MERMAID

mermaidproject.eu

Seventh Framework Programme
Theme [OCEAN.2011-1]
“Innovative Multi-purpose off-shore platforms: planning, design and operation”
Grant Agreement no.: 288710
Start date of project*: 01 Jan 2012 - Duration: 48 month*

Shallow, deep and ultra-deep water foundation technologies

Deliverable: D 3.2	
Nature of the Deliverable:	Report
Due date of the Deliverable:	August 1, 2013
Actual Submission Date:	August 6, 2013
Dissemination Level:	Confidential
Produced by:	**UC Researchers:** Iñigo Losada, Raul Guanche
Contributors:	**UC Researchers:** Iñigo Losada, Raul Guanche, Lucía Meneses **LWI Researchers:** Andreas Kortenhaus, Kaan Koca
Work Package Leader Responsible:	Iñigo Losada, UC
Reviewed by:	Work package members

Version	Date	Revised Pages	Description of Changes
1.0	15-04-2013	-	1st Draft released
1.1	6-08-2013	-	2nd Draft released
1.2	3-09-2013		**Final Report**. Without Grid connections description (this point will be incorporated by ENEL in WT 3.4).

Table of contents

1 Introduction

European Oceans will be subject to a massive development of offshore infrastructures in the near future. The most foreseeable are offshore energy production facilities, offshore wind farms, exploitation of wave energy, the expansion of electrical connections and also the development and implementation of marine aquaculture. All these activities will give rise to a greater need for offshore infrastructures to support the installation, operation and maintenance of these facilities. However both economic cost and environmental impact have to be reduced in order to increase the viability of the marine space.

MERMAID Project aim is to consider the feasibility of the renewable energy offshore structures to use for other purposes, such as sustainable aquaculture or creating habitats for the proliferation of marine communities.

Work Package 3 (WP3) consists in development of renewable energy conversion from wind and waves. The main aim of WP3 is to contribute to the exploration of conceptual technical designs of innovative MUPs, integrated offshore platforms to harvest ocean energy and offshore wind together with other utilizations such as aquaculture, transportation, etc.

The WP3 is composed of 5 tasks. These tasks encompass an assessment of the ocean energy resources (wind, waves and currents), an analysis of current offshore technology that could be applied to renewable energy technology, a study of existing energy conversion devices, a conceptual framework to assess the integration of different energy convertors in a single multi-use offshore platforms and an assessment of environmental impact for multi-use offshore platforms.

This report presents a detailed analysis of oil and gas floating and fixed common concepts, paying special attention to their applicability to renewable energy, structural and dynamics properties, marine climate limitations, material problems, etc.

The offshore technology review has been organized in two subtasks:

- Shallow water foundation technologies (<50m)
- Deep and ultra-deep water foundation technologies (>50m)

Section 1.1 includes a brief description of the Task 3.2, including the main objectives and a description of the task structure. Furthermore, section 1.1 describes the three subtasks that compose the Task 3.2.

1.1 Task 3.2: Offshore technology

This task has generated specific knowledge in order to transfer the background of the oil and gas industry applied to offshore renewable energy sector.

Like it has been said at the previous section, the offshore technology review has been organized into the following subtasks:

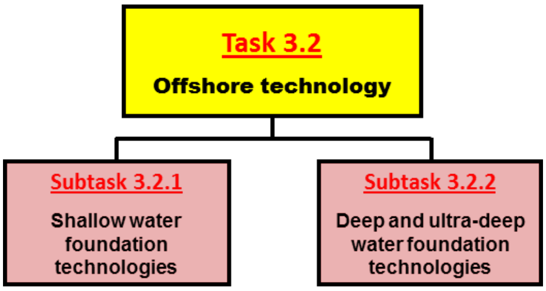


Figure 1. Structure of the Task 3.2: Offshore Technology

One of the purposes of this task is to identify potential new foundation concepts to support wind energy turbines and the new innovation technologies in order to develop an innovative MUP.

Another aim of this task is the identification of the most promising concepts for the four selected sites. This point is related to *Deliverable D7.1 Site specific conditions*.

Next, a brief description of each subtask is given.

1.1.1 Subtask 3.2.1 Shallow water foundation technologies

The goal of this subtask is to review of state of the art of offshore foundations and their use in shallow water conditions.

This report includes a brief description of the main fixed foundations technologies used for offshore wind turbines, included among the most important features as, advantages and disadvantages and, risks and challenges. (See 2.4.2 Fixed Foundations).

1.1.2 Subtask 3.2.2 Deep and ultra-deep water foundation technologies

In the second subtask, the main objective is to review different offshore technologies for deep and ultra-deep waters, with the ultimate goal of gaining knowledge for the selection of the optimal technology for MUP development.

The following are the partial objectives needed to complete this task:

- Analysis of the most common offshore floating technologies.
- Analysis mooring system technologies
- Analysis of the offshore foundation technology applicable to renewable technology.

- Study of the potential new foundations concepts.
- Identified synergies with other projects.
- Review the principal international design guidelines.

1.2 The structure of the report

The structure of this document is as follows.

First of all, it has been described the state of the art in offshore technology, the history in Oil&Gas industry and the main differences with the renewable energy sector, in sections 2.1, 2.2, 2.3, respectively.

Sections 2.4 and 2.5 describe the foundation structure and mooring system concepts. In Section 2.5 it has been analyzed the mooring system technology for offshore floating structures, for which it has been necessary to study the technical requirements of renewable energy foundations, and the mooring concepts used to this day. It has been reviewed different offshore technologies for shallow, deep and ultra-deep waters, and it has been paid special attention to those innovative structures already proven o (or?) near to prototype stage.

Furthermore, in section 2.6 it has applied the offshore foundation technology to renewable energy. Then, in section 2.8, the synergies with other European projects such as TROPOS, H2OCEAN, and MARINA Platform have been identified

Section 2.9 briefly describes standards and guidelines of the four main institutions of certification in the offshore industry.

Then, Chapter 3 synthesizes the experimental and numerical analysis performed, of the most relevant floating foundations for offshore wind concepts.

Finally, in Chapter 4 the selection of the most promising concepts for a MUP at the four selected sites is performed.

2 State of the art in offshore technology

2.1 Definition of foundation

An offshore foundation is a structure that has been designed to endure the load of wind, waves and currents as well as self-weight and remain stable.

Foundations are a very important component when planning the installation of any offshore facility, and are particularly important depending on the water depth. Offshore foundations can be classified into 2 groups: "*shallow water foundation technologies (less than 50 m of water depth)*" and "*deep (more than 50 m of water depth) and ultra-deep water foundation technologies (more than 150 m of water depth)*".

Shallow water foundation technologies correspond in the majority of cases to fixed structures, the main categories are: compliant structures, gravity base structures (GBS), jackets, monopiles, tripiles, etc. (See Figure 2). Fixed structures became increasingly expensive and difficult to install as the water depth increased.

Deep and ultra-deep water foundation technologies are based in floating structures. These types of structures have been used since the 1970s for oil drilling. A floating support structure is recognized by the fact that the support comes from the water and not from the ground. Generally, the contact to the seabed is through anchor lines, also called mooring cables or mooring lines. Many forms of floating structures have been developed over the years, and the main categories are: TLP, FPSO, semi-submersible and SPAR.

Nowadays, because of the recent growth of marine renewable energies, new needs have emerged in the offshore industry. In the last years, multiuse platforms (MUPs) have been developed, which combine multiple functions within the same infrastructure, offering significant economic and environmental benefits.

These platforms differ from the rest of platforms developed to date, since it must meet the requirements of each activity implemented in it.

The MUPs have been classified into two categories: “Offshore Hybrids” and “Energy Islands” according to the following definitions:

- OFFSHORE HYBRIDS: floating or fixed platforms using wind energy converters combined with or within an additional wave and/or tidal energy device. (See Figure 3 (a)).

- ENERGY ISLANDS: multipurpose platforms are generally very big, that utilize many possible sources of renewable energy from the ocean, i.e. wind, solar, wave, sea current, tidal current and biomass energy. Moreover, due to the available space on the platform, combination with other activities and/or functionality is suggested. (See Figure 3 (b)).

Figure 2. Typical Fixed Support Structures: (a) GBS (Thornton Bank.1. Source: C-Power). (b) Jacket (Thorton Wind Farm. Source: C-Power). (c) Monopile (Princess Amalia. Source: belwind.eu). (d) Tripod (Alpha Ventus. Source: Alpha Ventus)

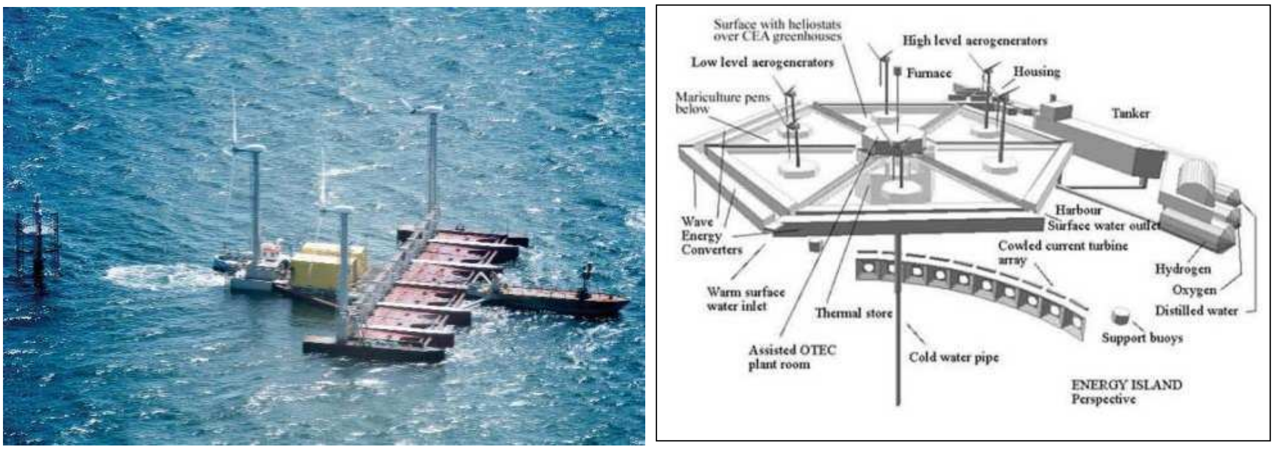


Figure 3. Multiuse Platforms: (a) Posseidon Platform (Source: Posseidon Floating Power). (b) Energy Island (Michaelis, D., 2002)

2.2 Historical development in Oil&Gas industry

The Oil&Gas industry has been exploiting offshore locations since the late nineteenth century. The first offshore platform was installed in the Gulf of Mexico in 6 meters of water (Floatec and Mustang, 2010). Since the installation of this first platform in the Gulf of Mexico over 50 years ago, the offshore industry has seen many innovative structures, fixed and floating, placed in progressively deeper waters and in more challenging and hostile environments.

By 1975, the water depth extended to 144 meters. Within the next three years the water depth dramatically leapt twofold with the installation of COGNAC platform that was made up of three separated structures, one set on top of another, in 312 meters (See Figure 4). COGNAC held the world record for water depth for a fixed structure from 1978 until 1991. Figure 5 shows the progression of fixed platforms since COGNAC platform.

Figure 4. COGNAC Platform installed in deepwater Gulf of Mexico (Source: Offshore Magazine)

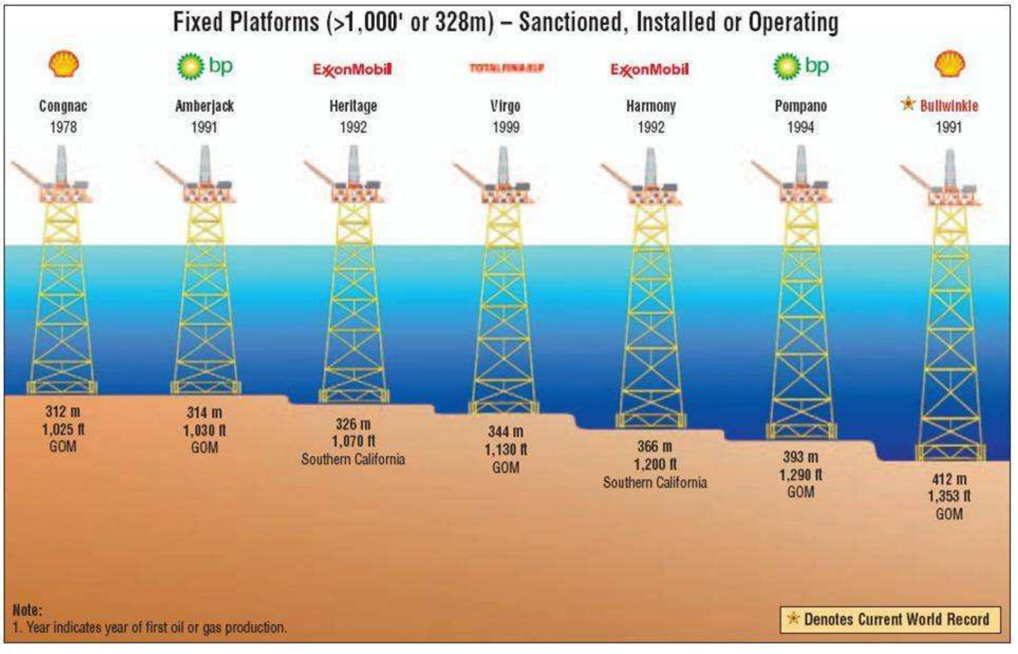
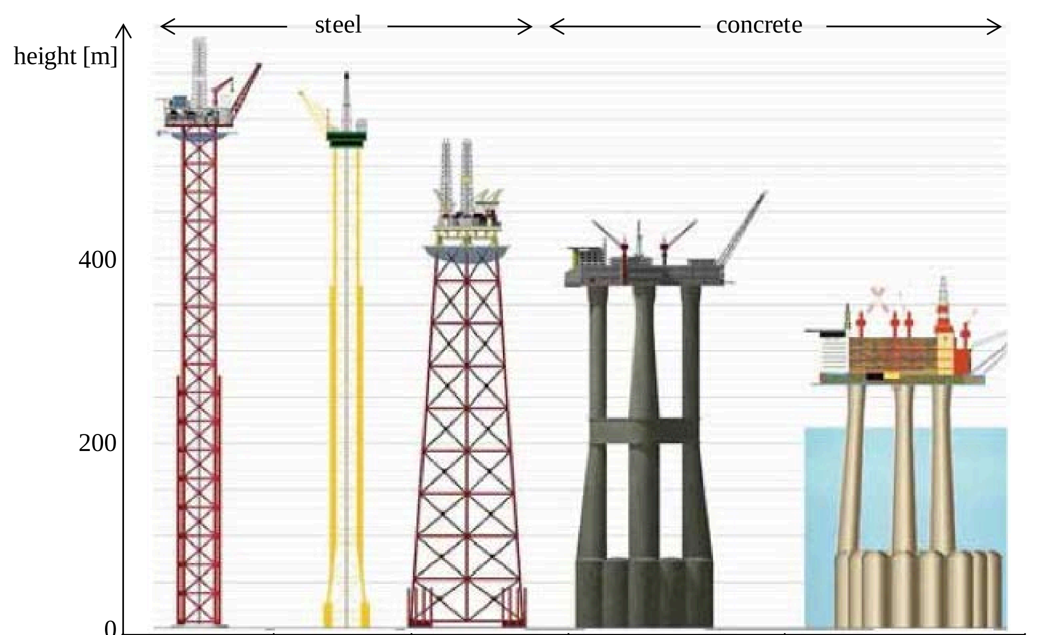


Figure 5. Progression of fixed platform from 1978 until 1992 (Source: Shell)

Nowadays, the tallest fixed oil platform is the Petronius Platform with more than 500m depth water installed (See Figure 6).



Petronius Platform	Baldpate Platform	Bullwinkle Platform	Troll A Platform	Gullfaks C Platform
1997	1998	1988	1996	1990
GOM	GOM	GOM	Nowegian Sea	Norwegian Sea

Figure 6. Overview of the tallest bottom-mounted oil platforms (modified from Tarelko, 2011)

Fixed structures became increasingly expensive and difficult to install as the water depths increased, and in the 1970s, floating production systems came to be used. The first Tension Leg Platform (TLP), Conoco's Hutton (see Figure 7) was installed in 1984 in 145 meters of water, in the Hutton Field (Offshore Magazine, 2003). A recent version, Shell’s Olympus TLP, is expected to be moored in 914 meters of water, and is said to be the largest TLP ever deployed for the Gulf of Mexico.

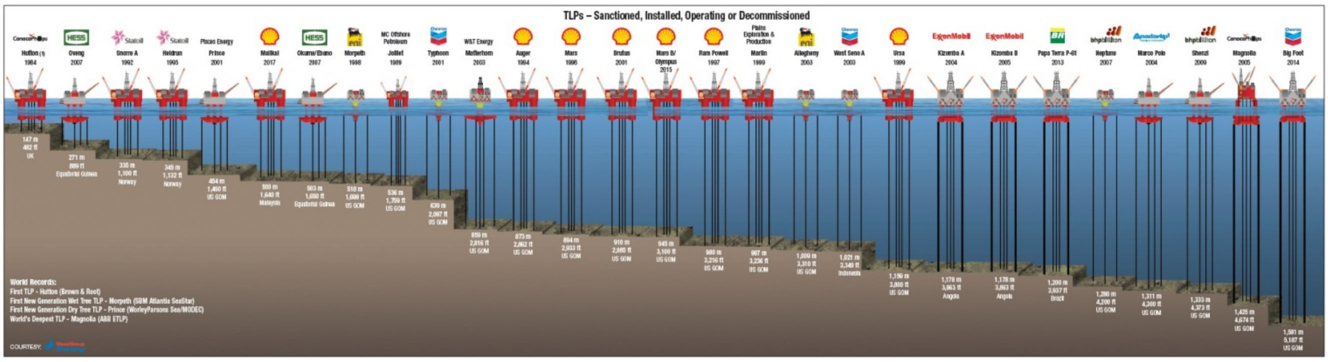


Figure 7. Progression of TLP platform (Source: Mustang)

In September 1997, the first SPAR designed for oil and gas production, the Neptune spar (see Figure 8), was installed in the Gulf of Mexico by Kerr McGee (now Anadarko), in 590 meters of water (Offshore Magazine, 2004). The world's deepest production platform is currently the Perdido, a truss spar in the Gulf of Mexico operated by the Shell Oil Company, with a mean water depth of 2,450 meters. Shell (2010) reported that the Perdido is one of their most challenging deep-water projects In 2007, a deep-draft Semi-submersible platform, Independence Hub, was designed and constructed by SBM Offshore in the Gulf of Mexico in 2,438 meters of water (Offshore Magazine, 2010). Since then SBM Offshore have been upgrading their innovative concept. Figure 10 shows the deepwater development tools in offshore industry.

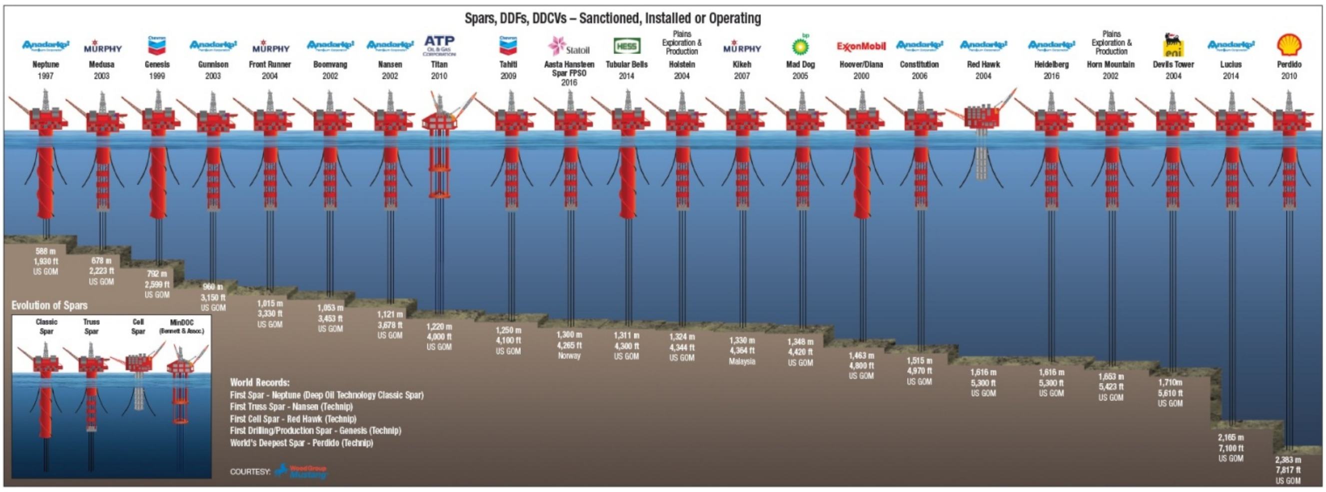


Figure 8. Progression of Spar platform (Source: Mustang)

Figure 9. Perdido SPAR platform decks (Source: Shell, 2010)

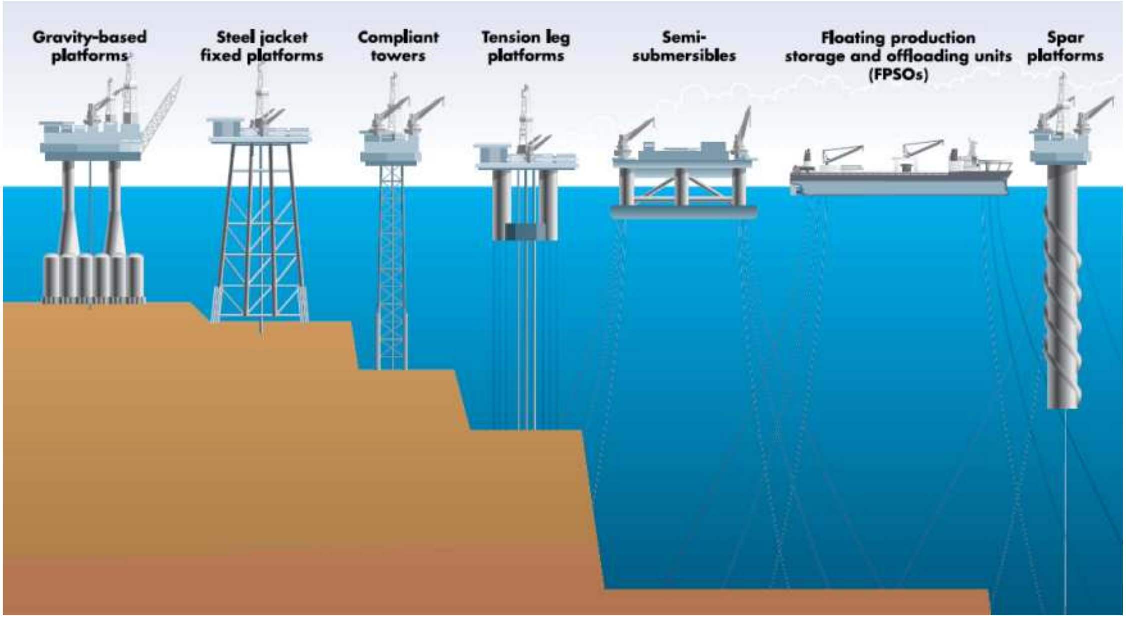


Figure 10. Deep-water development tools (Source: Shell, 2010)

The main types of floating production systems are FPSO (floating production, storage, and offloading system) (See Figure 10). FPSOs consist of large monohull structures, generally (but not always) ship-shaped, equipped with processing facilities. These platforms are moored to a location for extended periods. However, the first floating production system, a converted semi-submersible, Argyle filed in the UK North Sea in 1975 (Chakrabarti, 2005), and they have become increasingly popular for production (See Figure 11).

Figure 11. TW 58, Argyll Oil Field - North Sea (Source: www.oilrig-photos.com)

The first ship-shaped FPSO was installed in 1977 by Shell International for the Castellon field, offshore Spain.

There were 40 semi-submersible and 91 FPSOs in operation or under construction for deep waters as of 2002 (Offshore, 2002). Figure 12 shows the Offshore industry milestones from 1990 until 2010 (Floatec, 2010).

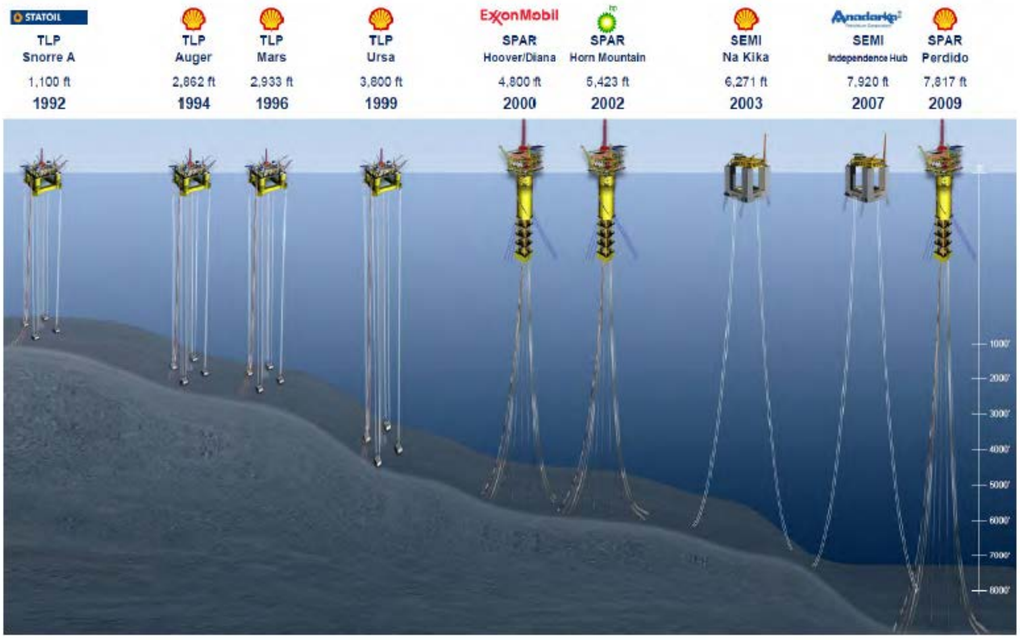


Figure 12. Offshore technology deepwater milestones. (Source: Floatec, 2010)

Table 1 shows a comparison of primary characteristics of the main type of floating offshore structures for Oil&Gas (Floatec, 2010).

Issue	TLP	Spar	Semi	Ship-Shape
Water Depth	More Sensitive	Less sensitive		
Platform Motions	Excellent – Very low vertical motions, i.e. heave, roll and pitch	Good – Low vertical motions (pitch to 8-10 deg). Sensitive to long period waves.	Motions limit application to wet trees	Motions limit application to wet trees
Transport	Single piece complete	Single piece hull	Single piece complete	Single piece complete
Installation	Quayside deck lift and integration	Hull upending and offshore deck lift and integration	Quayside deck lift and integration	Shipyard module lift and integration
Mooring System	Vertical tendons	Taut or semi-taut spread mooring legs		Spread catenary or turret moored
Mooring Footprint	Small and compact, same dimensional order as hull	Large, approximately 2X water depth. Impacts field development layout, but allows drilling flexibility.		
TTR Support	Short stroke tensioners	Air cans or long stroke tensioners	N/A	N/A
Wellbay	Conventional, within columns	Confined within moonpool	N/A	N/A
Storage Capability	No	Yes, but not typical	No	Yes, typical

Table 1. Comparison of Primary Characteristics (Source: Floatec, 2010)

The Oil andGas technology offers the renewable energy industry the ability to move large structures offshore where the resources are stronger and more consistent whilst reducing environmental impact.

Most of the technology developed for offshore oil and gas production, and relevant to the offshore wind industry, is available in the public domain.

Mooring systems for these floating structures have matured to allow deployment in depths well over 1000 meters. While this is deeper than any currently planned marine renewable projects, the mooring technology in the Oil and Gas industry will permit development of anchoring systems for marine renewable energies offshore floating platforms. Mooring system will be analyzed in detail in section 2.5.

The next section describes the main difference between the Oil &Gas industry and renewable energy sector.

2.3 Differences between the Oil&Gas industry and renewable energy sector

The offshore energy industry has several synergies with the Oil&Gas industry. More than 50% of the project value in offshore renewable energies is what oil and gas contractors do every day: building offshore structures, installing structures, laying cables, hooking up equipment, commissioning equipment and so on (Pretofac, 2012). However, they have also many important differences.

Any structure used in offshore Oil&Gas exploration and production constitutes a vital part of a successful energy production, vital both in terms of construction costs, of safety, of human lives and the environment, and in terms of revenues from the production. This entails that the Specifications, Standards and Recommended Practices for the design of offshore structures are very restrictive.

An offshore floating platform for marine renewable energies is simpler and much cheaper to build than an Oil&Gas platform (See Figure 13). For the majority of the Oil&Gas structures the design loads are governed by the oceanographic parameters: waves and currents, and the high topside loads, while for the marine energy platforms the topside loads are less important and are the environmental loads conditions (waves, currents and wind) the design loads (Jacobsen, V. and Rugbjerg, M., 2005). Furthermore, the renewable energy platform will be un-manned except for maintenance and repair, the environmental impact from damaged structure is limited, and at the end, the value of energy production per foundation unit is far less than the value from oil production from a platform. So the marine energy should reduce costs in each of the phases of design, installation, operation and maintenance to achieve economic efficiency.

On the other hand, marine energy platforms installed in deep and ultra deep water have an important difference than the Oil&Gas platforms that is the design of the mooring system. While the technology concept can be inherited from Oil&Gas, in marine renewable energy industry, the mooring system accounts for the 27% of CAPEX (Garrad Hassan, 2012). So, one of the big challenges of the marine renewable energy platform is the optimization of mooring systems.

Figure 13. Semi-submersible structures: (a) TROLL B (North Sea, 1995); (b) WINDFLOAT 2MW Phase I , Installed 2011

Table 2 summarizes the main synergies and differences between offshore Oil&Gas and offshore renewables.

Synergies vs Competition
Strong Synergies:
Safety, Design Standards, Materials
Lessons Learned:
Construction & Installation Techniques
Capitalization & Cash flow Management
Similar Requirements:
Manpower and Equipment
Differences
Economy of Scale:
Massive Return Investments vs Offshore Wind Marginal Market
Hazards:
Life, environment and structures
Mechanical Loadings Location:
Water depth; Distance to shore

Table 2. Offshore Oil and Gas vs Offshore Renewables

One of the strongest lessons learned from the offshore Oil&Gas industry is that the offshore Oil&Gas has established industry standard practice, a foundation on which the offshore wind industry can build. This is particularly true in the areas of safety, design and materials science.

2.4 Foundation concepts

In the present section, a more detailed description of the different foundation concepts available will be given. First, floating concepts will be analyzed and next, fixed foundations will be reviewed.

2.4.1 Floating foundations

The principal development of floating platform has been realized by oil and gas industry. The most common floating structures are: Spar, Semi-submersible, FPSO, TLP, SeaStar and Min-Doc (See Figure 14).

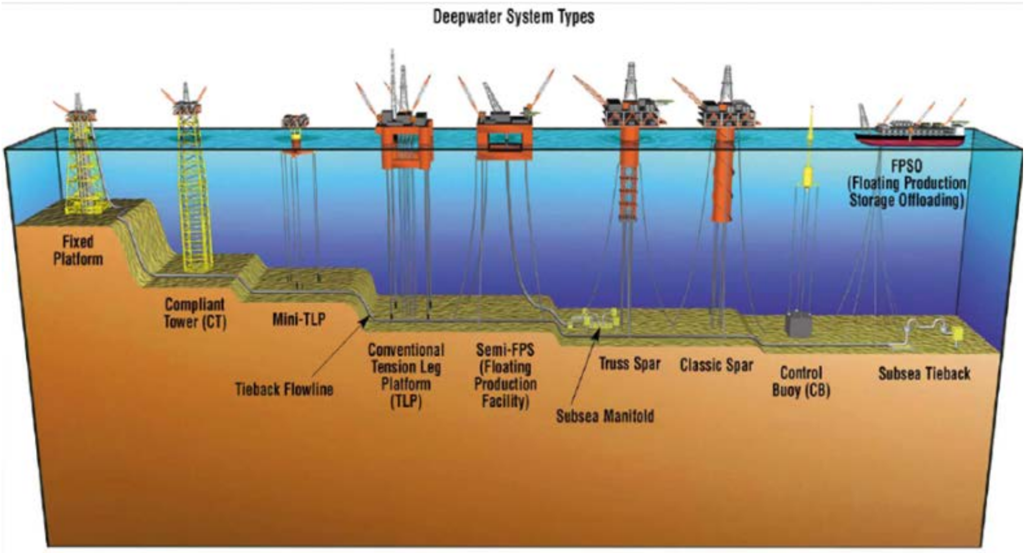


Figure 14. Deepwater System Types (Offshore Magazine, 2005)

The floating structures may be grouped as a renewable energy use or not use for renewable energy, in terms of their applicability to renewable energy using the experience in Oil&Gas industry. To date, only a few concepts have been developed to use as floating structure for renewable energy, this concepts are SPAR based concepts, Semi-submersible and TLP platforms. Barge concepts have been conceptually developed, but never applied in a real scale concept.

A classification system that divides all platforms into three general categories based on the physical principle or strategy that is used to achieve static stability:

- *Ballast*: Platforms that achieve stability by using ballast weights hung below a central buoyancy tank which creates a righting moment and high inertial resistance to pitch and roll and usually enough draft to offset heave motion. Spar-buoys apply this strategy to achieve stability.

- *Mooring Lines*: Platforms that achieve stability through the use for mooring line tension. The tension leg platform (TLP) relies on mooring line tension for righting stability.

- *Buoyancy*: Platforms that achieve stability through the use distributed buoyancy, taking advantage of weighted water plane area for righting moment. This is the principle used in a barge or semi-submersible platform.

The following section gives a detailed explanation of the most common floating concepts.

Semi-submersible platform

Semi-submersible marine structures are well known in the oil&gas industries. Semi-submersibles are multi-legged floating structures with a large deck. These legs are interconnected at the bottom underwater with horizontal buoyant members called pontoons.

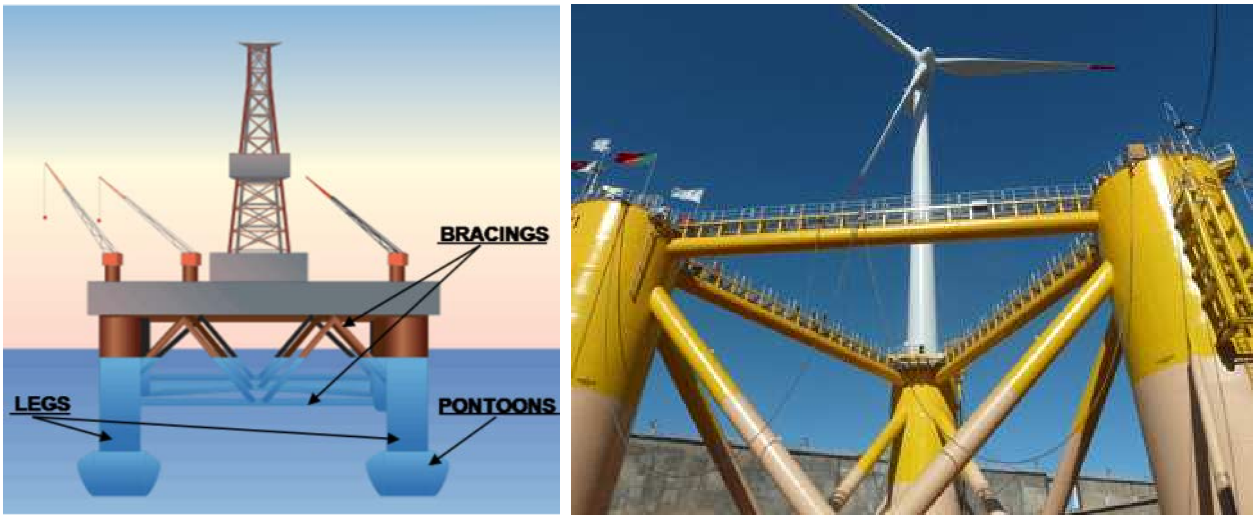


Figure 15. Semi-submersible structure. (a) Semi-submersible structure concept for Oil&Gas. (b) WindFloat Concep for wind energy.

The pontoons provide a relatively large water plane area, as is desirable for transit, but when submerged for stationing they give a higher movement damping. The columns connecting the pontoons to the upper deck present a lower water plane area for operation. The lower water plane area is desirable to reduce motion characteristics from waves, especially during swell seas and storms.

These structures have a relatively low transit draft that allows them to be floated to a stationing location, where they can add ballast, usually by taking on seawater, to assume a relatively deep draft or semi-submerged condition for operation.

Semi-submersible platform presents the next characteristics:

- Stable position, small movements.
- Easily Mass Produced.
- Catenary or Taut mooring.
- High heel angles.
- Dry-docking possible.

Barge floater/FPSO

The FPSO generally refers to a ship-shaped structures with a several different mooring systems used by the offshore oil and gas industry for the processing of hydrocarbons and for storage of oil.

The main issue for deep water is to get the required buoyancy to achieve stability. These structures are moored with spread mooring system and in many cases the mooring system includes internal and/or external turrets.

The FPSO are present in the Oil&Gas industry with more than 110 units. These structures are virtually permanent, which favor lower installation costs, quick disconnection and are less reliant on seabed conditions.

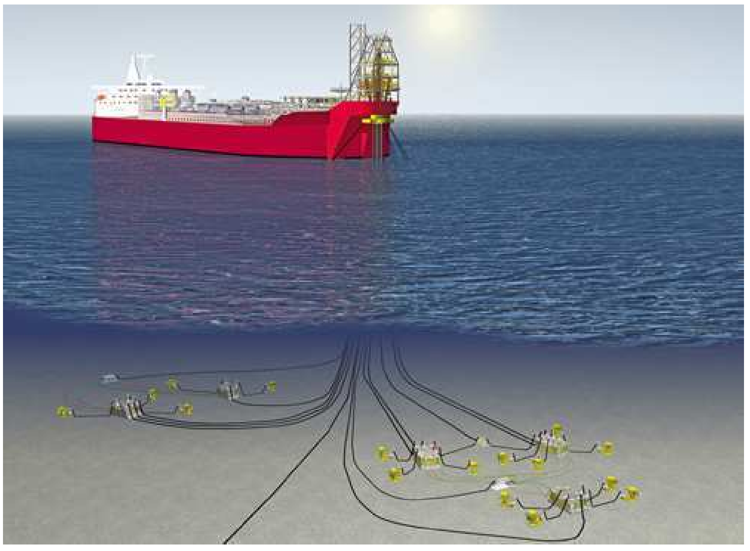


Figure 16. FPSO platform. (Source: www.MODEC.com)

SPAR floater

The spar concept is a large deep draft, cylindrical floating caisson designed to support the topside loads. Its buoyancy is used to support facilities above the water surface. It is generally, anchored to the seafloor with traditional mooring system (that is, anchor-spread mooring) to maintain its position. The solid ballast reduce the position of the gravity center and increase the stability of the buoy, which produces very favorable motion characteristics compared to other floating concepts. Low motions and a protected center well (will?) also provide an excellent configuration for deepwater operations.

Spars concepts in the oil and gas industry are usually split in 3 classes: Traditional spar structures with a circular cylindrical hull, truss spars in which the middle part of the hull is replaced by a truss structure (e.g. the Nansen SPAR) and cell SPAR (e.g. Red Hawk) in which the hull consists of multiple ring stiffened tubes, connected by horizontal and vertical plates (See Figure 17).

The main characteristics of the spar concept are:

- Stable design: small and slow motions.
- Less sensitive than TLPs to water depth and payload.
- Straightforward installation.
- High mass, deflection and heel angles.
- For very high depths.
- Sensitive to long period waves.

Figure 17. The SPAR concept. (a) Statoil concept (Aasta Hansteen field, 2012). (b) HyWind (Statoil)

Tension leg platform

The mooring system of a TLP is vertically moored compliant platform, and consists of tubular steel members called tendons. The group of tendons at each corner of the structure is called a tension leg.

The tendon system is highly tensioned due to excess of buoyancy of the platform hull. The high tension limits horizontal offsets to a small percentage of water depth. Vertical motions of the TLP are nearly non-existent due to the tendon's high axial stiffness (low elasticity). Moreover roll and pitch motions are also negligible. It is compliant in the horizontal direction, permitting lateral motions (surge and sway).

Therefore, TLP is very effective once installed. However, the tendon system is critical to performance and must be carefully designed, fabricated, inspected and installed to ensure long term performance and robustness.

The main characteristics of TLP concept are:

- Limited motions (heave, roll and pitch). Improved motion characteristic compared to Spar and Semi-submersibles.
- High performance.
- Smaller steel weight (+).
- Small footprint area on seabed (+).
- Site – Constrained. High depth.
- High cost of mooring system.
- Vertical mooring system does not provide active control horizontal position. Sensitive to yaw load.
- Difficult installation and maintenance.

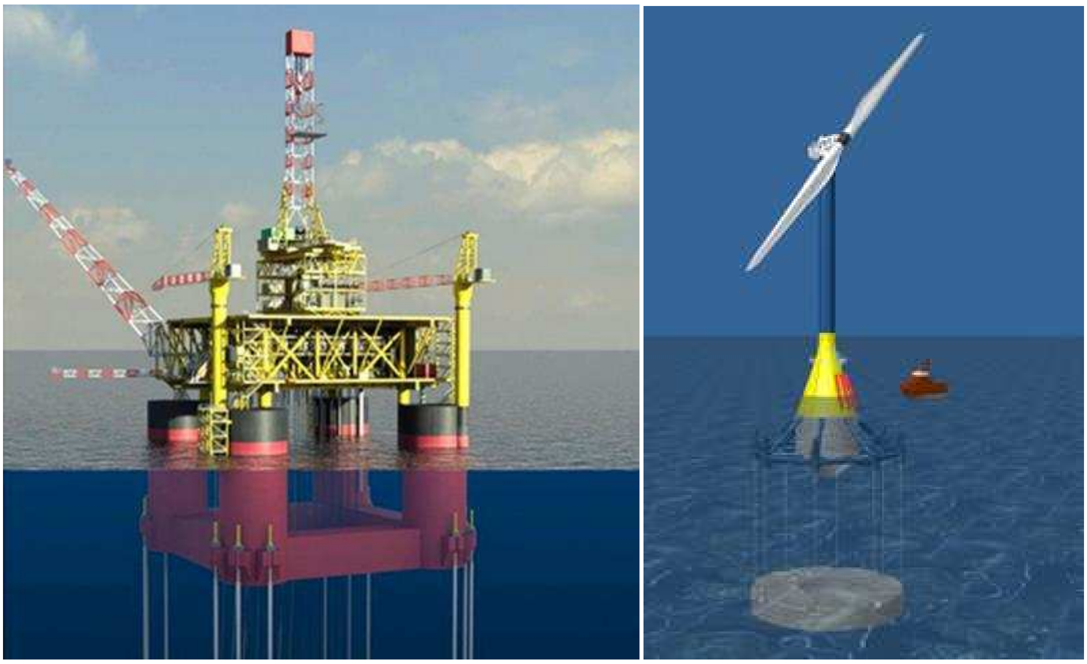


Figure 18. TLP concept. (a) HYUNDAI TLP structure for Oil&Gas. (b) Blue H TLP concept for wind energy

Seastar

Nowadays, Seastar platform has been used in the oil and gas industry. This kind of floating platform (Seastar platforms) are like miniature tension leg platforms. The SeaStar has a relatively small size and low cost, which are important advantages. Seastar could be considered as a singular TLP from renewable energy point of view.

The platform consists of a floating rig, much like the semi-submersible type. A lower hull is filled with water when drilling, which increases the stability of the platform against wind and water movement. In addition to this semi-submersible rig, however, Seastar platforms also incorporate the tension leg system employed in larger platforms. Tension legs are long, hollow tendons that extend from the seafloor to the floating platform. These legs are kept under constant tension, and do not allow for any up or down movement of the platform. However, their flexibility does allow for side-to-side motion, which allows the platform to withstand the force of the ocean and wind, without breaking the legs off.
Seastar platforms are typically used for smaller deep-water reservoirs, when it is not economical to build a larger platform. They can operate in water depths of up to 1070 meters.

Structural benefits of the SeaStar platform are (Offshore Magazine, 1996):

- The tension-leg mooring system suppresses nearly all vertical motions. The tension leg mooring provides much better motions than any comparably sized structure using catenary mooring. The motions are comparable with much larger TLPs.
- The single surface-piercing column allows the hull and deck to be independently designed and optimized.
- The foundation can have either driven piles, drilled and grouted piles, or suction piles. Redundancy can be incorporated by using a template with additional piles.
- Tendons are pre-installed which reduce installation risk.
- The hull can either be wet-towed or dry-towed to location. After the hull is connected to the pre-installed tendons, the deck section can be lifted into place.
- The platform's relatively large base dimensions increase tendon separation and improve their effectiveness.

