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Seventh Framework Programme
Theme [OCEAN.2011-1]
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Grant Agreement no.: 288710
Start date of project: 01 Jan 2012 - Duration: 48 month

Energy converters

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Offshore wind energy converters

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Table of contents

1 Introduction

Today's wind turbines are huge compared to those of just one decade ago, and the trend of the industry is toward larger machines. Although wind turbines seem to be simple machines, they are complicated machines to control, particularly if high performance and good efficiency are needed. Safe and high performance of these machines is possible only through technological progress in control systems, electronics, communications, and their integration with the laws of mechanics that govern the behavior of such machines.

Understanding the rules of nature and the behavior of a wind turbine, together with the ways its operation can be regulated as desired, is called "wind turbine technology." This subject requires specialized knowledge from different areas linked together, to work on them, and to carry out further research and development on their functionality.

Wind and water have been two main energy sources for humanity. Watermills and windmills have been used for applications such as milling grain for food production and irrigation, where animals would otherwise have been used as power source. Early reports and remaining ruins of Persian vertical-axis (its axis of rotation is vertical) windmills can be traced back for 1000 years. The famous Dutch windmill, with a horizontal axis (its axis of rotation is horizontal), existed since the twelfth century.

The new era of interest in wind turbines for generating electricity started in the 70s because of the oil crisis of 1972. European countries were more affected than other countries and placed full attention on this renewable source of energy. Before 1992, commercial wind turbines were very small (225 kilowatts), but as a result of technological progress, by the end of 2002 turbine size had grown by a factor of 10. As inland and offshore wind farms were being developed in European countries, North America's attention to renewable energy was brought back.

With the installation of a record 6183 MW (megawatt) wind farm (a wind power generation facility where numerous wind turbines are installed) in 2005, wind energy achieved the European Commission's 40000 MW target for 2010, 5 years ahead of time. In 2005 Denmark obtained 20% of its total electric energy requirement from wind. Between 2000 and 2008 the wind industry in the United States showed a growth of around 29% every year, with 5249 MW installation in 2007 and 8500 MW installation in 2008. Although the industry, like other market segments, suffered in 2009, it is envisioned that wind can supply 20% of U.S. electricity by 2030. According to the European Wind Energy Association (EWEA), in 2009 a total of eight new wind farms consisting of 199 offshore wind turbines, with a combined power generating capacity of 577 MW, were connected to the grid in Europe.

In the near future, European seas will be subjected to a massive development of marine infrastructures. The most obvious structures include offshore wind farms, constructions for marine aquaculture and the exploitation of wave energy. The development of these facilities will increase the need for marine infrastructures to support their installation and operation and these will unavoidably exert environmental pressures on the marine ecosystems. It is therefore crucial that economic costs, the use of marine space and the environmental impacts of these activities remain within acceptable limits. Hence, offshore platforms that combine multiple functions within the same infrastructure offer significant economical and environmental benefits.

2 Wind energy conversion

2.1 Introduction

Wind energy is a source of renewable power which comes from air currents flowing across the earth's surface. Wind turbines harvest this kinetic energy and convert it into usable power which can provide electricity for home, farm, school or business applications on small (residential), medium (community), or large (utility) scales.

Wind energy is today one of the fastest growing sources of new electricity generation worldwide. These growth trends can be linked to the multi-dimensional benefits associated with wind energy:

- Green power: The electricity produced from wind power is said to be "clean" because its generation produces no pollution or greenhouse gases. As both health and environmental concerns are on the rise, clean energy sources are under growing demand.
- Sustainable: Wind is a renewable energy source, it is inexhaustible and requires no "fuel" besides the wind that blows across the earth. This infinite energy supply provides a stable investment in the energy economy.
- Affordable: Wind power is a cost-competitive source of electricity, largely due to technological advancements, but also because of the economies of scale, as more of these machines are manufactured and located around the world.
- Economic Development: Wind power is a locally-produced source of electricity that enables communities to keep energy incomes in their own economy. Job creation (manufacturing, service, construction, and operation) and taxes are other economic development benefits for communities utilizing wind energy.

Wind Energy has a number of advantages and a small number of drawbacks. Some advantages common to offshore and onshore wind energy:

- No pollution and global warming effects: Wind turbines do not lead to pollution which is one of the biggest advantages of wind energy. Note that there are costs associated with the equipment used to build and transport wind equipment but harvesting wind energy leads to no pollution.

- Low costs: The cost of wind energy has reached the level of gas powered energy and can be generated at extremely low rates with favorable conditions.
- Big industrial base: Wind energy has become a mainstream source of energy and a large industrial base already exists. This allows a rapid deployment of wind power in most places around the world. The number of wind turbine producers is increasing with a number of Asian firms entering the industry.
- No fuel cost: Wind energy does not require any fuel like most other sources of renewable energy. This is a huge advantage over other fossil fuels whose costs are increasing at a drastic rate every year. Price shocks due to high fuel costs are a big risk with fossil fuel energy these days.

Offshore wind harvesting has some advantages over onshore wind harvesting:

- No noise pollution: Wind turbines produce a slight whirring noise which has led to problems with people living nearby. Some farmers have also complained that their livestock, like sheep, get affected by the movement of the wind blades. Offshore wind farms are located far away from the coast avoiding such noise problems for humans or wildlife.
- No injuries to birds: Older wind farms on land frequently cause deaths and injuries to birds though this has been reduced with modern wind turbines. Offshore wind farms do avoid this problem entirely as they are located in the middle of the ocean, where birds don’t frequently fly.
- No loss in scenery: Offshore wind farms are outside the landscape being away from the coast.

On the other hand, the most important disadvantage of offshore wind over onshore wind is:

- Cost: This is the biggest disadvantage of offshore wind power over onshore wind energy. Note it can cost between 2.5 and 3.5 times more to generate electricity from offshore wind turbine farms than the wind farms built on land. There are a number of factors that determine this rise in the price such as wind speeds, marine operations etc. However offshore wind industry is still in a research state compared to the relatively mature level of the land based wind industry.

2.2 Wind energy converters classification

While many people think that wind turbine means a three-blade rotor on top of a tower, there are other types of wind turbines that can catch energy from wind, as other versions of wind turbines exist. The three blade type of turbine is the most popular, tested, economical and practical one today; this is the reason why they are the most popular one.

There are properties that every wind turbine has to fulfill, while some other properties are characteristics from each type of wind turbine. Having a high power coefficient and a large starting torque are among the desirable characteristics, whereas having a high solidity is a negative point. In a propeller turbine, solidity is the ratio of the area of the blades to the area of a circle swept by the blades. For instance, a three-blade turbine has less solidity compared to a four-blade turbine with the same size blades. To compare the solidity of various types of turbines, one can use the weight ratio; for instance, out of two turbines having the same power, the one with heavier blades has more solidity.

When air flows around an object, two forces act on the object, drag and lift. Accordingly, there are turbines that work based on either of these forces. Thus, in general, there are lift -based (or lift -type)turbines and drag-based (or drag-type) turbines. This categorization is based on the type of active force that makes the turbines turn.

Turbines can also be classified based on their axis, whether it is horizontal or vertical. Axis here refers to their main shaft about which the rotating parts rotate. Certain turbine types can work only with a horizontal axis, while others can work with horizontal or vertical axis, and even they can be installed with their axis at an angle. In this sense, a wind turbine can be classified as a horizontal-axis wind turbine (HAWT) or a vertical-axis wind turbine (VAWT). Even without more details about any particular turbine, one can see a major difference between a horizontal-axis wind turbine and a vertical-axis wind turbine. Since in most cases wind blows horizontally, a wind turbine whose axis is horizontal (HAWT) is sensitive to the direction of wind. This is not true for a turbine with vertical axis (VAWT), because no matter what the direction of wind is, such a turbine can catch the wind.

2.2.1 Horizontal axis wind turbines

The most popular wind turbine has three blades on top of a mast or tower and is called a propeller turbine as it looks like the propeller of an airplane. A propeller turbine is a lift-type turbine since it works based on the lift force on the blades. Although usually it comes with three blades, it can have a smaller or larger number of blades. Research, however, has shown that three blades are the best combination; that is, from balance, efficiency, and other viewpoints such as how it looks and the impact it has on an observer.

In a propeller turbine, wind flows along the turbine shaft; that is, wind blows perpendicular to the blade plane (an imaginary plane that contains the blades). Since in open air wind normally blows horizontally the propeller turbine shaft has to be horizontal. Therefore a propeller turbine is a horizontal-axis wind turbine.

A propeller turbine can be mounted in two ways as far as the wind direction is concerned: upwind and downwind, as shown in Figure 2.1. In the upwind configuration, blades are in front of the tower, whereas in the downwind configuration wind hits the tower before it reaches the turbine blades. In practice, the two configurations have different performance because of the effect of the tower on the wind flow.

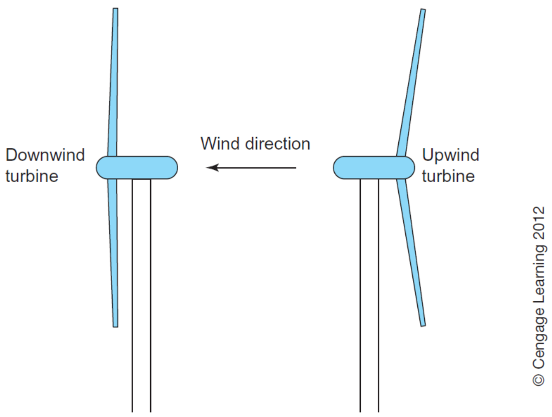


FIGURE 2.1 *Two different installation designs for propeller wind turbine. Source: [13]*

2.2.2 **Vertical axis wind turbines**

VAWT turbine principal advantage is the fact that all the other equipment such as generator and gearbox do not need to be on the top of the tower, as is usually the case for a HAWT. So, they are easier to access when necessary. Most frequently VAWT turbine types are presented below.

H-rotor

An H-rotor is a vertical-axis wind turbine in the shape of H. The two vertical segments of the letter H are the active blades, which are connected to the shaft by the middle segment. The two blades have the form of an airfoil and the turbine works based on lift force. The schematic of this type of turbine is shown in Figure 2.2. Since this turbine has a vertical axis, it is not sensitive to wind direction.

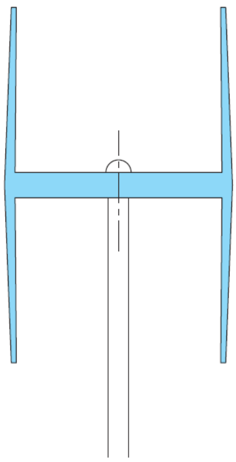


FIGURE 2.2 *Schematic of an H-rotor. Source: [13]*

The lift forces on the two blades of an H-rotor generate a torque about the turbine shaft that rotates the turbine as it is shown in Figure 2.2. Note that during operation, one blade is upwind and one blade is downwind. The aerodynamic angle of attack varies constantly for each blade during rotation. The downwind blade moves between 180° and 360° wake of the upwind blade and, thus, captures less energy than the other blade (the wind speed in this area is reduced due to the energy extracted by the upwind blade). Having two blades causes the operation of an H-rotor to pulsate. For this reason, it can have three (or more) blades in order to make its operation smoother, as shown in Figure 2.3.

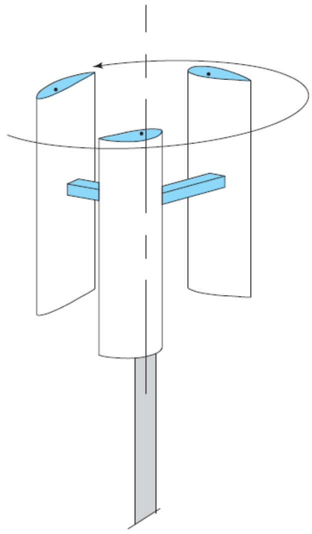


FIGURE 2.3 *A three-blade H-rotor. Source: [13]*

Darrieus turbine

A Darrieus turbine or Darrieus machine is more or less similar to an H-rotor in terms of having a vertical axis and working based on lift forces on the blades. The difference is the way the blades are attached to the shaft. A Darrieus turbine has the shape of an egg beater. Instead of the blades being attached to the shaft in the center, they are continued from both up and down and they are curved. The blades are attached to the shaft at both ends. Figure 2.4 shows a picture of a Darrieus machine. The curvature of the blades allows the vertical shaft to be supported by a number of wires. In this sense, the main tower supporting the turbine shaft does not need to be as solid and strong as it must be in an H-rotor. A disadvantage of a Darrieus machine is that it does not have a good starting torque. This means that at low wind speeds it cannot easily start to rotate. After it starts rotating, however, it has a good torque and can continue to generate electricity.

FIGURE 2.4 *A Darrieus machine. Source: [13]*

Despite the two main advantages of vertical-axis turbines (not being sensitive to wind direction change and most of the components being accessed from the ground), not many Darrieus machines have been built in the past, and none is made today. Preference is given to propeller turbines.

Savonius rotor

A Savonius rotor is a drag-type turbine, named after its inventor, Sigurd J. Savonius. Its construction is relatively simple compared to the previously described wind turbines. In the simplest form a Savonius rotor consists of two half-cylinder shown in Figure 2.5. At each moment one blade captures the wind while the other moves against the wind, thus opposing the wind. The net torque to rotate the turbine is the torque from the blade capturing the wind energy minus the resistive torque that the other blade receives against moving. This is the case for all the drag-type turbines. One can add more half cylinders on the shaft in order to increase the capacity of wind capture. This is equivalent to increasing the length of the cylindrical sections, if all the sections are aligned. Alternatively a second set can be installed at 90° from the first half cylinders. This adds to the uniformity of rotational torque on the shaft, since with only two half cylinders the absorbed power pulsates (this is not uniform as the rotor turns).

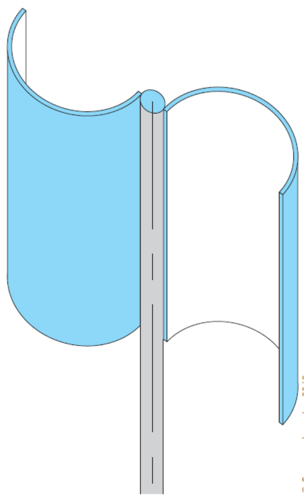


FIGURE 2.5 *Construction of a simple Savonius rotor. Source: [13]*

A Savonius rotor has about half of the power capture capability of the other (lift -based) turbines. That is to say, its power coefficient in the best situation is about a half of the magnitude that can be reached by, say, a propeller turbine. Also, its construction inevitably involves a large mass (high solidity), which makes it very bulky. Among the advantages of a Savonius rotor is its ability to capture low speed winds and to have a good starting torque. Also, it can be installed either vertically or horizontally; that is, its axis can be horizontal or vertical. If a Savonius rotor is installed horizontally, then the direction of wind matters for its operation. Small units of Savonius turbines can be used for rooftop mounting if desired, provided that their operational speed is low and the building has sufficient structural strength.

3 Horizontal axis turbine technology

In this section, the major components of horizontal axis turbines are presented. Some of these components, nevertheless, are essential for all types of wind turbines. For simplicity, the terms “propeller type” and “three-blade” are omitted, and when “wind turbine” is used, reference is made to the three-blade propeller-type wind turbine, which is always installed with a horizontal axis and is the most common commercial wind turbine.

A wind turbine must harvest the mechanical energy from wind and convert it to electrical energy. So, it has both mechanical components and electrical components.

The mechanical components will be described first, and afterwards the electrical components. Both categories then can be divided into primary components (those without which a turbine cannot work) and the secondary components that either are much smaller, or could be deleted based on the design of each particular turbine. Table 3.1 helps to categorize the components. In addition to the components/equipment shown in the table, a wind turbine is equipped with control systems required in modern turbines. The major control systems that comprise mechanical, electrical, and/or hydraulic components are blade pitch system and turbine yaw system. Certain modifications can be expected in the future generations of wind turbines.

Wind turbine major components		
Mechanical	Primary	Tower, nacelle, rotor, foundation
	Secondary	Gearbox, brake
Electrical	Primary	Generator, transformer
	Secondary	Anemometer, vane, rectifier, inverter

Table 3.1

A wind turbine primarily consists of a tower, a nacelle, a rotor (a hub and three blades), and a foundation, which cannot be seen. The blades are connected to a central hub, which rotates with them. The whole assembly is called rotor. The rotor is mechanically isolated from the rest of the turbine that does not rotate with wind. The blades and hub rotate the main shaft, which goes inside an enclosed space on the top of the tower. This enclosed space is called the nacelle. The nacelle houses the gearbox, generator, and all the other necessary components such as heat exchangers, coolers and heaters, other motors and gears and so on, as it will be described later. Figure 3.1 shows three of the major components of a modern turbine with a tubular tower. The fourth component, the foundation, is in the ground and cannot be seen.

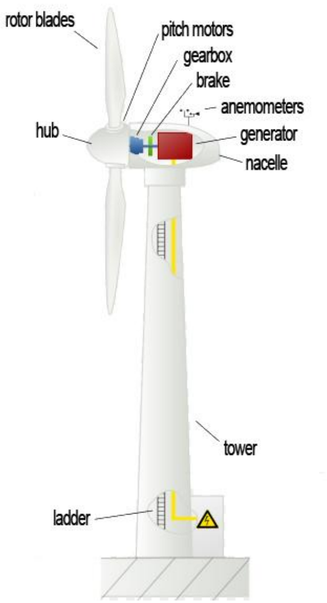


FIGURE 3.1 *Picture of a typical modern wind turbine with tubular tower. Source: [14]*

3.1 Rotor: blades and hub

Rotor refers to all the rotating parts of a turbine. Blades are the parts of a wind turbine that catch the wind energy. Lift forces in the three blades give rise to a torque at the turbine shaft and turn it. Blades have the form of an airfoil. The size of the airfoil is not the same along the length of each blade. This is partly because of the aerodynamic property that the tip of a blade must become smaller and be rounded, and partly because of the mechanical strength that the root of a blade must be stronger, thus larger and thicker, than the other parts.

In an electric fan, all the blades are connected to a central part, the hub, which holds the blades together, so that all the blades can rotate together. In an electric fan the blades and hub are just one piece. This piece is attached to a shaft and the rotation of the shaft can rotate the blades. A wind turbine presents more or less the same construction, except for two fundamental differences. The first difference is that in a wind turbine, since the size is larger, the blades and hub are separate parts that can be attached together. The second difference is only with modern commercial turbines. In the older turbines (constructed up to 15 years ago), the blades were fixed to the hub with bolts and there was no relative motion between the hub and any of the blades. Modern turbines are equipped with pitch control. In a turbine with pitch control capability, a blade is not fixed to the hub and can rotate with respect to the hub about its (blade's) axis. In this way, the angle between a blade and a fixed mark on the hub can be changed. This angle, called pitch angle, can be changed up to between 90° and 100°. A wind turbine having this capability is called a variable pitch turbine. The aim of changing pitch angle is to modify the amount of lift force from wind on the blade, thus changing the amount of energy grasp from wind. This can be used to control the turbine. Another application of this capability is to minimize the force on blades when a turbine is supposed to be stopped.

All the mechanisms to change the pitch angle are located inside the hub, including electric or hydraulic motors that force the blades to turn. Normally all the blades are rotated together and by the same amount. When the blades are turned such that there are no aerodynamic lift forces on the blades, the blades are said to be feathered, or in feathered position. When the blades are not feathered they can catch the wind energy.

The hub and the blades always rotate together when a turbine is working, they drive the turbine shaft. All the energy grasped from wind is conducted to the turbine shaft. The size of a turbine determines how much energy can be harvested from the wind, in other words the blade size determines the potential energy that can be absorbed. In today's turbines the size of blades is much larger than those of the past, and they are still growing. Blades must be strong enough to resist all the forces that are applied on them. At the same time, they must be light in order to reduce dynamic effects and cost. Today's blades are hollow and made of composite material. This means that their structure consists of a hollow shell, reinforced when necessary. Figures 3.2 and 3.3 show the inside of a blade.

Figure 3.2 shows the entrance of the blade. In a turbine, this entrance is inside the hub and can be opened for access when necessary.

FIGURE 3.2 *A quality inspector examines the interior of a wind turbine blade at the Siemens Wind Turbine Blade. Source: AP Photo/The Hawk Eye, John Lovretta*

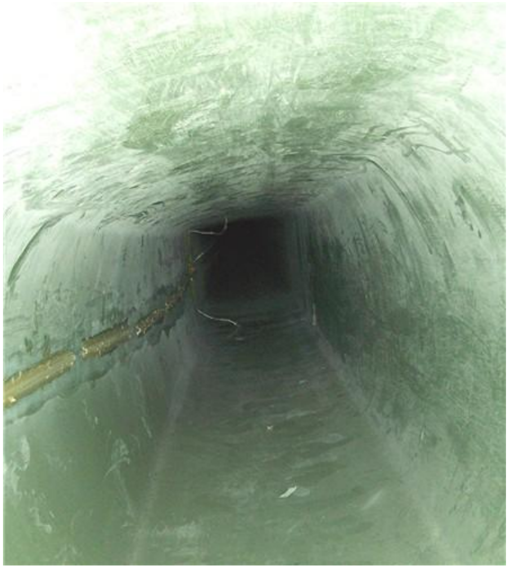


FIGURE 3.3 *The middle (of the three) compartments inside a turbine blade. Source: [15]*

Figure 3.3 shows the middle compartment, which is larger than the other two. Figure 3.4 shows a hub from 2 MW wind turbine. In most turbines, the hub is accessible from outside; thus in order to get into the hub and the blades, when necessary, one must climb to the nacelle roof.

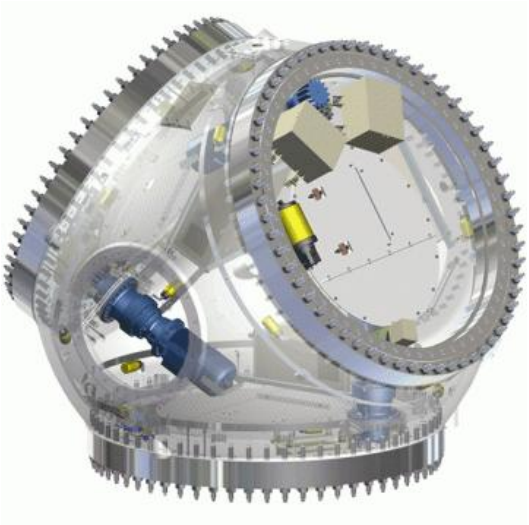


FIGURE 3.4 *Hub system from 2MW wind turbine TEMBRA. Source: www.tembra.com*

3.2 Nacelle

The intermediate part between the rotor and the tower is the nacelle. The nacelle does not rotate with the rotor, but it must rotate with respect to the tower. This rotating motion, called yaw, is necessary in order to face the turbine to the wind stream, as the direction of wind is highly variable. This motion is provided by the yaw system, which comprises a number of yaw motors and a yaw gear.

The output shaft from the rotating rotor goes inside the nacelle. The shaft transfers the mechanical energy to a generator, to be converted into electrical energy. In most of today's turbines this transfer is not direct and there is a gearbox between the main shaft (rotor output) and the high-speed shaft (the generator input). Thus, various equipments are housed inside the nacelle.

Figure 3.5 shows the inside of a generic nacelle, indicating the main shaft, the gearbox, the generator, and other components. An overhead crane, also shown, makes lifting and displacement of heavy objects easier during maintenance works.

The nacelle is a compartment not fixed to the tower and not fixed to the hub. "Not fixed" here implies that there are bearings between the two that allow them to move with respect to each other; that is, the assembly of hub and blades rotate with respect to the nacelle, and the nacelle rotates about the tower axis (yaw movement).

The nacelle serves the following purposes:

- Houses the gearbox, generator, coolers for the gearbox oil, heaters for winter time, turbine brake system, motors and gear for yaw system, the wind direction and speed measurement systems, the transformer for turbine energy supply, and other equipment based on the turbine design.
- Allows yawing of the turbine; that is, adjusting the turbine orientation to the wind direction.

- Provides counterweight for the hub and blades' weight.

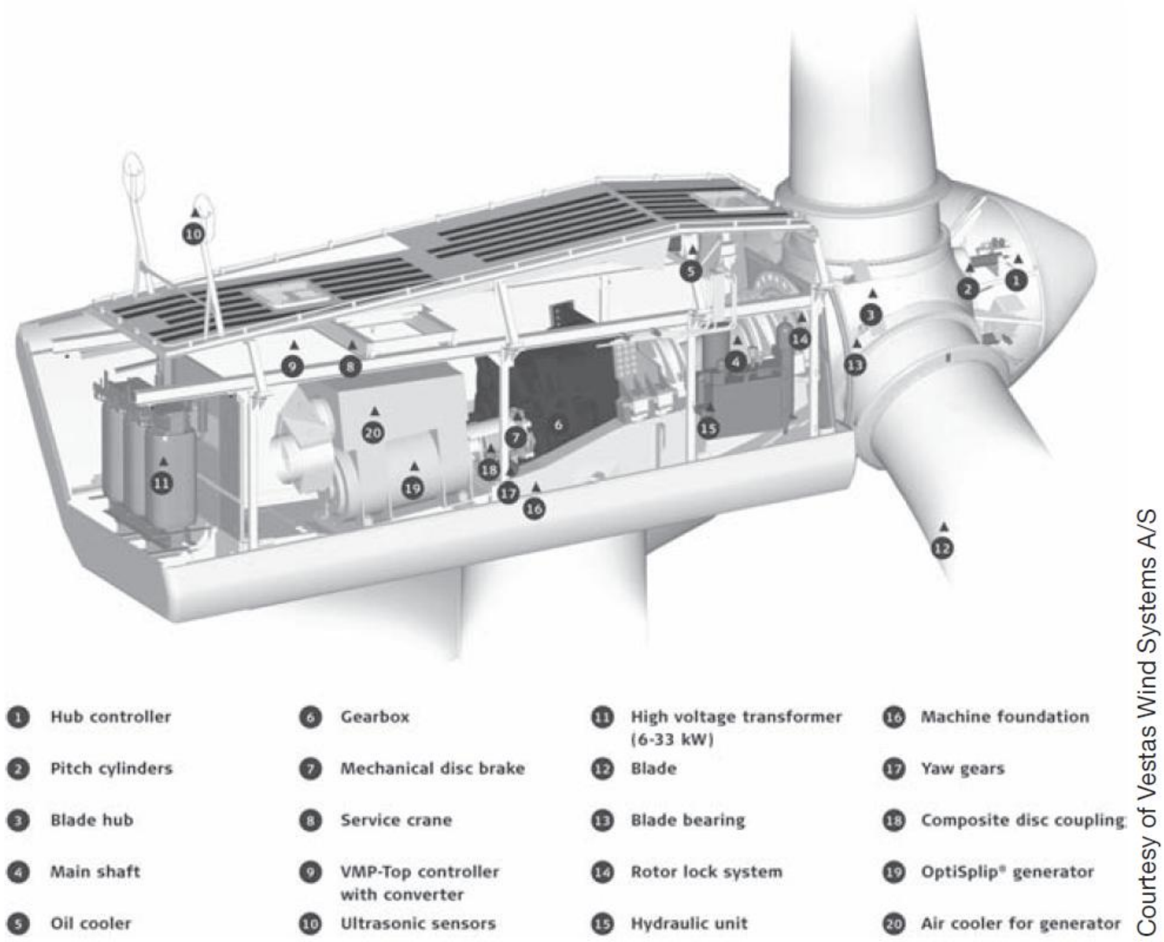


FIGURE 3.5 *Inside a nacelle.Source: [13]*

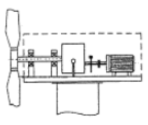
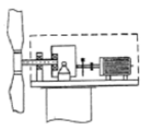
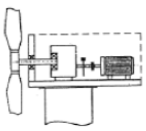
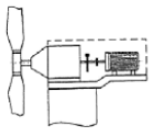
All the equipment mentioned in the first item of the previous list is among the essential components of a typical turbine, with minor differences based on the particular design of turbines by different manufacturers.

A nacelle can be a bedplate (platform) on which all the equipment is mounted, plus a cover or shell to make an enclosed room. The cover does not take any load and can be made of a light substance such as composite material. Alternatively, instead of a platform, the components themselves, particularly the gearbox, which is the largest component, can be part of the structure of the nacelle bedplate. In either way, the nacelle is usually heavy (including all the components in it), and the tower must be strong enough to hold the weight of the nacelle and the rotating parts.

3.3 Shaft and bearings

The rotor shaft bearing supports the blades and rotor and transmits torque to the gearbox. The bearing loads and rotating speeds vary considerably due to constantly changing winds.

At wind speeds below the cut-in wind speed (i.e. the minimum wind speed required for power generation), the rotor shaft will idle resulting in low-speed, low-load operation. At wind speeds above the cut-in speed, the rotating speed increases above the rated speed, resulting in average loads. In the case of wind gusts, the blades and rotor will exert large loads on the rotor shaft bearing. Such changes in the load, moment and rotating speed also affect the gearbox bearing. One of the features of wind turbine bearings is that they operate in a wide range of loads from light to heavy loads (when exposed to wind gusts).

Structure	Blade-side bearing	Generator-side bearing	Features
	SRB SRB SRB	SRB CRB DTRB	• Two bearings are used. • The gearbox is supported on the rotor shaft.
	SRB	CRB	• The generator-side bearing is also used as the gearbox's input bearing.
	SRB	CRB	• The generator-side bearing is also used as the gearbox's input bearing. • The load on the blade-side bearing is supported by the nacelle.
	TRRB DTRB	—	• No rotor bearing is used and the rotor load is borne by the gearbox bearing.

SRB : Spherical roller bearing CRB : Cylindrical roller bearing
DTRB : Double-row tapered roller bearing TRRB : Triple-row cylindrical roller bearing

Table 3.2 *Source: [16]*

Rotor shaft bearings repeat start, acceleration, deceleration and stop operations irregularly as they are exposed to fluctuation of load. Therefore, the optimal specifications for various parameters, including bearing type, clearance, number of bearing rollers, crowning and cage must be examined for every condition (minimum load, average load, maximum load).

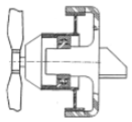
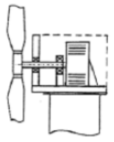
Structure	Blade-side bearing	Generator-side bearing	Features
	TRRB DTRB	CRB	● Direct drive ● Outer ring rotation
	SRB DTRB	CRB CRB	● The load on the blade-side bearing is supported by the nacelle. ● Inner ring rotation

Table 3.3 *Source: [16]*

Table 3.2 shows the structures of the shafts that use a gearbox to increase blade speed to the rated speed of the induction generator. Bearings suitable for each rotor shaft type are also shown. Table 3.3 shows the structures of the shaft of synchronous generators not equipped with a gearbox.

3.4 Power train

3.4.1 Drive train with gearbox

A complete wind turbine drive train consists of all the rotating components: rotor, main shaft, couplings, gearbox, brakes, and generator.

The drive train of Figure 3.7 shows the rotor attached to a main shaft driving the generator through the gearbox. Within this essentially conventional architecture of multi-stage gearbox and high speed generator, there are many significant variations in structural support, in rotor bearing systems and in general layout

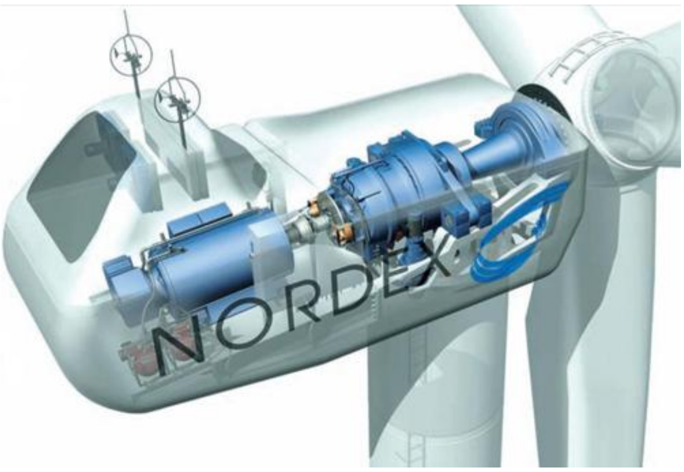


FIGURE 3.7 *A nacelle with conventional gearbox. Source: Nordex*

Most wind turbine drive trains include a gearbox to increase the speed of the input shaft to the generator. An increase in speed is needed because wind turbine rotors, and hence main shafts, turn at a much lower speed than is required by most electrical generators. Small wind turbine rotors turn at speeds on the order of a few hundred rpm. Larger wind turbines turn more slowly. Most conventional generators turn at 1800 rpm (60 Hz) or 1500 rpm (50 Hz).

Some gearboxes also perform functions other than increasing speed, such as supporting the main shaft bearings. These are secondary to the basic purpose of the gearbox, however. The gearbox is one of the heaviest and most expensive components in a wind turbine. Gearboxes are normally designed and supplied by a different manufacturer to the one actually constructing the wind turbine. Since the operating conditions experienced by a wind turbine gearbox are significantly different than those in most other applications, it is imperative that the turbine designer understand gearboxes, and that the gearbox designer understand wind turbines. Experience has shown that under designed gearboxes are a major source of wind turbine operational problems.

All gearboxes have some similarities: they consist of torque transmitting parts, such as shafts and gears, machine elements such as bearings and seals, and structural components, such as the case. In most cases there is a single input shaft and a single output shaft, but in at least one case (Clipper Windpower's Liberty) there is multiple output shafts connected to multiple generators. Beyond that there are two basic types of gearbox used in wind turbine applications: parallel-shaft gearboxes and planetary gearboxes.

In parallel-shaft gearboxes, gears are carried on two or more parallel shafts. These shafts are supported by bearings mounted in the case. In a single-stage gearbox there are two shafts: a low-speed shaft and a high-speed shaft. Both of these shafts pass out through the case. One of them is connected to the main shaft or rotor and the other to the generator. There are also two gears, one on each shaft. The two gears are of different size, with the one on the low-speed shaft being the larger of the two. The ratio of the pitch diameter of the gears is inversely proportional to the ratio of the rotational speeds. There is a practical limit to the size ratio of the two gears that can be used in a single-stage parallel-shaft gearbox. For this reason, gearboxes with large speed-up ratios use multiple shafts and gears. These gears then constitute a gear train. A two-stage gearbox, for example, would have three shafts: an input (low-speed) shaft, an output (high-speed) shaft, and an intermediate shaft. There would be gears on the intermediate shaft, the smaller driven by the low-speed shaft. The larger of these gears would drive the gear on the high-speed shaft.

Planetary gearboxes have a number of significant differences from parallel-shaft gearboxes. Most notably, the input and output shafts are coaxial. In addition, there are multiple pairs of gear teeth meshing at any time, so the loads on each gear are reduced. This makes planetary gearboxes relatively light and compact.

In planetary gearboxes, a low-speed shaft, supported by bearings in the case, is rigidly connected to a planet carrier. The carrier holds three identical small gears, known as planets. These gears are mounted on short shafts and bearings and are free to turn. These planets mesh with a large-diameter internal or ring gear and a small-diameter sun gear. When the low-speed shaft and carrier rotate, meshing of the planets in the ring gear forces the planets to rotate, and to do so at a speed higher than the speed of the carrier. The meshing of the planets with the sun gear causes it to rotate as well. The sun gear then drives the high-speed shaft, to which it is rigidly connected. The high-speed shaft is supported by bearings mounted in the case [24].

3.4.2 **Direct drive technology**

The motivation for direct drive is to simplify the nacelle systems, increase reliability and efficiency and avoid gearbox issues. A general trend towards direct drive systems has been evident for some years, although there are considerable challenges in producing technology that is lighter or more cost-effective than the conventional geared drive trains. Although these developments are under a continuous improvement, direct drive turbines have not yet had a sizeable market share. The exception is Enercon, which has long supplied direct drive generators employing a synchronous generator and having an electrical rotor with windings rather than permanent magnets. Most other direct drive designs are based on PMG (Permanent Magnet Generator) technology, using high-strength Neodymium magnets. In July 2008, Siemens installed the first of two new 3.6 MW direct drive turbines to assess whether direct drive technology is competitive with geared machines for large turbines. The two turbines, which have rotor diameters of 107m, use a synchronous generator and permanent magnets.

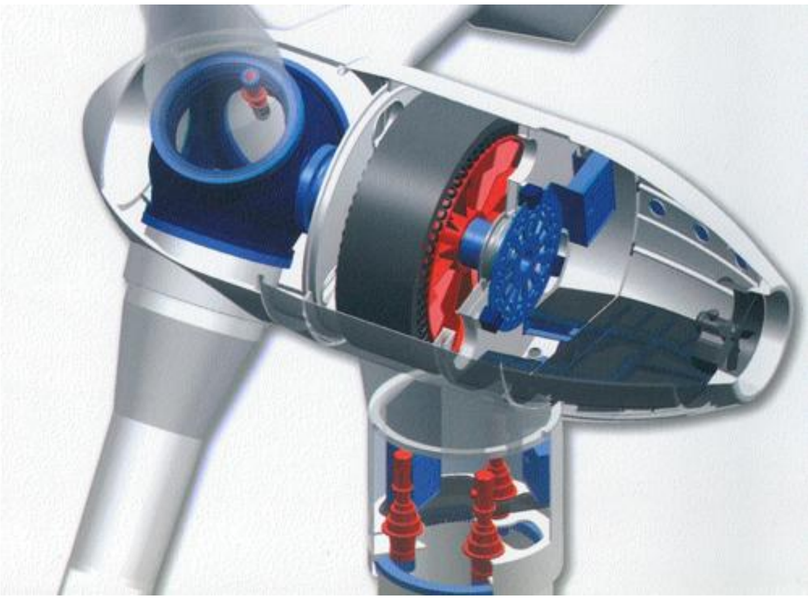


FIGURE 3.8 *A direct drive gearbox design. Source: MTorres*

MTorres wind industry activities started in 1999, leading to development of the TWT-1500, a 1500 kW wind turbine with a multi-pole synchronous generator. The nacelle layout of the MTorres wind turbine using direct drive technology is shown in the schematic diagram of Figure 3.8.

The Netherlands manufacturer Lagerwey supplied small wind turbines for a number of years and, at a later stage, developed wind turbines of 52, 58 and 72 m diameter with direct drive generators. The LW 52 and LW 58 were wound rotor synchronous machines like Enercon's. Largerwey then sought to develop a larger 1.5 MW direct drive turbine with Zephyros, the Zephyros LW 72. The first installation, located in the Netherlands, used a permanent magnet generator design and generation at medium voltage (3 to 4 kV). Subsequently, Zephyros separated from Lagerwey and was acquired by Harakosan. Xiangtan Electric Manufacturing Co Ltd (XEMC) with Harakosan has established XEMC Windpower. Moreover XEMC has also acquired Darwind and plans to install two 5 MW direct drive prototypes in 2010. Thus all the direct drive technology for turbines up to 5MW developed in the Netherlands around the Lagerwey/Zephyros design concepts is now owned by XEMC.

Another notable development in direct drive has come from the Vensys designs, which derive from the Genesys 600 kW prototype of 1997, developed at Saarbrucken University. Vensys turbines may see increasing market presence through the interests of the Chinese developer Goldwind.

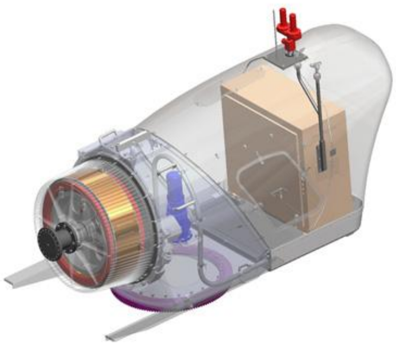


FIGURE 3.9 *Direct drive train concep. Source: Northern Power Systems*

Northern Power Systems (NPS) developed the Northwind 100 wind turbine. Several hundred 100 kW turbines have been installed, often in remote locations. Their direct drive generator originally employed a salient pole wound rotor technology, but in line with most new direct drive designs, they have since developed a permanent magnet generator design and an innovative power converter design (Figure 3.9).

3.4.3 **Compact drive train**

Compact drive train is a hybrid system, which is in the middle between the conventional solution with three stages of gearing at megawatt scale, and direct drive solutions, which generally demand rather a large diameter generator. The intention is to have a simpler and more reliable gearbox, with a generator of comparable size, leading to a dimensionally balanced and compact drive train.

This design route was launched in the Multibrid concept licensed by Aerodyn. The inventor, George Bohmeke, has pursued that technology with the Finnish company WinWind.

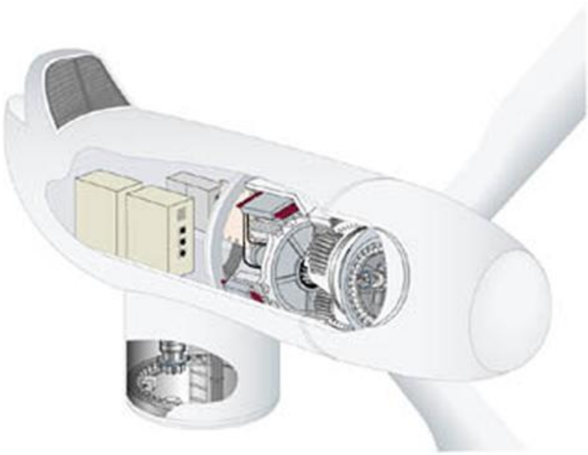


FIGURE 3.10 *WinWind 3 MW. Source: WinWind*

A characteristic of the system is the more balanced geometry of gearbox and generator, leading to a compact arrangement. The nacelle need not extend much aft of tower centerline (Figure 3.10), as it is generally appropriate for offshore machines, unless it will be accommodating electrical power equipment, such as the converter and transformer.

The structural economy achieved with such an integrated design is well illustrated in Figure 3.10, with the main nacelle structure tending towards an open shell structure, a broadly logical result since, rather like the hub, it also connects circular interfaces (yaw bearing and main rotor bearing) that have substantial angular spacing.

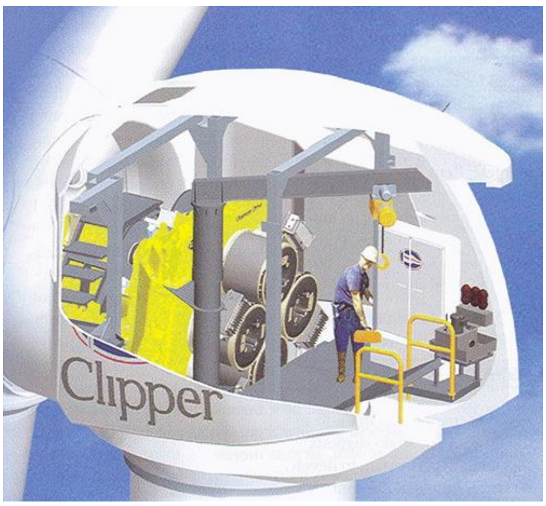


FIGURE 3.11 *Clipper Wind Liberty Wind Turbine with Multi-PMG System Source: Clipper*

Clipper Wind (Figure 3.11) manufactures 2.5 MW wind turbines, with a hybrid drive train of very distinctive design. After initial research into systems with multiple induction generators, Clipper developed a system with an innovative gearbox with outputs to four PMGs. As with other hybrids, this again leads to a very compact drive train. A subsidiary of Clipper Windpower Plc, Clipper Windpower Marine Ltd, has obtained 6M€ DECC (UK Department for Energy and Climate Change) funding for development of blades in the "Britannia Project", a 10 MW offshore wind turbine claimed to be scheduled for deployment in 2011.

FIGURE 3.12 *5 MW Multibrid Wind Turbine. Source: Multihibrid*

Prokon Nord Energiesysteme GmbH, based in Leer, acquired the previous Multibrid company in 2003. The prototype M5000 shown in Figure 3.12 was installed in Bremerhaven, and commissioned in 2005. The Multibrid technology was subsequently acquired by Areva in June 2008. Distinctive features of the M5000 include a highly compact integrated slow rotating drive system, comprising a single main bearing (no main shaft), a single-stage gearbox and a medium speed PMG (58 –147 rpm). With a tower head mass of 310 tones, the M5000 is apparently the lightest wind turbine rated around 5 MW. Turbine installation is recently completed (November 2009) in the Alpha Ventus offshore project comprising 6 Areva Multibrid M5000 and 6 Repower 5M wind turbines.

3.4.4 Drive train with hydraulic circuit

Hydraulic components have figured in drive train design for some time in motors, brakes, fluid couplings or torque limiting systems. Hydraulic drives comprising pump(s) and motor(s) for main power transmission were employed in the unsuccessful Bendix 3 MW prototype of the early 1980s. Key problems were inadequate capacity, efficiency, reliability and life of existing commercial hydraulic components – the lack of components specifically designed for the needs of efficient wind power generation.

The Scottish company, Artemis has addressed the problems found in the Bendux prototype and has developed a high efficiency, long life, ring cam pump, with electronically controlled poppet valves to suit wind turbine applications. The resulting ring cam pumps are very rugged and reliable. Those, for example, made by the Scottish supplier MacTaggart Scott are welded into the hulls of submarines for life. Development work, which will subsequently consider wind power transmission systems in the 5 to 10 MW range, is progressing with funding assistance from the UK Carbon Trust. Artemis claims that a 20% mass reduction in nacelle systems can be obtained, because the power density of hydraulic machines is at least three times higher than the most advanced electric motor.

Another recent use of fluidic systems is in the Voith transmission system, adopted by De Wind (now owned by Composites Technology Inc.). This is essentially a way of releasing a variable speed in the gearbox, thereby allowing direct connection of a synchronous generator to the output and hence avoiding the need for an electrical power converter.

