing	1
[1] EEW GROUP	Manufacturing	6
[1] HOCHTIEF SOLUTIONS	Manufacturing Consultancy	1
[1] IDESA	Manufacturing	1
LORC	Research Center	1
[1] MGB	Manufacturing	5
[1] MPI OFFSHORE	Installation	1
[1] MT HOJGAARD	Design Manufacturing Installation Consultancy	1
NIRAS	Design Manufacturing Installation Consultancy	3
[1] PIHL	Manufacturing	1
RAMBOLL	Manufacturing Consultancy	7
[1] SIF GROUP	Manufacturing	1
[1] SMULDERS	Manufacturing	1
[1] WESERWIND GMBH	Manufacturing Installation	1
Individual Referrals		3
TOTAL		**48**

(1) Includes the company's email

Table 10. **List of companies contacted in the stage 1**

During the second stage of this searching phase, the main source used to look for experts within companies related to offshore wind support structure was LinkedIn. Thanks to this social network of professionals numerous candidates were contacted and asked to take part in the survey, raising the number of potential respondents from 48 to 98. Besides, other 5 potential candidates were obtained through references of authors from studies and analysis used during the development of the thesis.

Beginning of round one

Just like in the “search of companies and selection of candidates” step, the “first round” was divided into two parts. The first part followed the first searching stage and, in the same way, the second succeeded to the second stage.

During the first part, a letter describing the survey was emailed to the list of companies identified earlier, and in addition, to the few personal email addresses which were obtained. This letter was sent out previously to the first questionnaire and had two purposes. On the one side, it was meant to send a personal request for participating in the survey and, on the other side, to let the potential candidates have a first glimpse of the research objectives. The process toke a couple of days and as soon as the acceptance was confirmed the first questionnaire was sent out straightaway.

The second stage was a consequence of the few responses received during the early days and its approach was focused on identifying and contacting specific experts rather than companies. In order to gain some time in the process, the introduction letter and the first questionnaire were mixed up so that the acceptance step could be skipped.

The first questionnaire was sent out on July 10th and participants were given a week to respond. However, due to some comments about the coincidence of this time with the vacation period, the deadline was extended until the end of July. During the following days some other experts reported issues regarding their unavailability to cooperate in the month of July but time did not permit to postpone the survey any longer.

Only one reminder notice was sent to those of which during the first stage had accepted to collaborate but, in the end, did not complete the survey. Nevertheless, no positive feedback was achieved.

Beginning of round two

Delphi method is an interactive process, after the first round, experts receive feedback on the responses of the group as a whole. The objective of the second questionnaire was to provide the group of experts with feedback on the results of the first questionnaire. A summary of the challenges and technological requirements indicated in the first questionnaire was used to formulate the first two questions of the second questionnaire, asking participants to identify the challenges and technological requirements they consider most important. Two additional questions were added asking participants to point out the offshore wind support structures which better meet the challenges and technological requirements that will be presented in the year 2020 and beyond.

The second questionnaire was distributed to the participants who took part in the first questionnaire and, besides, to other experts who were unable to fill out the first questionnaire but manifested an interest in completing the second round.

Chapter 4

Survey Results

4.1 Responses to the first questionnaire

Responses to the first questionnaire were received between July 11th and July 31st. Even though the number of acceptances to participate in the survey amounted to 23, the final number of respondents was reduced to only 13 out of 100 sent emails. That is a 13 per cent rate of response of all the individuals who were contacted. However, 3 of these respondents did not complete the whole questionnaire, what reduces the rate of successfully filled out surveys to just a 10 per cent.

As mention in the previous chapter, some of these emails were sent to the information email address of some companies and, the rest, to individual experts. Specifically, the number of experts contacted directly amounted to 85, in contrast to only 15 information email addresses. Regarding the number of responses to the questionnaire, practically all of them came from the group of professionals (9 out of 10). As for the 3 individual referrals obtained, only one of them filled in the entire questionnaire.

The length and detail of the responses from this first round varied among each respondent. This is a consequence of the open-ended nature of the questions. All the responses were read and analyzed, and those which contained similar ideas were grouped and categorized. Subsequently all the different categories were listed so that they could be ranked and prioritized in the second round.

Following, the results to the four questions of the first questionnaire are collated and shown to determine the contribution of the group of experts.

Question 1

Offshore Wind Support Structures Environment

Significant Changes	Experts sharing this opinion
The industry will move into deeper waters (over 100m) using economically attractive floating wind support structures	7
Bottom fixed support structures will be optimized (manufacturing, mass production, installation, design, lifetime)	4
Floating support structures will take over bottom fixed	3
Few suitable locations will be available below deep waters	2
More commercial partnering with, for instance, several support structure manufactures forming joined ventures	2
Improved and verified support structures will arise	1
A new supply chain for floating support structures as well as improved and verified concepts will arise	2
New designs of support structures for vertical-axis wind turbines	1
Oil & Gas companies will be involved in offshore wind	1
Vessels operations will be further optimized to accommodate rough weather, wave heights, etc.	1
Structures will become more flexible	1

Table R1-Q1. **Summary of responses to Question 1**

Question 2

Offshore Wind Support Structures Look

Main Features	Experts sharing this opinion
Updated and optimized support structures are foreseen rather than new concepts	7
New and simpler concepts will be developed	3
Support structures will no longer be made of steel but of lighter materials	
Support structures will be able to withstand more powerful turbines	
Support structures will be grouped in order to create large scale forms, harnessing synergies like O&M	
Support structures will hold towers with several turbines	
New design codes will continue evolving	
Damping of structures will be actively and something the customer decides on	
Besides the deep water market, floating support structures will get more foothold on shallower waters	
Monopiles will stretch its limits of application in terms of water depth	
Weight of jackets will be lower but complexity and cost high	