Figure 19. SeaStar concept. (Source: www.keppelom.com)

Min-Doc

Several versions of MinDoc have been developed that range in topside loads of 20 Tn to 320 Tn and water depths of 450 meters to near 3050 meters, and having traditional rectangular as well as T-shaped and triangular topsides. The MinDOC designs are a combination of features of the spar and the semi-submersible platforms.

The ballast system was simplified as compared with typical semi-submersible design (and featured an over-the-top pump-in and pump-out system) that eliminated the possibility of transferring ballast from one column to another. Due to the internal subdivision and stability characteristics, the application of ballast system requirements of the spar (3) was appropriate for the MinDOC.

From a dynamic response perspective, the MinDOC also behaves more like a spar than a semi-submersible, with very good heave and pitch motions, as needed to support dry trees, top-tensioned risers (TTRs) and steel catenary risers (SCRs).

Although the three-column version is preferred for several reasons pertaining to efficiency, four-column versions have also been studied.

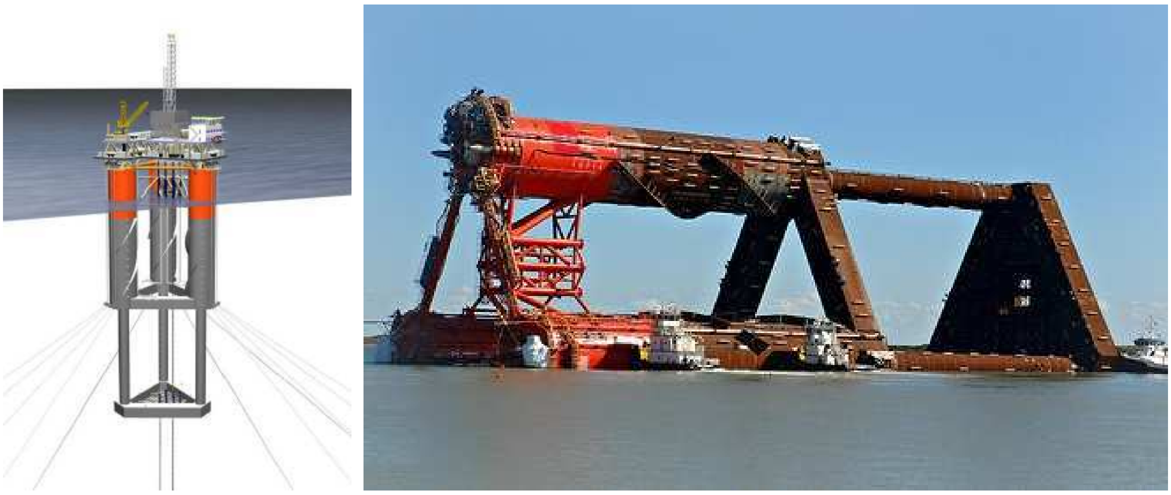


Figure 20. MinDoc concept: Telemark MC 941/2, US Gulf of Mexico, ATP Titan

Table 3 shows a summary of characteristics of main structures for renewable energy.

Platform Design Challenge	Floating Platform Technical Challenges		
	Platform Stability Classifications		
	Buoyancy (Barge)	Mooring Line (TLP)	Ballast (Spar)
Design Tools and Methods	-	+	-
Buoyancy Tank Cost/Complexity	-	+	-
Mooring Line System Cost/Complexity	-	+	-
Anchors Cost/Complexity	+	-	+
Load Out Cost/Complexity (potential)	+	-	
Onsite Installation Simplicity (potential)	+	-	+
Decommissioning & Maintainability	+	-	+
Corrosion Resistance	-	+	+
Depth Independence	+	-	-
Sensitivity to Bottom Condition	+	-	+
Minimum Footprint	-	+	-
Wave Sensitivity	-	+	+
Impact of Stability Class on Turbine Design			
Turbine Weight	+	-	-
Tower Top Motion	-	+	-
Controls Complexity	-	+	-
Maximum Healing Angle	-	+	-

Key: + = relative advantage; - = relative disadvantage; blank = neutral advantage

Table 3. Floating Platform Technical Challenges (Source: NREL: Engineering Challenges for Floating Offshore Wind Turbines)

2.4.2 Fixed Foundations

Although modern technology derived from offshore wind engineering distinguishes between “foundation” and support structure” (see Figure 21), in this section these terms have been used interchangeably.

This section provides a brief description of various fixed foundations used for offshore wind turbines. Fixed foundations have all in common that the loads and forces are exerted into the soil and that their suitable water depth is not greater than 50 m (Teich, 2013). Fixed foundations include monopiles, gravity-base, jacket, tripod, tripile and suction bucket solutions, as shown in Figure 22.

Monopile foundations have been selected for most of the installed wind farms so far. Concrete gravity-base foundations have also been used in several projects. As the turbine size increases, they are moved to deeper waters where jacket structures are expected to become more attractive.

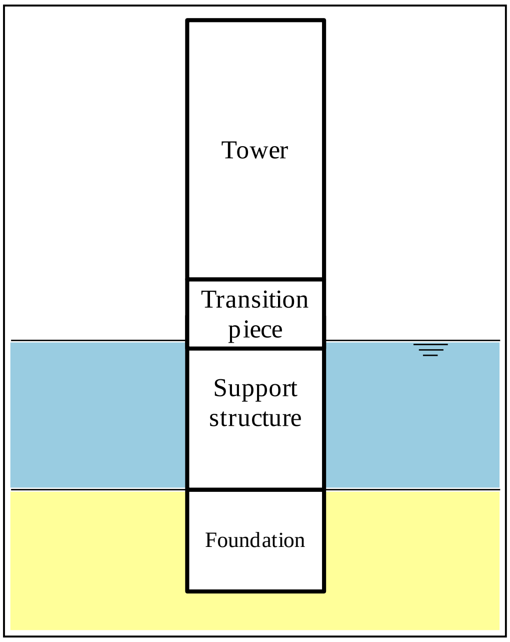


Figure 21. Parts of an offshore structure for a wind turbine (excluding rotor, generator and tail)

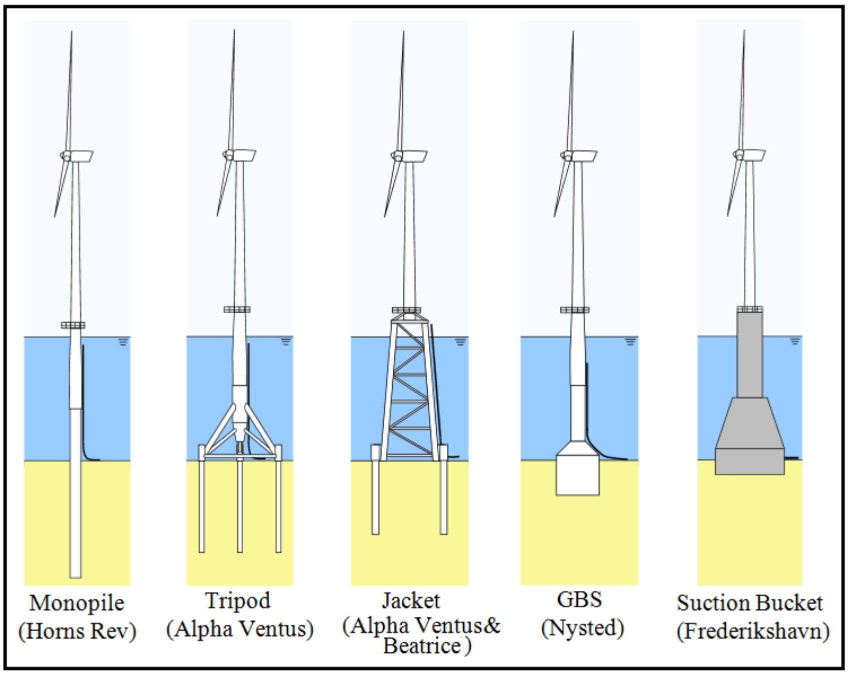


Figure 22. Overview of fixed foundations for offshore wind energy (de Vries, 2007)

The selection of the foundation type depends on a variety of factors, which can be divided into technical limitations, cost considerations, and environmental constraints. These may include factors such as (Williams et al. 2011):

- Contractor capability in terms of:
    - General confidence and experience
    - Monopile / jacket lifting and handling
    - Driving / drilling equipment

- Fabrication limits

- Permit and Regulatory Limits
  - Noise limitations (piling)
  - Impact on sediment transfer
  - Coverage of seabed (footprint)

- Wind turbine size (in terms of rotor diameter, hub height, rated power and nacelle weight)

- Water depth

- Likelihood of sea ice

- Ground conditions

- Metocean conditions

The final decision is usually made based on cost and risk assessments, that is, the lowest cost solution with an acceptable risk. In the following sections, the proven foundations for offshore wind turbines are discussed in more detail.

Monopile foundation

Monopile foundation solutions (Figure 22) are based on design experience from the offshore oil and gas industry, which has then been adapted for the offshore wind farm industry. Due to its lower cost, simplicity, and appropriateness for shallow water (10-30 m) with moderate wave loading (Powered, 2012), it has been the most widely used foundation type, particularly for the projects in the sandy North Sea seabed (EON, 2012).

The monopile foundation is very similar to that of onshore wind turbines. The monopile foundation consists of a cylindrical steel pile that is thrust far down in the bottom (usually about 30 meters) by pile-driving or drilling (Hammar et al., 2010). The piles support the weight of the tower and turbine, mainly by using friction between the pile walls and the seabed. The vertical loads can easily be transferred to the soil through wall friction and tip resistance. The lateral loads, in comparison much larger, are transferred to the foundation through bending. The loads are subsequently laterally transferred to the soil. To provide enough stiffness the diameter of the monopile foundation has to be large enough (Upwind, 2007), which increases with the increase in size of the turbine (See Table 4). This attracts relatively high hydrodynamic loads. Due to the loading weight stress, the diameter of the foundation and the depth of piling can be adjusted. The monopile foundation typically weighs around 500 tons, making it one of the lighter foundations. On the deeper sites like Walney 2, the monopiles weight up to 810 tons and are up to 69 m long (URL 3).

Installed monopiles typically extend to above 5 to 10 m of the sea surface. To make the structural connection between the monopile foundation and the wind turbine tower, a transition piece is installed over or inside the monopile. The transition piece also permits adjustment to account for out of vertical tolerance of the installed monopile and supports external secondary steelwork such as J-tubes, boat landings and working and intermediate access platforms. Typically, the transition piece, having a greater diameter, is fitted over the monopile externally and secured by grouting the annulus between the transition piece and pile, using a high strength, low shrinkage grout. Alternatively, the turbine tower can be bolted directly to a flange on top of the monopile.

The monopile foundation is easy to manufacture and install (Upwind, 2007). For example, it is possible to seal the ends of the piles and float them individually or together to site (Lesny, 2010). However, during the installation a pile equipment of big lifting capacity is required (Hammar et al., 2010). From arrival at site, the complete installation of a foundation takes less than 24 hours (EON, 2012). A brief typical installation sequence is as follows:

- Transportation of monopiles to offshore site via vessel, barge or float-out (with the monopiles bunged to give positive buoyancy) (Figure 24)
- Up-ending pile by jack-up crane vessel with buoyancy assistance if necessary;
- Monopiles lowered to seabed location, with pile weight providing initial seabed penetration;
- Installation of monopiles progressed by driving (piling), vibration, drilling or a combination as required by site specific soil conditions and technical and economic viability;
- Installation of transition piece, alignment and grouting; and
- Installation of ancillary equipment, such as J-tubes and boat landings if not integral to transition piece.

The sequence is repeated for each foundation, initiated by the jack-up installation barge positioning itself in position at the pre-determined turbine location. Some photos from the manufacturing, transport, and installation process are shown in Figure 23 and Figure 24, respectively.

Monopile delivered to harbor | Monopiles loaded out on jack-up barge | Monopile being up-ended for installation

Figure 23. Manufacturing and delivery of monopile (EON, 2012)

Figure 24. Installation of monopile (EON, 2012).

The monopile foundation is generally used in waters with a maximum depth of 25 meters (DNV-OS-J101, 2010) and may not be applicable beyond these water depths as stiffness requirements may lead to such large diameters that are impossible to manufacture due to limitations on the size of the steel plates that can be produced by steel mills (Upwind, 2007). This also makes the installation more difficult as there are no hydraulic hammers available on the market which can drive larger monopiles into the seabed. Therefore, sites with deeper water, severe waves and currents, and larger turbines may require the implementation of more complex and sturdier designs, such as the jacket, the tripod, or the tripile. At sites with high currents and high amount of sand movements, scour protection is also of great importance. Therefore, many investigations have focused on scour problems around the monopile foundations. An overview of these studies is provided in section *2.6.1 Hydraulic model studies on fixed foundations*.

Suitable soil conditions for monopiles are sand and silt layers (URL 1). It is less suitable in seabed conditions consisting of high density of boulders, and rocky bottoms since they will make the installation process more complicated (pre-drilling). Furthermore, the monopile is suitable for seabed conditions such as stone mixed bottoms, sand or clay where there is underlying bed.

The disadvantages of the monopile foundations are that the required size of the monopile drastically increases as turbine size increases and site conditions become more challenging, which results in more weight (see Table 4). Therefore, sites in deeper water, with harsh waves and currents, and larger turbines may require the implementation of more complex designs, such as the jacket, the tripod, or the tripile (AWS Truewind, 2009). Another disadvantage is the difficult decommission of the monopile foundations (Westgate & DeJong, 2005). Furthermore, underwater noise that occurs during the drilling/driving needs careful consideration (URL 1; Teich, 2013). An overview of the advantages and disadvantages of monopiles is shown in Table 6.

An alternative monopile solution currently under development comprises a steel reinforced concrete design. Ballast Nedam Offshore and MT Piling have studied a novel foundation concept for Offshore Wind Turbines called the *drilled concrete monopile*, for the Vattenfall study project “Foundation Concepts for the Kriegers Flak Wind farm.” Such structures would typically comprise a number of pre-cast concrete ring sections. These could be fitted together and grouted prior to floating out to the construction site. Once the monopile is transported to the site, its installation follows the same sequence as described for steel monopiles except that the pile is expected to be positioned by drilling from the inner radius of the pile, after initial seabed penetration by weight of the monopile. Drill cuttings are removed from the pile hole and typically allowed to disperse naturally at the seabed surface. Piling with a hammer is not an appropriate technique for this type of foundation design. The main reasons for developing this concept are (URL).

- Concrete monopiles are inexpensive compared to steel monopiles: concrete is less vulnerable to price fluctuations.
- Unlimited fabrication capacity and a wide range of suppliers are available.
- Underwater noise can be prevented.
- The method can be used for various soil types, even where boulders are present.

Concrete monopiles have been designed for a 3,6 MW and for a 5 MW Wind Turbine in a water depth of 30 meter. The calculations are based on two for the Kriegers Flak site representative soil profiles (a sand and a clay profile). Table 5 shows the results of the calculation.

The design of monopiles is still under development. It is possible that increasingly combinations of steel and concrete, in a range of configurations will occur. Additional changes are likely to see an increase of the in-ground dimensions increase without a corresponding change in the in-water dimension. The design parameters presented here are believed to represent the widest realistic range and thus adequately assess the full range of expected design evolution options as they interact with the environment.

Installed turbine power	Pile diameter
3-4 MW	4-5 m
5-6 MW	5-6 m
7-10 MW	6-8 m

Table 4. Monopile diameter of an offshore support structure as a function of installed turbine power (Williams, 2011b)

Indicative monopile dimensions for the Kriegers Flak site		
Dimensions	**3.6 MW**	**5 MW**
Outer diameter (m)	6.5	6.9
Wall thickness (mm)	500	700
Pile length (m)	61	64
Weight (tons)	1450	2200

Table 5. Overview of monopile foundation characteristics (after Teich, 2013; Williams, 2011; EON, 2012)

Monopile foundation	
• Monopile foundations can be used in waters with a maximum depth of 25 meters • Made of steel, one monopile foundation weighs up to 800 tons • About 30 meters of the monopile is driven into the seabed • Monopiles are the most common foundations so far, especially for projects in the sandy North Sea seabed • From arrival at site, the complete installation of a foundation takes less than 24 hours	
Advantages	**Disadvantages**
• Known structure from onshore wind • Easy design • Less seabed preparation necessary • Low costs • Easy transportation and fabrication • Most economical solution for shallow water	• Deep soft soils unfeasible • Large pile diameters in deeper waters necessary • Scour protection • Heavy piling/drilling needed • Difficult disassembly • Steel is expensive and needs corrosion protection
Risks	**Challenges**
• Changes of seabed conditions have a large effect on the natural frequency and fatigue • Underrating the maximum wave loads	• Reducing piling/drilling noises • Reducing weight by individual adaption to each site • Developing maintenance strategy to avoid fatigue • At this stage, the monopile diameter is limited to about 6 m and the wall thickness is limited to about 100 mm at the mudline and the total weight of the monopile up to about 900 Tons.

Table 6. Monopile foundation characteristics

Gravity base foundation

An alternative to the monopile foundation is the gravity base foundation. The gravity base foundation differs from the monopile in that it is not driven into the seabed (See Figure 22), but rather rests on top of the seabed. Gravity base foundations are designed with the objective of avoiding tensile loads (lifting) between the bottom of the foundation and the seabed (DNV, 2010). At present, this design is the second most installed foundation after monopile. Gravity-based foundations are used in shallow waters (with a maximum depth of 30 meters) (EON, 2012) and have proven to be very cost effective (URL 1).

A gravity base foundation stands directly on the seabed and its stability is ensured by a very heavy weight of the construction (Teich, 2013). A base consisting of a concrete caisson or a steel container is plunged into the bottom where it is filled up to and above the level of the surrounding seabed with ballast stones, concrete or other high density materials (Hammar et al., 2010). The foundation has a large flat base to resist overturning moments imposed by the rotor. The structure can also incorporate “skirts” around the perimeter, which penetrate up to approximately 2 m into the seabed depending on seabed conditions, helping to resist horizontal movement. The size is dependent on the water depth and the wave conditions. An ice-breaking cone is normally used in icy waters and the ice-cone can also be used as an access platform. A horizontal seabed and sites with economic transport conditions are required for this type of foundation (Williams, 2011b). This is specifically suitable in areas without tidal changes which are the case in the Baltic Sea.

Gravity base foundations are typically installed in fabrication sites on dry land, transported to site by barge, or towed by tug whilst floating under their own buoyancy, and lowered into position on a prepared seabed by controlled adjustment of their buoyancy. Depending upon site geologic conditions, this foundation may require significant site preparation including dredging, filling, leveling, and scour protection (AWS Truewind, 2009). Therefore, the soft top layer has to be removed and a leveling has to be done (Marx et al., 2012) prior to placing the foundation. The potential depth of sediment removal is estimated to be up to 3 m. Once leveled, there is the potential need for the addition of a stone bedding layer if appropriate to site conditions. Once the seabed preparation is done, the gravity base foundation can be correctly positioned and placed on the base soil layer (Lesny, 2010; URL 1). Ballast material consisting of stones or other suitable material is then filled inside the foundation to ensure final stability (URL 1). These foundations may have ancillary equipment (J-tubes, boat landings etc.) already incorporated.

Gravity base foundation relies on a wide footprint and massive weight to counter the forces exerted on the turbine from the wind and waves. Whilst each gravity base foundation can weigh over to 7000 tons, they can be easily removed during decommissioning phase of the project. Since this structure is installed on the seabed without drilling, installation leads to lower acoustic noise (Powered, 2012). Some photos depicting the manufacturing and installation process of gravity base structures are shown in Figure 25 and Figure 26, respectively.

Figure 25. Manufacture and delivery of Gravity base foundation (EON, 2012)

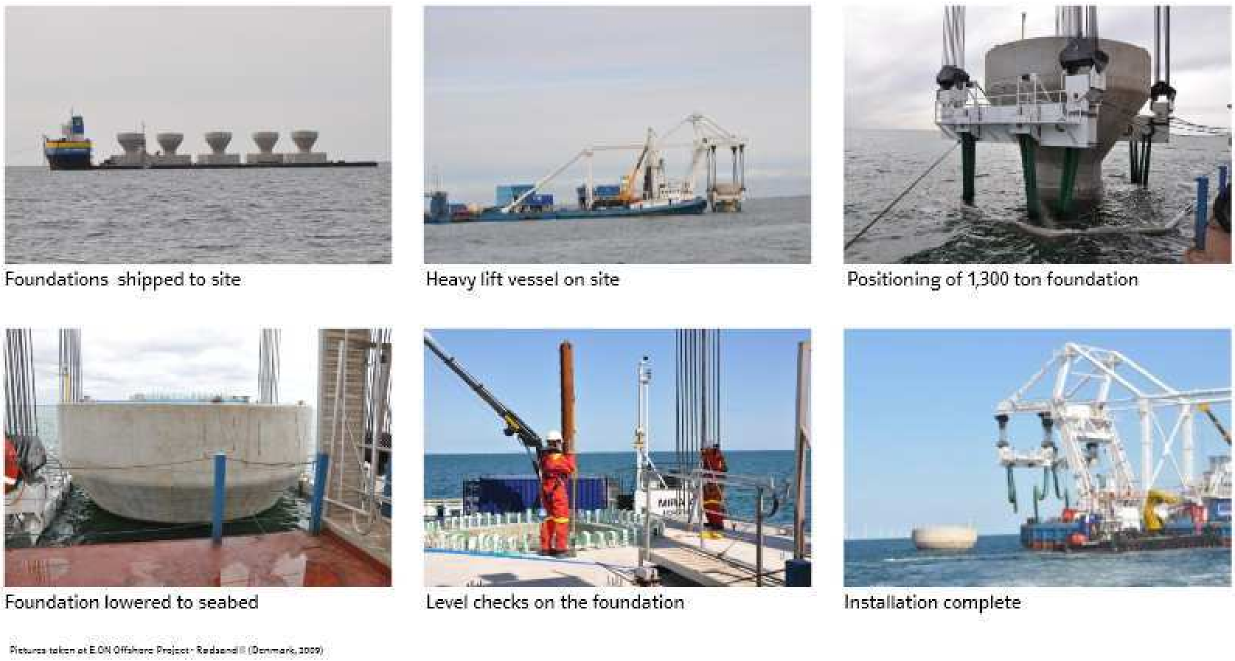
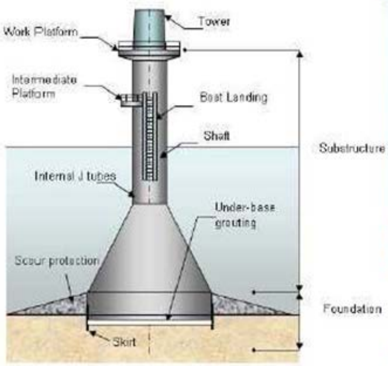


Figure 26. Installation of Gravity base foundation (EON, 2012)

Taking into account the aforementioned, many disadvantages associated with gravity base foundation systems can be identified. As it achieves stability by its own weight, it is a very huge and massive structure. Therefore, installation process may result in special requirements such as the capacity of the installation vessel or the size of the workspace (WEU, 2013). Scour is also the one of important factors due to its high reliance on surface soil (Singh et al., 2010; WEU, 2013)

Overall, gravity base foundations can be installed easier and much cheaper than known steel foundations as one does not need expensive jack up vessels, offshore cranes or hammers (URL 2). However, it needs to sustain its development in order to move up the ladder (WEU, 2013). In terms of acceptance, the WEU (2013) has reported that after the Middelgrunden, Rødsand 1, Lillgrund and Rødsand 2 wind farms in the Baltic Sea, the Belgian Thornton Bank I wind farm is the only project to have used concrete gravity base foundations in the North Sea. Six foundation structures, each up to 3000 tons were lifted into the water then transported to site and installed using the sheerleg crane Rambiz. This solution proved to be relatively expensive for the specific location, and a jacket foundation has been selected for the next two phases of the Project. It must be pointed out that piling and drilling caused additional costs – even sometimes more than expected. Using gravity base foundations, these installation costs can be avoided (URL 2). An overview of advantages and disadvantages of gravity base structures is provided in Table 7.

<table>
<tr><th colspan="2">Gravity Base Foundations</th></tr>
<tr><td colspan="2">• Gravity foundations are preferably used in waters with a maximum depth of 30 meters
• Made of reinforced concrete, one gravity foundation can weigh up to 1,400 tons at a height of 15 meters
• To increase weight and stability, gravity foundations are often filled with gravel and stones
• From arrival at site, the complete cycle of installation of a foundation takes less than 24 hours</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• No piling/drilling
• Completely disassembling possible
• Concrete does not need corrosion protection
• Less fatigue sensitive
• Independent of the steel price</td><td>• Vulnerable against scour
• Small range of suitable water depth
• Seabed levelling and preparation necessary
• Base covers a lot of the seabed
• Difficult transportation
• Large construction site is needed
• Heavy construction</td></tr>
<tr><th>Risks</th><th>Challenges</th></tr>
<tr><td>• Vulnerable against periodic forces
• Future seabed conditions have to have guaranteed high stability</td><td>• Improvement of the design
• Decreasing need of material</td></tr>
<tr><td colspan="2">

</td></tr>
</table>

Table 7. Overview of gravity base foundation characteristics (after Teich, 2013; Williams, 2011; EON, 2012)

Jacket foundations

Jacket structures have long been used in the Oil and Gas industry for offshore exploration and production facilities and have currently been deployed as foundations (Figure 22) for offshore wind turbines. They are characterized by low weight and suitable water depths over 20 meters. The most common types are four-sided jackets, however, three-sided jackets are also available in the market (URL 1). Jacket foundations are made of many welded slender beams and attached to the seabed by piles at each leg (Teich, 2013). The piles are driven into the seabed by a hydraulic hammer to suitable depths. Bedrock and big boulders might be a problem (URL 1). It is very important to drill all these piles at the same time because drilling each pile individually can cause stability problems (Lesny, 2010). Installation of the jacket will typically require the transportation by barge of prefabricated units, with transition piece already in place, to the site for orienting and placing on the seabed. There is limited or no requirement for seabed preparation. The jacket is secured through the insertion of piles through the pile sleeves at each leg which, if soil conditions allow, will typically be driven into the seabed. The piles can be preinstalled using a template or installed through the jacket sleeves. The connection between the piles and the jacket can be by grouted or swedged. Grouting is cheaper but requires a longer period of stable weather. A swedged connection is done by inserting a hydraulic tool inside the jacket pile, expanding the tool and thereby causing a permanent deformation between the jacket sleeve and the monopile. Swedging is a fast but expensive method (URL 1). Although, the amount of work to assemble a jacket design is relatively high, it is argued that this is compensated by a lower need of materials to reach an adequate stiffness (Williams, 2011b). Therefore, it can be cost efficient at water depths greater than 40 m (Powered, 2012). Transporting these large structures is also not easy, particularly if many turbines are installed (de Vries, 2007). However, they do not require such heavy piling as in the case of monopile foundations (Hammar et al., 2008). Furthermore, the transition piece for a jacket foundation is complex and more expensive compared to the that for monopile. The transition piece requires significant design consideration and constitutes a large part of the overall weight of the structure. Some photos depicting the manufacturing and installation process of jacket foundations are given in Figure 27 and Figure 28, respectively.

Jackets at Burntisland Fabrication, Scotland | Jackets at Eemshaven port, Netherlands | Jackets being shipped to site

Figure 27. Manufacturing and delivery of jacket foundation (EON, 2012)

Jacket foundations during transport

Installation complete

Offshore transformer station on jacket foundation at alpha ventus wind farm

Figure 28. Installation of jacket foundation (EON, 2012)

The advantages of jacket foundations are that they are not very sensitive to wave loading as the structure attracts only small wave loads and is very stiff as well as have lower soil dependency. Therefore, they can be installed in deeper waters or in water with high waves as well as at sites with poor soil conditions without increasing the steel weight drastically. It is assumed that by using jacket structures as foundations, greater maximum depth application is feasible compared to all other foundation options available for wind turbines (Singh et al., 2010). Because of its geometry, the jacket foundation is able to be relatively light weighted for the strength that it offers, weighing approximately 600 tons (AWS Truewind, 2009). It is also possible to use standardized dimensions of pipes, connections, etc., which will keep the costs down when building a large number of foundations in a farm. Furthermore, the necessary materials (i.e. pipes) are already available due to their prevalent use in this same industry (AWS Truewind, 2009). Generally, scour protection is less important compared to other fixed foundation types (Westgate & DeJong, 2005).

The disadvantages are that it is more complicated to arrange with secondary steel such as boat landing systems, etc., and the installation procedure is also more complicated and expensive (URL 1). An overview of advantages and disadvantages of jacket foundations is provided in Table 8.

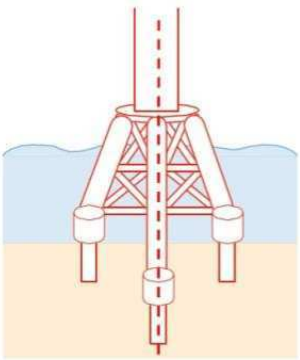
<table>
<tr><th colspan="2">Jacket foundations</th></tr>
<tr><td colspan="2">• Jacket foundations can be used in water depths of more than 40 meters
• Made of steel, one jacket foundation weighs up to 500 tons with a total height of up to 45 meters
• In the manufacturing of the jackets, many single steel beams need to be welded together
• Next to monopile and gravity foundations, jacket foundations are the third most common type of foundation, quite often also used for transformer stations
• Jacket foundations are also used for the installation of larger offshore structures like offshore transformer stations with a weight of up to 2,400 tons
• From arrival at site the complete installation of a foundation takes up to three days.</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• High stiffness
• Resistance against overturning
• Knowledge from Oil and Gas Industry
• Suitable water depths 40 to 50 m
• Less sour protection needed
• Lightweight</td><td>• High amount of welding
• Complicated transportation
• Drilling/piling is necessary
• Steel is expensive and needs corrosion protection
• Unpractical in shallow waters</td></tr>
<tr><th>Risks</th><th>Challenges</th></tr>
<tr><td>• Vulnerability of the slender beams (i.e. ice, ship collision)</td><td>• Reducing piling/drilling noises
• Reducing the costs of welding</td></tr>
<tr><td colspan="2"> </td></tr>
</table>

Table 8. Overview of jacket foundation characteristics (after Teich, 2013; Williams, 2011; EON, 2013)

If the jacket support structure has to be decommissioned, the piles are cut and the steel structure is moved to dry land. Once manufacturing and deployment practices can be scaled up to economically meet the needs of large projects, these foundations will likely become the predominant deeper water foundation type.

Tripod foundation

The tripod foundation (see Figure 22) can be described as a monopile foundation in the water column, and eventually all the way to the bottom, where it is divided into a triangular frame of relatively slender still members (compared to one simple monopile foundation), connected to the main tubular by means of a joint section (Hammar et al., 2008; de Vries, 2007; Teich, 2013). Due to this frame, the load is distributed across multiple attachment points and a greater bottom surface compared with a monopile foundation. From the main joint downwards the transfers of load relies mainly on axial loading of the members. The piles are also mainly loaded axially (de Vries, 2007). This allows the tripod foundation to be shallower and lighter than the monopile foundation. The technical design of the tripod foundation may differ a lot between producers and due to the existing conditions such as depth, weight stress and bottom substrate (Hammar et al., 2008). From an installation point of view, the tripod poses challenges as it cannot be transported as easily as a monopile foundation (de Vries, 2007). Photos from manufacturing and installation are shown in Figure 29 and Figure 30.

Tripods being welded in Norway | Tripod up-ended for shipping | Tripods arriving at Wilhelmshaven port

Figure 29. Manufacturing and delivery of tripod foundations (EON, 2012)

Heavy-lift crane ship on site | Tripod foundation lowered to seabed | Installation complete

Figure 30. Installation of tripod foundation (EON, 2012)

The suitable water depth for this foundation is around 20-40 meters. It is best suited on undisturbed sediment, but is adjustable to most bottom substrates (SGS, 2005). Scour protection may be needed at sites with high currents (Teich, 2013). Due to the piling, a tripod foundation is not a good alternative in areas with many boulders (DWIA, 2013). One of the greatest advantage of a tripod foundation is its ability to be installed on deeper waters compared to gravity and monopile foundation (Hammar et al., 2008). Furthermore, there is no need for seabed preperation prior to installing a tripod foundation.

It must be noted that the main joint is a complex element that is susceptible to fatigue and requires much effort in designing and engineering. The triple leg configuration makes directionality of wind and wave loads more of an issue, when compared to the monopile (de Vries, 2007). Table 9 provides an overview of the characteristics, advantages, and disadvantages of the tripod foundations.

Tripod Foundation	
• Tripod foundations can be used in waters with a maximum depth of 40 meters • Made of steel, one tripod foundation weighs up to 700 tons with a total height of up to 50 meters • In an extensive manufacturing process, all different pieces of the tripods have to be welded together • Tripods are still in the development phase and are rarely put to use in offshore wind installations	
Advantages	**Disadvantages**
• Suitable to a wide range of soil types • Resistance against overturning • High stiffness • Valuable solution in consideration of environmental and economic aspects	• Piling/drilling needed • Difficult disassembly • High costs due to braced design • Vulnerable to ice loads • Scour protection at high currents • Difficult transportation • Steel is expensive and needs corrosion protection • Impractical in shallow water • High amount of work necessary for construction, installation, transport
Risks	**Challenges**
• Corrosion due to high amount of steel is used • Problematic scour depth, due to its spreaded design	• Reducing piling/drilling noises • Eliminating scour problem and decrease weight by enhancing the design

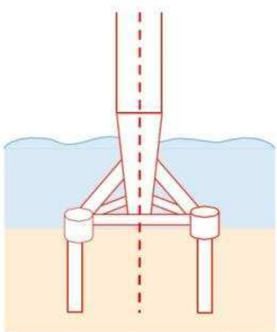


Table 9. Overview of tripod foundation characteristics (Teich, 2013; Williams, 2011; EON, 2013)

Tri-pile

Conceived and developed by the German wind turbine manufacturer Bard, the tripile foundation is a relatively new adaption of the traditional monopile foundation (URL 3). Instead of a single beam, three piles (approx. 3 m) are driven into the seabed, and are connected just above the water's surface to a transition piece using grouted joints. This transition piece is connected to the turbine tower's base and has to handle huge forces. Therefore, heavy welding is necessary for transition piece in order to avoid fatigue, which increases the cost of this foundation (Williams, 2011). Transition piece weighs around 490 tones and features far more welding than is present in monopile transition pieces (URL 3).

Each pile can – depending on water depth and soil conditions – be up to 90 m high and weigh up to 400 tons (URL 3). The increased strength and wider footprint created by the three piles is expected to allow for turbine installation in water up to 50 meters in depth. The tripile design is easily adaptable to a variety of conditions, as each or all of the piles can be manufactured appropriately to match site-specific conditions while still being connected to the standard transition piece (de Vries, 2007; EWEA, 2009).

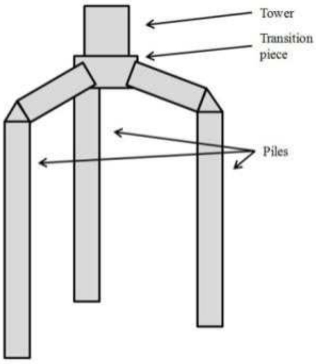
Due to its spread-legged construction, the transport of this foundation is very complicated. On challenge during installation is to position the three piles accurately. Once the positioning is done by means of seabed template and Global Positioning System, the piles are hammered down one by one (URL 3). This process is performed with hydraulic hammers and extremely noisy. Therefore, in view of concerns regarding the health of fish and sea mammals will force companies to develop new installation technique in order to mitigate the noise.

Afterwards, the tops of the piles rise above the sea, allowing subsequent operations to be performed above water. This contrasts with monopiles, where a large part of the transition piece is below the mean sea level. Then, the transition piece is lowered onto the piles, with each leg-end aimed into the pile. To ensure that the transition piece is leveled, a hydraulic solution has been developed by the industrial tools company Enerpac. The so-called Synchronous Lifting System consists of three hydraulic cylinders per pile. The hydraulic cylinders adjust the vertical spacing between pile and transition piece leg, thus enabling quick and precise leveling (Enerpac, 2009a). Once leveled, the annulus between transition piece leg and pile is filled with grout, and the cylinders remain on the structure for several days while the grout settles. There is thus no bolted or welded connection between the piles and the transition piece: The loads and forces are transferred by the grout alone (Enerpac, 2009b).

The first installation of tri-pile by Bard, was of a single foundation and turbine in Hooksiel, Germany. The following year, installation started for the one of the world's largest offshore wind farm, Bard Offshore 1 (URL 3).

Figure 31. The Bard 5.0 MW turbines, supported by tripile structures at 40 m water depth at the offshore plant 'Bard Offshore 1'. Photo: Bard Offshore

An overview of the characteristics, advantages and disadvantages of the tripile solution is provided in Table 10.

<table>
<tr><th colspan="2">Tripile foundation</th></tr>
<tr><td colspan="2">• The idea is support wind turbine on three legs rather than one, and it will be more stable
• The tripile consists of three piles and a transition piece (above water)
• These foundations are suitable for water depths of between 25 and up to around 50 meters.</td></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>• Simple design
• Improved stiffness compared to monopiles
• Suitable to a wide range of soil types
• Automated levelling process
• Resistance against overturning</td><td>• Labor-intense manufacturing
• Heavy welding needed
• Large amount of steel
• Steel is expensive and needs corrosion protection
• Complicated transportation
• Drilling/piling is necessary
• Difficult transportation</td></tr>
<tr><th>Risks</th><th>Challenges</th></tr>
<tr><td>• Fatigue of the transition piece</td><td>• Reducing piling/drilling noises
• Decreasing the costs of welding</td></tr>
<tr><td colspan="2">

</td></tr>
</table>

Table 10. Overview of tripile foundation characteristics (Teich, 2013; Williams, 2011; EON, 2013)

Suction bucket foundation

Suction bucket foundations (Figure 22) have been originated from the oil and gas industry. A suction bucket is a large diameter cylinder closed at the top. Suction bucket foundations can conceivably be applied to any of the foundation types previously described as an alternative to driving piles deep into the seabed. Although research still continues, the development of bucket foundations was set back substantially by a significant failure in 2007 during a demonstration phase (de Vries, 2007; Teich, 2013).

Instead of a slender beam being driven deep below the surface, bucket foundations employ a wider based cylinder, which does not extend as far below the floor, but still adequately resists loading due to its greater diameter and reactive soil forces. For example, the diameter of the prototype for Frederikshaven Wind Farm in Denmark is 12 meters (URL 3). Depending on soil conditions encountered at a site, the suction bucket alternative may be preferable to slender piles for economic reasons and for ease of installation. This foundation does not work in very shallow waters due to the insufficient pressure difference (Teich, 2013). Sufficient hydrostatic pressure is required in order for this concept to be effective. Therefore, it is well suited for water depths at around 40 m. In accordance with the designer, this concept is suitable for different soil conditions and even for layered soils. Seabed preparation is generally required prior to installing a suction bucket foundation (Powered, 2012). One of the biggest advantages of suction bucket foundations is that no piling is necessary during the installation, which significantly reduces the installation costs. The designers are working towards new installation methods where less load on the caisson occurs. Therefore, the stresses on the material are reduced, which decreases the amount of steel needed. Furthermore, this concept can be scaled for either single column of multi-legged turbine tower designs. Furthermore, suction bucket foundation can be easily decommissioned. It is presently installed as a prototype in The North Sea and Frederikshavn, Denmark. An overview of the characteristics, advantages and disadvantages of the suction bucket solution is provided in Table 11.

Suspension Bucket Foundation	
• These foundations are suitable for maximum water depths of around 50 m.	
Advantages	**Disadvantages**
• No piling/drilling • No separate transition piece is needed • New developments increase the suitable soil range • No scour protection is needed • Complete and easy decommission	• Expensive welding • Corrosion protection is needed • Installation procedure is not fully conceived • Transport vessel is yet to be defined
Risks	**Challenges**
• Not suitable in rocky soils	• Decreasing amount of steel material • Developing installation processes without seabed preparation

Figure 45 The prototype for Horns Rev 2 site (North Sea, Denmark). It weighs 165 tons, the skirts are 12 meters in diameter and 6 meters in height.

Table 11. Overview of suction bucket foundation characteristics (Teich, 2013; Williams, 2011; EON, 2013)

2.4.3 Innovation

To date, 66.5% of operating offshore wind turbines (see Figure 32) have been deployed using monopiles, either driven into the sea bed or fitted into drilled sockets and grouted into place as required. Considering the limited range of water depths and turbine sizes for the great majority of projects, together with the ease of financing intertwined with their track record, it is not surprising that 64.3% of the foundations under construction (see Figure 33) are also monopiles (WEU, 2013). However, taking into account the needs for the offshore wind industry, particularly in the context of deep waters and bigger turbines set to feature in European offshore wind projects, it is not surprising to find new and innovative structures from foundation specialists today.

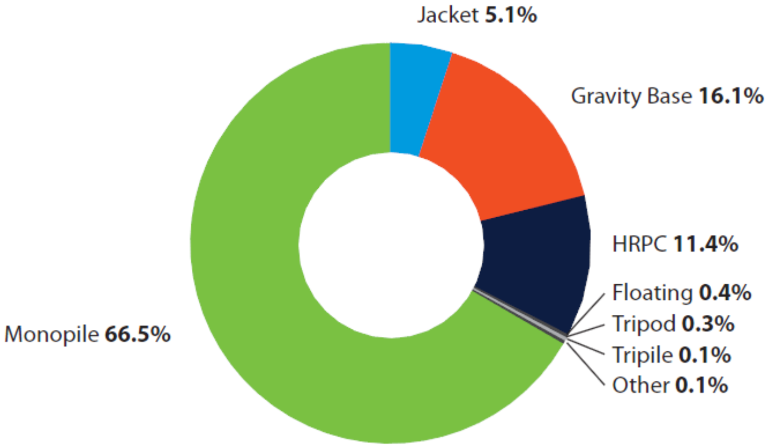


Figure 32. Market share of operating wind turbine foundations (WEU, 2013)

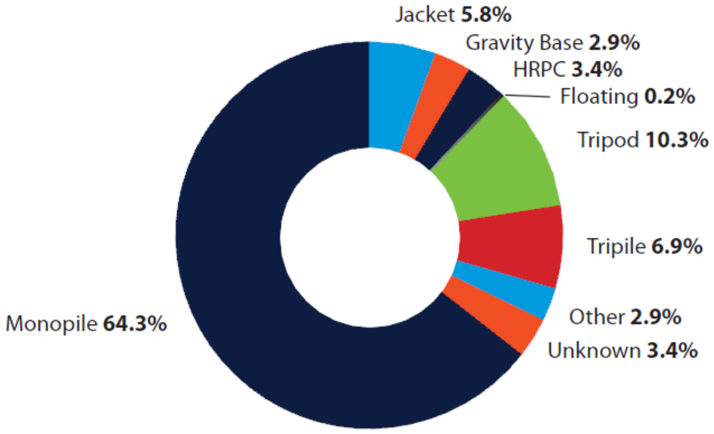


Figure 33. Market share of wind turbine foundation under construction (WEU, 2013)

It is widely anticipated that the current market share will alter in the next decade with projects moving to deeper and far shore locations, the deployment of larger capacity turbines, new geographical markets opening up and cost-reduction programs advocating innovation in technology. WEU (2013) has reported the expectation in the near term (<5 years), as shown in Figure 34.

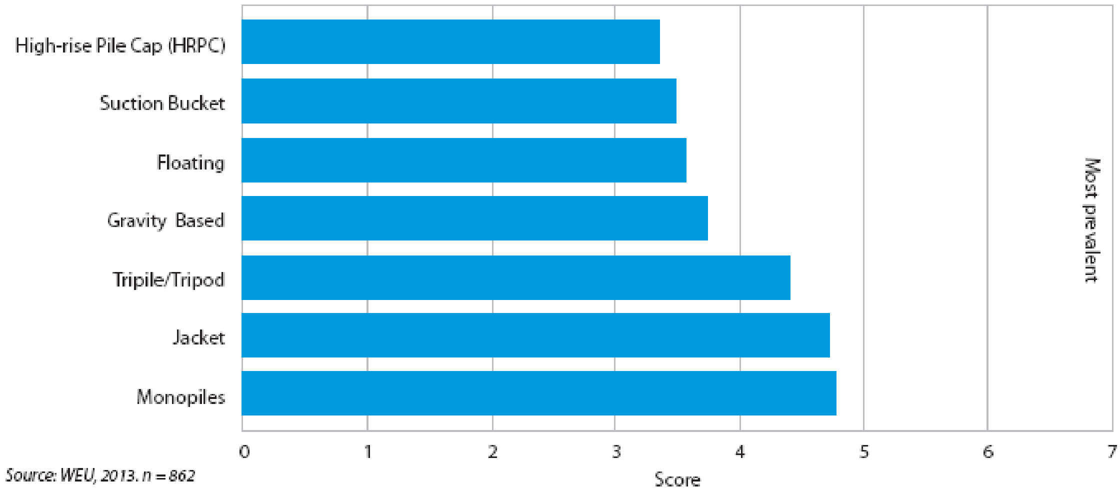


Figure 34. How do you anticipate this market share to play out in the near term (5 years)

The design, fabrication, and installation of turbine foundations in an offshore wind farm makes up around 30% of its' total capital costs. As a result, *innovative and cost-effective* foundation designs could lead to significant reductions in capital costs for future wind farms. Table 12 shows potential cost saving opportunity offered by foundation innovations (TINA, 2012).