The Voith WinDrive system uses a hydrodynamic torque converter to provide the variable speed relationship between the output shafts. WinDrive is essentially a mechanical solution to variable speed operation, based on a torque converter in combination with a planetary gear system. As a fluid machine, the torque converter is well matched to the wind turbine rotor and due the fluid in the converter the system decouples the input and output shafts absorbing input torque spikes and providing damping of vibrations.

With WinDrive, added mechanical complexity and cost in the gear system is compensated by elimination of the cost, mass and losses of an electrical power converter. The damping and compliance, intrinsic in the hydrodynamic coupling, ensures that a synchronous generator can be used. The Voith technology is long established in industrial drives, but the wind power application presents new challenges, especially in fatigue life and efficiency, which Voith have been addressing.

3.5 Brakes

Turbines need to be stopped on various occasions, such as for maintenance works, strong winds, components malfunctions, and so on. This is independent of time, weather conditions, and turbine settings. Therefore it is necessary that each turbine is equipped with mechanical braking system that prevents the rotor from turning. When a turbine is in the shut-down condition, it is yawed out of wind and its blades are feathered, so that the aerodynamic force to turn the rotor is minimum. This is not sufficient and the immobility must be ascertained by additional means, like brakes.

Wind turbines are usually equipped with a proper brake similar to an automobile disk brake that would be applied when not working. This brake system is usually mounted on the high-speed shaft (before the generator). In addition to this, for the maintenance work, or when a turbine must be stopped for a long time, the rotor can be locked in a position by inserting a pin inside a hole in a disk attached to the main shaft. In this way, the rotor is locked to the body of the nacelle and cannot move. A wind turbine brake is illustrated in Figure 3.13.

FIGURE 3.13 *A typical wind turbine brake. Source: http://www.windpowerengineering.com*

When a turbine is not in operation, that is, when a turbine is turned off, it must be kept in a fixed position and stopped from moving. In other words, the turbine must be parked. This is very important for any maintenance job on the turbine. It is very dangerous and can be fatal to work on a turbine if it is not braked. Also, during operation, whenever a turbine must be stopped, for example, in wind speeds below the cut-in and over the cut-out speeds, a turbine must be prevented from rotating. This is achieved by the turbine brake system, which can be similar to the brakes in a car, usually the disk brakes, installed on the high-speed shaft. In addition to a disk and pads for parking the turbine in a fixed position, some turbines are equipped with a pin and a hole in a convenient position.

This is an extra safety measure that is used during maintenance work. During the work, the pin is inserted manually into the hole by a technician who is going to work on the turbine. This makes sure that the rotor cannot rotate. It is also helpful to keep the three blades in one or more predefined position. For certain jobs on the hub or the blades, the turbine must be kept in a particular position.

3.6 Pitch control: aerodynamic brake

The blade pitch control mechanism rotates the blades about their longitudinal axis with respect to the hub. This mechanism necessarily must operate from inside the hub. This can be done by an electric or a hydraulic actuator.

Usually, the three blades must be adjusted to the required value simultaneously. Pitching the blades alters their angle of attack; or better said, it changes the angle of attack of each segment in a blade by the same amount. As a result, the wind power capture capacity of the turbine changes. Adding this capability involves more components and more cost. Nevertheless, nowadays every megawatt size turbines are equipped with blade pitch control capability.

By pitching blades the range of power capture capacity of blades can be altered dramatically from minimum to maximum. Thus, for each wind speed, one may catch between zero and the maximum possible power from wind. The variation of pitch angle, in fact, alters the power coefficient (Cp) of the turbine.

When a turbine is not in production, the blades are feathered by pitch control. Older turbines were stall, instead of pitch, controlled. When stall occurs, the lift force decreases and the drag force increases. This can also happen in airplane wings, which is not desirable. At a certain angle of attack, the local circulation of air behind the airfoil creates a vacuum area, as result of a increase in the drag force and a decrease in the lift force. Figure 3.14 illustrates a stall condition. This condition does not simultaneously happen for the whole blade, since the angle of attack is not the same along the length of a blade in a wind turbine. Since the angle of attack depends on the wind speed and the rotational speed of the blades (that is, the relative speed of air with respect to blade), stall condition can occur in a part of a blade, depending on the twist angle. Then the entire lift and drag forces on a blade can change, which leads to the change of harvested power. A blade can, thus, be designed (by varying the twist angle) such that after a certain wind speed, the power grasp capacity does not increase (and even decreases). The behavior of an airfoil designed in this way is such that at higher wind speeds stall happens. Therefore, unless the angle of attack is reduced, the lift force on the airfoil decreases and the drag force increases. This by itself is a regulatory action that decreases the power capture of a turbine and prevents it from over speed at higher wind speeds.

When the drag forces on the blades increase, however, this extra drag force must be resisted by the whole structure of a blade and then by the tower. This is one of the disadvantages of stall-controlled wind turbines.

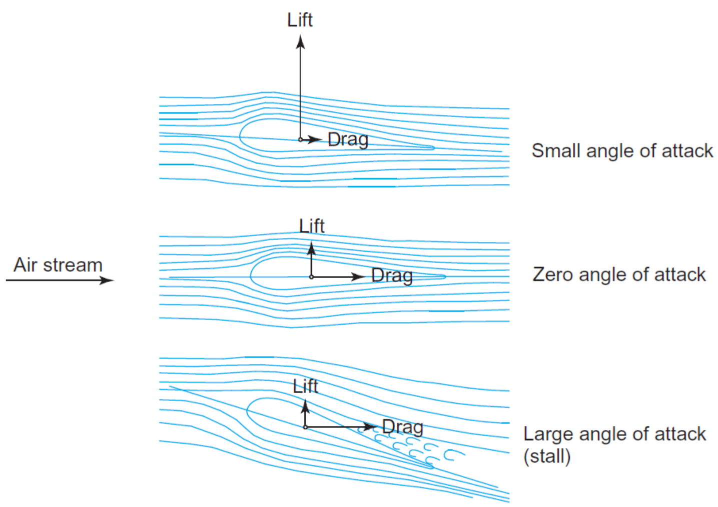


FIGURE 3.14 *Stall in an airfoil. Source [13]*

FIGURE 3.15 *A turbine with fixed blades. Source: [13]*

Figure 3.15 shows a turbine with fixed blades.

In some older (and smaller) turbines, an auxiliary braking mechanism came into action at higher rotational speeds of a blade. This mechanism would reduce the aerodynamic lift forces and prevent a turbine from speeding. It consisted of a normally hidden and locked plate that comes off the blade and makes more air resistance for blade rotation. Figure 3.16 depicts such a mechanism. The idea was a passive self-regulatory action, but this often did not work properly and the plate retraction into hidden position failed. So, putting the blade back to normal had to be done manually, which is time consuming.

Instead of this braking system, a tip brake was implemented in which the tip of each blade was a separate piece. In the normal working condition, the tip was aligned with the rest of the blade, forming one uniform blade. In case of overspeed, the centrifugal forces on the tip section of the blade would trigger a mechanism to open. The blade tip then would rotate by 90°. This action modified the aerodynamic behavior of a blade and, as a result, the blade slowed down. This type of brake is shown in Figure 3.17. This mechanism could also suffer from failure to go back to its normal position.

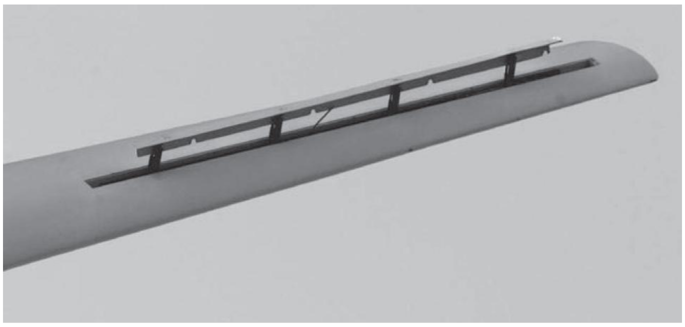


FIGURE 3.16 *Braking mechanism to prevent a turbine from overspeed. Source: [13].*

FIGURE 3.17 *Tip braking system. Source: www.icnetwork.co.uk*

3.7 Bed plate / Main frame

The main frame is the central assembly platform at the tower head. It accommodates the drive train, the generator carrier, the azimuth bearing, the azimuth drives, the nacelle cover and many other small components. Then a well designed main frame may have a complex geometry. A simpler alternative is a cast support which provides more freedom of design when compared to a welded construction. Another advantage is that the complex geometry proposals from the topology optimization method can be realized more precisely in cast technique. Cast frames not only offer cost benefits when produced in major quantities but also require a minor testing effort.

The common practice is to use welded constructions for prototypes where major design modifications are still to be expected on the way to series production and for designs with anticipated low production quantities. Figures 3.18 and 3.19 show the mainframe of two different wind turbines by TEMBRA.

FIGURE 3.18 *Mainframe 2MW wind turbine TEMBRA (Source: tembra.com)*

FIGURE 3.19 *Mainframe 3 MW wind turbine TEMBRA (Source: tembra.com)*

3.8 Blades

In an electric fan, the blades rotate and the result is air pushed ahead. In a wind turbine, the flow of the air forces the blades to rotate. A blade is not flat but it is twisted between its root and its tip. The reason for this is explained later. Also, a blade is narrower at the tip than at the root. Figure 3.20 shows a schematic of a typical blade of a wind turbine. The effect of the wind on each segment is a force, pushing the segment back as well as lifting it. These forces are referred as force components, since in combination they represent the force from wind on each segment. The sum of all the force components pushing the segments results in pushing and bending a blade. The sum of all forces lifting the segments causes the rotation of the blade. The effect of each segment on the blade rotation also depends on how far the segment is from the shaft axis. So, the segments that are near the blade tip have a greater share in blade rotation and the segments near the root have a lesser contribution.

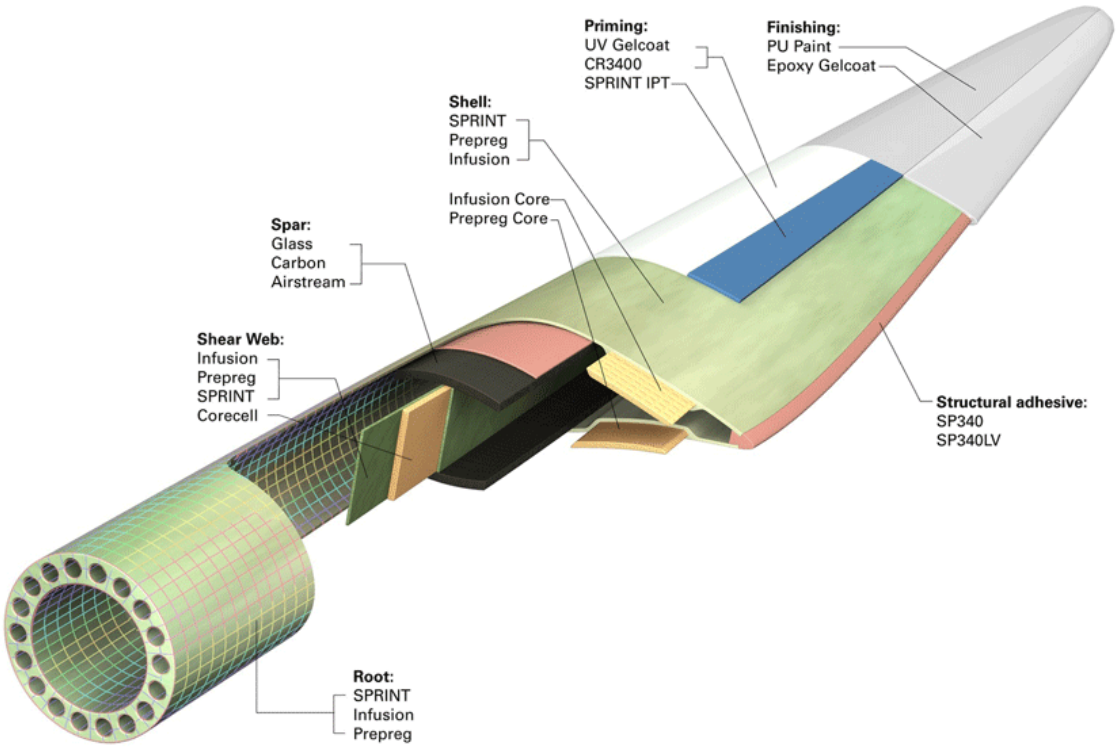


FIGURE 3.20 *A typical blade of a modern wind turbine. Source: www.*hypersizer*.com*

A rotational motion is created by a torque. The torque of a force depends on the magnitude of the force and the distance of the force from an axis. In a propeller wind turbine, each blade can be divided into a number of segments. The lift force on each segment causes a torque about the turbine shaft, trying to rotate it. The turbine rotates as a result of the sum of all the torques of the lift forces on all the blade segments. The concept of dividing a blade to a number of segments is just to help our understanding of how wind causes the turbine to turn.

3.9 Yaw system

When working, a horizontal-axis wind turbine must orient itself with the wind direction. This is one of the automated functions of a turbine based on determining the direction of wind at every instant. The control loop for yaw motion can be independent of the other functions. A number of motors working in parallel are employed for this purpose. The arrangement can be different from one turbine to another. However, this mechanism usually consists of a large ring gear (approximately the size of the tower top), and the yaw motors are a set of gears that turn the yaw ring gear [see Figure 3.21]. This turns the nacelle with respect to the tower with a slow motion.

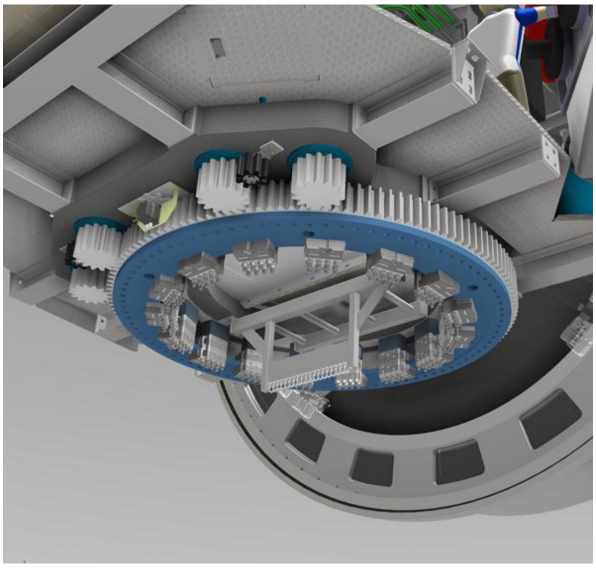


FIGURE 3.21 *Yaw system infography. Source: TEMBRA*

3.10 Tower

The tower supports the other parts and holds them in the air (off the ground). Thus, the tower must be structurally strong to withstand the weights of the components it supports and the forces from wind that can easily bend or break the tower if it is not strong enough. In the earlier turbines lattice towers were used. These towers are like the ones used for overhead transmission lines, made up of a number of metallic bars that are bolted or welded together. These towers can have various designs based on the height. Figure 3.23 shows a row of wind turbines with lattice towers.

FIGURE 3.23 *Turbines with lattice tower. Source: http://www.windfarmbop.com*

Modern turbines have tubular towers made up of rolled steel in the form of a cylinder or sometimes slightly tapered in the form of a conic, which make both manufacturing and transportation easier. The segments are attached together by bolts once in the final location site during the turbine erection, starting from the lowest segment that is attached to the tower foundation. The bolts for attaching the bottom section are outside the tower, whereas the other tower sections are connected from inside, which gives an easier accessibility and a better external look. Each segment is lifted by a crane and bolted to the segment below it. Each tower segment can be up to 18–21 m long. Each tower segment has a platform at its bottom. This makes it easier for climbing and descending, since each segment is isolated from others, as well as the fact that a person can rest in the middle, before continuing farther up or down. Usually the height of a turbine tower is the same as the diameter of the blades.

The diameter of a tubular tower can be (3–4 m). If it is tapered, it has a smaller diameter on the top. Some towers can be made of a concrete lower segment and the upper segments are metallic (steel). All tubular towers have an entrance door at the bottom. From the safety point of view, this door must be kept locked and only authorized people can have access. The tubular towers have a number of advantages over the lattice towers. Among them are:

- Tubular towers make an enclosed space, which can be more protective for electric and communication cables and other components, such as a winch for lifting equipment, against weather conditions (snow, ice, cold, dust, sunshine, etc.).
- They are more protective for people climbing the turbine for maintenance and other purposes against wind, cold, rain, snow, and so on. This includes the periodic check on the fastening torque of the bolts attaching the tower segments together.
- They can better accommodate any personnel-lifting equipment, such as a ladder. Newer turbines can be equipped with a one-person lift, which makes it easier for a maintenance person to climb the turbine.
- Birds are not tempted to make their nests on the tower elements, as frequently seen with the lattice towers.
- They have a nicer look.

On the other hand, lattice towers have the advantage of easier transportation (as the parts can be assembled on site) and certain maintenance work, such as painting them, is easier. The most common facility to climb a turbine is a ladder that is fixed to each segment of the tower. The ladder is usually welded to the inside body of the tower. In the very latest turbines the ladder can be attached to the tower by magnets. This reduces the manpower of manufacturing the tower, as well as reducing the local stresses due to welding.

Any turbine tower must be able to withstand all the various forces from the wind. A turbine is like a high-rise building, which is subject to heavy weight and large lateral forces from wind. For any heavy structure, the foundation must be strong enough to withstand the forces. Because soil is not strong, the foundations of large structures are mounted on a number of piles that are inserted in the ground by hammering action. The piles go deep into the ground and have the effect of being attached to the ground like nails hammered into wood.

This is not practiced for wind turbines, since the area of a tower is small (compared to a high-rise building). Instead, a large and heavy foundation is made for a turbine tower that can keep the turbine upright and can resist all the forces. Under each wind turbine, hidden in the ground, there is a relatively large concrete foundation with a sufficiently large mass. The size of a turbine foundation depends on a number of factors, including the turbine size, weather conditions in the region, the type of soil, depth.

3.11 Wind energy conversion

Wind power has been used for irrigation pumping and milling grain for centuries. Wind is a clean, safe and renewable form of energy. Modern wind turbine generators are highly sophisticated machines, taking full advantage of state-of-the-art technology, led by improvements in aerodynamic and structural design, materials technology and mechanical, electrical and control engineering and capable of producing several megawatts of electricity.

There are two primary physical principles by which energy can be extracted from the wind; these are through the creation of either lift or drag force (or through a combination of the two). The difference between drag and lift is illustrated by the difference between using a spinnaker sail, which fills like a parachute and pulls a sailing boat with the wind, and a Bermuda rig, the familiar triangular sail which deflects with wind and allows a sailing boat to travel across the wind or slightly into the wind.
Drag forces provide the most obvious means of propulsion, these being the forces felt by a person (or object) exposed to the wind. Lift forces are the most efficient means of propulsion but being more subtle than drag forces are not so well understood.

The basic features that characterize lift and drag are (see [20]):

- Drag is in the direction of air flow
- Lift is perpendicular to the direction of air flow
- Generation of lift always causes a certain amount of drag to be developed
- With a good aerofoil, the lift produced can be more than thirty times greater than the drag
- Lift devices are generally more efficient than drag devices

The wind systems that exist over the earth’s surface are a result of variations in air pressure. These are due to the variations in solar heating. Warm air rises and cooler air rushes in to take its place. Wind is merely the movement of air from one place to another. There are global wind patterns related to large scale solar heating of different regions of the earth’s surface and seasonal variations in solar incidence. There are also localized wind patterns due the effects of temperature differences between land and seas, or mountains and valleys. Wind speed generally increases with height above ground. This is because the roughness of ground features such as vegetation and houses cause the wind to be slowed.

Wind speed data can be obtained from wind maps or from the meteorology office. Unfortunately the general availability and reliability of wind speed data is extremely poor in many regions of the world. However, significant areas of the world have mean annual wind speeds of above 4-5 m/s (meters per second) which makes small-scale wind powered electricity generation an attractive option. It is important to obtain accurate wind speed data for the planned site before any decision can be made as to its suitability.

The power in the wind is proportional to (see [23], [13]):

- the area of windmill being swept by the wind
- the cube of the wind speed
- the air density - which varies with altitude

Although the power described above gives us the power in the wind, the actual power that can be extracted from the wind is significantly less than this figure suggests. The actual power will depend on several factors, such as the type of machine and rotor used, the sophistication of blade design, friction losses, and the losses in the pump or other equipment connected to the wind machine. There are also physical limits to the amount of power that can be realistically extracted from the wind. It can be shown theoretically that any windmill can only possibly extract a maximum of 59.3% of the power from the wind (this is known as the Betz limit, see [25]).

There are two main families of wind machines as described before: vertical axis machines and horizontal axis machines. These can in turn use either lift or drag forces to harness the wind. The horizontal axis lift device is the type most commonly used. In fact other than a few experimental machines virtually all windmills come under this category.

There are several technical parameters that are used to characterize windmill rotors. The tip-speed ratio is defined as the ratio of the speed of the extremities of a windmill rotor to the speed of the free wind. Drag devices always have tip-speed ratios less than one and hence turn slowly, whereas lift devices can have high tip-speed ratios (up to 13:1) and hence turn quickly relative to the wind.

The proportion of the power in the wind that the rotor can extract is called the coefficient of performance (or power coefficient or efficiency; symbol Cp) and its variation as a function of tip-speed ratio is commonly used to characterize different types of rotor. Due to the Betz limit there is an upper limit of Cp = 59.3%, although in practice real wind rotors have maximum Cp values in the range of 25%-45%.

Solidity is usually defined as the percentage of the area of the rotor, which contains material rather than air. Low-solidity machines run at higher speed and tend to be used for electricity generation. High-solidity machines carry a lot of material and have coarse blade angles. They generate much higher starting torque (torque is the twisting or rotary force produced by the rotor) than low-solidity machines but are inherently less efficient than low-solidity machines. The wind pump is generally of this type. High solidity machines will have a low tip-speed ratio and vice versa.

There are various important wind speeds to consider (see [13], [18], [19]):

- Start-up wind speed - the wind speed that will turn an unloaded rotor.
- Cut-in wind speed - the wind speed at which the rotor can be loaded.
- Rated wind speed - the wind speed at which the machine is designed to run (this is at optimum tip-speed ratio).
- Furling wind speed - the wind speed at which the machine will be turned out of the wind to prevent damage.
- Maximum design wind speed - the wind speed above which damage could occur to the machine.

3.12 Existing examples

3.12.1 NREL 5MW

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL), through the National Wind Technology Center (NWTC), has sponsored conceptual studies aimed at assessing offshore wind technology suitable in the shallow and deep waters off the U.S. offshore continental shelf (OCS) and other offshore sites worldwide. To obtain useful information from such studies, use of realistic and standardized input data is required. There are reports and documents with the turbine specifications of what is now called the "NREL offshore 5-MW baseline wind turbine" and the rationale behind its development. The objective was to establish the detailed specifications of a large wind turbine that is representative of typical utility-scale land- and sea-based multimegawatt turbines, and suitable for deployment in deep waters.

More information: http://www.nrel.gov/

3.12.2 Nowitech 10MW

NOWITECH 10 MW turbine has been specified to incorporate a number of state of the art features. The design will be open to the public and completely documented, such that researchers worldwide can analyze the turbine, and compare, exchange and discuss results with a common basis. The NOWITECH 10 MW reference turbine introduces a new support structure concept. Designed for a water depth of 60m and wave climate resembling the Doggerbank site, located in the southern North Sea. The support structure consists of a full height lattice tower. This concept has been developed at NTNU and promises less steel weight and cost than the traditional hybrid solution (where a tubular tower is connected to an offshore jacket by an expensive transition piece). The new design was analyzed with FEDEM Windpower and has been automatically sized and optimized. Figure 3.24 shows the lattice tower and turbine from NOWITECH.

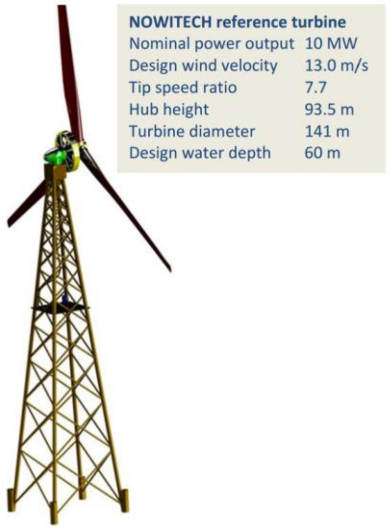


FIGURE 3.24 *Nowitech 10MW wind turbine. Source: www.sintef.no/projectweb/nowitech/*

More information: www.sintef.no/projectweb/nowitech/

4 Operation and maintenance

4.1 Introduction

Operation and maintenance of offshore wind farms is more difficult and expensive than equivalent onshore wind farms. Offshore conditions difficult the foundation and ejection of wind turbines in their final destination. The commissioning operations and accessibility for routine servicing and maintenance is also a major concern. During harsh winter conditions, a complete wind farm may be inaccessible for a number of days due to sea, wind and/or visibility conditions. Even with favorable weather conditions, operation and maintenance tasks are more expensive than onshore, being influenced by the distance of the OWECS from shore, the exposure of the site, the size of the OWECS, the reliability of the turbines, and the maintenance strategy under which they are operated.

Offshore installations require specialist lifting equipment to install and change out major components. Such lifting equipment can usually, but not always, be sourced locally and at short notice for onshore wind farms.

The severe weather conditions experienced by an OWECS dictate the requirement for high reliability components coupled with adequate environmental protection for all components exposed to sea conditions. Consequently, the requirement for remote monitoring and visual inspection becomes more important to maintain appropriate turbine availability levels.

4.2 Land Based Comparative Data

Operational information for onshore wind turbines has been collected for a number of years directly relevant for operation and maintenance issues.

WindStats newsletter is a quarterly international wind energy publication with news, reviews, wind turbine production and operating data from over 12,000 wind turbines in Denmark, Germany, Belgium, USA, Sweden, Spain and The Netherlands. However, WindStats provides very limited information for 1 MW plus turbines. A more relevant source of operating information is provided by turbine manufacturers who either have data in their publicity material or will usually provide data on request.

The overall picture of turbine availability is very good for all major manufacturers who have turbines in full production. For instance, Vestas V66, Enercon E66, Bonus 1.3 MW, Nordex 1.3 MW, Enron/Tacke 1.5 MW all have fleet-average availability of at least 97%. Information on maintenance effort to achieve this is practically unavailable, except through fault reports published in Germany and Denmark (summarised in WindStats).

Monthly wind turbine statistics for Sweden are published by SwedPower AB, and are available on the internet at www.elforsk.se/varme/varm-vind.html.

Published statistical information on the availability, accessibility and reliability of offshore wind turbines is limited to site specific information released at the discretion of wind farm operators. Therefore every study must rely on published data from the few truly existing offshore wind farms constructed since 1991. Offshore wind farms are usually small in comparison to onshore wind farms, although large scale wind farms, typically around 100 machines, are anticipated.

Operation and maintenance data for onshore wind turbines are readily available as detailed above. However, the environmental conditions associated with offshore installations render this data inadequate.

4.3 Offshore O&M Models

Maintenance strategies have been developed in the Opti-OWECS project using Monte Carlo simulations. A simple expert system has subsequently been developed based upon analytical trend curves determined from a large number of Monte Carlo simulations [1].

In the Monte Carlo model, the site accessibility as well as possible failures of the wind turbines in the OWECS is simulated stochastically on an hour to hour basis. The response in terms of deployment of maintenance and repair crew, and equipment, is simulated simultaneously in the model. These results in the determination of the instantaneous and overall availability of the OWECS. These also provide the instantaneous and overall costs associated with the adopted maintenance strategy under the assumed site conditions.

As mentioned above, expert systems [2] have been developed to represent the trend lines found from the far more comprehensive Monte Carlo simulation model. This simple approach enables the assessment of availability and O&M costs for a given OWECS with its O&M strategy as a function of the distance to shore and site (whether) conditions. The analytical functions used in this expert system have also been used for the concept evaluation. With them, the OWECS availability and O&M costs could then be determined and optimized for a range of scenarios. [3].

4.4 Maintenance Strategies

The availability of a wind turbine largely depends on the O&M strategy adopted by the operators of a wind farm. Given the limited amount of offshore O&M data, strategic planning is immature, however a number of options were developed in the Opti-OWECS study:

- No maintenance (run to failure): Neither preventative nor corrective maintenance is executed, and major overhauls are performed every five years. One of the few alternatives is exchanging a whole turbine if availability drops below a predefined minimum or after a certain amount of operational hours. Given the current level of turbine failure rates, this option is not presently viable.

- Corrective maintenance: Repair carried out soon after a turbine is down, or, alternatively, wait until a certain number of turbines are down. No permanent maintenance crew is needed.

- Opportunity maintenance (condition based): Executing maintenance on demand based on sensor measurement or other indicators of system status.

- Periodic maintenance: Scheduled visits performing preventive maintenance, and corrective actions performed as necessary by a permanent dedicated maintenance crew.

The Opti-OWECS study concluded that O&M strategy should be optimized with respect to localized energy production costs rather than pure capital or O&M costs. Further, the availability of OWECS with commercial offshore wind turbines without significantly improved reliability and without optimized operation and maintenance solution may be unacceptably low, e.g. 70% or less.

In conclusion, given current reliability and failure modes of commercial offshore wind turbines, which have been adapted from onshore models, a reduced level of preventative and corrective maintenance is not a viable option at this stage in the development of the offshore wind energy industry.

4.5 O&M Offshore Experience

4.5.1 Availability

Onshore wind turbines are now enjoying availability levels in excess of 97% with appropriate routine servicing and responsive maintenance actions. However, in practice, this typically equates to visiting a wind turbine four times a year, either for regular service or for repair tasks. [1].

Vestas provided a comparison between availability rates for the Fjaldene onshore wind farm and Tuno Knob offshore wind farm [4]. Average availability for Fjaldene is quoted as 99.3% mainly due to the proximity of this windfarm to Vestas Central Service Department.
While Tuno Knob average availability is quoted as; 97.9%, 98.1%, and 95.2% for the years 1996 to 1998 respectively [5].

4.5.2 Operational expenditure

As stated above, operating expenditure for offshore wind farms is considerably higher than the equivalent onshore facility. Offshore operations are in the region of five to ten times more expensive than work on land, and these costs are exacerbated by inflated prices prevalent within the offshore oil and gas industry. For example, the day rate for an offshore lifting vessel, which will be well over capacity for the wind industry, will typically cost at least ten times than of an appropriate land based crane.

Also, onshore equipment can be sourced and mobilized within a short period of time, usually within hours, and available on site within a day. Offshore lifting cranes are uncommon, and will generally have to travel a considerable distance to an offshore wind farm site, hence the requirement for careful scheduling of such vessels movements. The economics of a large wind farm (100 machines) may justify the purchase of a dedicated purpose built lifting vessel which would be available during installation and for maintenance throughout the wind farms lifetime. However, it is commercially expedient to dispense with the need for expensive lifting vessels after installation and hire lifting equipment during scheduled major overhaul. Given relatively calm sea conditions, it is possible to use a floating barge to transport and operate a land based crane offshore. The floating barge need only be a crude construction incurring minimal expenditure, hence be procured and stored for and at a dedicated wind farm.

General maintenance tasks are carried out using less specialized equipment which is generally purchased for the design life of the wind farm.

Operation and maintenance costs mainly related to the wind turbine can account up to 30% and more of the energy costs. [6].

4.5.3 Serviceability

The service demand of the present generation of offshore wind turbines in terms of man-hours is in the order of 40 to 80 hours [7]. Service visits are paid regularly, (except in the more demanding first year) about every six months. A more major overhaul will be undertaken every five years, and will take around 100 man hours to complete. [1].

Experience from Tuno Knob show that the total number of service visits have been between 35 to 70 visits per year, with an average of approximately 5 visits per turbine per annum. The number of cancelled visits (last moment cancellations due to weather) makes up about 15% relative to the number of service visits performed [8].

4.5.4 Access for maintenance

Gaining access to an OWECS for routine servicing and emergency maintenance is difficult or impossible in harsh weather conditions due to wave heights, wind speeds and poor visibility. The traditional and obvious method for transporting personnel and equipment is by boat, which is limited to relatively benign sea states. Wave heights above one meter present serious concerns for health and safety issues and damage to equipment.

Since the beginning of offshore wind farm development, suggested methods for gaining safe access have included:

- Helicopter
- Underwater tunnels
- Wheeled platforms for turbines in close proximity to the shoreline
- Amphibious vehicles where caterpillar tracks transport a platform over a firm and stable seabed
- Small hovercraft or ice roads for frozen seas.

For the present discussion, only the principle advantages and disadvantages of boat (plus jack-up) or helicopter access will be considered:

- Boat Access

Advantages:

- Well proven method of inshore transportation.
- Relatively cheap equipment expenditure.

Disadvantages:

- Impractical for wave heights greater than 1m (dependent on vessel).
- Transfer of personnel and equipment difficult in rough conditions.

- Jack-up

Advantages:

- Vessel can be raised above waves to provide a stable access platform.
- Heavy equipment can be transferred.

Disadvantages:

- Requires firm seabed conditions.
- Existing jack-up vessel designs are too large, hence purpose built designs are necessary.
- High cost of vessel.
- Installation sequence must be previously defined (cable installation later on).
- Sensitive to wave conditions during deployment and retraction of legs.

- Helicopter Access

Advantages:

- Sea state is not a major issue.
- Quick transfer of personnel and equipment from land to turbines.

Disadvantages:

- Cost of equipment and qualified operating staff.
- Turbine must be shut down and locked prior to boarding, and flying is restricted to good visibility and wind conditions.
- Not possible to use for certain wind turbine fault conditions (for instance yaw bearing failure).
- Expensive and cumbersome (landing platforms needed on each turbine).

Helicopter access is routinely used for oil and gas installations and offshore lighthouses, however it is unlikely that this mode of transportation can be reasonably considered for OWECS.

From recent reported experience, it was not possible to access Vindeby turbines in heights of more than 1 meter using an 8 meter vessel. Nevertheless turbines reported had an accessibility of 83% of the required times during the first 12 months of operation in 1992. However, during the worst month of the year accessibility fell to 45%. It was found that the conical foundation amplified waves, making boat landing more difficult especially in winds from the north or north-west. Access was limited to wind speeds of less than 7-8 m/s from the north or north-west and 12 m/s from other directions. There was solid ice around foundations and also blocking the boats nearby home harbor which also prevented access for several weeks, although this amount of ice was unusual. Travelling time of approximately 30 minutes in each direction also affected availability and maintenance. [9].

At Tuno Knob a 32 foot fiberglass boat (forward control fishing boat with flat stern) is used for service rounds. The boat weighs about 11 tones and is equipped with a 185 hp diesel engine [8].

In conclusion, there are a number of current projects addressing the issue of improving access to offshore wind turbine installations. Mostly the focus on maintaining is in boat access methods with emphasis on addressing the issue of motion compensation or complete removal of the vessel from the water at the turbine location. The potential for using small purpose built jack-up vessels with integral crane is also possible assuming a sufficiently large wind farm is to be served. However, access using small purpose-built landing craft continues nowadays to be the most pragmatic and economic solution.

Improvements made to the base of OWECS to facilitate safe personnel access include:

- Fixed platforms fixed to tower above splash zone with fender posts to absorb vessel impact.
- Flexible gangways extended from the vessel and held in the lee of the OWECS base.
- Installation of friction posts against which the vessel maintains a forward thrust during transfer.
- Facility for winching the vessel out of the water during harsh sea conditions.
- Winch / netting for personnel and equipment.

As mentioned above, there are significant advantages in eliminating the need for specialist lifting vessels which are currently necessary during overhaul or major component replacement. For a number of current offshore wind turbines, crane facilities (either permanent or temporary) within the nacelle are capable of lifting some of the heaviest components. At Tuno Knob, special electrical cranes were installed in each Vestas V39 turbine to allow replacement of major components, such as rotor blades or generators, without using a large and expensive floating crane. However, all other currently available turbine models require external cranes for the more demanding lifts, although Vestas claim to be able to change rotor blades with on-board cranes on their V80 2 MW machine.

4.6 Designs for Reduced Maintenance

The issue of accessibility can also be addressed by improvements in offshore wind turbine reliability. Both planned and, more importantly, unplanned maintenance levels can be reduced by increasing the reliability and hence availability of the turbine. Particular emphasis is being placed on reliability issues from component level through to overall design improvements such as corrosion protection and component sitting.

NEG Micons new 2 MW turbine has a fiberglass cabin within the nacelle which encloses the transformer, power and control cabinets within a controlled nacelle environment.

4.6.1 Component reliability

Rotor blades

Current OWECS utilize a three bladed configuration, and it appears that this will continue to be the popular choice of turbine manufacturers. However, two bladed configurations incorporating alternative hub structures may see a rise in popularity given the opportunity to operate turbines at higher rotor speed and without visual constraints. The main advantages from a reliability perspective are the reduction in the number of components, reduced complexity of the hub and easier rotor lifting. The track record of teetering mechanisms is not favorable, and for this reason these may be avoided for offshore use.

Gearboxes

Onshore turbine manufacturers, notably Enercon and Lagerwey, usually use direct drive generators eliminating the need for a gearbox. Current offshore turbines manufactured by leading manufacturers favor geared drive transmissions. Being the widely recognized as the number one item for mechanical failure and servicing supervision, it would appear a progressive step to move to direct drive systems.

Aerodyn who are currently designing the 5MW Multibrid Technology favor a drive-train consisting of single stage planetary gears, combined with a slow rotating generator, therefore eliminating fast-running components which are prone to wear. [10]

Generators

In general, induction generators require less maintenance than synchronous generators. They do not require a DC source and being inherently simpler and robust they are the most common generators in onshore wind turbines.

To protect standard induction generators from marine environments, the generator is totally enclosed with integral insulation to protect the internals from salt and high levels of moisture.

Onshore generators rely on air cooling, which is not recommended for offshore applications. Closed system water cooling or air-to-air heat exchange prevents the risk of corrosion from maritime cooling air.

Direct Drive Systems

Ring type direct drive systems have been developed for onshore wind turbines, primarily by Enercon and Lagerwey. Direct drive systems dispense with the historically problematic gearbox, where the drive train generator and rotor rotate at the same speed of around 20 rpm for a 2 MW OWECS.

The advantages of direct drive generators are obvious; no gearbox with associated high speed rotating parts, no gearbox oil contamination and leakage, and less routine servicing, to name a few. However, the direct drive generator for megawatt turbines is extremely heavy, bulky and the large diameter required changes the visual appearance of the nacelle. The added tower top mass coupled with increased wind loading increases tower stresses and hence tower dimensions.

The ring generators developed by Enercon are multipole synchronous machines with the copper windings impregnated with resin for environmental protection. Heat is dissipated by conduction via the high surface area steel structure.

ABB’s Windformer is a large diameter gearless generator using permanent magnets rather than coils or electromagnets. No transformer is required as the power is produced at 25 kV DC, compared with AC at less than 1 kV for most turbines. Halved lifetime maintenance costs as well as arguable benefits of up to 20% higher power conversion efficiencies have been claimed [11].

Electrical & Electronic Components

Electrical and control system failures account for the highest percentage of failures. In 2000, failures of electrical and controls systems accounted for exactly 50% of the need for wind turbine repairs [12]. Typically, failures of this nature occur due to the number of components, poor electrical connections, corrosion, lightning strikes, etc.

Potting of electronic printed circuit boards and reduction in the number of components are necessary for offshore conditions.

Hydraulic Systems

Elimination of problematic hydraulic systems employed in yaw damping, blade pitching and braking systems should be realized whenever possible. Electrical actuation is preferable and eliminates the possibility of oil leakage leading to secondary component failure and potential fire risks.

4.6.2 Corrosion protection

The main methods of marine corrosion protection for offshore installations, recently developed within the offshore oil and gas industry, are selection of corrosion resistant materials, two-pack epoxy coatings, cathodic protection, and creation of controlled environments for sensitive equipment.

The potential wind farm sites being considered in the North and Baltic Seas present harsher maritime conditions in terms of severe sea conditions and higher salinity levels.

More work is needed in developing support structures which can withstand stresses caused by wind and wave loading, together with reductions in material fatigue strength caused by corrosion. Cathodic protection technology of subsea structures is in the front end engineering design, with consideration of state-of-the-art paint systems and metal spray coatings particularly for application within the splash zone.

4.6.3 Control and condition monitoring

Surveys of machine outages reveal that around half of unplanned shutdowns on onshore turbines are caused by faults and trips in the electrical and electronic control systems. To reduce the number of unplanned visits to an OWECS, automatic re-set and remote re-set facilities are now becoming common in all new turbines. Nowadays there is an increasing number of sensors and monitoring equipment used to register; data, minor faults requiring only notification, or major faults which shut the turbine down automatically.

There is also an increment in the use of SCADA (System Control And Data Acquisition) systems, monitoring signals and alarms. This information is transmitted between the turbine and the onshore control station. Control personnel can interact with the monitoring system to over-ride the turbine controller if necessary.

Internet connections, webcams and sophisticated vibration monitoring for example can now be used to detect a limited number of pending failures prior to their occurrence.

4.6.4 Back-up power

Power for the turbine controller, electrical actuators, monitoring and communications systems are drawn from the turbines gross output, or imported from the grid system.

In the event of loss of turbine power generation or lost of electrical grid connection, there is no power at the isolated turbine for maintenance work or to keep turbine systems running. At Horns Rev, it is intended to have a back-up diesel generator sited on the substation platform to provide power in case the electrical connection to shore got broken.

5 Conclusions

An important aspect of future wind turbine development is the requirement to adapt existing onshore designs to cope with harsh maritime environments.

As indicated in the previous sections, reductions in the lifetime O&M costs of OWECS will require the following to be addressed:

- Development of appropriate maintenance strategies for scheduled and unscheduled maintenance, reflecting the constraints on OWECS in terms of access.
- Improvement of access methods for unscheduled and scheduled maintenance.
- Development of access methods which are less sensitive to wind/wave conditions.
- Reduce time required for offshore working.
- Designs for reduced maintenance by:
    - Reduction in overall number of components and simplicity of design.
    - Modular design approach which facilitates the interchange of faulty modules.
    - Use of high reliability integrated components.
    - Re sitting of electrical units into an environmentally controlled section of the turbine.
    - Implementation of offshore corrosion protection technology.
    - Development of effective conditioning monitoring and remote control systems.

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Wave energy converters

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Table of contents

1 Introduction

Oceans cover approximately 75% of the earth's surface. According to REPAP2020 [1], the main markets for ocean energy in 2020 will be Europe's Atlantic Arc Commission (Denmark, Ireland, Portugal, Spain, France and the United Kingdom) which has the best resources for wave, tidal and marine current energy along the western costs bordering the Atlantic Ocean.

Winds created by the differential heating of the earth's surface by solar energy, blow along the sea and create waves. The characteristics of the resulting waves depend on the amount of transferred energy, which is a function of the wind speed, duration and the distance covered (fetch) (Czech & Bauer, 2012; IPCC, 2011). The wave energy is measured in terms of kilowatts per meter of wave front (kW/m) and can be converted into electricity by wave energy converters (WECs) in a number of ways.

There are various reasons why wave energy is considered as an alternative renewable energy source and why it has attracted and encouraged many companies involved in the energy sector. Waves are well distributed around the world, thus making wave energy widely distributed. The total global wave energy resource has been predicted up to 80000 TWh/year and the studies has demonstrated that, with conservative economic and environmental constraints, WECs could be capable of capturing around 2.5% of this global resource satisfying over 10% of the annual global electricity consumption of approximately 18000 TWh (Krohn et al., 2013; Thorpe, 1999). It is also known that energy density of waves exceeds that of wind increasing the amount of energy available (Czech & Bauer, 2012). Therefore, wave energy can significantly contribute to energy mix of Europe whilst helping to reduce greenhouse gas emissions. Furthermore, through the use of satellites, waves can be predicted and modelled 1-2 days in advance which enable electricity usage to be planned and managed. Needless to say, wave energy can be seen as the right choice as the majority of the world's population resides near the coast where the wave energy is generated.

Intensive research has been carried out and several methods have been developed to harness energy in waves. There are currently more than 140 WECs at different stages of development from concept to demonstration. Each WEC works with a different method of operation that leads to different amount of electricity in different wave conditions. Several renewable energy companies, in close cooperation with the academia, are putting all their time and effort to the Research & Development (R&D) of these technologies. As a result, technologies are increasingly diverging. However, WECs have still been experiencing R&D challenges to be overcome before commercialization takes place, and the techno-economical feasibility of these devices has yet to be proven in full-scale real sea conditions. Therefore, it is still unclear which concept(s) will stand out from this competition and materialize in real business. Another important question is: will there be one WEC solution as in wind industry (with horizontal axis turbines) or two-three with different operation principles based on wave resources characteristics, proximity to the coast, etc. in the upcoming years? This question can be, to a certain extent, answered based on how much energy each of the tested devices is expected to generate, and at what prize. However, in order to give a more realistic answer, many prototypes, in real sea and for a long period of time, are strongly needed (Weber, 2012).

With massive wave resources around the world, wave energy technology will most likely take up more and more space in the seas in the upcoming years. Global wave energy activities have particularly increased in the last years with the construction of a number of large scale, full scale and demonstration test centres in Europe and the USA (EquiMar, 2011a; Mueller et al., 2010; SOWFIA, 2011; WAVEPLAM, 2009). Plans for new test centres in Asia [2] and the USA [3] are also being established. This accessibility is of paramount importance for device developers as test centres facilitate the WECs testing at large scales in a systematic way whilst helping them to gain required operational experience for the latter stages of R&D.