Table R1-Q2. **Summary of responses to Question 2**

Question 3

Offshore Wind Support Structures Challenges

Code	Challenges
a	**Potential to bring support structure costs down despite the upscaling of weight, loads, turbine's capacity and water depth**
b	**Response to the scarcity of suitable areas in terms of soil quality and water depth**
c	**Overcoming potential supply chain bottlenecks to commercially meet the future demand (e.g., installation vessels availability)**
d	**Reduction of operation & maintenance requirements**
	Enhancement of support structures decommissioning to reduce environmental disturbances
e	**Increment support structures life-span**
f	**Need to create and maintain experienced and skilled staff so that workforce shortage can be avoided**
g	**Capacity to develop support structures that can deal with deeper waters**
h	**Accommodate more flexibility and movement from the structures**
i	**Establishment of achievable and accessible political and commercial conditions**
j	**Streamlining of support structures and installation vessels sourcing and competences in design to meet the goals imposed by governments in the implementation of offshore wind parks**

Table R1-Q3. List of responses to Question 3

Question 4

Offshore Wind Support Structures Technological Requirements

Code	Technological Developments
A	**Mass production techniques to deliver productivity gains and to reduce costs**
B	**New manufacturing methodologies that process a wider range of products requirements (materials, designs, weight, lifetime)**
C	**New support structures with little or no below water working required**
D	**Ability to assemble support structures and turbines in one go**
E	**A support structure with the capacity for putting up several turbine towers, sharing anchors and providing wave stability**
F	**Adoption of mobile support structure to perform O&M activities onshore**
G	**Unified methodologies and protocols among the different manufacturers to devote all the efforts to one generic design**
I	**Methods to accommodate the distance to shore for hub-transformer stations connecting several wind parks**
J	**Inclusion of decommissioning in the life cycle assessment**
K	**Support structure designs easily decommissioned with no marine operations required**
[illegible]	**Creating artificial island at sea and installing turbines on them to simplify installation**

L	**Creating artificial island at sea and installing turbines on them to simplify installation issues and maintenance activities**
M	**New O&M methods for rapid and safe access to the support structure, reducing dependency on the weather conditions**
N	**Development of support structures compatible with newer and more performant turbines**
O	**Optimizing support structure designs by integrating lighter, cheaper, more durable and hybrid composite materials**
P	**Anti-corrosion technology integrated in the support structure (e.g., use of special type of steel and coating)**
Q	**Improve current methods in the business to be implemented in a timely manner and without any conservatism (e.g., safety margins in the design supply chain)**
R	**Rather than a particular technological development it is important to maintain a constant flow of investment in research**

Table R1-Q4. List of responses to Question 4

4.2 Responses to the second questionnaire

This second questionnaire was distributed on the 3rd of August and participants were giving 10 days to complete it, 12th of August included. Just like in the situation of the initial round, the participation rate was affected by the vacation period. After sending the requests to participate in the second round, several automatic e-mail replies were received indicating that the person contacted was on holidays.

Overall, the number of responses increased with respect to the first round, being collated in this case 17 questionnaires. This may be interpreted as a consequence of the close-ended type of questions, what makes less time-demanding the process to complete the survey. Nevertheless, four of these questionnaires had to be ruled out because several misinterpretations while filling out the survey. As enunciated in the statements of the question 5 and 6, respondents were asked to indicate "only" the five challenges or technological requirements which they consider most important. In those four questionnaires, all the different options of those questions were rated, giving null the outcomes. In addition, there was another questionnaire no fully completed where question 8 and 9 were empty. Finally, from all the participants in the second questionnaire, only 5 of them took part in the round one.

Since Delphi Survey is an iterative method, in the second round, participants receive the results of the group in the first round as a whole. Therefore, the purpose of this process is to provide participants with feedback on the responses of the previous stages. The lists of responses to the Question 3 and 4 (Table R1-Q3, Table R1-Q4) were used to formulate the two first questions of the second part. Apart of choosing the options considered most important, each expert individually submitted a rank to reflect the priority order of the most important challenges and technological requirements. The ranks were rated with 5, 4, 3, 2 and 1, being 1 the most important and 5 the least important. The importance of each option is calculated by the multiplication of the number of times an option has been placed in a specific rank with the capacity factor of that rank. Afterwards, these values are added and then divided by the number of total responses. Finally, the option different to 0 and with the lowest absolute value represents the most preferable choice.

For instance, in the case of the challenge voted as the most important:

Potential to bring support structure costs down despite the upscaling of weight, loads, turbine's capacity and water depth

$$\textbf{\textit{Rating average}} = \frac{\sum (Number\ of\ responses\ within\ each\ rank\ X\ Rank\ capacity\ factor)}{Total\ number\ of\ responses}$$

Responses rated as 1 = 9

Responses rated as 2 = 2

Responses rated as 3 = 1

Responses rated as 4 = 0

Responses rated as 5 = 0

Response count = 12

$$\textbf{\textit{Challenge rating average}} = \frac{\sum ((9\ X\ 1) + (2X\ 2) + (1\ X\ 3))}{12} = 1{,}33$$

With regard to the Question 7 and 8, the selection of offshore wind support structure concepts more likely to overcome successfully the challenges and technological requirements selected in the previous questions, was based on the on the number of votes given by the participants to the options selected as the most important.

For instance, in the case of the challenge voted as the most important:

Potential to bring support structure costs down despite the upscaling of weight, loads, turbine's capacity and water depth

Among the participants who selected this challenge as one of the 5 most important, the support structure concept with the biggest amount of votes to successfully overcome it is the "Jacket".