Water depth	Foreseeable innovation impact potential by 2020	Innovation impact potential by 2050	Requirement
<30m	40% CAPEX reduction	70% LCOE contribution reduction	Improved jackets, gravity based foundations and suction buckets
30-60m	40% CAPEX reduction	70% LCOE contribution reduction	
60-100m	60% CAPEX reduction	70% LCOE contribution reduction	Floating foundations

Table 12. Potential cost savings opportunities offered by from innovation (TINA, 2012)

Monopiles have proven to be a viable technology up until around 30m, but above this water depth, it is of great importance to evaluate the cost curves and to consider queries regarding loads and so on. As steel is expensive and monopiles are not yet a proven technology for water depths greater than 30 m, it is anticipated that gravity base foundations will obtain a significant market share in deepwater projects (URL 2). It is also highlighted that in case of gravity base foundations, their benefit on the supply chain and potential for cost reduction will require further innovation until they start affecting the share of existing offerings in the next decade (URL 2).

The industry is currently working on a development to move away from grouted connections between the monopile and the transition piece. Van Oord Offshore Wind Projects is developing a foundation concept for water depths up to 25m, in which no transition piece is present at all. The wind turbine tower will be installed directly at the flange of the monopile, so a transition piece is no longer necessary. Secondary steel will be installed after the monopile has been installed. This concept will be applied at the Eneco Luchterduinen Wind Farm (URL 16)

As underlined in the WEU (2013), today, a gap remains in the foundation supply chain as large steel fabrication suppliers do not see offshore wind as a core part of their business and small specialist manufacturers struggle to take on the level of risk and investment required. The plan is to overcome such hurdles through funding programs and public support mechanisms. At the same time it is believed that a successful competitive market will encourage innovation and contribute positively to the minimization of costs in a shorter time frame.

New designs for the main foundation installation vessel are expected to shape up as the market shows signs of evolving. The industry has to focus on safe transfer of monopiles and transition pieces from the logistics harbor to the offshore location. It is expected that improvisations or introduction of new foundation installation technology is going have a major bearing on costs in the future.

One can expect more focus on areas, such as, working conditions for foundation installation. As indicated by The Crown Estate's Offshore Wind Cost Reduction Pathways Study (Crown Estate, 2012), a lot is expected from floating dynamic positioning or DP vessels. These are going to be larger than the current jack-up vessels and would carry more jackets on their deck. Also, a floating installation vessel would be able to carry pre-assembled foundations straight out to site. As the offshore wind farm market evolves, one would argue, so too will the related support devices and supply chain processes, which will in effect streamline costs (URL 16).

Implication for the offshore foundations

There are seven main types of foundations (support structures) that can be considered for offshore wind energy projects:

- Monopiles
- Gravity base structures
- Tripods
- Tripiles
- Jackets
- Suction buckets
- Floating foundations – different concepts are under development

Choice of foundation type depends on site-specific conditions including water depth and seabed properties as well as the size and weight of the turbines being used. All of these designs are still developing and the structures that are able to offer the best proposition to developers will gain hold in a new rapidly growing and global market.

- Today's offshore wind industry is dominated by monopile foundations, constituting 66.5% of operating wind farms and 64.3% of wind farms under construction (WEU, 2013).
- Jackets and gravity base types of foundations follow with 5.0% operating, 5.7% under construction and 15.9% operating, 2.9% under construction (WEU, 2013).
- Tripods have a limited presence in the operating landscape, with 0.3% of the total, but reach 10.3% in projects under construction (WEU, 2013).

- Of the operating wind farms, 63% of foundations are submerged in waters of less than 30 m, and supporting turbines of 2 to 5 MW (WEU, 2013)
- Of the known met masts used or to be used in the offshore wind industry, 44% are erected using monopiles. Many alternative technologies are also deployed for demonstration purposes, due to the lower loads inherent to their operation (WEU, 2013)
- Cost reduction is one of the main challenges for the sector and extensive research is being carried out to address it.

Furthermore, Table 13 is created in order to summarize the advantages and limitations of each offshore foundation type.

Type of foundation	Suitable water depths	Advantages	Limitations
Monopile	10-30 m	Easy to manufacture, very extensive and transport, experience, low seabed preparation	High noise, and competitiveness depending on the seabed, scour protection
Gravity base	<30m	No piling/drilling thus no noise, inexpensive, less fatigue sensitive, suitable for 5MW turbines	Seabed preparation, difficult transportation, vulnerable against scour
Jacket	<40 - 50m	High stiffness, comparably less noise, suitable for 5MW turbines	Expensive, heavy welding, subject to wave loading and fatigue failure, unpractical in very shallow waters.
Tripod	<40m	High stiffness, adequate for heavy large-scale turbines, suitable to a wide range of soil types, less noise in drilling, suitable for 5MW turbines	Labor intensive Complex to manufacture, difficult to transport
Tripile	25-50 m	Simple design, suitable to a wide range of soil types, automated leveling process	Labor intensive, heavy welding, expensive, drilling is necessary but less noise
Suction bucket	<50m	No piling, relatively easy to install and easy to remove, no transition piece, no scour protection	Extensive welding, further research is needed

Table 13. Summary of offshore foundations

2.5 Mooring system

In this chapter will be analyzed mooring systems and components applied for the floating foundations. They will be evaluated from the functional requirements for renewable energy platforms perspective.

2.5.1 Introduction

The main aim of a floating platform is ensure enough stability conditions in order to allow the proper development of the industrial process located on it. Their behavior resembles as much possible that of a fixed platform. Therefore mooring systems are crucial part of the design.

The mooring system consists of freely hanging lines connecting the platform to anchors, dead weights or piles, on the seabed, positioned at some distance from the platform.

The principle components of a mooring system are (see Figure 35):

- Chain, wire or rope or their combination.
- Anchors or piles.
- Fairleads, bending shoes or pad eyes.

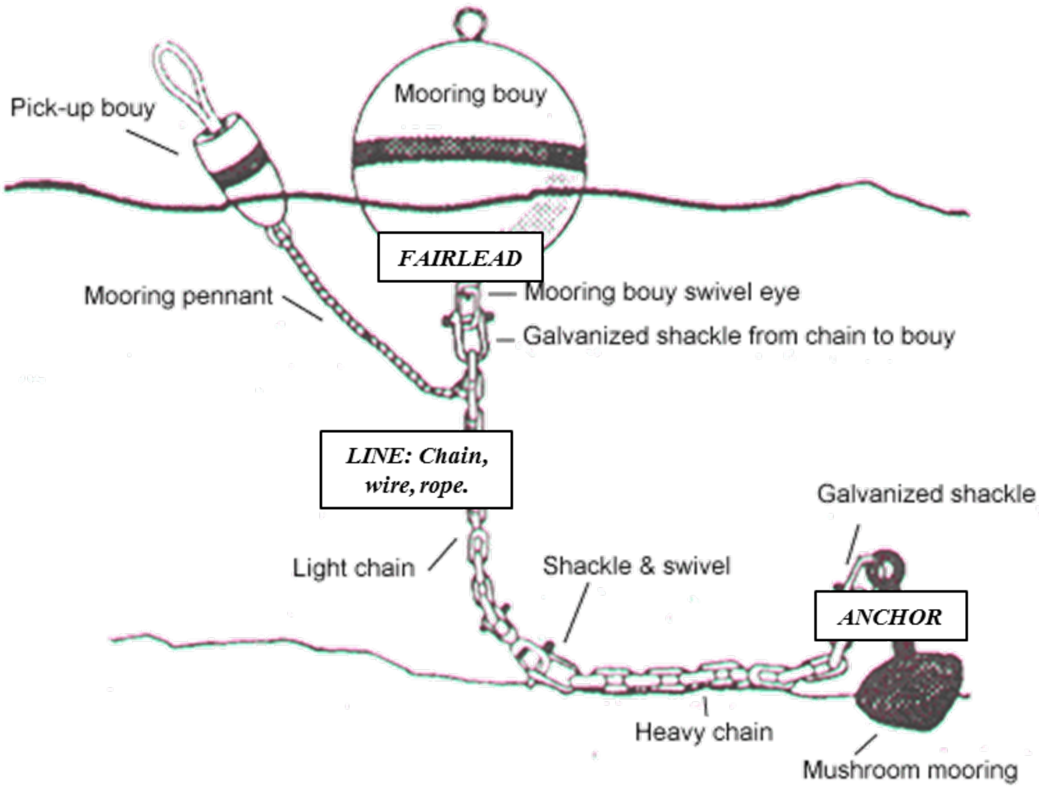


Figure 35. Mooring system diagram

Lines are composed in general of a combination of metallic chains, metallic or synthetic wires (See Figure 36). Steel chain and wire rope (steel and synthetic ones) have conventionally been used for mooring floating platforms. Synthetic cables require a higher safety factor (thus higher costs) than chains, essentially due to the different experience gained in their use (respectively short-term and long-term experience). Synthetic lines are used for special cases when low weights are required. It is frequently required that the fraction of mooring line at the touchdown point is formed by a chain, more resistant to wear. The chain has shown durability in offshore operations. It has better resistance to bottom abrasion and contributes significantly to anchor holding capacity (Mermaid, 2013). The tension on the mooring line, and therefore the restoring forces, are close related to platform movements. In the case of a conventional catenary mooring system, mooring line forces will increase or decrease as it lifts off a settles on the sea bed.

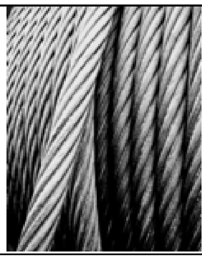
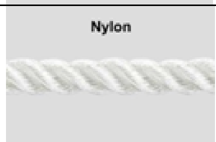
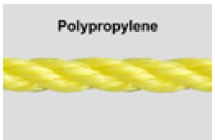
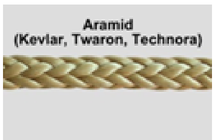
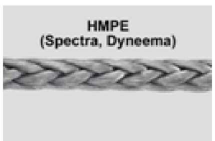
Mooring line	Characteristics	Costs	Image
Chain	• Broad use experience • Readily available • Depending on required proof strength Grade 3.3S or 4 should be used for offshore moorings. • Unsuitable for water depths greater than 450 m • Susceptible to corrosion • Good catenary stiffness effect • Good abrasion and bending properties • Suitable for long term moorings but require regular inspections	Medium	
Steel Wire Rope	• Broad use experience • Spiral Strand, Six strand and Multi-Strand wire ropes are readily available. • Only Spiral Strand is suitable for long term mooring applications. • Unsuitable for water depths greater than 900 m • Susceptible to corrosion • Extreme bending must be avoided.	Low	
Polyester Rope	• High dry and wet strength • Moderate stretch • Frequent use in deep water taut moorings • Most durable of all fiber line materials • Moderate cost	High	
Nylon	• High dry strength • High stretch • Wet strength about 80% that of dry • Low fatigue life • Moderate cost	High	
Polypropylene & Polyethylene	• Low weight • Moderate stretch • Low strength • Low melting point • Susceptible to creep • Low cost	High	
Aramid	• Very low stretch • High strength to weight ratio • Minimum bending radius similar to steel wire rope • Low abrasion resistance • High cost	High	
HMPE	• Low stretch • High strength to weight ratio • Replacing wire for towing – increased handling safety • higher static and dynamic stiffness over aramid and polyester (ABS, 2011) • High cost	High	

Figure 36. Mooring line characteristics

Oil & Gas industry usually deploys very expensive mooring systems; mainly because the extremely dramatic failure consequences. Moreover, the added value of the fossil fuels is higher than renewable energies and they only have to install out a few units. Nevertheless renewable energies added value is lower and per marine renewable farm there will be hundreds of units in the future. Because of that, the two major requirements for a MUPs mooring system are to withstand the environmental and other loadings involved in keeping the device on station, and to be sufficiently cost effective so that the overall economics of the device remain viable. Rather than simply considering the mooring as an additional cost item in the overall economics of the device, the mooring system in many cases should be designed as an integral element of the overall system and contribute to its power extraction efficiency and thus to the income stream.

2.5.2 Technical requirements for renewable energy foundations

Since the mooring system of MRE floating devices will be a crucial part of the design from the technical and economic point of view, it is important to have a clear image of the technical requirements.

There will be three sources of requirements:

1. Environmental conditions: They will be given by the final location of the MRE farm, There will be four environmental main loads: (1) Wave loads, (2) Currents, (3) Sea level and (4) Wind. There will be other load sources like ice, marine growth or earthquake that must be also considered. Most of them are only loading the floating structure, however they have a clear influence on the mooring system.

2. Stability conditions: A floating structure, as is has been said must be designed ensuring standard stability requirements. Those must be ensured during the whole life of the concept under operational, extreme and accidental conditions.

3. Energy conversion requirements: Depending on the primarily energy conversion technology considered there will be different requirements. They might be focused on extremely stable concepts like wind energy devices; or focused on extremely movable concepts like point absorbers like Wavebob (resonant point absorber), concept that has been designed to be extremely movable.

In summary, any floating platform must be able to withstand any environmental load situation and also provide sufficient stability. Moreover the sea-keeping must be compatible with the energy conversion technology considered in terms of accelerations and displacements.

From the classical design procedure point of view, the functional and technical requirements for the mooring system include (Chakrabarti, 2005):

- Offset limitations. Ability to keep the structure floating at the chosen location within specified tolerances under normal operational load and under extreme conditions during the lifetime of the platform. Provide a horizontal movement envelope for the platform that enabling a safe and reliable cable connection and layout.

- Lifetime before replacement. All components must have adequate strength, fatigue strength and durability during the operational life. The effect of marine corrosion needs to be considered for a prediction of service life.
- Counter static and dynamic horizontal forces induced from wind, waves, current and inertia from the moving offshore platform. Provide sufficient yaw stiffness to enable stable working conditions for the device. For substructures moored by tension legs (tethers) provide sufficient stiffness in heave, roll and pitch to limit dynamic responses in these directions of freedom.
- Deployability.
- Positioning capabilities.
- Low component cost to competitive energy production.
- The mooring should not adversely affect the efficiency of FOEP.

2.5.3 Mooring concepts

Catenary

This particular concept is one of the most used and simplest one. The horizontal stiffness of the mooring lines is provided by the distributed weight over the length of the line, and to less extent the axial stiffness of the line itself. See Figure 37. The catenary chain and chain-wire-chain systems are widely used in offshore oil and gas applications and may provide a very cost effective system depending on water depth, and offshore wind turbine vertical load capacities allow. Installation of such systems may be performed by a large fleet of anchor handling vessels available in the worldwide market. The major drawback is the large vertical force to be carried by the floater, especially in deeper waters. Catenary systems are typically most attractive in water depths from 50 to 500 meters.

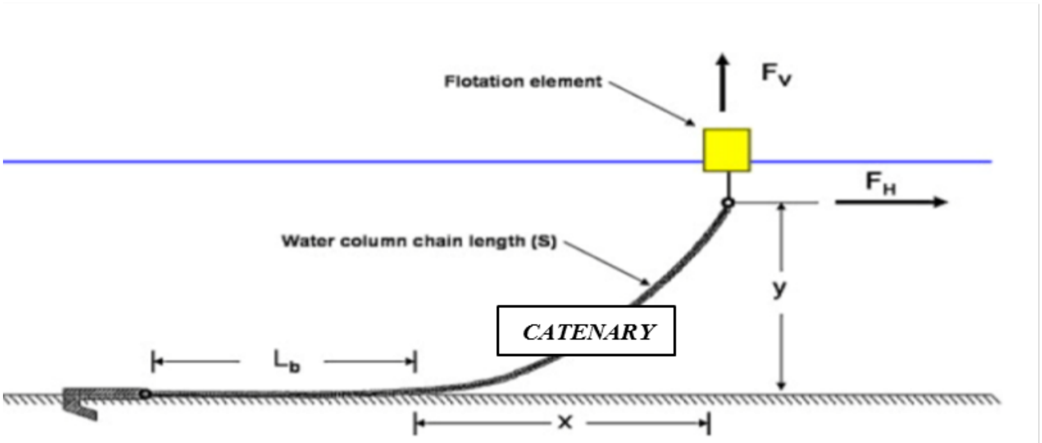


Figure 37. Catenary system (Fredriksson et al, 2008)

Taught leg

The horizontal stiffness of the mooring is provided by axial stiffness of the mooring system, sometimes in combination with vertical displacement of the floating platform. See Figure 38. The taught leg mooring is used for offshore oil and gas applications using synthetic rope like polyester, or the stiffer and stronger high modulus polyethylene fiber rope (HMPE). Some systems may combine steel wire and chain into these systems, especially near the top and bottom ends. Installation of such systems will require vessels with more specialized equipment and training for safe handling of the rope segments. Dependent upon the water depth the taught leg systems may interact significantly with the vertical motions of the offshore wind turbine. A system designed in-between a catenary and taught leg system is called a “semi-taught” system. These systems may be used over nearly all water depths, from less than 100m much more than 1000m. Wind farms in water depths of more than 500-1000m are not expected to be very attractive due to mooring and cable cost.

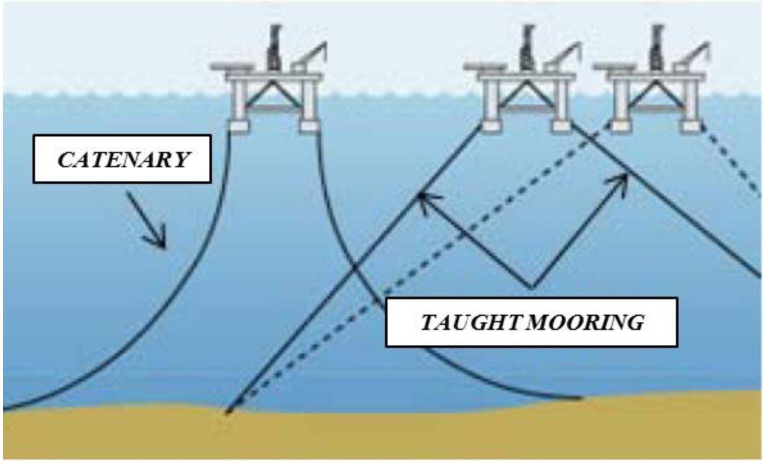


Figure 38. Difference between Catenary and Taught system

Tension leg (tether)

The Tension Leg mooring system is vertically oriented and consists of tubular steel members called tendons. The group of tendons at each corner of the structure is called a tension leg. (See Figure 39).

The principle of the tension leg mooring system is that platform's buoyancy exceeds the weight of it and hence causes a pretension in the vertical cables which keep the platform on location.

Heave, roll and pitch have high natural frequencies due to high tendon axial stiffness. Surge, sway and yaw are compliant modes due to quite low tendon geometric stiffness. Vertical motions are excited by the first order wave forces, while horizontal motions appear due to the second order wave forces with very low frequency (Natvig & Teigen 1993).

With steel wires tension legs (tethers) the most attractive water depth range is from 300 to 800m, but with carbon fiber tethers this depth range may be extended to depths well over 1500m, if such water depths are considered to be attractive. The floating offshore wind turbine horizontal stiffness will be determined by the total pretension provided by excess buoyancy divided by the tether length, indicating a requirement for large floaters in deeper waters.

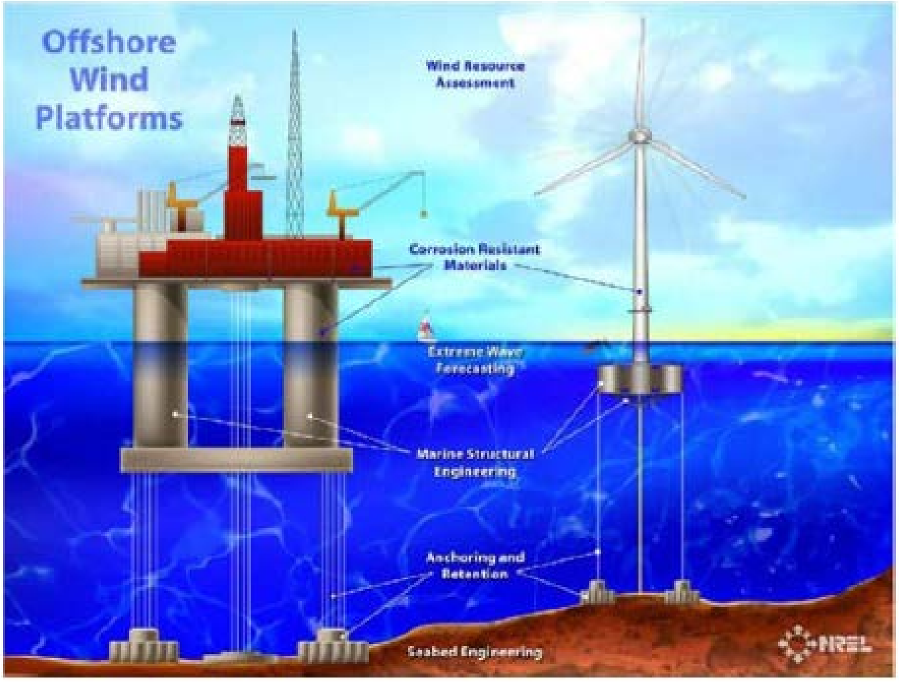


Figure 39. TLP system for different floating platforms (Source:NREL)

Single Point Moorings

A Single point mooring, SPM, also known as single-buoy mooring or SBM (see Figure 40) is a loading buoy anchored offshore, that serves as a mooring point and interconnects for tankers loading or offloading gas or liquid products. SPMs are the link between geostatic subsea manifold connections and water tankers. They are capable of handling any size ship, even very large crude carriers (VLCC) where no alternative facility is available. Example of a single point mooring system in renewable energy industry is Pelamis, that it use a similar mooring system, although is a specific designed for it (see section 2.6.2 Numerical studies on fixed foundations).

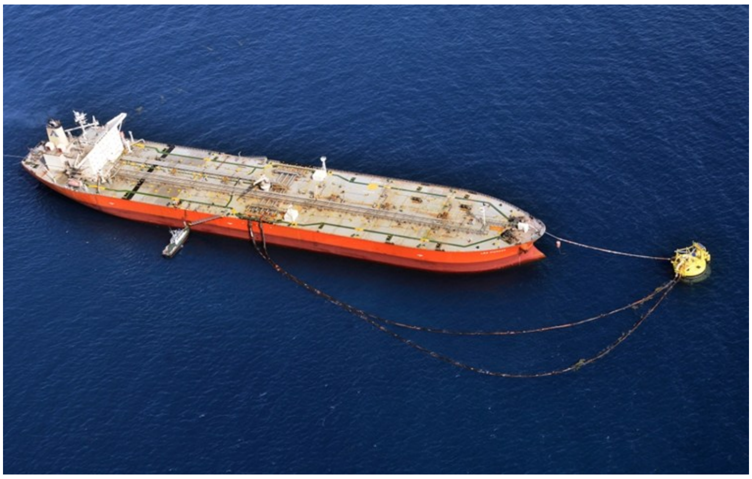


Figure 40. Vessel with a single point mooring. (Source: Leighton Offshore)

The MUPs required a detailed study based on the needs of the devices installed on the platform (see Figure 41). E.g. a MUPs with wind and wave energy converters, that turns towards the waves, an anchor system which allows full 360 degrees rotation is needed. This type of mooring will be able, a standard system from the oil and gas industry is used: the **Turret Mooring System**.

Turret mooring is widely used on so-called FPSO vessels. FPSOs typically extract oil and gas from fields far away, refine it and store it, and then offload it onto a transport vessel. Because of the oil extraction (through pipelines), a FPSO has to remain at the exact same position regardless of weather conditions. For this purpose, the vessel is secured with a Turret Mooring System.

The turret is in its essence a buoy held in place by three or more mooring lines. The mooring lines are secured with anchors. A tugboat drags the anchors into the seabed until a given tension is achieved.
The mooring lines have enough slack for the turret to move up and down when water levels rise and fall – but because of the number of mooring lines, the horizontal position remains the same with little deviation. Thus, a platform installed at more than 40 meters depth will be able to follow the rise in the sea level. The system is suited for depths high than 40 meters.

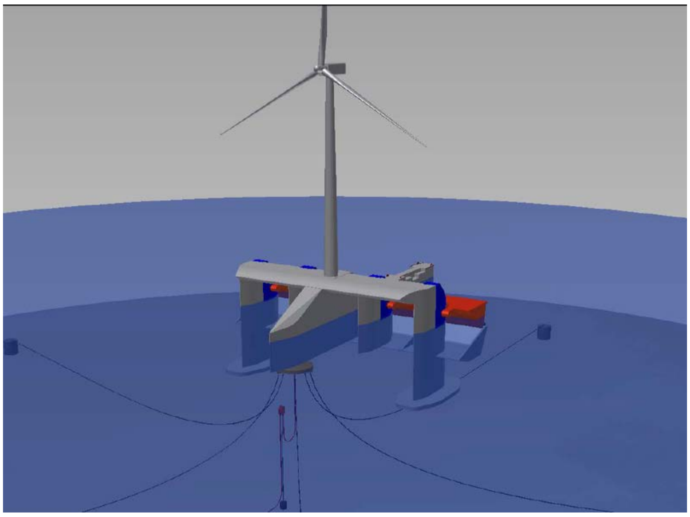


Figure 41. Posseidon 37 Floating Platform (Source: http://mhk.pnnl.gov)

2.5.4 Analysis of mooring systems technology

A variety of mooring configurations have been developed over time for the station keeping of floating vessels and a comprehensive guide can be found in Barltrop (1998). The simplest method is to use a gravity anchor on a single line mooring (Robert E. Harris, 2004). However this provides, amongst other limitations, no redundancy and clearly multiple mooring lines are desirable for reliability. Increasingly specific requirements for the station keeping of floating vessels, in particular in the oil industry, have resulted in the evolution of sophisticated mooring designs. Spread moorings using catenary lines are common for semi-submersible platforms and vertical tethered moorings for TLP platforms. In some cases spread moorings are not suitable since they essentially fix the heading angle. To enable a vessel to weathervane into the incident waves a rotating turret mooring or a single point attachment from the vessel to a fixed or floating structure/buoy is utilized, hence the term single point mooring (SPM). Furthermore active mooring or dynamic positioning (propulsion) could be a station keeping option for wave energy converters (WECs) (Robert E. Harris, 2004). Table 14 summarizes the mooring configurations already exposed and their suitability for renewable energy foundations applications.

	Technical Characteristics	Cost	Installability	Movements	Type of Anchor	Advantages	Disadvantages
Catenary System	Horizontal load capacity based on the gripping ability the length of the anchor and catenary	Low	Easy	High for 6 DoF	All	* Cheap anchor * Easy Installation * Adaptation to tidal variation	* Heave motion * Large floating weight to counteract string * Low platform restricted movement
Taught Leg	Horizontal and Vertical load capacity based on the friction generated between the surface of the ground anchor and soil	Medium	Difficult	It depends on the specific configuration of each design.	* Pilot * Suction Pilot * Gravity Anchor *Plane Anchor *Helicoidal Anchor	* Used by Offshore industry * withstand high lateral forces * Less chain is needed	* Expensive Anchor * Heave motion * Difficult Installation
Tension Leg	Horizontal and Vertical load capacity based on the friction generated between the surface of the ground anchor and soil	High	Medium	* High surge movements * Small Heave, Pitch and Roll movements	* Pilot * Suction Pilot * Gravity Anchor *Plane Anchor *Helicoidal Anchor	* Very good heave and angular motions * Less chain is needed	* Complexity and cost of the mooring installation

Table 14. Mooring configurations for renewable energy foundations

Floating structures that are moored impose a variety of load conditions on the anchor system. These loads range from vertical uplift loads for a TLP to almost horizontal loads on a catenary mooring line such as for a floating production system.

To meet this challenge a number of anchor concepts are available including conventional driven pipe piles, the drag embedment anchor, the popular suction anchor, as well as hybrids such as the suction embedded plate anchor (SEPLA), which are described below (Mermaid, 2013):

- *Gravity anchor/deadweight anchor*. Horizontal holding capacity is generated by one or more dead weights providing friction force between seabed and anchor. The main disadvantage of this type is the low reaction force to weight ratio meaning that in order to secure any sizeable buoyant structure, the scale of anchors is extremely large. The raw material is inexpensive but massive amounts are needed to achieve the desired capacity. It is suitable for all seabed types; however the friction with a rocky seabed will be much less than acquired in a deeply sedimented bed. In shallow water the anchor itself can be subject to significant loading, which can cause greater required mass to provide the necessary holding power (Aquatera, 2012). In terms of installation, their large size and cumbersome nature require specialist lift vessels with lift capacity and sizeable deck space. A modular installation is also possible in some situations allowing for smaller lifts. The use of gravity anchors for any sizeable wave energy converter in shallow and intermediate water depths may be viewed as a last resort due to their handling requirements (Aquatera, 2012). In case of dense sandy soils, drag-embedment anchor and suction anchor types may be alternatives to very large deadweight anchors as both options, in such conditions, offer relatively easy embedment and the advantage of a much higher reaction force to weight ratio (Aquatera, 2012). Sound & Sea Technology Engineering (2009) summarizes the key features of the gravity anchors as:

    - Large vertical reaction component, allowing shorter mooring line scope
    - No setting distance
    - Lateral load resistance decreases rapidly with increase in seafloor shape
    - Reliable holding capacity because most capacity due to anchor mass
    - Simple on-site construction possible, tailored to task
    - Size limited by load handling equipment
    - Material for construction readily available and economical
    - Reliable on thin sediment over rock
    - Mooring line connection easily to inspect and service
    - In shallow water, the large mass can be undesirable obstruction
    - Lateral load resistance is low compared to other anchor types
    - Operates well as a sinker in combination with drag-embedment anchors to allow shorter scope
    - A good energy absorber when used as a sinker with non-yielding anchors (pile and plate)
    - Lateral load resistance is low compared to most anchors expect for very hard bottom conditions

- *Drag-Embedment Anchor*. Drag-embedment anchors have been widely used in the oil and gas industry in order to moor semi-submersibles, SPM buoys, and floating production systems. They are the most common solution for most anchoring applications in intermediate and shallow water depths where sediment conditions allow penetration to appropriate working depths (Aquatera, 2012). They are operated by only resisting horizontal loads. The modern drag embedment anchors can resist horizontal loadings as great as 50 to 100 times the anchors weight in appropriate seabed conditions (Aquatera, 2012). Horizontal holding capacity is ensured in the main instalment direction by the embedment of the anchor in the seabed. Such anchors are suitable for applications where anchor movements over time may not be critical. The weight of the chain attached to the shank causes line tension to drive the fluke deeper. Drag-embedment anchors are suitable for all types of soil conditions varying from soft clays to dense soils and commented soils. Sand and hard clays provide higher holding capacities than soft clays. Rocky substrates or substrates, where rock exists at a shallow depth below sediment cover are not suitable (Aquatera, 2012). Furthermore, using an anchor with a greater surface area (greater weight) leads to higher holding capacity. Capacities of up to 1500 tonnes are possible (Aquatera, 2012). In terms of installation, this type involves a dragging-in operation, typically by anchor handling tug. It is one of the lowest cost anchor types and may be suited for catenary moored systems (in shallow to deep waters) where placement precision is of the order of a few meters and horizontal mooring forces do not exist. Since these anchors are designed to withstand horizontal loads, the mooring footprint can be significantly large, which - in the case of an array of WECs – can significantly reduce the number of WECs deployed in any given area. The array must also enable vessels to manoeuvre for installation, maintenance and removal operations (Aquatera, 2012). Sound & Sea Technology Engineering (2009) summarizes the key features of the drag-embedment anchors as:

- A wide range of anchor types and sizes available
- Standard off the shelf equipment
- High capacity (up to 1500 tonnes) achievable
- Can provide continuous resistance even though maximum capacity has been exceeded
- Anchor is recoverable
- Performs poorly in rock seabed
- Behaviour is erratic in layered seabed
- Lower resistance to uplift loading
- Large line scope is required to cause near horizontal loading at the seabed unless used with deadweights
- Usable with wire or chain mooring lines
- Penetrating/dragging anchor can damage buried cables or pipelines
- Loading must be limited to one direction for most anchor types and applications
- Exact anchor placement limited by ability to predict setting distance
- Holding capacity decreases rapidly, particularly in sand, if line angle at the seabed is < 6 deg.

- *Driven Pile/Suction Anchor*. Horizontal and vertical holding capacity is generated by forcing a pile mechanically or from a pressure difference into the ground, providing friction reaction along the embedded length of the pile. Driven pile are the most commonly used anchors for offshore oil production units, since many years of experience has proven that piles are very reliable and can achieve high load capacity. They are used where less expensive anchors such as gravity, drag-embedment and plate anchors cannot be used. The most common piles are long slender tubular piles (L/D ratio > ~10), which are typically manufactured from rolled steel sections. Diameters are in the range of 0.50 to 2.50 m for the large mooring systems. Driven piles are installed vibrating the pile into the seabed. Hammers exist; however, can be prohibitively expensive due to need for templates. In case the seabed is rock or composed of thin sediment over rock, the piles cannot be placed by driving. Therefore, in this case, an oversize socket must be pre-drilled for a pile to be inserted and grouted in place. The major disadvantages of driven or drilled grouted piles for offshore use are high cost and the need for expensive specialized installation equipment (Sound & Sea Technology Engineering, 2009). Suction anchors are a commonly used alternative to the driven-pile embedment anchor. The mooring line is directly attached to the upper part of the pipe. Their use in the offshore industry (particularly for soft soil in deep water) has been increasing. They also perform effectively in normal sand seabed; however, perform poorly for hard bottom conditions. Because of their welded construction it might be expensive to manufacture. However, they are easier and cheaper to transport. Compared to tubular piles, they are shorter and often have greater diameter ranging up to 10 m for soft soil. An important feature of suction piles is their ability to be extracted and recovered by reversing the pump to apply pressure inside the pile. Suction anchor is suited for catenary and taut mooring lines.

Sound & Sea Technology Engineering (2009) summarizes the key features of the pile anchors as:

- Requires specialized installation equipment
- Can be installed and performs well on substantial slopes
- High lateral capacity achievable
- Can be designed to accommodate scour and resist shallow mud flows
- Resists high uplift as well as lateral loads, allowing short scope moorings (taut)
- Can be installed in hard seabed (rock and coral) by drilling and grouting
- Drilled and grouted piles require more specialized skills and installation equipment
- Wide range of sized and shapes are possible (pipe, structural shapes)
- More extensive and better quality site data are required than for other anchor types
- Anchor setting is not required
- Short mooring line scopes possible due to uplift resistant anchor capability
- Special equipment (pile extractor) may be required for tubular piles
- Suction piles are removable by reversing installation pump
- Pile anchor need not protrude above seabed.
- Driven piles cost competitive with other anchor types when driving equipment is available.

- *Vertical load anchor*. Horizontal and vertical holding capacity is generated due to a specific embedment anchor, allowing loads not only in the main instalment direction. These anchors are designed to carry high vertical loads and can be more suitable for anchoring F-WECs which have a dynamic response to environmental loads that characterize high vertical excursion.

- *Drilled and grouted anchor*. Horizontal and vertical holding capacity is generated by grouting a pile in a rock with a pre-drilled hole. The pile is similar in size and shape to a driven pile. Drilled and grouted piles are more reliable and can achieve higher vertical loads than driven piles, but are more expensive because they require heavy installation equipment.

- *Driven Anchor plate*. Plane anchors are large plates that resist extraction when embedded deeply into the seabed. The principle of this system is quite similar to that of the suction anchor. One of the key advantages is that when tension loads are applied to the plate, it rotates in the soil, allowing to involve a much larger wedge of soil with respect to suction anchor. Plates can be driven, vibrated, jetted, augured, shot or dragged into the seabed. Driving can be accomplished with a pile driver or a suction pile. They can be effective in hard seabed conditions where drag-embedment anchors are ineffective. Driven plates can absorb very high vertical loads and they are particularly suited for taut mooring lines. Sound & Sea Technology Engineering (2009) summarizes the key features of the driven anchor plates as:

- High capacity achievable
- Resists uplift as well as lateral load, allowing short-scope moorings (taut)
- Higher holding-capacity-to-weight ratio than other anchor types
- Accurate anchor placement is possible; minimizes environmental impact
- Does not protrude above the seabed
- Possibly susceptible to strength reduction due to cycling loading in loose sand/coarse silt seabeds
- Driven anchor typically not recoverable
- Drag-in plates are recoverable
- Anchor cable may be susceptible to abrasion or fatigue
- Driven plates effective in soft and hard seabeds and in coral
- Can be placed on moderate slopes
- Penetration is controlled and can be monitored
- Suction driven plates limited to soft seabeds
- Driven plate installation with surfaced-powered equipment limited to shallow depths
- Suction driven and drag-in plates are not depth limited.

The anchor type must be chosen with consideration of the mooring configuration, location and the requirements of a long term mooring. A more detailed information about the selection of appropriate anchor type for WECs can be found in D 3.3.2 of the Mermaid (Mermaid, 2013). Requirements for components of a long term mooring are discussed in the offshore standard DNV_OS_E301 (2010), where long term mooring is defined for floating units positioned at the same location for five years or more. Table 15 describes different characteristics of the main anchor types.

	Characteristics	Cost	Vertical Load	Retrievable	Installation Problems	Environmental Impact	Advantages	Disadvantages
Gravity Anchor	Horizontal holding capacity is generated by dead weight providing friction between seabed and anchor.	Low/Medium	YES	YES	Medium	Medium	* Be used in any type of ground, including in rocky soil. * No preparation is necessary background.	* Need large amounts of material, especially in the case of TLPs.
Drag-Embedment Anchor	Horizontal holding capacity is generated in the main instalment direction by the embedment of the anchor in the ground and depending of the installation depth of the anchor into the ground.	Medium	NO	YES	Low	Low	* Low cost	* No high vertial/horizontal load ratio
Driven Pile	Horizontal and vertical holding capacity is generated by forcing a pile mechanically or from a pressure difference into the ground, providing friction along the pile and the ground.	High	YES	NO	High	Medium	* Widely used in Offshore industry * High horizontal holding capacity * To be able to use in rocky soil with preparation	* Subject to corrosion * Higher cost with depther water * Difficult decomissioning
Suction Pile / Suction Caisson	Horizontal and vertical holding capacity is generated by forcing a pile mechanically or from a pressure difference into the ground, providing friction along the pile and the ground.	High	YES	YES	Medium	High	* Widely used in Offshore industry * Usable in (very) deep water	* Very expensive in deep water * Cannot be retrieved after use * Cannot be use in rocky soil.
Suction Embedded Anchors	Horizontal and vertical holding capacity is generated by the shear between the layers of soil.	Medium/High	YES	YES	Low	Medium	* very high towed load/weigth ratio *Small size/small place is needed in support vessel	* Not all types can be use in TLPs * Cannot be use in rocky soil
Helical Anchors	Horizontal and vertical holding capacity is generated by the shear between the layers of soil.	Low/Medium	YES	YES	Medium	High	* Low cost in shallow water	* Expecial systems are needed for its intallation * Cannot be use in rocky soil

Table 15. Anchor characteristics and relative costs (OTC, 2003; NREL, 2005; EquiMar, 2009; Johanning, L., 2009)

2.6 Previous work on fixed foundations

2.6.1 Hydraulic model studies on fixed foundations

Hydraulic model studies on fixed foundations have mostly focused on dynamic behavior of these structures under the action of wave, wind and current loads and/or on their stability affected by scour. It was found that most studies have focused on monopile foundations. Some of these laboratory studies are provided in Table 16, which is then followed by an overview of laboratory studies on flow characteristics around a monopile foundation in Table 17, and equilibrium scour depth formulae for wave-induced scour in Table 18.

Researcher	Focus	Foundation type	Model scale	Key results
Houlsby & Byrne (2000)	Response of Suction Caissons to Transient Combined Loading	Suction caisson	N.A.	• Experiments were carried out at different vertical loads, showing that the response depends on the vertical load level. • Nondimensional relationships were established which accounted for this dependency. • Surprisingly, the rate of loading had little impact on the load displacement behavior for the experiments undertaken.
Wienke & Oumeraci (2005)	Breaking wave impact on vertical and inclined slender cylinders	Monopile	1:10	• The impact force was shown to strongly depend on the distance between breaking location and cylinder, leading to five different loading cases. • An analytical description for the impact force was developed.
Grüne et al. (2005)	Innovative scour protection design for monopile using geotextile sand containers	Monopile	1:10	• Basic test series were performed with single containers and container groups with different container weights, varied in sizes and percentages of filling. • The stability of sand containers is not only a function of the total weight. • Other influences are the percentage of filling and the direction of wave approach, which are smaller for container groups compared to single containers due to interaction effects in a group. • The stability increases with increasing percentage of filling.
Sparboom & Oumeraci (2006)	Bending behaviour in single and group configurations	Monopile	1:10	• Regular non-breaking waves on the group configurations of monopiles did not decrease the wave load in comparison to a single monopile. • For the Jonswap-Spectrum, a small decrease of the wave load was determined for the group configuration compared to the single configuration.
Wang et al. (2006)	The response of suction bucket foundation in fine sand layer under horizontal dynamic loading	Suction bucket	N.A.	• It was shown that there is no liquefaction occurring when the amplitude is smaller than a critical value. Nevertheless, when the amplitude is bigger than the critical value, the sand surrounding the bucket softens or liquefies, and settles gradually to form a saddle-type hole. The size of the hole is bigger in the direction of loading than that perpendicular to the loading direction • It was shown that there exists an optimized ratio of the bucket's height to the diameter, at this condition, the sand bearing the strongest loading in unit contact area, which makes the responses acute.
Whitehouse et al. (2006)	Scour in shallow water	Monopile	1:36	• Scour depth up to 7 m was observed. • The scour slope is around 30° and aligns downstream.
Wang et al. (2006)	The response of suction bucket foundation in fine sand layer under horizontal dynamic loading	Suction bucket	N.A.	• It was shown that there is no liquefaction occurring when the amplitude is smaller than a critical value. Nevertheless, when the amplitude is bigger than the critical value, the sand surrounding the bucket softens or liquefies, and settles gradually to form a saddle-type hole. The size of the hole is bigger in the direction of loading than that perpendicular to the loading direction • It was shown that there exists an optimized ratio of the bucket's height to the diameter, at this condition, the sand bearing the strongest loading in unit contact area, which makes the responses acute.
De Vos et al. (2007)	Wave run-up	Monopile	N.A.	• Waves can damage the facility infrastructure. Therefore, adjustment of foundations relating to the main wave direction is of great importance
Yang et al. (2010)	Loading and scour around jacket foundation	Jacket	1:36	• The fixed bed experimental analysis was focused on the evaluation of the hydrodynamic force and on the prediction of the maximum breaking wave load on the jacket type offshore wind turbine foundation under shallow water condition. • The results of fixed bed experiment indicate the maximum horizontal forces on the wind turbine foundation have a good agreement with those from the designed values and also validate the structure design of the engineering consulting company. • A four-layer scour protection was tested and found to be effective in preventing scour around jacket type foundation of offshore wind turbine.