Over the last years, wave energy sector has taken positive steps towards commercial viability. The most advanced WECs are now progressing beyond full scale single device demonstration and the device developers have established plans for multi-device array demonstration with multi-megawatts projects.

This report provides an overview of the different wave energy conversion technologies. It starts by discussing the types of wave energy technologies and their technical features. This is followed by a detailed evaluation of WECs. Finally, the most promising WECs for further evaluation to be used in multi-purpose offshore platforms are provided as input for other work packages.

2 Wave energy development status

2.1 Definition and background

Devices which are able to capture the energy within waves and transform it into electricity are known as “wave energy converters” (WECs). Even though the development of first WECs dates back to 1799 (Ross, 1995), modern research into WECs has begun in late 1970s triggered by the oil crisis and when Stephen Salter published a notable article in Nature in 1974 (Salter, 1974). A summary of what had been achieved as early as 1978 can be found in the proceedings of the Wave Energy Conference 1978 in London [4]. This was followed by another conference in Edinburgh in 1979 named “Power from Sea Waves” which was then published in a book (Count, 1980). The first and second symposia on wave energy utilization took place in Gothenburg and Trondheim in 1980 and 1982, respectively, followed by another symposium in 1985, which were also gathered into an edited book (Evans & Falcão, 1985). Since then, extensive research on wave energy has become increasingly evident. Several books (Brooke, 2003; Charlier & Justus, 1993; Cruz, 2008; McCormick, 2007; Ross, 1995; Shaw, 1982, etc.), conference/journal papers (Bahaj, 2011; Clément et al., 2002; Drew et al., 2009; Falcão, 2006, 2010; Heller, 2012; Nielsen et al., 2006, etc.) and reports (AEA, 2006; Amar & Suarez, 2011; BOREAS, 2012; Cruz & Elkinton, 2009; Csiro, 2012; Czech & Bauer, 2012; Dooher et al., 2011; Falnes, 2007; IEA, 2011; Nielsen, 2012; Previsic et al., 2004; Thorpe, 1992, 1999; Vennetti, 2012, etc.) have been published that outline the basic principles and progress of WECs development around the world. Recent projects have also contributed to this by yielding project reports on the progress of WECs (EquiMar, 2010; ORECCA, 2011b; SI OCEAN, 2012; WAVEPLAM, 2009). Since 2010, IEA-OES [5] has also initiated to publish regular bulletins to highlight the R&D, government policies, device deployments and projects in OES member countries. Furthermore, more than 1000 wave energy conversion techniques patented in Japan, North America and Europe (Clément et al., 2002), and the number has significantly increased since then. A list of selective patents can be found in Appendix A. Over the last years, wave energy R&D has also gathered momentum in Japan (Kinoshita, 2012; Maruyama, 2012), Korea (Hong & Song, 2012; Hyun, 2012) and China (Dengwen, 2012). The first Asian Wave and Tidal Energy Conference [8] was held in 2012 to deliver an update on recent global activities with a distinctly particular interest in the Asia region and also the first Korea-Japan Joint Workshop on Ocean Renewable Energy [9] took place in 2012.

2.2 Development stage

WECs are still at a very early stage of technological development whilst wind energy technologies are relatively mature and growing rapidly with a considerable number of large-scale projects on the horizon. One of the important differences between the wind and wave energy industry is that wind energy technologies have been initiated onshore, and then applied to offshore whilst WECs are, by and large, initiated offshore which strongly affect and prolong the development process of WECs. It is therefore said that wave energy is some ten to fifteen years behind the wind energy industry in terms of technological maturity (Holmberg et al., 2011). Figure 2.1 shows the different maturities between wind and wave energy technologies. From the figure, it is clear that deep offshore wind industry has the highest growth capacity and contribution to European Energy Mix in medium term whilst wave industry has a huge potential in long term. Furthermore, another form of marine energy, tidal energy industry has demonstrated convergence of technology over the last decades with almost 50% devices being bottom-mounted horizontal axis tidal energy converters (Carbon Trust, 2011).

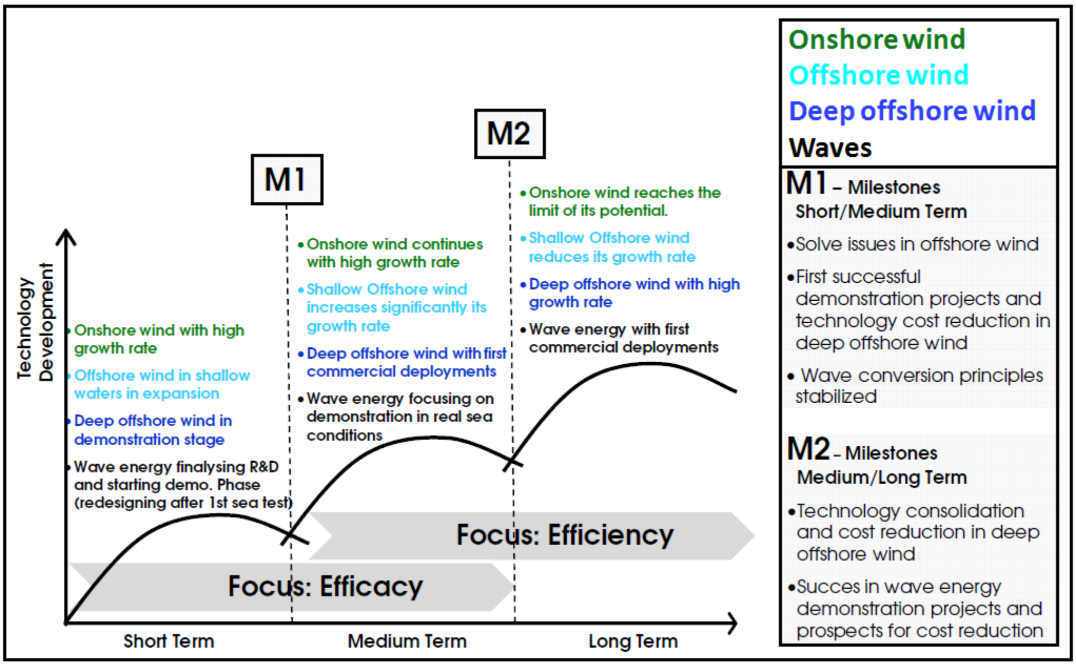


Figure 2.1 *- Commercialization map for wave and wind energy (EDP, 2010).*

As the number of wave energy developers narrows, the remaining devices may should make a faster progress towards full scale demonstration. Developers generally needed to go to full scale to get offshore experience and results. However, costs to move to full scale are prohibitively high, and can represent an unacceptable risk for the investors.
Successful commercialisation of WECs therefore requires vigorous testing at all scales from concept and theory, to small-scale model, intermediate scales, and full ocean tests. This development path is a very long, complicated, and costly process with many technical barriers to overcome. Therefore, a large amount of time, money and effort is required to successfully develop a WEC. *"Following a development plan is not a guarantee for success, but not following one is probably a pathway to disappointment, lost time and wasted resources."* said Holmes and Nielsen (2010). Considering this, one can say that a structured approach offers more probability of success and also gives the possibility of assessing devices in a similar manner and setting the basis for funding schemes.
It is important to assess the real degree of advancement of WECs, to increase the credibility of the performance stated by the investments when it comes to awarding funds. This way, with a well focused funding, public resources are not wasted and development of validated technologies can be accelerated (WAVEPLAM, 2009).

2.2.1 Existing standards and guidelines

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, became interested in wave energy and took over the role from the UK. As a result, Offshore Wave Energy Converter Project (OWEC1)[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

[1] The Offshore Wave Energy Converter Project – 1, Danish Wave Power APS, 1996 (EU Joule Contract No: JOU2-CT93-0394.

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 (Fig. 2.2) 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 2.3 shows some of the guidelines and standards which have been so far developed and released in conjunction with the pioneering research institutions. It worthy to remark that this list is not exhaustive. A brief review and analysis of these standards are not provided in this report, however a detailed information on these standards and guidelines can be found in EquiMar (2010) and Wavetrain (2007).

***Figure 2.2** - Main bodies engaged in drafting standards and protocols (after WAVEPLAM, 2009).*

***Figure 2.3** - Standards, equitable approaches, and best practice manuals.*

2.2.2 Five-stage approach

There are several ways to categorize the development stages of emerging technologies. This report is focused on the *"best practices"* developed in conjunction with the pioneering wave energy bodies (mainly listed in the Fig. 2.2). The "Technology Readiness Level" (TRL)

approach established by the US Space Agency (NASA) to manage the development of technology as part of the space programme is now widely used to describe the state of a technology programme. TRLs have also been extensively used by US Department of Defence, UK Ministry of Defence, and US Department of Energy to administer the development of high risk, novel and complex technology for military and the space programmes. Conventional TRLs consist of nine development levels that enable the assessment of the technology maturity through its advancement.
In Marine Engineering, in view of Ireland's ambitious plans and extensive projects to develop marine energy, "*Ocean energy: development & evaluation protocol*" was published by HMRC (2003) taking the OWEC1 development schedule as a basis. NASA's TRL approach has been adapted in this protocol and proposed to provide a structured five-staged programme to develop buoyant type WECs (second generation WECs) with the aim of mitigating financial and technical risks during development of devices. Even though the five-staged approach is restricted to buoyant type WECs, it is since then adopted in many publications (Heller, 2012; HMRC, 2003; Holmes, 2009b; O'Callaghan, 2012), even if this protocol was tailored to the Irish plans.
On a more national level, the European Marine Energy Centre (EMEC) in the UK also facilitated the development of a series of 12 guidelines on various topics such as wave or tidal resource assessment, manufacturing, maintainability, and so on. Those guidelines, published in 2009 [8], were adopted as starting drafts for a new sub-group called TC 114 created by International Electrotechnical Commission (IEC) in 2007 (IEC TC 114) to address the international standardization of marine energy conversion systems.

Over the last few years, in an attempt to develop a standardized path to development, an International Structured Development Plan has been created particularly through the International Energy Agency – Ocean Energy Systems group [5] and through the European FP7 EQUIMAR project [9]. The five-staged approach is now accepted as *"best practices"* for the development and assessment of WECs worldwide.
Figure 2.4 shows the five-staged approach progress from small scale model tests to intermediate tests and finally full scale sea demonstration. This structured programme presents a logical path of development based on different stages, whilst mitigating the technical and financial risks, through Stage Gate criteria (see Fig.s 2.4-2.5) where a WEC must fulfil at the end of each stage before passing the latter stage of the development programme. Therefore each phase relies on testing, optimizing and validating in order to avoid unexpected and unsatisfactory results in the latter stages.
From figure 2.5, it is clear that WECs may require many modifications, however, it should not go back to former stages. It is poor practice to transfer maintained design problems to the next stages where a solution is significantly more difficult and expensive to solve [10]. Over the years, many failures occurred as the many device developers have jumped directly to full scale after the initial investigations at small scales. This caused very difficult and prohibitively expensive problems to handle (Weber, 2012). Weber (2011, 2012) underlined the importance of improving performance and optimizing solutions by investing more at earlier stages. It is vital that all stages are planned carefully so that the maximum benefit can be derived from them, whilst developing the device properly and correctly. Further information on the structured development schedule and test programs can be found in Holmes and Nielsen (2010) and EquiMar (2011c).

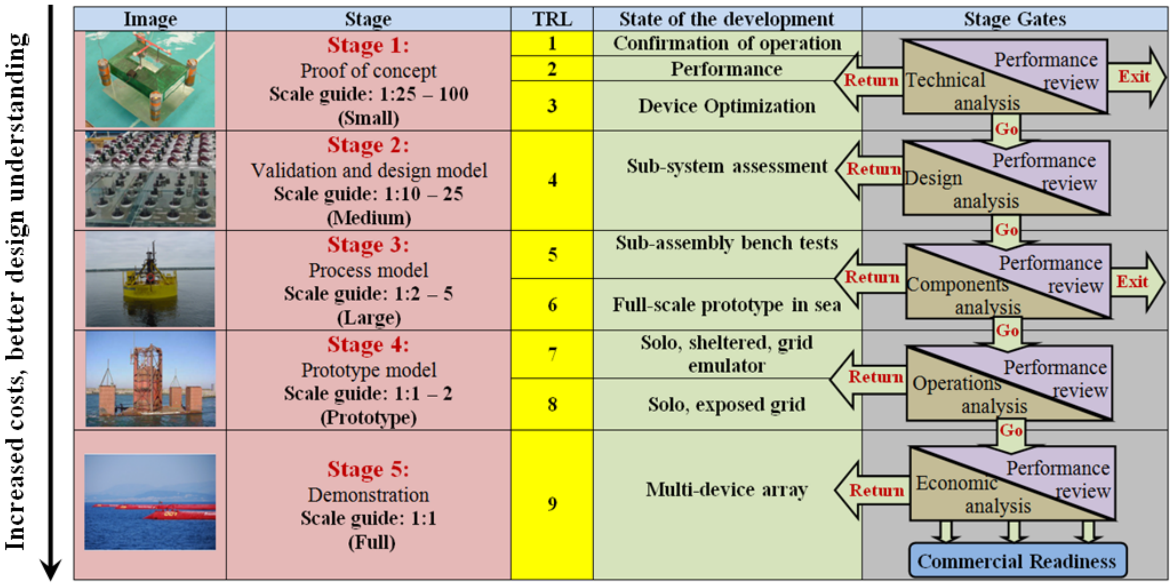


Figure 2.4 *- An outline of the structured five-stage development programme (after EquiMar, 2011b).*

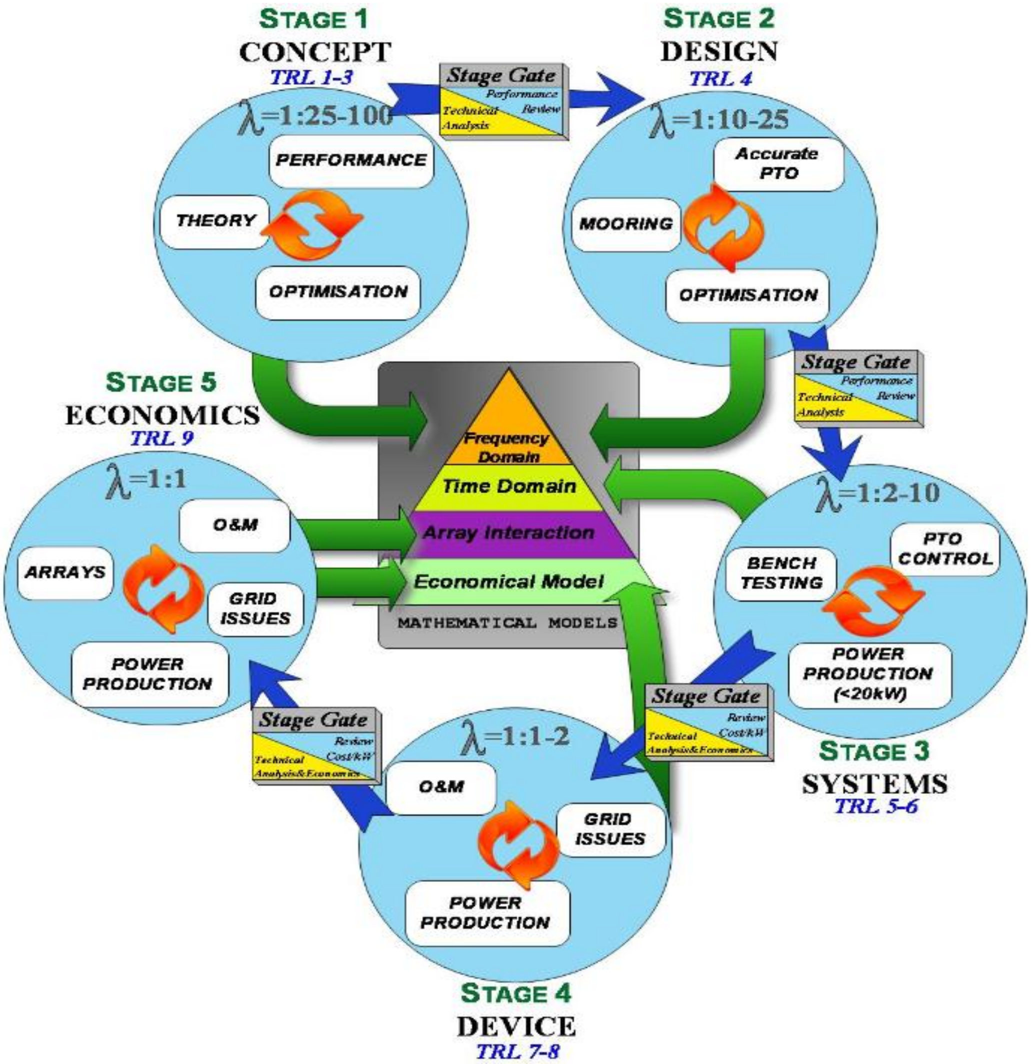


Figure 2.5 *- Structured Device Development Plan with details on tests (EquiMar, 2011b).*

Concerns have been raised over the last years due to increasing divergence of technologies. To better assess the performance of the WECs worldwide, further internationally recognized guidelines are needed in order to assess and analyse all devices in a same manner, and provide technology developers access to global market. The lack of the internationally recognized standards leads to a negative influence on the credibility of the performance stated by technology developers, which might become a serious problem when it comes to awarding (Holmes, 2009a). On the whole, international guidelines not only offer greater technology mobility but also increase the potential of the device to benefit from the funding schemes.
Other standards are provided by IEC-TC 114 (summarized in Tab. 2.1), and they are denoted by the 62600 series (e.g. 62600-1, 2, 3), furthermore some of them are already available at IEC website [11]. 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.

Project Team	Title	Published/ Pub. Date
PT62600-1	Terminology	Yes / 2011-12
PT62600-2	Design requirements for marine energy systems	Lack of information
PT62600-10	Assessment of mooring systems for marine energy converters	No / 2013-12
PT62600-30	Electrical power quality requirements for wave, tidal and other water current energy converters	No / 2015-10
PT62600-100	Power performance assessment of electricity producing wave energy converter	Yes / 2012-08
PT62600-101	Wave energy resources assessment and characterization	No / 2013-10
PT62600-102	Wave energy converter power performance assessment at a second location using measured assessment data	No / 2014-08
PT62600-103	Guidelines for the early stage development of wave energy converters: Best practices & recommended procedures for the testing of pre-prototype scale devices.	No / 2014-07

Table 2.1 *- Guidelines currently being developed by IEC-TC 114 [11].*

Weber (2012) proposed another metric called the “Technology Performance Level” (TPL) in addition to TRL. Similar to TRLs on a scale of 1 to 9, it measures the economics of the technology, and is inversely related to the cost of energy. Figure 2.6a shows the hypothetical development trajectories displayed in a matrix of TRLs over TPLs. In the figure, the orange hypothetical trajectory shows technology readiness before performance, the green hypothetical trajectory shows technological performance before readiness, and the black diagonal shows the case of performance and readiness developed together. At low TRLs, the performance of a WEC is uncertain and development costs are relatively low, whilst at high TRLs the performance are less uncertain and development costs are prohibitively high (Weber, 2012). Therefore, iterating technology and making optimization at high TRLs will also be very expensive. The risk is that high uncertainty at low TRLs may result in overestimated TPL which might lead surprises and unexpected economic problems as the device progresses towards high TRLs. Hence, Weber (2012) suggested that technology development costs (high TPL at high TRL) would be minimized by keeping systems fundamentals flexible (improving performance and optimizing solutions by investing more) at low TRLs (research phase) and fixed at high TRLs (development and demonstration phase), which in turn will result in a trajectory above the diagonal, as shown in figure 2.6b. Weber (2011; 2012) also discussed the methods needed to be effective in delivering a TPL increase before an increase in TRL. Objective technological assessment tools and methods are crucial in determining the associated TPL metrics and in facilitating the improvement of the WEC system components. Through this way, for example a WEC with a high TPL at low TRL can be achieved. Furthermore, economic assessment described by Deane et al. (2012) and Babarit et al. (2012) can be used to show how lifecycle economic viability can be considered at low TRLs, given in Fitzgerald and Bolund (2012).

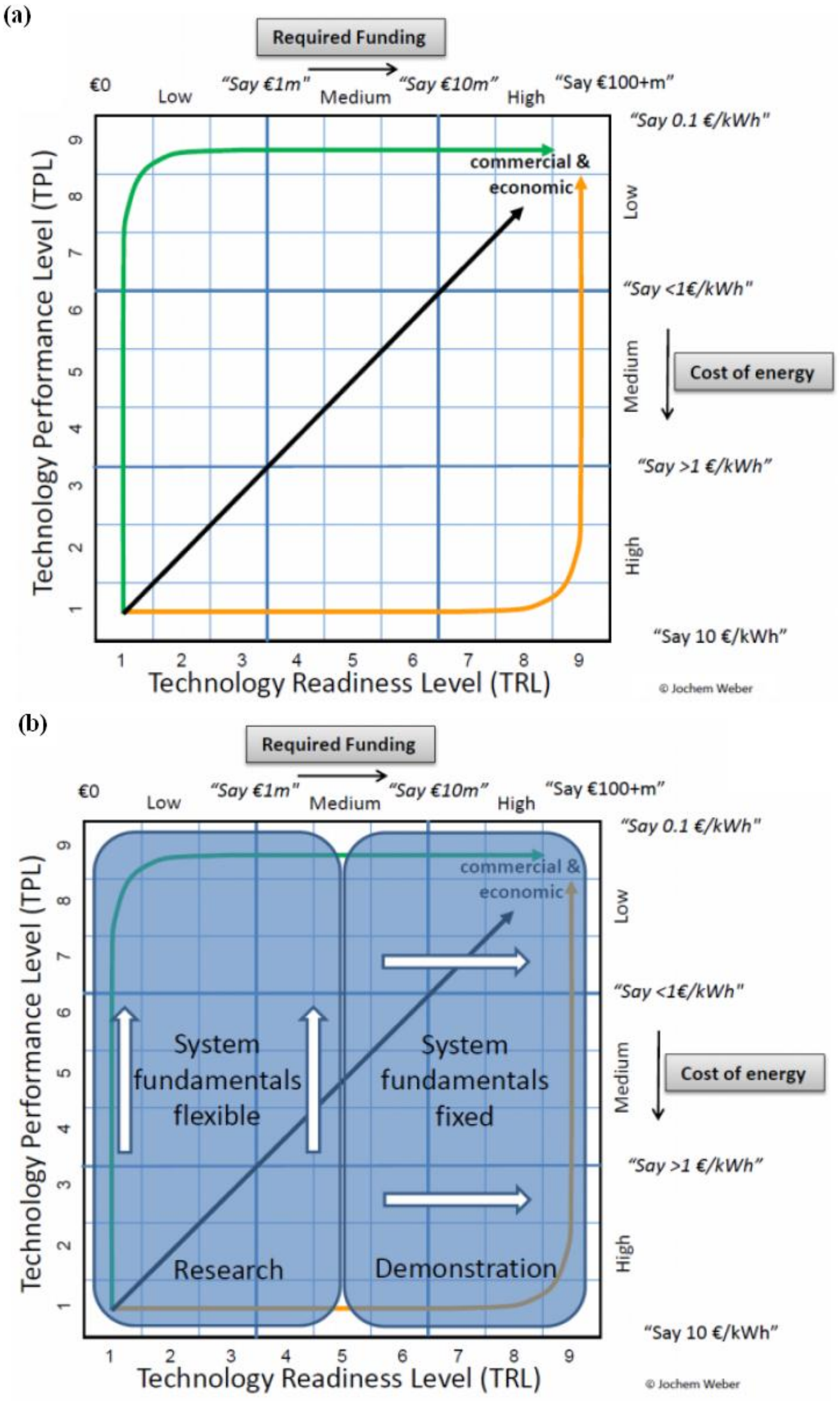


***Figure 2.6** - Generic WEC technology development trajectories and domains (Weber, 2012).*

2.2.3 **Development trends**

The global distribution of the individual WEC R&D is shown in figure 2.7. As seen from the figure, the WEC industry is dominated by the USA (with 24 WECs) and UK (with 17 WECs) with massive wave energy resources to exploit and the experience/industrial base to develop devices. However, the UK is still the global leader of the industry in terms of technological maturity which is then followed by USA and Australia.

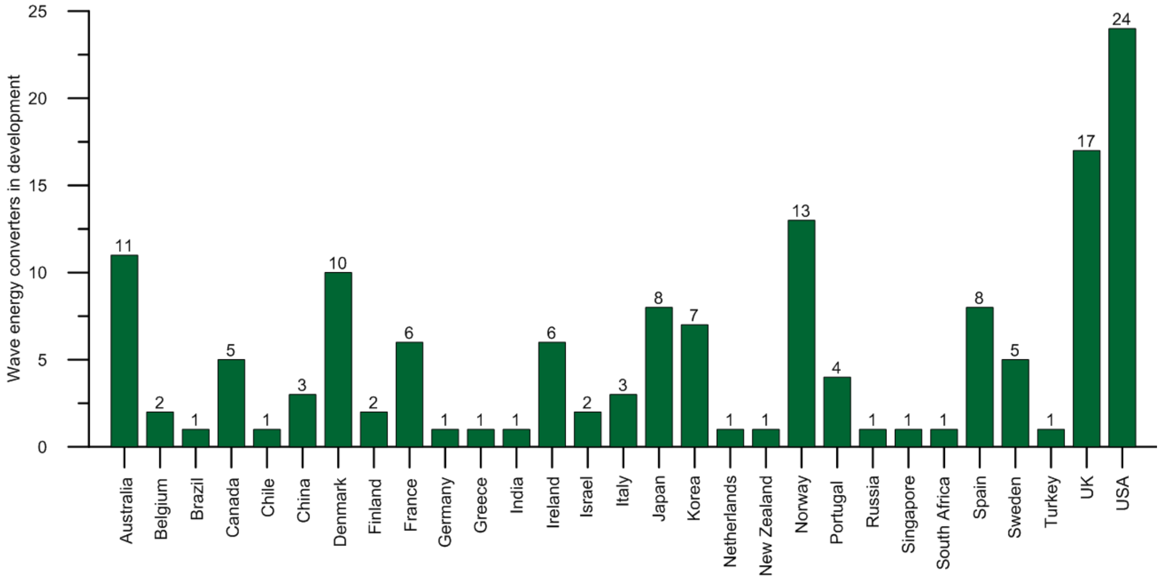


Figure 2.7 *- Global status of WECs, demonstrating the high level of activity in the USA and the UK, relative to the rest of the world (as of 03.02.2013).*

In order to explore the recent trend in wave energy activities, a comparison must be done with the previous reports and projects. The 2006 IEA OES Annex I Report (AEA, 2006) and 2009 IEA OES Annex I Report (Khan & Bhuyan, 2009) identified 53 and 77 WECs, respectively. These numbers are depicted in figure 2.8, with the state of the art information obtained in this study. From the figure, it is clear that the number of WECs has almost doubled over the last four years, with 147 WECs under development as of 2013.

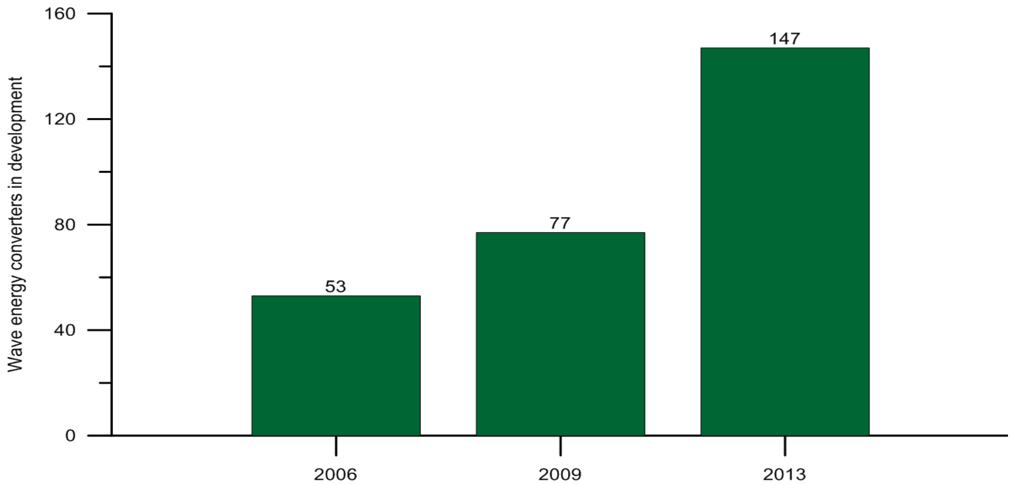


Figure 2.8 *- WECs currently in development compared to 2006 and 2009 (as of 03.02.2013).*

2.2.4 **Current R&D status of devices according to five-staged approach**

Figure 2.9 shows the current development status of WECs based on five-staged approach. It must be mentioned that WECs which could not pass the inactive criteria are disregarded in this study. From the figure it is possible to note that there are a relatively high number of WEC technologies emerging whilst many WEC devices have progressed to more advanced stages. Forty-nine prototypes are currently being tested at sea (or completed – in search of funding – preparing for the next stage), while fifteen prototypes are now undergoing at full or near full scale (grid connected). Considering the Stage 4 and 5, it can be said that the costs and performance of these devices has just started to be quantified with greater certainty. The developers must demonstrate not only that their devices will work in the real sea conditions, but also that the costs and performance meet their expectations and their investor's expectations (Carbon Trust, 2011). These front-running WECs must therefore now focus on cost reductions with improved technological performance, different innovative materials and improved Operation and Maintenance (O&M) techniques. It seems that these devices are nowadays of particular importance since the proof of their performances and costs, in Stage 4 and Stage 5, may increase the confidence in the industry, thus giving access the future investments in the wave energy sector.

In addition to emerging technologies, there are also other technologies which is considered as an idea (yet to be proven), indicating that the total number of WECs are still growing. It can be said that, the greater the number of technology in the sector, the greater the level of competition. Based on the previous experience in wind and tidal projects, it is clear that increasing competition may lead to better cost-competitiveness in longer term. However, the increasing number of WECs at this stage indicates that R&D is not yet close to converging on an optimum design.

An increase of the prototypes in real sea for a long period of time will not only increase the knowledge on components, equipment and materials, but will also increase the best practices and hard-won knowledge in installation and O&M. As a result, existing expertise in such WECs can be used in new and emerging concepts so that the new device developers do not have to reinvent the wheel. Carbon Trust (2011) stated that a pipeline of promising next generation concepts should be maintained and developed, but with a high quality threshold.

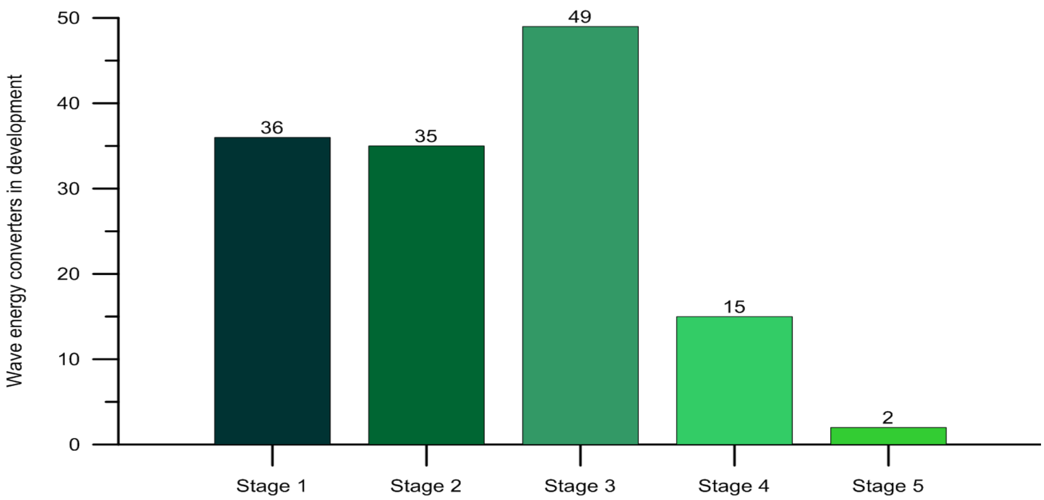


Figure 2.9 *- Current R&D on WECs based on five-staged approach (as of 03.02.2013).*

In order to explore the distribution of R&D progress across the world, figure 2.10 is depicted. Although the USA has the greatest concentration of technologies, the UK appears to have the most advanced WECs. Australia and Denmark has also advanced technologies (Stage 4), but with a smaller pool of devices.

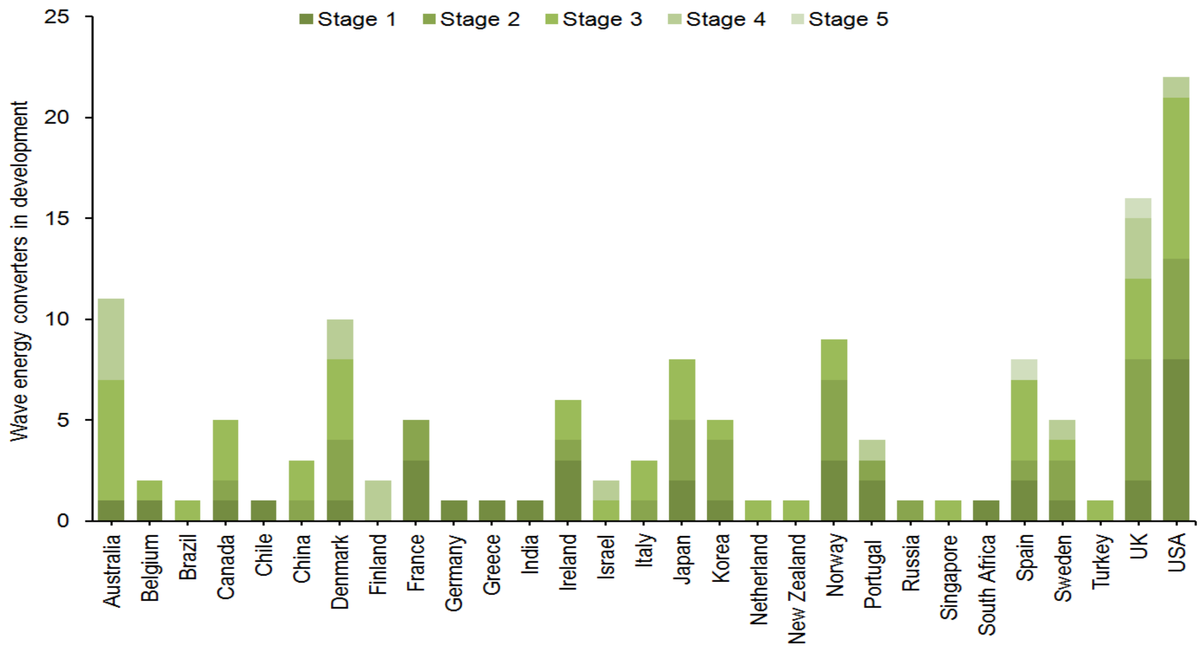


***Figure 2.10** - Current R&D distribution worldwide (as of 03.02.2013).*

2.3 Classification of WECs

WECs can be classified in several ways: according to the device location, to its position related with the incoming wave direction or to conversion principle. There are also other classification system, e.g. according to the ratio buoyancy/inertia or based on the primary conversion component as suggested to EquiMar Protocol (Deliverable 5.2, "Device classification template", available at the webpage http://www.equimar.org). In the following the first three classification methodologies are examined.

2.3.1 Position vs. shoreline

The 'historical' classification based on the device location distinguishes among three classes: shore-line, near-shore or off-shore.

1. Shore-line (first generation)

   Due to practical and economic reasons WEC units were first directly installed at the shore-line, therefore they are also called as 'first generation' devices. In general these devices have their own foundation on the coast or in breakwater structures for harbour protection. Main advantages are:
   - unnecessary design of mooring systems,
   - absence of long submerged electrical cables,
   - easy installation and maintenance.

   On the other hand, these devices can exploit a milder wave climate with respect to the off-shore available wave power and therefore to be effective the installation site should be an hot-spot. Locations that would be suitable for these installations are often protected areas.

   Specific design issues include:
   - sedimentation inside the chambers (in case of Oscillating Water Column devices) or in the storage basins (in case of Overtopped devices) in case of sandy coastlines, a problem that has still not been analysed in depth;
   - high wave reflection and eventual scour at the foundation to be prevented by an appropriate protection layer.

2. Near-shore (second generation)
   These devices are typically installed at water depths of 20-30m and at a distance of about 500m from the shore, i.e. in shallow water. In this area, the wave height increases feeling the bottom (shoaling), and therefore also the wave power is higher than at the shore. The near-shore devices require high costs of installation and maintenance with respect to the on-shore devices, but at the same time their visual and environmental impact is generally low.

3. Off-shore (third generation)
   As a consequence of the higher available wave energy density and of the continuous technology development (taking advantage of the knowledge developed for offshore oil platforms), third generation of devices are installed at the open sea, even if the installation costs rise. These devices are typically installed in deep water (i.e. water depth greater than 40m) and consist of moored floating units, usually employing principles and ideas from the first and second generation devices. Recent projects focus on devices that can provide high levels of energy when they are arranged in wave farm.

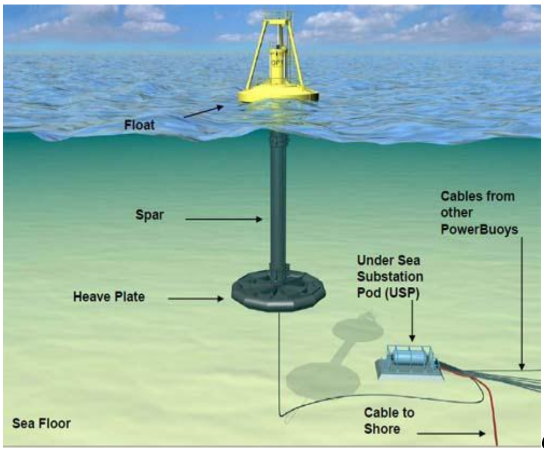
2.3.2 **Position vs. wave direction**

A second classification is based on the WEC ability to intercept and attenuate waves. Therefore the classification considers the WEC position with respect to the dominant direction of the incident wave front. Even within this classification it is possible to consider three groups: point absorbers, attenuators and terminators.

1. Point absorber
   A point absorber is a device whose size is small compared to the wave length. It is able to capture energy –regardless the incoming wave direction– from a wave front greater than its physical dimension (for example, PowerBuoy device shown in Fig 2.11*a*). These devices normally involve a floating structure composed of a first relatively immobile component and a second moving component, which follows the wave motion (e.g. a floating buoy which slides inside a fixed cylinder).

2. Attenuator
   An attenuator has its principal axis parallel to the incoming wave direction, it is usually a floating device composed by several segments (for a total device length typically greater than the wave length) and converts the energy due to the relative motion of those parts. This relative motion activates the power take-off system (which is usually placed between two segments), therefore the mooring system should allow the unit to weathervane into the predominant wave direction to avoid negative effects on the WEC efficiency. An example is the Pelamis device shown in Fig 2.11*b*.

3. Terminator
   A terminator has its principal axis oriented as the wave crest, i.e. orthogonal to the incoming wave direction, and acts as a significant obstacle to wave propagation. Typical installations were on- or near-shore, however nowadays there are also floating off-shore terminators as the Wave Dragon, see Fig. 2.13*b*.



a)

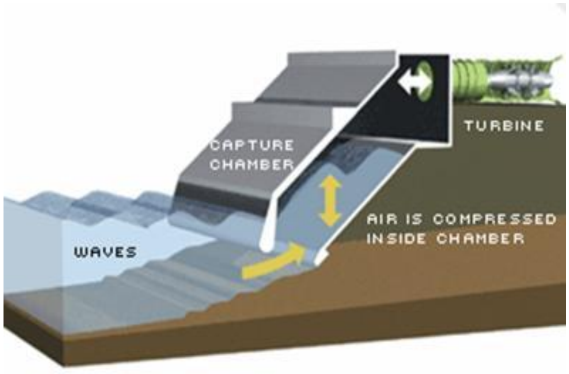

b)

Figure 2.11 *- Examples of devices:*
a) point absorber (PowerBuoy device, website http://www.oceanpowertechnologies.com)
b) attenuator (Pelamis device, website http://www.pelamiswave.com)

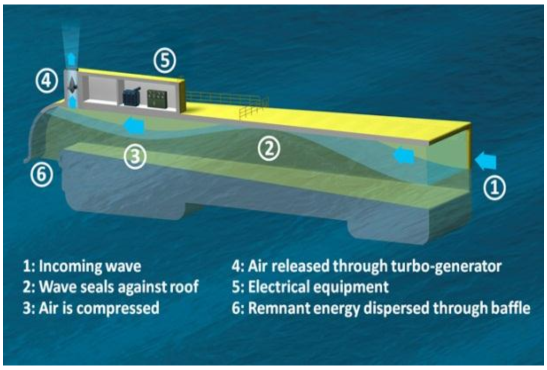
2.3.3 **Operating Principle**

A last, but most common kind of classification (proposed by Falcão and Rodrigues, 2002) is based on the conversion principle. The three categories are: Oscillating Water Columns, Overtopping devices and Wave Activated Bodies.

1. Oscillating Water Column (OWC)
   This kind of WECs is very common and studied. It usually consists of a partially submerged structure with a chamber at the bottom (i.e. below the sea water line) from which waves enter the structure. Wave crests cause the water column to rise and compress the air in the chamber, while the wave troughs cause the water column to fall and the air pressure to drop. The power take-off system is typically based on air turbines, which are activated by the alternative compression/decompression of the air in the chamber. To this purpose, the Wells self-rectifying air turbines (i.e. able to rotate regardless to the airflow direction) are commonly used. The Limpet is an example of on-shore OWC (see Fig. 2.12*a*). The on-shore OWC can also be integrated in structures for the harbour protection, as the REWEC [12], taking into account environmental aspects, such as visual and acoustic impacts. There are also several floating OWC devices, among them for example the OWEL Grampus WEC (see Fig. 2.12*b*).



a)



b)

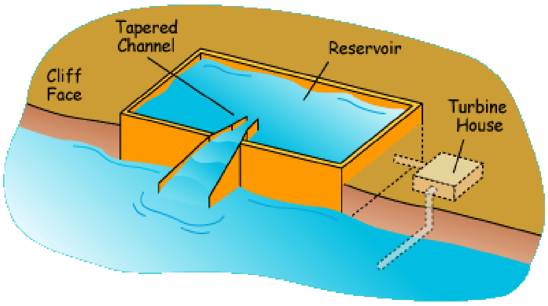
Figure 2.12 *- Examples of devices:*
a) fixed OWC (Limpet device, website http://www.wavegen.co.uk/what_we_offer_limpet.htm)
b) floating OWC (OWEL, website http://www.owel.co.uk)

2. Overtopping Device (OTD)

The power production concept is based on the conversion of the potential energy: waves run-up along a ramp, overtop in a storage reservoir above the sea level and the power is then obtained by exploiting the difference of water level between the reservoir and the sea (usually by low head Kaplan turbines), similarly to a hydroelectric plant.

The first prototype based on this technology was the Tapchan (see Fig 2.13*a*). Another fixed OTD is the Sea Slot-cone Generator (SSG), which is suited to be placed in harbour breakwaters and consists of a multi-reservoir ramp.

This technology has been later adapted to offshore use by means of floating ramps: an example of floating OTD is the Wave Dragon device (see Fig. 2.13*b*).



a)


b)

Figure 2.13 *- Examples of devices: a) fixed OTD (Tapchan device, http://taperedchannelwaveenergy.weebly.com/tapchan-model.html) b) floating OTD (WaveDragon device, website http://www.wavedragon.net)*

3. Wave activated Bodies (WAB)

These devices are usually composed by several parts, which interact due to the progressive wave action along the device. In fact waves activate the oscillatory relative motions of parts of the device or of one part with respect to a fixed reference. WABs can be further divided into sub-categories, based on the main solicited relative motion (heave, pitch and roll), for example: heaving buoys, pitch/surge devices, surge/heave/pitch devices and yaw/heave devices. The motions of surge, sway and yaw require instead external forces from the mooring system, even if the possibility of a body part to interact with a near element leads to an "autonomous system", reducing single mooring forces. Usually WAB devices are also considered as attenuator, for example the Pelamis (see Fig. 2.11*b*) and the DEXA (see Fig. 2.14).

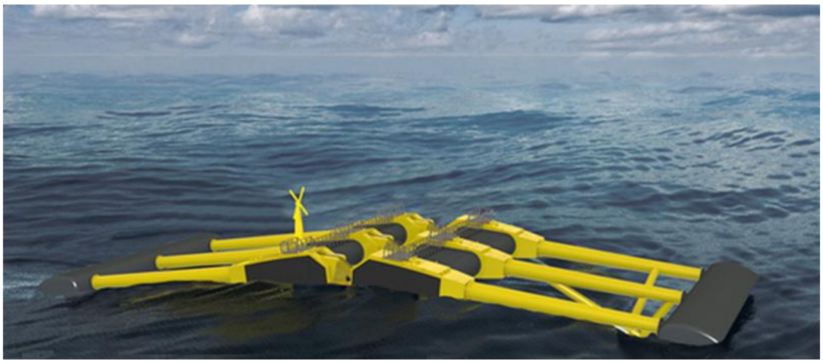


Figure 2.14 *- Example of a floating WAB (DEXA prototype, website http://www.dexawave.com/)*

The categories described above include most -but not all- of the technologies being developed today. For example, there are devices which exploit the wave energy and water particles movement at the surface (oscillating wave surge converters). A more detailed collection of the WEC concepts is summarized in Clément et al. (2002) as well as in Ingram et. al. (2011). Furthermore, sometimes it is usual to describe a same WEC using more than one kind of classification. For example, common shoreline devices are OWCs or fixed OTDs, while OTDs are also usually terminators. The relationship between the three main classifications and an overview on the possible operating principles at the three defined locations with schematic drawings of WECs are provided in the following tables (see Tab. 2.2 and 2.3).