Following, the results to the four questions of the second questionnaire show the opinion of the respondents.

Question 5

Offshore Wind Support Structures Challenges

Code	Challenges	Rating Average	Response Count
a	Potential to bring support structure costs down despite the upscaling of weight, loads, turbine's capacity and water depth	1,33	12
g	Capacity to develop support structures that can deal with deeper waters	2,78	9
f	Need to create and maintain experienced and skilled staff so that workforce shortage can be avoided	2,89	9
i	Establishment of achievable and accessible political and commercial conditions	2,13	8
b	Response to the scarcity of suitable areas in terms of soil quality and water depth	3,71	7
d	Reduction of operation & maintenance requirements	4,00	7
c	Overcoming potential supply chain bottlenecks to commercially meet the future demand (e.g., installation vessels availability)	3,60	5
j	Streamlining of support structures and installation vessels sourcing and competences in design to meet the goals imposed by governments in the implementation of offshore wind parks	3,50	4
	Enhancement of support structures decommissioning to reduce environmental disturbances	5,00	2
h	Accommodate more flexibility and movement from the structures	2,00	1
e	Increment support structures life-span	5,00	1

Table R2-Q5. Challenges rating average

Question 6

Offshore Wind Support Structures Technological Requirements

Code	Technological Developments	Rating Average	Response Count
A	Mass production techniques to deliver productivity gains and to reduce costs	1,38	13
O	Optimizing support structure designs by integrating lighter, cheaper, more durable and hybrid composite materials	2,50	6
C	New support structures with little or no below water working required	3,50	6
B	New manufacturing methodologies that process a wider range of products requirements (materials, designs, weight, lifetime)	2,40	5
I	Methods to accommodate the distance to shore for hub-transformer stations connecting several wind parks	2,80	5
R	Rather than a particular technological development it is important to maintain a constant flow of investment in research	4,00	5
N	Development of support structures compatible with newer and more performant turbines	2,75	4

M	New O&M methods for rapid and safe access to the support structure, reducing dependency on the weather conditions	4,25	4
Q	Improve current methods in the business to be implemented in a timely manner and without any conservatism (e.g., safety margins in the design supply chain)	4,50	4
G	Unified methodologies and protocols among the different manufacturers to devote all the efforts to one generic design	2,67	3
P	Anti-corrosion technology integrated in the support structure (e.g., use of special type of steel and coating)	3,67	3
D	Ability to assemble support structures and turbines in one go	2,50	2
E	A support structure with the capacity for putting up several turbine towers, sharing anchors and providing wave stability	4,50	2
K	Support structure designs easily decommissioned with no marine operations required	5,00	2
L	Creating artificial island at sea and installing turbines on them to simplify installation issues and maintenance activities	4,00	1
F	Adoption of mobile support structure to perform O&M activities onshore	0,00	0
J	Inclusion of decommissioning in the life cycle assessment	0,00	0

Table R2-Q6. Technological requirements rating average

Question 7

	Code	Monopile	Bravity Base	Jacket	Tripod	Tripile	Spar	Semisub. Platf.
Challenge classified as 1	a	2	1	7	2	-	6	4
Challenge classified as 2	g	1	-	3	1	-	6	6
Challenge classified as 3	f	3	3	4	3	2	6	5
Challenge classified as 4	i	4	2	5	3	2	5	5
Challenge classified as 5	b	1	1	2	1	1	4	2

Table R2-Q7. Support structure concepts most likely to overcome the 5 most important challenges

Question 8

	Code	Monopile	Bravity Base	Jacket	Tripod	Tripile	Spar	Semisub. Platf.
Tech. Req. classified as 1	A	2	3	7	2	-	7	5
Tech. Req. classified as 2	O	2	-	2	1	-	3	3
Tech. Req. classified as 3	C	3	3	3	3	-	2	3
Tech. Req. classified as 4	B	2	-	4	1	1	4	2
Tech. Req. classified as 5	I	2	3	4	3	2	2	3

Table R2-Q8. Support structure concepts most likely to overcome the 5 most important technological requirements

Chapter 5

Conclusions

5.1 Clarifications

Choosing the most suitable type of support structure for an offshore wind park is a decision which depends on numerous factors. The cost of manufacturing, the seabed requirements during the installation process, the capacity of the structure to withstand wind and wave loads, the water depth or the structure environmental impact are just a few examples of the aspects which may tip the balance in favor of one alternative or another. It is necessary to know the main characteristics of each choice and its advantages and disadvantages so that it is possible to have a clearer idea about which support structures could be chosen or ruled out in the development of a particular project. In this regard, Chapter 2 of this thesis aims to understand the differences, as well as the most favorable conditions, of the most currently employed offshore wind support structures.

Subsequently, this project tries to move a few steps forward in terms of the current status of the offshore wind industry. For this reason, the focus of the research is transferred to the year 2020 and beyond. Within this future scenario, the thesis aims to define the new environment features and the properties that support structures should present by that time. It also analyzes which support structures are the most likely to succeed the challenges and technological requirements that the sector will need to deal with in that hypothetical future.

Due to the particularities of the method used in the project, a Delphi survey, it is important to clear up some aspects beforehand in order to avoid possible misinterpretations of the results.

Delphi survey is a process where the results are greatly influenced and limited by the participation and opinion of the experts contacted. The first hurdle that needs to be overcome is how to obtain a representative number of experts who are willing and, at the same time, can be available to participate along the different rounds of the survey. Following this first obstacle, the next has to do with the quality of the responses collected. It is necessary a big effort and a total commitment from the participants when answering questions. The higher the commitment, the more valid and righter the final conclusions are.