Table 16. Overview of laboratory studies on fixed foundations (extended from Teich, 2013)

Researcher	Focus	Foundation type	Model scale	Key results
Pfoertner et al. (2011)	The wave loading and the stability of the Ocean brick system	Monopile	1:50	• The tentative stability analyses, including the effect of wind on the monopile, have shown that the OBS structure is stable against overturning while the safety against sliding needs to be enhanced.
Prepernau et al. (2008) Schmidtke & Oumeraci (2012)	Scour around monopile – large scale tests	Monopile	1:10	• As expected the relative scour depth *S/D* increases exponentially with *KC*, thus confirming the scour formula by Sumer and Fredsøe (2001). • The development of the scour hole depends on the initial seabed conditions around the pile. The effect of the initial conditions on the scour depth increases with the incident wave energy. • The published results of small-scale tests compared to the large-scale tests are affected by scale effects.
Luxmoore (2012)	Wave loading on monopile and jacket in 30-60 m water depths; the effects of	Monopile and jacket	1: 60	• Complementary numerical simulations with Amazon 3D (Incompressible Navier Stokes solver) • Wave loading in a multi-directional representative sea was evaluated. • Investigation of steep wave loading, run-up and deck slam was performed. • Extreme and rogue wave structural loads were also evaluated. • Floating body simulations will be extended to full 3D
Nielsen et al. (2012)	Scour caused by breaking waves	Monopile	N.A.	• Various monopiles were exposed to plunging breakers that were breaking at various distances from the pile. • It was found that the scour was caused by turbulence generated by the breaking and was diverted toward the bottom by the pile. • The maximum scour depth found was approximately 0.60D. • This was smaller than the scour observed around piles exposed to current; however, in some cases it was an order of magnitude larger than the scour caused by non-breaking waves.
Wilms et al. (2012)	Wave induced scour development; design of scour protection system	Strabag Gravity base	1:17 1:50	• The tests on scour development without a scour protection system showed that the main areas which are vulnerable to scour are the contact areas of the foundation • The experiments showed that a scour protection system is necessary for the given and investigated wave boundary conditions; the performance of the selected protection system using geotextile sand containers is verified • Complementary numerical simulations indicated an amplification of the resulting flow around the foundation under combined loads (waves and current), but without significant change of the flow pattern
Stahlmann and Schlurmann (2012)	Scour development	Tripod	1:12 1:40	• The results showed a general variability of scour depending on the load boundary conditions and structural parameters. • Scours occurred both at the foundation piles and directly under the structure, which in this form could not be predicted using standard approaches, but which has to be taken into account when regarding the soil mechanical stability and the final dimensioning of the foundations. • Complementary numerical simulation using Openfoam • In-situ measured scour data
Lombardi et al. (2013)	The natural frequency and the long-term performance of a wind turbine model founded on clay soil	Monopile	1:10	• The dynamic response of the physical model is very sensitive to the flexibility of the foundation. The presence of the foundation provides increased flexibility and increased damping of the system. • The natural frequency of a monopile supported wind turbine founded on clayey soil may change with number of cycles of repeated loading. For clayey soil, a decrease in natural frequency is expected depending on the strain level in the soil next to the pile and the ratio of system frequency to the forcing frequency. • Practical guidance for choosing the diameter of monopile foundations was proposed.
Bredmose et al. (2013)	Dynamic excitation of monopiles by steep and breaking waves	Monopile	1: 80	• The measured wave field and structural response are reproduced numerically with a fully nonlinear potential flow solver for the undisturbed wave kinematics, combined with a finite element model with Morison-based forcing. • It was found that the largest accelerations occur for breaking waves. • Further statistical analysis showed that while the majority of the measured accelerations increase with increasing depth, the extreme accelerations increase for reduced depth. This was attributed to wave breaking.

Table 16 (Continue). Overview of laboratory studies on fixed foundations (extended from Teich, 2013)

Authors	**Fluid**	**Hydrodynamic force**	**Re_D**	***KC***	**Bed characteristics**	**Methods**	**Focus, key results, and limitations**
Dargahi (1989)	Water	Steady current	8400-46000	-	Rigid flat bed with slight surface roughness	Hydrogen bubble visualization Hot film anemometer Pressure transducers	• HVS and WVS. • At least five vortices upstream of the pile which mutually interact and merge for $20000<Re_D<39000$. • Increasing number of vortices with Re_D • The flow separation at sides of the pile was delayed near the bed due to the effect of near bed turbulence. • Different flow patterns at downstream with Re_D • Results are limited to the vertical symmetry plane. • Limited to the rigid flat bed case!
Apsilidis et al. (2010)	Water	Steady current	26000 48000 117500	-	Rigid flat bed	Time-resolved Particle Image Velocimetry (TR- DPIV)	• HVS. • Influence of the Re_D on horseshoe vortices based on time averaged analysis (velocity, vorticity). • Bimodal instability is not universal characteristics of the junction flows. • No specific trend between the average position of main vortex and Re_D • Limited to the rigid flat bed case! • Limited to the vertical symmetry plane upstream of the pile!
Sumer et al. (1992)*	Water	Waves	2000-9000	<25	Rigid flat bed	Hydrogen bubble visualization Laser Doppler Anemometry	• Horseshoe and lee-wake vortices visualization near the bed. • Additional bed shear stress measurements in U shaped water tunnel • No horseshoe vortices and vortex shedding for $KC<6$. • A relationship between the equilibrium scour depth and KC number. • Only laminar flow! • Limited to the laminar incoming wave boundary layer!!! • Lacked knowledge about the three-dimensional structures, their development and effect on scour! • Limited to the fixed flat bed case!!! • Hydrogen bubble visualization is insufficient to explain the dynamics of vortices!
Sumer et al. (1997)	Water	Waves + pure oscillatory flow	2000-9000	<25	Rigid flat bed	Hydrogen bubble visualization Laser Doppler Anemometry	• Horseshoe and lee-wake vortices visualization near the bed. • Additional bed shear stress measurements in U shaped water tunnel • No horseshoe vortices and vortex shedding for $KC<6$. • Qualitative demonstration of secondary vortices upstream of the pile. • Limited to the laminar incoming wave boundary layer!!! • Lacked knowledge about the three-dimensional structures, their development and effect on scour! • Limited to the fixed flat bed case!!! • Hydrogen bubble visualization is insufficient to explain the dynamics of vortices!
Faraci et al. (2000)	Water	Waves	276 - 1265	<25	Fixed flat bed Movable bed	Hydrogen bubble visualization Structured light technique	• Visualization of horseshoe vortices in fixed flat bed case (to ensure that the horseshoe vortices are formed) • Scour measurements in movable bed case. • No HVS exist for $KC<6$ and $Re_D<50$ • They proposed two hyperbolic relations between the duration of the main horseshoe vortex and two dimensionless parameters (KC and Re_D). • Limited to the laminar incoming wave boundary layer!!! • Limited to fixed flat case!!! • Hydrogen bubble visualization is insufficient to explain the dynamics of vortices!

Table 17. Summary of the available laboratory studies on flow characteristics around a vertical pile (Koca and Oumeraci, 2012)

Authors	Fluid	Hydrodynamic force	Re_D	*KC*	Bed characteristics	Methods	Focus, key results, and limitations
De Vos et al. (2008)	Water	Waves	14000 - 40000	7.9 - 10.8	Rigid flat bed	2D-PIV	• Breaking and non-breaking waves. • In a horizontal plane 0.5 m above a flat bottom and in a vertical symmetry plane at different model scales (1/50,1/100 Froude scaling). • Only a limited increase in amplification factor of bed shear stress due to breaking compared to non breaking wave. • They did not concern with the unsteady vortices and the dynamics of CTS. • Their experience showed that PIV methods are appropriate for measuring flow velocities under waves.
Williamson (1985)	Water	Pure oscillatory flow	β_1=Re_D/KC =255 β_2=Re_D/KC =730	<60 visualization <35 force measurements	Rigid flat bed	Flow visualization using surface particles in U tube Force measurements (strain gauges)	• Flow visualization and force measurements around single and pairs of free cylinders. • Definition of vortex dynamics and shedding regimes behind of the pile near free surface. • The process of pairing vortices from a previous half cycle .with those in a present half cycle is fundamental to all the patterns. • They defined vortex shedding regimes as a function of KC. • Flow reversal has a major effect on the magnitudes of the fluid-induced forces, and also on the fundamental frequency of the lift force.
Melville and Raudkivi (1977)	Water	Steady current	12700	-	1)Fixed flat bed 2)Fixed scoured bed after 30 min. 3)Fixed equilibrium scour hole	Hydrogen bubble visualization Dye injection Hot film anemometer	• HVS and WVS. • The existence of a non-scour inducing single horseshoe vortex during all stages • Results are presented in four vertical planes and one horizontal plane for the scoured bed cases and centerline symmetry plane for flat bed case. • Not sufficient to provide the coherent structure dynamics.
Dargahi (1990)	Water	Steady current	39000	-	Flat bed towards to equilibrium scour Clear water scour	Hydrogen bubble visualization Hot film anemometer	• Qualitative description of the vortex flow patterns as scour hole evolves in the symmetry plane. • Importance of vortex shedding for scour development in the wake. • Limited to the vertical symmetry plane and qualitative observations.
Dey (1995)	Water	Steady current	19836	-	Frozen equilibrium scour hole Clear water scour	Five hole pitot tube	• HVS • Measurements in different azimuthal planes in the horseshoe vortex region (0º,15º,30º,45º,60º,75º) upstream of the pile. • Limited to the equilibrium scour hole. • Limited to the one level of Re_D • Insufficient measurements. • However, measurements were insufficient to explain the unsteady vortices and their dynamics interactions.
Ahmed and Rajanutram (1998)	Water	Steady current	23400-32500	-	1)Fixed smooth bed 2)Fixed rough bed 3)Mobile bed with equilibrium scour hole	Preston tube	• Down-flow • The influence of bed roughness and scour hole on down-flow characteristics. • Limited datasets (10 tests). • Measurements: limited to the vertical symmetry plane upstream of the pile. • Measurement system is insufficient.
Graf and Istiarto (2002)	Water	Steady current	$\approx 10^5$	-	Equilibrium scour hole Mobile bed-clear water scour	Acoustic Doppler Velocimeter Profiler (ADVP)	• HVS and WVS. • Mean characteristics of the flow. • Strong horseshoe vortex upstream of the pile. • Flow reversal towards the water surface behind the pile. • Strong TKE at the foot in front of the pile and in the wake • Measurements: limited to the vertical symmetry plane! • Limited to the one level Re_D and only equilibrium scour hole. • Spatial and temporal resolution of the measurement system was low.

Table 17 (Continue). Summary of the available laboratory studies on flow characteristics around a vertical pile (Koca and Oumeraci, 2012)

Authors	Fluid	Hydrodynamic force	Re_D	*KC*	Bed characteristics	Methods	Focus, key results, and limitations
Muzzammil and Gangadharaiah (2003)	Water	Steady current	39000	-	i) rigid flat bed, ii) solidified scoured bed at different stages, and iii) mobile bed by using Mudflow visualization technique.	Mud-flow visualization Vortex probe and gauge	• Main horseshoe vortex diameter and its shape inside the scour hole • As a result of the rigid bed study, they reported the mean size of the main horseshoe vortex was 20% of the pile diameter. • As the scour hole evolves, the HV sinks completely into the scour hole and its mean size increases linearly with the depth of scour • No quantitative data on coherent structure dynamics and their influence on scour. • Results: limited to the symmetry plane upstream of the pile! • Limited to one level of Re_D
Dey and Raikar (2007)	Water	Steady current	42840	-	Frozen intermediate scour holes and equilibrium scour hole	Acoustic Doppler Velocimeter (ADV) Vernier point gauge	• HVS investigation in different azimuthal planes around the pile (0º, 45º, 90º). • The horseshoe vortex circulation decreased with azimuthal angle. • The horseshoe vortex circulation increased with scour hole size. • Limited to the one level of ReD. • Limited capability of ADV particularly near wall.
Unger and Hager (2007)	Water	Steady current	50000-3500000	-	Flat bed towards to equilibrium scour depth –clear water regime	Planar Particle Image Velocimetry (PIV) Laser Distance Sensor Ultra-sonic sensor	• Down-flow and HVS • Half circular pile. • Simultaneous measurements of scour depth and velocity vectors at certain times. • The horseshoe vortex and down-flow are the main scour agent. • Data basis for numerical simulations, the most detailed study so far. • 2-D PIV is not sufficient to explain the interaction of the main eddies. • Measurements: limited to the vertical symmetry plane upstream of the half pile and different horizontal planes around the half circular pile.
Kirkil et al. (2008)	Water	Steady current	16000	-	Equilibrium scour hole- clear water scour	Large Scale Particle Image Velocimetry (LSPIV) Non dispersive tracer inside the scour hole at different levels Complementary LES	• HVS and WVS. • The structure of the HVS was found to be more complex hitherto indicated in the literature. • Highly dynamic interaction of HVS, detached shear layers, and WVS. • Results: in different azimuthal planes (0º, 45º, 90º) around the pile. • Limited to the one level of Re_D and the equilibrium scour hole.
Sumer et al. (1992)*	Water	Waves Steady current	3400 94000	4,4 - 102	Live-bed scour	Video recording Laser Doppler Anemometry (for KC)	• Scour (final configuration) • The scour depth increases with increasing KC number and approaches its steady current value for large KC. • A relationship between the equilibrium scour depth and KC number. • Only quantification of scour depth by small scale PM tests.
Kobayashi (1992)	Water	Waves	2736	5.2	Flat bed Equilibrium scour hole	LDA	• The effect of bottom topography on the flow fields. • The shape and size of the lee-wake vortices deformed inside the scour hole. • No HVS and vortex shedding took place due to the small KC number. • Limited to the laminar incoming wave boundary layer!!!

Table 17 (Continue). Summary of the available laboratory studies on flow characteristics around a vertical pile (Koca and Oumeraci, 2012)

Authors	Fluid	Hydrodynamic force	Re_D	*KC*	Bed characteristics	Methods	Focus, key results, and limitations
Kobayashi and Oda (1994)	Water	Waves	Laminar	3,95-30	Clear-water scour	Sand profile meter	• Time evolution of scoured bed profiles • KC is the main parameter governing the scour process. • Shape of the scour hole can be classified into three regimes: twin-horn shaped; transient-shaped; and cone-shaped • Each regime of scour corresponds to different flow patterns. • Scour depth has a poor relation to the shields parameter. • Only quantification of scour depth and regimes by small scale PM tests.
Carreiras et al. (2000)	Water	Regular Waves	1300-5300	11- 23		ADV Scour depth meas.	• Scour (final configuration) around a single pile and a group of piles • The effect of breaking waves. • Improvement of Sumer (1992) formula. • The scour hole is influenced by the ripple formation and dynamics under breaking wave's effect. • Only quantification of scour by small scale PM tests.
Sumer and Fredsoe (2001)	Water	Waves-alone Current-alone Waves+current	7300-21000	abr-26	Live-bed scour	LDA (for KC) Video camera for scour hole development	• Scour (final configuration) • Differing directions in currents and waves • Development of formula for the prediction of the equilibrium scour depth • The scour depth approaches its steady current value for values of U_{cw} larger than 0.7. (U_{cw}=U_c/U_c+U_m) • Only quantification of scour by small scale PM tests.
Rudolph and Bos (2006)	Water	Waves+current	5000-30000	0-10	Live-bed scour	Velocity meas. (ukw) Ruler for scour	• The angle between the wave and current was 60^0. • Development of formula for the prediction of the equilibrium scour depth • Only quantification of scour by small scale PM tests.
Umeda (2011)	Water	Waves	1500-28000	2 - 40	Clear-water scour Live-bed scour	Digital stereo-photography Velocity: video monitoring of scour process	• Scour depth and scour regimes around a pile • Scour regimes and scour depths are influenced by shields parameter and KC number. • Ten scour regimes were identified (see Fig. 1.5)

Table 17 (Continue). Summary of the available laboratory studies on flow characteristics around a vertical pile (Koca and Oumeraci, 2012)

Author & Formula	Parameters	Remarks
Sumer et al. (1992): $\frac{S}{D}=1{,}3[1-exp(-0{,}03(KC-6))]$ $KC \geq 6$	$KC = U_m T/D$ U_m = Máximum undisturbed flow velocity at the bed T = Wave period D = Pile diameter	• Small scale. • Regular waves. • Live-bed scour. • Initial condition=flat bed. • No scour geometry. • No sediment parameters. • Without external turbulence.
Carreiras et al. (2000): $\frac{S}{D}=1{,}3[1-exp(-0{,}06(KC-6))]$ $KC \geq 6$	$KC = 2\hat{a}/D$ $2\hat{a}$ = Stroke of the horizontal excursion D = Pile diameter	• Small scale. • Regular waves. • Live-bed scour. • Initial condition=flat bed. • $11 < KC < 23$. • No scour geometry. • No sediment parameters. • Without external turbulence.
Sumer and Fredsøe (2001): $\frac{S}{D}=1{,}3[1-exp(-0{,}03(KC-6))]$ $KC \geq 6$	$KC = U_m T/D$, $U_m = \sqrt{2\sigma_U}$ $\sigma_U^2 = \int_0^\infty S_U(f)\,df$ U_m = Undisturbed orbital velocity at the bed f_p = Peak frequency of the wave power spectrum σ_U = Root mean square (RMS) value at the orbital velocity at the bed $S_U(f)$ = Power spectrum of U, and frequency	• Small-scale. • Irregular waves. • Live-bed scour. • Initial condition=flat bed. • No scour geometry. • No sediment parameters. • Without external turbulence.
Rudolph and Bos (2006): $\frac{S}{D}=1{,}3[1-exp\{-A(KC-B)\}\{1-U_{cw}\}^c]$ $KC \geq B$ $A = -0{,}03 + 1{,}5U_{cw}^4$ $B = 6exp(-5U_{cw})$ $C = 0{,}1$ $U_{cw} = U_c/U_c{+}U_w$	$KC = U_m T_p/D$ U_m = Máximum undisturbed flow velocity at the bed T_p = Peak wave period D = Pile diameter U_c = Current induced velocity U_w = Wave induced velocity U_{cw} = Relative flow velocity	• Small-scale. • Irregular waves + currents. • Live-bed scour. • Initial condition=flat bed. • $KC < 10$. • No scour geometry. • No sediment parameters. • Without external turbulence.
Oumeraci (2009): $\frac{S}{D}=1{,}3[1-exp\{-A(KC-B)\}]$ $A = -0{,}025 + 0{,}75U_{cw}^{2,6}$ $B = 7{,}5exp(-4{,}7U_{cw})$ $U_{cw} = U_c/U_c{+}U_w$	$KC = U_{max} T_m/D$ U_m = Máximum undisturbed flow velocity at the bed T_p = Mean wave period D = Pile diameter U_c = Current induced velocity U_w = Wave induced velocity U_{cw} = Relative flow velocity	• Large-scale. • Irregular waves. • Live-bed scour. • Initial condition=flat bed. • Initial condition=existing scour. • 11 < KC < 39. • No scour geometry. • No sediment parameters. • Without external turbulence.
Dey et al. (2011): $\frac{S}{D}=c[1-exp(-m(KC-6))]$ $KC \geq 6$	U_m = Máximum undisturbed flow velocity at the bed T = Wave period D = Pile diameter c and m = Coefficient and exponent, respectively dependent on n n= Clay proportion (by weight) in sand – clay mixture	• Small-scale. • Regular waves. • Live-bed scour. • Initial condition=flat bed. • 12 < KC < 95. • Independent of sediment size (only clay proportion). • Without external turbulence.
Zanke et al. (2011): $\frac{S}{D}= 2{,}5[1-0{,}5(U_m/u_c)]\,x_{re}$ $x_{rel} = x_{eff}/1 + x_{eff}$ $x_{eff} = 0{,}03\pi(1-0{,}35u_c/U_m)(d_0/D-1{,}91)$	$KC = U_m T/D$ U_m = Máximum undisturbed flow velocity at the bed U_m = Mean velocity in the case of steady current u_c = Critical velocity for beginning of sediment motion T = Wave period D = Pile diameter d_0 = Length of near bed water displacement during a half period x_{eff} = The relatived sediment displacement during a half period (effective for scour development)	• Compiling the literature data from small-scale tests. (one large scale test dataset). • Wave/steady current/tidal. • Live-bed scour/clear water scour. • Initial condition=flat bed. • Whole range of KC. • No scour geometry. • Sediment characteristics included in the critical velocity. • Without external turbulence.

Table 18. Summary of Equilibrium Scour Depth Equations for wave-induced scour around a monopile (Koca and Oumeraci, 2012)

2.6.2 Numerical studies on fixed foundations

Numerical studies on fixed foundations have mainly focused on the hydrodynamic loads due to waves. Of particular importance has been monopile foundation. Some of these investigations are provided in Table 19.

Researcher	Focus	Foundation type	Key resuts	Numerical method
Dalhoff et al. (2007)	Integrated Load and Strength Analysis for Offshore Wind Turbines with Jacket Structures	Jacket	• A sample calculation of a 5 MW OWT with jacket foundation in relatively deep water (45 m) compared to existing offshore wind farm. • It was shown that the wind loads are governing the fatigue design while the wave impact is only of minor importance.	3D FEM
Abdel-Rahman & Achmus (2008)	The effect of a change in the lateral load direction on the overall response of laterally loaded foundation piles in sand	Monopile	• It was found that the preload can significantly affect the pile behavior. Due to recent load history, the pile stiffness increases. The quantity of this increase is dependent on the angle between the directions of preload and current load and on the magnitude of the preload in relation to the current load.	3D FEM with Abaqus.
Achmus et al. (2008)	The behavior of large-diameter monopiles under monotonic and cyclic loading taking the interaction between the pile and the subsoil into account	Monopile	• It was found that the p-y method in its present form is not suitable to account for the behavior of large-diameter piles. • The results of parametric studies for monopiles under monotonic design load and under cyclic loading are presented. • Based on these results, considerations and recommendations are made concerning the design of large-diameter monopiles	3D FEM
Kuo et al. (2008)	The emphasis of this study is to evaluate the lateral response of monopile foundation with a scour.	Monopile	• The lateral displacement and rotation of the large-diameter monopile under monotonic and cyclic loading are affected significantly by scour. • To ensure the serviceability of wind energy converters, an additional pile length can be considered as an alternative method to the scour protection	FEM
Hearn and Edgers (2010)	Analyses of a large diameter monopile representative for a 3 to 5 MW wind turbine in dense sand that may be encountered in the southern North Sea and offshore the Northeast United States	Monopile	• The results suggest that the API method over predicts soil resistance and under predicts pile deflection for large diameter monopiles subjected to lateral load and in stiff soils.	P-y method and 3-D FEM
Li et al. (2010)	The liquefaction degree and deformation of sand sediment around bucket foundation	Suction bucket	• Deformation of sand sediment increases with the increase of loading amplitude and skeleton's elastic modulus and the decrease of frequency. • The maximum vertical deformation on the surface of sediment is 0.25 times of bucket depth away from loading side. • The maximum horizontal deformation is on the loading side.	Simplified in-house spring model
Schløer et al. (2011)	Investigation of fully nonlinear irregular unidirectional wave-forces.	Monopile	• Stream function theory in a few occasions underrates the wave forces acting on the monopile, in the extreme wave load design.	
Pappusetty & Pando (2013)	Long term monopile head behavior for ocean energy converters under sustained low amplitude lateral loading	Monopile	• This study presented predictions of monopile head deflections under sustained cyclic loading using p-y based methods as well as 3D dynamic FEA. • Results from this study showed that API p-y curves used for offshore piles do not adequately predict the gradual pile head displacements observed experimentally. • Modified p-y curves were developed for pseudo-static cyclic loading, which do a better job than API p-r curves, but still greatly underpredict deformations. • In contrast, the 3D FEA were found to capture reasonably well the general observed trends of gradual accumulation of pile head rotation and lateral deformation with increasing constant amplitude lateral load cycles.	3D FEM

Table 19. Overview of numerical studies on fixed foundations (extended from Teich, 2013)

Researcher	Focus	Foundation type	Key resuts	Numerical method
Baarholm et al. (2013)	Quantification of the dynamic amplification for the Kvitebjorn jacket platform in North Sea	Jacket	• Non-linear time domain irregular wave simulations have been performed for the Kvitebjørn jacket platform located in the North Sea with the aim to quantify the dynamic amplification. • Based on the quasi-static response and dynamic response, equivalent dynamic amplification factors (EDAFs) were calculated for different response measures in the jacket.	• USFOS 8.5 for time domain analysis • WABIRK (inhouse software of DNV) for wave kinematics
Lim and Tao (2013)	Anew recommended innovative design to overcome problems associated with the fabrication of large circular cylinders is introduced by replacing the circular cylinder with a vertical pile of octagonal crosssectional shape.	Monopile	• Scaled Boundary Finite Element Method (SBFEM) is developed to calculate the wave diffraction forces acting on the octagonal cylinders where no fundamental solutions known exist. • The difference of the diffraction forces induced by waves acting on both the circular and octagonal cylinders is approximately similar. • Thus the innovative wind turbine foundation where a conventional circular cylinder is replaced by an octagonal cylinder could hence be justified, providing a good illustration where the SBFEM could be used for direct engineering applications, where optional forms are being considered. • The SBFEM produces accurate results with only a small number of elements being used, indicating the reduction of computational time.	Scaled Boundary Finite Element Method (SBFEM)
Peng et al. (2013)	Impact of nonlinear wave groups on cylindrical monopiles	Monopile	• Four nonlinear wave groups are selected from fully nonlinear waves generated by a 2D ComFLOW model, representing wave groups with the largest or the second largest crest heights, the largest wave height and a wave group consisting of consecutive large waves. These four wave groups are used to investigate the wave loads on the foundation and the platform in a 3D ComFLOW model. • Model results show that the maximum wave loads on the foundation and the platform by nonlinear wave groups are determined by their individual wave crest height. • This study presented a relationship between platform level and wave impact on the platform, as the vertical force on the platform is the combination of buoyancy force (if inundated) and wave impact force due to wave run-up. • Results also showed that wave loads on the foundation and wave impact on the platform decrease as the wave period increases from 13s to 16s (typical wave period at German Bight). • A wave group can cause a larger wave load on the foundation and the platform than regular waves, considering a regular wave height equal to the maximum wave height, regardless of the associated wave period (period of individual wave or peak period).	ComFLOW wave model

Table 19 (Continue). Overview of numerical studies on fixed foundations (extended from Teich, 2013)

Researcher	Focus	Foundation type	Key resuts	Numerical method
Ong et al. (2013)	An engineering approach to dynamic analysis of offshore monopile wind turbines	Monopile	• The finite element model of the wind turbine is established. • Dynamic response analyses of the NREL 5MW monopile OWT at 20m water depth have been carried out. • For a given current speed, parametric studies have been carried out by including the effects of different wind-wave loading and soil conditions. The mean internal bending moment about the y-axis (*BMave*) increases from the tower-top towards the seabed and it reaches the maximum value at a position slightly beneath the seabed surface. Beneath this point, *BMave* decreases as the depth increases. A similar feature is observed for the standard deviation of the internal bending moment about the y-axis • The maximum displacement in the x-direction (*Ux,wave*) is observed at the tower-top, and it decreases as the vertical position decreases towards the bottom-tip of the foundation. • Different soil conditions change the eigen frequency of the wind turbine significantly. • The difference between the *Ux,wave* profiles for different soil conditions increases as the vertical position increases. • Different soil conditions lead to different *BMave* andsectional shear force distributions in the soil layers.	FEM with Abaqus
Philippe et al. (2013)	A novel approach to efficiently simulate the structural dynamics of a concrete Gravity Based Foundation	Gravity base foundation	• This paper shows the interest of an integrated modeling strategy combining multifiber finite element beams with nonlinear constitutive laws, nonlinear soil structure interaction (macroelement) and nonlinear wave modelling for the structural dynamic modelling of concrete gravity base foundations. • The model reproduces complex nonlinear phenomena such as decrease in the structural stiffness due to damage, permanent strains, and the amplification of the horizontal top displacement due to soil structure interaction. • Results have to be validated using more advanced and time consuming numerical models, including 3D FEM models for soil-structure interaction and CFD models for fluid-structure interactions. Once validated, the model will be applied on a variety of design load cases including fatigue limit states and extreme limit states.	• Wind turbine dynamics - FAST design code from NREL • Hydrodynamic loads on the GBF - hydrodynamic tools from Ecole Centrale Nantes (ECN) • Wave kinematics - In house nonlinear HOS incident wave model • Diffraction loads - In housediffraction/rad ation code Aquaplus • Soil-structure interaction – in-house model from GeM Lab.
Zheng (2013)	Comparison of wave forces on a monopile with classical random wave models and the state of the art fully nonlinear random wave model	Monopile	• This study compared classical random wave models with the state-of-the-art fully nonlinear random wave model (FNRW) when they are applied to calculate the random wave loading on a monopile structure that has been commonly used in offshore wind farms. • Two wave conditions, #1 for shallow water and #2 for water of a finite depth, are investigated for wave elevations and the comparisons of wave forces focus on #1. • Refer to paper for the results	Fully nonlinear random wave model

Table 19 (Continue). Overview of numerical studies on fixed foundations (extended from Teich, 2013).

Researcher	Focus	Foundation type	Key resuts	Numerical method
Buren and Muskulus (2013)	Suitability of the p-y method for lattice tower foundation design intended for up to water depths of 60 m	Jacket	• The data obtained from both the geometric pile design study using the custom built pile design program, and the aeroelastic analyses of the selected cases highlights the impact of soil site conditions and design standard parameters on the p-y method and its application for offshore wind turbines support structures. • Alterations in the soil classification and layer profiles at the site have a large impact not only on the geometric layout of the pile, but the deflections and fatigue of the support structure as well. • It was shown that despite not affecting the maximum deflection of the piles, the soil and design standard parameters can nevertheless have an impact on the fatigue life estimation of the structure. • According to the results of this study, pile foundation models which are specifically suited for dynamic simulations are needed.	Aero-servo-hydro-elastic simulation HAWC2, GL Garrad Hassan Bladed or FEDEM WindPower
Li et al. (2013)	Installation of offshore wind turbine monopiles using floating vessels instead of jack-up vessels with the focus on the phase of lowering the monopile from above the sea water to the sea bed.	Monopile	• The monopile rotational resonant motions are excited by wave loads on the monopile in short waves, while in longer waves the motions are mainly induced by the floating vessel motions. • When a jack-up vessel is used, the lifting system is more sensitive to shorter waves. The responses reduce with increasing Tp. However, the responses decrease from short to intermediate waves and increase in longer waves when using the floating vessel. • The vessel type affects the rotational motions of the monopile. The rotations by using a floating vessel are much larger than using a jack up vessel in long waves due to the influence of the vessel motions. • The landing contact force in the landing phase increases greatly by using larger landing stiffness. Larger landing stiffness also provides better control on the pile end tip motion in steady state, which could be beneficial for the pile penetrating into the soil by its self-weight. • Limitation of the numerical model and future work was also discussed	Marintek SIMO - time domain simulations
Sui et al. (2013)	Development of a 3D integrated model for wave-induced seabed response and liquefaction potential around the square pile	Monopile (square)	• The numerical results indicated that wave-induced pore pressure reduces rapidly with an increasing seabed depth, and the maximum pore pressure and largest liquefaction potential can be identified in front of the square pile foundation. • It was also found that the phenomenon of liquefaction may occur inside the seabed soil while the upper layer remains un-liquefied.	• FUNWAVE – wave-pile interaction • (WINBED – seabed deformation (Biot's poro-elastic theory)

Table 19 (Continue). Overview of numerical studies on fixed foundations (extended from Teich, 2013).

Researcher	Focus	Foundation type	Key resuts	Numerical method
Wasjø et al. (2013)	A concept for combined installation of the substructure and turbine in one single operation without the need of expensive installation vessels is described	Gravity base foundation	• The main focus is the reduction of installation costs for wind farm developments. • A new concept is proposed based on a GBS substructure. • The concept appears to be technical feasible, and may introduce a cost saving compared to the more common steel jacket solution. • A cost saving potential in this early phase of 17 % is identified compared to the more common steel jacket solution. The cost saving is related to the installation process.	FEM with AquaSim
Hamann et al. (2013)	Ship collision behavior with gravity base foundations of offshore wind turbines	Gravity base foundation	• The conducted simulations showed that a simple and cost effective investigation of the collision process is possible using the finite element method. • The design of a gravity base foundation can be optimized regarding ship collision by variation of selected parameters using this method	FEM with Abaqus/Explicit 6.10

Table 19 (Continue). Overview of numerical studies on fixed foundations (extended from Teich, 2013).

2.7 Application of the offshore foundation technology to renewable energy

The objective of this section is to describe market developments in the energy industry. It has made an analysis of most different types of floating and fixed platforms for marine renewable energy that exist today, whether for extracting energy from waves or currents, offshore wind power generation, or other energy.

2.7.1 Prototypes developed in wind energy sector

Wind energy is the leading renewable energy technology. Among support structures for wind turbines, the least used and proven are the floating designs. This is an area where the number of blueprints, ideas, and plans stands in contrast to the actual number of floating turbines. At the end of 2012, the average water depth of wind farms was 22 m and the average distance to shore 29 km. Looking at projects under construction, consented or planned, it is clear that average water depths and distances to shore are likely to increase, with projects announced up to 200 km from shore and in water depths of up to 215 m (EWEA, 2013) (See Figure 42).

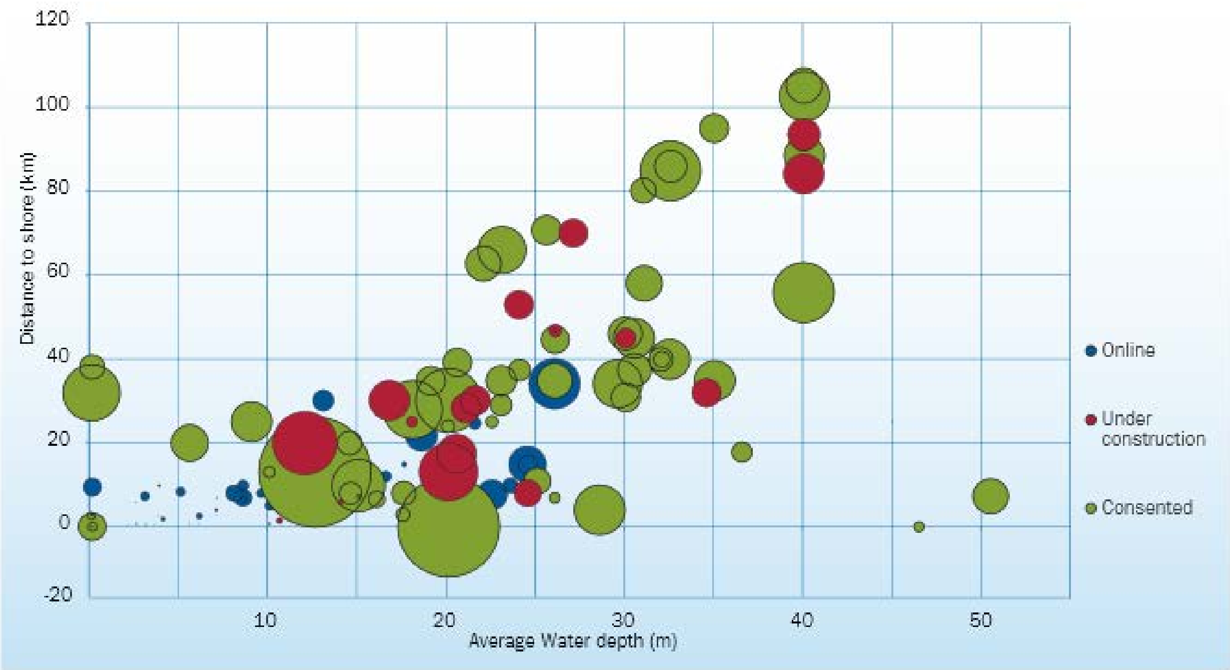


Figure 42. Average water depth and distance to shore of online, under construction and consented wind farms

To this day, only a few wind turbines in the world stand on a floating support structure. One is the Hywind in Norway, fitted with a turbine from Siemens. Another is the Windfloat, installed off the coast of Portugal, with a Vestas turbine. Moreover, a couple of scale models float in the oceans: the Blue H, near Italy, and Sway, a prototype in the waters of Norway (Lorc knowledge, 2011). There are available some extensive documents that have already been published that review in detail the already existing floating offshore wind foundation concepts and projects. A formidable example is: “Floating Offshore Wind Foundations: Industry Consortia and Projects in the United States, Europe, and Japan (Main(e) International consulting LLC. May 2013).

Next, in Table 20 an overview of offshore wind turbines already mounted over fixed structures is shown.

Foundation	Material	Weight (ton)	Water Depth (m)	Distance to shore (km)	Project	Country	Status
Monopile	Steel	400-630	15-19	19-20	Anholt	Denmark	Com.
Monopile	Steel	280	4.2-6.4	10	Arklow Bank 1	Ireland	Com.
Monopile	Steel	215	16-19	16	Baltic 1	Germany	Com.
Monopile	Steel	N.A.	23-44	32	Baltic 2	Germany	Prog.
Monopile	Steel	N.A.	15-20	7.5	Barrow	UK	Com.
Monopile	Steel	300-550	20-37	46	Belwind 1	Belgium	Com.
Monopile	Steel	N.A.	6-11	1.6	Blyth	Belgium	Com.
Monopile	Steel	N.A.	6	3-4	Bockstigen	Sweden	Com.
Monopile	Steel	400	2-8	6.4	Burbo Bank 1	UK	Com.
Monopile	Steel	730	21-31	69	Dantysk	Germany	Prog.
Monopile	Steel	250	10-18	18	Egmod Aan Zee	Netherlands	Com.
Monopile	Steel	N.A.	1-4	1	Frederikshavn	Denmark	Com.
Suction bucket	Steel	N.A.	1-4	1	Frederikshavn	Denmark	Com.
Monopile	Steel	700	24-34	26	Greater Gabbard	UK	Com.
Monopile	Steel	225-423	0-15	7	Gunfleet Sands 1+2	UK	Com.
Monopile	Steel	N.A.	5-12	8.5	Gunfleet Sands 3 Demo	UK	Prog.
Monopile	Steel	450-700	12-28	13-18	Gwynt y môr	UK	Prog.
Monopile	Steel	180-230	6-14	14-20	Horns Rev 1	Denmark	Com.
Monopile	Steel	N.A.	9-17	30	Horns Rev 2	Denmark	Com.
Monopile	Steel	60	1-2	0.3	Irene Vorrink	Netherlands	Com.
Monopile	Steel	100	5	0.04	Kamisu	Japan	Com.
Monopile	Steel	247-292	5	8.5-13.5	Kentish Flats 1	UK	Com.
Monopile	Steel	71-89	5-10	0.75-0.8	Lely	Netherlands	Com.
Monopile	Steel	320-480	8.5-16.3	6-8	Lincs	UK	Prog.
Monopile	Steel	650	0-25	19-20	London Array 1	UK	Com.
Monopile	Steel	199-266	6.3-11.2	5-9	Lynn and Inner Dowsing	UK	Com.
Monopile	Steel	626	22-26	53	Meerwind Süd und Ost	Germany	Prog.
Monopile	Steel	250	41585	7-8	North Hoyle	UK	Com.
Monopile	Steel	N.A.	16-29	37	NorthWind	Belgium	Prog.
Monopile	Steel	320	19-24	23	Prinses Amalia	Netherlands	Com.
Monopile	Steel	193-235	6.5-12.5	8	Rhyl Flats	UK	Com.
Monopile	Steel	Max. 720	18-23	15-30	Riffgat	Germany	Prog.
Monopile	Steel	N.A.	2-12	11-13	Robin Rigg	UK	Com.
Monopile	Steel	300	10-13	3.5	Samso	Denmark	Com.
Monopile	Steel	Max. 200	5-10	2.3	Scroby Sands	UK	Com.
Monopile	Steel	375-530	17-22	17-23	Sheringham Shoal	UK	Com.
Monopile	Steel	90-160	8-16.5	1.5	Teesside	UK	Prog.
Monopile	Steel	N.A.	20-25	11.3-11.5	Thanet	UK	Com.
Monopile	Steel	Max 110 Max 165	7.1-9.9	8-12.5	Utgrunden 1	Sweden	Com.
Monopile	Steel	N.A.	21-26	14.4-18	Walney 1	UK	Com.
Monopile	Steel	Max. 805	8	21-26	Walney 2	UK	Com.
Monopile	Steel	N.A.	6-10	4	Yttre Stengrund	Sweden	Com.

Table 20. Overview of offshore wind turbines

Foundation	Material	Weight (ton)	Water Depth (m)	Distance to shore (km)	Project	Country	Status
Gravity base	Concrete	2800	0.5-2	0.05-0.1	Avedore Holme	Denmark	Com.
Gravity base	Concrete	N.A.	2	0.5	Breitling Demonstration	Germany	Com.
Gravity base		N.A.	11.9	3	Choshi	Japan	Com.
Gravity base	Concrete	N.A.	10	8-13	Donghai Bridge 1	China	Com.
Gravity base	Concrete	N.A.	3	0.6	Ems Emden	Germany	Com.
Gravity base	Concrete	N.A.	3-8	2-6	Kemi Ajos	Finland	Com.
Gravity base		N.A.	14	1.4	Kitakyushu Demo	Japan	Prog.
Gravity base	Concrete	N.A.	8-21	7	Kårehamn	Sweden	Prog.
Gravity base	Concrete	3900	4-10	7	Lillgrund	Sweden	Com.
Gravity base	Concrete	1800	3-5	2	Middelgrunden	Denmark	Com.
Gravity base	Concrete	1600-1800	6-10	10.8	Nysted 1	Denmark	Com.
Gravity base	Steel	400	9	1.2	Pori Demo	Finland	Com.
Gravity base	Concrete	1300-1900	6-12	8.8	Nysted 2	Denmark	Com.
Gravity base	Concrete	N.A.	0-2	0.1	Ronland	Denmark	Com.
Gravity base	Concrete	1604-1879	6-16	10.6	Sprogo	Denmark	Com.
Gravity base	Concrete	2700-3000	12-27.5	26-27	Thornton Bank 1	Belgium	Com.
Gravity base	Concrete	N.A.	3-6	6	Tuno Knob	Denmark	Com.
Gravity base	Concrete	N.A.	3-6	1.5-3	Vindeby	Denmark	Com.
Gravity base	Concrete	N.A.	3-13	7	Vindpark Vanern	Sweden	Com.
Jacket	Steel	480	30-45	45-60	Alpha Ventus	Germany	Com.
Jacket	Steel	N.A.	23-44	32	Baltic 2	Germany-Kriegers Flak	Prog.
Jacket	Steel	760	45	23	Beatrice Demo	UK	Com.
Jacket	Steel	N.A.	34	45	BelWind 2 Demo	Belgium	Prog.
Jacket	Steel	N.A.		1.2	Jeju Demo	South Korea	Com.
Jacket	Steel	450-550	22-25	57	Nordsee Ost	Germany	Prog.
Jacket	Steel	500	17-21	9.5-14	Ormonde	UK	Com.
Jacket	Steel	N.A.	32	70	Suizhong Demo	China	Com.
Jacket	Steel	550	12-27.5	26-27	Thornton Bank 2	Belgium	Prog.
Jacket	Steel	550	12-27.5	26-27	Thornton Bank 3	Belgium	Prog.
Tripod	Steel	710	30-45	45-60	Alpha Ventus – Borkum West 1	Germany	Com.
Tripod	Steel	700	28-33	44-60	Borkum West 2	Germany	Prog.
Tripod	Steel	850	39-41	115-138	Global Tech 1	Germany	Prog.
Tripile	Steel	610	40	90-101	Bard Offshore 1	Germany	Prog.
Tripile	Steel	610	2-8	0.4	Hooksiel Demo	Germany	Com.

Table 20 (Continue). Overview of offshore wind turbines

Figure 43 also shows a comprehensive breakdown of wind turbine foundation technology for the operating, under construction and consent authorized project pipeline worldwide. It is clear that the industry is dominated by monopile foundation which is followed by emergence of several alternatives.

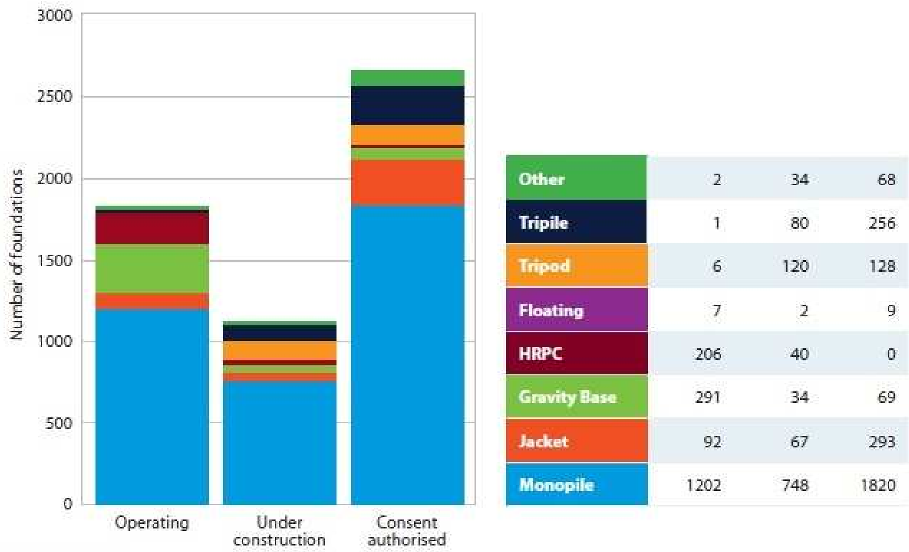


Figure 43. Compherensive offshore wind foundation type landscape (WEU, 2013).

Next, a more detailed review of some of the most innovative concepts (fixed and floating) is shown.