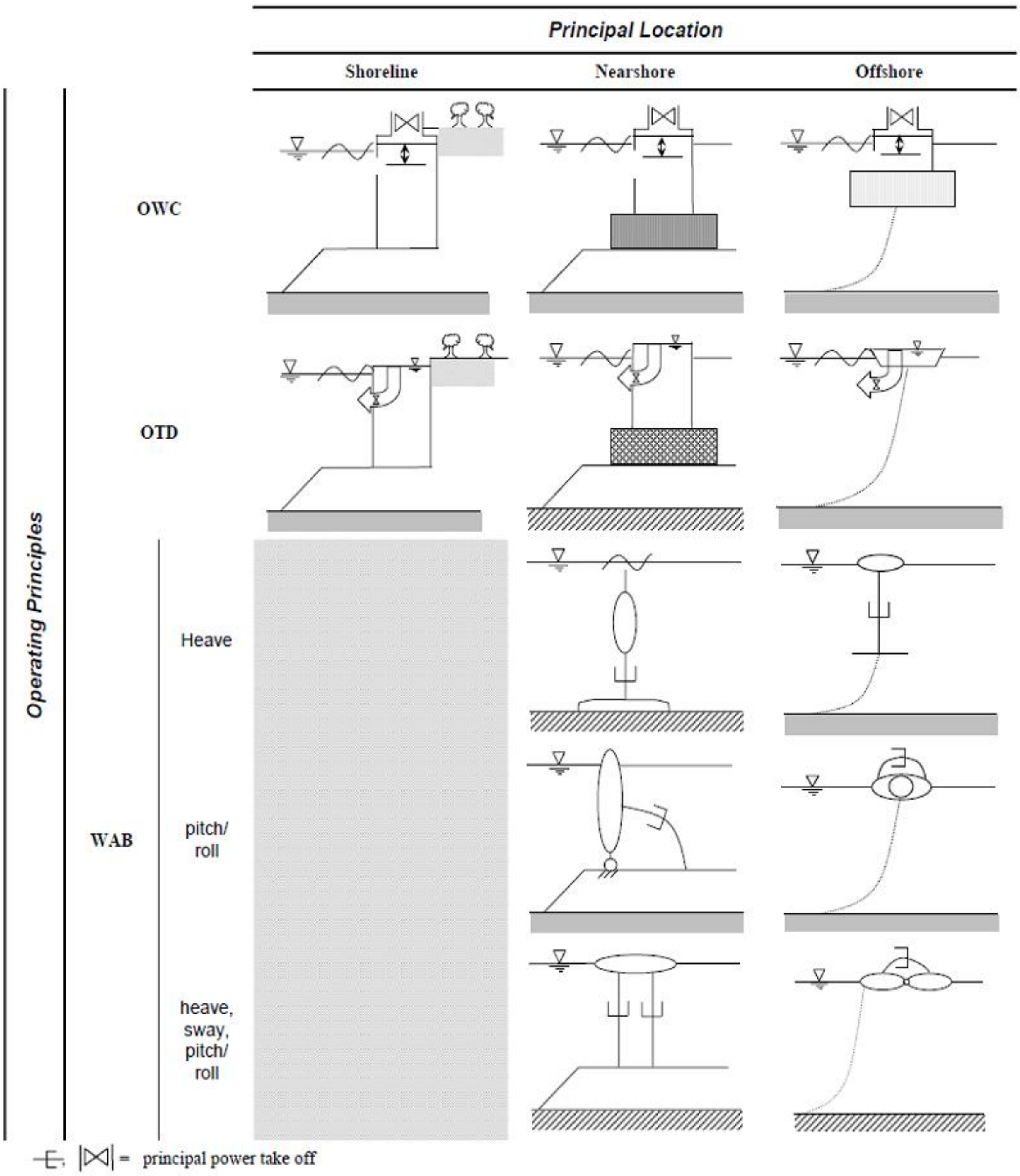


Table 2.2 *- Schematic representation of the WECs taking into account the shoreline distance and their functional principle, proposed by Harris et. al., 2006.*

		Directional Characteristic	
	Point Absorber	**Terminator**	**Attenuator**
Principal Location **Shoreline**		OWC, OTD	
Nearshore	WAB	OWC, OTD, WAB	WAB
Offshore	WAB	OWC, OTD, WAB	WAB

Table 2.3 *- Combination of three classifications proposed above, combination proposed by Harris et. al., 2006.*

2.4 Wave energy sector challenges

Designs vary from WEC to WEC, however, each design faces similar challenges that must be overcome before successful commercialization. Energy Technologies Institute (ETI), UK Energy Research Centre (UKERC, 2010) sent an update to UKERC Marine Energy Technology Roadmap (UKERC, 2008) and identified 47 key challenges (mostly technology challenges) and summarized them into the following five areas:

- Device and system demonstrators
- Sub-components
- Guidelines and standards
- Tool development
- Infrastructure and enablers

The challenges and associated activities within each of these areas were ranked for the needs of the UK marine energy sector. This roadmap has been briefly discussed in one of the deliverables of the SI Ocean Project (SI OCEAN, 2012) and will be discussed in more detail together with the other sector challenges in the later stages of the SI Ocean project. The EU-OEA Ocean Energy roadmap 2010-2050 (EU-OEA, 2010) and the IEA Ocean Energy Systems Vision reports (Huckerby et al., 2012) have highlighted and discussed challenges from the European and international perspective. The ORECCA European Offshore Renewable Energy Roadmap (ORECCA, 2011a) has identified specific technical challenges and underlined generic areas and components where cooperation with offshore wind and knowledge transfer from other sectors such as offshore engineering may aid to address some of the key challenges faced by the European ocean energy sector (SI OCEAN, 2012). ORECCA (2011a) has also prioritised the technology challenges and associated activities within offshore wind and ocean energy sectors according to the sector needs.

The key challenges that the wave energy sector is experiencing are given in figure 2.15 and provided in this section based on the information given in the SI Ocean project (SI OCEAN, 2012).

Figure 2.15 *- High level sector challenges (ORECCA, 2011a; SI OCEAN, 2012).*

2.4.1 **Predictability**

Waves are stochastic in nature, and prediction of wave height and period requires first to know the wind velocity and direction. Wave period and significant wave height are also dependent on a number of factors beyond wind direction, such as fetch and bathymetry, etc., making the predictability of wave energy output a challenging task. Wave predictability is generally possible with a number of days in advance, as waves result from wind action across the surface of the ocean, and so wave energy does not fluctuate instantaneously with wind. Each WEC type will respond differently in varying wave climates. Improvement of the predictability of energy output, from a given wave climate, is a topic that can be developed for specific devices and, as developers gain knowledge at-sea testing, power matrixes will be developed showing power output and device response for several sea conditions (SI OCEAN, 2012).

For improved predictability of energy output, UKERC (2008) has highlighted the following activities:

- improve resource analysis and weather forecasting;
- improve hydrodynamic and primary power conversion modelling;
- improve understanding of the interactions in the WEC arrays;
- improve modelling of combined waves and currents.

2.4.2 **Manufacturability**

Manufacturability of WECs will improve as devices move from the first full scale prototypes, into commercial production. Current devices are bespoke designs but, in the future, devices will be materialized. Key links within the supply chain, such as component suppliers and service providers, are now starting to undertake development work for ocean energy device manufacturers, as ocean energy is perceived to be a future growth area (SI OCEAN, 2012). There is currently limited design consensus amongst WECs. This directly influences the supply chain solutions for wave energy sector. A streamlined manufacturing process will allow for benefits in both learning-by-doing and economies of scale (SI OCEAN, 2012). The design of device components and sub-systems can allow for optimized manufacturing techniques. Furthermore, other materials were tested (fatigue behaviour, etc.) for certain devices to be considered as a steel substitute, in fact steel is widely used in present devices (Carbon Trust, 2011). New materials will bring different challenges in terms of manufacturing tolerances, and the scale of component that can be created (SI OCEAN, 2012).

2.4.3 **Installability**

An easy and quick installation would of course facilitate WEC farms. The installability of a WEC depends on its location, i.e. water depth, seabed characteristics and bathymetry.
As described before, WECs can be installed either on the shoreline (water depths typically < 15m), on shallow water near the coast (water depths typically < 25m) or in deeper offshore waters (water depths typically > 25m). The location of WECs has a significant effect on the foundation and mooring type used (see Fig. 2.16). For example shore-line WECs are usually integrated into civil engineering structures; near-shore WECs are usually supported by bottom-mounted support structures to keep their position or are directly fixed to the seabed. Whereas, offshore devices are floating or sub-merged and moored to the seabed. They can make use of tight or slack moorings depending on the type, location, and the Power take-off (PTO) system of the structure. There are numerous mooring, anchoring and foundation options. There also exist alternative mooring techniques that can be adapted from the Oil and Gas industry. Further information on foundations and moorings which are used to fix WECs in position are given in sections 5.1 and 5.2.

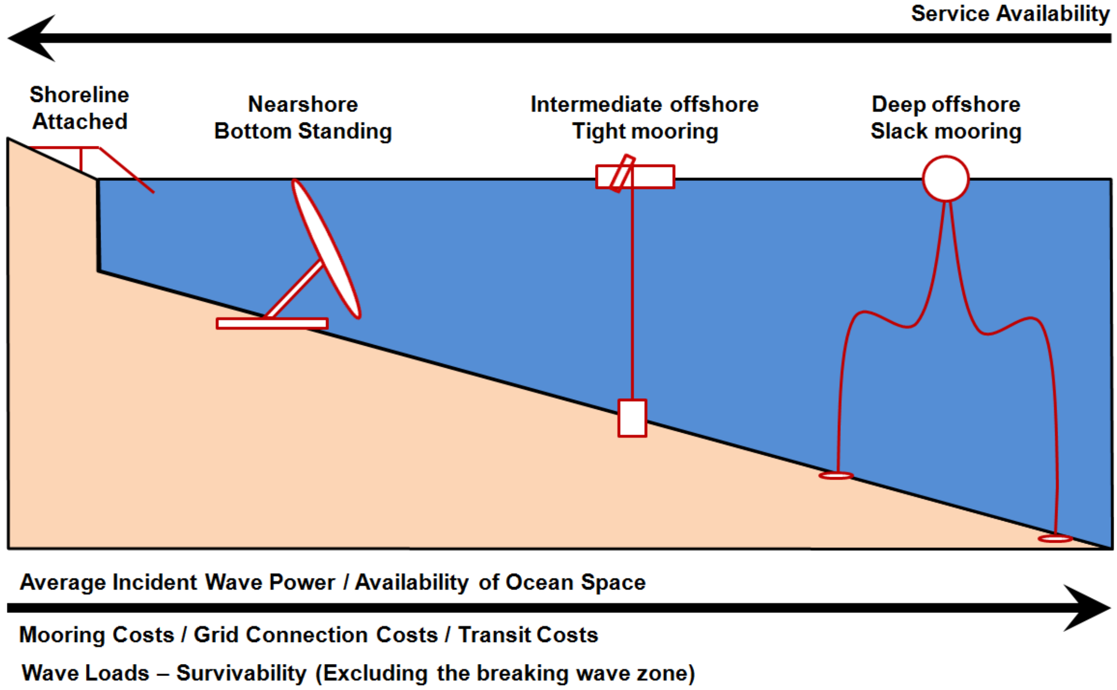


Figure 2.16 *- Support structure and mooring configurations for WECs based on location.*

Furthermore, the sector needs advanced installation techniques and affordable installation vessels. Much of the device installation and intervention that has taken place so far has utilized vessels from the Oil and Gas industry, the price of which can fluctuate greatly depending on demand and spot-market price (SI OCEAN, 2012).

The location of WECs also influences the energy resources and cost of the energy transportation. The costs vary with the water depth and distance to the shore (AMEC Environment & Infrastructure UK Limited, 2012). Costs associated with WECs are analysed in Chapter 6.

The location of WECs also significantly influences the design of the WEC structure. A significant challenge for the wave energy industry is demonstrating the survivability of a device. Advantages and disadvantages for each location are summarized in Table 2.4.

Urgent needs for better install-ability can be listed as (UKERC, 2008):

- establishment of fabrication, transport and installation infrastructures;

- development of cost-effective support structures, moorings, anchorage and connection methods;
- development of electrical connectors, submarine cabling networks and improved network integration.

Zone	On-shore	Near-shore	Off-shore	
			Shallow draught	Deep draught
Advantages	Potential lower/ shared cost (capital, O&M) Lower technology risk Easy access for service & maintenance Fixed cable Connections Smaller individual machines	Cabling costs not Excessive Can harness nearshore physics such as surge Power pack can be on-shore (also disadvantage) Short journey for service & maintenance	Depth range suits large devices of varying concepts, significant site availability Wave power not diminished by proximity to land Permitting potentially easier	Facilitates devices with deep draught Larger power rated devices possible Moderately higher resource No visual obstruction Minimal environmental impact
Disadvantages	Site availability is limited Potential for farms is limited Environmental / permitting factors may be an issue Wave climate can be unstable	Survivability issue due to shore proximity Site availability potentially low Environmental/permitting issues may be significant On-shore PTO planning permission required	Installation, O&M can be problematic due to distance from shore Mooring may be difficult Accessibility & cabling can be difficult	Installation, O&M, access can be problematic and expensive Mooring may be difficult Cabling very expensive Limited site availability close to markets

***Table 2.4** - Advantages and disadvantages for each zone (WAVEPLAM, 2010).*

2.4.4 Survivability

Wave energy is generally captured by converting relative motion of different structures (or the wave itself) into power. The wave motion acting on these structures causes huge forces that must be handled by WEC structure and mooring. Forces vary constantly within the expected operated conditions, and transferred throughout the device components (SI OCEAN, 2012). In addition, Carbon Trust (2011) has shown that WECs, in the medium term, need to extract energy from high energy sites to be able to compete with other renewable energy technologies. These sites accommodate large extreme waves and thus extreme wave forces which can damage the WECs. Therefore, WECs need to be over-dimensioned compared to the expected average operating conditions in order to withstand the extreme conditions, which highly increase the cost of the device (Czech & Bauer, 2012). WECs should withstand these forces within life expectancy of 10-20 years (Halloran, 2010). Special attention should also be given to the effects of corrosion and bio-fouling (BOREAS, 2012). Urgent needs for better survivability design of the devices can be listed as (Mueller et al., 2010; UKERC, 2008):

- state of the art and efficient statistical analysis tools for short-medium term prediction of extremes. Based on these data, device developers can calculate the fatigue and ultimate force loadings that the device will experience;
- development of design methods for cost effective survival. Developing a survivable device that generates electricity at affordable levels makes cost of the device prohibitively high;
- establishment of guidelines and standards for testing, operating of the systems.

2.4.5 **Reliability**

Developing a device to guarantee an efficient operation for long periods in the marine environment is probably the most pressing challenge. Both survivability and reliability are the key factors for the performance of the device over the life cycle. However, they have very different drivers. Reliability is governed by the detailed aspects of the systems design, such as whether a generator can operate over 20-25 years, can a hydraulic system switch valves every 10 seconds over the life cycle of the system?, etc. Device developers are challenged by the huge cost of failures that are often prohibitively expensive. Hence, providing the reliability of the system over lifecycle is the fundamental part of the WEC design about which wave energy developers should be very careful. Increased reliability will reduce unplanned maintenance requirements (SI OCEAN, 2012).
Needs for better reliability of the devices are listed below (Mueller et al., 2010; UKERC, 2008):

- improvement in coaling, sealing, monitoring;
- establishment of component reliability statistical database.

2.4.6 **Operability**

The operability of WECs must be proven in the off-shore environment. Demonstration of reliable device operation, proof of performance in real sea conditions and survivability under extreme conditions will increase the credibility of the technology in the wave energy sector (SI OCEAN, 2012). There is a need to improve offshore access, operation and maintenance techniques and strategies for better operability of the devices (UKERC, 2008).
Furthermore WECs often need to be tuned based on the typical wave climate, in order to extract the maximum energy from the wide range of wave heights and frequencies of the site. To achieve this target, the developers should achieve optimum resonance with the most common wave height/length, whilst still achieving reasonable efficient capture from less common waves (Carbon Trust, 2011).

2.4.7 **Affordability**

Whilst in short term, capital investment is needed to support the deployment of the first arrays of WECs, in long-term device affordability will determine the economics of the project (SI OCEAN, 2012). An affordable WEC requires innovation and cost reductions. The Carbon Trust Accelerating Marine Energy report (2011) and the Marine Energy TINA report (Low Carbon Innovation Coordination Group, 2012) have highlighted the role that innovation could play in order to reduce the technology and development costs.

3 Power Take-Off (PTO) systems

The deliverable 5.2, drawn by the EquiMar Project, defines the Power Take-Off (PTO) system as the place where the mechanical motion is converted to a more useful form of energy. In case of WECs or renewable energy conversion, the useful form of energy hereby considered is electricity. Then, of course, the electricity might be fed into the grid, rather than consumed locally to supply off-shore loads. Therefore, the PTO is made up of all of the elements needed to convert the captured energy of the waves into electrical energy, including the control system to cooling and lubrication of the moving parts, to power conversion systems to support the production of electric energy compliant with network specifications, as shown in figure 3.1.

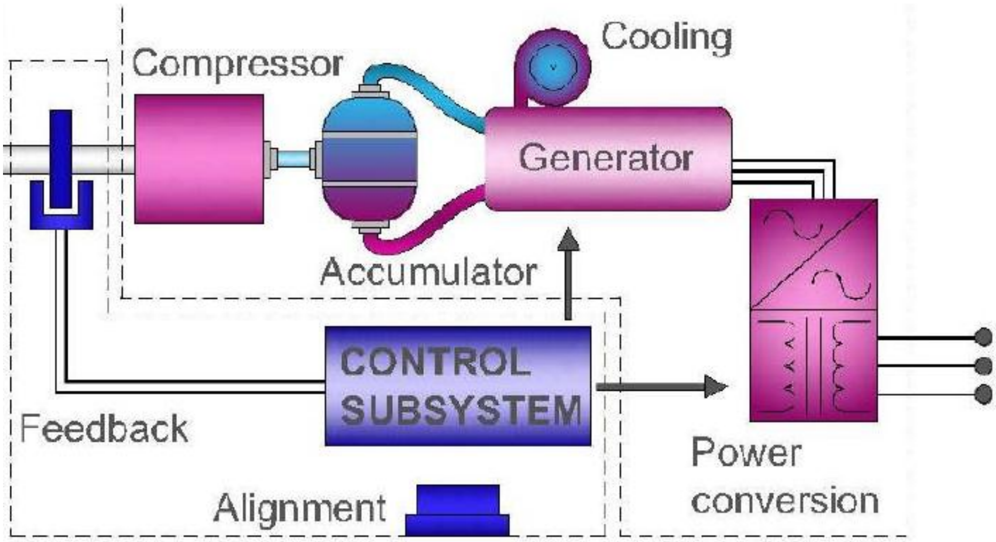


***Figure 3.1** – PTO subsystem*
(Source EquiMar D5.2- Device classification template).

The energy conversion procedure strongly varies among the several WECs, making the PTO classification quite complex. The OES-IA dealing with the dynamic characteristics of wave and tidal energy converters, presents an ocean energy device classification, that does not explicitly refer to the PTO system but is very useful to understand its key elements.
The scheme, conceptually valid also for tidal devices, shows that the energy of waves is somehow captured in different ways, then transferred to a prime mover and finally converted into electrical energy by means of a generator. Potentially, at each stage the intervention of the control system and of a storage system can take place (see Fig. 3.2).

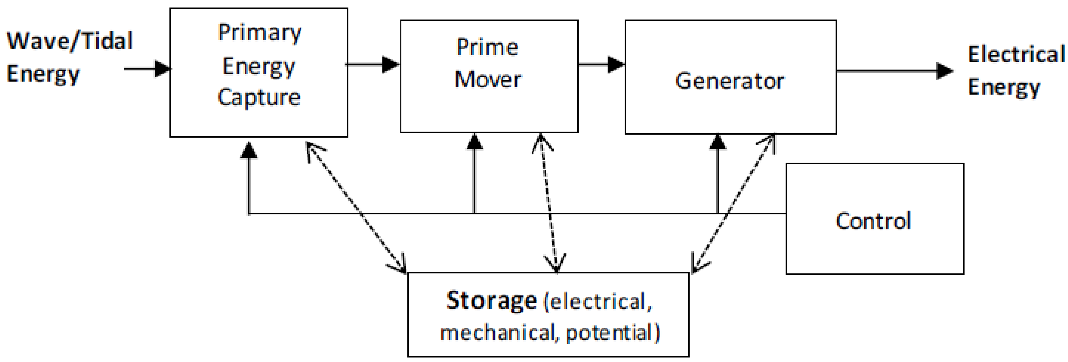


***Figure 3.2** - Key elements for WEC power conversion.*

The primary power capture stage is activated by a fluid power in case of OWC or OTD devices or by the motion of a WAB and then it can be considered mechanical power. Different prime movers are therefore used according to the operating principle of the WECs. In particular, the first element of the PTO, i.e. the prime mover, converting the output of the

- air turbines of the OWC, that drive rotating generators
- hydraulic turbines of the OTD, that drive rotating generators

According to OES-IA, the different prime movers can be classified as:

- Air Turbines
- Hydraulic Turbines
- Hydraulic Motors
- Direct Mechanical Drives

The following paragraphs report a brief description of each prime mover.

3.1 Air turbines

Air turbines are used to convert air motion into mechanical torque, which drives the electrical generator. To date, air turbines have been used almost exclusively in OWCs, either on-shore or floating. There are currently three different types of self-rectifying air turbines: Wells turbine, Impulse turbine and Dennis-Auld turbine.

Over the last 30 years, many different turbine designs have been examined, the most important of which are hereby listed.

Wells turbines:

- Wells turbine with guide vanes;
- turbine with self-pitch-controlled blades;
- biplane Wells turbine with guide vanes;
- counter-rotating Wells turbine.

Impulse turbines:

- impulse turbine with self-pitch-controlled guide vanes;
- impulse turbine with active-pitch-controlled guide vanes;
- impulse turbine with fixed guide vanes;
- McCormick counter-rotating turbine.

Radial turbines:

- radial turbine with fixed guide vanes;
- radial turbine with active-pitch-controlled guide vanes.

Cross-flow and Savonius turbines.

3.1.1 **Wells turbines**

The Wells turbine takes its name from its inventor Dr. Alan Wells (in the mid-1970s in Queens University, Belfast). It is a self-rectifying, low pressure axial-flow turbine, meaning that its torque is not sensitive to the direction of the air flow, that makes the turbine ideally suited for OWC applications (e.g. Limpet, Mutriku), providing active phases both in the upward and downward movement of the water column itself. Rectification is obtained thanks to the symmetrical airfoil with respect to its plane of symmetry in the plane of rotation and perpendicular to the air stream (Manabu and Setoguchi, 2012), see figure 3.3.

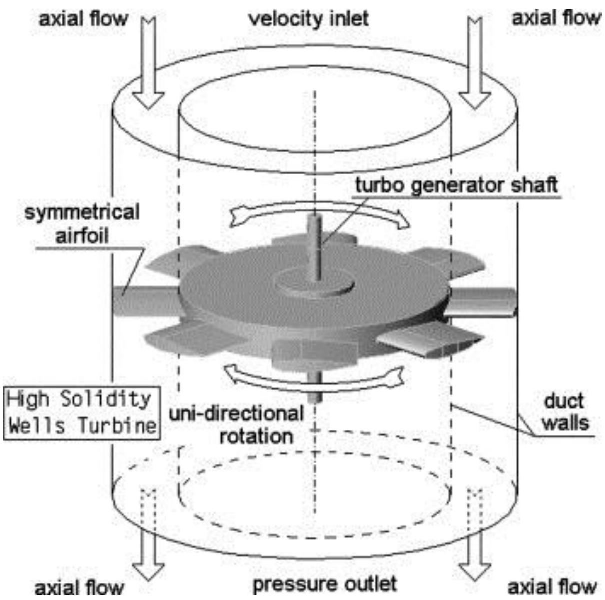


Figure 3.3 *- Wells turbine schematics.*

It is the most common type of air turbines due to the its number of features such as (Lopez et al., 2013). Furthermore:

- it has a relatively high speed rotation with low air flow velocity,
- it has a good peak efficiency (0.7-0.8 for a full-sized turbine), and
- it is relatively cheap to construct.

On the other hand, it has several disadvantages (Falcao, 2010; Lopez et al., 2013)such as:

- low or even negative torque at (relatively) small flow rates,
- aerodynamic noise,
- drop (possibly a sharp drop) in power output due to aerodynamic losses at flow rates exceeding the stall-free critical value,
- relatively big diameter for its power (e.g. 2.3m for the single rotor 400kW turbine of the Pico OWC plant, 2.6m for the counter-rotating 500kW turbine of the Limpet Islay II plant, and 3.5m for the Osprey plant)

It has a number of versions as given before:

- wells turbine with guide vanes;
- turbine with self-pitch-controlled blades;
- biplane Wells turbine with guide vanes;
- counter-rotating Wells turbine.

Figure 3.4 reports the efficiency of the Wells turbine. It reaches values of around 60% (Drew et. al., 2009) with peak of 70-80% for a full sized turbine in near-shore condition (Falcao, 2010). The expected behaviour in real operating conditions, where the pressure head continuously varies from positive to negative values, is better approximated by the averaged, i.e. the blue line in the figure. Generally its efficiency is lower than the efficiency of a turbine with constant air stream direction and asymmetric airfoil, mainly because symmetric airfoils have a higher drag coefficient than asymmetric ones, even under optimal conditions.

A way to obtain a wider efficiency curve, following the experience of Kaplan water turbines, is to control the setting angle of the rotor blades, even if an increase in complexity and therefore cost has to be expected. Figure 3.5 a), b) and c) show respectively a turbine with self-pitched controlled blades, a bi-plane Wells turbine and a counter-rotating Wells turbine.

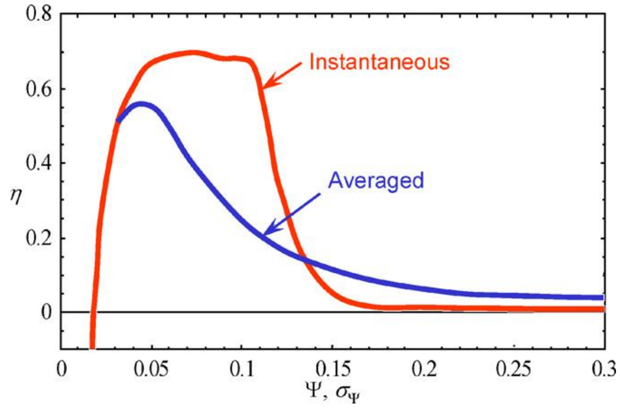


Figure 3.4 *- Aerodynamic dimensionless efficiency curves of a Wells turbine (from model testing results). It is represented the instantaneous and averaged efficiency of a single rotor Wells turbine with guide vanes versus the available pressure head.*

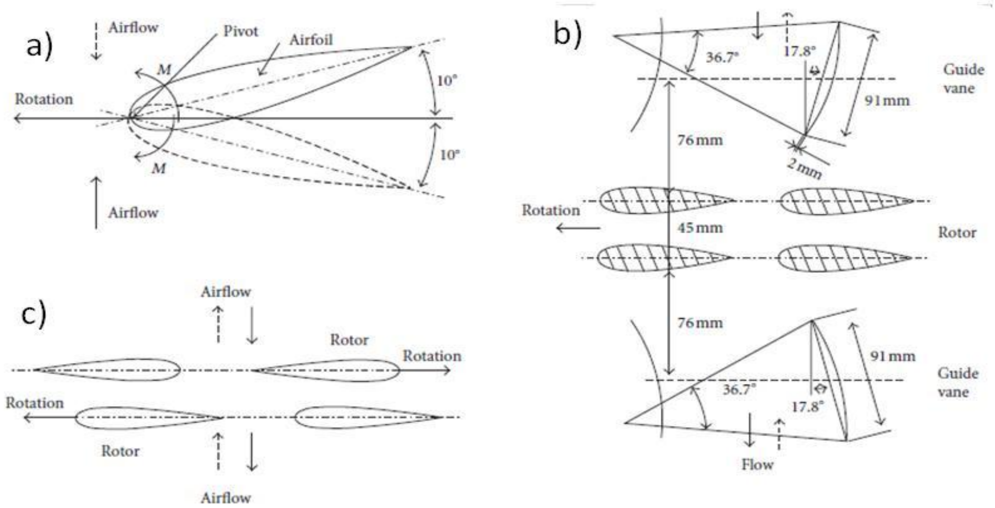


Figure 3.5 *- a), b), c) - Types of Wells turbines (source Manabu and Setoguchi, 2012).*

Despite the relatively low efficiency, the simple design and the possibility to operate at high rotational speeds allowing the utilization of a high speed generator (cheaper than the slow ones) makes this turbine a considerably economical and reliable solution.

3.1.2 **Dennis-Auld air turbine**

The so-called Dennis-Auld turbine was developed in cooperation between the University of Sydney and the Australian Company Oceanlinx. It is presently used in all the OWCs developed by the company GreenWave, BlueWave and OgWave. It is a self-rectifying turbine similar to a variable pitch Wells turbine. It utilizes variable pitch rotor blades to improve operating efficiency, and is specifically designed for the OWCs.

The blades are located on the periphery of the rotor hub in a neutral position, parallel to the axial direction of the flow rather than tangential to the direction of rotation as in the Wells and Impulse Turbines (see Fig. 3.6). In figure 3.7, the different positions of the blades over one cycle are shown. The Dennis-Auld Turbine has a much larger pitching range than the variable pitch Wells turbine, therefore, it has a much greater solidity (total blade area divided by turbine swept area) which increases the efficiency of the device (Falcao, 2010; O’Sullivan et al., 2010; Gareev, 2011; Lopez et al., 2013).

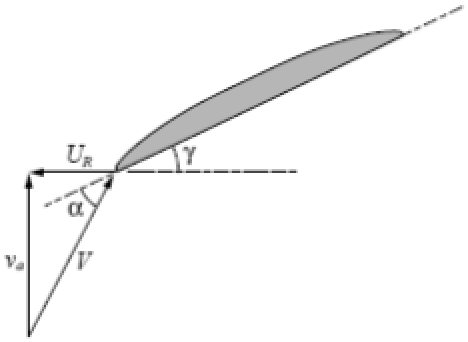


***Figure 3.6** - Blade design for a Dennis-Auld turbine.*

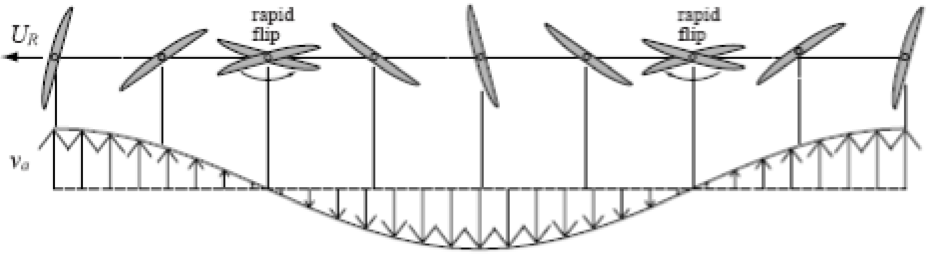


***Figure 3.7** - Blade pitching sequence in oscillating flow for a Dennis-Auld turbine.*

Efficiency of a Dennis-Auld turbine is given in figure 3.8, as a function of flow ratio. As shown in the figure, a wide range of high efficiency corresponds to low rotational speeds/high torques.

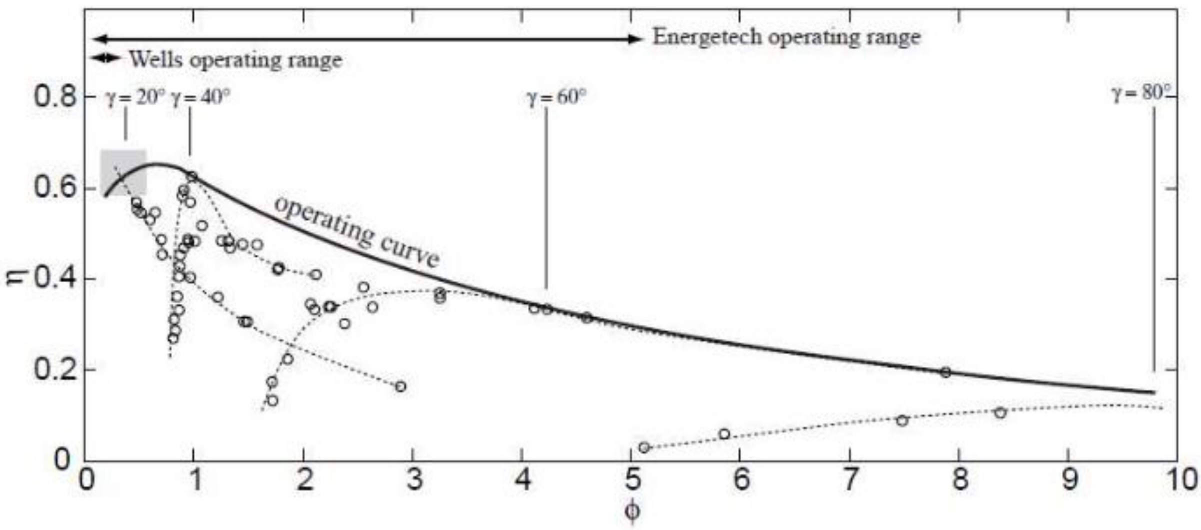


***Figure 3.8** - Efficiency curves for a Dennis-Auld turbine, as a function of flow ratio.*

3.1.3 **Impulse turbines**

Invented in 1975 by I.A. Babinsten, the self-rectifying impulse turbine represents the most popular alternative to the Wells turbine. In order to assure the self-rectifying behaviour, two rows of guide vanes are placed symmetrically on both sides of the rotor.

Left side of figure 3.9 illustrates an impulse turbine with fixed guide vanes, while the right part shows an impulse turbine with self-pitch-controlled guide vanes (Setoguchi et. al., 2001). In this type of turbine pivots placed on the casing wall, at the end of the guide vane chord, allow the guide vanes to rotate around them under the effect of aerodynamic moment caused by the oscillating airflow. With this type an efficiency increase can be obtained linking each vane of one side of the rotor to a vane of the other side.

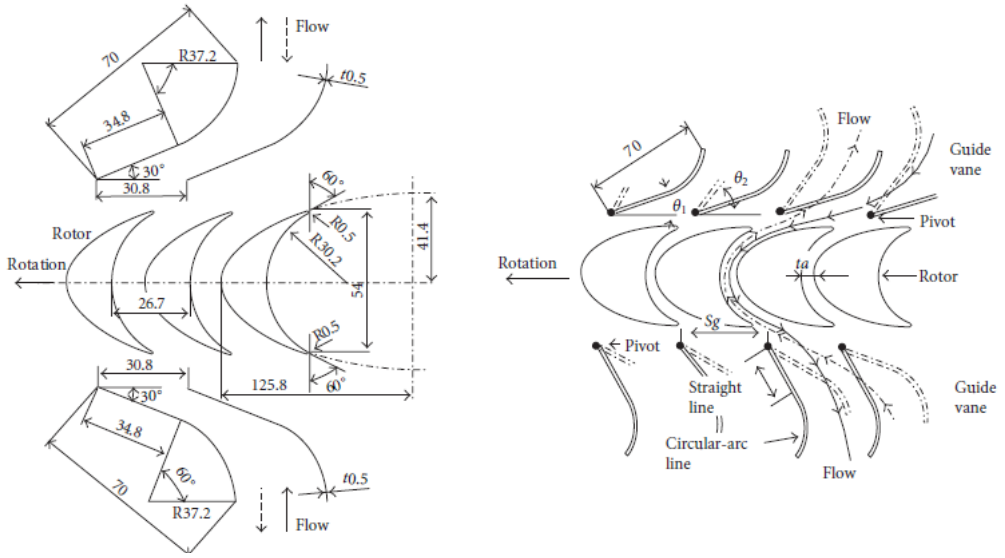


Figure 3.9 *– Left side: Impulse turbine with fixed guide vane (Manabu and Setoguchi, 2012). Right side: Impulse turbine with self-pitched controlled guide vanes (Setoguchi et. al., 2001).*

Recently a version with active-pitch controlled guide vanes obtained by means of hydraulic actuator has been proposed and tested (Thiebaut et. al., 2011).
The types with variable geometry guide vanes, developed to overcome the disadvantages of Wells turbines, are characterized by better efficiencies than the one with fixed guide vanes (a strong efficiency limit is given by aerodynamic stalling at the downstream row of guide vanes) even if they have to face with design, maintenance, operating life and cost issues due to the presence of moving parts and the necessity to withstand many daily oscillation cycles. Generally, in comparison to the Wells turbine, impulse turbine has smaller blade speed and dimensions for the same power output and they produce less noise.
Figure 3.10 shows the outline of the McCormick turbine: a prototype model of counter-rotating impulse turbine that showed average efficiencies near 0.3. Principal drawbacks are recognized in noise generation and balance of gearing cost.

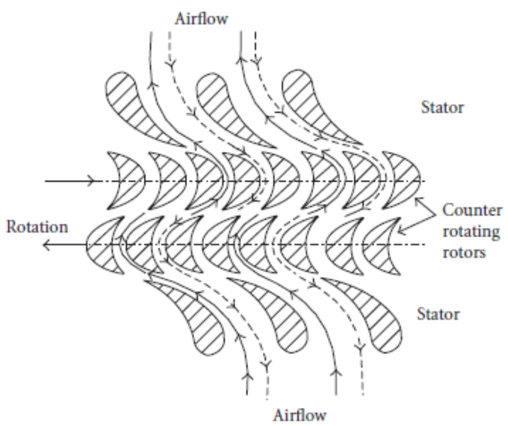


Figure 3.10 *- McCormick turbine (source Manabu and Setoguchi, 2012).*

Recently, Takao and Setoguchi (2012) discussed the state of the art of air turbines and proposed a twin-impulse turbine (see Fig. 3.11) as a novel air turbine for wave energy conversion.

The main problem with the impulse turbine lies in the large aerodynamic losses due to excessive incidence flow angle at the entry to the second row of guide vanes, which is a result of the required symmetry of the guide vane rows with respect to each other (Falcao et al., 2013). In order to reduce these losses, a variety of turbine configuration has been proposed.

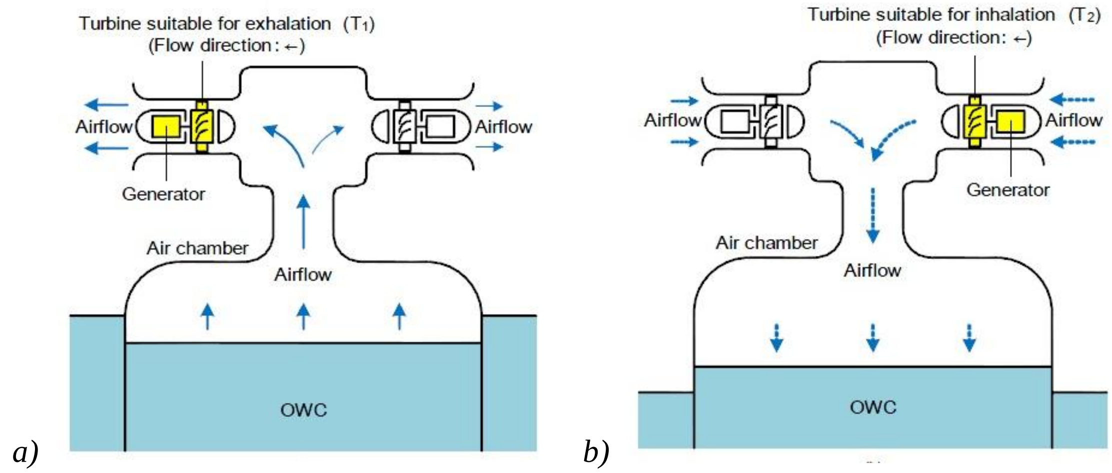


Figure 3.11 *- Principle of twin impulse turbine.*
(a) Exhalation, (b) Inhalation (Takao and Setoguchi, 2012; Okuhara et al., 2012).

3.1.4 **Radial turbines**

Radial turbines, self-rectifying, are essentially a radial version of impulse turbines. A radial-flow turbine has a pair of guide vane rows on each radial side of the rotor and the flow is both centripetal and centrifugal according to the typical reversing flow of an OWC, as shown in figure 3.12.
To improve the efficiency a version with active-controlled guide vanes has been proposed by Takao et al. (2005).

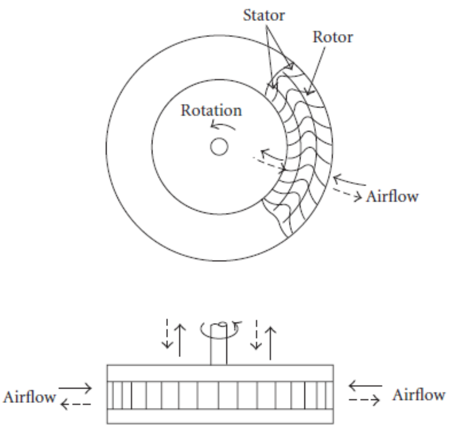


Figure 3.12 *- Radial turbine (source Manabu and Setoguchi, 2012).*

Another innovative impulse turbine, named HydroAir, was proposed and patented by Dresser-Sand, which aims at reducing the aerodynamic loss by radially and axially offsetting the guide vanes with respect to the rotor blades in order to reduce the kinetic energy at the entrance to the second guide vane row (Natanzi et al., 2011). This led to a bulky machine with peak efficiency claimed to reach 70%. The HydroAir turbine has been tested off Port Kembla, Australia in 2010 with 1:3 scale floating OWC prototype, Oceanlinx Mk3. However, due to its mechanical complexity, this turbine has not been favoured by OWC developers (Falcao et al., 2011).

Recently, as an alternative to the self-rectifying axial-flow turbine, an innovative self-rectifying impulse air turbine, significantly different from previous conceptions and called "KymanAir biradial turbine" (see Fig. 3.13) has been proposed (Falcao et al., 2011). In this situation, the flow into, and out of, the rotor is radial and the turbine is symmetrical with respect to a plane perpendicular to the rotation axis. Two configurations of this turbine exist; in the first configuration, the guide vanes are radially offset from the rotor, reducing aerodynamic losses. In another configuration, the guide vanes can slide axially, in such a way that the guide vane row placed at the outlet from the rotor is removed from the flow space, which completely avoids the stalling losses at the second row of guide vanes [13].

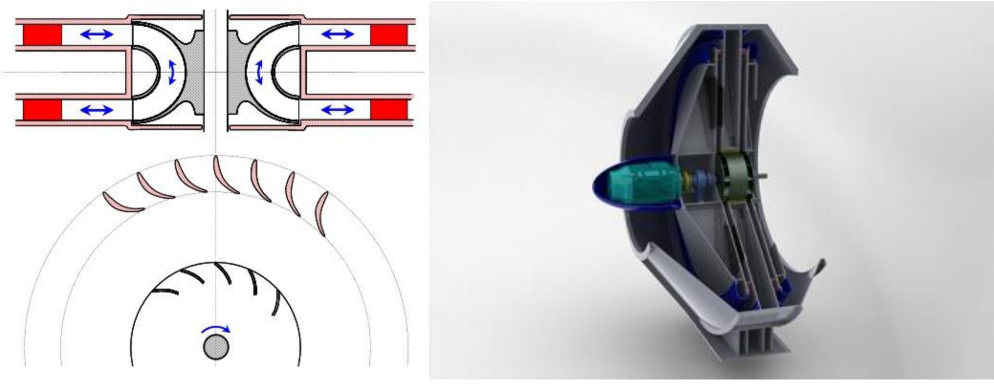


Figure 3.13 *- The KymanAir biradial turbine, with the guide vanes radially offset from the rotor (Falcao et al., 2011; Kymaner website).*

It was reported that, the aerodynamic tests performed in the IST-Lisbon laboratory confirmed the validity of the prediction model used in the design stage, with peak efficiencies close to 80% [13]. The following features have been claimed by the developer:

- very compact axially unlike the HydroAir,
- highest known efficiency of air turbines, peaking at about 80%,
- relatively low aerodynamic noise,
- suitable for a wide range of installations including those exceeding 1MW unit power,
- self-starting,
- wide operational bandwidth in a large variety of sea states, unlike the Wells turbine,
- energy storage through easy integration of a large flywheel,
- mechanically simple and reliable, unlike the controlled guide vane impulse turbine,
- moderate rotational speed (under 1'000 rpm in most cases).

3.1.5 **Cross-flow and Savonius turbines**

Several version of cross flow and Savonius turbines have been proposed up to now and tests under steady flow conditions have been conducted (e.g. Akabane et al., 1984; Katsuhara, et. al., 1987). According to Kaneko et al. (1991) starting and running characteristics of these types of turbines are poorer than the ones of Wells Turbines .