In these terms, the conclusions obtained in this project need to be taken with a grain of salt. The number of experts involved in the survey has been too low compared to the number of applications submitted, and thus, the number of responses achieved is not very representative. In the round 1, the participation rate was just a 10 per cent of the total sent requests. In the round 2, although the participation was slightly higher, it did not even reach a 20 per cent rate. With these values, even though all the experts consulted have a large experience in the topic of the thesis, the results cannot be judged as very reliable.

Another problem identified during the survey process was the lack of homogeneity among the group of respondents. Just to give an example, because the number of experts with a background on semisubmersible platforms has been low in comparison to the ones with knowledge on jackets, the results may have led to a situation where either a support structure has been underestimated or the other overrated. This heterogeneity among the respondents knowledge was also observed when trying to cope all the lifetime stages of a support structure. In the end, it was not possible to get equal representation from all the areas.

Concerning the quality of the responses, the outcomes did not meet the initial expectations either. Brevity in responses or some signs of laziness, like giving the same answer for different questions, are some of the issues identified.

Finally, it is also essential to keep in mind that only 5 individuals out of the 10 experts who took part in the round 1 participated in the round 2. Therefore, it should not come as a surprise if discrepancies and different points of view between the assertions of the questionnaire 1 and questionnaire 2 were observed.

Having expressed all these concerns and in order to avoid falling into an error, only the ideas and thoughts shared by a solid number of participants will be highlighted. Individual contributions that have not achieved a consensus of the group's results as a whole have been omitted from the outcomes. In conclusion, and as has been already stated, the results and judgments must be treated “only” within the boundaries of this particular Delphi survey.

5.2 Discussion

In the questionnaire 1 the experts were first asked about their opinion on the changes that the offshore wind industry may experiment and on how the future support structures would look like.

One of the changes where participants seem to have reached an agreement has to do with the tendency of the industry to move toward deeper water. Water depth is an unquestionable key factor, but will it be possible for the industry to develop support structures economically feasible at deep waters? According to the results obtained, 70 percent of the experts consider this change likely to be achieved by floating support structures. Besides, this change is also related to one of the challenges identified as the most important in the year 2020, "*the capacity to develop support structures that can deal with deeper waters*".

The next point where seems to be a consensus is the discussion of, whether or not, by 2020, new concepts of support structures will emerge to stand up to the ones currently employed. Again, 70 per cent of the respondents think that the most likely scenario will be defined by updates and optimization of actual support structures rather than the appearance or new revolutionary solutions.

When choosing between bottom fixed and floating support structures it is difficult to define a specific path from the responses of the questionnaire 1. To draw conclusions on this matter it is better to analyze responses of questionnaire 2.

The rest of the views from these two first questions has been omitted in the conclusions due to lack of unanimity among respondents.

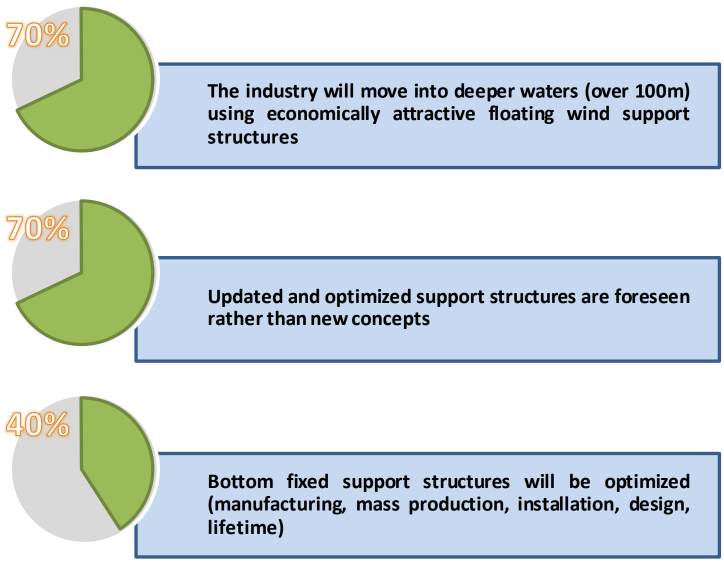

Figure 8. Agreements from Question 1 and Question 2

Challenges

The existing business of offshore wind support structure needs to identify the scope for future challenges and to establish the key lines of research and development to maintain the industry successfully. Questionnaire 2 sheds some light on the areas which should be the center of attention in 2020 and on what type of support structures have the biggest potential to accomplish those targets.

Following there is a graphic which relates both the main challenges in the year 2020 and the most promising support structures to overcome them.