Windfloat Platform (Principle Power, 2010)

Windfloat is a semi-submersible floating support structure for offshore wind turbines with a simple, economic and patented design, already installed off the coast of Portugal near Abruçadoira. The innovative features of the Windfloat dampen wave and turbine induced motion, enabling wind turbines to be sited in previously inaccessible locations where water depth exceeds 50m and wind resources are superior. Further, economic efficiency is maximized by reducing the need for offshore heavylift operations during final assembly deployment and commissioning. Multiple projects are in development for the installation of commercial Windfloat units in both European and US offshore wind farms. (See Figure 44).

Figure 44. WindFloat Platform (Source: Principe Power)

The Windfloat consists of a tri-column-stabilized floating structure. The Windfloat stability is given by water entrapment (heave) plates at the base of each column. The plates improve the motion performance of the system significantly due to damping and entrained water effects. In addition, Windfloat's closed-loop hull trim system mitigates mean wind-induced thrust forces. This secondary system ensures optimal energy conversion efficiency following changes in wind velocity and direction. The mooring system employs conventional components such as chain and polyester lines to minimize cost and complexity. It uses pre-laid drag embedded anchors.

The key numbers of Winfloat are summarized in Table 21:

Power rating	**≈ 3.0-10MW**
Rotor diameter	**≈ 120-170m**
Turbine hub height	**≈ 80-100 m**
Hull Draft	**< 20 m**
Operational Water Depth	**> 40 m**
Conventional mooring components	(**4 lines**)

Table 21. Windfloat key numbers (Principle Power, 2010)

There are three advantages to the WindFloat foundation: first, its static and dynamic stability provides sufficiently low pitch performance enabling use of commercial offshore wind turbines; second, its design and size allow for onshore assembly; third, its shallow draft allows for depth independent siting and wet tow (fully assembled and commissioned) to sites not visible from shore. Primary markets are transitional (30-60m) and deep (>60m) water offshore wind sites in the US and Europe, previously inaccessible, and estimated to have greater than 2 terawatt (TW) of resource potential. Secondary markets include sites in Asia and other Oceanic countries.

The Windfloat is fitted with patented water entrapment (heave) plates (see Figure 45) at the base of each column. The plates, as it said before, improve the motion performance of the system significantly due to damping and entrained water effects. This stability performance allows for the use of existing commercial wind turbine technology.

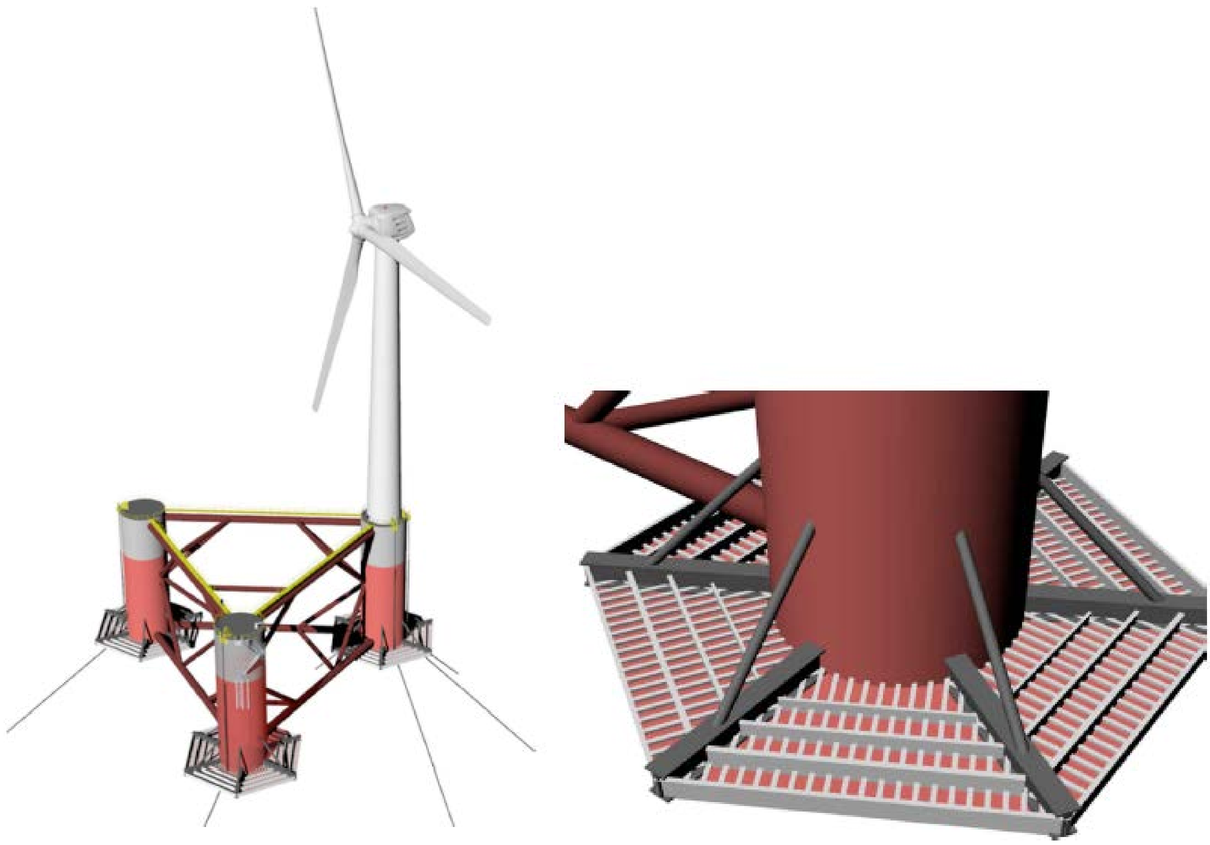


Figure 45. Detail of the structure of WindFloat Platform

The design of the WindFloat enables the structure to be fully assembled onshore and towed to its final location. All fabrication and qualification is completed at quayside in a controlled environment. Deployment cost savings are significant when compared with monopile/jacket support structures which require offshore heavylift operations.

The mooring system employs conventional components such as chain and polyester lines to minimize cost and complexity. Through the use of pre-laid drag embedded anchors, site preparation and impact is minimized.

Hywind Platform (Statoil, 2009)

The Hywind (from Statoil) in Norway, fitted with a turbine from Siemens, is the world’s first full-scale floating wind turbine, that use a spar-type support structure for the Hywind concept. In 2009, Statoil invested around NOK 400 million in the construction and further development of the pilot, and in research and development related to the wind turbine concept. The public corporation Enova SF, whose aim is to promote the transition to environmentally friendly energy use and energy production in Norway, has granted NOK 59 million in support for the project (See Figure 46).

Figure 46. Hywind Platform (Statoil, 2009)

The floating structure consists on a spar buoy concept made of a steel cylinder filled with a ballast of water and rocks. It extends 100 metres beneath the sea’s surface and is attached to the seabed by a three-point mooring spread. Hywind is the world’s first full-scale floating wind turbine.

The key numbers of Hywind are summarized in Table 22:

Turbine size	**2.3MW**
Rotor diameter	**82.4m**
Turbine height	**65 m**
Turbine weight	**138 Tn**
Hull Draft	**100 m**
Operational Water Depth	**200 m**
Displacement	**5300 m3**
Diameter at water line	**6 m**
Diameter submerged body	**8.3m**
Conventional mooring components	(**3 lines**)

Table 22. Hywind key numbers (Statoil, 2009)

The Hywind concept combines known technologies in a completely new setting and opens up the possibility for capturing wind energy in deep-water environments. The core expertise acquired by Statoil as a leading operator of offshore oil and gas fields has played a very important part in the development of the Hywind concept.

The primary intention of the demo concept was not to derive revenues from the power generated by Hywind, but to test how wind and waves affect the structure. Hywind has generated 15 MWh of production since startup in 2010. Statoil will continue to test throughout 2011 and 2012 in order to gain further data for optimising the next generation of Hywind. The goal now is to commercialize the concept, by developing a supplier market to reduce costs so that floating wind power can compete in the energy market.

As the Hywind concept is perfectly adapted to deep waters close to large power consumption regions throughout the world, combined with a unique ability of flexible location choice provides considerable market opportunities. The expertise gained through the demo turbine, combined with the group's financial strength and innovative ability, puts Statoil in a good position to develop this technology into to a cost competitive offshore wind concept.

BlueH TLP Platform (BlueH Group Technologies Ltd, 2007)

It is important to note that Blue H's design is not merely a theoretical concept, but one which is currently undergoing a rigorous research, development and practical installation path to improve its robustness and become fit for the purpose of reliably generating offshore wind energy. BlueH is the most advanced existing experience of TLP concept.

As proof of concept, Blue H built and successfully launched into the water towards the end of 2007 a large-scale 75% size prototype SDP (see Figure 47). In the summer of 2008 this was installed along with a small wind turbine in 113 meter deep water at a distance of 11.5 nautical miles (21.3 km) off the coast of Southern Italy, near the site of the future offshore Tricase project, a world's "first". After 6 months at sea, the unit was decommissioned early in 2009.

Figure 47. BlueH TLP Fase 1. (Source: BlueH Group Technologies Ltd)

In 2008, Blue H also started engineering its second proof of concept, a tension legged platform for a 2 MW floating wind turbine which it intends to complete in 2012 and install in its Tricase wind farm. (See Figure 48).

Figure 48. BlueH TLP Fase 2 (Source: BlueH Group Technologies Ltd)

The 2 MW unit will be followed by the deployment of the final proof of concept: a larger pre-production floating turbine in 2014, combining Blue H's platform with a 3rd party offshore turbine.

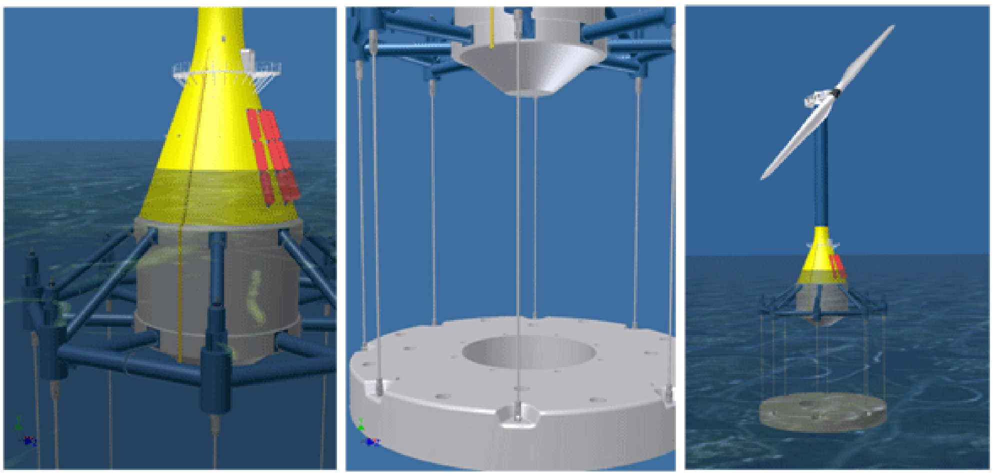


Figure 49. BlueH TLP Fase 1 (Source: BlueH Group Technologies Ltd)

In the mid-term, Blue H will continue to co-develop sites in key markets with specialized site development partners. In order to promote its deep water floating technology, Blue H pioneered and developed by itself one deepwater 90 MW site, the Tricase wind farm, which is close to securing its final permit. Ultimately however, Blue H does not see itself as a developer of sites, expecting the market for deepwater floating platforms to be established before the end of the decade.

Iberdrola Flottek –TLP

The Spanish company Iberdrola is developing two TLP variants to be used with a 2MW and 5MW wind turbines (see Figure 50). Two different designs with a scale of 1/35 and 1/40, respectively as well as two innovative installation systems for these offshore structures, consisting of a barge-pontoon and float mechanism were tested (URL 4). It is claimed by the company that it can be even used in shallow water depths.

Figure 50. Two TLP designs by Iberdrola

Gicon SOF – TLP

Using the Tension Leg Platform (TLP) approach, GICON SOF Floating Offshore Foundation (see Figure 51) is a floating, load-bearing structure for offshore wind turbines with numerous advantages over conventional foundations such as monopiles, gravity foundations and jackets. It can also be deployed in shallow water depths, which makes it a viable alternative to other floating foundations (URL 5).

- Deployable in water depths of 20 meters to 350 meters
- Low manufacturing costs
- Able to be completely assembled in port and therefore not reliant on favorable weather conditions.
- Towable as a complete unit (including turbine) from port-side assembly location to deployment site
- Collision-friendly
- Lower geotechnical demands on seafloor
- Maintenance-friendly
- If required, entire structure is interchangeable

- Supports small-to-medium sized supply-chain companies via modular construction method

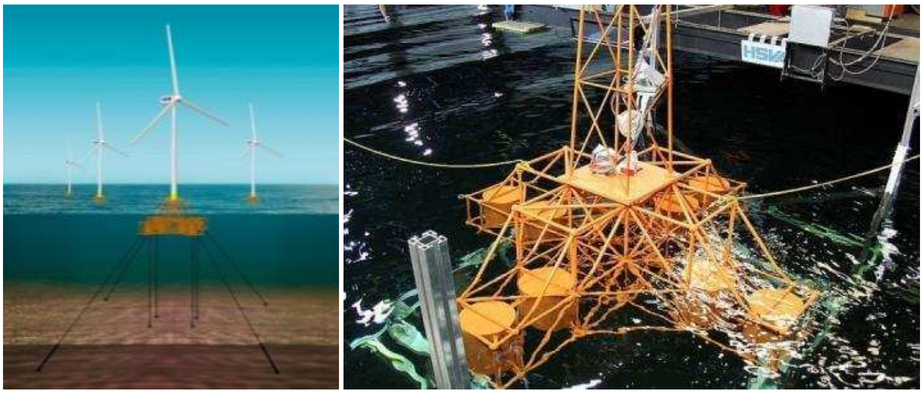


Figure 51. Gicon SOF Floating offshore foundation concept (URL 5)

A full-scale pilot of the GICON SOF will be constructed in 2013/2014 and installed in the German Baltic Sea in 2014.

Ideol Platform

IDEOL platform (see Figure 52) is a ring-shape surface floater with shallow draught and very compact dimensions. Thanks to the exceptional dynamic behavior of the Damping Pool system developed and patented by IDEOL, the floating foundation is compatible with any commercial offshore wind turbines without modification (URL 6). Based on a construction in concrete, the IDEOL solution can scale to mass production for very large wind farms, with on-site construction, high local content and versatile construction methods, depending on site conditions and local procurement options (URL 6).

Thanks to its reduced cost, the IDEOL floating foundation is competitive with bottom-fixed ones starting from 35 meters water depth. It has been designed following the highest safety standards and relies exclusively on offshore oil and gas industry proven and qualified components (URL 6).

Figure 52. Ideol floating foundation by Ideol Offshore (URL 6)

IDEOL is currently working with partners on the construction and installation of two commercial scale demonstrators in 2014 (EWEA, 2013).

Middelgrunden offshore wind farm – gravity base foundation

The developer is Middelgrunden Vindmollelaug, Kobenhavns Energy, Copenhagen, Denmark. The farm consists of 20 turbines emplaced in a large arc of 3.4 km in length with turbines spacing of 172 m. The project has a rating of 40 MW using the 2 MW Siemens SWT-2.0-76.

The energy production potential is 85 GW.hr/year. The construction lasted over the period June 2000 – December 2000. The Middelgrunden offshore wind farm was the largest offshore wind farm at the time of its completion. The turbines were assembled onshore in three parts then floated to their foundations where they were erected with cranes fitted to a jack up barge (URL 19)

Figure 53. Middelgrunden offshore wind farm Denmark

London Array – monopile foundation

As the offshore wind farm industry sets new requirements to the design practice, recent experience has led to new and innovative solutions for specific components such as the grouted connection. These solutions are implemented in the COWI design, which reflects the most recent knowledge developed within monopile foundation design. These designs are certified by DNV. As lead designer on the largest offshore wind farm in the world, the 630 MW London Array offshore wind farm, COWI has now taken the lead in the design of monopile foundations. The London Array offshore wind farm comprises 175 monopile foundations in water depths varying from 0 to 25 meters in different soil conditions. The piles have a 4.7 meter or 5.7 meter diameter, and the foundations attain total lengths of up to 85 meters. The London Array foundations were designed in a COWI lead joint venture with IMS for Aarsleff-Bilfinger|Berger JV (URL 20, 21).

Alpha Ventus wind farm – Tripod and Jacket foundation

Alpha Ventus was commissioned as the first German offshore wind farm in April 2010. The construction phase proper was a brief 12 months, a pioneering feat in a location with a water depth of about 30 meters and a distance from the coast of 60 kilometers. The Alpha Ventus offshore wind farm is located in the open sea of the Exclusive Economic Zone (EEZ) of the Federal Republic of Germany (URL 22)

Reflecting its role as offshore test site, Alpha Ventus operates two types of wind turbines (WT) with two different foundation designs, namely, tripod and jacket foundation. The rated output of the wind farm is 60 MW. Experience gained in construction and operation is an input into the further development and expansion of the German offshore wind power industry.

Figure 54. Tripod and jacket foundations used in Alpha Ventus wind farm

SeaTower's Cranefree foundations – *Gravity base foundation*

Cranefree Gravity (CFG) foundations (see Figure 55) developed by Seatower enable low total project costs. This is particularly due to the efficient deployment method: Tow the foundation to site, lower it to the seabed by water ballasting, inject concrete under the foundation, and pump sand into it. Onsite installation requires weather windows of only 12 hours, and can be done in up to 2 m significant wave height (Hs). Weather delays are thereby reduced by up to 80%. Only standard equipment (towing vessels) is used, which is inexpensive and readily replaced if required. Furthermore, the concept requires no dredging or pile hammering. The foundations are made of a combination of concrete and steel (URL 7).

Figure 55. Cranefree Gravity (CFG) foundation

1. Prefabrication of steel

The possibility of doing prefabrication at fabrication yards anywhere in the world can have a significant impact on the total project cost. The steel parts are designed in sections that can be efficiently transported and assembled (URL 7, 8)

2. Construction

The construction can be undertaken in harbors available for instance along the coasts of the North Sea Basin. A draft of only 5-6 m and limited land areas are required. The CFG concept favors local content, which can be important for the project. Load out can be done in several ways, but always cost-efficiently – without the need of a heavy-lift crane vessel (URL 7, 8)

3. Transportation and installation

Towing can take place in up to 5 m wave height (Hs). The weather windows needed for the on-site installation are only 12 hours of up to 2 m Hs. This means reduced weather downtimes, and thereby reduced risk of project delays. Avoiding large crane vessels and jack up barges saves money and removes a number of major risks related to such vessels – for instance the risk of sudden unavailability of the vessel during a project (due to breakdown, contractual issues or other). Should delays occur anyway, the project can catch up simply by deploying additional towing vessels. CFG foundations require no dredging, pile hammering or other seabed preparations. Piling and dredging are increasingly being restricted to protect the environment (URL 7, 8).

4. Operation

Similar gravity structures have been used for almost 40 years in the North Sea and elsewhere. These foundations are many times bigger than Cranefree Gravity foundations. This track record means that teething problems have been tackled previously. Even though the concept is innovative, the engineering is proven and well understood. There is no maintenance required during the operational phase (URL 7, 8).

5. Decommissioning

Decommissioning is achieved by a reversal of the installation process, using towing vessels only. No parts of the foundation are left behind at the installation site (URL 7, 8).

High-Rise Pile Cap (HRPC) foundations

While considered by some not to be truly offshore foundation types – do have a relatively high share of the market, at 11.5% of the operational projects. HRPC is a derivative of an onshore foundation type and is limited to soft soils and shallow waters. This type of foundation has especially been preferred in the mud flats of China, while its future application is limited by the number of suitable offshore sites (WEU 2013).

Furthermore, *Carbon Trust Offshore Wind Accelerator (OWA)* ran a global competition in 2009 in order to identify innovative, cost-effective, and robust foundation designs that could be used for the challenging conditions that will be encountered in UK Round 3 projects: water depths of 30-60m, complex soils, and harsher metocean conditions. Their competition attracted more than 100 entries from all over the World, from leading civil engineers and naval architects to marine experts in the oil and gas industry. As a result of a two-stage selection process, the following concepts were selected and it has been planned that these concepts will be demonstrated at full-scale by the OWA Partners. They have the potential to reduce the total cost of foundations in a wind farm by as much as 30% (URL 9)

Universal Foundations - Suction bucket monopile

The Bucket Foundation (see Figure 56) is a unique concept and quality proven hybrid design which combines the main recognized aspects of a gravity base foundation, a monopile, and a suction bucket. The Bucket foundation is said to be “universal”, thus it can be applied to and designed for various site conditions (URL 10).

1. Structure
    - Less steel, simple welds
    - Suitable for 30-60m

2. Installation
    - Fewer offshore operations and smaller vessels and equipment
    - Simpler installation as foundation towed to site
    - No piling
    - Less scour protection required
    - Potential to be cheaper than jackets due to its elegant installation method

3. Decommissioning
    - Easier to retrieve for decommissioning

Figure 56. Universal foundation (URL 11)

KeyStone - Innovative Jacket

1. Structure (URL 9)
   - Twisted jacket uses less steel vs. conventional jackets
   - Elegant engineered transition piece
   - Uses innovative composite materials
   - Proven in Hurricane Katrina
   - Suitable for 30-60m

2. Installation (URL 9)
   - Faster installation time
   - Fewer installation maneuvers
   - No driving template required
   - Improved utilization of deck space increases transportation efficiency

The Keystone 'twisted jacket' prototype foundation (see Figure 57 and Figure 58) was successfully installed at SMart Wind's Hornsea site in October 2011 to support a met mast. The design is 20% lighter than optimized jackets and simpler to fabricate. In 2013 and 2014, it may be demonstrated with ideally 5 MW+ turbines, in water depth of 30m+, and North Sea metocean conditions (URL 9, URL 11).

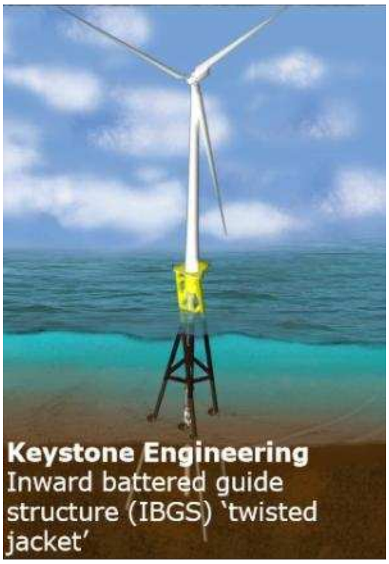


Figure 57. Keystone innovative twisted jacket (URL 10)

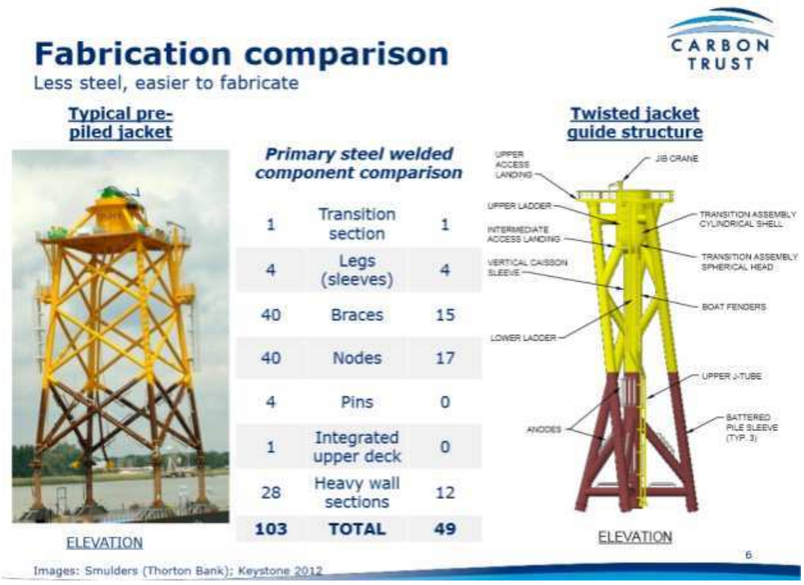


Figure 58. Fabrication comparison of KeyStone innovative jacket and typical jacket foundations (URL 12)

Gifford/BMT/Freysinet – Gravity structure

The GBF Integrated Solution for Offshore Wind Turbines (Figure 59) avoids many of the supply chain hot-spots and inefficiencies of other methods. Previous methods involved jack-up barges and floating cranes, which are costly and in short supply. This solution minimizes offshore operations and maximizes onshore assembly works, thus improving safety and quality, whilst enhancing productivity and surety of delivery as less of the process is weather dependent (URL 13).

1. Structure (URL 9, 13)
   - Slipforming stem – reduces production time
   - Mass fabrication process developed
   - Concrete prices less variable than steel
   - Suitable for 30-45m

- Suitable for a wide range of sea bed soil conditions

2. Installation (URL 9, 13)
    - Cheaper, bespoke unmanned vessel transports structure to wind farm
    - Entire foundation / turbine structure may be transported

3. Decommissioning (URL 9, 13)
    - Structure easy to de-ballast and remove

Figure 59. Gifford BMT Fretssinet solution (URL 12).

SPT Offshore & Wood Group: Tribucket

1. Structure (URL 9, 14)
    - Self-installing tribucket
    - Entire foundation / turbine structure assembled in port
    - Suitable for 30-60m

2. Installation (URL 9, 14)
    - Entire foundation / turbine structure transported to wind farm
    - Standard marine equipment
    - No piling or drilling

In early 2012, SPT Offshore successfully installed the Hong Kong Met Mast.

Figure 60. SPT Offshore self-installing wind turbine (URL 15)

2.7.2 Prototypes developed in wave energy sector

Wave power devices extract energy directly from the surface motion of ocean waves or from pressure fluctuations below the surface. Through time several concepts to extraction of energy from waves have been invented and developed. More than 100 concepts are globally in varying levels of development and several are in demonstration phases, so in this section only has been analyze the main wave converters.

The foundation concepts for wave energy converters are very similar to the concepts that are previously described for wind energy. For example, the wave energy converter in Figure 61 is fixed to the seabed with a gravity base foundation. An overview of different foundation options for wave energy converters is given in Table 23.

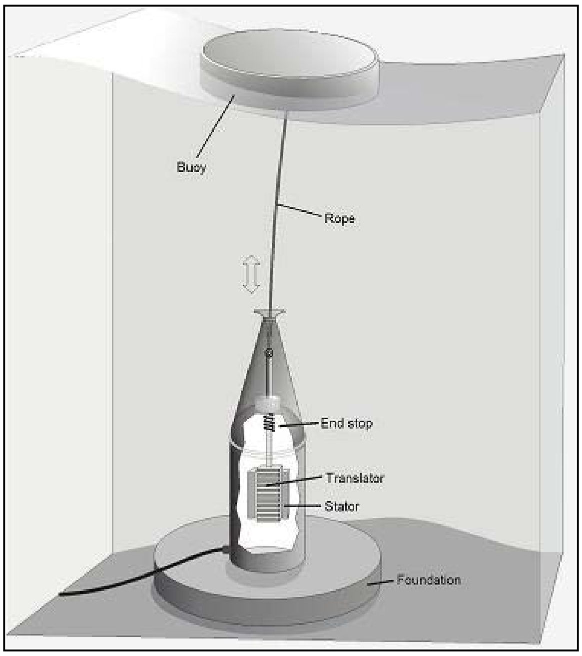


Figure 61. Wave energy converter bottom-mounted by a gravity base structure (URL 17)

	Monopile	Spread-legged structure	Jacket	GBS	Semi-submersible
Water depth	< 10 m	< 15 m	< 50 m	> 50 m	< 40 m
Assembly	driven piles	driven piles	heavy lift vessel	heavy lift vessel	float-over barge
Advantages	low cost fabrication	low cost fabrication	well known offshore structure	long life-cycle	easy assemble and disassemble
Disadvantages	depth limited by 10 m	depth limited by 15 m	heavy welding necessary	seabed preparation necessary	only suitable in deep waters

Table 23. Overview of different foundation options for wave energy converters (modified from Stallard et al., 2010)

Next a more detailed review of some of the most innovative concepts is shown.

Pelamis Technology (Pelamis Wave Power)

Pelamis is an offshore wave energy converter that uses the motion of waves to generate electricity. The machine operates in water depths greater than 50m and is typically installed 2-10km from the coast.

The machine is rated at 750kW with a target capacity factor of 25-40 per cent, depending on the conditions at the chosen project site. On average one machine will provide sufficient power to meet the annual electricity demand of approximately 500 homes (see Figure 62).

Pelamis Wave Power have produced six full-scale Pelamis machines to date, including two of the latest 'P2' design machine, built for utility customers E.ON and ScottishPower Renewables.

Figure 62. Pelamis wave energy converter (Source: Pelamis Wave Power)

The Pelamis machine is made up of five tube sections linked by universal joints which allow flexing in two directions. The machine floats semi-submerged on the surface of the water and inherently faces into the direction of the waves. As waves pass down the length of the machine and the sections bend in the water, the movement is converted into electricity via hydraulic power take-off systems housed inside each joint of the machine tubes, and power is transmitted to shore using standard subsea cables and equipment. (See Figure 63).

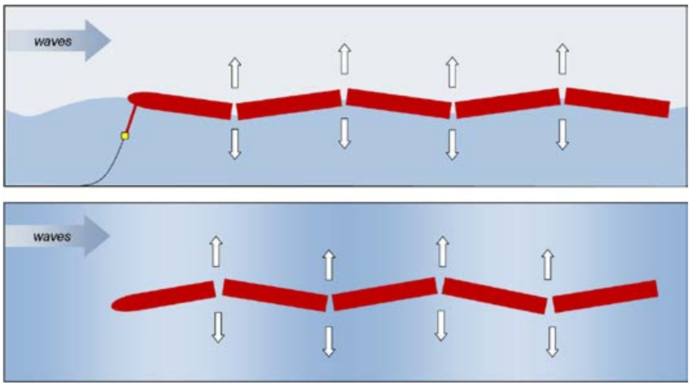


Figure 63. Pelamis wave energy converter (Source: Pelamis Wave Power)

Each of the power take-off units at the joints of the machine are identical, and operate independently from each other with redundancy of all main components.

Project boundary markers, as stipulated by the governing navigational authority, will need to be installed prior to Pelamis associated equipment in order to delineate the area to be avoided by marine traffic. Usually cardinal marker buoys are the standard method to mark out the boundaries of offshore renewable projects.

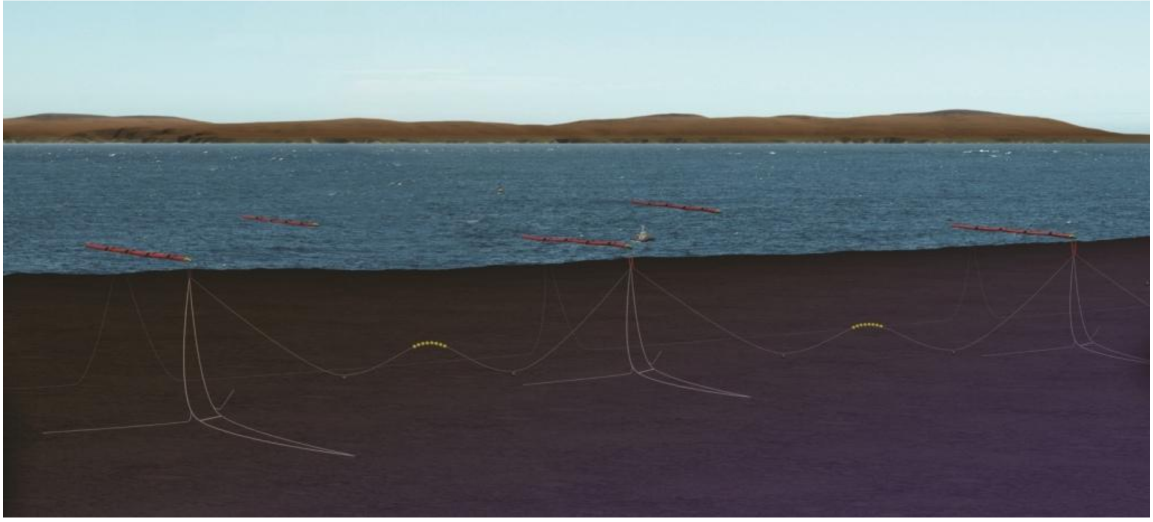


Figure 64. Pelamis wave energy converter and the mooring System (Source: Pelamis Wave Power)

Each machine requires its own individual mooring spread consisting of the main moorings and a yaw restraint line. The main moorings consist of a number of anchors connected to a central point. The yaw restrain line is a simple single anchor and mooring line configuration. The majority of components in the mooring system are standard, off-the-shelf equipment commonly used in the oil & gas and shipping industries. (See Figure 64).

There is scope for neighbouring mooring spreads to share anchor points, depending on the anchoring techniques employed at the site. The Pelamis mooring spread has been designed to minimise its footprint area, allowing the highest concentration of MW capacity to seabed space and reducing infrastructure costs (on a typical site approximately 15MW of generating capacity could be installed within 1km2).

A power export cable is required to take the power from site to shore. The export cable is laid by contracted cable installers in the manner and route identified in the development and specification stage (note larger projects may require more than one power export cable). From each array of Pelamis machines a dynamic down feeder cable connects to the export cable, with the machines in the array connected together via dynamic inter-connector cables. The dynamic cables are installed after the mooring spreads are complete and are then connected to the export cable. This split allows the export cable to be installed ahead of the other offshore infrastructure, in turn allowing work on the onshore sub-station to be conducted in parallel with the offshore work. Once connected, the subsea cable network can be commissioned and tested for integrity from the substation, prior to machine installation.
The machine is connected to its anchoring and electrical infrastructure through a patented latching system located at the end of a mooring yoke. This system allows the machine to be quickly, easily and safely connected and disconnected from its subsea infrastructure. This connection/disconnection of the Pelamis machine is a routine operation conducted as part of a normal operations and maintenance programme, and is discussed in more detail under 'Operations & Maintenance'.

OPT PB150 PowerBuoy (Ocean Power Technologies)

The PB150 PowerBuoy, developed and manufactured by Ocean Power Technologies, Inc. (OPT), is a utility-scale clean energy device peak-rated at150 kilowatts. The PB150 is modular, and can be configured in arrays of 50-100 MW or more, using OPT's proprietary Undersea Substation Pod (USP) to combine the power from multiple buoys. (See Figure 65). Table 24 shows the PB150 specifications.

Figure 65. OPT Buoy (Source: Ocean Power Technologies)

Peak Generator Rating /Max. Daily Avg.	**866 kW / 150 kW**
Capacity factor (range)	**30% -45%**
Overall Length	**144 ft.**
Height above waterline	**29.5 ft.**
Float diameter	**36.1 ft.**
Weight	**150 tons**
Design life	**25 years**
Output Voltage & Frequency	**600 V at 60 Hz** **575 V at 50 Hz**
Power Factor:	**± 0.9**
Mooring	**Three-point**
Deployment	**Tow-out with standard tug**
Wave height (range for normal operation)	**1 to 6 meters**
Water depth (min)	**55 meters**

Table 24. OPT Buoy Characteristics (Source: Ocean Power Technologies, 2012)

A PB150 wave park consists of the PowerBuoys, a USP, and the transmission cable to shore (see Figure 66). Up to ten PB150 PowerBuoys can be connected to each USP. The PowerBuoy creates electricity from the vertical motion of the float relative to the stationary spar. This motion drives a mechanical system coupled to generators and produces AC electricity. The electricity is rectified and inverted into grid-compliant AC, which has been certified to international interconnection standards.

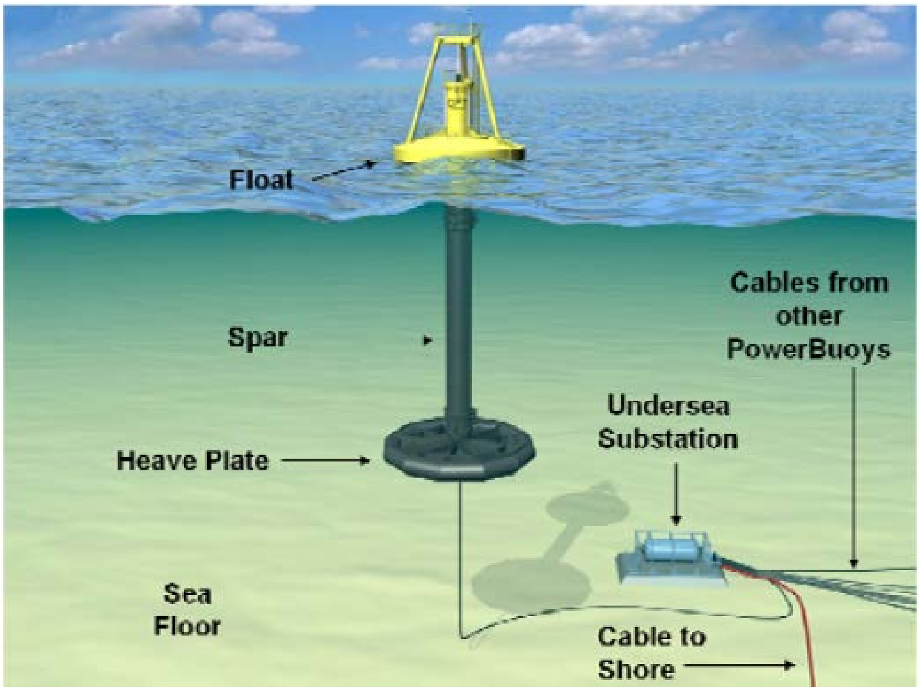


Figure 66. PB150 Power Buoy System (moorings not shown). (Source: Ocean Power Technologies).

The PB150 PowerBuoy, developed and manufactured by Ocean Power Technologies, Inc. (OPT), is a utility-scale clean energy device peak-rated at150 kilowatts. The PB150 is modular, and can be configured in arrays of 50-100 MW or more, using OPT's proprietary Undersea Substation Pod (USP) to combine the power from multiple buoys.

OPT's PowerBuoy technology is environmentally benign, having received the highest environmental rating of a Finding of No Significant Impact ("FONSI") in Hawaii and a similar preliminary finding in Oregon.

The ability to predict wave energy up to 72 hours in advance allows utilities to integrate OPT wave energy with their existing fossil and renewable resource portfolios. The PB150 has been tested in the harsh environment of the North Sea, producing power of over 45 kW in wave heights as low as two meters. The core technology in the PB150 was ocean-tested for over a year in Hawaii, including the first-ever grid connection of a wave energy device in North America. The PB150 structure and 3-point mooring system have been certified by Lloyd's Register, and PowerBuoys have been insured by Lloyd's syndicates for over 13 years. Figure 67 shows the main dimensions of PB150 Power Buoy.

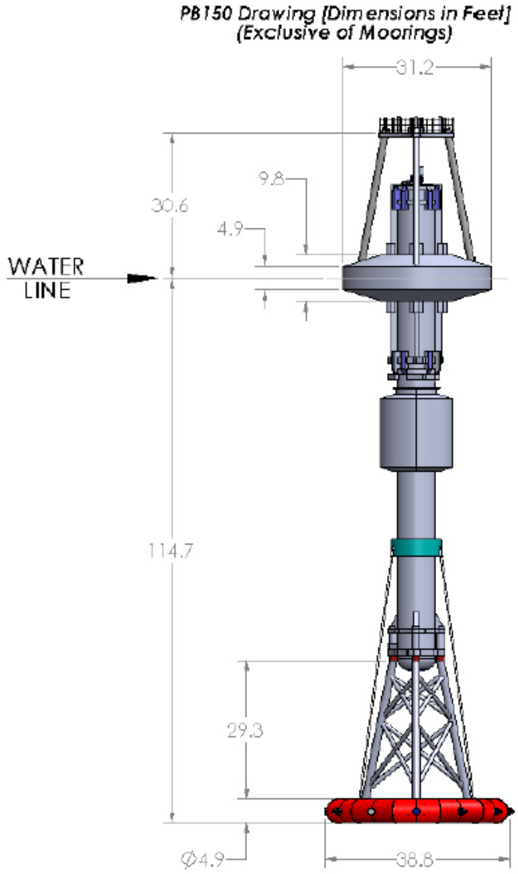


Figure 67. OPT Buoy Dimensions (Source: Ocean Power Technologies, 2012)

OYSTER Wave Power (Aquamarine Power, 2003)

Aquamarine Power's Oyster wave power technology captures energy in near shore waves and converts it into clean sustainable electricity. Essentially Oyster is a wave-powered pump which pushes high pressure water to drive an onshore hydro-electric turbine. (See Figure 68 and Figure 69).

Wave power is generated by wind blowing over the surface of the ocean far out at sea. The action of the wind transmits energy into waves. These waves can travel vast distances with little energy loss before breaking on the shore. Our Oyster device is designed to harness this energy and convert it into electricity.

Figure 68. OYSTER Wave Power. (Source: Aquamarine Power)

Figure 69. OYSTER Wave Power. (Source: Aquamarine Power)

The Oyster wave power device is a buoyant, hinged flap which is attached to the seabed at depths of between 10 and 15 meters, around half a kilometer from the shore. This location is often referred to as the near shore.

Oyster's hinged flap, which is almost entirely underwater, pitches backwards and forwards in the near shore waves. The movement of the flap drives two hydraulic pistons which push high pressure water onshore via a subsea pipeline to drive a conventional hydro-electric turbine.

In the future, subsea pipelines will connect multiple Oyster wave energy devices to a single onshore plant. Ultimately Oyster will be installed in wave farms of several hundred connected devices generating hundreds of megawatts of electricity.
By locating Oyster in the near shore, we are able to capture a high proportion of the energy available in the ocean whilst avoiding the severe storms which occur further out to sea.
The milestones of the Oyster device are:

- 2003: Scale model testing of Oyster begins.
- 2005: Aquamarine Power established to commercialize Oyster.
- 2008: Fabrication of first full-scale Oyster 1.
- 2009 - 2011: Oyster 1 sea trials.
- 2011: Fabrication of Oyster 800.
- 2012: Oyster 800 sea trials commence.

WAVESTAR (Wave Star, 2011)

The Wavestar machine draws energy from wave power with floats that rise and fall with the up and down motion of waves. The floats are attached by arms to a platform that stands on legs secured to the sea floor. The motion of the floats is transferred via hydraulics into the rotation of a generator, producing electricity.

In 2009 a prototype test section was installed at Hanstholm. The Wavestar prototype is a 2-float section of the full 20-float machine (see Figure 70). Table 25 shows the difference between the Hanstholm prototype and the commercial Webstar.

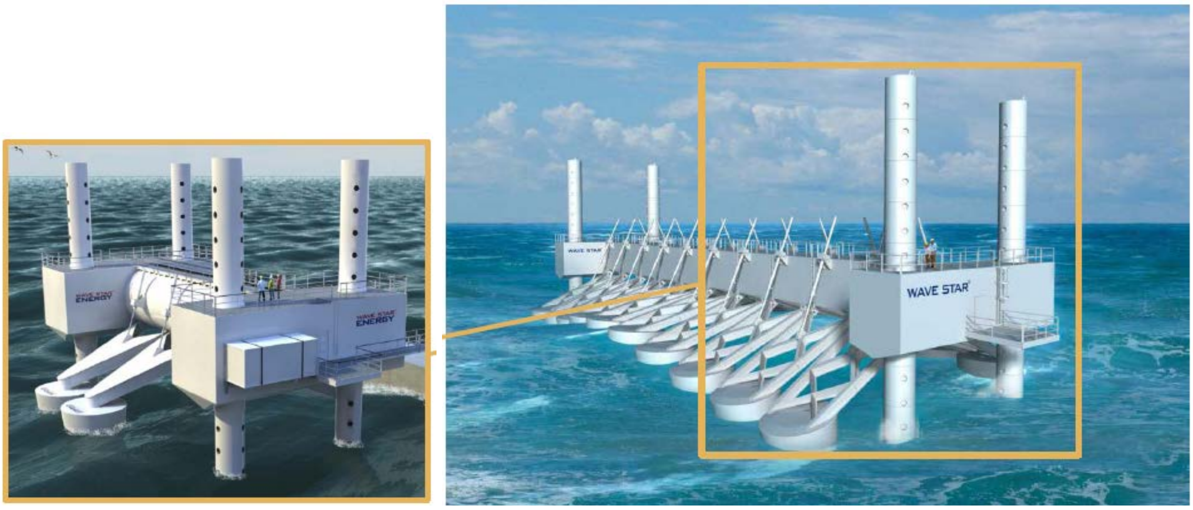


Figure 70. Wavestar platform. (Wave Star, 2011)

PARÁMETER	Hanstholm prototype	Comercial Wavestar 0.6 MW
Number of floats	**2**	**20**
Float diameter	**Φ5 m**	**Φ5 m**
Arm length	**10 m**	**10 m**
Weight	**1000 ton**	**1600 tn**
Nominal electrical power	**110 kW**	**600 kW**

Table 25. Wavestar parameters. (Wave Star, 2011)

In general there have been no major problems with the design of the prototype. All structural and mechanical components in the WEC have proven functionality as intended. The WEC has survived two large storms with no damages and no service afterwards. Only minor design faults with the float design, the jacking-system, and some electrical problems have been identified and corrected (See Figure 71).