3.1.6 **Comparison of Air turbines**

Setoguchi and Takao in 2006 made an extensive review of air turbines comparing the starting and running characteristics, peak efficiency and stall margin of a Wells turbine with guide vane, a turbine with self-pitch-controlled blades, a biplane Wells turbine with guide vanes, an impulse turbine with self-pitch-controlled guide vanes and an impulse turbine with fixed guide vanes.

The comparison was made looking at principal turbine characteristics in steady flow condition (by model test and calculation) and evaluating the turbine characteristics coupled with an OWC under irregular flow conditions (by simulation): the authors consider these last wave condition crucial to select the most suitable turbines for wave power conversion since performance of the wave power converter also depends on the OWC's energy absorption efficiency, which is closely related to the pressure difference across the turbine.

Tables 3.1-2 show a comparison between turbine peak efficiency values under steady flow conditions and under irregular flow conditions, respectively.

Turbine Type	Wells turbine with guide vanes	Wells turbine with self-pitch-controlled blades	Biplane Wells turbine with guide vanes	Impulse turbine with self-pitch-controlled guide vanes	Impulse turbine with fixed guide vanes
Peak turbine efficiency	0.492	0.496	0.534	0.564	0.390

Table 3.1 *- Peak efficiency of various air turbines under steady flow conditions (Setoguchi & Takao, 2006; Takao & Setoguchi, 2012).*

Turbine Type	Wells turbine with guide vanes	Wells turbine with self-pitch-controlled blades	Biplane Wells turbine with guide vanes	Impulse turbine with self-pitch-controlled guide vanes	Impulse turbine with fixed guide vanes
Peak turbine efficiency	0.30	0.44	0.34	0.47	0.37

Table 3.2 *- Peak conversion efficiency of air turbines under irregular flow conditions (Setoguchi & Takao, 2006; Takao & Setoguchi, 2012).*

Setoguchi and Takao (2006,2012) highlighted that impulse turbines have the potential to be superior to the Wells type turbines in overall performance under irregular flow conditions and they are capable to maintain their efficiency over a wider range of flow rates.

Comparing simulated performance of Wells versus impulse turbines in a real OWC, it was found that Wells turbine are less suited for applications characterised by large air pressures oscillations (e.g. energetic seas) than impulse ones, due to the fact that impulse turbines are less constrained by Mach number effects and centrifugal (Scuotto and Falcão, 2005).

Recently, as part of the development programme of the KymanAir biradial turbine, aerodynamic tests were performed in the IST-Lisbon laboratory, and conversion efficiencies of various air turbines were compared, as it is shown in Fig. 3.14 (Falcao et al., 2013; [13]); the KymanAir biradial turbine has the highest efficiency, up to 80%.

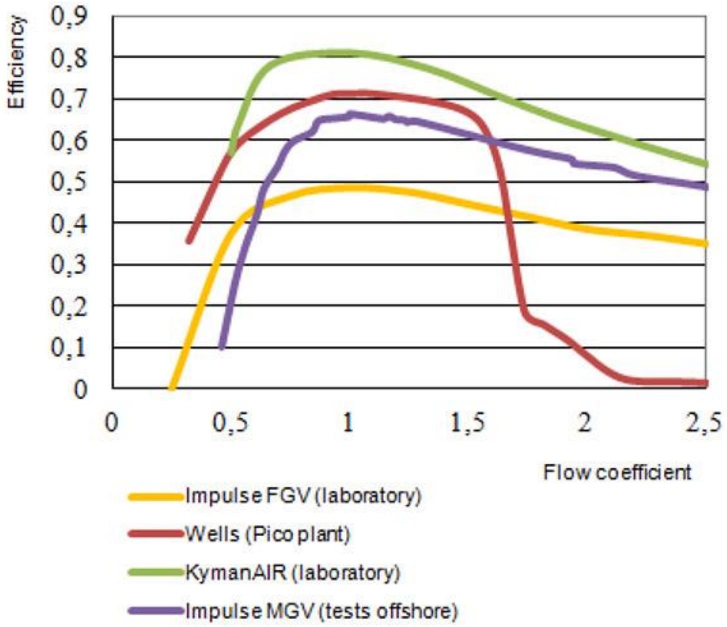


***Figure 3.14** - Comparison of efficiencies of different air turbines (Kymaner website).*

3.1.7 Air turbine uses in WEC devices

As already stated, air turbines have been widely used for OWCs, either on-shore, near-shore or off-shore, Wells turbine being the most diffused. Following Takao and Setoguchi (2012) the relevant applications are:

- single rotor with guide vanes diameter of 2.3m, capacity of 400kW used in Pico,
- bi-plane turbine, diameter of 1.2m, rated output of 75kW, Islay, U.K. with no guide vanes,
- counter-rotating, 2 turbines, NACA0012, 7 blades per rotor, diameter of 2.6m, capacity of 2x250kW, installed in the LIMPET, Islay, U.K., which is the world's first commercial wave power station,
- counter-rotating, diameter of 3.5m, used in OSPREY.

Figure 3.15 provides an overview of the Limpet commercial plant (a), and Osprey prototype (b), onshore and near-shore OWCs by WaveGen and the Oceanlinx (c), off-shore floating OWC by Oceanlinx, now looking also at the near-shore market.

An overview of WECs which use an air turbine to generate electricity is shown in table 3.3.

Converter schematics of Pico OWC is given in figure 3.16, based on the conventional approach in wind engineering.

a)

b)

c)

***Figure 3.15** - Applications of Wells turbines.*
a) Limpet; b) Osprey; c) Oceanlinx

Technology	Company	PTO system
Limpet	WaveGen	Air turbine-Wells
Mutriku	WaveGen/EVE	Air turbine-Wells
PICO	Wave Energy Centre	Air turbine
OE Buoy	Ocean Energy Ltd.	Air turbine
OWEL	Offshore Wave Energy Ltd.	Air turbine
Multi Absorbing Wave Energy Convertor (MAWEC)	Leancon Wave Energy	Air turbine
GreenWave	Oceanlinx	Air turbine- Dennis-Auld
OgWave	Oceanlinx	Air turbine- Dennis-Auld
BlueWave	Oceanlinx	Air turbine- Dennis-Auld
Bombora	Bombora Wave Power	Air turbine

Table 3.3 *- Overview of OWC devices equipped with air turbine (to be updated).*

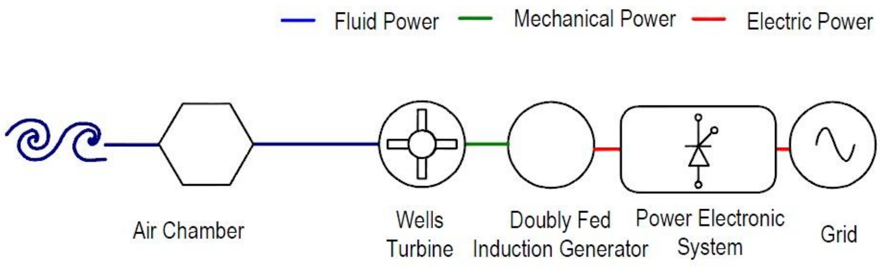


Figure 3.16 *- Converter schematics of Pico OWC.*

3.2 Hydraulic Turbines

This technology has been used for many years in hydro-power generation plants. The hydraulic turbines may be classified in two main categories (Lopez et al., 2013; see table 3.4):

- reaction turbine
- impulse turbine

Type	High head (> 50 m)	Medium head (10 – 50 m)	Low head (< 10 m)	
Impulse turbines	Pelton Multi-jet Pelton Turgo	Cross-flow Multi-jet Pelton Turgo	Cross-flow	
Reaction turbine		Francis (spiral case)	Propeller	Francis (open-flume) Kaplan

Table 3.4 *- Categorization of reaction and impulse turbines (Lopez et al., 2013).*

The above definition is related to the ability of the hydraulic machine to use pressurized or atmospheric pressure water flow. The impulse turbine (or action turbine) can recover only the kinetic energy of the water flow while the reaction turbines use both kinetic and pressure energy.

The *Specific Speed* of a turbine is the speed, expressed in rounds per minute (rpm) or radians per second (rps) at which a similar model of the turbine would run under a head of 1m, when of such size as to develop 1kW. This definition becomes very useful in order to identify the application range of each type of hydraulic turbine. IEC 60193 standard defines the term n_{QE}:

$$n_{QE} = \frac{\omega \cdot \sqrt{Q}}{E^{\frac{3}{4}}}$$

where:
Q = Discharge [m^3/s]
E = specific hydraulic energy of machine [J/kg]
ω = Rotational speed of the turbine [rps]
H = Net head [m]
P = Power [kW]

Table 3.5 classifies turbines according to the n_{QE} typical range.

Turbine type	n_{QE}
Pelton one nozzle	0.005...0.025
Pelton "n" nozzles	$0.005\ n^{0.5}...0.025\ n^{0.5}$
Cross-flow	0.03...0.22
Francis	0.05...0.33
Kaplan, propeller, bulbs	0.19...1.55
Pumps in turbine mode	0.11...2.20

***Table 3.5** - Hydraulic turbines classifications.*

Another definition of *Specific Speed* is made in term of rotational speed (rpm) and net head H (m)

$$n_Q = \frac{n \cdot \sqrt{Q}}{H^{3/4}} \qquad n_Q = 333 * n_{QE}$$

The following figure show the position of the classes of turbine in terms of head and n_Q.

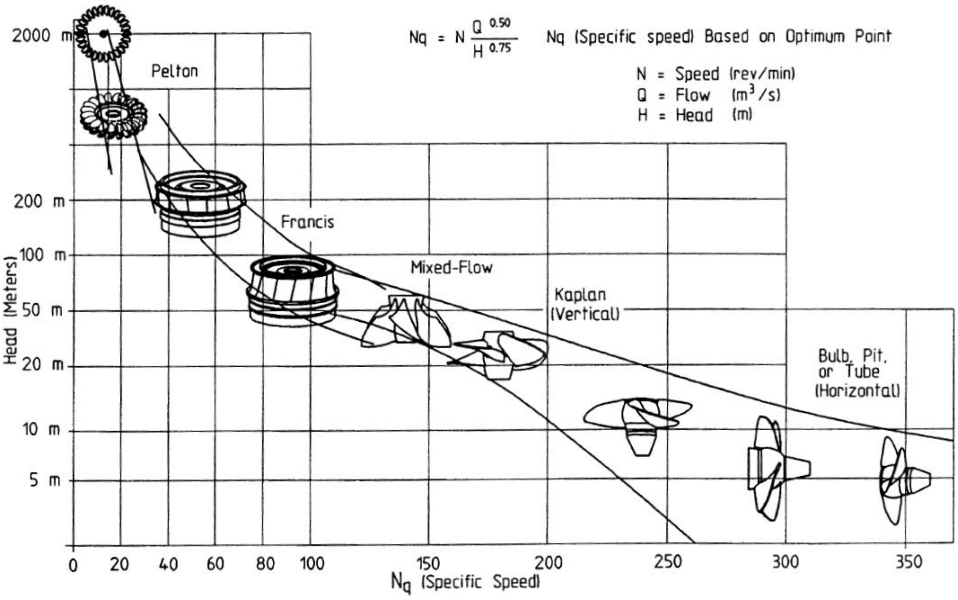


***Figure 3.17** - Main turbine applications (H- n_Q).*

The head ranges where the different turbines are normally employed are shown in Table 3.6

Turbine type	**Head range (m)**
Kaplan and Propeller	$2 < H_n < 40$
Francis	$25 < H_n < 350$
Pelton	$50 < H_n <$ 1'300
Crossflow	$5 < H_n < 200$
Turgo	$50 < H_n < 250$

***Table 3.6** - Head range by turbine type.*

The relative efficiency of three main types of turbine, referenced to the Francis turbine, as function of specific speed N_q is shown in figure 3.17.

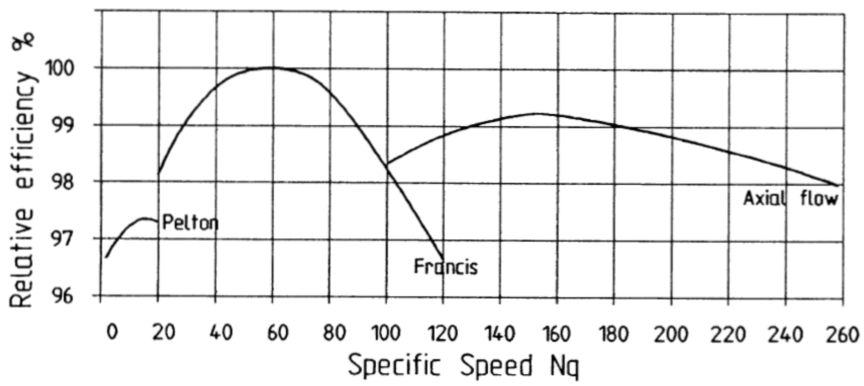


***Figure 3.17** - Main turbine applications (H-Nq).*

The following chart shows application of all main types of water turbine, depending by head and flow.

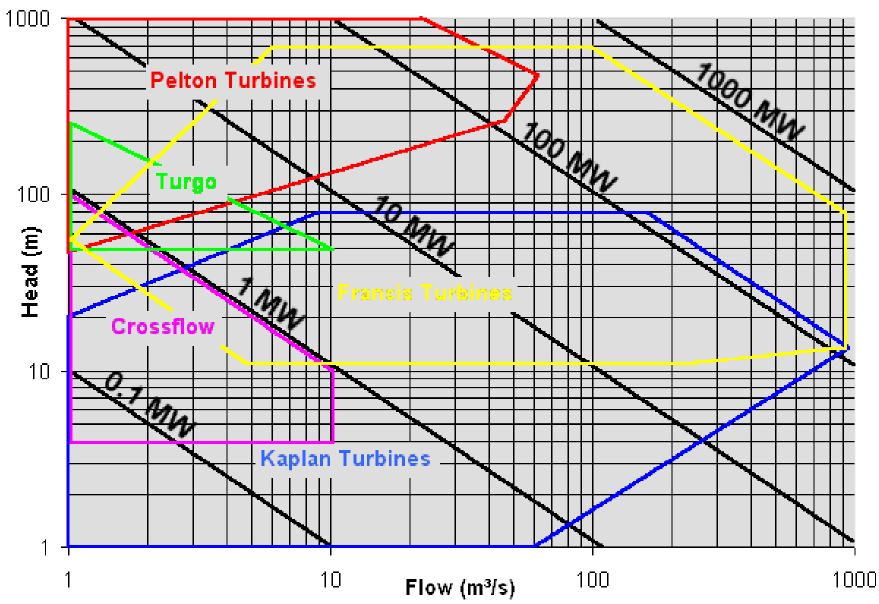


***Figure 3.18** - Turbine application chart (H-Q).*

3.2.1 Impulse turbines

An impulse turbine is driven by high velocity jets of water directed into several curved blades mounted around a wheel, where the flow is reversed (see Fig. 3.19). The resulting change in momentum (impulse) is transferred to the turbine, so that the turbine spins. All the impulse turbines work at atmospheric pressure condition.

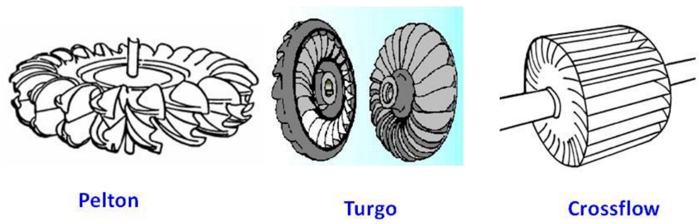


***Figure 3.19** - Impulse turbine runners.*

Pelton and Turgo are suitable to medium-high head range, while cross-flows cover medium-low head application. Impulse turbines have no flow technical limits, except for very low efficiency.

Pelton turbines
Pelton turbine is the most common type of impulse turbine. It is installed in horizontal axis configuration in case of 1, 2 or 3 jets, an example of 2 jets turbine is shown in figure 3.20. From 4 to 6 jets Pelton turbine has vertical axis. Due to the relatively high rotational speed, this turbine is always directly coupled to the generator.

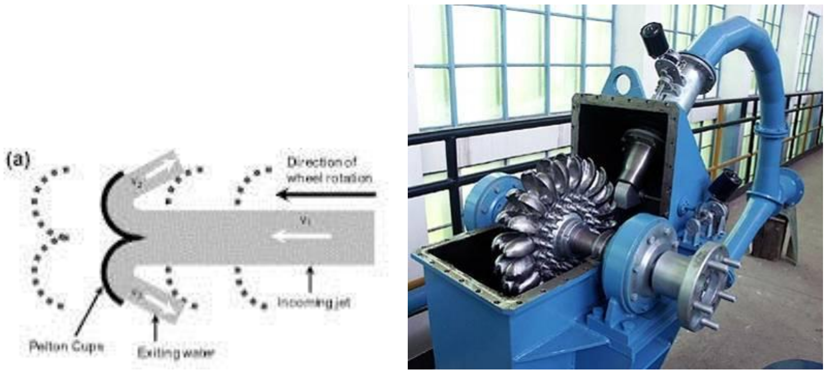


Figure 3.20 - *Two jets horizontal axis Pelton turbine.*

The symmetrical configuration of the runner does not transfer any significant axis thrust to the shaft so, in horizontal configuration, there is not the need of a thrust bearing. The Pelton turbine has an efficiency curve vs. power output depending on the number of the jets (see Fig. 3.21). The maximum efficiency achievable is about 92% in large power turbines.
Pelton turbines are not suitable for OTDs, as they are very efficient in high head and low flow applications. However, they are suitable for oscillating wave surge (e.g. Oyster).

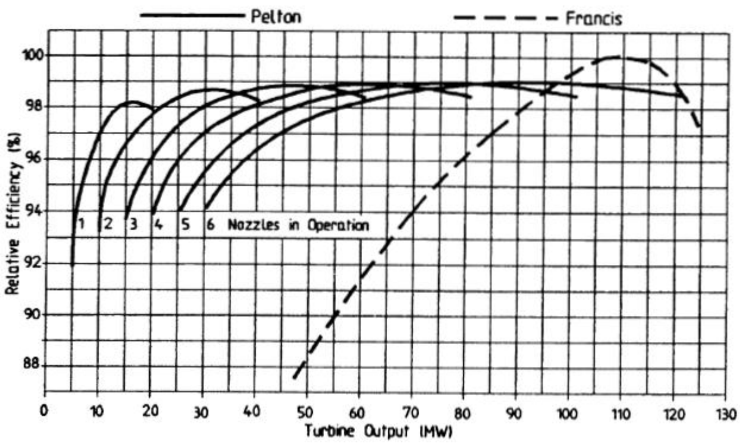


Figure 3.21 - *Multi-jet Pelton turbine efficiency (compared with Francis).*

Turgo turbines
Turgo's specific speed is positioned between Pelton and Francis. The runner of a Turgo turbine is similar to Pelton type but it is asymmetrical, as shown in figure 3.22. The water jet impact the wheel, with an angle of 20° with respect to the rotational plane of the runner.

The nozzle may be in single or multiple configuration, increasing the specific speed with the square root of jets number. The net head is in the range 50-250m. The asymmetric runner creates an axis thrust. Due to the multiple impact of the jet to the runner's blades, the runner diameter is lower than an equivalent multi-jet Pelton; hence, rotational speed is higher and generators with lower number of poles may be used, reducing its cost and weight. The maximum efficiency is lower than 85%.

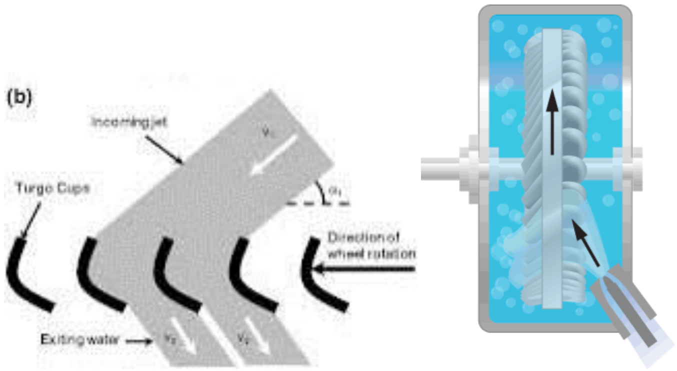


Figure 3.22 *- Turgo turbine.*

Cross Flow

The application field is in the head's range of 5-200m, with specific speed n_Q in the range 10-75. The Cross Flow turbines are simply and robust hydraulic machines, characterized by relative low efficiency (typically <85%) but with very flat efficiency curve (see Fig. 3.23). In most of its applications (h<50m) the Cross Flow turbine is coupled to generator by means of a gearbox.

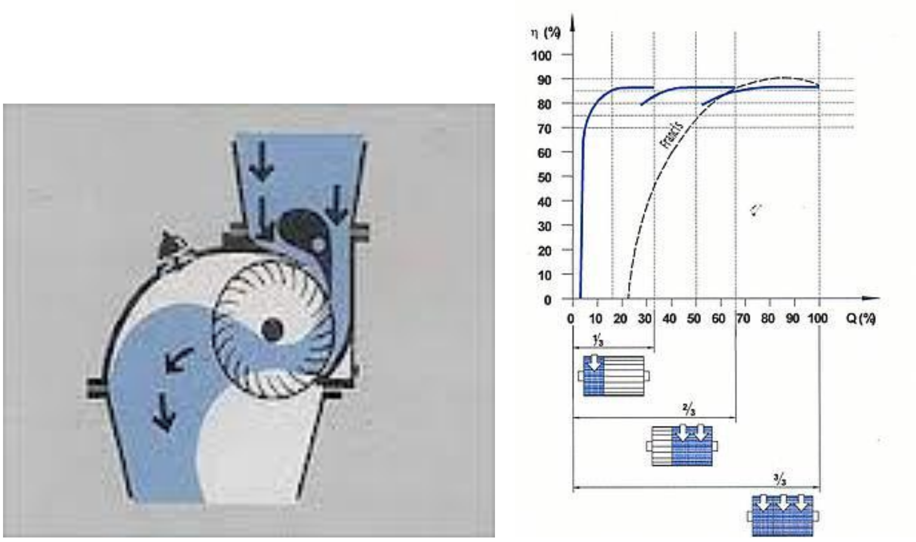
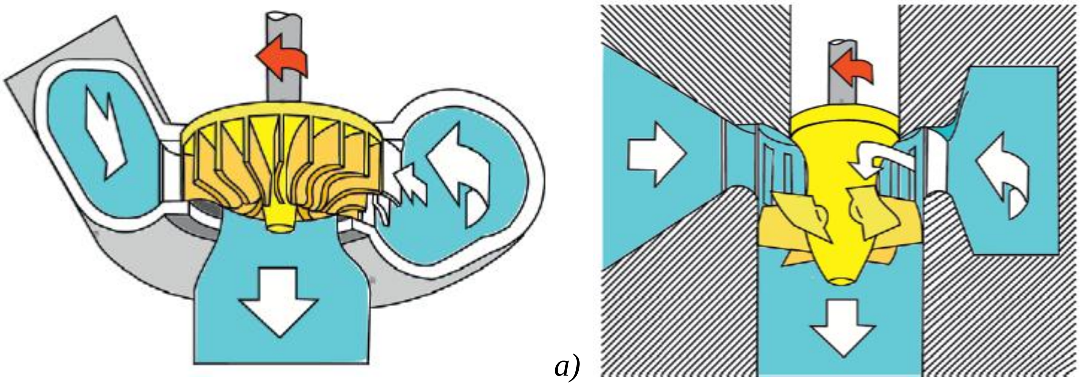


Figure 3.23 *- Cross Flow turbine.*

3.2.2 **Reaction turbines**

Reaction turbines as Francis or Kaplan/Propeller are normally employed with medium head and, in case of Kaplan/Propeller, low head and large discharge flow (see Fig. 3.24).

The reaction turbine runner operates in pressurized conditions and, by means of draft tube, utilize also the head available from the turbine axis to outlet level. This kind of turbine has safe operation limits due to onset of vibration and/or cavitation.



a) b)

Figure 3.24 *- Reaction turbine runners (a) Francis (b)Kaplan propeller (Lopez et al., 2013).*

Kaplan turbines

Kaplan and propeller turbines are axial-flow reaction turbines, generally used for low heads from 2 to 40m. Kaplan turbines are also suited for WECs (e.g. SSG, Drakoo). Kaplan turbine has adjustable runner blades and may or not have adjustable guide- vanes (see Fig. 3.25).

Kaplan double-regulated turbine has high (< 94%) and flat efficiency curve. Runner blades and guide vane position has to be in relationship to obtain the max efficiency point for any value of head. Kaplan turbine can work between 15% and 100% of the maximum design discharge. Single regulated Kaplan allows a good adaptation to varying available flow but is less flexible in the case of important head variation.

Figure 3.25 *- Kaplan runner.*

Francis turbines

The Francis turbine is the most frequently employed and powerful type in hydropower applications (see Fig. 3.26). The flow in the runner is radial centripetal. The control of the power is obtained by guide vanes. This turbine has the highest efficiency, up to 95% in the largest size. Technical limits of operation can occur below to 40% of rated flow.

These turbines are suited for high head applications, but they are not usually used in WECs. Francis turbine is basically a modification of Kaplan turbine in which water flow radially inwards into the runner (Lopez et al., 2013).

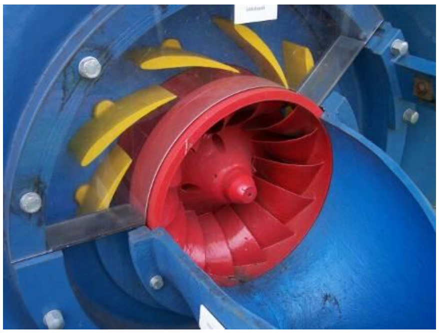


***Figure 3.26** - Francis turbine.*

Figure 3.27 shows the efficiency of Kaplan and Francis turbines. Kaplan can work between 30% and 100% of the maximum design discharge.

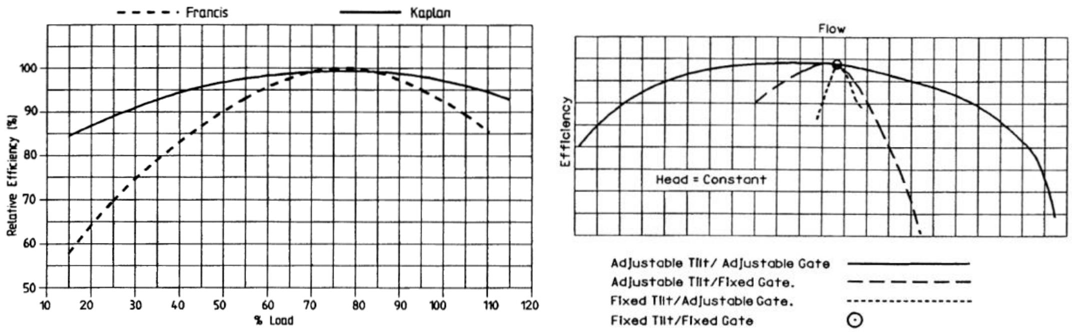


***Figure 3.27** - Kaplan/propeller efficiency curve.*

3.2.3 **WECs equipped with hydraulic turbines**

The employment of water turbines on PTOs for wave energy extraction is actually limited to three main categories of conversion systems (with the exception of the Drakoo OWC device developed by Hann-Ocean Energy):

- Submerged pressure differential
- Oscillating wave surge converter
- Overtopping

These categories of WECs, employing water turbines, are developed to be located near-shore or on-shore; one exception is Wave Dragon.

Submerged pressure differential

The extraction of energy is obtained by the pressure variation induced by waves travelling above a submerged buoy (point absorber). The reaction force caused by interaction with seabed foundation consent the activation of linear alternative volumetric water pump (ram, cylinder). Non-return valves give an intermittent flow of pressurized water inside a pipe connecting the single device to main pipeline ended on-shore in a Pelton turbine-generator aggregate. This technology is developed by Carnegie Wave Energy Ltd with CETO system (see Fig. 3.28).

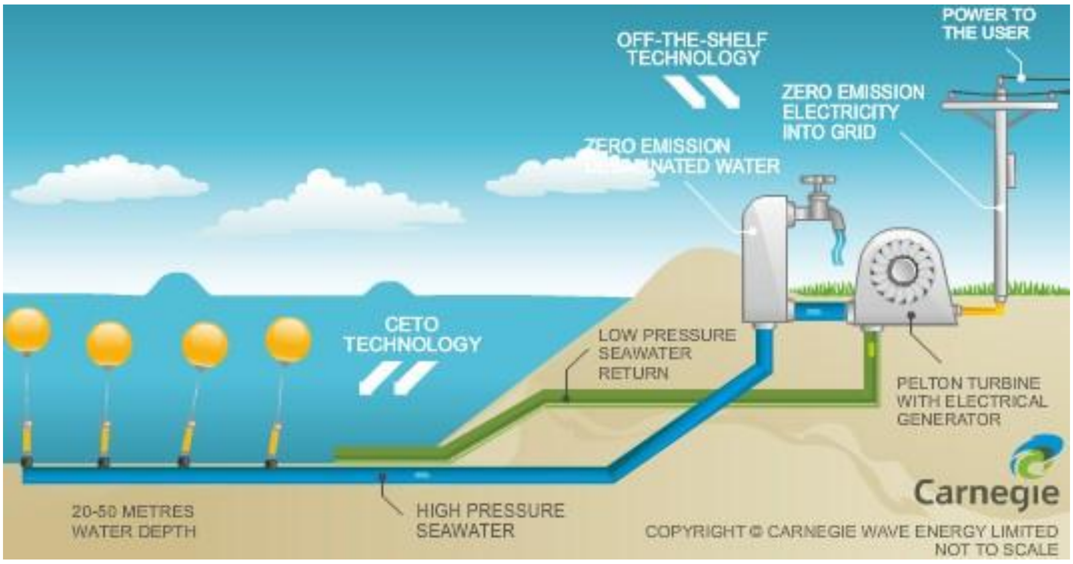


Figure 3.28 *- CETO wave energy system (source: Carnegie Wave Energy Ltd).*

The pressurized water flows in a closed circuit and low pressure pipeline returns the same water to the pump. Banks of water-gas pressure accumulators may be useful to limit the pulsations in the water pressure and get available a storage capacity.
The best efficiency operation of Pelton turbine is at fixed pressure and constant rotational speed, with variable flow depending on the average energy collected by the farm of submerged pressure differential devices.
The maximum rated efficiency of Pelton turbine (with a size <1MW) is 90%. Considering that the max efficiency of a synchronous generator direct coupled to the turbine is 95%, the TG rated overall efficiency is about 85% (excluding head loss in the pipeline and ram efficiency).

Oscillating wave surge converter
An oscillator hinged to a seabed foundation convert the elliptical movements of water caused by waves into alternative forces. Kinetic energy of the moving flap is converted into hydraulic energy using double-acting hydraulic cylinders to pressurise water (Cameron et al., 2010) The pipeline, collecting the high pressure water, is connected to a Pelton turbine-generator located on-shore.

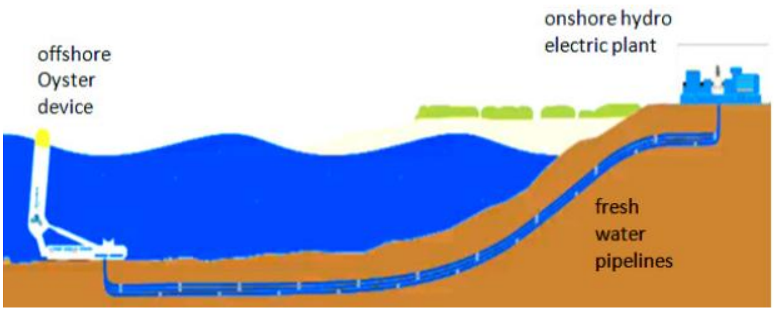


Figure 3.29 *- Oyster OSWC converter (source: Aquamarine Power Ltd).*

The Pelton turbine is directly coupled to an asynchronous generator operating at variable speed. A flywheel, present on the shaft, is the main storage system to smooth the variability of the power source inside a wave cycle. The presence of an array of flap converging to a single Pelton PTO has the effect of further damping of power peaks. The control system of PTO mainly works on the Pelton turbine nozzles to control the flow and with AC/AC converter to govern the speed.

Overtopping Device
These devices mainly consist in a small and low head hydropower facility. The kinetic and potential energy is extracted from waves in form of potential energy only, stored into a basin having the water level above the main sea level (from 1 to 5m). The volume of basin impacts on the capacity of PTO to maintain constant level between the impact of two successful waves. The PTO consist of a propeller turbine coupled to rotating generator. The most representative floating OTD is Wave Dragon (see scheme Fig. 3.30).

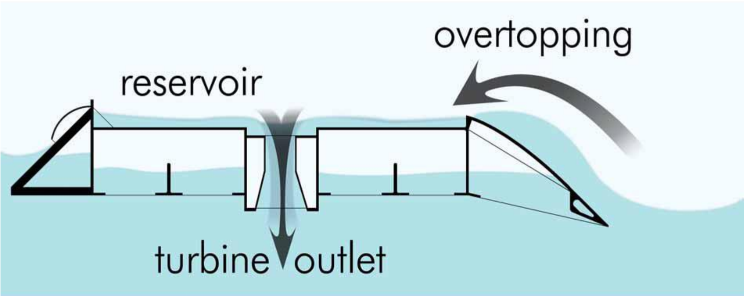


Figure 3.30 *- Wave Dragon hydraulic layout.*

The harsh environmental conditions which are exposed the turbine-generator aggregates suggest the employ of simple hydraulic system so the propeller type turbine with fixed guide vane are used. Converter schematics of the Wave Dragon is given in figure 3.31, based on the conventional approach in wind engineering.

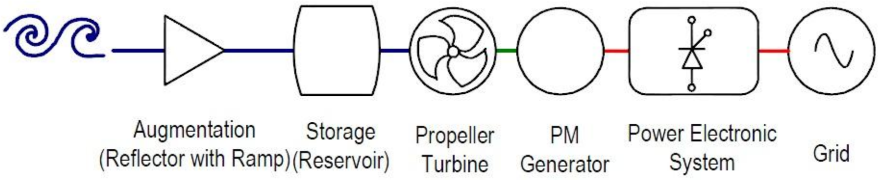


Figure 3.31 *- Converter schematics of the Wave Dragon.*

This type of TG has only one best operating point for each flow and head, assumed fixed rotation speed. The control system may operate only to control the rotation speed by means of a variable frequency converter. The variable speed acts a control of discharged flow under the objective of maintain the water level into the basin at the highest height above the average sea level consented by the sea state.
Sea climate, dimensions of WEC, rated flow and head affect the way the system will be used. The PTO may be designed with only one full regulated Kaplan or with multiple propeller type not regulated on-off turbine-generator.

At the moment the best solution seem be the employ of multiple TG system governed at variable speed. When the turbines enter in their technical operation limits they are hydraulically disconnected by means of cylindrical gate or siphon.

An overview of WECs which uses hydraulic turbines on PTO is given in table 3.7.

Technology	Type	Company	PTO system
Oyster	Oscillating Wave Surge Converter	Aquamarine Power	Hydraulic turbines
BioWave	Oscillating Wave Surge Converter	BioPower Systems	Hydraulic turbines
CETO III	Submerged pressure differential	Carnegie Wave Ltd.	Hydraulic turbines
Waveberg	Attenuator	Waveberg	Hydraulic turbines
Wave Plane	Overtopping	WavePlane	
Wave Roller	Oscillating Wave Surge Converter	AW Oy	Hydraulic turbines
Wave Dragon	Overtopping	Wave Dragon	Hydraulic turbines
SSG	Overtopping	Wave Energy AS	Hydraulic turbines (multi-stage Kaplan)
Drakoo	Oscillating Water Column	Hann-Ocean	Hydraulic turbines (Kaplan)
Pelagic	Point absorber (hybrid)	Pelagic Power	Hydraulic turbines
Intentium	Attenuator	Intentium AS	Hydraulic turbines (impulse)
Seatricity	Point absorber	Seatricity Ltd.	Hydraulic turbines

***Table 3.7** - Overview of WECs equipped with hydraulic turbines.*

3.3 Hydraulic Circuits

Hydrostatic transmissions are widely recognized as excellent solutions to convert alternative motion into rotary, especially when variable output velocity is required. A hydrostatic transmission offers fast response, maintains precise velocity under varying loads and allows to control speed, torque, power or, in some cases, direction of rotation when required (Payne et al., 2007; Manring and Luecke, 1998). Energy conversion from very large forces or moments applied by e.g. the waves on slowly oscillating bodies is particularly suitable to high-pressure oil systems.

In hydrostatic transmission systems, the oil is circulated in a closed circuit between a hydraulic cylinder, or a set of them, and a hydraulic motor connected to a generator to produce electric energy. The circuit is generally equipped with oil/gas accumulators to damp peak loads and to provide a smooth operation of the generator. By using cheap and available high-pressure gas accumulators the energy can be stored over a few wave periods (Henderson, 2006; Falcao, 2010).

Figure 3.32 shows a schematic representation of the hydraulic PTO (Lopez et al., 2013). Along the circuit, low and high pressure accumulators, an hydraulic cylinder (actuator) and a motor connected to the generator can be seen. In the reference scheme, a series of check valves is installed in order to provide a mono-directional flow independently from the upwards or downwards movement of the actuator following the motion of the waves by means of the floating buoy. These valves are generally actively controlled to provide a variable reaction torque.

Control is provided also by the hydraulic motor that shall be able to operate at variable capacity, i.e. variable flow rate but almost constant rotational speed. The variable capacity of the hydraulic motor makes it worth to use a constant speed, standard generator (in the range of 1000 to 3000 round per minute), avoiding the need of interposing power electronics between generator and the grid to ensure the production of electric energy compliant with the grid codes.

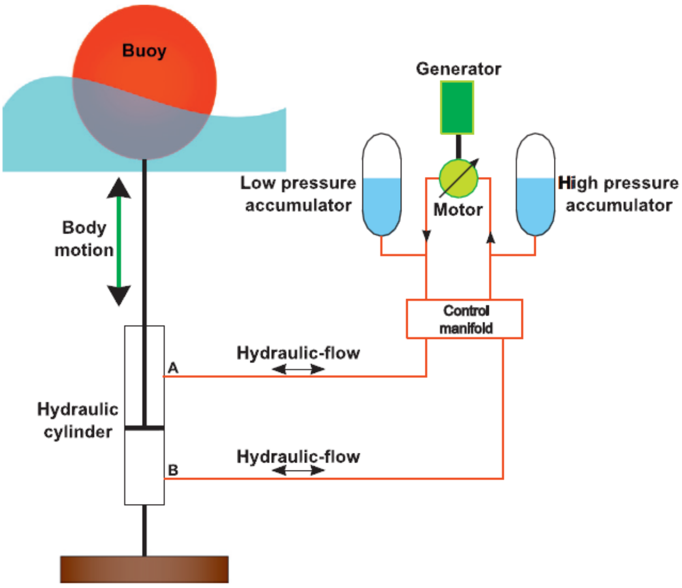


Figure 3.32 *- Schematic representation of the hydraulic PTO.*

The most common hydraulic motor is the axial-piston bent axis variable-displacement machine (see Fig. 3.33) available from a few manufacturers in the rated power range between a few kW and about 1MW, with operating oil pressures up to 350bar (Falcao, 2010).
As already stated, oil/gas (typically nitrogen) accumulators provide a key role to ensure a smoother operation of the whole system (Salter et al., 2002). Figure 3.33 provides a general, simplified reference scheme to understand the principles of operation of the system. Several possible layouts including different bypasses, accumulators and control strategies are under study. The constant pressure PTO represents the most attractive solution as widely described in Costello et al. (2011), where a comparison between constant and variable pressure hydraulic PTOs for wave energy applications has been assessed, the main results are shown in table 3.8.

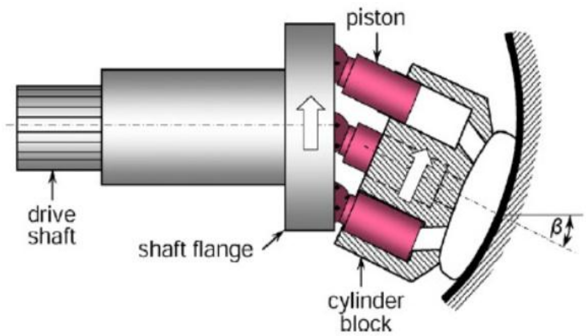


Figure 3.33 *- Schematic representation of a variable-displacement hydraulic motor of axial-piston bent-axis type (Falcao, 2010).*

System:	Variable Pressure PTO		Constant Pressure PTO	
Motor Type:	Axial Piston	Digital Displacement ™	Axial Piston	Digital Displacement ™
Highest absorbed Power:	100%	100%	96%	96%
Highest Shaft Power:	65%	78%	69%	88%
PTO efficiency:	65%	81%	74%	91%

Table 3.8 *- Comparison of hydraulic PTO efficiencies.*

Significant increases in efficiency are achieved in case a digital control (Digital Displacement™ control) is applied to the system as also highlighted in Schlemmer et al. and in Rampen et al. (2000), because it is avoided and efficiency losses in off-design conditions, where WECs operate in the uppermost of the time. Comparable efficiencies have been calculated by Henderson (2006), estimating losses in the primary transmission system of about 20%, averaged on wide operating conditions.
Advantages and disadvantages of hydraulic PTO systems are given in table 3.9.

Advantages	**Disadvantages**
Directly suitable for certain movements	Amount of hardware required (maintenance)
Energy storage (accumulator)	Pressure losses
Flexibility • Water turbine in seawater is used • Single accumulator and generator for multiple devices (more efficiency and less maintenance) Possibility of using an onshore facility (easier maintenance and monitoring)	Environmental impacts • Detrimental fluids • Risk of leaks

***Table 3.9** - Advantages and disadvantages of hydraulic PTO systems (Principle Power, 2012).*

3.3.1 WECs equipped with hydraulic circuits

Today, the majority of the WECs use a hydraulic PTO system (see Fig.s 3.32-3.34) due to the robustness, compactness and light weight properties of such systems. Furthermore, low maintenance is theoretically required, even if several failures in hydraulic houses and connectors leakages have been reported Cruz (2008), Henderson (2006), Salter et al. (2002).
An overview of WECs which uses hydraulic PTO system is given in table 3.10.

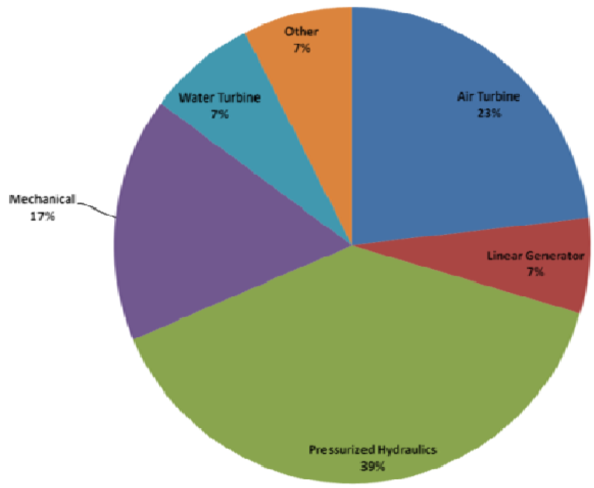


***Figure 3.34** - PTO system usage among WECs (Principle Power, 2012).*

Converter schematic of AquaBuoy and Pelamis is given in figure 3.35, based on the conventional approach in wind engineering.

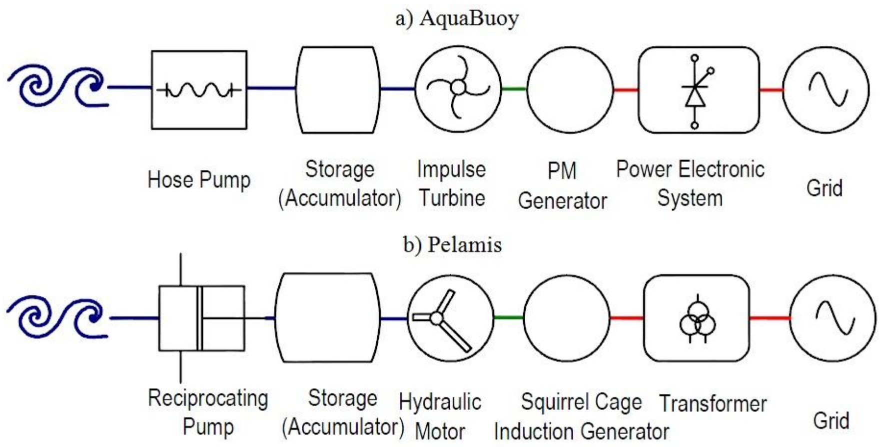


Figure 3.35 *- Converter schematics of AquaBuoy and Pelamis devices.*

Technology	Type	Company	PTO system
WaveBob	Point absorber	Wave Bob AB	Hydraulic Circuit
Aqua Buoy	Point absorber	Finavera	Hydraulic Circuit
WaveStar	Point absorber – Multi	Wave Star Energy	Hydraulic Circuit
Pelamis	Attenuator	Pelamis Wave Power	Hydraulic Circuit
Wave Rider	Point absorber	Wave Rider Energy	Hydraulic Circuit
Anaconda	Bulge wave	Bulge Wave	Hydraulic Circuit
Squid	Point absorber	Albatern	Hydraulic Circuit
Dexa-Wave	Attenuator	Dexa Wave Energy Aps.	Hydraulic Circuit
SeaRev	Point absorber	Ecole Centrale de Nantes	Hydraulic Circuit
Langlee	Oscillating wave surge converter	Langlee Wave Poer	Hydraulic Circuit
COPPE	Point absorber	Seahorse Wave Energy	Hydraulic Circuit
Wave Roller	Oscillating wave surge Converter	AW-Energy Oy	Hydraulic Circuit
Sea Wave Power Plant	Attenuator	S.D.E. Ltd	Hydraulic Circuit

Table 3.10 *- Overview of WECs equipped with hydraulic PTO system).*

3.4 Direct-drive systems

Direct drive systems are characterized by the absence of a mechanical interface between the device and the electrical generator so, being simple and requiring fewer moving parts, they have lower maintenance requirements and higher efficiencies. However direct drive machines have to face with size and weight issues since the speed of the generator equals that of the prime mover, typically about two orders of magnitude lower than that of conventional rotary generators, and power generation requires to react large forces directly acting on the generator itself.
Direct drive systems have been used in the wind industry as an alternative to gearbox drive trains mainly for reliability issues and as, a consequence, in the marine energy sector they could offer an attractive option in terms of improved system efficiency, reliability and robustness too.