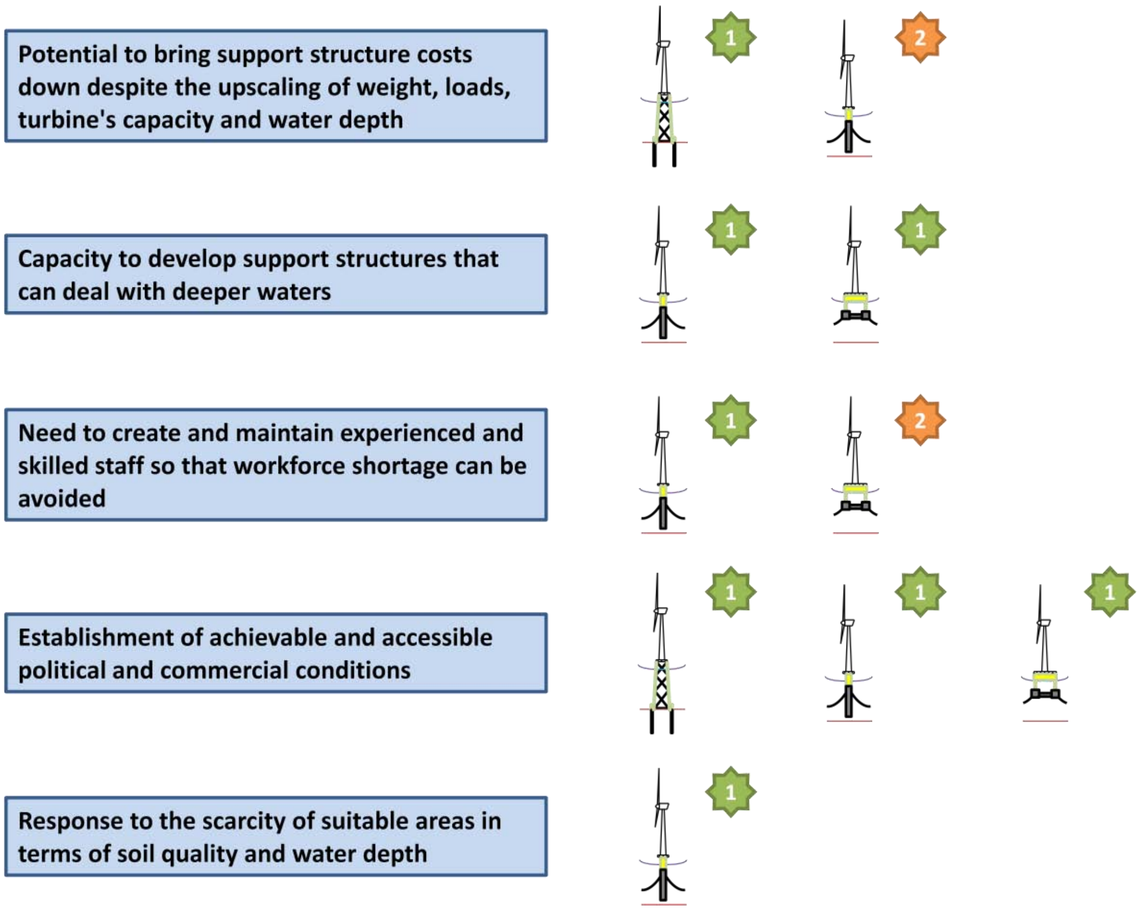

Figure 9. **Link between the most important challenges and the support structures likely to face them. 1 and 2 indicate the solutions assessed as the first and second choice respectively**

Based on the Figure 9, the first conclusion that could be drawn is that 3 types of support structures could be disregarded for future analysis: monopiles, gravity base, tripods and tripiles. Neither of them appears as the most voted choice in any of the main challenges. The case of tripiles is the most remarkable. Probably affected by its short time of application in the offshore wind business, this alternative presents the lowest number of votes in the survey.

Jackets score relatively well among all the different challenges but, in the challenge rated as the most important, “*potential to bring support structure costs down despite the upscaling of weight, loads, turbine's capacity and water depth*”, is where it gets the highest score. It gives an idea of the bright future that this structure may have.

With regard to the affinity for problems associated with deep waters, spars and semisubmersible platforms achieve the highest number of votes. In the case of spars, this result can also be seen in their capacity to deal with scarcity of suitable areas for constructing new parks.

The necessity to maintain the flow of skilled workforce and to establish political and commercial conditions, are the challenges where votes are most uniformly distributed among all support structures.

Technological requirements

Conclusions also focus on the technological advancements to face those challenges. A wide range of improvements in design, fabrication and installation of offshore wind support structures were stated, though only in a few of them a firm opinion was detected. A summary of the results is shown in the next figure.