Figure 71. Performance history of the Wavestar prototype at Hanstholm (Source: Wave Star, 2013)

This machines are available to be installed in synergy with wind turbines (see Figure 72).

Figure 72. Wavestar machines in synergy with wind turbines

2.7.3 Prototypes developed in tidal energy sector

Tidal energy is one of the most relevant technologies associated to the sea energy conversion. This type of energy encompasses two different technologies: the traditional power plants and those based on tidal streams).
The tidal energy is the energy stored by the ocean due to the tides produced by the combination of different effects:

- The gravitational effect of the Sun and the Moon
- The Earth's rotation
- Other factors, such as different ocean depths at different places, odd shapes of the continents, Earth tilt, etc.

Depending on the location, tides can be considered as the longest sea waves, with high periods (12-24 hours) and wavelengths comparable to the length of the Earth's equator circumference.
Considering the different ways of using this type of energy, the technologies are classified in the following way (Buigues et al., 2006):

- Traditional Tidal Power Plants
- Tidal Streams Power Plants

In this section, the focus will put on the tidal stream power plants.

Tidal stream energy presents one of the most exciting emerging forms of renewable energy. Tidal streams, unlike many other forms of renewable energy, are a consistent source of kinetic energy caused by regular tidal cycles influenced by the phases of the moon. Intermittency is a problem for wind, wave and solar power as the sun doesn't always shine and the wind doesn't always blow. These sources of renewable energy often require backup from traditional forms of power generation. However, the inherent predictability of tidal power is highly attractive for grid management, removing the need for backup power from back-up plant powered by fossil fuels. Tidal turbines are installed on the seabed at locations with high tidal current velocities, or strong continuous ocean currents and extract energy from the flowing water (Marine Current Turbine).

For tidal energy converters three main foundations exist: Gravity based foundation, Mid-weight tripod anchored foundation and the Mono-/ Multi-pile foundation. Table 26 gives a brief overview of the different foundation options for tidal energy converters and their requirements.

	Gravity based structure	Mid-weight tripod anchored support structure	Mono/ Multi-pile support structure
Water depth	deep water	deep water	< 30 m
Installation time	long	short	short
Installation costs	low	low	high
Maintenance costs	high	moderate	low
Large-scale farm development	difficult	possible	feasible

Table 26. Overview of the main support structures for tidal energy converters (modified from Stallard et al., 2010)

Below some of the tidal energy converters are analyzed.

SEAGEN (Marine Wind Turbines)

The SeaGen S 1.2MW commercial demonstrator has been developed on the basis of results obtained from SeaFlow, the world's first full-size tidal turbine installed by Marine Current Turbines off Lynmouth Devon in 2003. It has taken the subsequent four years for Marine Current Turbines to design and build SeaGen and secure the necessary environmental and planning consents (See Figure 73).

Figure 73. Seagen generator (Source: Alternative Energy, 2007, MetaEfficient, 2008).

SeaGen S is a commercial demonstration project with permission to operate in Strangford Lough for a period of up to 5 years. It is intended as the prototype for commercial applications of the technology that will follow.

The 1.2MW SeaGen S system is capable of delivering up to 10MWh per in Strangford, which totals up to 6,000MWh per year. This is approximately the rate of energy capture of a 2.4MW wind turbine. Tidal energy is therefore more predictable than wind and potentially twice as productive. (Source: Marine Wind Turbines). SeaGen will be the world's largest ever tidal current device by a significant margin, and will generate clean and sustainable electricity for approximately 1000 homes. It is also a world first in being a prototype for commercial technology to be replicated on a large scale over the next few years (Alternative Energy, 2007)

SeaGen S, is composed of a surface piercing tower, with a cross beam and twin power trains. The system has been subject to 3 years of rigorous engineering testing and analysis. SeaGen U, a non-surface piercing system is being developed for deeper water sites, this will use the same power trains developed for SeaGen S which has undergone extensive testing, but will utilise a different support structure. Design and testing of the SeaGen U support structure is currently underway.

Open Centre Turbine (Open Hydro)

The Open-Centre Turbine is designed to be deployed directly on the seabed. Installations will be silent and invisible from the surface and they will be located at depth water (See Figure 74). The blade tips are retained within the outer housing which clearly defines the moving component and the turbine is designed to generate energy at a slow rotational speed. (Source: Open Hydro, a DCNS company).

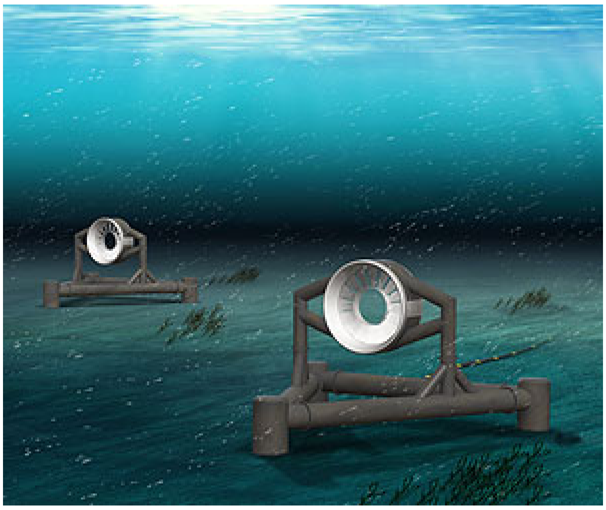


Figure 74. Open Centre Turbine (Source: Open Hydro)

The Open-Center Turbine generates electricity via a solid state permanent magnet generator encapsulated within the rim. The Open-Center Turbine includes an only one moving part and has a low manufacture cost (Open Hydro, a DCNS company).

2.8 Identified synergies with the other projects

There are currently several projects underway across Europe. All of these projects have a common objective to reduce greenhouse gas emissions and increase the proportion of energy consumption produced by renewable energy.

SI OCEAN

The Intelligent Energy Europe project, Strategic Initiative for Ocean Energy (acronym SI Ocean), has officially started on 23 June 2012. The project is coordinated by the Association in close cooperation with 6 partners: The European Commission's Join Research Centre, the UK Carbon Trust, Portugal's Wave Energy Centre, Edinburgh University, Renewable UK and the Danish Hydrological Institute. The goal of this project is to engage a large number of European stakeholders to identify practical solutions to removing a range of barriers to large scale wave and tidal energy deployment. A key focus will be on increasing participation and input from the commercial sector, namely utilities, large industrial organizations and technology developers. Their expertise and practical experience will build on the knowledge already cultivated by research centers and academic institutions. More information about the project can be found at http://www.si-ocean.eu/.

MARINET

Marine renewable energy systems – wave energy and tidal-stream converters as well as offshore-wind turbines for electricity generation – are mostly at the pre-commercial stage of development. These systems require research and testing to be undertaken at a series of scales and specialized facilities along the path to commercialization. MARINET (Marine Renewable Infrastructure Network) is an EC-funded infrastructure initiative comprising a network of research centers and organizations that are working together to accelerate the development and commercial deployment of these technologies. The initiative aims to streamline and facilitate testing by offering periods of free-of-charge access to world-class test facilities and by developing joint approaches to testing standards, research and industry networking & training. More information about the project can be found at http://www.fp7-marinet.eu/.

SOWFIA

This project, coordinated by the University of Plymouth, aims to achieve the sharing and consolidation of pan-European experience of consenting processes and environmental and socio-economic impact assessment (IA) best practices for offshore wave energy conversion developments. Studies of wave farm demonstration projects in each of the collaborating EU nations are contributing to the findings. The study sites comprise a wide range of device technologies, environmental settings and stakeholder interests. The overall goal of the SOWFIA project is to provide recommendations for approval process streamlining and European-wide streamlining of IA processes, thereby helping to remove legal, environmental and socio-economic barriers to the development of offshore power generation from waves. The project has officially started on October 1, 2010 and will end on September 30, 2013. More information about the project can be found at http://www.sowfia.eu/.

TROPOS

TROPOS is a European collaborative project which aims at developing a floating modular multi-use platform system for use in deep waters, with an initial geographic focus on the Mediterranean, Tropical and Sub-Tropical regions, but designed to be flexible enough so as to not be limited in geographic scope. TROPOS gathers 19 partners from 9 countries (Spain, the United Kingdom, Germany, Portugal, France, Norway, Denmark, Greece and Taiwan), under the coordination of

PLOCAN. Thanks to its different modules, the floating platform system will be able to integrate a wide range of possible sectors: ocean renewable energy and food (aquaculture) resources will be exploited, the platform will serve as a hub for maritime transport and innovations in the leisure sector, and will also fulfill functions for oceanic observation activities. The platform will be composed of a central unit and functional modules**,** in particular the floater concept (submersible, floating or deep submersible units), that will be adapted to each area where it is implemented. Nevertheless, one conceptual design basis will be developed for all versions of the platform. The Project has officially started on February 1, 2012 and will continue until January 31, 2015. More information about the project can be found at http://www.troposplatform.eu/.

H2OCEAN

H2OCEAN - Development of a Wind-Wave Power Open-Sea Platform Equipped for Hydrogen Generation with Support for Multiple Users of Energy - is a project aimed at developing an innovative design for an economically and environmentally sustainable multi-use open-sea platform. Wind and wave power will be harvested and part of the energy will be used for multiple applications on-site, including the conversion of energy into hydrogen that can be stored and shipped to shore as green energy carrier and a multi-trophic aquaculture farm. The unique feature of the H2OCEAN concept, besides the integration of different activities into a shared multi-use platform, lies in the novel approach for the transmission of offshore-generated renewable electrical energy through hydrogen. This concept allows effective transport and storage of the energy, decoupling energy production and consumption, thus avoiding the grid imbalance problem inherent to current offshore renewable energy systems. H2OCEAN started its activities on the 1st of January, 2012 and will end on the 31st of December, 2014. More information about the Project can be found at http://www.h2ocean-project.eu/.

DEMOWFLOAT

Funded by FP7 of the European Commission, the objective of the DEMOWFLOAT project is to demonstrate the long term Windfloat performance, operationality, maintainability, reliability, platform accessibility, feasible grid integration on a modular basis, among several other aspects with an impact on availability of the system and, therefore, on the cost of produced energy. WindFloat enables harnessing wind power at sea in deep water (depths greater than 40 m) for conversion to clean renewable electrical energy. This prototype project is located 6 km offshore Póvoa de Varzim (Portugal), at a depth of about 42 m. The closest villages are Aguçadoura and Apúlia. Project started in October, 2009 and will end likely to be end of 2013. More information about the project can be found at http://www.demowfloat.eu/.

MARINA Platform

Research in the MARINA Platform project will establish a set of equitable and transparent criteria for the evaluation of multi-purpose platforms for marine renewable energy (MRE). Using these criteria, the project will produce a novel, whole-system set of design and optimization tools addressing, inter alia, new platform design, component engineering, risk assessment, spatial planning, platform-related grid connection concepts, all focused on system integration and reducing costs. These tools will be used, incorporating into the evaluation all, presently known proposed designs including (but not limited to) concepts originated by the project partners, to produce two or three realizations of multi-purpose renewable energy platforms. These will be brought to the level of preliminary engineering designs with estimates for energy output, material sizes and weights, platform dimensions, component specifications and other relevant factors. This will allow the resultant new multi-purpose MRE platform designs, validated by advanced modeling and tank-testing at reduced scale, to be taken to the next stage of development, which is the construction of pilot scale platforms for testing at sea. The project has officially started in January, 2010 and will end in June, 2014. More information about the project can be found at http://www.marina-platform.info/.

HiPRWind Project

HiPRWind is the largest offshore wind R&D project funded by the EU Framework Programmes in terms of budget. It is focused on developing very large floating wind systems that may unlock cost-efficient renewable energy production from deep water areas all around the world. he project consortium brings together a strong team of European partners from large industry, SME's, applied R&D Centers and Universities, and is led by the Fraunhofer Institute for Wind Energy and Energy System Technology. It started in November 2010 as a part of the EU 7th Framework Programme for energy research and will end in November, 2015. More information about the project can be found at http://www.hyperwind.eu/.

UPWIND Project

UpWind was a European project funded under the EU's Sixth Framework Programme (FP6) that ran from 2006 to 2011. The project looked towards the wind power of tomorrow, more precisely towards the design of very large wind turbines (8-10MW), both onshore and offshore. UpWind is focused on design tools for the complete range of turbine components. It addressed the aerodynamic, aero-elastic, structural and material design of rotors. Critical analysis of drive train components was carried out in the search for breakthrough solutions. The UpWind consortium, composed of 40 partners, brought together the most advanced European specialists of the wind industry. The findings of the project were disseminated through a series of workshops. More information about the project and final reports can be found at http://www.upwind.eu/.

PolyWEC project

PolyWEC investigates on new concepts and mechanisms for wave energy harvesting that are based on Electroactive Elastomer (EEs) through a multidisciplinary approach that includes competencies on WEC design/tests, fluid dynamics simulation/test, control/mechatronics and material science. The aim of the Project is to develop new knowledge and new technologies aiming at:

- Optimising EE materials for WEC applications,
- Conceiving new electro-mechanical configurations for PolyWECs,
- Studying the fluid-EE interaction through numerical simulations,
- Performing wave-tank tests of small scale prototypes,
- Providing economic and environmental assessment.

The project started on November 1, 2012 and will end on October 31, 2016. More information about the project can be found on http://www.polywec.org/.

ORECCA - Off-shore Renewable Energy Conversion platforms

The objectives of the project are to create a framework for knowledge sharing and to develop a research roadmap for activities in the context of offshore renewable energy (RE). In particular, the project will stimulate collaboration in research activities leading towards innovative, cost efficient and environmentally benign offshore RE conversion platforms for wind, wave and other ocean energy resources, for their combined use as well as for the complementary uses.
Duration: 03/2010 - 08/2011 (18 months)
http://www.orecca.eu/web/guest;jsessionid=60A614C5A41C67E83AC98FCF3831E88B

SAFEWIND - Multi-scale data assimilation, advanced wind modeling and forecasting with emphasis to extreme weather situations for a secure large-scale wind power integration

The aim of this project is to substantially improve wind power predictability in challenging or extreme situations and at different temporal and spatial scales. Going beyond this, wind predictability is considered as a system design parameter linked to the resource assessment phase, where the aim is to take optimal decisions for the installation of a new wind farm
Duration: 09/2008 - 08/2012 (48 months)
http://cordis.europa.eu/projects/rcn/87776_en.html

7MW-WEC-BY-11 - Pilot Demonstration of Eleven 7MW-Class WEC at Estinnes in Belgium

This action focuses on demonstrating the development of a cost-effective large scale high capacity wind park using new state-of-the-art multi megawatt turbines coupled with innovative technology used to stabilize the grid. A key objective of the '7-MW-WEC-by-11' project is to introduce a new power class of large-scale Wind Energy Converters, the 7MW WEC, onto the market. The new 7MW WEC will be designed and demonstrated at a large scale: eleven such WECs will be demonstrated in a 77 MW wind park close to Estinnes (Belgium).
Duration: 08/2008 - 08/2012 (48 months)
http://cordis.europa.eu/projects/rcn/90994_en.html

NORSEWIND - Northern Seas Wind Index Database

NORSEWInD is a programme designed to provide a wind resource map covering the Baltic, Irish and North Sea areas. The project will acquire highly accurate, cost effective, physical data using a combination of traditional Meteorological masts, ground based remote sensing instruments (LiDAR & SoDAR) and Satellite acquired SAR winds. The resultant wind map will be the first stop for all potential developers in the regions being examined, and as such represents an important step forward in quantifying the quality of the wind resource available offshore.
Duration: 08/2008 - 08/2012 (48 months)
http://www.norsewind.eu/

PROTEST - PROcedures for TESTing and measuring wind energy systems

The objective of this pre-normative project is to set up a methodology that enables better specification of design loads for the mechanical components. The design loads will be specified at the interconnection points where the component can be "isolated" from the entire wind turbine structure (for gearboxes for instance the interconnection points are the shafts and the attachments to the nacelle frame). The focus will be on developing guidelines for measuring load spectra at the interconnection points during prototype measurements and to compare them with the initial design loads.
Duration: 03/2008 - 08/2010 (30 months)
http://cordis.europa.eu/projects/rcn/86247_en.html

RELIAWIND - Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation.

RELIAWIND consortium, for the first time in the European Wind Energy Sector, and based on successful experiences from other sectors (e.g. aeronautics) will jointly & scientifically study the impact of reliability, changing the paradigm of how Wind Turbines are designed, operated and maintained. This will lead to a new generation of offshore (and onshore) Wind energy Systems that will hit the market in 2015

Duration: 03/2008 - 03/2011 (36 months)
http://cordis.europa.eu/projects/rcn/88411_en.html

TOPFARM - Next generation design tool for optimisation of wind farm topology and operation

The TOPFARM project addresses optimization of wind farm topology and control strategy as based on detailed aeroelastic modeling of loads and power production in a coherent manner. The outcome of the TOPFARM project is a toolbox, consisting of advanced dynamic wake load models, power production models, cost models and control strategy models, and the synthesis of these models into an optimisation tool.
Duration: 12/2007 - 12/2010 (36 months)
http://cordis.europa.eu/projects/rcn/86364_en.html

WAVEPORT (2009-2012)

Demonstration & Deployment of a Commercial Scale Wave Energy Converter with an Innovative Real Time Wave by Wave Tuning System", with the aim to demonstrate a large scale grid connected Powerbuoy Technology.

SEANERGY 2020 (2009-2012)

The objective of the SEANERGY 2020 project is to formulate and to promote concrete policy recommendations on how to best deal with and remove maritime spatial planning (MSP) policy obstacles to the deployment of offshore renewable power generation. LNEG has been participating in this project.

2.9 International design guidelines

2.9.1 Oil & Gas & Shipping guidelines and standards

There is an extensive experience in the oil and gas industry with the design and installation of the foundations/mooring systems for various offshore structures. Several guidelines, rules and regulations have been established to control their designs, which are relatively conservative due to the danger of environmental damage and potential life lost such as:

ABS (American Bureau of Shipping)

ABS provides practical guidelines for the design, construction, operation and maintenance of offshore installations. Table 27 shows the BV guidelines for the Oil and Gas industry.

Reference	Title
ABS	Guide for Building and Classing Facilities on Offshore Installations (Facilities Guide
ABS	Guidance Notes on Reliability Centered Maintenance (2004)
ABS	Guide for Building and Classing Floating Production Installations (FPI Guide
ABS	Rules for Building and Classing Offshore Installations (Offshore Installations Rules)
ABS	Rules for Building and Classing Offshore Installations (Offshore Installations Rules)

Table 27. ABS guidelines for the Oil and Gas industry

Bureau Veritas

BV develops rules and guidelines for the benefits of maritime industry. Table 28 shows the BV guidelines for the shipping industry (Marina platform, 2012).

Reference	Title
NR 183	Towage at sea of vessels or floating units
NI 199	Cyclic fatigue of nodes and welded joints of offshore units
NR 216	Rules on materials and welding for the classification of marine units
NR 266	Survey of materials and equipment at works for the classification of ships and offshore units
NR 320	Certification scheme of materials and equipment for the classification of marine units
NI 422	Type approval of non-destructive testing equipment for the classification of ships and offshore units
NI 423	Corrosion protection of steel offshore units and installation
NR 426	Construction survey of steel structures of offshore units and installation
NI 432	Certification of fiber ropes for deepwater offshore services
NR 445	Rules for the classification of offshore units (offshore rules)
NR 467	Rules for the classification of steel ships (ship rules)
NR 493	Classification of mooring systems for permanent offshore units
NR 494	Rules for the classification of offshore loading and offloading buoys
NI 534	Guidance note for the classification of self-evaluation units
NI 537	commercial ships
NI 539	Spectral fatigue analysis methodology for ships and offshore units
NR 546	survey
NR 578	Rules for the classification of Tension Leg Platforms
NI 198	Underwater welding – general information and recommendations
NI 409	Guidelines for corrosion protection of seawater ballast tanks and hold spaces
NR 476	Approval testing of welders
NR 480	Approval of the manufacturing process of metallic materials

Table 28. BV guidelines for the Oil and Gas industry

Within BV's references, NR (Rule Notes) are technical publications about marine units, giving requirements used for certification and classification by BV. NI (Guidance Notes) are also publications giving information and technical advices on marine units, but they must not be considered as rules for classification and certification. BV's literature may be accessed via BV's website in the section General Info/BV Rules: http://www.veristar.com/wps/portal

API (American Petroleum Institute)

Table 29 shows the API guidelines for the shipping and Oil and gas industry (Marina platform, 2012).

Reference	Title
API RP 2GEO	Geotechnical and Foundation Design Considerations
WSD	Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design
API RP 2A-LRFD	Planning, Designing and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design
API RP 2FPS	Planning, Designing and Constructing Floating Production Systems
API RP 2T	Planning, Designing and Constructing Tension Leg Platforms
API RP 2SK	Design and analysis of stationkeeping systems for floating structures
API RP 2SM	Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring
API RP 14F	Design, Installation, and Maintenance of Electrical Systems for Fixed and Floating Offshore Petroleum Facilities

Table 29. API guidelines for the Oil and Gas industry

CSA (Canadian Standard Association)

Table 30 shows the CSA guidelines for the Oil and gas industry.

Reference	Title
CSA S471	General Requirements, Design Criteria, the Environment and Loads.
CSA S474	Concrete Structures, Offshore Structures.

Table 30. CSA guidelines for the Oil and Gas industry

DIN (Deutsche Institut für Normung)

Table 31 shows the DIN guidelines for the Oil and gas industry (Marina platform, 2012).

Reference	Title
DIN EN 10225	Weldable structural steels for fixed offshore structures - Technical delivery conditions
DIN EN 12495	Cathodic protection for fixed steel offshore structures

Table 31. DIN guidelines for the Oil and Gas industry

ISO (International Organization for Standardization)

Table 32 shows the ISO guidelines for the shipping, oil and gas industry (Marina platform, 2012; Alawa et al, 2009). ISO standards developed for the oil and gas industry are also shown in Figure 75.

Reference	Title
ISO 19900	General requirements for offshore structures
ISO 19901	Specific requirements for offshore structures
ISO 19901-1	Petroleum and natural gas industries -- Specific requirements for offshore structures -- Part 1: Metocean Design and Operating Considerations
ISO 19901-2	Specific requirements for offshore structures–Part 2: Seismic design procedures and criteria
ISO CD 19001-2	Seismic design procedures and criteria
ISO 19901-4	Specific requirements for offshore structures-- Part 4: Geotechnical and foundation design considerations (Petroleum and natural gas industries)
ISO 19902	Fixed steel offshore structures
ISO 19903	Fixed concrete offshore structures
ISO 19904-1	Floating Offshore Structures – Part 1: Monohulls, semi-submersibles and spars
ISO 19905	Site-specific assessment of mobile offshore units
ISO 13819-1	Petroleum and natural gas industries - Offshore structures – Part 1: General requirements
ISO 14688	Geotechnical investigations and testing - identification and classification of soil Part 1: Identification and description.
ISO 10042	Arc-welded joints in aluminum and its weldable alloys – Guidance on quality levels for imperfections
ISO 76	ISO 76: Static Load Ratings for Rolling Bearings.
ISO 281	Dynamic Load Ratings and Rating Life of Rolling Bearings.
ISO 6336	Calculation of load capacity of spur and helical gears.
ISO 6802	Rubber and plastics hoses and hose assemblies – Hydraulic pressure impulse test without flexing.
ISO 6803	Rubber and plastics hoses and hose assemblies – Hydraulic pressure impulse test with flexing.
BS EN ISO 14001:2004	Environmental Management System Certification
ISO / IEC	17020 General criteria for the operation of various types of bodies performing inspections
ISO 12944	CSM Paints and varnishes - Corrosion protection of steel structures by protective paint systems; marine, offshore, estuaries, coastal areas with high salinity

Table 32. ISO guidelines for the Oil and Gas industry

Figure 75. Organization of ISO standards for the oil and gas industry.

Lloyd's Register

The Lloyd's Register Rules and Regulations set appropriate standards for design, construction and lifetime maintenance providing all the information needed for classification purposes. Table 33 shows the Lloyd's Register guidelines for the oil and gas industry.

Reference	Title
Lloyd's Register	Rules & Regulations For The Classification Of A Floating Offshore Installation
Lloyd's Register	Rules & Regulations For The Classification Of Fixed Offshore Installations 1989 Full Set
Lloyd's Register	Rules & Regulations For The Classification Of Mobile Offshore Units
Lloyd's Register	Rules & Regulations For The Construction & Classification Of Submersibles & Underwater Systems
Lloyd's Register	Rules for Floating Offshore Installations at a Fixed Location (FOIFL)

Table 33. Lloyd's Register guidelines for the Oil and Gas industry

NACE (National Association of Corrosion Engineers)

Accredited by the American National Standards Institute (ANSI), NACE establishes standards on different categories, one of them being the guidelines for the materials and corrosion of marine structures/ships. Table 34 shows the NACE guidelines for the oil and gas industry (Marina platform, 2012).

Reference	Title
NACE SP0108	Corrosion Control of Offshore Structures by Protective Coatings
NACE SP0176	Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated with Petroleum Production

Table 34. NACE guidelines for the Oil and Gas industry

DNV (Det Norske Veritas)

DNV establishes rules and regulations for the classification of ships, floating offshore platforms and other floating marine structures. Table 35 shows the DNV guidelines for the shipping, oil and gas industry (after Marina platform, 2012).

Reference	Title
DNV OS C101	Design of offshore steel structures, general (LRFD method)
DNV RP B401	Cathodic protection design
DNV OS E301	Position Mooring
DNV OS C502	Offshore Concrete Structures
DNV-OS-B101	Metallic Materials
DNV-OS-C103	Structural Design of Column Stabilised Units (LRFD method)
DNV-OS-C104	Structural Design of Selfelevating Units (LRFD method
DNV-OS-C105	Structural Design of TLPs (LRFD method)
DNV-OS-C106	Structural Design of Deep Draught Floating Units (LRFD method),
DNV-OS-C201	Structural Design of Offshore Units (WSD method)
DNV-OS-F201.	DYNAMIC RISERS (Global Load Effect Analysis Guidelines as it pertains to umbilicals)
DNV-OS-C501	Composite Components
DNV-OS-E303	Certification of Fibre Ropes for Offshore Mooring
DNV-RP-C203	Fatigue Design of Offshore Steel Structures
DNV CN 30.6	Structural Reliability Analysis of Marine Structures (Classification Note)
DNV-RP-A202	Documentation of Offshore Projects

Table 35. DNV guidelines for the Oil and Gas industry

GL (Germanischer LLoyd)

GL has been developing technology, safety and quality standards in a wide variety of fields. GL developed and published a guideline in 2007 named “Rules for classification and construction.”

MMS (Minerals Management Service)

On October 1, 2011, the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly the Minerals Management Service (MMS), was replaced by the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) as part of a major reorganization. Table x shows the MMS studies for the shipping, oil and gas industry (Alawa et al, 2009).

Reference	Title
MMS Project 067	Rig Mooring Reliability
MMS Project 116	Impact of Annual Ice with a Cable-Moored Platform
MMS Project 133	Synthetic-Fiber Mooring Lines for Deepwater floating Production Facilities
MMS Project 139	Operation RIGMOOR
MMS Project 194	Calibration of Mooring Design Code for Floating Drilling and Production Platforms
MMS Project 200	Securing Procedures for Mobile Drilling Units (MODU's) in the Gulf of Mexico
MMS Project 238	Recommended Procedure for Design of Drag-Embedment (Fluke) Anchors
MMS Project 315	Engineers Design Guide to Deepwater Fiber Moorings
MMS Project 316	Reliability Study for Synthetic Moorings
MMS Project 344	Durability of Polyester Rope Moorings
MMS Project 362	Deep Water Anchor Reliability
MMS Project 366	Dynamic Analysis Tool for Moored Tanker-Based FPSOs, including Large Yaw Motions
MMS Project 368	Response of Tanker Based FPSO to GOM Hurricanes
MMS Project 369	Polyester Rope Analysis Tool
MMS Project 389	Characterizing Polyester Rope Installation Damage
MMS Project 394	Interim Damage Criteria for Replacing Damaged Polyester Rope
MMS Project 407	Damage Tolerance of Synthetic-Fiber Mooring Ropes; Phase I: Small- Scale Experiments
MMS Project 407	Damaged Polyester Rope- Large Scale Experiment
MMS Project 423	Foundation/Mooring Risk of FPSOs
MMS Project 437	Reliability Analysis of Deepwater Anchors
MMS Project 447	Qualifying Composite Tendons and Risers
MMS Project 557	Numerical Modeling of Torpedo Anchors
MMS Project 575	Torpedo Piles for Gulf of Mexico Applications
MMS Project 591	Evaluate Accuracy of Polyester Subrope Damage Detection Performed by ROVs Following Hurricanes and Other Events
MMS Project 592	Connector Designs for Top and Bottom Tendon Connections
MMS Project 603	Stability of Tension Leg Platforms with Damaged Tendons

2.9.2 **Offshore wind Energy guidelines and standards**

Among the many guidelines and standards presently available, often with a mainly national focus in the respective country, there are four main institutions publishing guidelines, standards or other helpful documents for the certification of (offshore) wind turbines (WT). These are the IEC, GL, Det Norske Veritas (DNV) and Bureau Veritas (BV). The guidelines by GL and DNV are mainly based on the IEC standard. The following sections will be grouped by these institutions and briefly describe the standards and guidelines.

IEC (International Electrotechnical Commission standards on offshore wind energy)

The IEC publishes several standards for testing and certification of onshore and offshore WT. The IEC-61400 series of standards are commonly referred as IEC wind turbine standards. These standards are prepared by the "IEC Technical Committee 88: Wind Turbines" (TC 88).
The *IEC-61400-1* (General Design requirements for wind turbines) (IEC, Wind turbines - Part 1: Design requirements, 2005) outlines general minimum design requirements for WTs and serves as a basis for the other standards. Therefore, it is not intended for use as a complete design specification or instruction manual. Moreover, it is not intended for OWT. It covers the basic topics concerning WTs like principal elements, external conditions, structural design, control and protection system, mechanical system, electrical system, assessment of a WT for site-specific conditions, assembly, installation and erection as well as commissioning, operation and maintenance.

The *IEC-61400-3* (Design requirements for offshore wind turbines) (IEC, Wind turbines - Part 3: Design requirements for offshore wind turbines, 2009) is an equivalent to the *IEC-61400-1*, but for bottom-fixed offshore wind turbines. Instead of the assessment of onshore site-specific conditions, it covers the foundation design and assessment of the external conditions at an offshore site, which includes assessment of wind conditions, waves, currents, water level, tides, sea ice, etc. The development of this standard was supported by the RECOFF (Recommendation for Design of Offshore Wind turbines) project. Efforts have been proposed in TC 88 to advance this offshore standard to include floating technology.

The *IEC-61400-13* (Measurement of mechanical loads) (IEC, Wind turbine generator systems - Part 13: Measurements of mechanical loads, 2001) describes processes for mechanical loads measurements. It mainly focuses on large horizontal axis WTs. It contains guidelines for safety during testing, load measurement programmes and measurement load cases, measurement techniques (e.g. data acquisition techniques and sensor accuracy and resolution), processing of measured data, and the final process of reporting the data.

Finally, the *IEC-61400-23* (Full-scale structural testing of rotor blades) (IEC, Wind turbine generator systems - Part 23: Full-scale structural testing of rotor blades, 2001) provides guidelines for the full-scale structural testing of WT rotor blades. Considered in this specification are static strength tests, fatigue tests and other tests determining blade properties. It provides information on general principles, blade data, differences between design and test load conditions, test loading, load factors for testing, evaluation of test load distribution in relation to design requirements, failure modes, test procedures and methods and gives an overview of other tests for determining blade properties. It also points out how to report the test results.

The *IEC-WT01* (IEC System for Conformity Testing and Certification of Wind Turbines; Rules and Procedures) (IEC, System for conformity testing and certification of wind turbines - Rules and procedures, 2001) is intended to facilitate international WT business by setting standards for certification based on the IEC standards as developed by the IEC TC 88[6]. The document defines a certification system for WTs which consists of type, component and project certifications. In the *type certification process*, satisfactory completion of the following parts leads to the final evaluation report, which is the basis for the type certificate:

- Design evaluation
- Type testing
- Manufacturing evaluation
- Foundation design evaluation (optional)
- Type characteristic measurements (optional)

The component certification can be understood as a type certification of the main components of a WT. Similar to the type certification process, it also consists of design evaluation, type testing and manufacturing evaluation. The fourth and final step here is the final evaluation after which the component certificates are issued. For the project certification, which purpose is to evaluate whether type-certified WT and particular foundation designs conform to external conditions, applicable construction and electrical codes for a specified site, the successful completion of the required site assessment, foundation design evaluation and the optional installation evaluation and operation and maintenance surveillance lead to the project certificate. The project certificate documents conformity for the completed tasks.

The IEC-WT01 also describes the component certification process. This procedure makes sure that a major component of a WT complies to design assumptions, specific standards and other technical requirements. It consists of design evaluation, type testing, manufacturing evaluation and final evaluation. After successful completion of these modules the component certificate can be issued. The process is similar to the type certification.

GL (Germanischer LLoyd)

GL published the "Guideline for the Certification of Offshore Wind Turbines" (Lloyd, Guideline for the Certification of Offshore Wind Turbines, 2007) in 2005 and reprinted it in 2007. This guideline is valid for type and project certification. The *type certification* confirms that the WT complies with the given WT class, fulfils the design assumptions and confirms that the manufacturing process, the component specifications, the inspection, the test procedures and the documentation are in agreement with the design documentation. There are four levels of assessment which are called C- and D-Design Assessment for prototypes and A- and B-Design Assessment for the final machine. In conjunction with additional conditions, these Design Assessments lead to the appropriate certificates. C- and D-Design assessments require a prior plausibility check of the design documentation. The D-Design assessment documents a pre-review of a WT design but is not to be used as a basis for manufacturing the prototype. It includes a plausibility check of the rotor blades, control and safety concepts, safety system, machinery components, electrical installations and the tower. The C-Design assessment is used for the prototype of WT. It includes electrical power and load measurements which are to be compared to simulated values. If the results do not significantly mismatch, the control system still may be adjusted. The assessment includes the same plausibility check as the D-Design assessment. These assessments are valid for a maximum of two years, the C-Design alternatively for a maximum of 4000 hours of full load, whatever comes first. Then, a statement for an A- or B-Design assessment shall exist. The A- and B-Design assessments are the basis for the final assessment and the resulting type certificate. They are attained if the following process is successfully completed:

- C- or D-Design assessment.
- Valid certification report.
- Assessment of design documentation and manuals *or* (1) Tests of rotor blade, gearbox, generator and electrical components and (2) witnessing of the commissioning.
- Certification reports on: Safety system and manuals, rotor blades, machinery components, tower and foundation (if needed), electrical installation and lightning protection, nacelle cover and spinner, witnessing of the commissioning.

If all those points are fulfilled, the A-Design assessment is given. If there are still items to be realized, the B-Design assessment is given. The A- or B-type certificate is given with the appropriate assessment if the design-related requirements are realized in production and erection, a quality management system of the manufacturer is established, a prototype is tested and a final assessment is implemented.

Project certificates are assigned to confirm that type-certified WTs meet site-specific requirements. These requirements have to be in conformity with the type certificates. For a project certification, the A- and B-Type certificate and the following additional procedures enable the final assessment to be given:

- Assessment of site design conditions
- Site-specific design assessment
- Examination of foundation
- Surveillance during production
- Surveillance during transport and erection
- Surveillance during commissioning

With the final assessment, the project certificate is issued. As for the type certificates, a B-Project certificate is valid for two years, whereas the A-Project certificate is valid for the intended lifespan of the project.

Recently, all parts of GL 2005 reviewed and improved. The new edition is called “the Gudeline for the Certification of Offshore Wind turbines (Edition 2012). Once published GL 2012 replaced GL 2005 and formed a new and trend-setting basis for certification activities to ensure safety and reliability of offshore wind turbines worldwide (Woebbeking et al., 2012).

Det Norske Veritas guidelines on offshore wind energy

DNV also publishes guidelines and provides product and project certification services for maritime energy systems. Those documents are organized hierarchically as follows:

1. *Offshore Service Specifications (OSS)* covers basic principles and procedures of the certification processes.
2. *Offshore Standards (OS)* describe the common technical regulations and criteria for approval as a basis for the technical certification. Together with other DNV guidelines and international codes and standards, they form the basis for:
3. *Recommended Practices (RP)* contains detailed information in step with actual practice. They accompany the DNV guidelines and other international recommended practices.

Currently, there are two OS concerning WTs by DNV available, the OS-J101 (Veritas D. N., DNV-OS-J101: Design of offshore wind turbine structures, 2004) and OS-J102 (Veritas D. N., DNV-OS-J102: Design and manufacture of wind turbine blades, offshore and onshore wind turbines, 2006). The *OS-J101* was published in October 2007 and deals with the design of OWT structures. It points out guidelines for several aspects of the structural design:

- Design of steel structures
- Design of offshore concrete structures
- Design and construction of grouted connections
- Foundation design
- Corrosion protection
- Transport and Installation
- In-service inspection, maintenance and monitoring

The OS-J102 was published in October 2006 and provides guidelines for the design and manufacture of WT blades, for offshore and onshore WTs. The following aspects are included in detail:

- Material qualification (fibre-reinforced plastics, sandwich core materials, adhesives etc.)
- Design analysis
- Blade manufacturing procedures
- Blade testing
- Documentation requirements
- Blade manufacture

The document also provides information about tried-and-tested analysis methods like FEM, buckling analysis or fibre failure analysis.

The DNV also published two RP, RP-A203 (Veritas D. N., DNV-RP-A203: Qualification procedure for new technology, 2001) and RP-C205 (Veritas D. N., DNV-RP-C205: Environmental Conditions and Environmental Loads, 2007). *RP-A203*, published in April 2001, points out recommended practices for fatigue design of offshore steel structures. It covers fatigue analysis based on S-N-data as well as on fracture mechanics. It points out the calculation of stress concentration factors and hot spot stress by means of FEM analysis as well as improvement of fatigue life by enhanced fabrication processes and the uncertainties to consider. *RP-C205*, dated April 2007, covers the environmental conditions and loads. It details practices to deal with the following topics:

- Wind conditions (wind data, wind modelling)
- Wind loads (pressure, forces etc.)
- Wave conditions (wave theories, kinematics, transformation etc.)
- Wave and current induced loads on slender members and large volume structures
- Air gap and wave slamming
- Current and tidal conditions
- Vortex induced oscillations

- General design principles like Partial Safety Factor Method or Simulation of Combined Load Effect or Simultaneous Load Processes
- Site Conditions (Wind climate, wave climate, current etc.)
- Loads and load effects
- Load and resistance factors
    - Materials
    - Hydrodynamic model testing

In June 2013, DNV KEMA published as new standard for floating offshore wind turbine structures (DNV-OS-J103: Design of Floating Wind Turbine Structures) that will help ensure safety and reliability in floating wind turbines, and give the nascent floating-turbine sector the confidence to continue its development to commercial maturity. The standard takes transportation, installation and inspection issues into account to the extent necessary in the context of structural design.

Bureau Veritas guideline on floating offshore wind turbines

BV published in November 2010 its first Guidance Note (Veritas B., 2010) focused on wind energy. It is also the first guideline covering the specific field of floating wind turbines. It focuses on the structural design of floating support structures with details on:

- the classification and certification process
- the external conditions to be taken into account
- the principles of structural design
- the criteria for stability and subdivision assessment

Lloyd's Register

Lloyd's Register released guidance on offshore wind farm certification in 2012. The document outlines the Lloyd's Register certificate ion requirements for all aspects of the design, build and operation of an offshore wind farm. It uses the IEC 61400 standard series as a basis and in particular IEC 61400-22 the international standard for wind energy certification. The design should also meet all local regulations which apply at the turbine's site, including safety regulations and electrical compatibility and grid connection requirements.

ABS (American Bureau of Shipping)

In the beginning of 2013, ABS published two guides, namely, "ABS, 2013: Guide for building and classing floating offshore wind turbine installations," and "ABS, 2013: Guide for building and classing bottom founded offshore wind turbine installations." The former provides criteria for the design, construction, installation and survey of permanently sited floating offshore wind turbine installations. It addresses three principal areas: the Floating Support Structure, the station keeping system, and onboard machinery, equipment and systems that are not part of the turbine Rotor-Nacelle Assembly (RNA). The latter guide provides criteria for the design, construction, installation and survey of bottom founded offshore wind turbine installations, which comprise permanently sited support structures and foundations of offshore wind turbines attached on and supported by the sea floor. These guides can be accessed at http://www.eagle.org

AWEA (American Wind Energy Association)

In October 2009, the American Wind Energy Association (AWEA), in collaboration with the National Renewable Energy Laboratory (NREL), began the process to develop a recommended practice document based on consensus among offshore wind energy and offshore industry experts that provides advice and guidance on the best practices for design, deployment, and operation of offshore wind turbines (OWTs) in the United States. This effort was motivated by industry and regulatory concerns that no single set of guidelines and standards could be identified that addressed the complete design, deployment, and operation of offshore wind turbines, and moreover, by the fact that unique conditions exist in the United States that cannot be directly compared to conditions at European offshore wind facilities. This AWEA effort, originally known as the Large Turbine Compliance Guidelines Initiative, has enlisted over 50 experts in the offshore wind community to develop this consensus document, now known as “AWEA OCRP 2012: Offshore Compliance Recommended Practices 2012.” The intent was to create a recommended practices document which refers to current best practices in the use of existing standards for planning, designing, constructing, and operating offshore wind facilities in U.S. waters. In general this effort was not intended to write original new best practices related to the committee members’ experiences.

2.9.3 Guidelines on wave energy

For wave energy converters (WEC), a document prepared by DNV and CarbonTrust as well as several guidelines by the European Marine Energy Centre (EMEC)[7] are currently available.

Even though first serious global wave energy research took place in the 1970s and early 1980s when several governments undertook national R&D programmes following the oil crisis, first protocols where device developers can refer to and follow first appeared in 2003. Majority of initial investigations took place in the UK in the early 1990s. The European Union (EU), through its operating Commission, then became interested in wave energy and took over the role from the UK. As a result, Offshore Wave Energy Converter Project OWEC 1 was funded by the European Commission under the Non-nuclear Energy JOULE II programme (WAVEPLAM, 2009). One section of the project was dedicated to establishment a device deployment programme which was documented in 1995. However, this programme could not become a standard approach to be applied.

Since the early 2000s, many research groups (See Figure 76) have shown significant progress in developing a series of standard, equitable approaches for both the development schedule and the test programmes of WECs from concept to demonstration. Figure 77 shows some of the guidelines and standards which have been so far developed and released in conjunction with the pioneering research institutions. It should be noted that this list is not exhaustive. A detailed information on these standards and guidelines can be found in (EquiMar, 2010; Wavetrain, 2007).

Figure 76. Main bodies engaged in drafting standards and protocols (after WAVEPLAM, 2009).

Figure 77. Standards, equitable approaches, and best practice manuals.

Furthermore, there are also other organizations, which have been involved with the design, construction, operation, and maintenance of the offshore structures for many years. These standards may also be adapted for wave and tidal energy converters. These organizations include:

- American Concrete Institute
- American Institute of Steel Construction
- American Petroleum Institute
- American Society of Mechanical Engineers
- American Welding Society

International Electrotechnical Commission standards on wave energy

The IEC founded the technical committee TC 114 in 2007 with national branches like the "PEL/114 Marine Energy"[9]in the UK and the "DKE Gemeinschaftskomitee 385" in Germany. These committees deal with the standardization of ocean energy devices and include members from several fundamental and applied research institutions, standardization and classification bodies and the industry. These committees deal with the standardization of ocean energy devices and include members from several fundamental and applied research institutions, standardization and classification bodies and the industry.

Project Team	Title	Published
PT62600-1	Terminology	Yes
PT62600-2	Design requirements for marine energy systems	Yes
PT62600-10	Assessment of mooring systems for marine energy converters	Yes
PT62600-30	Electrical power quality requirements for wave, tidal and other water current energy converters	No
PT62600-100	Power performance assessment of electricity producing wave energy converter	No
PT62600-101	Wave energy resources assessment and characterization	No
PT62600-102	Wave energy converter power performance assessment at a second location using measured assessment data	Yes
PT62600-103	Guidelines for the early stage development of wave energy converters: Best practices & recommended procedures for the testing of pre-prototype scale device.	No

Table 36. Guidelines currently being developed by IEC-TC 114 (IEC, 2013) Source: wave energy converter report

Some of these documents are already available at IEC website (IEC, 2013). Based on these guidelines, each WEC concept can be treated in the same way while determining the technological maturity and performance, which might increase the funding opportunities for WECs that have higher performance. The power matrices measured at sea can be compared to results obtained by physical modelling and numerical modelling, which will feed into and further accelerate R&D efforts.