As far as wind and tidal energy are concerned, rotary generators -either synchronous or asynchronous- are by far the most largely used. When it comes to the exploitation of the alternative motion of waves, linear generators appear to be the most interesting solution. Figure 3.36 shows an example of this technology developed by Kimoulakis et al. (2010).

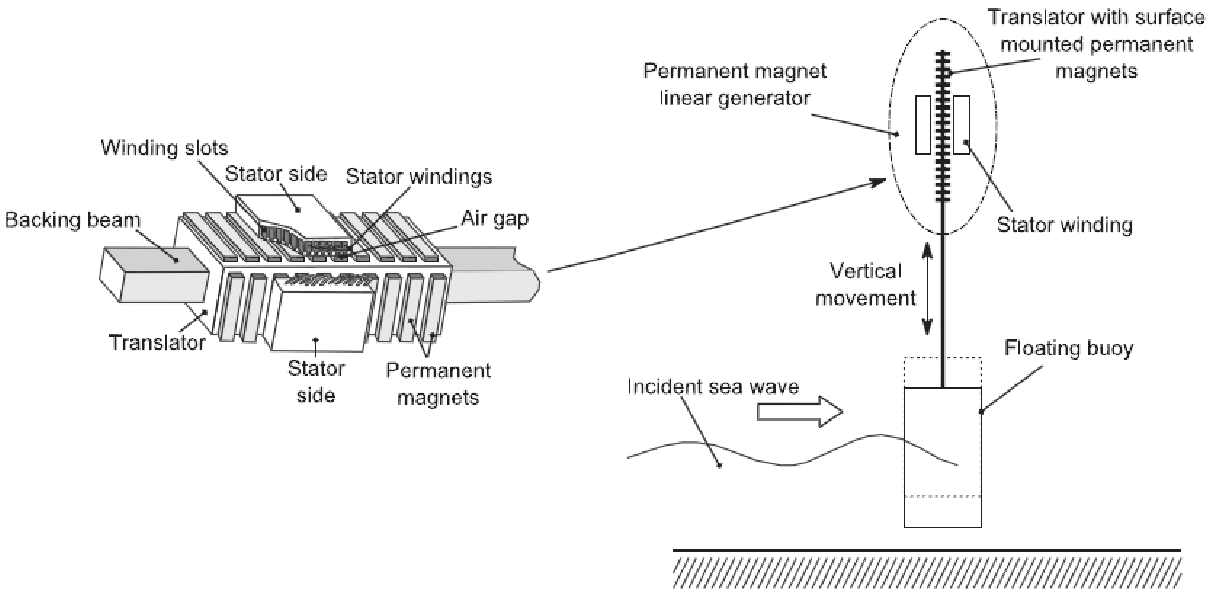


Figure 3.36 - *Permanent magnetic linear generator configuration and the mechanical system for electric power generation from waves.*

Different types of linear generators can be used for marine applications, for example induction, synchronous with electrical excitation, permanent magnet and switched reluctance linear machines, but studies have highlighted that permanent-magnet synchronous type is the most suitable machine for wave energy conversion (Polinder et al., 2007), Drew et al. (2009).
According to Drew et al. (2009) a linear generator is made up of a translator (as the rotor in a rotary machine) directly coupled to a heaving buoy, with the stator containing windings, mounted in a relatively stationary structure (connected to a drag plate, a large inertia, or fixed to the sea bed). The principle of energy conversion is the same of conventional rotary generators: voltage is induced in the stator as a consequence of a change in magnetic flux from translator motion; currents flows in the stator to oppose to forces(torques) applied to the moving component.
The power output profile of a linear electrical generator need a conversion stage to obtain a signal appropriate for grid connection. Figure 3.37 shows a typical Electro Motive Force (EMF) plot from a variable reluctance permanent magnet machine excited by a sinusoidal displacement, characterized by high variability both in frequency and in amplitude.

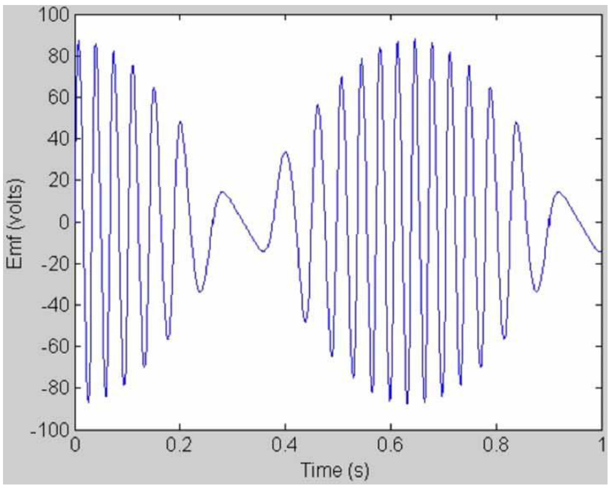


Figure 3.37 - *Typical Electro Motive Force (EMF) plot from a linear generator (source Drew et. al.,2009).*

The conversion to a sinusoidal fixed voltage and at the correct frequency can be obtained by the use of power electronics and normally need a rectification stage: this one can be both passive (e.g. simple diode bridge) and active (this allows to enhance active power in case of power factor not equal to 1).

According to Polinder et al (2007), direct drive marine renewable systems require an integrated design approach in order to properly consider the structural and bearing requirements of linear generators relative to magnetic forces and environmental loadings issues (non-reversing loads due to wind, tidal currents and cyclic loading due to wave action).

Advantages and disadvantages of direct-drive PTO systems are given in table 3.11. Salter (2010) highlighted the importance of further research (bearing arrangements, sealing arrangements, corrosion, electrical generator topology and associated power, etc.) into the direct-drive WECs to determine optimized electrical and mechanical designs for particular wave energy devices. Direct drive linear or rotary generators may provide a route to reduced costs within future generations of WEC (SI OCEAN, 2012).

Advantages	Disadvantages
Direct conversion of movement of devices	No filtered power output
Simple system	No storage
Amount of moving parts (maintenance and survivability)	

Table 3.11 *- Advantages and disadvantages of direct-drive PTO systems (Principle Power, 2012).*

3.4.1 WECs equipped with direct drive

The concept of direct drive has been demonstrated within the Archimedes Wave Swing (AWS) device that consists of an air-filled chamber with a floater moving up and down according with troughs and crests of waves and where a double sided linear permanent generator has been used. Figure 3.38 shows a picture of the AWS prototype (*a*) and the calculated efficiency (*b*) of the generator under various wave amplitudes and periods: values over 90% are reachable in wide range of wave characteristic parameters (Mueller et al. 2007).

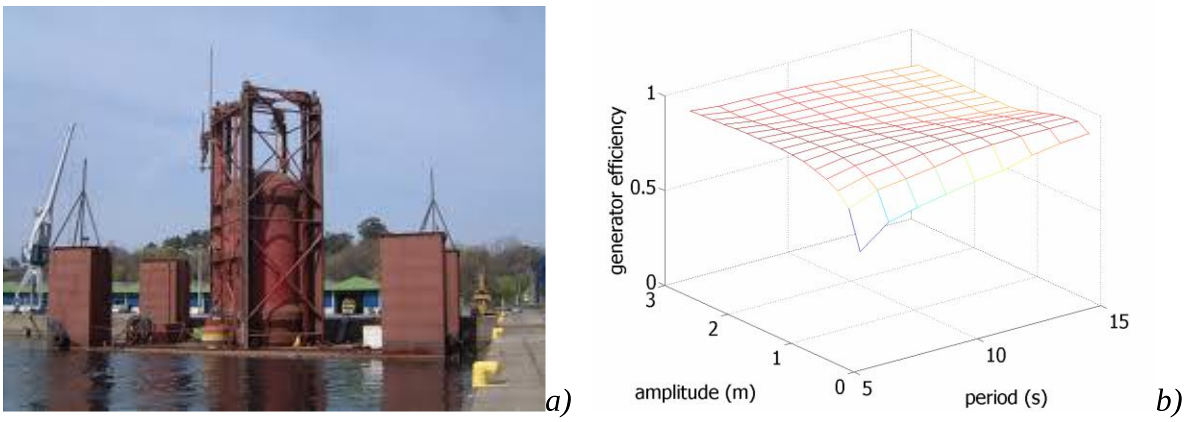


Figure 3.38 *- a) Archimedes Wave Swing (AWS) prototype*
b) AWS generator calculated efficiency.

Converter schematics of AWS is given in figure 3.39, based on the conventional approach in wind engineering. The upgraded system, AWS –III, uses an air turbine (Wells turbine) to generate electricity.

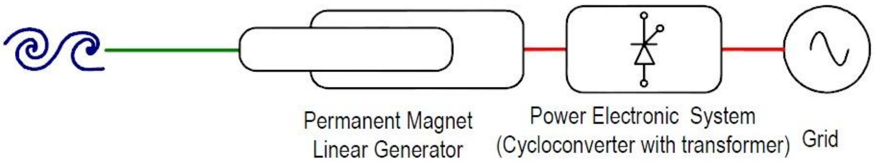


Figure 3.39 *- Converter schematics of AWS device.*

More recently, heaving buoys equipped with linear generators were tested at sea off Sweden by Seabased, and Oregon, USA (Falcao, 2010)
An overview of WECs which uses direct-drive PTO system is given in table 3.12.

Technology	Type	Company	PTO system
OPT PowerBuoy	Point absorber	Ocean Power Technologies	Direct drive
Seabased	Point absorber	Seabased AB	Direct drive
AWS 1*	Submerged pressure differential	AWS Ocean Energy	Direct drive
Wello Penguin	Rotating Mass	Wello Oy	Direct drive
CorPower	Point absorber	CorPower Energy	Direct drive
StingRay	Point absorber	Columbia Power Technologies	Direct drive
WECD	Point absorber	Neptune Wave Power	Direct drive
Lever Operated Pivoting Float system	Point absorber	Resen Waves	Direct drive
Nemos	Attenuator	Nemos GmbH	Direct drive

* This project ended.

Table 3.12 *- Overview of WECs equipped with direct-drive PTO system.*

3.4.2 **Electro Active Polymers**

Traditional WEC technology relies on rigid components (such as wave-interacting hulls, mechanical/hydraulic transmissions and electromagnetic generators), which are made of stiff, heavy, shock-sensitive, corrosion-sensitive and costly metallic (and rare-earth) materials, as well as costly and bulky power conditioning systems (such as step-up transformers and frequency changers/rectifiers). This severely limits the cost-effectiveness of the energy that could be produced by ocean waves.
Electro Active Polymers (EAPs) materials, also referred to as Electroactive Elastomers (EEs), are highly deformable rubber-like solid polymers which are either dielectric or conductive.
The sequential stacking of multiple conductive and dielectric EAP layers yields the simplest form of EAP transducer, that is a *deformable capacitor* capable of converting mechanical energy into electricity and vice-versa (Pelrine et al, 2001)
EAP transducers are currently being investigated as an enabling technology for next generation WECs. In their most ambitious embodiment, EAP-based WECs integrate all the required components into a single soft, lightweight, resilient, corrosion-resistant and economic elastomeric electro-active body, which undergoes liquid-like deformations under the action of sea waves thereby converting the kinetic and potential energy of water into high-voltage direct-current electricity. EAP-based WECs are currently under scientific investigation in several research centers all over the world. For example, Stanford Research Institute initiated this field of research with the development of a first prototype of a simple point-absorber system (Chiba et al., 2008)
PERCRO laboratory of Scuola Superiore Sant’Anna is coordinating an EU-Project called PolyWEC (FP7-FET-Energy, Prj.Ref 309139) that is focused on the development of new

concepts of EAP-WECs and their evaluation through a campaign of wave-tank test (Vertechy et al, 2013).
Two important European companies, Bosch and Single Buoy Mooring, have recently started research initiatives to develop first full scale prototypes of EAP-based WECs (Wattez et al, 2012; Scherber et al, 2013).
Vertechi et. al. (2013) evaluated the use of Dielectric Elastomer (DE) transducers (see Fig. 3.40) as PTO system in OWCs in three different layouts. As a result of this study, a multi-physic lumped-parameter dynamic model accounting for the hydro-electric-elastic response of coupled OWC systems was presented. This work will be extended to more accurate models (including hydrodynamic radiation and non-uniform electro-elastic deformations) for realistic Poly-OWC devices with three dimensional and complex geometries.

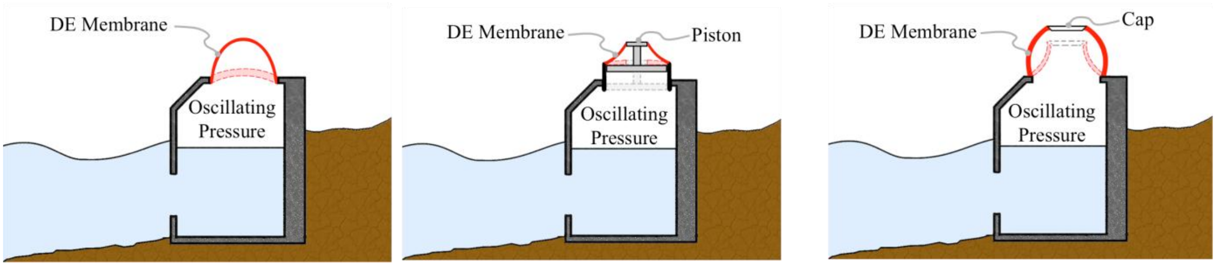


Figure 3.40 *- Schematic of possible implementations of Poly-OWC.*

4 Materials

4.1 Survivability in the marine environment

WECs are installed in an aggressive environment, where it is required their correct operation for a long period of time, possibly without frequent maintenance operations. Thus, the materials used in the manufacture must be carefully evaluated to the survival of the entire system in the marine environment, taking into account:

- corrosion;
- fatigue;
- corrosion by fatigue;
- corrosion by stray current;
- wear and fatigue wear;
- fouling;
- impact of loads and fractures.

The phenomena listed above are mutually dependent and complex interactions can be achieved, e.g. the combined fouling and corrosion effects, but can be poorly described due to the rather limited current knowledge.

Main materials for WEC components come out to be steel, concrete, composites (laminated materials and sandwich structures) and some high-density polymers (PE, PVC, etc.). Material requirements of WECs for steel, composites and concrete components can be covered mostly by the DNV codes referenced as OS-C101 (DNV, 2011), OS-C501 (DNV, 2010b) and OS-C502 (DNV, 2012), respectively (DNV, 2005).

4.1.1 Corrosion and corrosion fatigue

Although chemical properties of sea water are almost constant in the open ocean there are still differences in the dissolved oxygen concentration, the pH, the temperature, the wave action, the suspended solids and the marine growth on surfaces. These differences can play a significant role on the phenomenon of corrosion.

Experience shows that in theoretically similar conditions, corrosion may occur in very different ways. Therefore an important preliminary requirement is to collect data on the corrosion and fouling at sites proposed for WECs installation.

Metals and alloys subjected to corrosion in the marine environment can be broadly classified into two groups:

1. the materials whose corrosion is strongly dependent on the oxygen available at their surfaces, such as the “mild” steel. Corrosion for this group of materials can be accelerated by an increase of the current speed.
2. the materials, such as the stainless steel, which form an adherent protective film of “passive” oxide on their surfaces. Corrosion tends to occur when the amount of oxygen is limited, such as in areas of stagnant water or below the fouling or in correspondence of fractures.

Copper alloys, widely used in the marine environment, have an intermediate response with respect to the two types of materials described above. In fact these materials tend to create passive films, which are sensitive to the effects of current speed, and therefore corrosion depends on the oxygen levels but occurs only for current speeds greater than a certain critical value. Localized corrosion, due to turbulence, impact or cavitation, can easily occur unless proper precautions and selection of alloys are analysed during the design phase.

Susceptibility to stress-corrosion cracking or hydrogen fragility in seawater when subjected to a constant stress represent alloys’ limitations. These limitations however are well known and can be taken into account by the designers, while corrosion influence on fatigue resistance and interaction between wear and corrosion are less documented. Thanks to the wide data collection made by the offshore oil industry, the information on “iron” steels can be

considered as highly reliable. In particular, studies have been focused on the effects of the stress frequency and of the cathodic protection on the propagation of cracks, although the knowledge of the fouling influence is not well known. Hudson et al. (1980) showed that in presence of corrosion fatigue, crack propagation can occur for the typical wave load frequencies (about 0.1 Hz) up to 6 times faster than for higher frequencies. The formation of stress corrosion cracks can be avoided by limiting the range of forces to which the material is subjected and through a careful metallurgical control.
Since seawater is a highly conductive electrolyte, the corrosion process is often modified by:

- galvanic effects;
- coupling in seawater of two metals with different potentials; figure 4.1 lists the “galvanic series” for the seawater, which represents possible corrosion manifestation due to the coupling of two different alloys (ASTM, G82-98);
- external electric current flow, in particular related to continual electricity current through one side of the structure (“stray current corrosion”). This phenomenon is usually difficult to eliminate in a structure with electrical equipment such as a WEC.

Corrosion can be influenced also by mechanical factors, such as stress from vibration (applied or residual, constant or cyclic), the wear, etc.

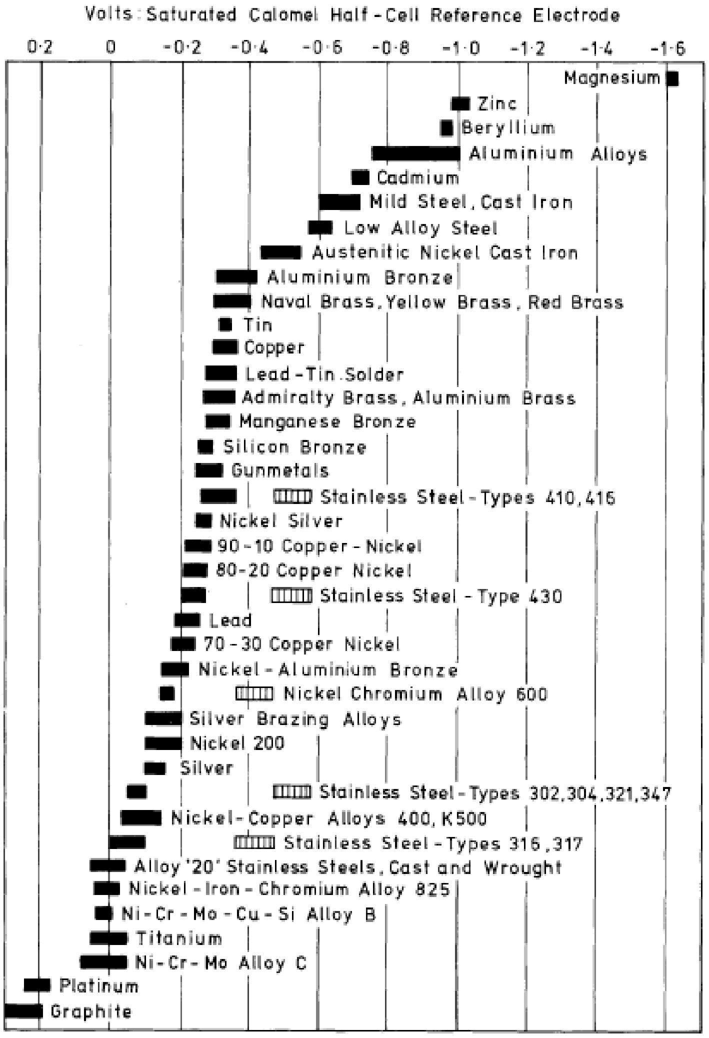


Figure 4.1 *- Metals and alloys galvanic series in seawater in motion (adopted from ASTM G82-98).*

Several expedients can be applied during the design phase in order to minimize corrosion, for example:

- the choice of corrosion resistant alloys and the study of their corrosion susceptibility factors;
- specific heat correction treatments, manufacturing techniques and production methods;
- careful inspection and quality control.

In case these advices are not applied, specific paintings (requiring maintenance every 5-6 years) can be adopted to protect steel from corrosion. However, the painting solution is not recommended due to its deterioration over time, leaching in the water and depositing on the sea bottom.

The two main methods of corrosion protection are coatings protection and cathodic protection. The modern claddings, usually developed for steels, are extremely effective when applied to *ad hoc* prepared surfaces and they should provide protection for about 10 years, in the absence of mechanical damage. For the submerged structures, cathodic protection is frequently used as an additional protection or as an alternative to claddings. Cathodic protection reduces corrosion to a cathode or to “sacrificial anodes” (for example, zinc or aluminium) or by means of an external system of “impressed currents”. The zinc cladding can be used as direct protection or as galvanic protection or as under-layer in case a mechanical damage occurs.

For example, on steel surfaces of Pelamis device, different protection measures are adopted, depending on surfaces exposure: a paint coating for surfaces exposed to the atmosphere and to splash actions, and a cathodic protection (using sacrificial anodes) for the submerged surfaces.

Another solution for WEC installations is to use non-metallic materials such as concrete, as in the DEXA converter (www.dexawave.com).

4.1.2 **Fractures**

In WEC installations reduced resistance due to direct wave impacts and brittle fractures have to be considered. Proper design studies and selection of adequate steels could avoid brittle fractures in large welded steel structures. Prolonged exposure to the sun of a large steel WEC side and to the seawater of another steel WEC side could reduce the material resistance in operation during the subsequent winter season. In the design of large floating structures special care should be paid to welds strength and integrity in correspondence of the mooring chains.

4.2 Steel

The steels are selected based on the availability, cost and mechanical properties (admissible stress, breaking resistance, welding, etc.). Corrosion is the main deterioration factor, it can appear as local metal loss, as reduction of fatigue strength, or through cracks due to stress.

Ideal steel cladding for sea installations should be economic, perfectly adherent to the surface, easy to apply and remove, resistant to the marine environment and to abrasion, non-conductive, non-toxic, and finally it should guarantee a perfect isolation of the steel surface from air and marine spray. A cladding satisfying all the mentioned requirements does not exist, hence a wide range of products have been generated to achieve an optimal compromise.

Poor cladding performance are often related to an inadequate steel surface preparation. Premature cladding damage is often due to hasty cladding painting on surfaces exposed cold/wet/windy weather.

In the shipbuilding industry the attention has been focused for a long time on the cost reduction and the simple application rather than on the long term performance. However for WECs installations it is essential to ensure that the first cladding system remains intact as long as possible, thus minimising maintenance interventions. In absence of serious mechanical damages the high performance cladding should provide protection up to 10 years without maintenance provided that they are properly applied.

Sprays and steel coating with another corrosion-resistant metal, such as cupro-nickel, are alternative to a cladding system. The main risk is represented by the galvanic corrosion in the eventual case of exposed steel.

The optimal choice seems therefore the manufacture of a pre-coating made of a sufficiently thick corrosion-resistant metal. The disadvantage of this solution is the high cost, but the large-scale use of “coated steel” for WECs may become economically favourable if the corrosion protection is guaranteed for the entire life of the installation.

The cathodic protection is widely used for the submerged structures made of steel, either alone or combined with varnish coating. The protective current is supplied either by the corrosion of a “sacrificial anode” (zinc, aluminium or magnesium) or through an “impressed current” coming from an external source employing an inert electrode. For WECs, which have electrical power readily available, the “impressed current” method seems the most advantageous system.

However improvements in the cladding system are required to guarantee few maintenance operations along all the life cycle. Furthermore it is essential to avoid a super-protection, which will reduce the steel potential below the required level to combat corrosion, and will lead to protective varnishes damage and even, in certain circumstances, increase the speed of propagation of fatigue cracks due to corrosion.

Classification of steel materials can be found in various documents prepared by the American Petroleum Institute (API), the American Institute for Steel Construction (AISC) and Det Norske Veritas (DNV). The offshore standard OS-C101 (DNV, 2011) generally regulates design of offshore steel structures (also relevant for WECs) which includes information and guidelines about “general information, design principles, load and load effects, structural categorisation, material selection, inspection principles, limit states, corrosion control and foundation design”.

4.3 Concrete

The concrete (often pre-cast and/or pre-stressed) is in general a very versatile material. Various cement types have been developed in order to guarantee design of resistant, durable and economic marine structures. The expertise gained with existing structures such as docks, ships, offshore platforms, etc. allows to consider concrete as a favourable material in the marine environment.

The required conditions for the production of acceptable concrete are in general well-known. Rigid specifications (in order to increase concrete durability in offshore platforms) have been introduced by the oil industry, however these constrictions increase also the production costs.

Steel can also be used as the reinforcement element in concrete, especially for fixed WECs type (such as LIMPET). Fatigue and corrosion of the reinforcement steel, integrated in the concrete, are still being studied, but they certainly can be overcome by careful design and quality control, ensuring the use of a resistant, dense, waterproof concrete and with an adequate thickness of the steel cover. General practice in the marine environment requires a 7 to 10cm concrete cover to protect the reinforcement steel. However, reinforcement could hardly be used for in-situ cast concrete installations. Additionally, in climates where frost is common reinforced concrete is not preferred for marine construction, basically due to the micro cracks developing on the surface and penetrating through concrete cover to the reinforcement steel.

Furthermore the cathodic protection is already widely used and in the future protection treatments of the concrete surfaces may be focused on minimising mechanical and chemical deterioration.

There are many examples of fixed WECs which are constructed mainly from reinforced concrete. These structures have cross-sectional areas ranging between 80–250 m^2, for example OWC types (LIMPET, Sakata, Mutriku, Vizhinjam, Pico, etc.) and overtopping types (TAPCHAN, SSG, etc.).

OS-C502 (DNV, 2012) standard regulates requirements for concrete which is used for construction of offshore structures. In this document, “safety philosophy, structural concrete and materials, loads and analyses requirements, detailed design of offshore concrete structures, construction, in-service inspection, maintenance and conditional monitoring” are covered.

4.4 Reinforced Plastic Materials and other Composites

Composites have been used in the marine industry since the mid of 1960s, starting mostly with the recreational boating industry. Since then, composite materials have been used in fabrication of various types of vessels such as racing powerboats, racing sailboats, utility vessels, passenger ferries, commercial ships, commercial deep sea submersibles, submarines, fishing vessels, lifeboats. Additionally, these materials have gained an important place for the construction of offshore structures such as platforms, submarine pipelines, piling forms and jackets and drilling risers.

Composite technology began with single-skin construction and developed to sandwich structures, new resin and material types and fabrication techniques. In today’s technology, composite materials consist of three different components: reinforcement materials (fiberglass, polymer fibers, carbon fibers), resins (polyester, vinyl ester, epoxy, thermoplastics) and core materials (balsa, thermoset foams, syntactic foams, cross linked PVC foams, linear PVC foam, honeycomb, PMI foam, FRP planking, core fabrics, plywood). Main reinforcement material for marine composite structures comes out to be the so-called “e-glass” thanks to its strength, workability and low cost. On the other hand, polyester resin, vinyl ester and epoxy are most widely used resin types in the marine industry, in the respective order. In order to transmit the shear forces across the sandwich structure of composites, the core material is an essential component since they are the main parameter of dynamic behaviour of composite materials (Greene, 1999). The most widely employed type of composites in the marine industry is the Glass Reinforced Polyester (GRP).

Plastic materials reinforced with glass fibres have a high chemical resistance, and this property makes the installation of these materials very suitable in corrosive marine environment. As mentioned above, GRP is widely used for the manufacture of boats and small ships. GRP is fatigue vulnerable and also it can reduce its strength over time due to marine spray, for these reasons adequate design safety factors are used in existing applications. To ensure a cost-effective use of GRP related to WEC installations a further GRP design development is required. And yet, composite materials provide the ability to choose and *fine-tune* the material, lamination and manufacturing method according to design requirements. Complex geometries can be easily fabricated with composite materials. This characteristic with some of them being non-conductive is a potentially important advantage for producing underwater turbines (Mohan, 2008).

Composites (e.g. GRP) are sometimes used for the fabrication of turbine blades of tidal energy devices and WECs. Steel has been the first choice of designers for fabrication of marine rotors. However, due to its high cost, fabrication problems of curved profiles and lower resistivity to aggressive marine environment, composites recently became a viable option for turbine blades (Marsh, 2004). In addition to turbines, there are examples of composites that have been used for shrouds, mounting frames and other components of offshore installation systems (Marsh, 2004).

5 Installation

This part is of importance when designing overall wave energy system. From the preliminary analysis, it has been observed that there is a range of options to fix the WECs.

5.1 Foundations

In general, foundation of an off-shore/marine structure has a vital importance; not only due to stability reasons, but also because it forms a remarkable percentage of the total construction cost. For this reason, selection of an appropriate foundation type for WECs is a crucial step for the general design. The foundations for multi-purpose off-shore platforms (MUPs) are treated in a greater detail in the MERMAID deliverables D 3.2.1 (Shallow Water Foundations) and D3.2.2 (Deep and Ultra-Deep Water Foundations). Thus, in this section, rather than focusing on the technical aspects of foundations, the emphasis will be given to the available selection criteria for type of foundation for WECs and to some application notes for WEC foundations in the light of available literature, guidelines and case histories.

5.1.1 **Relevant foundation types for WECs**

Generally the main foundation types (DNV, 2005) can be listed as follow:

1. Gravity-type foundations (gravity base, caisson body, etc.);
2. Pile foundations (including mono-pile, braced mono-pile, steel pile jacket a.k.a. piled lattice, tripod etc.);
3. Bucket foundation (suction bucket);
4. Anchor foundations (pile anchors, gravity anchors, suction anchors, fluke anchors, plate anchors, etc.).

The first three types are usually associated to fixed WECs, whereas the forth one is relevant for floating WECs. For the sake of giving a complete picture, a very brief description of the most common relevant foundation types for WECs is presented below.

5.1.1.1 Gravity Base Foundations

Gravity base foundations, as the name implies, use their own weight to resist against the loads exerted by the superstructure as well as hydrodynamic loadings. This foundation differs from the mono-pile mainly because it is not driven into the seabed, but rather sits on top of the seabed. It is designed to avoid tensile loads (lifting) between the bottom of the foundation and the seabed (DNV, 2010). In modern wind engineering, it is used in shallow waters (with a maximum depth of 30m) (EON, 2012) and have proven to be cost effective [14]. If the underlying soil layer has sufficient bearing and shear capacity, this type of foundations can be a convenient and cost effective solution. In fact it is the most common foundation type for marine structures.

Generally prefabricated concrete (either reinforced or pre-stressed) and steel can be used in construction of this kind of foundations (Gerwick, 2007). 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 structure can also incorporate skirts around the perimeter, which penetrate up to approximately 2m into the seabed depending on seabed conditions, helping to resist horizontal movement. The global foundation size is dependent on the water depth and the wave conditions (Williams, 2011b). Furthermore, this type of foundations is specifically suitable in areas without tidal changes which are the case in the Baltic Sea.

Depending on geologic site conditions, this foundation may require significant seabed 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 (Lesny, 2010;

Marx et al., 2012) before the foundation placing. Once leveled, there is the potential need for the addition of a stone bedding layer depending on the site conditions. Ballast material consisting of stones or other suitable material (concrete or other high density materials) is then filled inside the foundation to ensure final stability.
Considering the operations for the seabed preparation, it is possible to declare that many disadvantages are associated with gravity base foundation systems. Furthermore, due to the final huge and massive structure, the installation process may result in special requirements such as vessel capacity or workspace size (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 they do not require expensive jack up vessels, offshore cranes or hammers as stated by Wind Energy Update [14]. However, it needs to sustain its development in order to move up the ladder (WEU, 2013). 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 also be avoided.

5.1.1.2 Mono-pile foundations

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

In this type of foundation, a pile is driven to the soil until it can bear the weight and the lateral loading exerted by the superstructure thanks to the shear between soil and pile. 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. Moreover, braced mono-pile, where inclined piles are connected to main mono-pile, can be used for increasing lateral capacity of the pile if needed (French et. al., 2009). To provide enough stiffness the diameter of the mono-pile foundation has to be large enough (De Vries, 2007), and it increases with the increase in superstructure. 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 mono-pile foundation is easy to manufacture and install (de Vries, 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).

At sites with high currents and high amount of sand movements, scour protection is fundamental. Therefore, many investigations have focused on scour problems around the mono-pile foundations. Suitable soil conditions for mono-piles are sand, silt layers or stone mixed bottoms [14]. 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).

One of the disadvantages of the mono-pile foundations is that the required mono-pile size drastically increases as the superstructure size increases. Another disadvantage is the difficult decommission of the mono-pile foundations (Westgate & DeJong, 2005). Furthermore, underwater noise that occurs during the drilling/driving needs to be carefully considered (Teich, 2013).

An alternative mono-pile solution is a steel reinforced concrete design. Ballast Nedam Offshore and MT Piling studied a novel foundation concept for Off-shore Wind Turbines called the *drilled concrete mono-pile*, for the Vattenfall study project "Foundation Concepts for the Kriegers Flak Wind farm". Such structures typically comprise a number of pre-cast concrete ring sections. These could be fitted together and grouted before floating out to the construction site. Following Ballast Nedam (2009), the main reasons for developing this concept are:

- concrete mono-piles are inexpensive compared to steel mono-piles, in fact 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.

The design of mono-piles is still developing. 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.

5.1.1.3 Steel Pile Jacket (Piled Lattice) foundations

This type of foundation is originated from Gulf of Mexico, and has been used in the oil and gas industry worldwide for off-shore exploration and production facilities. It was applied for a wide range of water depths (from 12-300m, and sometimes even more than 300m). It is currently deployed as foundations for off-shore wind turbines and often characterized by low weight and suitable water depths over 20m. The most common types are four-sided jackets, however, three-sided jackets are also existent in the market [15].

Jacket foundations are made up 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. It is very important to drill all these piles at the same time because drilling each pile individually can cause problems of stability (Lesny, 2010). In this type of foundation, the jacket section is prefabricated on shore as a steel space frame and then, at the site, it is connected to the piles driven previously into the seabed. These jacket structures can be designed in many different forms (Gerwick, 2007).

There is almost 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 mono-pile. Swedging is a fast but expensive method. Although, the amount of work to assemble a jacket design is relatively high, this is compensated by a lower need of materials to reach an adequate stiffness (Williams, 2011). Therefore, it can be cost efficient at water depths greater than 40m (Powered, 2012).

Even the transportation of these large structures is not easy, particularly if many energy conversion systems (i.e. wind turbine, WECs) are installed (de Vries, 2007). However, they do not require such heavy piling as in the case of mono-pile foundations (Hammar et al., 2008).

The main advantages of jacket foundations are the low sensitiveness to wave loading, their high stiffness and their low soil dependence. Therefore, they can be installed in deeper waters or in water with high waves or also at sites with poor soil without increasing the steel weight drastically. Thanks to its geometry, the jacket foundation is able to be relatively light weighted for the strength that it offers, weighing approximately 600tons in current wind energy applications (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. Generally, scour protection is less important compared to other fixed foundation types (Westgate & DeJong, 2005).

The disadvantages are the high complexity of arrangement with secondary steel such as boat landing systems, etc., and that the installation procedure is also more complicated and expensive [16].

If the jacket foundation has to be decommissioned, the piles are cut and the steel structure is moved to the 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.

5.1.1.4 Tripod Foundations

The tripod foundation can be described as a mono-pile foundation and ultimately all the way to the bottom, where it is divided into a triangular frame of relatively slender still members (compared to one simple mono-pile 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 leads to a greater bottom surface compared with a mono-pile 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 mono-pile foundation. The technical design of the tripod foundation may significantly differ among producers and due to the existing conditions such as depth, weight stress and bottom substrate (Hammar et al., 2008). This type of foundations is not as common as mono-pile or jacket foundations due to its complexity in the design and installation (French et. al., 2009).

From an installation point of view, the tripod poses challenges lies in the transportation, in fact it cannot be transported easer as a mono-pile foundation (de Vries, 2007). The suitable water depth for this foundation in wind turbine applications is around 20-40m. It is best suited on undisturbed sediment, however, it 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 as stated by Danish Wind Industry Association [17].

One of the greatest advantage of a tripod foundation is its ability to be installed on deeper waters compared to gravity and mono-pile foundation (Hammar et al., 2008). Furthermore, there is no need for seabed preparation prior to installing a tripod foundation. However, 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 mono-pile (de Vries, 2007).

5.1.1.5 Bucket Foundations

Suction bucket foundations have been originated from the oil and gas industry. A suction bucket is a large diameter cylinder closed at the top. A bucket shaped cylinder (one end open and one end closed) is place upside down on the sea bottom and the water in between the bucket and the seabed is pumped out which drives the bucket deeper and deeper into the seabed until the desired penetration depth is reached. Suction bucket foundations can generally be applied to any of the foundation types previously described as an alternative to driving piles deep into the seabed. Even though research 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 to loads due to its greater diameter and reactive soil forces. 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), in fact sufficient hydrostatic pressure is required in order for this concept to be effective. Therefore, it has been rated as feasible up to 40m (Ibsen et. al., 2005).

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 presently working towards new installation methods where lower loads on the caisson occur, reducing the stresses on the material and in turn decreasing the needed amount of steel.

5.1.2 Selection of foundation types for WECs

The type of WEC to be employed (see Section 2.3) is doubtlessly decisive on selection of the foundation type to be used. On the other hand, the design of a foundation is a site-specific task by its nature. A site investigation should generally yield information about the range of soil strength properties, stiffness and damping parameters, deformation properties (modulus of elasticity), permeability, in-situ relative density, stress history, etc. This investigation is typically constituted by the following type of surveys (DNV, 2011 Sect. 11 Article A200):

- site geology survey (including soil stratigraphy),
- topography/bathymetry survey of the seabed,
- geophysical investigations for correlation with borings and in-situ testing,
- soil sampling with subsequent laboratory testing (with undisturbed samples if possible),
- in-situ tests, e.g. cone penetrations tests.

In addition to these information, the metocean data (wind, wave, tidal current, etc.) as well as morphological properties of the project site (i.e. sand mobility, dune migration, etc.) should also be taken into account when considering a specific foundation type for WECs.

As mentioned in the preceding paragraphs, the cost of the foundation is an equally important ingredient of type selection criterion to bear in mind. A brief summary of foundation types is presented in the table 5.1 along with the applicability limits, main advantages and drawbacks of each foundation type stated above. This table is adapted from the original version appeared in one of the published deliverables of the EU-FP7 project EquiMar (Stallard et. al., 2010).

	Mono-piles	**Braced Mono-piles**	**Piled Lattice**	**Suction Bucket**	**Gravity-Based**
Soil	Sand, Clay, Weak Rock. No rocks (driven piles)	Sand, Clay, Weak Rock. No rocks (driven piles)	Sand, Clay, Weak Rock. No rocks (driven piles)	Sand or Clay, no rock at all	Sand or Clay. Adequate shear & bearing pressure
Depth	< 10m	< 15m	< 50m	< 40-45m	> 50m
Fabrication	Rolled steel (up to 100 mm thick), Diameters up to 6.5 m	Rolled steel (up to 100 mm thick), Diameters up to 6.5 m	Standard off-shore jacket techniques	Fabricated so far up to 16m diameter simply by rolled and welded steel	Requires dry dock with > 10m draft
Foundation Install	Driven piles	Driven raked piles	Heavy lift vessel	Hydrostatic pressure push by sucking out sea-water	Bed excavation & preparation.
Topside Install	Float-over barge	Float-over barge	Heavy lift vessel	Float-over barge if single bucket and heavy lift vessel if a jacket to be installed	Heavy lift vessel
(+)	Cheap fabrication Extensive experience from wind engineering	Cheap fabrication High lateral capacity Simple installation	Compact, High stiffness Standard off-shore structure Less noise compared to mono-pile	High lateral and uplift capacity Relatively easy installation	Low skilled fabrication Less fatigue sensitive Long life No noise during installation Relatively inexpensive
(-)	Specialist installation vessel Depth limited by lateral capacity < 10m depth Scour protection High noise	Depth limited by installation < 15 m depth	Complex to fabricate Expensive Fatigue sensitive	Technology still being developed/not mature, risk of internal collapsing due to suction, difficult decommission ing	Dry dock Bed preparation Low moment resistance Scour vulnerability Difficult transportation Decommissio ning

***Table 5.1** - Summary of foundation types (extended from Stallard et. al., 2010).*

5.1.3 Case Histories of WEC Foundations

In the literature, there are not many reported case histories as far as the foundations of WECs are specifically concerned. Two examples will be included here.

Aquamarine Power Ltd. constructed and installed a near shore oscillating wave surge converter, the *Oyster-1*, at the European Marine Energy Centre's (EMEC's) test site at Billia Croo, near Stromness in Orkney (UK) in the summer of 2009. In this project they considered three different foundation types: gravity base, pad foundations with rock anchors and bored piles. In their site they have encountered hard sandstone sea bed. Also sea bed was seen to have steps and gullies up to 3m high. In this uneven sea bed, the size of the gravity base foundation was found impractical. Furthermore, they rejected the pad foundation with rock anchors solution due to the difficulties at the levelling of each section of the pads and difficulties in the necessary underwater operations with divers involved. At the end, they opted for a pile foundation (Collier et al., 2008).

In another application, an OWC was attached on a certain segment of Mutriku Harbour breakwater (ES). In this project a gravity base foundation was found as an appropriate solution considering that the breakwater was necessary to be built in the first hand. For constructing the foundation, a trench with dimensions of 14.5x102x0.5m was dredged on the sea bottom along the breakwater alignment. Afterwards, a 20cm grading concrete was poured and a 90cm wide reinforced slab was built on it as foundation. On top of the foundation, the prefabricated parts of the WEC were installed by anchoring with re-bars (Torre-Enciso et al., 2009).

5.1.4 Remarks on foundation design for WECs

DNV suggests the partial coefficient method (DNV, 2011) to be used in the design of WEC foundations. The potential failure modes of an off-shore foundation are also applicable to WECs. These include -but not limited with- sliding/overturning/bearing failure, settlements or displacements, risk of liquefaction, scouring around the foundation. Some specific modes can be peculiarly critical for a given WEC system depending on the site and on the type of loads that the superstructure exerts on the foundation. An example of load, exerts by a superstructure on the foundation, can be the cyclic lateral force/overturning moment exerted to a gravity-type foundation on a fine-grained loose soil (Sumer, 2013).

It is also important to remark that there is no historical case of WEC installation on a seismically active site. Considering the severity of earthquake loading, especially for fixed WEC, this kind of loads should be kept in mind during the selection process of foundation type.

5.2 Moorings

Deep water installations offer a high amount of available wave power, but -at the same time- expose WECs to extreme loads undoubtedly greater than in near-shore installations (Ruol et al., 2009). Extreme loads, to which the device and its mooring must resist, are directly responsible for the costs of WECs (Masuda et al., 2002), while the energy to be sold is produced in ordinary load conditions (Falcão and Rodrigues, 2002).
The mooring design has been derived for some years from the experience learn with the off-shore structures (Isaacson & Nwogu, 1987) and shipbuilding. Despite this fact, a relatively high rate of floating WECs have failed in their efforts due to an inadequate mooring system. Functional and structural inadequacy may affect also the efficiency of energy conversion (Martinelli et al., 2009). In fact, the moorings must ensure that the device remains close to

the point where it was originally placed, but at the same time, they must allow the relative movement of the device to convert a sufficient quantity of energy.
The existing data models have not provided so far criteria for design, stability, durability and reliability of devices and moorings, so that field data based on physical model tests are required, in order to fully evaluate the device behaviour. More reliable devices and lower management costs would certainly result in more competitive energy production from wave energy market.

5.3 Regulations and norms

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.
An overview of the main regulations/standards proposed by the authorities listed below is in table B.1, see Appendix B.

1. API (American Petroleum Institute): Regulations and guidelines for the off-shore oil and gas platforms (floating and fixed). These regulations include several design constituent criteria. This guideline is available at the site www.api.org.
2. DNV (1989 and later): DNV establishes rules and regulations for the classification of ships, floating off-shore platforms and other floating marine structures. Criteria for the classification and design specific mooring systems parts (chains, anchors, etc..) are also proposed. For example, DNV-OS-E301 section 2 specifies a mooring analysis process for position mooring systems (column-stabilized units, ship-shaped units, single point moorings, loading buoys and deep draught floaters or other floating bodies relying on catenary mooring, semi-taut and taut leg mooring systems) that may be relevant for WECs. For wind energy, DNV KEMA recently published a new standard for floating off-shore wind turbine that will help to ensure safety and reliability in floating wind turbines, and might also be applied to WECs.
3. ISO (International Organization for Standardization): provides standard criteria for the design of mooring systems of ships and off-shore structures (criterion dates back to 1975, ISO 3505, while the most recent was in 2009, ISO 19901-6).
4. ABS (American Bureau of Shipping): provides practical guidelines for the design, construction, operation and maintenance of off-shore installations. For example it provides rules for the construction and classification of single point moorings (1996), the guide for the off-shore mooring chain certification (1999) and the guidelines on the application of synthetic ropes for offshore mooring (1999). ABS is also currently working on the development of engineering standards for wind turbines. For example, in the beginning of 2013, with two guides ("*ABS, 2013: Guide for building and classing floating offshore wind turbine installation*s," and "*ABS, 2013: Guide for building and classing bottom founded offshore wind turbine installations"*).These guidelines were originally developed for wind energy conversion systems may also be applied to WECs.
5. BV (Bureau Veritas): BV develops rules and guidelines for the benefits of maritime industry. For example, the "rules for the classification of off-shore units" (BV NR 445) referable to surface units, semi-submersible units, self-elevating units, SPAR, TLP, buoys, etc. Moreover, the "rules for the classification of floating establishments" (BV NR 580) are applicable to floating units moored and anchored in smooth stretches of water, and detail the assignment and maintenance of the type and service notation floating establishment. These rules are always being updated. For wind energy, BV also issued their first guidance note (BV, 2010), which is focused on the structural design of floating support structures. This guidance may also be applied to WEC systems.