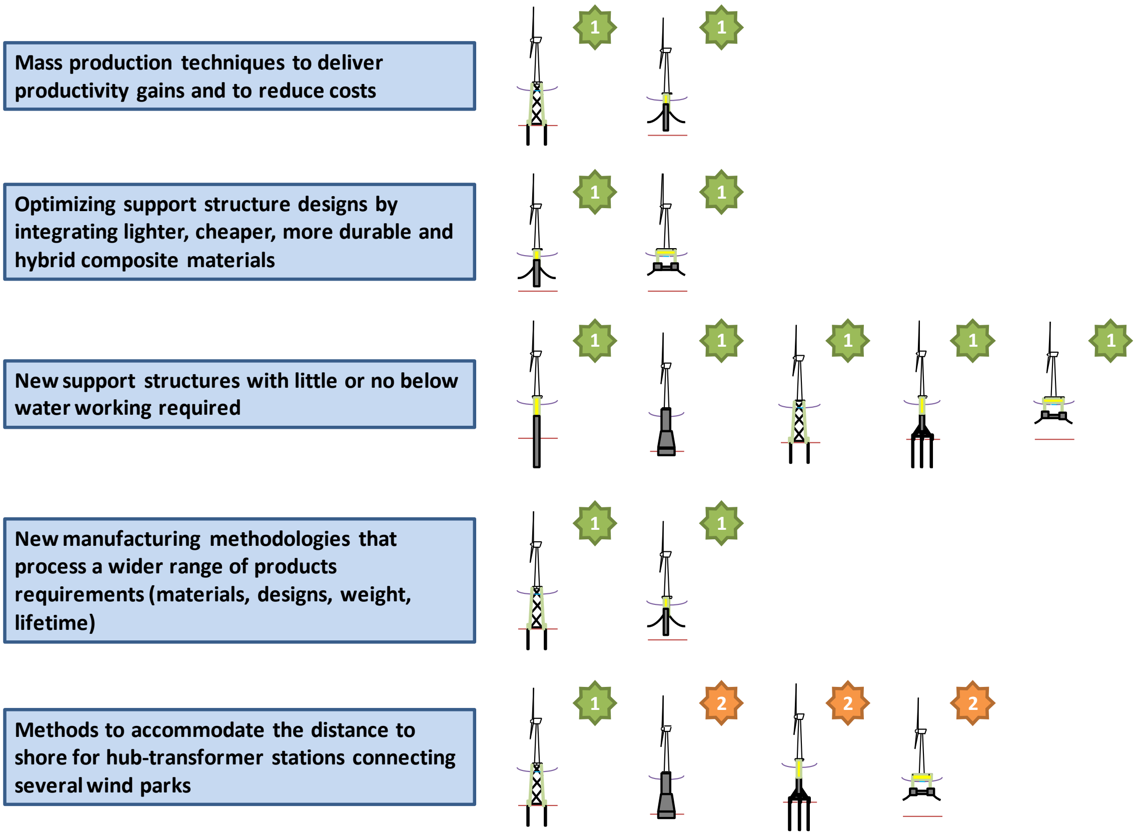

Figure 10. **Link between the most important technological improvements and the support structures likely to face them. 1 and 2 indicate the solutions assessed as the first and second choice respectively**

"*Mass production techniques to deliver productivity gains and to reduce costs*" is the improvement rated as the most important and, like in the challenge of drooping costs, jackets and spars are the most promising solutions. The same scores are register in the case of new manufacturing methods.

Floating foundations are the ones performing the best for improvements in their design, indicating that they still have a gap to fill to become cost effective.

In terms of eliminating the work below water and accommodating the distance for hub-transformers stations, the performances from the different support structures remain relatively constant.

5.3 General Overview

In this thesis an assessment about the capacity of current concepts of offshore wind support structures to accomplish and cope successfully the challenges and technological requirements that the business needs to deal with in the future has been completed. The thesis includes a list and a description of those challenges and technological requirements and, consequently, it also quantifies their grade of influence. In this regard, the thesis fulfills the target of identifying the concepts more likely to prevail in that future environment. Furthermore, it also explains the main properties and features that those concepts of support structures should present.

The research methodology selected to predict this future scenario has been implemented successfully according to its steps. This technique, the Delphi method, has turned to be really flexible and superficially simple for forecasting technological developments, like in the case of offshore wind support structures. However, four factors have been identified as crucial to make the most of this technique. The Delphi participants need to meet the following requirements: relevant knowledge on the topic to study, capacity and willingness to participate, sufficient time to complete the whole surveys and effective communication skills. Unfortunately, not all of them have been fully achieved during this thesis and therefore the credibility of the results must be in tune with this fact.

Nonetheless, concerning these results, some contributions can be assessed as positive. In general terms, the outcomes have shown a relation with the conclusions from other recent studies and publications. The industry is turning toward floating wind support structures. In the Delphi survey, these type of support structure have scored relatively well against the more likely scenarios described, proving to be a technology with tremendous potential. In addition to this, main concerns identified in the thesis such as the upscaling of costs, the need to deal with deeper waters or manufacture lighter projects, are also in line with the demands already marked by the industry.

This detected relation may be due to the fact that next relevant changes in the industry will take place in a significantly longer temporal horizon. Perhaps it is just a consequence of the lack of effort from the participants in their attempt to discern a future beyond the already known. One way or another, it is undeniable that, at least, the results of the thesis follow the right direction.

Annex 1

List of Operational Offshore Wind Projects in Europe – 2011

Belgium

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Belwind Phase I	165	55	2010	15 to 37	46 to 51	Monopile	Van Oord
Thornton Bank Phase I	30	6	2008	12 to 27	27 to 30	Gravity Base	GeoSea
Total	**195**	**61**					

Denmark

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Vindeby	4,95	11	1991	2,5 to 5	2,5	Gravity	
Tunø Knob	5	10	1995	0,8 to 4	6	Gravity	
Middelgrunden	40	20	2001	2 to 6	2	Gravity	MT Højgaard
Horns Rev I	160	80	2002	6 to 14	14	Jacket	Sif Smulders MT Højgaard
Nysted I	165,6	72	2003	6 to 10	6 to 10	Gravity	Aarsleft
Samsø	23	10	2003	11 to 18	3,5	Monopile	Bladt
Frederikshavn	10,6	4	2003	3	0,8		
Horns Rev II	209,3	91	2009	9 to 17	30	Monopile	Bladt Aarself Bilfinger Berger
Sprongø	21	7	2009	6 to 16	2	Gravity Base	Aarself Bilfinger Berger
Avedøre	7,2	2	2009	0,5	0,001	Gravity Base	
Poseidon	0,033	3	2010	7	3	Floating	
Nysted II	207	90	2010	6 to 12	23	Gravity Base	Aarsleft Bilfinger Berger
Total	**853,7**	**400**					

Finland

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Kemi Ajos I	24	8	2008	3	1	Gravity Base	
Pörl I	2,3	1	2010	9	2	Gravity Base	Technip
Total	**26,3**	**9**					

Germany

Germany

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
ENOBA Offshore	4,5	1	2004	2	1		
Breitiling	2,5	1	2006	2	1		
Hooksiel	5	1	2008	2 to 8	0,4	Tripile	BARD
Alpha Ventus	60	12	2010	30	43	JacketTripod	Aker Kvaerner BiFab
BARD Offshore 1 (partially completed)	20	4	2010	40	100	Tripile	Cuxhaven
Baltic I	48,3	21	2011	16 to 19	17	Monopile	EEW Group
Total	**140,3**	**40**					

Italy

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Tricase Blue H (3:4 scale) * Decommissioned	0,08	1	2008	113	21	Floating TLP	Blue H Technology
Total	**0,08**	**1**					

Ireland

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Arklow Bank	25,2	7	2004	2,5 to 5	10	Monopile	Sif Smulders
Total	**25,2**	**7**					