Guide published by Det Norske Veritas and Carbon Trust

The DNV CarbonTrust document is named "A guide to assessment and application of engineering standards and recommended practices for wave energy conversion devices" (Veritas D. N., Guidelines on design and operation of wave energy converters. A guide to assessment and application of engineering standards and recommended practices for wave energy conversion devices, 2005). Its purpose is to provide information on the application of existing codes and standards mainly from other offshore and maritime industries to wave energy devices. The document describes a qualification process which can be applied to different stages of development or to devices with new design aspects where other codes and standards may not be adequate. It can also be used as an improvement tool to achieve adequate functional requirements and as a systematic demonstration of reliability and levels of risk. It refers to other DNV OS and RP for a consistent approach in standardization. The guide consists of some sections about the qualification process and building blocks, standards and safety and reliability targets. It also gives advice on mass production of devices. Moreover, it helps with qualification of new and unproven technology by outlining general considerations and describing a qualification process. The following topics are dealt with as well: failure mode identification and risk ranking, value management and life cycle analysis, reliability and cost, risk assessment.

European Marine Energy Centre documents on wave energy devices

A set of standards for marine energy have been developed under the coordination of EMEC. Currently[10], there are twelve guidelines. On some topics there are common documents for both wave and tidal energy converters and separate documents on other topics. In the following details are given only for the most relevant documents. The guidelines concerning specifically wave energy are currently the following:

- Assessment of Performance of Wave Energy Conversion Systems: This document outlines a methodology for addressing the performance of wave energy conversion systems at open sea test sites. The document is meant to provide a common process for the measurement of the power output of the wave energy conversion system depending on the sea state. It establishes a framework for reporting of measurement results and to estimate the energy production at a prospective site. It applies to floating and bottom-mounted wave energy conversion systems operating in the open sea which already are post-prototype machines. The topics concerning the test site are mainly: Bathymetric survey, tidal height measurement, current and wave modelling. Concerning the measurements in general, wave energy conversion system power output, wave and meteorological measurements and calculation of performance indicators are the primarily fields of interest.

- Assessment of Wave Energy Resource.
- Tank Testing of Wave Energy Conversion Systems.

The following guidelines for marine energy comprise both wave and tidal energy:

- Guidelines for Health & Safety in the Marine Energy Industry
- Guidelines for Marine Energy Certification Schemes: This document provides a common basis for the certification of marine energy converters, a basis for acceptance of operating bodies and mutual recognition of certificates. It also has the objective to communicate the framework of certification for the wave and tidal energy sector, its extent and the definition of common deliverables by certification bodies. It includes information on type certification and project certification.

Guidelines for Design Basis of Marine Energy Conversion Systems: This document applies after the formative steps in the development of the tidal device have been undertaken and the general layout, operational functions etc. have been determined. It establishes general principles for a design basis document for a marine energy conversion system. It consists of a step-by-step guide a designer can follow to understand the factors that influence the design of a device and to choose the right design procedures. It is not only applicable to wave, but also to tidal stream energy converters, from the prototype design to the final design stage. The covered topics include the device description, environmental factors, loading and fatigue design guidances as well as floating structures or foundation and support structures:

- Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems
- Guidelines for Grid Connection of Marine Energy Conversion Systems
- Guidelines for Project Development in the Marine Energy Industry
- Guidelines for Manufacturing, Assembly and Testing of Marine Energy Conversion Systems: This document shall give manufacturers and purchasers information on manufacturing practices appropriate to the marine energy industry by making available an initial framework for providing consistency among the companies. It covers all marine renewable energy devices including tidal current generators, wave energy converters and offshore wind turbines. It covers the fields of manufacture and workmanship, welding including inspection and testing of welds, assembly, electrical installation, surface coatings and factory and acceptance testing.

The documents on Performance Assessment, Resource Assessment and the Guidelines for Marine Certification Schemes have been suggested as part of the work program for the Technical Committee TC - 114 of the International Electrotechnical Commission.

EquiMar Protocols & Deliverables

EquiMar (URL 24) (full project title - Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact) started in April 2008 to run for three years. It was funded as part of the EU Framework 7 and had 23 European partners. The main objective was to produce protocols (URL 25) as follows: Resource Assessment; Tank Testing; Environmental Assessment; Sea Trials; Deployment and Performance; Project Assessment and Market Assessment (Griffiths, 2011).

The protocols themselves consist of high level documents covering the key principles for the subject areas each of which sets a framework for a series of more detailed reports (deliverables) (URL 26) some of which are detailed protocols. These deliverables provide advice and relevant back ground information and may include a mixture of recommended methods, lists of types of instrumentation describing their functions and indicating some of their shortcomings, some short lists of commercial products are included as well as case studies (Griffiths, 2011)

The deliverables range far wider in content than any formal standard could. They contain a great deal of information that provides good guidance to the user, but are not always fully objective in terms of carefully stating requirements of a procedure or attributes required of a hardware item without placing any influence on the reader to direct their attention to specific equipment types or suppliers (Griffiths, 2011).

The deliverables are not structured on the lines of a standard, the structures are logical and helpful and as academic papers that have a much wider appeal than just the academic community; they are very readable and informative.

Standards are produced internationally to remove barriers to markets and to provide normative reference points for regulatory purposes. However, the EquiMar protocols have not been written as drafts specifically to put forward as applications for new work within the international standards making community. They have not been written to comply with the form of international standards as described in BS 0:2005 but they provide significant advice and background that is supplementary and explanatory regarding aspects covered by the standards (Griffiths, 2011).

DTI Protocols for Performance Measurement

In 2004 the UK Department of Trade &Industry (DTI) opened their Marine Renewable Development Fund (MRDF) a sum of £42 million intended to provide grants to technology developers enabling small pre-commercial arrays of marine energy converters to be deployed. The terms and conditions for these included the requirement that testing of arrays should follow protocols provided by DTI for testing of both wave energy converters and tidal energy converters (Smith & Taylor, 2008; Pitt, 2009). The protocols were prepared by Edinburgh and Heriot Watt university personnel with industry involvement being engaged through workshops. This approach is an excellent method for preparation of standards and has been used subsequently to good effect. These protocols were specific to the MRDF requirements and were not written in a style and format for standards. It is vital that standards apply to as wide a variety of situations and locations as possible so as to achieve widest use and acceptance. Unfortunately, no technology developer was able to fulfill the requirements of the MRDF at a viable cost, within the financial constraints, so although the protocols provided helpful information, they were never used for the purpose for which they were intended (Griffiths, 2011).

2.9.4 Standards, guidelines and comparable documents on tidal energy

For tidal energy devices, documents from IEC, GL, DNV and EMEC are discussed in the following.

International Electrotechnical Commission standard development on tidal energy

The IEC Technical Committee 114 was already introduced in section 2.2.1 due to its work on guidelines related to wave energy and generally to marine energy. In addition to the upcoming Technical Standards listed in section 2.2.1, a Technical Standard dedicated to tidal energy is planned:

- IEC TS 62600-200: Performance assessment of tidal energy converters

Germanischer Lloyd guidelines on tidal energy

The Guideline for the Certification of Ocean Energy Converters, Part 1: Ocean Turbines (Lloyd, Guideline for the Certification of Ocean Energy Converters, Part 1: Ocean Turbines (Draft), 2005) by GL is a draft which was published in 2005. It defines current turbines as machines which convert kinetic energy of sea currents to electrical energy.

The goal is to only specify general guidelines for safety evaluations of the current turbines. The reason for this is that current turbines can be constructed in many different ways so the guidelines for the certifications have to be adaptable to many concepts.

The standard is valid for type and project certifications (cf. section 2.1.2 for the definition of the two types of certifications). For the *type certification*, there is the A/B- and the C-Design assessment. The C-Design assessment is done before the prototype of the machine is constructed.
To complete this certificate, a description of the safety systems and electrical components, engineering drawings of the components and the complete load calculations have to be filed. In a second step, loads and power output of the machine are measured and compared to the computed values. The control unit may only be changed if this does not significantly influence the loads. The C-Design assessment is valid for a maximum of two years or 4000 hours of operation under full load. The A/B-Design assessments are the requirement for the final assessment and for getting the certificate. The B-Design assessment is given, if some, and the A-Design assessment, if all of the following requirements are met:

- Loads and safety concept
- Load assumptions
- Manuals
- Tests and trials of: FRP components, gearbox
- Certification reports on: Safety system and manuals, Rotor blades or lift generating device, machinery components, support structure, electrical equipment, condition monitoring systems, commissioning

When the A-Design assessment is issued, the design requirements must be implemented in production and erection, a quality management system has to be set up and finally a prototype test including a prototype trial of the gearbox has to be accomplished to get the final assessment. This final assessment leads to the type certificate. The *project certification* guarantees that a type-certified machine with its supporting structure meets location-specific requirements. In this process, the actual condition of the environment, sea bottom, sea and grid at the planned location is compared with the constraints described in the design documentation. It is valid for the duration of the expected operation time. The following requirements have to be met for a project certification:

- Creation of a "design basis" for the location evaluation containing all influences required for load calculations.
- Comparison of the environmental conditions at the location with the assumptions from the type certificate, doing additional calculations as needed.
- Manufacturer surveillance to make sure the quality requirements are met by the manufacturer.
- Transport and installation surveillance.
- Commissioning surveillance to make sure the turbine works as expected and meets all requirements.

To maintain the validity of the certificate, periodic monitoring of one or all turbines is required.

Det Norske Veritas guidelines on tidal energy

DNV has published only one document on sea current turbines, the OSS 312 (Veritas D. N., DNV-OSS-312: Certification of Tidal and Wave Energy Converters, 2008). It contains the procedural part of the certification process. In the near future, the technical details for the industry will be outlined by the DNV Offshore Standards and DNV RP, but they are not available yet. As a substitute, one is referred to RP A203 (Qualification procedure for the new technology) (Veritas D. N., DNV-RP-A203: Qualification procedure for new technology, 2001) and partly to OSS 401 (Technology qualification management) (Veritas D. N., DNV-OSS-401: Technology Qualification Management, 2006). The RP A203 describes a general process for the certification of new technology for which no mature state of the art exists yet. The qualification process is based on failure mode analysis in cooperation with certification authorities. If the technology is tried and tested, the certification is done according to the relevant standards. Else, the following steps are executed:

- Failure mode identification and Risk Ranking
- Concept improvement, if needed
- Selection of appropriate qualification methods
- Evaluation of the probability of success
- Analysis and testing
- Reliability Assessment

If all steps are completed, the certificate is issued.

European Marine Energy Centre documents on current energy devices

The EMEC published a set of guidelines for marine energy conversion systems which are freely available on their website[11]. Currently, the following documents on tidal energy in general are offered:

- Assessment of Performance of Tidal Energy Conversion Systems
- Assessment of Tidal Energy Resource
- Guidelines for Health & Safety in the marine energy industry

- Guidelines for Marine energy certification schemes
- Guidelines for Design basis of Marine Energy Conversion Systems
- Guidelines for Reliability, maintainability, survivability of Marine Energy Conversion Systems
- Guidelines for Manufacturing, Assembly and Testing of Marine Energy Conversion Systems
- Project development in the Marine Energy Industry

The guidelines for certification and analysis of resources and performance were propounded to the IEC by the EMEC-lead IEC branch committee.

3 Experimental and numerical analysis of the most relevant floating foundations for offshore wind concepts

There are two potential philosophies regarding to MUPs conceptualization: (1) create areas were different activities share the same space with different purposes and (2) create platforms where different activities are allocated. In order to identify the compatibility of different activities in both philosophies, the dynamic performance of the activities must be analyzed. On the present section, based on numerical models and on physical tests, the dynamic performance of floating offshore wind concepts will be studied. Two different questions will be addressed. First of all, floating offshore wind structures used to be massive; so they can allocate other uses like aquaculture or wave energy for example. Therefore, based on the numerical and physical analysis output the suitability of different concepts in order to integrate an integrated multipurpose concept will be addressed. Second and finally, based on the results of the present section, the compatibility of single use platforms sharing the same space with other uses will be identified.

3.1 Concepts analyzed

On previous sections the existing technologies have been analyzed. From this analysis we can conclude that Spar based concepts, Semisubmersibles and Tension Leg Platforms are identified like the most promised concepts from the offshore wind energy point of view.

Each concept shows a significantly different performance under operating and extreme conditions, since they are based on different physical principles. In general terms, spar concepts have a good behavior thanks to its deep draft which contributes to large stability of these concepts. Thanks to its small water plane area these concepts show reduced wave exciting forces. TLPs concepts have an excellent heave and angular motion thanks to the mooring system, but their complexity and cost of the mooring installation play a significant role. Finally semisubmersible concepts have a good behavior due to its big water plane area, which increase the flotation inertia and therefore the heeling moment.

Nowadays, as it has been said on previous sections, only a few of floating concept have been already deployed. Based on them three basic concepts will be reengineered, simulated numerically and physically tested at Univeristy of Cantabria facilities. The information obtained will be used as a reference for the later technology selection.

One is the Hywind (from Statoil) in Norway (see section 742.7.1 *Prototypes developed in wind energy sector*). Another example is the Windfloat project (from Principle Power), already installed off the coast of Portugal near Abruçadoira (see section 742.7.1). Finally the last most promising technology is the TLP concept (see section 742.7.1). (See Figure 78).

Figure 78. Prototypes developed in wind energy sector: (a) Hywind (Statoil). (b) Windfloat (Principle Power). (c) BlueH TLP (BlueH)

3.2 Objectives and methodology

3.2.1 Objectives

The main objectives present section are:

- Analysis of the wave-structure interaction of deep sea offshore wind concepts
- Mooring system performance analysis
- Identify weakness and strength of deep sea floating concepts

In order to achieve the main objectives the following partial objectives are considered:

1) Design a set of physical scale model tests where the following items will be tested:
    a. Analysis of natural periods, damping coefficients and added mass of each concept for the six degrees of freedom (DOF).
    b. Determination of response amplitude operators (RAOs) for the 6 DOF.
    c. Analysis of the concept performance under irregular waves: operational and extreme conditions:
        i. Movements, velocities and accelerations will be analyzed
        ii. Moring system performance
    d. Determination of concept model oscillations in 6 DOF and loads on the anchors for a set of states of extreme waves.
2) Calibration of a numerical model and extension of the physical test.

3.2.2 Methodology

To achieve the objectives outlined in the previous section, the experimental and numerical works will be organized as follows.

First of all, three different devices will be designed and constructed based on the three available technologies (Spar, Semisubmersible and TLP). The concepts will be based on the already existing concepts (Hywind, Windfloat and BlueH). The design will be carried out based on existing semi empirical approximations as well as using numerical tools as SESAM (DNV).

Once each concept will be defined and validated, the final set-up of the test will be established. The scale will be chosen as a compromise between cost of the project and the test facility requirements. The construction of the model will be outsourced to a specialist workshop.

The test plan will be composed by the following phases:

Phase 1: Model characterization

During this first phase, each model will be tested in order to determine the distribution of mass, the coordinates of the center of gravity (KG), center of buoyancy, the metacentric height (GM), the axial stiffness of the mooring system, etc.

Phase 2: System characterization

Once the geometric and mass characteristics of the model are determined, 6DOF decay tests will be carried out. The decay tests will give the following information:

1) Natural period of the concept
2) Damping coefficient of the device (dimensional and non-dimensional)
3) Added mass the concept on each DOF in conjunction with static offset tests.

After the decay tests, the static offset test will be carried out. Based on the moored structure, the stiffness of the mooring system will be assessed in order to obtain a database for numerical model calibration and to know the mooring system stiffness.

Finally, it will be identified the response amplitude operator (RAO) of each DOF. It will be generated based on the comparison between a collection of regular waves of small amplitude and the dynamic response of the model. Movement, velocities and acceleration of the structure will be assessed by means of the Qualysis system (QTM).

This phase is very relevant, since all the information obtained is key for a correct calibration of numerical models.

Phase 3: Dynamic performance of the concept

Finally the floating model will be exposed to a set of operational and extreme wave conditions. The dynamic behavior of the each concept will be recorded as well as the performance of the mooring system.

The target climate conditions used will correspond with Cantabrian Offshore Site (COS) sea conditions. Mainly because they are rough enough and they are representative of most of the selected sites.

Finally a numerical tool like SESAM (DNV) will be calibrated with laboratory test results. Since the planned tests are mostly focused on wave-structure interaction, wind and current interaction with each concept will be addressed numerically. A 5MW wind turbine will be considered, NREL 5MW (Jonkman J. et al 2009) wind turbine will be as a representative wind turbine.

Once the numerical model is calibrated and considering wind and current action, a final representative model of each concept will be available and used in order to address the dynamic performance of each design.

3.3 Model description

On the present section the description and main characteristics of the each concept will be summarized. Some of them will be analyzed experimentally and numerically and some of them will be only analyzed numerically and based on calibration coefficients previously obtained.

3.3.1 SPAR based model

Hywind model has been used a benchmark case. Based on literature and information free available a similar concept has been re-engineered. On Figure 79 the final concept is schematized and on figure XX the proposed setup is shown.

The main characteristics of the device are summarized as follows:

Test scale: 1/ 50
Mooring system: three mooring lines equally spaced (120º)
Water depth: 150m
Mooring lines length: 430m
Mooring line pretension: 490.7 KN
Mooring line dry weight: 141 kg/m

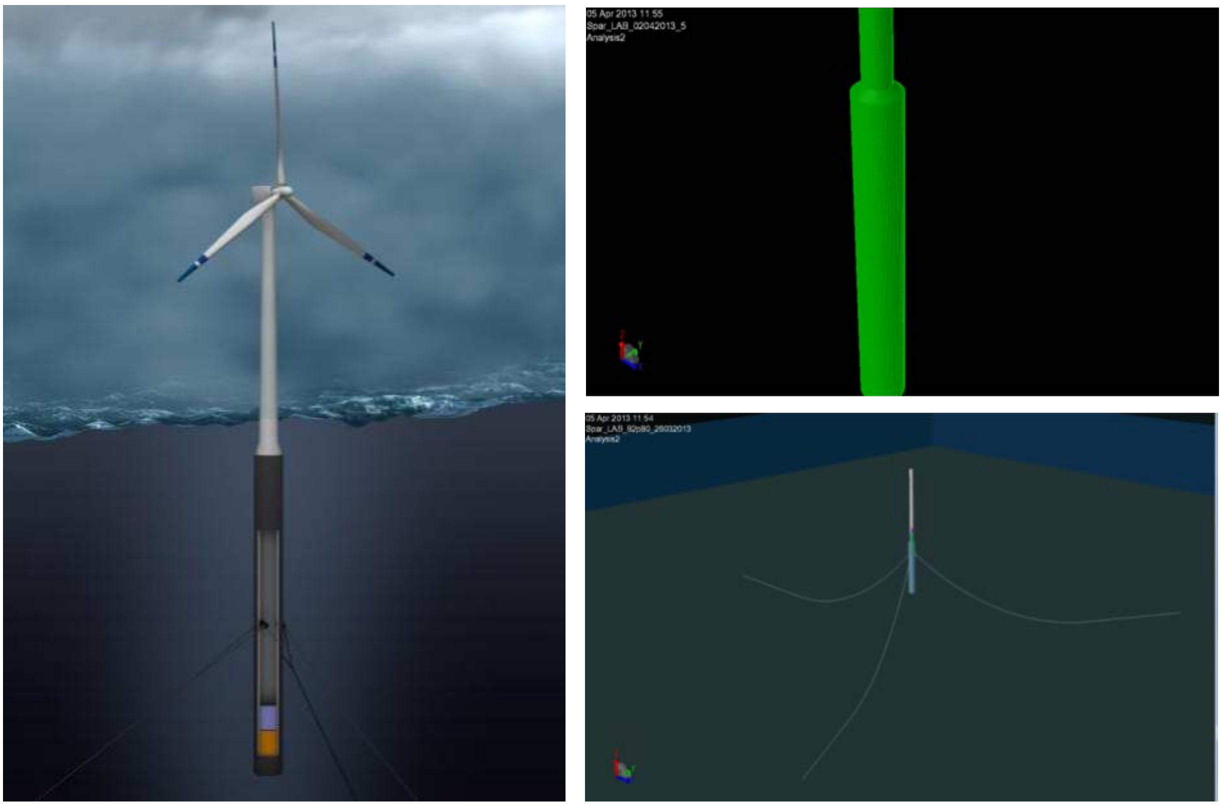


Figure 79. Spar based concept

Thanks to the axial symmetry of the structure and the symmetry of the mooring system two configurations will be tested (see Figure 80).

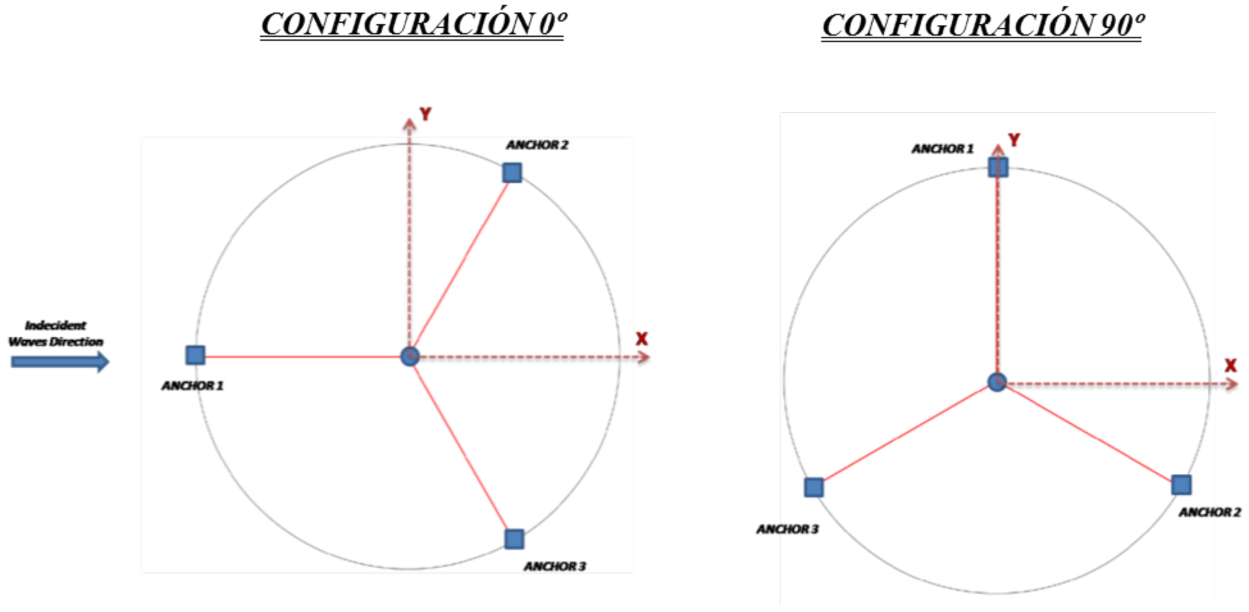


Figure 80. Test configurations

3.3.2 **Semisubmersible model**

Windfloat model has been used a benchmark case. Based on literature (Roddier, D et al 2010) and on information free available, a similar concept has been re-engineered. On Figure 81 the final concept is schematized and on Figure 82 the proposed setup is shown.

The main characteristics of the device are summarized as follows:

Test scale: 1/60
Mooring line pretension: 130 KN
Mooring line setup: 4 mooring lines 2 mooring lines attached to the turbine triangle corner and one on each triangle corner.
Water depth: 50 m
Mooring line length: 233 m
Mooring line dry weight: 221 Kg/m

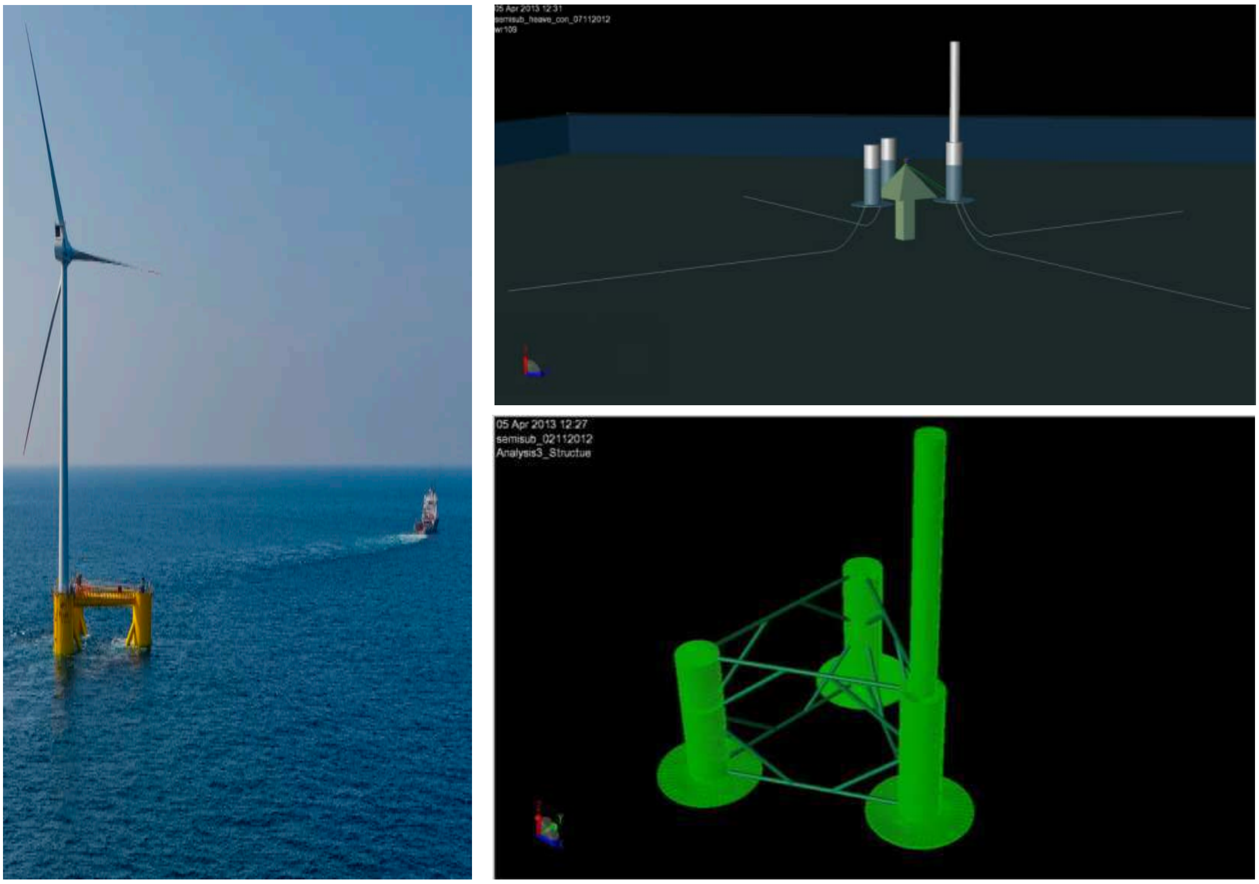


Figure 81. Semisumersible based concept

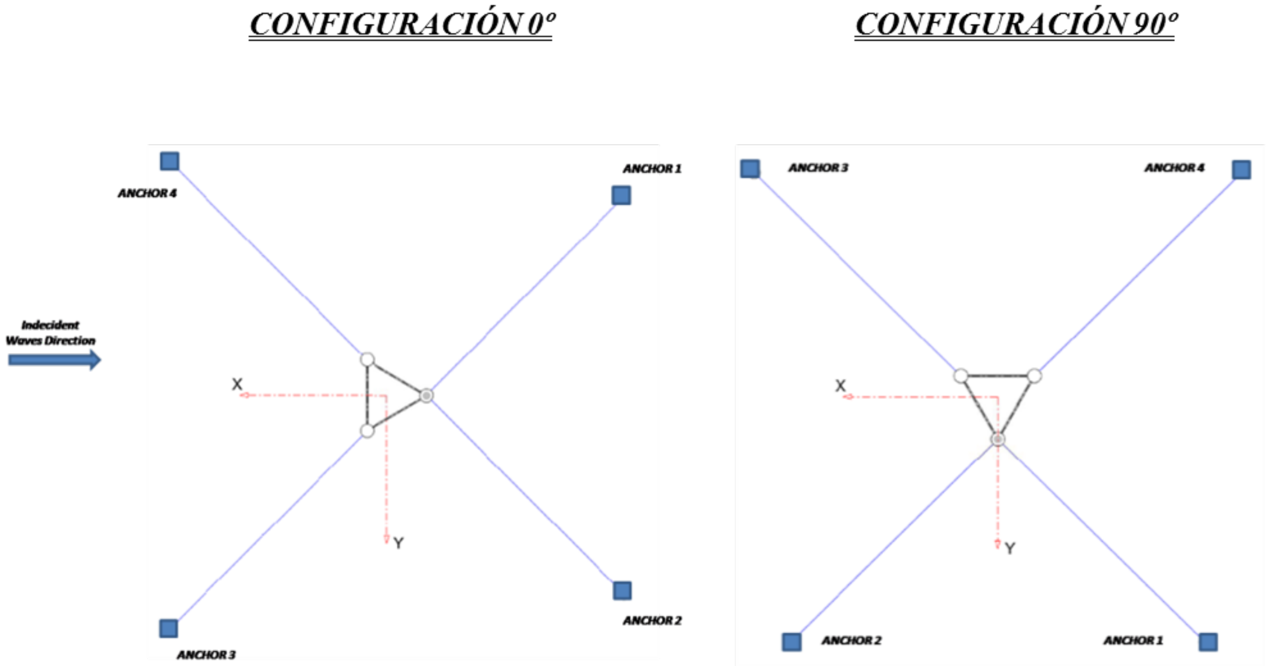


Figure 82. Test configurations

3.3.3 **TLP model**

MIT TLP model has been used a benchmark case. Based on literature and information (Sclavounos, P. et al 2010) a similar concept has been re-engineered. On Figure 83 the final concept is schematized and on Figure 84 the proposed setup is shown.

The main characteristics of the device are summarized as follows:

Test scale: 1/100
Mooring lines setup: 8 taut lines, 2 lines per support.
Water depth: 100m
Mooring line lenght: 47.65m
Mooring line diameter: 0,126m
Mooring line pretension: 150 KN
Mooringl linge dry weight: 75.40 kg/m

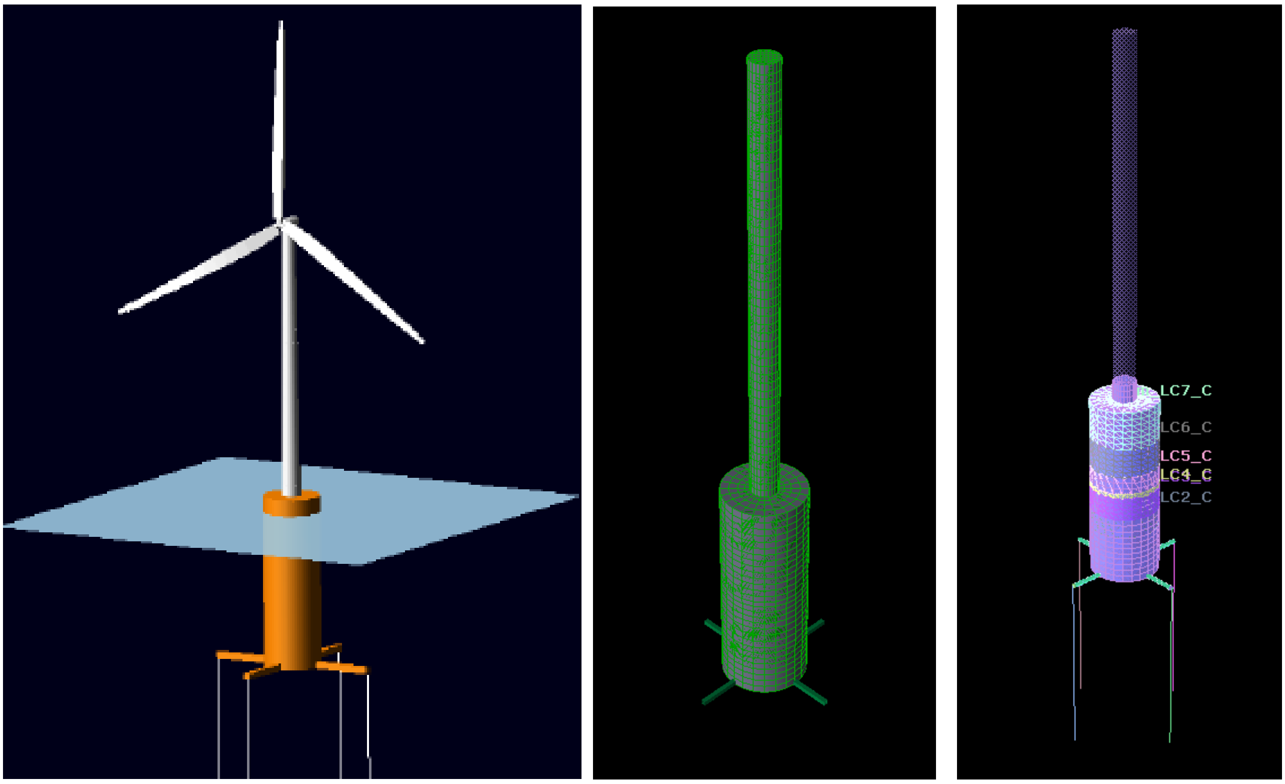


Figure 83. TLP based concept

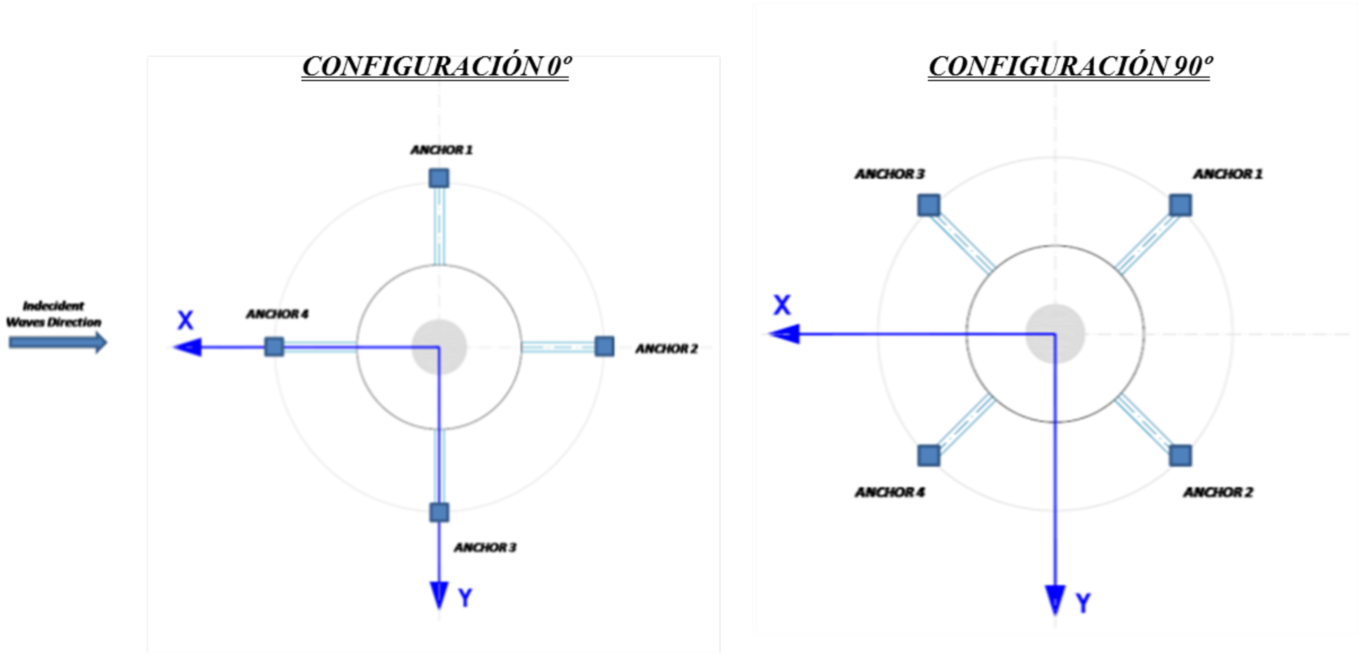


Figure 84. Test configurations

3.4 Expected results

The expected results are summarized as follows:

- Movements, velocities and accelerations of the platform will be addressed under different metocean conditions. This is particularly useful in order to identify potential incompatibilities with other uses.
- Mooring system performance. The mooring system is an important part of the system because ensures the integrity of the design and because it is a significant part of the cost.

3.5 Work plan

The present task have to be finished by the end of 2013, therefore the numerical and experimental works will be carried out from late spring to late summer.

4 Identification of the most promising concepts for the selected sites

Typically an offshore renewable energy foundation is required to:

1. Securely support the conversion system under operational and survival marine conditions
2. Facilitate safe access and a safe working environment for maintenance and operational activities

The options available for the MUP are considered in the preview sections, and can be classified under the following types:

1. Monopile
2. Tripod
3. Tripile
4. Jacket foundations
5. Gravity base foundations
6. Suction bucket foundations
7. Floating foundations

In order to obtain realistic results from the aforementioned assessment, realistic input data is required. Therefore, site specific information will be collated and the aforementioned most promising concepts will be applied to the four case study sites as discussed below:

4.1 Southern North sea site. Overview of parameters – Project Gemini Site

- averaged water depth 30 – 35 m
- semi-diurnal tide
- 85 km offshore, 55km north of Schiermonnikoog
- harsh wave conditions (large fetch length NW and SW)
- maximum tidal current 1~1.5 m/s
- Relatively shallow - fixed platform
- 150 Siemens turbines upgraded SWT-3.6 wind turbine (4MW)

http://www.4coffshore.com/windfarms/gemini-netherlands-nl18.html

General information	
Name	Gemini
Country	Netherlands
Region	Friesland
Development status	Consent authorized

Table 37. General Information. Project Gemini Site

Power and turbines	
Project capacity	600 MW
Turbine capacity	4 MW
Number of turbines	150
Rotor diameter	130 m
Foundation	Monopile

Table 38. Power and turbines. Project Gemini Site

Location and environment	
Sea	North Sea
Area	68 m2
Depth range (Chart datum)	32-34 m
Depth range stated by developet	28-36 m
Distance from shore	70.2 km

Table 39. Location and environment. Project Gemini Site

Ports	
Installation base	Eemshaven
Operation and maintenance	Eemshaven

Table 40. Ports. Project Gemini Site

Grid	
Offshore transformers	Gemini Substation 1, Gemini Substation 2
Grid connection point	Eemshaven
Cable landing point	Eemshaven

Table 41. Grid. Project Gemini Site

4.2 Baltic site. Overview of parameters – Kriegers Flak Site

In Baltic Site, Kriegers Flak site has been selected for MUP which is located at the intersect of Danish, German, and Swedish exclusive economic zones. Kriegers Flak site is planned for MUP using gravity base wind turbines and offshore aquaculture.

- Located 30 – 40 km from shore
- Mean water depth at shoal 25 – 30 m
- Stable bed, mainly sand
- Wind: significant resource
- Depth at Kriegers Flak varies between 20 and 26 m (Danish sector);
- Seasonal pycnocline establish between 18 and 20 m;
- Salinity in surface constant at 7-8 psu
- Temperature: 0 – 18 °C
- Located on path for deep water renewal of the Baltic
- Increased vertical mixing may be important for deep water inflow and the Baltic ecosystem
- Located on main path for nutrient transport out of the Baltic

http://www.4coffshore.com/windfarms/enbw-baltic-2-germany-de52.html
http://www.lorc.dk/offshore-wind-farms-map/baltic-2?os_free=kriegers

General information	
Name	EnBW Baltic 2 (formerly known Kriegers Flak)
Country	Germany
Region	Exclusive Economic Zone (Baltic-Kriegers Flak)
Comment	39 monopiles for depths of 23 to 35 meters and 41 jacket foundations for depths of 35 meters and above. Wide array of soil conditions from fine sands to gravel to cobbles.
Development status	Consent authorized

Table 42. General Information. Kriegers Flak Site

Power and turbines	
Project capacity	288 MW
Turbine capacity	3.6 MW
Number of turbines	80
Rotor diameter	120 m
Foundation	Monopile and jacket

Table 43. Power and turbines. Kriegers Flak Site

Location and environment	
Sea	Baltic Sea
Area	30 km2
Depth range (Chart datum)	20-42 m
Depth range stated by developet	23-44 m
Distance from shore	32 km

Table 44. Location and environment. Kriegers Flak Site

Ports	
Installation base	Nyborg, Denmark and Sassnitz-Mukran
Operation and maintenance	Sassnitz-Mukran

Table 45. Ports. Kriegers Flak Site

Grid	
Offshore transformers	EnBW Baltic 2 Substation
Grid connection point	EnBW Baltic 1 substation
Cable landing point	Bentwisch, near Rostock

Table 46. Grid. Kriegers Flak Site

4.3 Atlantic site. Overview of parameters – Project Cantabrian Offshore Site (COS)

The Atlantic Coast and Irish Sea are relatively attractive for all three offshore renewable energy technologies – offshore wind, wave and tidal – due to high resource levels.
The Atlantic Coast is an area rich in natural resources and resource potential, supporting traditional sectors such as maritime transport, tourism, fishing, aquaculture, seafood processing and sand and gravel extraction. New sectors, such as offshore renewable energy, marine biotechnology and deep-sea mining are emerging

(SeaEnergy: http://www.ewea.org/fileadmin/files/library/publications/reports/Seanergy_2020.pdf).

- Averaged water depth 50 – 250 m
- Mix of sandy and rocky seabed, mostly limestone
- 3 - 20km from shore. 7 km far from Santander
- Very rough wave and wind conditions
- Maximum tidal current 1.5 cm/s
- Deep water site - floating platform

General information	
Name	Cantabrian Offshore site (COS)
Country	Spain
Region	Cantabria
Development status	-

Table 47. General Information. Cantabrian Offshore Site (COS)

Location and environment	
Sea	Atlantic Ocean
Area	100 km2
Depth range (Chart datum)	50 - 250 m
Depth range stated by developet	-
Distance from shore	3 - 20 km

Table 48. Location and environment. Cantabrian Offshore Site (COS)

Ports	
Installation base	Santander
Operation and maintenance	Santander

Table 49. Ports. Cantabrian Offshore Site (COS)

4.4 Mediterranean site. Overview of parameters

The Mediterranean basin is currently a less attractive sea basin for offshore renewable energy development, largely because it is a deep sea basin with few suitable areas close to shore.

There are currently no offshore wind farms in the Mediterranean, because the water is deep, and current commercial substructures are limited to 40m to 50m maximum depths. This restricts the potential to exploit offshore wind development in the Mediterranean (http://www.ewea.org/fileadmin/files/library/publications/reports/Deep_Water.pdf)

The Aqua Alta Oceanographic Platform (of ISDGM/CNR), which has been chosen to represent the potential site for the MERMAID MUP in the Mediterranean.

- Located in the Northern Adriatic Sea, East of Italy
- 16 km off the coastline of Venice
- 16m of depth
- Equipped with a meteo-oceanographic station and records:
  - Atmosphere: wind, temperature, humidity, solar radiation, rain
  - Sea: waves, tide, temperature

General information	
Name	Acqua Alta platform
Country	Italy
Region	Venice
Development status	-

Table 50. General Information. Acqua Alta platform

Location and environment	
Sea	Northern Adriatic Sea
Area	-
Depth range (Chart datum)	16 m
Depth range stated by developet	-
Distance from shore	16 km

Table 51. Location and environment. Acqua Alta platform

Ports	
Installation base	Venice
Operation and maintenance	Venice

Table 52. Ports. Acqua Alta platform

4.5 Ranking of foundation concepts for each site

According to the description of the sites performed above, next the analysis of the main structural solutions available for the MUP, obtaining a ranking for each site, will be shown.

Southern North site

Due to the Southern North site characteristics, and specially the averaged water (30 – 35 m), the best solutions are the fixed structures. Bellow the ranking of the best fixed structures for Southern North site:

1. Gravity base structure (GBS)
2. Jacket
3. Suction bucket foundations
4. Monopile

Monopile solutions are close to their technical feasibility limit. Jacktets based solutions are feasible as well as GBS, because of that both of them are on top of the ranking. Suction bucket foundations can also be applied but, more information about soil conditions is needed.