6. 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. For example, recently published guidance note "Floating offshore installations assessment of structures – guidance on calculations" provides guidance on the analysis procedures for assessment of the structure of offshore units that operate at a fixed location.
7. NACE (National Association of Corrosion Engineering): Accredited by the American National Standards Institute (ANSI), NACE establishes standards on different categories, for example the guidelines for the materials and corrosion of marine structures/ships.
8. BOEMRE (Bureau of Ocean Energy Management, Regulation and Enforcement), formerly known as MMS (Mineral Management Service): The MMS were in the process of reviewing international standards and guidance documents for alternative energy systems developed by the DNV, GL, IEC, Energistyrelsen (Denmark), and the British Wind Energy Association. They have been also assessing the applicability of certain API and ISO standards for off-shore energy systems, operating systems as well as management practices (Alawa et al, 2009).
9. DIN (Deutsche Institut für Norming): DIN is the German Institute for Standardization, and it develops standards and technical rules as a service to industry, the state and society as a whole.
10. GL (Germanischer Lloyd): GL has been developing technology, safety and quality standards in a wide variety of fields. Based on their long standing experience in the maritime and renewable energy sector, "Guideline for the certification of ocean energy converters – Part I: Ocean current turbines" was established in 2005 and is permanently being further developed. This guideline does a thorough job of identifying load cases for operational, installation and survival analysis. For off-shore wind energy, GL published the "Guidelines for the certification of offshore wind turbines" in 2005. Recently, all parts of GL 2005 have been reviewed and improved. The new edition is called "The guideline for the certification of off-shore wind turbines" (2012). When it was 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). GL also conducts assessments, verifications for wind, wave and tidal energy devices on the basis of its own guidelines as well as international standards.
11. IEC (International Energy Agency): IEC standards cover a vast range of technologies from power generation. For off-shore wind energy, IEC has published the standard "Design requirements for offshore wind turbines (IEC-61400-3, 2008). 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 and so on (Orecca, 2011c). However, it does not include specific component resign requirements or design formulae. The standard relies on the use of recognized design standards as the basis for sizing of the structural elements in the support structure. It generally refers to the ISO standards and allows for the use of other industry guidelines such as GL, API and DNV.

Since a specific indication is still not existing, the above regulations have been used also for WECs, even if the risk associated to WECs installation is lower than for vessels and off-shore platforms. In general, the tolerable failure risk is much higher for off-shore oil and gas installations rather than for WECs since the failure is connected to the loss of human lives or severe environmental pollution. However redundancy, durability and reliability represent essential factors for a safe employing of such devices.

More recently, the Carbon Trust (2006, [18]) has provided recommended practices for the assessment and application of floating WECs, considering the entire life cycle. It covers several topics including structural design criteria, foundation design and mooring analysis and appendixes on fatigue analysis methodology and wave modelling and loads.

5.3.1 **Requirements**

Floating WECs (f-WECs) require a mooring system in order to ensure station keeping, and more specifically to limit the drift, ensure alignment of directional WECs with the prevailing wave conditions, avoid impact with other structures and excessive loads on the electric power umbilical.

In general, the mooring system must be sufficiently rigid to allow docking for inspection and maintenance, and at the same time sufficiently flexible to minimize the forces acting on anchors, mooring lines, electricity transmission cables and on the device itself. The contemporary satisfaction of this double prerequisite usually leads also to preserve a good energy conversion efficiency. Only in exceptional cases the stiffness of the mooring lines is an active element of the conversion principle used by the device itself.

In details the functional mooring requirements are:

- to maintain the floating structure on station within specified tolerances during the whole life of the concept under normal operating load and extreme storm load conditions, that is generally more severe and frequent than for normal mooring installations;
- the excursion of the device must not permit tension loads in the electrical transmission cable(s) and should allow for suitable specified clearance distances between devices in multiple installations; contact between mooring lines, or contact with the device itself must be avoided;
- the mooring system must be sufficiently compliant to the environmental loading to reduce the forces acting on anchors, mooring lines and the device itself to a minimum (unless the stiffness of the mooring itself is an active element in the wave energy conversion principle used);
- the mooring have to be sufficiently compliant to accommodate the tidal range at the installation location, and sufficiently stiff to allow berthing for inspection and maintenance purposes;
- the mooring system should also require as little inspection and maintenance as possible over the in-service life of the device. It should be possible to remove the f-WEC from the site (or remove one f-WEC from the energy farm), with easy re-installation, without damaging any components or reducing the service life of the system.
- mooring anchors must also be designed to accommodate hazardous conditions such as sediment transport, earthquake, and cables and so on;
- the mooring systems should be designed to keep devices at optimum orientation relative to the waves;
- the mooring system design should not adversely affect the performance of the WEC device;
- single mooring legs must be capable of repair or replacement without affecting neighbouring devices or necessitating removal of the WEC device.

The system should limit the environmental impact as much as possible. Environmental factors to be considered include damage to the local environment, visual impact, and any effect on the local eco-system.

In case of a wave farm, the design of moorings should account for:

- the adequate free distance between the various systems device-anchor in order to avoid contacts among the mooring lines;
- the possibility to remove one device without any problems to the mooring systems of the others placed around it;
- the risk that a device loses/breaks its mooring system leading first to damages to the closest devices, and later the possibility that the drifted device becomes an hazard to ships and other maritime systems.

5.3.2 **Typologies**

There are essentially two types of mooring classifications, the functional and the geometrical. The functional classification distinguishes among:

1. passive mooring system, when position maintenance is the only mooring requirement and the movements allowed to the device entail a limited effect on the device efficiency;
2. active mooring system, if the mooring rigidity is an important factor in the dynamic device response. These effects/movements can contribute to reach the resonance conditions and thus affect the energy conversion efficiency;
3. reactive mooring system, if it provide a reaction force. They are suitable especially when the PTO exploits the relative movement between the body and the fixed bottom.

The geometrical classification identifies the following classes (based on the layout configuration): spread (multi-point), single-point and dynamic moorings.

1. Spread mooring systems. They consist of multiple mooring lines attached to the floating body (see Fig. 5.1a) in order to limit horizontal excursions and allowing a large compliance. They do not allow the floating body to rotate about its hull, according to wind, wave and current prevailing directions. It comprises catenary, taut lines and composed multi-lines, as shown in table B.2. Active mooring or dynamic positioning (propulsion) could be an expensive station keeping option.
2. Turret mooring (internal or external). A catenary moored turret attached to a floating structure allows weathervane around it (see Fig. 5.1b).
3. Catenary Anchor Leg Mooring (CALM). The floating structure is linked to a catenary moored buoy and it is able to weathervane around such buoy (see Fig. 5.2a).
4. Single Anchor Leg Mooring (SALM). The floating structure is linked to a single anchored buoy and it is able to weathervane around it (see Fig. 5.2b).
5. Articulated Loading Column (ALP). The floating structure can weathervane around a bottom hinged column, which has a swivel above the water line.
6. Fixed Tower Mooring. The floating structure is able to weathervane around the mooring point which is composed by an anchored tower into the seabed.

Example and more details regard the typologies described above are present in the table B.2 in the Appendix B. This table reports the main mooring system configuration types and their suitability. To describe their appropriateness in relation to the position maintenance and installation costs the following criteria: “high”, “medium”, “low”, have been used. For example, mooring systems characterized by high installation costs but which can potentially improve energy conversion have been defined as “medium” suitability.

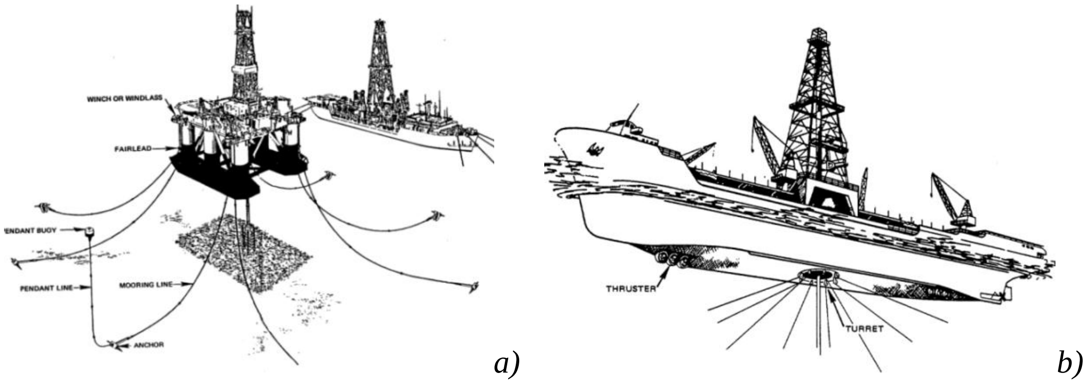


Figure 5.1 *- Spread mooring system (a) and internal turret mooring (b) (API, 1987).*

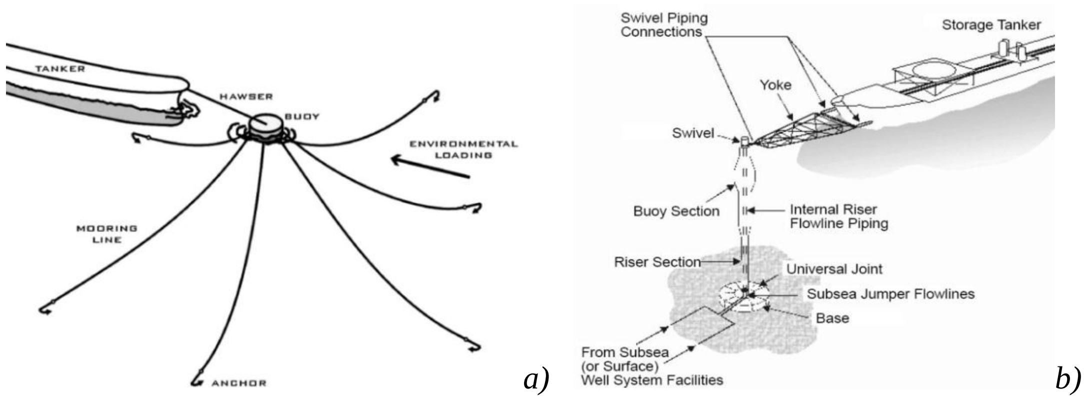


Figure 5.2 *- CALM (a) (Sagrilo et al.,2002) and SALM (b) (API, 2001).*

It is impossible to recommend an optimal mooring configuration and connection method due to the wide diversity of WEC types and performance characteristics as well as the general lack of long term operational data. More hydraulic models and prototype testing coupled with theoretical analysis are required to understand WEC behavior and the influence of the mooring system on performance. The further understanding gained from this complete development process can be used to improve design practices and to establish guidelines and standards based on experience directly with WECs.

The most economic option for the lines is the free hanging catenary configuration. Unfortunately this may not be able to allow for a sufficient extension without excessive loads when the tidal range is large. Another disadvantage of such a configuration could be the restraining stiffness affecting the f-WEC dynamic (Harris et al., 2004). First and second classification can be combined to choose the best F-WEC mooring type (see Tab 5.2).

Selection of the proper mooring can be done using traditional methods in case of the passive and reactive type. For active moorings, i.e. when the system stiffness is fundamental, the process involves many iterative steps. The overall efficiency needs to be evaluated and -if not correct- the design have to be reconsidered.

		Passive mooring	Active mooring	Reactive mooring
Spread mooring		■	■	
Turret mooring		■		■
Single Point	Catenary Anchor Leg Mooring (CALM)	■	■	
	Single Anchor Leg Mooring (SALM)	■	■	■
	Articulated Loading Platform (ALP)	■		■
	Fixed mooring tower	■		■

Table 5.2 *- Combination of the functional and geometrical mooring system classifications.*

Fitzgerald (2009) proposes three examples of f-WECs and compares compliance and costs. From his research, there should be a tendency to keep large structures to maintain mooring and operational costs down. He also shows that costs of the mooring are quite essential in the f-WEC sector (see Fig. 5.3). It may be concluded that, during f-WEC design, a detailed analysis of the mooring system is fully justified.

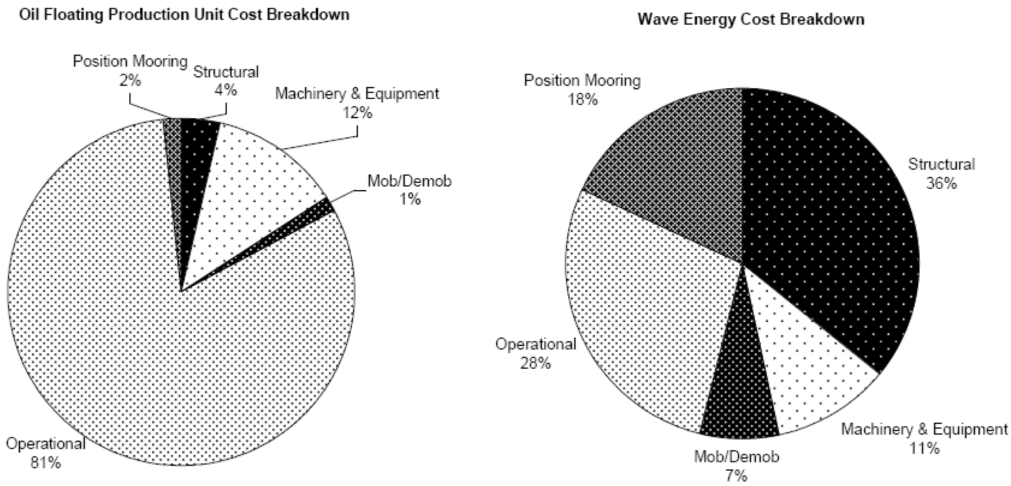


Figure 5.3 *- Cost breakdown and relevance of mooring system for oil floating platforms and for f-WECs (Fitzgerald, 2008).*

It is also worthy to note that a two-year EU funded project launched by Dundee University, GeoWave [19], will conduct industry-specific research on a variety of new generation off-shore anchors and mooring components deemed to be suitable for mooring WECs. The team will use complementary methodologies such as numerical, analytical and experimental modeling in association with field trials in order to further understand responses of mooring systems and develop design solutions for the wave energy sector

In 2009, the specialist Committee V4 Ocean, Wind and Wave Energy Utilization was given the mandate by the 17th International Ship and Offshore Structures Congress. The committee stated that conventional chain catenaries are not good at absorbing dynamic loads, whereas the synthetic ropes have advantages in absorbing large dynamic loads induced by waves. Furthermore, the necessity of the guidelines for the design of mooring systems for wave energy converter arrays was also underlined. Under this point of view, also the IEC sub group TC 114 is currently developing the guideline “Marine Energy – Wave, tidal and other water current converters – Part 10: The assessment of mooring systems for marine energy converters”.

5.3.3 **Mooring lines**

Table 5.3 describes some mooring lines (in general constituted by a combination of metallic chains, metallic or synthetic wires) and their characteristics. 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).

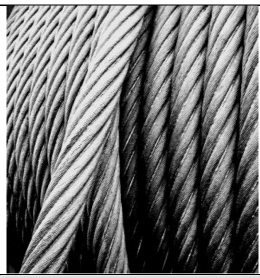
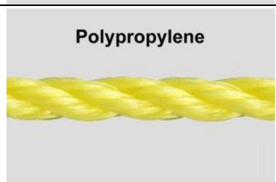
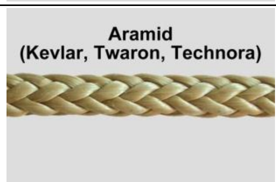
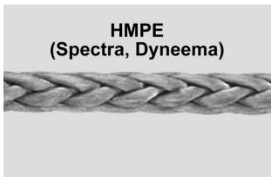
Mooring line	Characteristics	Costs	Image
Chain	Broad use experience Readily available Depending on required proof strength (grade 3 or 4 should be used for off-shore moorings) Unsuitable for water depths greater than 450m Susceptible to corrosion Good catenary stiffness effect High abrasion and bending 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 fibre 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	

***Table 5.3** – Mooring lines characteristics.*

Chains are typically the first choice due to low cost, reliability, good resistance to bottom abrasion and durability in off-shore operations. Chains can be obtained in several grades, which are characterized by a different proof tensile strength. In general, three grades (RQ3, RQ3S and RQ4) are provided for off-shore mooring systems, whereas grade RQ5 is characterized by the highest proof tensile strength (ABS, 1999.a). Moreover, they provide a good catenary mooring stiffness to comply horizontal and vertical excursions. However, it requires periodic inspections and maintenance to keep it clean from bio-fouling that can increase the weight per unit and also damage the chain due to excessive abrasion, caused by relative rotation of the links (API, 1999). Moreover, corrosion represents a possible threaten for chain integrity. Figure 5.4 shows the most frequent chains breakage or damage typologies.

Figure 5.4 *- Typical failure modes (Chaplin 1998). Left: a coiled wire damage due to high torque load. Right: Slipping damage of a six-strand cables.*

In order to minimize the vertical load on f-WECs, the alternative solution to chains are synthetic lines. 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. Most common materials are nylon, polyester, polypropylene, Kevlar, high density polyethylene (Dyneema). Conversely from chains, where the resistant force is due to their weight, the synthetic lines offer a resistance which depend on their elastic characteristics.

The weight and elasticity properties of the ropes make them more common for very deep water applications. Axial compression and hysteretic heating may reduce the initial rope resistance (although considerable change in axial stiffness after installation could require one or more re-tensioning). Fish bites can represent a serious problem (Harris et al, 2004). Therefore, fibre rope segments in mooring lines are normally protected by an outer jacket, which has an adequate resistance to hydrolysis, chemical corrosion, creep phenomena, fish bites, friction and shear, with a proper flexibility at minimum exposure temperatures in order to meet the requirement to protect the rope core.

Figure 5.5 provides chains, wire ropes and fibre price trend per meter of length as a function of the minimum breaking load. However data collected so far are limited and cannot be considered fully representative.

The mooring system is composed by several components (e.g. chains, connection points, anchors, etc.). Each components must be chosen with specific criterion, mainly depending on the mooring type, on the WEC life time and on the site (installation water depth, nature soil of the sea-bottom, maximum tidal excursion, etc.).

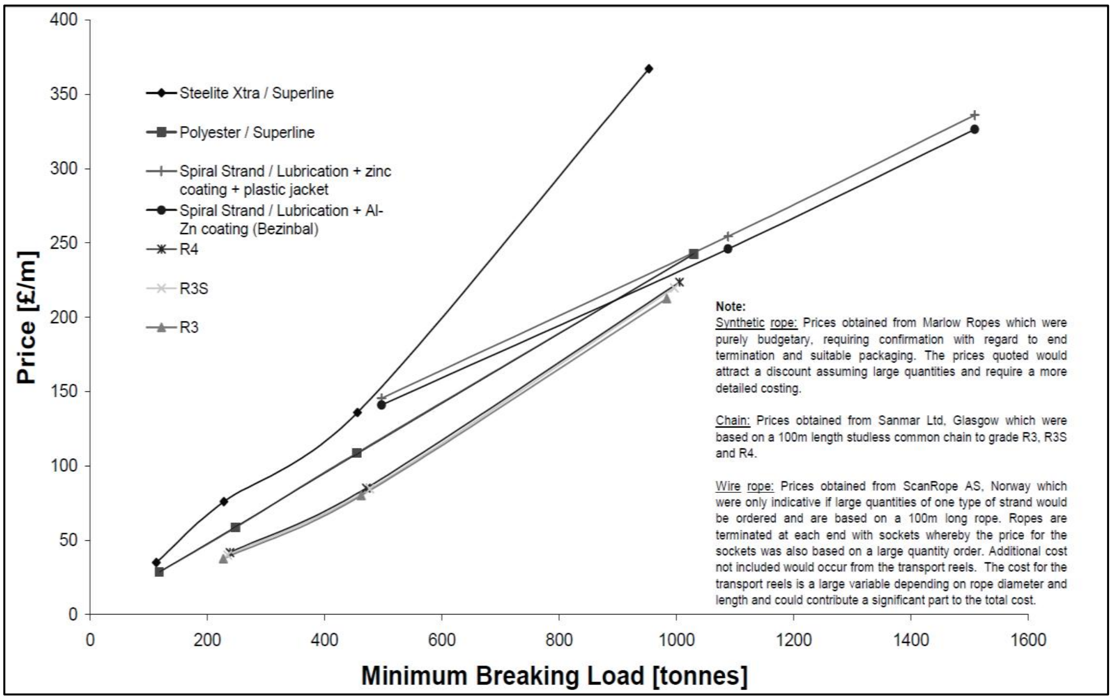


Figure 5.5 *- Chains, wire ropes and fibre price per meter of length as a function of the minimum breaking load (source: Harris et. al. 2006).*

5.3.4 **Layout of mooring lines**

Line orientations are based on the WEC geometry and on the prevailing directions of winds, waves and currents. Several schemes to moor floating structures are currently provided, but they can be ideally summarized as follows:

- symmetric layouts;
- asymmetric layouts.

Generally, the asymmetric mooring schemes are to be avoided, adopted only where strong winds or currents come from one direction only or for steep bed variations, whereas the symmetric ones are especially employed when the prevailing wind and current directions are very variable. The most commonly used patterns are the 30-60° eight line and the symmetric eight line (see Fig. 5.6).

Each individual line may be formed by a composition of different parts made of chain or wire, with the addition of floats, clumps, or chain tails (drag chains) used as an alternative to a clump weight.

The lines may be displaced in several configurations, possibly in combinations with a spring buoy (e.g. surface buoy) which offer advantages such as reduced loads on f-WEC devices and increased vertical f-WEC clearance. The stiffness matrix, more precisely the mixed terms in the horizontal, vertical and rotational degrees of freedom (DoF), can significantly change due to different vertical adopted layouts.

Figures 5.7 shows the possible chain configurations according to Fitzgerald (2009), which mainly differ for the horizontal/vertical load-displacement curves.

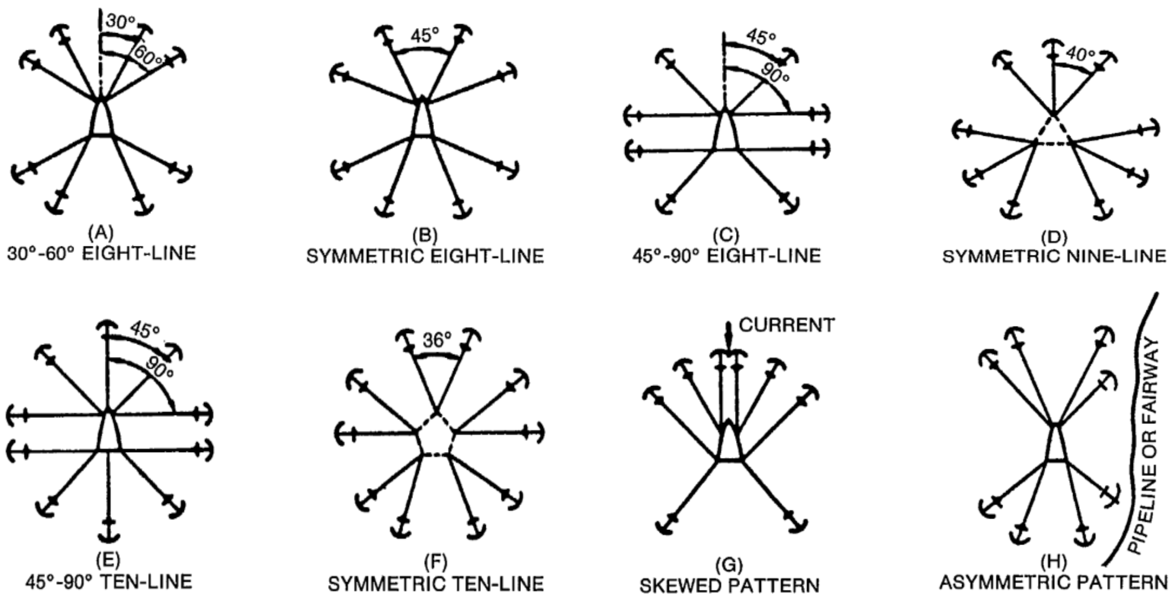


Figure 5.6 *- An overview of the most used horizontal layout for mooring systems (API, 1987).*

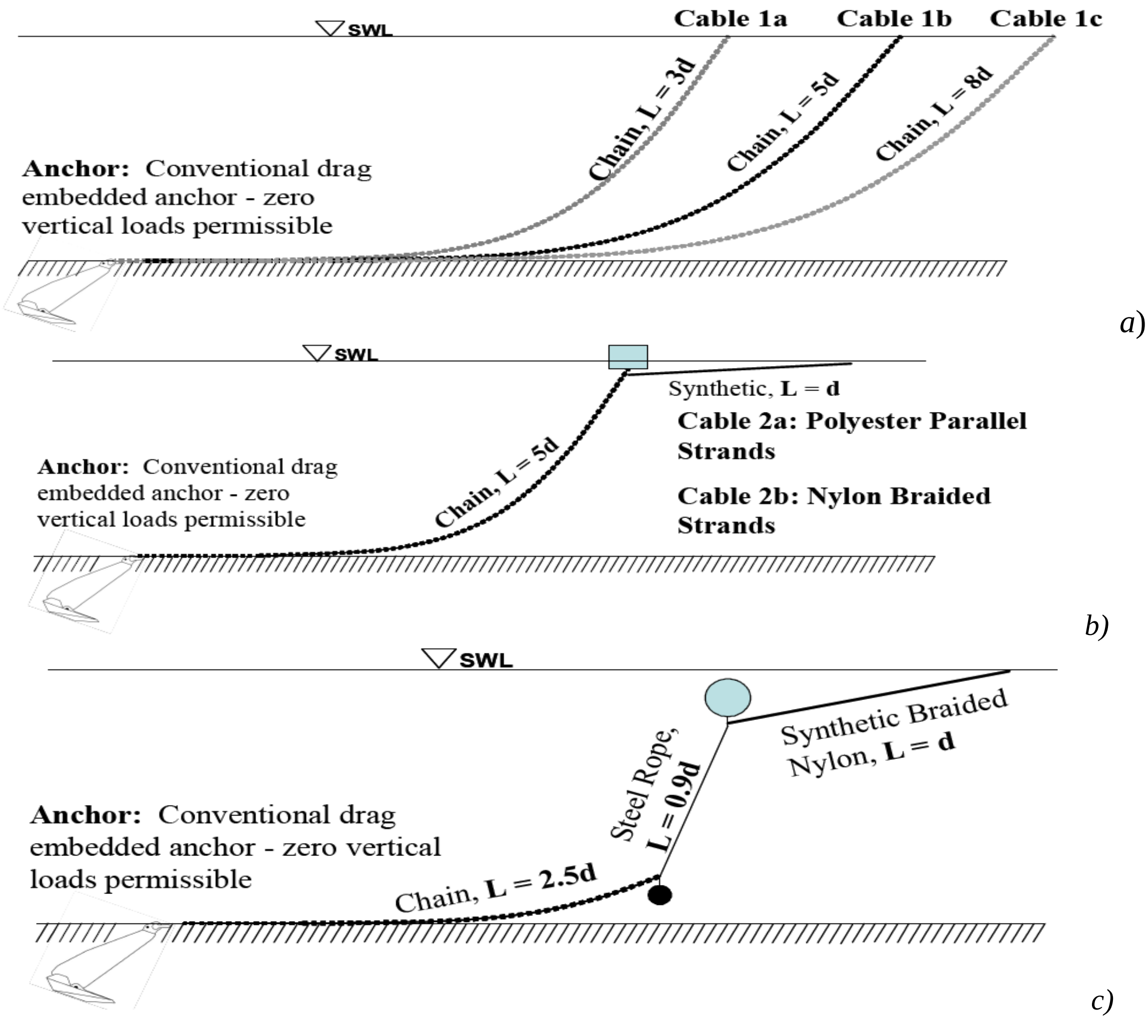


Figure 5.7 *- a) Simple Catenary mooring; b) Catenary mooring with added surface buoy ; c) Catenary mooring with added surface buoy and clump weight (Fitzgerald, 2009).*

5.3.5 **Anchors**

The location and the use of a specific mooring configuration or mooring line material often requires a specific anchor type (Musial et al, 2004).

1. *Gravity anchor/deadweight anchor* (see Fig. 5.8). Horizontal holding capacity is generated by one or more dead weights providing friction force between seabed and anchor. The main disadvantage 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 in case of WECs. It is suitable for all seabed types; however the friction with a rocky seabed will be much less than acquired in a deeply sediment 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 WEC 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).

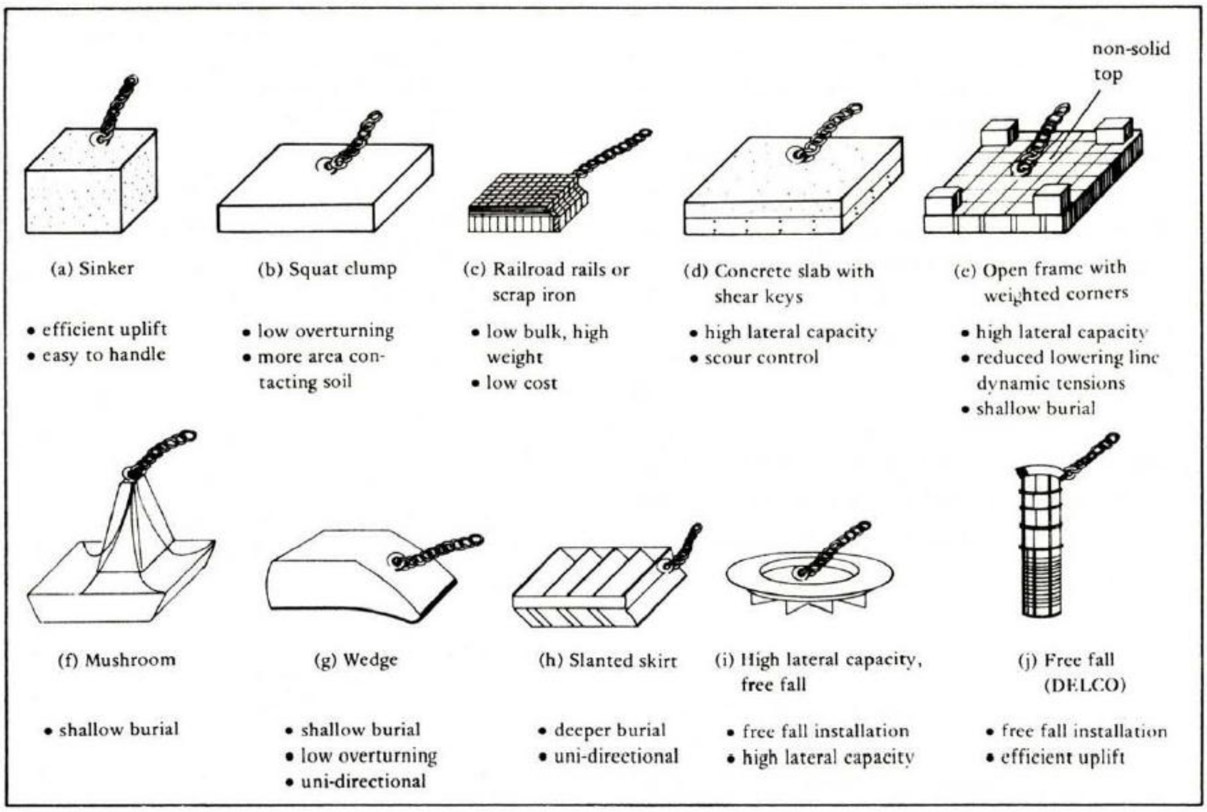


Figure 5.8 *- Type of gravity anchors (Sound & Sea Technology Engineering, 2009).*

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

- 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

2. *Drag-Embedment Anchor* (see Fig. 5.9). They 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 resisting horizontal loads only, i.e. the horizontal resistance is ensured in the main instalment direction by the embedment of the anchor in the seabed. The modern drag embedment anchors can resist horizontal loadings as great as 50 to 100 times the anchors weight in appropriate seabed conditions (capacities of up to 1500 tons, Aquatera, 2012). 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). 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
    - High capacity (up to 1500 tons) achievable
    - Can provide continuous resistance even though maximum capacity has been exceeded
    - Anchor is recoverable
    - Performs poorly in rock seabed
    - Behavior 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°.

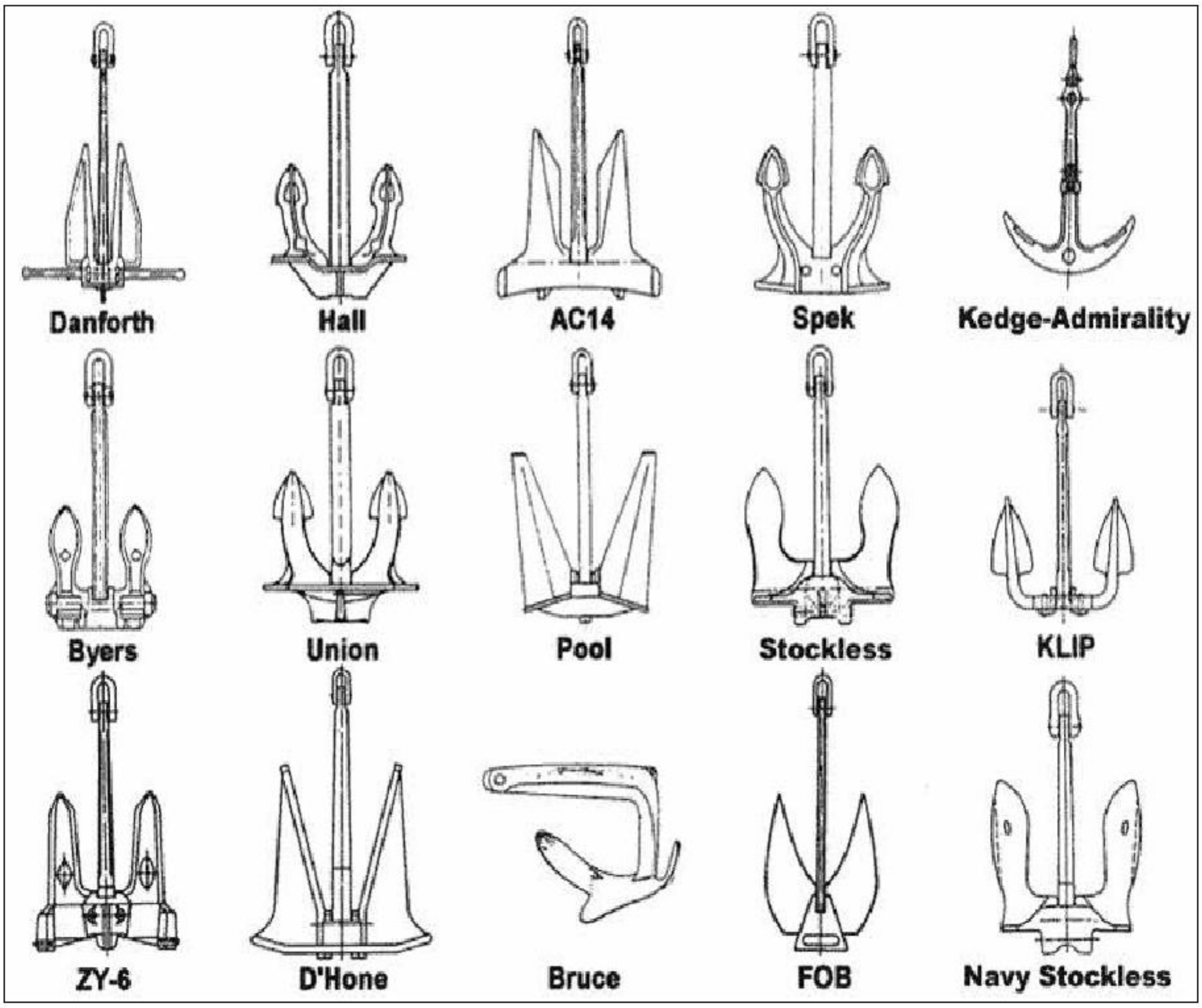


Figure 5.9 *- Conventional drag embedment anchor types (Sound & Sea Technology Engineering, 2009).*

3. *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 off-shore 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 0.5-2.5m 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. Suction anchors, shown in Figure 5.11b, are a commonly 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.

4. *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.

5. *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.

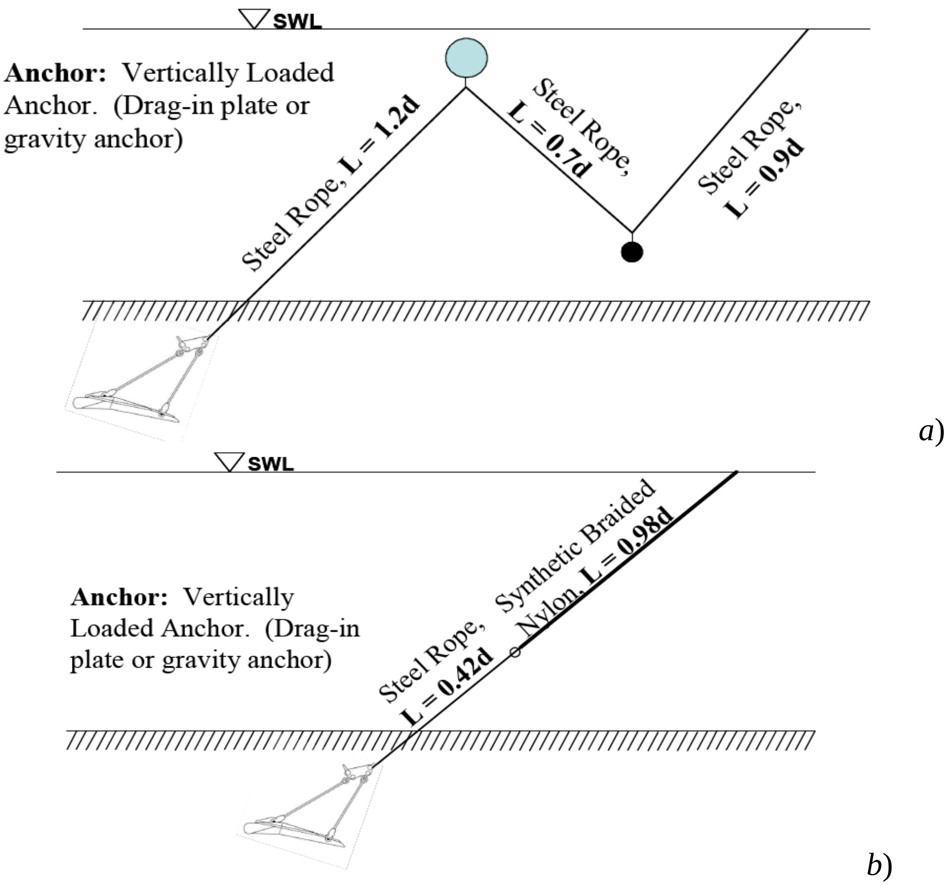


Figure 5.10 *- a) Vertical loaded anchor with compliance using weights and buoys; b) Tension tether. Vertically loaded anchor with compliance using cable elasticity (Fitzgerald, 2009).*

6. *Driven Anchor plate*. They 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 soil wedge 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. They can absorb very high vertical loads and they are particularly suited for taut mooring lines. Sound & Sea Technology Engineering (2009) summarizes the key features 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 seabed
    - 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 seabed and in coral
    - Can be placed on moderate slopes
    - Penetration is controlled and can be monitored
    - Suction driven plates limited to soft seabed

- Driven plate installation with surfaced-powered equipment limited to shallow depths
- Suction driven and drag-in plates are not depth limited.

Figure 5.11 represents some example of different anchor kinds.
The selection of the appropriate anchor type for WECs can be performed based on the following criteria (Sound & Sea Technology Engineering, 2009):

1. holding capacity: amount of holding required;
2. soil type: properties of soil and layer thickness;
3. weight: amount of weight that can be carried;
4. equipment: size and characteristics of anchor installation equipment;
5. directionality: drag anchors may provide little uplift capacity and mainly hold in one direct, whereas plates and piles may provide high omnidirectional capacity;
6. performance: acceptability of anchor drag as well as the amount of available real estate for mooring systems will affect the anchor specification.

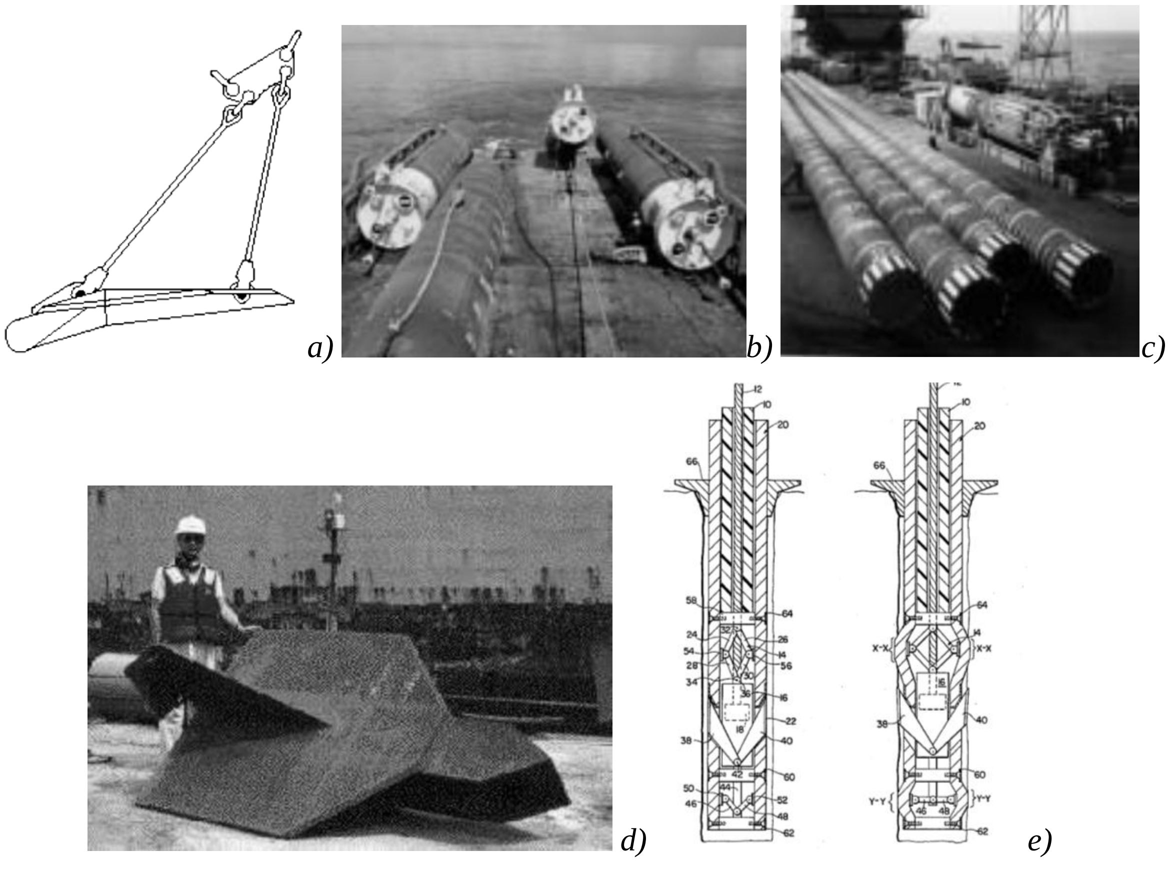


Figure 5.11 *- a) gravity anchor; b) Suction anchor; c) Fixed rod; d) Anchors with fixed rod. Source: Musial et al, 2004; e) Anchors with pre-drilled rod.*

Table 5.4 is very useful in the initial selection of possible anchor types suited to the various above mentioned mooring configurations. There are many anchoring options that may be appropriate for any of the three mooring configurations. Almost any of the anchor types can be designed to work with each mooring configuration, but there may be an optimal or equivalent choices based upon seafloor conditions, available installation assets, load and load direction, and cost. The choices presented in the table have a color legend described at the bottom of the table (Sound & Sea Technology Engineering, 2009).