Netherlands

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Lely	2	4	1994	7,5	0,75	Monopile	
Irene Vorrink	16,8	28	1996	2	0,03	Monopile	
Egmond aan Zee	108	36	2007	19 to 22	8 to 12	Monopile	Bladt
Prinses Amaliawindpark	120	60	2008	19 to 24	23	Monopile	Sif Smulders
Total	**246,8**	**128**					

Norway

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Hywind	2,3	1	2009	220	12	Floating Spar	Technip
Sway (1:6 scale)		1	2011			Floating Spar	Sway A/S
Total	**2,3**	**1**					

Portugal

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
WindFloat Phase I	2	1	2011	40 to 50	7,5	Floating Semisubm.	
Total	**2**	**1**					

Sweden

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Bockstigen	2,75	5	1998	6 to 8	3	Monopile	
Utgrunden I	10,5	7	2001	4 to 10	7	Monopile	
Yttre Stengrund	10	5	2002	8 to 12	4	Monopile	
Lillgrund	110,4	48	2007	2,5 to 9	10	Gravity Base	Hotchief
Gässlingegrund	30	10	2009	4 to 10	4	Gravity Base	PEAB
Total	**163,7**	**75**					

United Kingdom

Project Name	Capacity MW	No. Of Turbines	Year Fully Operational	Water Depth m	Distance to Shore km	Foundation Type	Foundation Supply
Blyth	4	2	2000	6	1	Monopile	
North Hoyle	60	30	2003	5 to 12	3 to 10	Monopile	Sif Smulders
Scroby Sands	60	30	2004	2 to 10	2,5	Monopile	Cambrian Engineering Isleburn Mackay Mcleod
Kentish Flats	90	30	2005	5	8,5	Monopile	MT Højgaard Sif Smulders
Barrow	90	30	2006	21 to 23	7	Monopile	Sif Smulders KBR
Beatrice	10	2	2007	40	25	Jacket	BiFab
Burbo Bank	90	25	2007	10	5,2	Monopile	MT Højgaard
Inner Dowsing	97,2	27	2008	10	5	Monopile	MT Højgaard
Lynn	97,2	27	2008	10	5,2	Monopile	MT Højgaard
Rhyl Flats	90	25	2009	4 to 15	8	Monopile	MT Højgaard
Robin Rigg	180	60	2010	5	9,5	Monopile	MT Højgaard
Gunfleet Sands	172,8	48	2010	2 to 15	7	Monopile	MT Højgaard
Thanet	300	100	2010	20 to 25	7 to 8,5	Gravity Base	Sif Smulders
Ormonde (partially completed)	120	24	2011	17 to 21	9,5	Monopile	BiFab
Walney I	183,6	51	2011	19 to 23	14	Monopile	Bladt EEW Group
Total	**1644,8**	**511,0**					

Annex 2

Questionnaire 1

ROUND 1. Offshore Wind Support Structures - Challenges & Technological Requirements by 2020 Exit

Offshore Wind Support Structures - Challenges & Technological Requirements by 2020

Dear Participant,

Thank you for contributing to this Delphi survey. Its purpose is to define the major challenges and technological development requirements that the offshore wind industry will have to face in terms of offshore wind support structure in the year 2020 and beyond, and consequently, give a preliminary evaluation of the optimal support structure, among all the current concepts, to meet these needs and changes.

Results of this study will help to identify areas with a significant impact on offshore wind support structures and over which a special focus on technological development is required.

Your participation as an expert on the offshore wind industry with particular knowledge on support structures will provide helpful information, vision and original ideas required for this study. Besides, it gives you the occasion to interact with the offshore wind energy community in defining directions with potential capacity to influence the support structure trends.

All responses will be treated anonymously and they will help to provide results and to reach a consensus. This Delphi survey is divided into two rounds of questions.

Following you will find the questionnaire for the first round. It is relatively short with only four questions. The thoughtfulness of your answers will reflect your value added.

Due to the vacation period the deadline for this first questionnaire will be flexible. However, since responses need to be analyzed and included in round two, if the first questionnaire could be completed within July, it would help to begin the second and last round in the early August.

Thanks a lot for your participation.

ROUND 1. Offshore Wind Support Structures - Challenges & Technological Requirements by 2020 Exit

Participant Information

1. Name

2. Email

3. Company / Position

4. Years of experience

5. Country

ROUND 1. Offshore Wind Support Structures - Challenges & Technological Requirements by 2020

Exit

Questionnaire 1

Instructions

The goal of this survey is to provide vision on the future challenges and technological requirements for the offshore wind support structures. Capacity for creativity thought is important to foreseen and describe a scenario that is not a reiteration of what has already been said today. This survey invites experts to move ahead and break down what will be saying ahead of the year 2020 and beyond. Try to imagine the environment that will surround and lead the offshore wind industry by that time, as it may not be the same as today.

Please, project yourself into the year 2020 and define what it will be and what the consequences will be for the offshore wind industry. You are not limited in any way to predict what will happen. Insight and creativity is required on all the questions.

Try to spend approximately equal time on each question, limiting your input to the 3 to 5 more important ideas for each question. You can use as many sentences as you want to describe each idea.

Note: In this study offshore wind support structure is defined as the whole part below the turbine tower, including the structure under the soil (foundation).

1. Industry:

In terms of support structures the offshore wind industry will be different by the year 2020 and beyond. Significant changes will occur in different areas such as design, manufacturing, installation processes, workforce, technology, supply chain , environmental impacts, economy or competition. For example, offshore wind support structures will be able to move along the sea and relocate themselves autonomously to take advantage of wind currents.

Please, describe your perception of what the environment for offshore wind support structures in the year 2020 and beyond, and list significant changes that will occurred by then.