Baltic site

Baltic site is a shallow water area (25 – 30 m), so the best foundation solution are fixed structures. In this case the best concepts are shown below:

1. Monopile
2. Gravity base structure (GBS)
3. Jacket
4. Suction bucket foundations.

In that particular case, monopoles and GBS are the most recommended solutions because of the water depth mainly. Nevertheless, more information about soil conditions are needed in order to select between both. Jacket based structure are technical feasible, however is economically non recommended because monopole and GBS are more competitive.

Atlantic site

The Cantabrian Offshore Site (COS), is mainly characterized for deep and ultra-deep waters, so the floating concepts are the only applicable solution. The main floating solutions are listed below:

1. Semisubmersible
2. Tension Leg Platform (TLP)
3. Barge floater/FPSO
4. Spar

Considering the water depth at the nearest port facilities, SPAR based solutions seems to be not feasible and self-supported solutions during the installation phase seems to be the most convenient solution.

Mediterranean site

The Mediterranean site is a very shallow water area (≈ 16m). Like the other shallow water area the foundation solution are the fixed technologies. In this area, the ranking of fixed structure are:

1. Gravity Base Structure (GBS)
2. Monopile
3. Suction bucket foundations

In this area, the jacket foundations are not recommended because, the cost of fabrication and installation are not competitive with GBS or monopole solutions.
This classification meets with the results of other researches done before. Then, Figure 85 shows the score foundation for different water depths (de Vries, 2007).

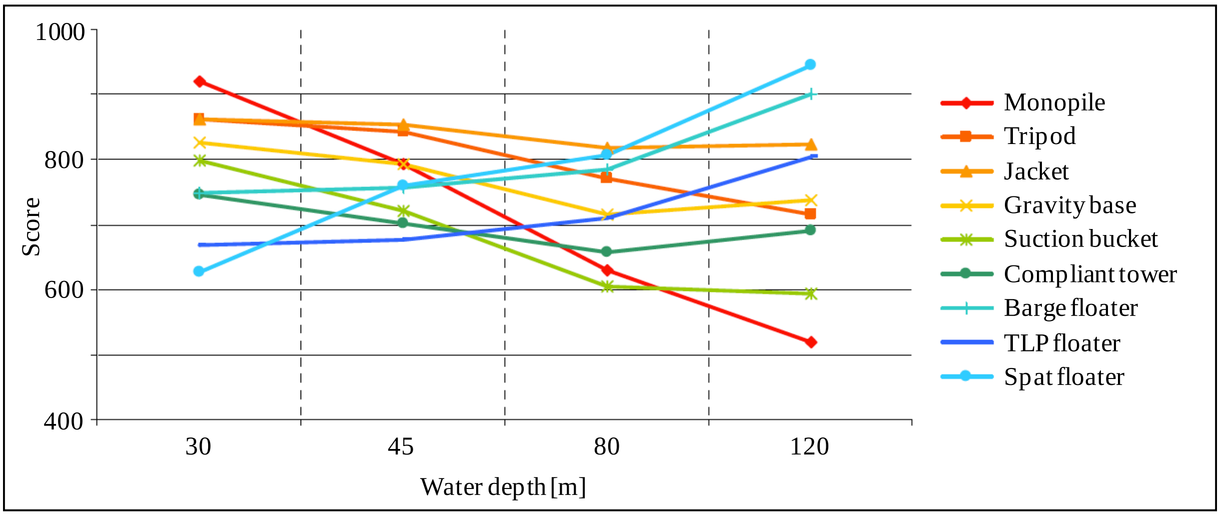


Figure 85. Scored foundations for different water depths (de Vries, 2007)

5 References

A Novel Concept for Self Installing Offshore Wind Turbines (2013)

Abdel-Rahman, K.; Achmus, M. (2008): Numerical Investigation of the Effect of Recent Load History on the Behaviour of Steel Piles under Horizontal Loading. In Proc. of the International Conference of the International Association for Computer Methods and Advances in Geomechanics (IACMAG), October 1-6, Goa, India.

ABS (2013): Guide for building and classing bottom founded offshore wind turbine installations. American Bureau of Shipping.

ABS (2013): Guide for building and classing floating offshore wind turbine installations. American Bureau of Shipping.

Achmus, M.; Abdel Rahman, K.M.; Kuo, Y.S. (2008): Design of Monopile Foundations for Offshore Wind Energy Plants. In Proc. of the 11th Baltic Geotechnical conference - Geotechnics in maritime engineering, 1, pp. 463-470.

Ahmed, F., Rajanatram, N. (1998): Flow around bridge piers. Journal of Hydraulic Engineering, 123(3): 288-300.

Alawa, A.;Cinq-Mars, R.S.;Feeney, P.J.;Irish, J.D.; Edson, D.V. (2009): Assess the design/inspection criteria/standards for wave and/or current energy generating device. Prepared by Free Flow Energy, Inc. for Minerals Management Service Engineering & Research Branch, Lee, New Hampshire, USA, 60 p.

An Integrated Approach for the Representation of Concrete Gravity Based Foundations for Offshore Wind Turbines (OMAE 2013)

An Integrated Approach for the Representation of Concrete Gravity Based Foundations for Offshore Wind Turbines (OMAE 2013)

An Investigation on the Suitability of the P-Y Method for Bottom-Fixed Offshore Wind Turbine Pile Design (OMAE 2013)

An Investigation on the Suitability of the P-Y Method for Bottom-Fixed Offshore Wind Turbine Pile Design (OMAE 2013)

API (2000): Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms Working Stress Design, RP 2A-WSD. American Petroleum Institute, Washington D.C., USA, 2000.

API (2000): Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms Working Stress Design, RP 2A-WSD. American Petroleum Institute, Washington D.C., USA, 2000.

Apsilidis, N.; Diplas, P.; Dancey, C. L.; Vlachos, P. P., Raben, S. G. (2010): Local scour at bridge piers: The role of Reynolds number on horseshoe vortex dynamics. Proceedings of the Fifth International Conference on Scour and Erosion (ICSE-5) November 7-10, San Francisco, California, USA.

AQUATERA LTD (2012): A REVIEW OF THE POTENTIAL IMPACTS OF WAVE AND TIDAL ENERGY DEVELOPMENT ON SCOTLAND'S MARINE ENVIRONMENT, ANNEX 1 – GUIDE TO TECHNICAL COMPONENTS RELEVANT TO WAVE AND TIDAL ENERGY, PREPARED FOR MARINE SCOTLAND.

AWEA (2012): OFFSHORE COMPLIANCE RECOMMENDED PRACTICES 2012: RECOMMENDED PRACTICES FOR DESIGN, DEPLOYMENT, AND OPERATION OF OFFSHORE WIND TURBINES IN THE UNITED STATES, AMERICAN WIND ENERGY ASSOCIATION.

AWS TRUEWIND (2009): OFFSHORE WIND TECHNOLOGY OVERVIEW. PREPARED FOR THE LONG ISLAND-NEWYORK CITY OFFSHORE WIND COLLABORATIVE, AVAILABLE AT HTTP://WWW.LINYCOFFSHOREWIND.COM/PDF/AWS%20TRUEWIND%20OFFSHORE%20WIND%20TECHNOLOGY%20FINAL%20REPORT.PDF

AWS TRUEWIND (2009): OFFSHORE WIND TECHNOLOGY OVERVIEW. PREPARED FOR THE LONG ISLAND-NEWYORK CITY OFFSHORE WIND COLLABORATIVE, AVAILABLE AT HTTP://WWW.LINYCOFFSHOREWIND.COM/PDF/AWS%20TRUEWIND%20OFFSHORE%20WIND%20TECHNOLOGY%20FINAL%20REPORT.PDF

BARLTROP, N.D.P. (1998), FLOATING STRUCTURES: A GUIDE FOR DESIGN AND ANALYSIS, VOL 1 & 2, OPL, LEDBURY, ENGLAND .

BUIGUES, G., ZAMORA, I., MAZÓN, A. J., VALVERDE, V., PÉREZ, F.J., (2006). "SEA ENERGY CONVERSION: PROBLEMS AND POSSIBILITIES". INTERNATIONAL CONFERENCE ON RENEWABLE ENERGIES AND POWER QUALITY, 2006.

BYRNE, B.; HOULSBY, G. (2004): EXPERIMENTAL INVESTIGATIONS OF THE RESPONSE OF SUCTION CAISSONS TO TRANSIENT COMBINED LOADING." J. GEOTECH. GEOENVIRON. ENG., 130(3), 240–253.

CARREIRAS, J. P.; LARROUDE, P.; SEABRA-SANTOS, F., MORY, M. (2000): WAVE SCOUR AROUND PILES. PROCEEDINGS OF THE 27TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING (ICCE). JULY 16-21, SYDNEY, AUSTRALIA.

CHAKRABARTI (2005). HANDBOOK OF OFFSHORE ENGINEERING. VOLUME 1. OFFSHORE STRUCTURE ANALYSIS, INC. PLAINFIELD, ILINOIS, USA.

CHAKRABARTI (2005). HANDBOOK OF OFFSHORE ENGINEERING. VOLUME 1. OFFSHORE STRUCTURE ANALYSIS, INC. PLAINFIELD, ILINOIS, USA.

CHAKRABARTI (2005). HANDBOOK OF OFFSHORE ENGINEERING. VOLUME 2. OFFSHORE STRUCTURE ANALYSIS, INC. PLAINFIELD, ILINOIS, USA.

CHAKRABARTI (2005). HANDBOOK OF OFFSHORE ENGINEERING. VOLUME 2. OFFSHORE STRUCTURE ANALYSIS, INC. PLAINFIELD, ILINOIS, USA.

CROWN ESTATE (2012): OFFSHORE WIND COST REDUCTION PATHWAYS STUDY, LONDON, UK.

DALHOFF, P.; ARGYRIADIS, K.; KLOSE, M. (2007): INTEGRATED LOAD AND STRENGTH ANALYSIS FOR OFFSHORE WIND TURBINES WITH JACKET STRUCTURES. GERMANISCHER LLOYD INDUSTRIAL SERVICES GMBH, BUSINESS SEGMENT WIND ENERGY HAMBURG, GERMANY.

Dargahi, B. (1990): Controlling mechanism of local scouring Journal of Hydraulic Engineering, 116(10): 1197-1214.

De Vos, L.; Frigaard, P.; De Rouck, J. (2007): Wave run-up on cylindrical and cone shaped foundations for offshore wind turbines. Coastal Engineering, vol. 54, pp. 17-29.

De Vos, L.; Troch, P., De Rouck, J. (2008): Experimental analysis of scale effects of the wave induced flow field around a monopile using particle image velocimetry. International Conference on Coastal Engineering (ICCE). August 31-September 5, Hamburg, Germany.

de Vries, W. (2007): Assessment of bottom-mounted support structure types with conventional design stiffness and installation techniques for typical deep water sites. UpWind EU project, WP4.

de Vries, W. (2007): Assessment of bottom-mounted support structure types with conventional design stiffness and installation techniques for typical deep water sites. UpWind EU project, WP4. (repeated)

Dey, S. (1995): Three-dimensional vortex flow field around a circular cylinder in a quasi-equilibrium scour hole. Sadhana 20(6): 871-885.

Dey, S., Raikar, R. V. (2007): Characteristics of horseshoevortex in developing scour hole at piers. Journal of Hydraulic Engineering, 133(4): 399-413.

Dey, S.; Helkjær, A.; Sumer, B. M., Fredsoe, J. (2011): Scour at vertical circular piles in sand-clay mixtures under waves. Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, 137(6): 324-331.

DNV-OS-E301 (2010). "Position Mooring". Offshore Standard. Det Norske Veritas. October 2010.

DNV-OS-E301 (2010). "Position Mooring". Offshore Standard. Det Norske Veritas. October 2010.

DNV-OS-J101 (2010): Design of offshore wind turbine structures, Det Norske Veritas, October 2010.

DNV-OS-J103 (2013): Design of Floating Wind Turbine Structures. Det Norske Veritas. June 2013.

DWIA (2013): www.windpower.org, Danish Wind Industry Association.

DWIA (2013): www.windpower.org, Danish Wind Industry Association.

Dynamic Analysis of Offshore Monopile Wind Turbine Including the Effects of Wind-Wave Loading and Soil Properties (OMAE 2013)

Dynamic Excitation of Monopiles by Steep and Breaking Waves: Experimental and Numerical Study (OMAE 2013)

ENERPAC (2009A): PRESS RELEASE: SYNCHRONIZED LEVELING OF TRIPILE.

ENERPAC (2009B): PERPENDICULAR AT SEA. OFFSHORE INDUSTRY.

EON (2012): EON OFFSHORE WIND ENERGY FACTBOOK. AVAILABLE AT HTTP://WWW.EON.COM/CONTENT/DAM/EON-COM/%C3%9CBER%20UNS/GLOBALE-EINHEITEN/2012_09_11_EON_OFFSHORE_FACTBOOK_EN_PDF_%20FINAL.PDF

EQUIMAR (2009): - DELIVERABLE 7-3-2 "CONSIDERATION OF THE COST IMPLICATIONS FOR MOORING MEC DEVICES".

EQUIMAR (2010): DELIVERABLE D9.1: REPORT ON THE STATE OF OCEAN ENERGY IN EUROPE: TECHNOLOGIES, TEST SITES, AND JOINT PROJECTS. AVAILABLE AT: HTTPS://WWW.WIKI.ED.AC.UK/DOWNLOAD/ATTACHMENTS/9142387/EQUIMAR+D+9.1+EU-OEA-2.PDF?VERSION=1.

ESTIMATION OF EQUIVALENT DYNAMIC AMPLIFICATION FACTOR (EDAF) ON A JACKET STRUCTURE (OMAE 2013)

EWEA (2009): WIND ENERGY - THE FACTS - PART I: TECHNOLOGY.

EWEA (2013): THE EUROPEAN OFFSHORE WIND INDUSTRY - KEY TRENDS AND STATISTICS 2012. AVAILABLE AT HTTP://WWW.SGURRENERGY.COM/WP-CONTENT/UPLOADS/2013/01/EWEA-EUROPEAN-OFFSHORE-WIND-INDUSTRY-2012-JAN-13.PDF

EWEA (2013): THE EUROPEAN OFFSHORE WIND INDUSTRY - KEY TRENDS AND STATISTICS 2012. AVAILABLE AT HTTP://WWW.SGURRENERGY.COM/WP-CONTENT/UPLOADS/2013/01/EWEA-EUROPEAN-OFFSHORE-WIND-INDUSTRY-2012-JAN-13.PDF

FARACI, C.; FOTI, E., BAGLIO, S. (2000): MEASUREMENTS OF SANDY BED SCOUR PROCESSES IN AN OSCILLATING FLOW BY USING STRUCTURED LIGHT. MEASUREMENT, 28: 159-174.

FLOATEC. CHRISTOPHER M. BARTON (2010). AN OVERVIEW OF OFFSHORE CONCEPTS. SPE EXPANDING FACILITIES KNOWLEDGE WORKSHOP. SESSION 1: OFFSHORE CONCEPTS SELECTION.

FLOATEC. CHRISTOPHER M. BARTON (2010). AN OVERVIEW OF OFFSHORE CONCEPTS. SPE EXPANDING FACILITIES KNOWLEDGE WORKSHOP. SESSION 1: OFFSHORE CONCEPTS SELECTION.

FREDRIKSSON, D. W., TSUKROV, I., HUDSON, P. (2008). "ENGINEERING INVESTIGATION OF DESIGN PROCEDURES FOR CLOSED CONTAINMENT MARINE AQUACULTURE SYSTEMS". AQUACULTURAL ENGINEERING 39 (2008) 91–102.

FREDRIKSSON, D. W., TSUKROV, I., HUDSON, P. (2008). "ENGINEERING INVESTIGATION OF DESIGN PROCEDURES FOR CLOSED CONTAINMENT MARINE AQUACULTURE SYSTEMS". AQUACULTURAL ENGINEERING 39 (2008) 91–102.

GRAF, W. H., ISTIARTO, I. (2002): FLOW PATTERN IN THE SCOUR HOLE AROUND A CYLINDER. JOURNAL OF HYDRAULIC RESEARCH, 40(1): 13-20.

GRIFFITHS, J.W. (2011): BENEFITS OF STANDARDS DEVELOPMENT FOR THE OCEAN ENERGY INDUSTRY. IN PROC. OF THE EUROPEAN WAVE AND TIDAL ENERGY CONFERENCE 2011, SOUTHAMPTAN, UK.

Griffiths, J.W. (2011): Benefits of standards development for the ocean energy industry. In Proc. Of the European Wave and Tidal Energy Conference 2011, Southamptan, UK.

Grüne, J.; Sparboom, R.; Schmidt-Koppenhagen, S.; Oumeraci, H.; Mitzlaff, A.; Uecker, J.; Peters, K. (2006): Innovative Scour Protection with Geotextile Sand Containers for Offshore Monopile Foundations of Wind Energy Turbines. In Proc. 30th Int. Conference on Coastal Engineering (ICCE).

Hammar, L.; Andersson, S.; Rosenberg, R. (2010): Adapting offshore wind power foundations to local environment.

Hammar, L.; Andersson, S.; Rosenberg, R. (2010): Adapting offshore wind power foundations to local environment.

Hearn, E. and Edgers, L. (2010) Finite Element Analysis of an Offshore Wind Turbine Monopile. GeoFlorida 2010: pp. 1857-1865. doi: 10.1061/41095(365)188.

Hildebrandt, A.; Sparboom, U.; Oumeraci, H. (2008): Wave Forces on Groups of Slender Cylinders in Comparison to an Isolated Cylinder due to Non-Breaking Waves. Proc. 31st Int. Conf. on Coastal Engineering (ICCE), Hamburg, Germany.

Hildebrandt, A.; Sparboom, U.; Oumeraci, H. (2008): Wave Forces on Groups of Slender Cylinders in Comparison to an Isolated Cylinder due to Non-Breaking Waves. Proc. 31st Int. Conf. on Coastal Engineering (ICCE), Hamburg, Germany.

http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29WW.1943-5460.0000148 (scour around monopile)

http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29WW.1943-5460.0000148

http://bruwind.eu/sites/default/files/Paper_EWEA_2013_Devriendt_Christof_v2.pdf (Monitoring of resonant frequencies and damping values of an offshore wind turbineon a monopile foundation) – FIELD STUDY -

http://discovery.dundee.ac.uk/portal/en/research/dynamic-soilstructure-interaction-of-monopile-supported-wind-turbines-in-cohesive-soil%283620e528-6d50-490b-b916-accbd298a2ce%29.html (Dynamic soil-structure interaction of monopile supported wind turbines in cohesive soil)

http://isotc.iso.org/livelink/livelink/fetch/2000/2122/639895/639896/4612559/WPC2 StandardsColumnsPosters2005.pdf?nodeid=4613433&vernum=0.

http://journals.tdl.org/icce/index.php/icce/article/view/6574

http://journals.tdl.org/icce/index.php/icce/article/view/6574 (Investigations on scour development around a gravity foundation for offshore wind turbines)

http://journals.tdl.org/icce/index.php/icce/article/view/6655

http://journals.tdl.org/icce/index.php/icce/article/view/6655 (Investigations on scour development at tripod foundations for offshore wind turbines: modeling and application) http://mragheb.com/NPRE%20475%20Wind%20Power%20Systems/Offshore%20Wind%20Farms%20Siting.pdf

http://orbit.dtu.dk/fedora/objects/orbit:115591/datastreams/file_bf137096-f7b5-4825-a048-1c31b2bddfbb/content (PhD thesis, 2012) (Interaction between seabed soil and offshore wind turbine foundations)

http://orbit.dtu.dk/fedora/objects/orbit:115591/datastreams/file_bf137096-f7b5-4825-a048-1c31b2bddfbb/content

http://utpedia.utp.edu.my/6053/

http://utpedia.utp.edu.my/6053/ (Experimental study on the effect of foundation configurations on dynamic responses of wind tower)

http://vbn.aau.dk/files/36941808/Dynamic%20Analysis%20of%20a%20Monopile%20Model.pdf (monopile)

http://vbn.aau.dk/files/36941808/Dynamic%20Analysis%20of%20a%20Monopile%20Model.pdf

http://vbn.aau.dk/files/77916828/Assessment_of_p_y_Curves_from_Numerical.pdf

http://vbn.aau.dk/files/77916828/Assessment_of_p_y_Curves_from_Numerical.pdf

http://www.bureauveritas.com/

http://www.bureauveritas.com/

http://www.cowi.com/menu/service/BridgeTunnelandMarineStructures/Offshorewindfarms/Offshorefoundations/Monopiles/Pages/Monopiles.aspx

http://www.dnv.com/

http://www.dnv.com/

http://www.emec.org.uk/standards.asp

http://www.emec.org.uk/standards.asp

http://www.gl-group.com/en/index.php

http://www.gl-group.com/en/index.php

http://www.iec.ch

http://www.iec.ch

http://www.ipublishing.co.in/ijcserarticles/twelve/articles/volthree/EIJCSE3161.pdf (Numerical evaluation of long term monopile head behavior for ocean energy converters under sustained low amplitude lateral loading)

HTTP://WWW.IPUBLISHING.CO.IN/IJCSERARTICLES/TWELVE/ARTICLES/VOLTHREE/EIJCSE3161.PDF

HTTP://WWW.ISOPE.ORG/PUBLICATIONS/PROCEEDINGS/ISOPE/ISOPE%202011/DATA/PAPERS/11TPC-287HARTWI.PDF

HTTP://WWW.ISOPE.ORG/PUBLICATIONS/PROCEEDINGS/ISOPE/ISOPE%202011/DATA/PAPERS/11TPC-287HARTWI.PDF

HTTP://WWW.OOAE.ORG/ATTACHMENTS/FILES/224/CONTENTS_07.PDF

HTTP://WWW.OOAE.ORG/ATTACHMENTS/FILES/224/CONTENTS_07.PDF (WAVE LOADS ON A MONOPILE IN 3D WAVES (OMAE 2012))

HTTP://WWW.RISOE.DK/VEA/RECOFF/

HTTP://WWW.RISOE.DK/VEA/RECOFF/

HTTP://WWW.SUPERGEN-WIND.ORG.UK/DOCS/PRESENTATIONS/5TH_SEMINAR_PRESENTATIONS/2012-EDINBURGHPRESENTATION-J_LUXMOORE.PDF (MODELING THE LOADING ON TURBINE SUBSEA STRUCTURES)

HTTP://WWW-CIVIL.ENG.OX.AC.UK/RESEARCH/OFFSHORE/REPORTS/WEVOL24NO4.PDF (SUCTION CAISSON FOUNDATIONS)

HTTP://WWW-CIVIL.ENG.OX.AC.UK/RESEARCH/OFFSHORE/REPORTS/WEVOL24NO4.PDF

IEC (2013): HTTP://WWW.IEC.CH/DYN/WWW/F?P=103:23:0::::FSP_ORG_ID,FSP_LANG_ID:1316,25. ACCESSED ON 07.03.2013.

JACOBSEN, V. AND RUGBJERG, M. (2005). OFFSHORE WIND FARMS - THE NEED FOT METOCEAN DATA. COPENHAGEN OFFSHORE WIND CONFERENCE 2005.

JACOBSEN, V. AND RUGBJERG, M. (2005). OFFSHORE WIND FARMS - THE NEED FOT METOCEAN DATA. COPENHAGEN OFFSHORE WIND CONFERENCE 2005.

JOHANNING, L. (2009). "MOORING SYSTEMS FOR WAVE ENERGY CONVERTERS: A REVIEW OF DESIGN ISSUES AND CHOICES".

JOHANNING, L. (2009). "MOORING SYSTEMS FOR WAVE ENERGY CONVERTERS: A REVIEW OF DESIGN ISSUES AND CHOICES".

JONKMAN, J., BUTTERFIELD, S., MUSIAL, W. AND SCOTT G (2009). DEFINITION OF A 5-MW REFERENCE WIND TURBINE FOR OFFSHORE SYSTEM DEVELOPMENT. TECHNICAL REPORT NREL/ TP 500-38060.

JONKMAN, J., BUTTERFIELD, S., MUSIAL, W. AND SCOTT G (2009). DEFINITION OF A 5-MW REFERENCE WIND TURBINE FOR OFFSHORE SYSTEM DEVELOPMENT. TECHNICAL REPORT NREL/ TP 500-38060.

JUILFS, J. (2006): BREAKING WAVE LOADS ON A VERTICAL SLENDER CYLINDER WITHIN A CYLINDER GROUP. GRADUATE STUDY, TU BRAUNSCHWEIG.

KIRKIL, G.; CONSTANTINESCU, S. G., ETTEMA, R. (2008): COHERENT STRUCTURES IN THE FLOW FIELD AROUND A CIRCULAR CYLINDER WITH SCOUR HOLE. JOURNAL OF HYDRAULIC ENGINEERING, 134(5): 572-587.

KOBAYASHI, N., ODA, K. (1994): EXPERIMENTAL STUDY ON DEVELOPING PROCESS OF LOCAL SCOUR AROUND A VERTICAL CYLINDER. PROCEEDINGS 24TH INTERNATIONAL CONFERENCE COASTAL ENGINEERING (ICCE). ASCE, APRIL 7, KOBE, JAPAN.

KOBAYASHI, T. (1992): 3-D ANALYSIS OF FLOW AROUND A VERTICAL CYLINDER ON A SCOURED BED. PROCEEDINGS OF THE 23RD INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING. OCTOBER 4-9, VENICE, ITALY.

KOCA, K.; OUMERACI, H. (2012): WAVE-INDUCED SCOUR AROUND MONOPILE FOUNDATIONS: PROCESS BASED MODELING, INTERNAL REPORT (CONFIDENTIAL).

KOCA, K.; OUMERACI, H. (2012): WAVE-INDUCED SCOUR AROUND MONOPILE FOUNDATIONS: PROCESS BASED MODELING, TU BRAUNSCHWEIG, INTERNAL REPORT (CONFIDENTIAL).

KUO, Y.S.; ACHMUS, M; KAO, C.S. (2008): PRACTICAL DESIGN CONSIDERATIONS OF MONOPILE FOUNDATIONS WITH RESPECT TO SCOUR, GLOBAL WIND POWER, BEIJING, AVAILABLE AT FILEADMIN/GIGAWIND/PAPERS...BE/PAPER_BEIJING_2008.PDF

LESNY, K. (2010): FOUNDATIONS OF OFFSHORE WIND TURBINES. VGE VERLAG.

LESNY, K. (2010): FOUNDATIONS OF OFFSHORE WIND TURBINES. VGE VERLAG.

LI, C.; LU, X.; WANG, S. (2010): ON THE CAPACITY AND DEFORMATION OF BUCKET FOUNDATION UNDER DYNAMIC LOADINGS. IN PROC. IF THE INTERNATIONAL OFFSHORE AND POLAR ENGINEERING CONFERENCE, BEIJING, CHINA, JUNE 20-25.

MARX, S.; SCHMIDT, B.; GÖHLMANN, J.; GÖTHEL, O. (2012): CONCEPTS OF GRAVITY BASE FOUNDATIONS. RAVE - INTERNATIONAL CONFERENCE, BREMERHAVEN, GERMANY.

MARX, S.; SCHMIDT, B.; GÖHLMANN, J.; GÖTHEL, O. (2012): CONCEPTS OF GRAVITY BASE FOUNDATIONS. RAVE - INTERNATIONAL CONFERENCE, BREMERHAVEN, GERMANY.

MELVILLE, B. W., RAUDKIVI, A. J. (1977): FLOW CHARACTERISTICS IN LOCAL SCOUR AT BRIDGE PIERS. JOURNAL OF HYDRAULIC RESEARCH, 15(4): 373-380.

MERMAID, “INTERNAL DELIVERABLE 3.3.2: WAVE ENERGY CONVERTERS,” EU PROJECT REPORT, 2013 (CONFIDENTIAL).

MODELING OF WAVE-INDUCED SEABED RESPONSE AND LIQUEFACTION POTENTIAL AROUND PILE FOUNDATION (OMAE 2013)

MODELING OF WAVE-INDUCED SEABED RESPONSE AND LIQUEFACTION POTENTIAL AROUND PILE FOUNDATION (OMAE 2013)

MUSTANG. DARYL B. RAPP (2010). AN OVERVIEW OF OFFSHORE CONCEPTS. CONCEPTS. SPE EXPANDING FACILITIES KNOWLEDGE WORKSHOP. SESSION 1: OFFSHORE CONCEPTS SELECTION.

MUSTANG. Daryl B. Rapp (2010). An Overview of Offshore Concepts. Concepts. SPE Expanding Facilities Knowledge Workshop. Session 1: Offshore Concepts Selection.

Muzzammil, M., Gangadhariah (2003): The mean characteristics of horseshoe vortex at a cylindrical pier. Journal of Hydraulic Research, 41(3): 285–297.

Nadeau, M. (2009): The standardization of Marine Renewable Energy Conversion Systems. in IEA OES Annual Report 2009.

Natvig, B.J. & Teigen, P. 1993. "Review of hydrodynamic challenges in TLP Design". Proceedings of the 3rd International Offshore and Polar Engineering Conference, Singapure, pp. 294 – 302.

Natvig, B.J. & Teigen, P. 1993. "Review of hydrodynamic challenges in TLP Design". Proceedings of the 3rd International Offshore and Polar Engineering Conference, Singapure, pp. 294 – 302.

Nonlinear Wave Group Impact on a Cylindrical Monopile (OMAE 2013)

Nonlinear Wave Group Impact on a Cylindrical Monopile (OMAE 2013)

NREL (2005). NREL-SR-500-40282 "Semi-Submersible Platform and Anchor Foundation Systems for Wind Turbine Support".

NREL (2005). NREL-SR-500-40282 "Semi-Submersible Platform and Anchor Foundation Systems for Wind Turbine Support".

Numerical Simulation of Ship Collision With Gravity Base Foundations of Offshore Wind Turbines (OMAE 2013)

Numerical Simulation of Ship Collision With Gravity Base Foundations of Offshore Wind Turbines (OMAE 2013)

Numerical Simulations for Installation of Offshore Wind Turbine Monopiles Using Floating Vessels (OMAE 2013)

Numerical Simulations for Installation of Offshore Wind Turbine Monopiles Using Floating Vessels (OMAE 2013)

Offshore Magazine, 2002. www.offshore-mag.com.

Offshore Magazine, 2002. www.offshore-mag.com.

OTC (2003). OTC 15265: "Industry Trends for Design of Anchoring Systems for Deepwater Offshore Structures", 2003.

OTC (2003). OTC 15265: "Industry Trends for Design of Anchoring Systems for Deepwater Offshore Structures", 2003.

Oumeraci, H. (2009): Evaluation report on composite modelling of piles and spheres, Task 5 - Scour around vertical slender monopile.Composite Modelling of the Interactions

Between Beaches and Structures (CoMIBBS), HydralabIII,Report JRA1-09-10 available at http://www.hydralab.eu: 75 p.

Pitt, E.G. (2009): Assessment of performance of wave energy conversion systems. Department of Trade and Industry.

Pitt, E.G. (2009): Assessment of performance of wave energy conversion systems. Department of Trade and Industry.

Powered (2012): Technological state of the art. Powered - green energy in Adriatic sea, pp. 49-64.

Powered (2012): Technological state of the art. Powered - green energy in Adriatic sea, pp. 49-64.

Prepernau, U.; Grüne, J.; Sparboom, U.; Schmidt-Koppenhagen, R.; Wany, Z.; Oumeraci, H. (2008): Large-scale model study on scour around slender monopiles induced by irregular waves. In Proc. International Conference on Coastal Engineering, Beijing, China.

Rahman, K.A.; Achamus, M. (2006): Behaviour of Monopile and Suction Bucket Foundation Systems for Offshore Wind Energy Plants.

Rahman, K.A.; Achamus, M. (2006): Behaviour of Monopile and Suction Bucket Foundation Systems for Offshore Wind Energy Plants.

Random Wave Forces on Monopile Wind Turbine Foundations: A Comparison of Wave Models (OMAE 2013)

Random Wave Forces on Monopile Wind Turbine Foundations: A Comparison of Wave Models (OMAE 2013)

Roddier, D., Cermelli, C., Aubault, A., Weinstein, A. (2010). WindFloat: A floating foundation for offshore wind turbines Journal of Renewable and Sustainable Energy 2 (3) , art. no. 033104

Roddier, D., Cermelli, C., Aubault, A., Weinstein, A. (2010). WindFloat: A floating foundation for offshore wind turbines Journal of Renewable and Sustainable Energy 2 (3) , art. no. 033104

Rudolph, D., Bos, K. J. (2006): Scour around a monopile under combined wave-current conditions and low KC-numbers. Proceeding of the International Conference on Scour and Erosion (ICSE). August 24-28, Amsterdam, the Netherlands.

Schmidtke and Oumeraci (2011): Zeitliche kolktiefenentwicklung um einen monopile unter wellen – erosion and sedimentation, 8. FZK-Kolloquium 2011, Hannover, Germany.

Sclavounos, P., Tracy, C., Lee, S. (2008) Floating offshore wind turbines: Responses in a seastate Pareto optimal designs and economic assessment. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE 6, pp. 31-41

Sclavounos, P., Tracy, C., Lee, S. (2008) Floating offshore wind turbines: Responses in a seastate Pareto optimal designs and economic assessment. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE 6, pp. 31-41

SGS (2005): Support Structure Concepts. SGS Group, report to Vattenfall, pp. 13.

SGS (2005): Support Structure Concepts. SGS Group, report to Vattenfall, pp. 13.

Singh, B.; Mistri, B.; Patel, R. (2010): Comparison of foundation systems for offshore wind turbine installation. ICTT Civil Engineering Papers.

Singh, B.; Mistri, B.; Patel, R. (2010): Comparison of foundation systems for offshore wind turbine installation. ICTT Civil Engineering Papers.

Smith, G.H.; Taylor, J. (2008): "Preliminary wave energy device protocol." Department of Trade and Industry.

Smith, G.H.; Taylor, J. (2008): "Preliminary wave energy device protocol." Department of Trade and Industry.

SOUND & SEA TECHNOLOGY ENGINEERING (2010): ADVANCED ANCHORING AND MOORING STUDY. PORTLAND, OR: OREGON WAVE ENERGY TRUST. 192 PP.Sparboom, U.; Hildebrandt, A.; Oumeraci, H. (2006): Group interaction effects of slender cylinders under wave attack. In Proc. 30th Int. Conference on Coastal Engineering (ICCE), ASCE.

Sparboom, U.; Hildebrandt, A.; Oumeraci, H. (2006): Group interaction effects of slender cylinders under wave attack. In Proc. 30th Int. Conference on Coastal Engineering (ICCE), ASCE.

Sparboom, U.; Oumeraci, H. (2006): Wave loads of slender marine cylinders depending on interaction effects of adjacent cylinders. In Proc. 25th Int. Conference on Offshore Mechanics and Arctic Engineering (OMAE), Hamburg, Germany.

Sparboom, U.; Oumeraci, H. (2006): Wave loads of slender marine cylinders depending on interaction effects of adjacent cylinders. In Proc. 25th Int. Conference on Offshore Mechanics and Arctic Engineering (OMAE), Hamburg, Germany.

Stallard, T.; Johanning, L.; Smith, G. (2010): Guidelines regarding the variation of infrastructure requirements with scale of deployment. Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact.

Stallard, T.; Johanning, L.; Smith, G. (2010): Guidelines regarding the variation of infrastructure requirements with scale of deployment. Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact.

Sumer, B. M., Fredsøe, J. (2001): Scour around pile in combined waves and current. Journal of Hydraulic Engineering: pp. 403- 411.

Sumer, B. M.; Christensen, N., Fredsoe, J. (1997): The horseshoe vortex and vortex shedding around a vertical wall mounted cylinder exposed to waves. Journal of Fluid Mechanics, 332: 41-70.

Sumer, B. M.; Fredsöe, J., Christiansen, N. (1992): Scour around vertical pile in waves. Journal of Waterway, Port, Coastal and Ocean Engineering, vol. 118(no. 1): pp. 15-31.

Teich, T. (2013): Comparison of offshore foundations in terms of their applicability to multi-use offshore platforms, Bachelor thesis, Leichtweiß Institute for Hydraulic Engineering and Water Resources, Technische Universität of Braunschweig, Germany.

Teich, T. (2013): Comparison of offshore foundations in terms of their applicability to multi-use offshore platforms, Bachelor thesis, Leichtweiß Institute for Hydraulic Engineering and Water Resources, Technische Universität of Braunschweig, Germany. (repeated)

Tina (2012): Technology innovation needs assessment – offshore wind power summary report.

Tina (2012): Technology innovation needs assessment – offshore wind power summary report.

Umeda, S. (2011): Scour regime and scour depth around a pile in waves. Proceedings of the 11th International Coastal Symposium. Journal of Coastal Research, SI 64, May 9-14, Szczecin, Poland.

Unger, J., Hager, W. H. (2007): Down-flow and horseshoe vortex characteristics of sediment embedded bridge piers. Exp Fluids, 42: 1-19.

URL 1 http://www.springerreference.com/docs/html/chapterdbid/332788.html

URL 1 http://www.springerreference.com/docs/html/chapterdbid/332788.html

URL 10 http://www.universalfoundation.dk/en/buckets/9/3/2

URL 10 http://www.universalfoundation.dk/en/buckets/9/3/2

URL 11 http://www.carbontrust.com/media/265248/owa-driving-down-cost-offshore-wind-7-march-2013.pdf

URL 11 http://www.carbontrust.com/media/265248/owa-driving-down-cost-offshore-wind-7-march-2013.pdf

URL 12 http://www.carbontrust.com/media/105310/foundations_presentation-2apr12-pdv.pdf

URL 12 http://www.carbontrust.com/media/105310/foundations_presentation-2apr12-pdv.pdf

URL 13 http://gbf.eu.com/index.html

URL 13 HTTP://GBF.EU.COM/INDEX.HTML

URL 14 HTTP://WWW.SPTOFFSHORE.COM

URL 14 HTTP://WWW.SPTOFFSHORE.COM

URL 15 HTTP://WWW.CARBONTRUST.COM/MEDIA/105330/OFFSHORE-WIND-ACCELERATOR-SATGE-1--JUNE-2010BS.PDF

URL 15 HTTP://WWW.CARBONTRUST.COM/MEDIA/105330/OFFSHORE-WIND-ACCELERATOR-SATGE-1--JUNE-2010BS.PDF

URL 16 HTTP://SOCIAL.WINDENERGYUPDATE.COM/OFFSHORE-WIND/FOUNDATION-INSTALLATIONS-FOCUS-DEEP-WATER-PROJECT-IMPROVEMENTS

URL 16 HTTP://SOCIAL.WINDENERGYUPDATE.COM/OFFSHORE-WIND/FOUNDATION-INSTALLATIONS-FOCUS-DEEP-WATER-PROJECT-IMPROVEMENTS

URL 17 WWW.SEABASED.COM

URL 17 WWW.SEABASED.COM

URL 18 WWW.PLYMOUTH.AC.UK

URL 18 WWW.PLYMOUTH.AC.UK

URL 19 HTTP://MRAGHEB.COM/NPRE%20475%20WIND%20POWER%20SYSTEMS/OFFSHORE%20WIND%20FARMS%20SITING.PDF

URL 2 HTTP://SOCIAL.WINDENERGYUPDATE.COM/OPERATIONS-MAINTENANCE/GRAVITY-BASE-FOUNDATIONS-BUILDING-ADVANTAGES-AND-NEW-INNOVATION

URL 2 HTTP://SOCIAL.WINDENERGYUPDATE.COM/OPERATIONS-MAINTENANCE/GRAVITY-BASE-FOUNDATIONS-BUILDING-ADVANTAGES-AND-NEW-INNOVATION

URL 20

URL 20 HTTP://WWW.COWI.COM/MENU/SERVICE/BRIDGETUNNELANDMARINESTRUCTURES/OFFSHOREWINDFARMS/OFFSHOREFOUNDATIONS/MONOPILES/PAGES/MONOPILES.ASPX

URL 21 HTTP://WWW.LORC.DK/OFFSHORE-WIND-FARMS-MAP/TUNO-KNOB?OS_SST=GRAVITY+BASED

URL 21 HTTP://WWW.LORC.DK/OFFSHORE-WIND-FARMS-MAP/TUNO-KNOB?OS_SST=GRAVITY+BASED

URL 22 HTTP://ALPHA-VENTUS.DE/

URL 22 HTTP://ALPHA-VENTUS.DE/

URL 23 http://www.dnv.com/press_area/press_releases/2013/dnv_kema_releases_floating_offshore_wind_turbine_structures_standard.asp

URL 23 http://www.dnv.com/press_area/press_releases/2013/dnv_kema_releases_floating_offshore_wind_turbine_structures_standard.asp

URL 24 EquiMar, http://www.equimar.org

URL 24 EquiMar, http://www.equimar.org

URL 25 EquiMar protocols from http://www.equimar.org/high-level-equimar-protocols-.html

URL 25 EquiMar protocols from http://www.equimar.org/high-level-equimar-protocols-.html

URL 26 EquiMar deliverables from http://www.equimar.org/equimar-project-deliverables.html

URL 26 EquiMar deliverables from http://www.equimar.org/equimar-project-deliverables.html

URL 3 http://www.lorc.dk/Knowledge/Wind/Support-structures

URL 3 http://www.lorc.dk/Knowledge/Wind/Support-structures

URL 4 http://canales.elnortedecastilla.es/varios/documentos/ensayos-en-canal.pdf

URL 4 http://canales.elnortedecastilla.es/varios/documentos/ensayos-en-canal.pdf

URL 4 http://www.bnoffshore.com/page_10352.asp):

URL 5 “GICON SOF Floating offshore platform factsheet”, http://www.gicon.de/en/sof

URL 5 “GICON SOF Floating offshore platform factsheet”, http://www.gicon.de/en/sof

URL 6 http://www.ideol-offshore.com/en

URL 6 http://www.ideol-offshore.com/en

URL 7 http://mth.com/~/media/Files/com/Offshore/Cranefree/MTH_seatower_fakta_highres.ashx

URL 7 http://mth.com/~/media/Files/com/Offshore/Cranefree/MTH_seatower_fakta_highres.ashx

URL 8 http://www.windcomm.de/_trash/obmc2010/downloads/PetterKaralSeatower.pdf

URL 8 http://www.windcomm.de/_trash/obmc2010/downloads/PetterKaralSeatower.pdf

URL 9 http://www.carbontrust.com/media/105314/foundation_innovators_29may2012.pdf

URL 9 http://www.carbontrust.com/media/105314/foundation_innovators_29may2012.pdf

Wang, Y.; Lu, X.; Wang, S.; Shi, Z. (2006): The response of bucket foundation under horizontal dynamic loading. Ocean Engineering, 33 (2006) 964–973.

Wave Diffraction Forces on Offshore Wind Turbine Piles With an Octagonal Cross Section (OMAE 2013)

Wave Diffraction Forces on Offshore Wind Turbine Piles With an Octagonal Cross Section (OMAE 2013)

WAVEPLAM (2009): Deliverables D 2.1 State of the Art Analysis - A Cautiously Optimistic Review of the Technical Status of Wave Energy Technology available at http://www.waveplam.eu/files/downloads/SoA.pdf.

Wavetrain (2007): Deliverable 7b: Device performance reporting – status outline. Available at http://www.wavetrain2.eu/files/21/cms_31c0c178a9fc26ffecffd8670e6d746d.pdf, 30 p.

Westgate, Z.J.; DeJong, J.T. (2005): Geotechnical considerations for offshore wind turbines.

Westgate, Z.J.; DeJong, J.T. (2005): Geotechnical considerations for offshore wind turbines. WEU (2013): Wind Energy Update – Offshore foundations report 2013.

WEU (2013): Wind Energy Update – Offshore foundations report 2013.

Wienke, J.; Oumeraci, H. (2005): Breaking wave impact force on a vertical and inclined slender pile – theoretical and large scale model investigations. Coastal Engineering, 41(3): 285-297.

Williams, D.; Clayton, J.; Gibberd, G. (2011): Industrial development potential of offshore wind in Ireland. Garrad Hassan.

Williams, D.; Clayton, J.; Gibberd, G. (2011): Industrial development potential of offshore wind in Ireland. Garrad Hassan.

Williamson, C. H. K. (1985): Sinusoidal flow relative to circular cylinders. Journal of Fluid Mechanics, 155: 141-174.

Woebbeking, M.; Argyriadis, K.; Dippel, M. (2012): New guideline for offshore wind turbines. Germanischer Lloyd, Germany.

Yang, R.; Chen, H.; Hwung, H.; Jiang, W.; Wu, N. (2010): Experimental study on the loading and scour of the jacket type offshore wind turbine foundation. In Proc. of the International Offshore and Polar Engineering Conference, Beijing, China, June 20-25.

ZANKE, U. C. E.; HSU, T. W.; ROLAND, A.; LINK, O., DIAB, R. (2011): EQUILIBRIUM SCOUR DEPTHS AROUND PILES IN NONCOHESIVE SEDIMENTS UNDER CURRENTS AND WAVES. COASTAL ENGINEERING, 58: 986-991.