2. Support structures:

Describe your perception of what the offshore wind support structures will look like in the year 2020 and beyond.

3. Challenges:

For your perception of the offshore wind support structures in the year 2020 and beyond, what are the challenges that must be met?

4. Technological requirements:

In order to meet these challenges, what are the significant technology developments that are required?

Annex 3

Questionnaire 2

Round 2. Offshore Wind Support Structures - Challenges & Technological Requirements by 2020 Salir de esta encuesta

Questionnaire 2

Instructions

This second round provides you with feedback on the results of the first questionnaire. The lists of challenges and technological requirements described in the first questionnaire have been summarized. The objective of this second round is to select the most important challenges and technological requirements that have been identified, by all the experts, for offshore wind support structures in the year 2020 and beyond. Furthermore, this second questionnaire aims to define, among some current concepts of offshore wind support structures, the ones which best fit the challenges and technological requirements that you have identified as most important.

In this second questionnaire you will find four short questions with a list of choices where you will be able to grade or mark with a cross the ones you consider most important.

1. Participant name

2. In the first round the following challenges for offshore wind support structures in the year 2020 and beyond were identified. What are the "5" challenges you think are most important? Please, classify in order of importance, giving 1 to the most important to 5 to the least important.

Note: Select only 5 ranking from 1 to 5

	1	2	3	4	5
Potential to bring support structure costs down despite the upscaling of weight, loads, turbine's capacity and water depth					
Response to the scarcity of suitable areas in terms of soil quality and water depth					
Overcoming potential supply chain bottlenecks to commercially meet the future demand (e.g., installation vessels availability)					
Reduction of operation & maintenance requirements					
Enhancement of support structures decommissioning to reduce environmental disturbances					
Increment support structures life-span					
Need to create and maintain experienced and skilled staff so that workforce shortage can be avoided					
Capacity to develop support structures that can deal with deeper waters					
Accommodate more flexibility and movement from the structures					
Establishment of achievable and accessible political and commercial conditions					
Streamlining of support structures and installation vessels sourcing and competences in design to meet the goals imposed by governments in the implementation of offshore wind parks					

3. In the first round the following technological requirements for offshore wind support structures in the year 2020 and beyond were identified. What are the "5" technological requirements you think are most important? Please, classify in order of importance, giving 1 to the most important to 5 to the least important.

Note: Select only 5 ranking from 1 to 5

	1	2	3	4	5
Mass production techniques to deliver productivity gains and to reduce costs					
New manufacturing methodologies that process a wider range of products requirements (materials, designs, weight, lifetime)					
New support structures with little or no below water working required					
Ability to assemble support structures and turbines in one go					
A support structure with the capacity for putting up several turbine towers, sharing anchors and providing wave stability					
Adoption of mobile support structure to perform O&M activities onshore					
Unified methodologies and protocols among the different manufacturers to devote all the efforts to one generic design					
Methods to accommodate the distance to shore for hub-transformer stations connecting several wind parks					
Inclusion of decommissioning in the life cycle assessment					
Support structure designs easily decommissioned with no marine operations required					
Creating artificial island at sea and installing turbines on them to simplify installation issues and maintenance activities					
New O&M methods for rapid and safe access to the support structure, reducing dependency on the weather conditions					
Development of support structures compatible with newer and more performant turbines					
Optimizing support structure designs by integrating lighter, cheaper, more durable and hybrid composite materials					
Anti-corrosion technology integrated in the support structure (e.g., use of special type of steel and coating)					
Improve current methods in the business to be implemented in a timely manner and without any conservatism (e.g., safety margins in the design supply chain)					
Rather than a particular technological development it is important to maintain a constant flow of investment in research					

Round 2. Offshore Wind Support Structures - Challenges & Technological Requirements by 2020 Salir de esta encuesta

Questionnaire 2

4. Which of the challenges facing offshore wind support structures in the year 2020 and beyond are more likely to be successfully met by the following current concepts of offshore wind support structure? For each of 5 challenges that you have selected as the most important in Question 1, indicate the current concept of offshore wind support structure more likely to overcome successfully that challenge.

The offshore wind support structures studied are: monopile, gravity base, jacket, tripod, tripile, spar and semisubmersible platform.

	Monopile	Gravity Base	Jacket	Tripod	Tripile	Spar	Semisubmersible Platform
Challenge classified as number 1	☐	☐	☐	☐	☐	☐	☐
Challenge classified as number 2	☐	☐	☐	☐	☐	☐	☐
Challenge classified as number 3	☐	☐	☐	☐	☐	☐	☐
Challenge classified as number 4	☐	☐	☐	☐	☐	☐	☐
Challenge classified as number 5	☐	☐	☐	☐	☐	☐	☐

5. Which of the technological requirements needed for offshore wind support structures in the year 2020 and beyond are more likely to be successfully achieved by the following current concepts of offshore wind support structure? For each of 5 technological requirements that you have selected as the most important in Question 2, indicate the current concept of offshore wind support structure more likely to adapt or accomplish successfully that technological requirement.

The offshore wind support structures studied are: monopile, gravity base, jacket, tripod, tripile, spar and semisubmersible platform.

	Monopile	Gravity Base	Jacket	Tripod	Tripile	Spar	Semisubmersible Platform
Tech. requirement classified as number 1	☐	☐	☐	☐	☐	☐	☐
Tech. requirement classified as number 2	☐	☐	☐	☐	☐	☐	☐
Tech. requirement classified as number 3	☐	☐	☐	☐	☐	☐	☐
Tech. requirement classified as number 4	☐	☐	☐	☐	☐	☐	☐
Tech. requirement classified as number 5	☐	☐	☐	☐	☐	☐	☐

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