Mooring Configuration	Anchor Type	Comments
Catenary	Deadweight	Skirted deadweight or enhanced deadweight (PHA) for limited sediment or rock.
	Drag	Primary choice for sediment seafloors. Broad use experience.
	Pile	Applicable but not recommended due to cost
	Plate	Applicable but requires more specialized installation equipment.
Multi-catenary	Deadweight	Skirted deadweight or enhanced deadweight (PHA) with sinkers to reduce line angle at PHA. May be a practical option for limited sediment or rock seafloors. Handling weight will drive cost.
	Drag	Must be used with sinkers to reduce line angle to near horizontal angle at the seabed. While this increase handling difficulty it may be a cost effective option because there is broad use experience with this type of system.
	Pile	Applicable but not recommended for single WEC installations due to cost unless equipment and expertise is readily available. Suction piles may be the preferred pile option for sediment seafloors. May be very cost effective for energy farms.
	Plate	Plate can be a cost effective option for single WECs but this depends upon the availability of installation equipment and expertise. Plates are not recommended when load sharing may be required for energy farms.
Taut	Deadweight	Applicable but large line loads require high weight to resist vertical and horizontal loads. On seafloors with rock or thin sediment this option should be considered.
	Drag	Cannot handle uplift loads.
	Pile	Broad use experience for soil and rock seafloors. Local expertise and equipment are important to the selection of the least cost pile type and installation method.
	Plate	May be the least cost option for sediment seafloors but not appropriate for rock.

Applicability
High
Medium
Low
Not Applicable

Table 5.4 *- Mooring configuration anchor options (Sound and Sea Technology Engineering, 2009).*

Furthermore, in order to summarize the characteristics, load range, applications, advantages, and disadvantages of the anchor types, table 5.5 is created.

Anchor type	Characteristics	Cost	Vertical Load	Retrievable	Installation Problems	Environmental Impact	Main application	Advantages	Disadvantages
Gravity anchor	Horizontal holding capacity is generated by dead weight providing friction between seabed and anchor.	Low / medium	Yes	Yes	Medium	Medium	Any type of soil and rock seabed, not in very deep water	Reliable holding capacity Can be used in any type of bed, including rocky soil No preparation necessary Easy to maintain the anchor position	Needs large amounts of material particularly in the case of TLPs. Possible huge size Not suitable for sloped topography (>10 degree)
Drag-embedment anchor	Horizontal holding capacity is generated in the main instalment direction by the embedment of the anchor on the ground and depending on the installation depth of the anchor into the ground.	Medium	No	Yes	Low	Low	Soft soil seabed	Low cost Extensive experience (a wide diversity of anchor types available)	No high vertical/horizontal load ratio Difficult to generate high holding capacity and stability particularly in the vertical direction Poor performance in rocky seabed Erratic behaviour in layered seabed Holding capacity decreases remarkably if line angle at the seabed > 6 degree
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	Any type of soil and rock seabed	Widely used in the oil and gas industry High horizontal and vertical holding capacity Can be used in any type of bed, including rocky soil High positioning accuracy Performs well on substantial slopes Wide range of sizes and shapes are possible	Subject to corrosion Higher costs with deeper water Difficult commissioning
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	Soft soil in deep water	Widely used in the oil and gas industry Easier and cheaper to transport Applicable in very deep water	Very expensive in deep water mainly due to the welded construction Cannot be retrieved after use Not suitable for rocky soils
Suction embedded plate anchors	Horizontal and vertical holding capacity is generated by the shear between the layers of the soil	Medium /high	Yes	Yes	Low	Medium	Soft soil in deep water	Easy installation and recovery Resists both horizontal and vertical loads Can be placed on moderate slopes	Expensive in construction Not easy to transport Not all types can be used in TLPs Cannot be used in rocky soils Anchor cable may be susceptible to abrasion or fatigue
Helical anchor/pile	Horizontal and vertical holding capacity is generated by the shear between the layers of the soil	Low/medium	Yes	Yes	Medium	High	Suitable for a variety of soil types Not suitable for active morphology	Relatively small footprint Cost efficient in shallow water depths	Not suitable for rocky seabed

***Table 5.4** - Characteristics of anchor types*
(OTC, 2003; NREL, 2005; Harris et al., 2004; EquiMar, 2009; Sound & Sea Technology Engineering, 2009, Aquatera, 2012).

5.4 Maintenance

During the estimated lifetime of WECs, regular maintenance is required in order to ensure efficient operation. In addition to this, the need for extraordinary maintenance is inevitable and unpredictable. In this section, maintenance strategies for WECs will be identified shortly. A further detailed account on maintenance of WECs was given by DNV, 2005 in section 25.2, albeit focusing mostly on preventive maintenance activities and inspection methodologies.

5.4.1 General maintenance requirements for WECs

Maintenance requirements for a WEC system (DNV, 2012), as well as other off-shore structures, can stem from the following:

- time-dependent effects,
- mechanical/chemical attacks,
- corrosion,
- seabed conditions
- stability,
- scour protection,
- loading/fatigue,
- electromechanical malfunctions (PTO, power transmission lines, etc.),
- damage from accidents,
- etc.

WECs are subject to similar aggressive environmental conditions with respect to off-shore oil and gas platforms (environmental class referred as MA; DNV, 2005). Yet, the maintenance problem of WECs comprises two enhanced difficulties:

1- the maintenance of movable operational/mechanical components (i.e. hinges, guide sliders, movable sleeves, etc.) subjected to seawater; the parts near/over surface or the parts continuously under water.

2- the maintenance of PTO systems (including also turbines). This kind of maintenance is specific to the selection of the PTO system which is dealt in chapter 3 of this document.

Even very simple regular maintenance tasks, such as lubrication, of submerged mechanical parts of WECs become a problem in the off-shore environment (Chau et al., 2012). The problem is not only due to technical complexities, like keeping the lubricant stuck on the surface; but also stems from the operational difficulties such as:

- difficulties in the WEC transportation,
- long and risky underwater operations,
- possible need for heavy lift vessels,
- possible need to disassemble certain parts while maintaining others, etc.

Considering that those components, due to the aggressive environment, would need a more frequent fashion of regular maintenance (or shorter intervals of replacement) than the on-shore counterparts, these kinds of maintenance activities comprise a serious burden in the total cost of the project. The above listed operational difficulties of regular maintenance tasks apply also to the extraordinary maintenance needs (e.g. repairs) and the activities to diagnose any irregular functional problem. To optimise the preventive maintenance requirements, a procedure called Reliability Centred Maintenance (RCM) is suggested (DNV, 2005), in which maintenance strategy is established on the basis of a systematic evaluation of failure modes and their negative effects on the WEC system. Recently, this (or a very similar) method has also been employed for the reliability evaluation of structural components of WECs (see, for example, Thies et al., 2009, 2011; Johanning et al., 2010). In such a probabilistic approach, the risk of each type of malfunction as well as the duration/difficulty/risk/cost of each corresponding preventive measure or repair can be expressed in terms of a probability density function. Overall duration/difficulty/risk/cost can be easily calculated thanks to Monte-Carlo simulations. The data to carry out such preliminary RCM analysis can be found in generic databases such as OREDA (Off-shore Reliability Data Handbook) (DNV, 2005). However, since the WEC applications are case-specific and there are many few case studies for each type of application, it would not be appropriate to expect that these analyses can “hit the bull’s-eye”. Large-scale laboratory modelling or prototype-scale tests are the major available tools to refine these analyses until the industry reaches to a mature level of experience.

As preceding paragraphs reveal, maintenance issue, as a whole, is one of the essential ingredients of *type selection* and *preliminary design* phases of the WEC projects. For instance, a WEC system integrated on breakwaters of a harbour would naturally have the advantage of easy access for maintenance (as well as operation and construction) which introduces simplicity and reduced operational costs (Falcao, 2010; Schoolderman et al., 2010). Also the size of infrastructure such as power transmission lines would be reduced which would indirectly affect the maintenance costs (i.e. less cable, less maintenance).

5.4.2 **Corrosion**

As a common maintenance problem of off-shore/marine facilities, control and monitoring of corrosion comes out to be an important issue for WECs, as well.
Main materials for WEC components are steel, concrete, composites (laminated materials and sandwich structures) and some high-density polymers (PE, PVC, etc.). Material requirements of WECs for steel, composites and concrete components can be covered mostly by the DNV codes referenced as OS-C101 (DNV, 2011), OS-C501 (DNV, 201b) and OS-C502 (DNV, 2012), respectively (DNV, 2005).

In seawater, corrosion is a principal and universal problem for steel, whether structural steel or reinforcing steel of a concrete element (Gerwick, 2007). Corrosion controls of structural steel for off-shore structures can be listed as:

- coatings and/or cathodic protection,
- use of a corrosion allowance,
- inspection/monitoring of corrosion,
- control of humidity for internal zones (compartments).

The method for corrosion control can be chosen according to the environmental condition to which the component is exposed. For atmospheric zone (not in seawater or very rarely exposed to seawater), coating should be sufficient for corrosion control. However, in the submerged and splash zones, cathodic protection becomes almost a necessity in addition to coating. If internal zones are exposed to seawater for a considerable fraction of time, same sort of an application is required. If the periodic replacement of anodes (and other critical components) is not foreseen in the design phase, galvanic anode cathodic protection systems is expected to have a design life at least equal to that of the WEC (DNV, 2010b).

Reinforcement steel elements are presumed to be protected against corrosion sufficiently by the concrete itself, provided that adequate coverage and a durable mix-design are maintained. However, reinforcement steel exposed to seawater in case of concrete defects, or due to any other reason, should be protected against corrosion by some additional means (DNV, 2005, 2010b).
If the damage of reinforcement steel occurs by corrosion, the cause should be determined before a reparation attempt. Steps, such as wrapping or installing cathodic protection must immediately be applied to prevent ongoing corrosion (Gerwick, 2007).

5.4.3 Abrasion

Abrasion is the scratching of the surface of structural elements by means of solid particles in the seawater. Moving ice at sea level, mobile sand on the seafloor or silt suspended in the seawater can be sources of abrasion. When such particles abrade a steel surface, they not only remove steel but also promote corrosion by removing the earlier rust coating and exposing bare steel to corrosion. To insulate a certain structural element from such damages, the element may be wrapped in a polymer sort of fabric (such as HDPE based) variations of which are commercially available. The performance of such coatings, however are reported to be only fair since they are subjected to delamination, disruption by water vapour bubbles and reflection of the concrete cracks below (Gerwick, 2007). Some expensive but more effective solutions can also be viable, such as metalizing with aluminium–zinc alloy or coating with titanium.

Some other sources of degradation, especially for reinforced concrete elements, can be sulphate attacks on concrete, wetting-and drying-cracks and freeze–thaw attacks.

5.4.4 Fouling

The main consequences on structures due to fouling are:

- increase of the structure weight and volume;
- increase of the surface roughness;
- increase of the drag coefficient;
- obstruction of pipes, ducts, valves and shutters;
- changes in the speed and mechanism of corrosion;
- changes in the timing of corrosion fatigue events;
- changes in the probability of occurrence of brittle fracture;
- reduction of the heat transfer efficiency of condensers;
- possible reduction of seal life;
- masking of the surfaces which impedes the routine inspection and maintenance.

The amount of fouling present on a structure is strongly site related, hence the available data in the literature (mainly for the oil platforms surrounding U.S.A.) may constitute only a rough guide to the assessment of the fouling intensity. Furthermore, the data are reliable especially for the fouling of barnacles and mussels. Table 5.5 synthesises the maximum fouling velocities observed on anchoring structures a relatively short period after installation.

NAVIGATION BUOYS			CHAINS (50m as diameter)
Mussel (dry condition)	Barnacle (dry condition)	Laminaria (wet condition)	
54 kg/(m^2*year)	30 kg/(m^2*year)	40 kg/(m^2*year)	23 kg/(m*year)

Table 5.5 *- Observed maximum velocities of fouling occurrence on anchoring structures.*

Experimental evidence shows that some surfaces are more affected by fouling compared to others. However it is important to remark that:

- so far only tests characterised by short duration of exposure have been largely carried out, and in the few tests with a prolonged exposure the final settlement of fouling communities was in general independent from the slow initial fouling velocity;
- comparative tests may be untrue. In fact, fouling tests carried out in the same place with two panels, one dark and the other bright, show that in the short term fouling is present only on the dark surface; however, due to fouling adaptability it has been proved that fouling readily attaches also bright surfaces, in absence of dark ones.

Many marine structures consist of protected metals, thus it is more important to study the fouling effect on the protection rather than on the metal. Some species are able to penetrate the paint film and cause a local protection loss and therefore an increase of corrosion. Interaction between fouling and cathodic protection systems has not been fully investigated yet: sometimes it has been observed a fouling increase sometimes the opposite.
Treatments currently used or proposed to prevent or contain fouling phenomenon are listed in Table 5.6.

TYPOLOGIES	EXAMPLES	STRUCTURES
Fouling removal	Manual, mechanic (with hydraulic tools)	Fixed off-shore structures
Direct poison injection	Chloride mixtures	Tubes, underground pipes, etc.
Anti-fouling painting	Cu paints, organic-metallic paints (with Cu, Hg, Zn)	Ships, tubes, underground pipes, etc.
Anti-fouling cladding	Cu alloys (91Cu, 10Ni)	Some ships, panels
Thermal treatments	Water, steam	Cooling water pipes

Table 5.6 *- Treatments to avoid or reduce the fouling.*

The optimal anti-fouling solution for WEC installation depends on several parameters, therefore a good knowledge of typical fouling speeds in the area and of ordinary maintenance planning (including device removal and assistance in calm water or in a dry dock) are required.
Anti-fouling paints have a limited useful life because they continuously release their toxic ingredients with a consequent high environmental impact; for example the paint used against barnacles is typically characterised by a release rate of about 0.1 $g/m^2/day$.
Nowadays low attention is given to the anti-fouling paints application to concrete structures.
Finally, for some platforms in the North Sea an alternative solution to the fouling was considered, i.e. the fouling control by using hot water (temperature> 50°C) or steam; this technique may also be applicable to WECs however does not solve the problem of environmental impact and cannot of course be applied in multi-functional installations where aquaculture and mariculture require the maintenance of survivability conditions.

5.4.5 **Maintenance Operations**

WECs maintenance operations are conducted in order to protect the structure/system from malfunctioning or make the system regain any lost functions. As a rule of thumb, procedures for maintenance, inspection and repair should be developed at an early stage of the design. Information regard frequency and choice of inspection methods should preferably be supplied by the developer/designer as a written guide of practice, i.e. a Maintenance Plan (including the In-Service Inspection Plan), which addresses planned and breakdown philosophies (DNV, 2005). As stated above in section 5.3.1, RCM strategies should be the major tool employed when creating Maintenance Plans. A list of spare parts should be prepared (including supplier, maintenance requirements and criticality of part data) and be included in the Maintenance Plan.
The maintenance strategy is generally based on the following principles;

- time based (calendar or running hour),
- condition based,

- functional testing, and
- corrective strategies.

As a rule of thumb, the inspection period of any component is not allowed to be longer than one fourth of the fatigue life of that component. It is also recommended to start with a conservative (shorter) inspection period in the beginning of the project and then re-adjust it (possibly shorten) once the site conditions can confidently be envisaged with the WEC system working properly (DNV, 2005). DNV also stresses the importance of personnel and operational safety during the maintenance operations of WECs; and strongly recommends that a good track record of all the maintenance efforts to be logged properly.

At this junction it would be convenient to note two more basic principles that should be checked before deciding and starting any maintenance operations (Gerwick, 2007):

1. carrying out repair/maintenance operation must NOT increase the risk of failure, if any.
2. the repaired/reconstructed/replaced element must NOT adversely affect the performance of the system.

5.5 Decommissioning

The decommissioning of a marine facility is an expensive and difficult operation, but it is dictated by the laws. Many international laws and national code of practices among Europe (United Nations Convention on the Law of the Seas –UNCLOS, IMO Convention on the Prevention of Marine Pollution–London Convention, Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR), Energy Act 2004 of UK, etc.) state that any abandoned or disused installation or structures in marine environment *shall be removed* (decommissioned) to ensure safety of navigation. In accordance with these, it is expected that, among Europe, this will be extended to all types of WECs. Recently, Department of Energy and Climate Change (DECC) of UK Government has published guidance notes for industry, revised on 01/2011, on the "decommissioning of off-shore renewable energy installations under the Energy Act 2004". It can be sensed that the guidance aims at developing a common language amongst Europe marine energy industry, in parallel with the other international codes. In order for the developers to get a complete "licence" for their installation, DECC requests a legitimate decommissioning programme to be submitted under the compelling power of Energy Act 2004, including financial security provisions. For example, Aquamarine Power, the developers of Oyster 2, has issued a decommissioning programme under this legislation (but only the "draft for proposal" version of this decommissioning programme is open to the public access).

A WEC should be designed to allow a safe and economic decommissioning as well as installation. Recycling of materials and possible re-use of equipment should be considered at the design stage in order to reduce both the cost and environmental impact of decommissioning.

Generally it can be said that construction of an off-shore facility is easier than decommissioning the same facility since the structures may be corroded, damaged or totally failed prior to decommissioning. Hence, the existing conditions must be investigated properly and each stage of the removal should be planned in a detailed manner (Gerwick, 2007). This also requires a very thorough calculation and handling of associated risk.

Requirements for marine operations during decommissioning of off-shore installations, in general, can be found in DNV code referenced RP-H102 (DNV, 2004). The technical guidelines and recommendations that the document gives cover "topsides, steel jacket substructures, loading columns and subsea installations". General requirements and steps for decommissioning such as planning, documentation, risks analysis, surveys, weather conditions and loads besides operation specific recommendations for off-shore crane lift operations, subsea operations, back-loading off-shore operations, transport from off-shore locations and on-shore transfer are also included in the latter.

A WEC system although comprises some characteristic features different than any other facility, is generally an off-shore installation which would be decommissioned under the same legislation and the same code/guidance of practice. In particular, depending on the type of WEC, the decommissioning of PTO module may be expected to include some different aspects than the other off-shore facilities. In the most general sense, for the sake of reconciliation with the EU directives about Waste Electrical and Electronic Equipment and Battery Disposal at the decommissioning stage of WECs, these issues must be considered in the design stages of WECs and during the selection of PTOs.

6 Rough analysis of costs

In projects related to power generation the cost is typically measured by the cost of energy production and it is expressed in c€/kWh. In this section, a description of how to perform the estimate of costs for WECs is provided, in order to define the overall feasibility of their installation.

Since marine energy conversion is a relatively recent technology field and it is mainly at its research stage there are few practical applications, hence there is a lack of application of economic assessment methods and procedures.
However an economic evaluation of the lifecycle WEC performance is fundamental for a wide range of users (from engineers, developers and analysts, to the politicians, investors, venture capitalists, banks and other financial institutions). It is worthy to remind that each type of user has, of course, specific interests and decision criteria, and this is another reason why there is not a unique economic assessment methodology. Actually this methodology is required if one wishes to compare the performance of installation with conventional technologies and other renewable sources at the same site.

A realistic evaluation of the economic investment of WECs installation should include both the costs and the revenues.
The Net Present Value (NPV) is the cash-flow sum for the entire duration of the investment discounted to the present day. A project with an NPV greater than zero has a return higher than the minimum interest rate allowed and may be considered advantageous to be carried on. The NPV can be expressed in installed €/kW (see next section for detailed information).
The NPV approach, applied to evaluate the cost of marine energy installation, combines the well-known and well-established methods and the representation of the various factors and effects depending on the different marine technologies.
This approach has been already applied by several users, among them:

1. the WaveNet Project detailed a global report (in 2003), including financial evaluation for WECs, where the economic evaluation is based on the cost of the generated electricity that is found through the application of a NPV approach with a discount rate of 10%.
2. the Marine Energy Challenge Programme evaluated the feasibility of different wave and tidal energy technologies; results are summarized in a report (issued in 2006), where current and future cost of energy generation is estimated through the NPV approach.
3. the Electric Power Research Institute made a global economic assessment procedure (Previsic et. al. 2004) for WECs focusing on the North American market.
4. the cost estimation for a farm of WECs can be found in Gross et al. (2007).

In general, the analysis of the cost components is complicated, because they are device/technology (e.g. offshore or on-shore installations)/development stage/site (water depth, seabed nature, extreme climate conditions, site accessibility, etc.) specific. Therefore so far a generic procedure has been proposed only theoretically.

6.1 The proposed economic model

Figure 6.1 shows the following main factors contributing to the NPV calculation:

1. the capital costs, including decommissioning/disposal (CAPEX),
2. the annual operational expenses (OPEX),
3. the revenue.

These factors contribute to the cash flow and they will be briefly described in the following subsections.

The NPV is defined as the total present value of a time series of cash flows. The cash flow of a project is the balance of the amounts of cash being received and paid by a business during a defined period of time.
Considering a single up-front capital investment cost I and annual cash flows c_i, in first approximation (i.e. by ignoring uncertainty and assuming r as single money discount rate for n years) the NPV can be calculated as:

$$NPV = \sum_{i=1}^{n} \frac{c_i}{(1+r)^i} - I$$

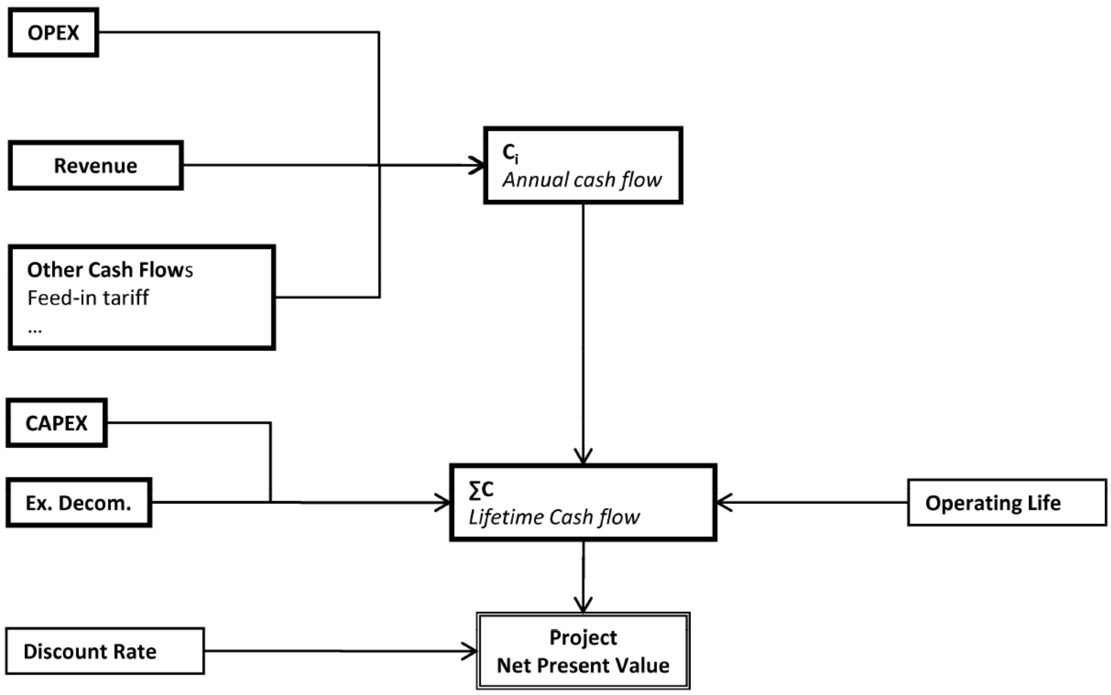


***Figure 6.1** - Net Present Value (NPV) calculation flowchart with a single discount rate.*

Similarly to figure 6.1, figure 6.2 reports a more complex approach, which includes also the interdependence among the different cash-flows.

The NPV has been recently evaluated through the Monte-Carlo simulations, which stochastically describe the uncertain parameters of the model, and find the NPV values as the result of multiple iterations. Each Monte-Carlo simulation considers a single random value for the probability distribution of each component. This approach was used for the costs analysis by Previsic et al. (2004).

For an innovative WEC concept, which exists only in model scale, it can be difficult to accurately extrapolate capital costs, reliability and power conversion related to the future scale of the real installation. The distributions used in the Monte-Carlo model should reflect these uncertainties. For example, the distribution describing the average damage frequency should show a greater variance for a device in its initial design stage than in a later stage of its development. Consequently, the risk and the economic feasibility vary with the different stages of the technological development, an example scheme is shown in figure 6.3.

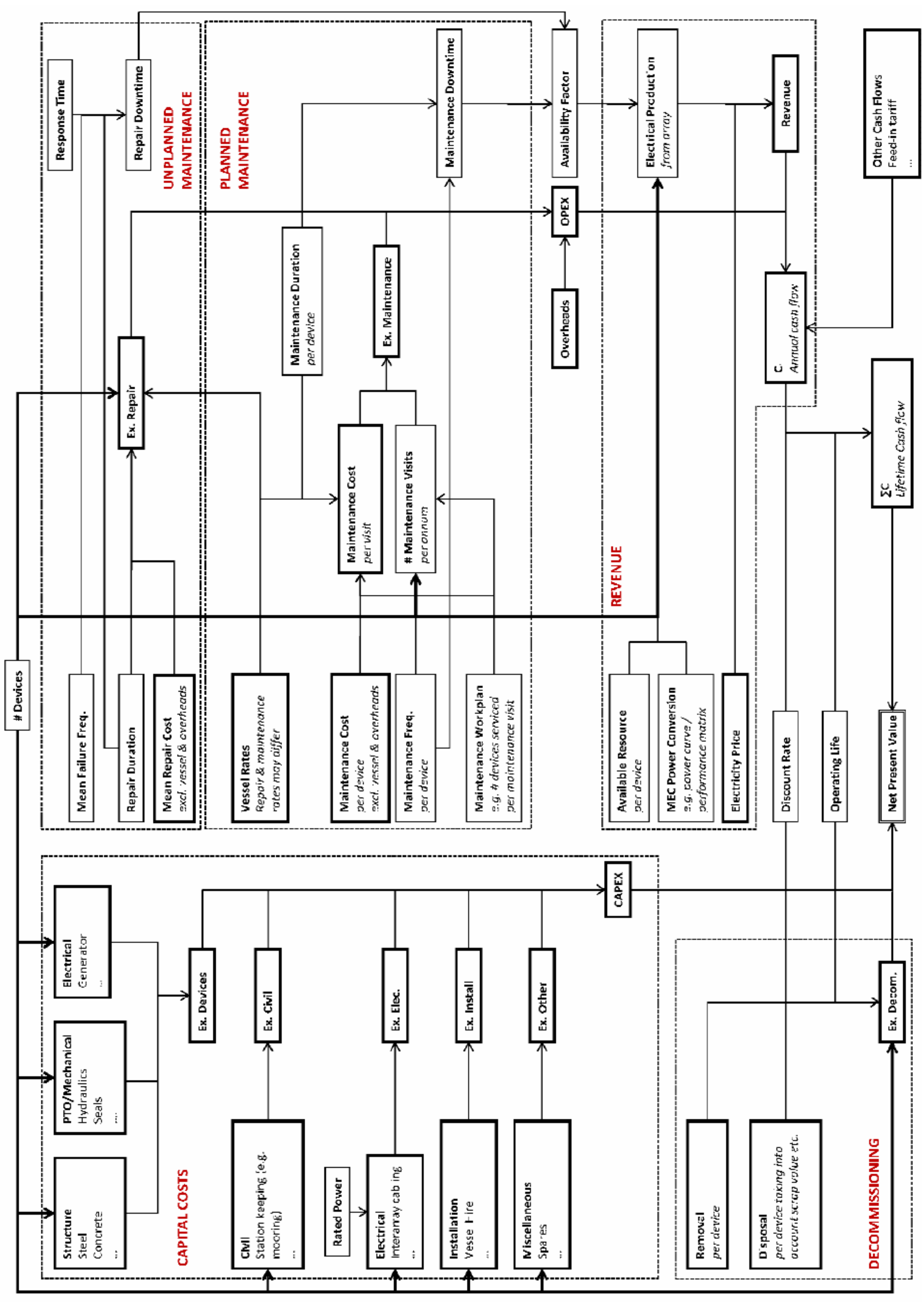


Figure 6.2 *- NPV calculation process (with a single discount rate) by Davey, T., et al., 2009. The calculation includes also the interdependence among the different cash-flows.*

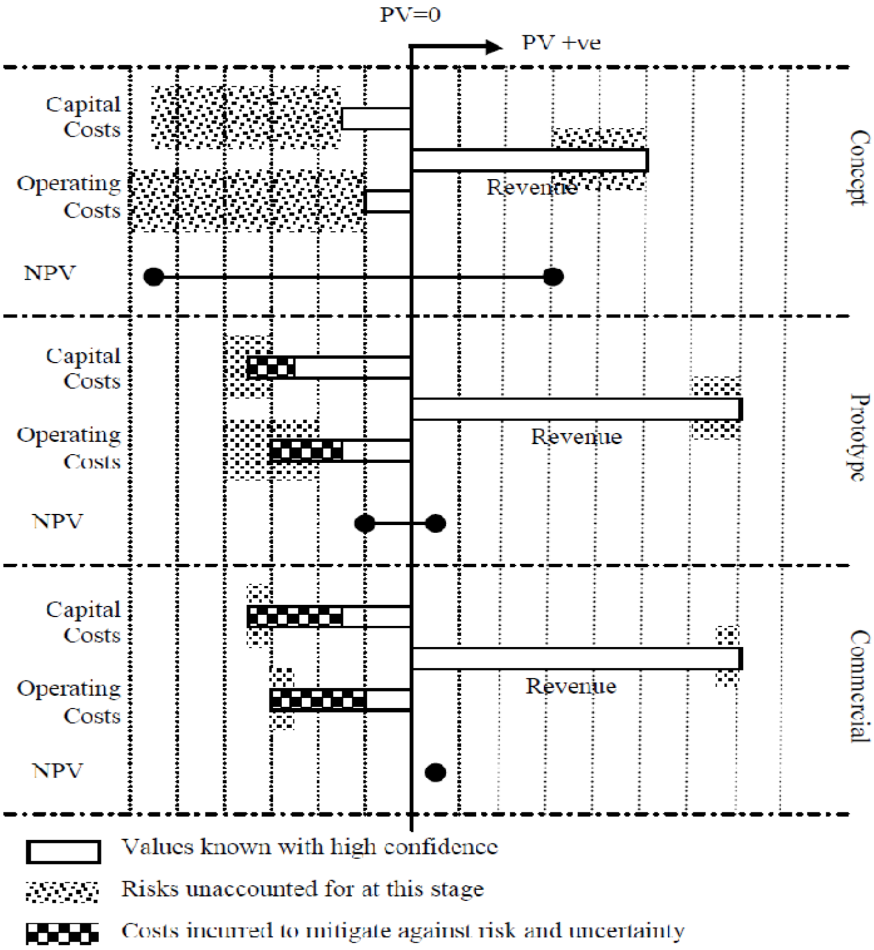


***Figure 6.3** - Rough representation of an economic evaluation for a WECs installation considering technological development, proposed by Ingram et al., 2011.*

6.1.1 Capital costs (CAPEX)

As it is presented in figure 6.4, the capital expenditures for a WEC installation includes the following costs items:

1. costs associated with the device. The cost of a WEC is determined by its components (body/ies and PTO), its functions (for example the energy production) and the design choices made. The prices of individual components and materials could potentially remain rather constant (except for unforeseen economic crises, which lead to fluctuations in the prices of various materials), while production costs (per device) should decrease with the evolution of the technology and with more efficient production techniques;
2. mooring system/foundation costs. The mooring system is supposed to maintain the WEC in position and to optimise its efficiency. Sometimes the cost of the mooring system is combined with the cost of the device itself and with the cost of the civil infrastructures involved;
3. costs of all the cables, including cable among devices in the wave farm installation and between the installation site and the shore-line;
4. costs of the network transmission.

Furthermore if one considers the entire WEC life cycle, also the costs of decommissioning should be accounted for and depend on several factors, for example the number of WECs to be removed and the selected decommissioning type (for instance, the removal of the WEC and then its demolition or the WEC disposal at sea e.g. in the form of an artificial reef).

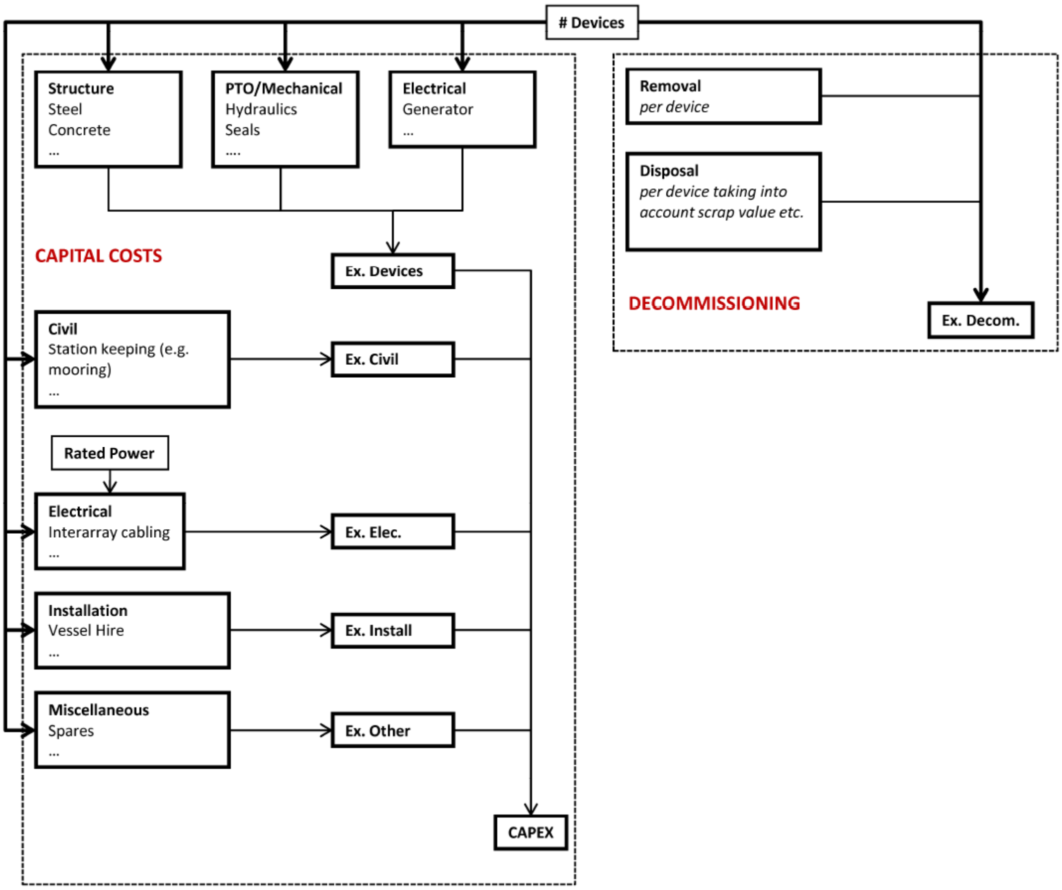


Figure 6.4 *- CAPEX items costs schematization, inform “Procedures for Economic Evaluation” Deliverable D7.2.1 (EquiMar Project).*

Figure 6.5 proposes the breakdown of the capital costs for a wave farm (Carbon Trust, 2006).

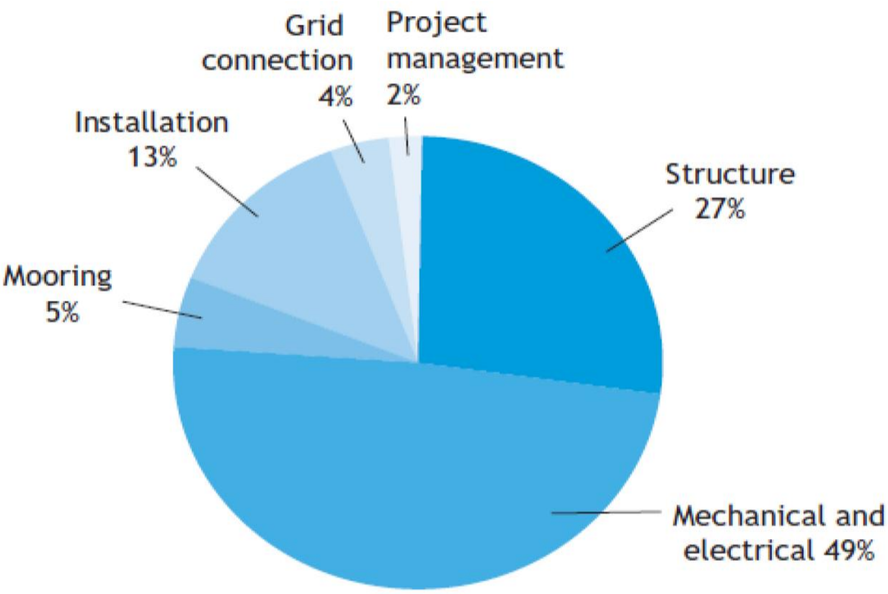


Figure 6.5 *- Influence rate of the CAPEX items costs, proposed by Carbon Trust (2006).*

6.1.2 Operational Expenditures (OPEX)

The WEC annual operational expenditure (OPEX) is primarily associated to:

1. ordinary maintenance: these costs are defined as the costs for the achievement of the design power production. These costs also include items such as the cost of the monitoring, insurance, vessel and equipment transportation, labour and consumable parts;
2. restoration (i.e. extraordinary maintenance): it is strictly associated to the "mean failure time", which depends on many factors, e.g. the failure mode (of each component and of the whole device) and the installation environment. The device realisation depends on the reliability of the technology, which should be already evaluated at the design stage through the analysis of the device components, for example through data obtained during the tests on prototype. It is expected that the reliability uncertainty will tend to decrease with the evolution of the technology and the progress of the operational experience and design. These analyses are usually based on laboratory or small-scale data, therefore the differences between scale and environmental conditions should be accounted for to avoid non-cautious conclusions.

The simplest -and common- approach is to assume that there is no connection between the two categories of maintenance: scheduled and unplanned, even if some scheduled maintenances are generally dependent on the reparation costs. Usually for WEC installation the ordinary maintenance is more recurring than the extraordinary maintenance, and in general, accessibility of the site and wave climate are key parameters for the maintenance operations planning.

The input cost items of the OPEX also contribute to estimate the Availability Factor, which indicate the overall efficiency of the entire lifetime of the WEC installation. An Availability Factor equal to 1 indicates that the device has no downtime, where the downtime is associated with maintenance operations that require the device to be taken offline. The downtime and in general the maintenance need to be considered also in the calculation of the expected revenue.

Figure 6.6 incorporates the calculation of the OPEX and of the Availability Factor.

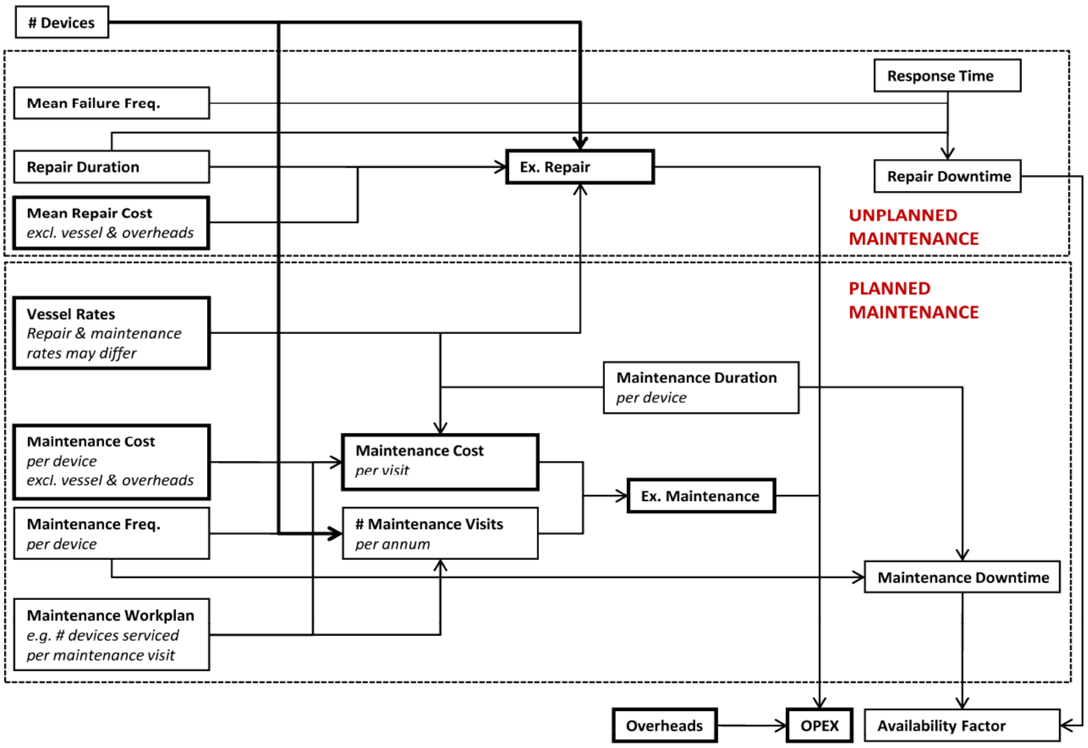


Figure 6.6 *- Flowchart of the OPEX and Availability Factor.*

6.1.3 Revenue

The amount of energy produced by the device determines the revenue of the project, excluding the fuel costs. The performance of a WEC is generally derived from the sea trials. The involved factors in the calculation of the WEC revenue are shown in figure 6.7 (including its downtime due to maintenance).

This procedure assumes that the conversion of energy is described as a device function and that it will not be interrupted due to maintenance or failures. Therefore the energy output of a WEC farm is function only of the available wave power and of the number of installed devices.

A revenue analysis should however specify the uncertainty of the power production due to the uncertainty of the wave resource and of the device performance. In particular the wave resource uncertainty varies according to the available historical data and -for a given installation- it may be reduced during sea tests trials thanks to a more detailed characterization of the site.

The comparison of different types of devices in the same site leads to the conclusion that the performance uncertainty is greater for devices at the early development stage.

Furthermore the electricity prices can be very volatile depending on the market, and generally tend to reflect the energy demand: high demand during the day and demand variation on a seasonal basis. A purchasing agreement can specify a fixed or seasonal price. For example, in the United Kingdom prices for energy produced by WECs are discounted respected to the average price of the wholesale market.

The future prices in the worldwide market are uncertain, even if there are funding programs aiming to help the marine technology development. In many countries (for example, in Germany), the risk of energy production from renewable sources is reduced by feed-in tariff (FIT). Other countries apply “green certifications” systems, i.e. setting targets of a minimum amount or percentage of electricity from renewable sources for electricity purchasers, and for each green energy unit purchased they receive a certificate (for example, the Renewable Obligation Certificate or ROC in the United Kingdom).

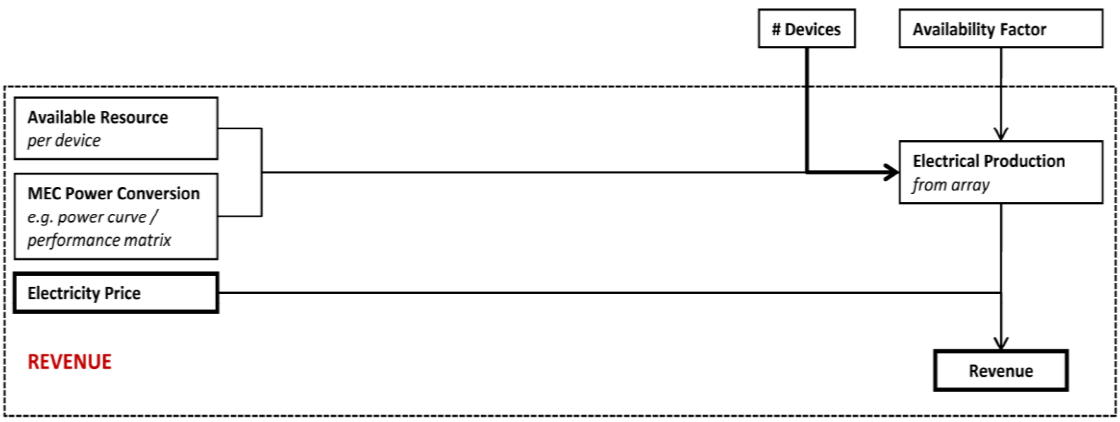


Figure 6.7 *- Revenue calculation flowchart.*

6.2 Examples of cost analysis

The Carbon Trust (2006) in UK addresses the cost competitiveness and cost reduction opportunities of wave and tidal energy converters in order to accelerate the marine energy development. As a result, the cost of wave energy was predicted to be between 26 and 93 €/kWh. Costs were broken down into CAPEX and OPEX expenses, however, a limited data was provided regarding device and wave resources characteristics, which makes reproduction difficult.

In 2007, the UK Department of Trade & Industry assessed the range of cost of electricity for 20 different renewable energy technologies. It was estimated that the cost of electricity would be between 24 and 54 €/kWh. A best estimate of 38 €/kWh represented the majority of both near-shore and off-shore WECs.

The study commissioned by the UK Department of Energy and Climate Change and the Scottish Government (Ernst & Young, 2010) performed a study to provide an assessment of the 2010 (actual and best estimate) generation costs for marine energy projects based on the marine energy resource in the UK.

Allan et al. (2011) calculated the economics of the wave and tidal energy converters for UK electricity generation. The study also underlined the need for incentives for marine renewable. In the same year, Dalton and Lewis analysed the cost of five different selected WECs (Pelamis, Wave Dragon, an OWC, a multipoint absorber, and a hydro pump type). It was reported that all financial results were heavily influenced by the size of the farm.

Recently, also TROPOS project (an EU funded project) which aims to develop a floating multi-use platform in deep water locations, carried out cost analysis. In terms of WECs, Pelamis was considered, because it has the most mature technology in the sector. The economics of the device was broken down into OPEX and CAPEX expenses.

In the figures 6.8and 6.9, the CAPEX and OPEX of the devices are compared based on the above mentioned publicly available in the literature.

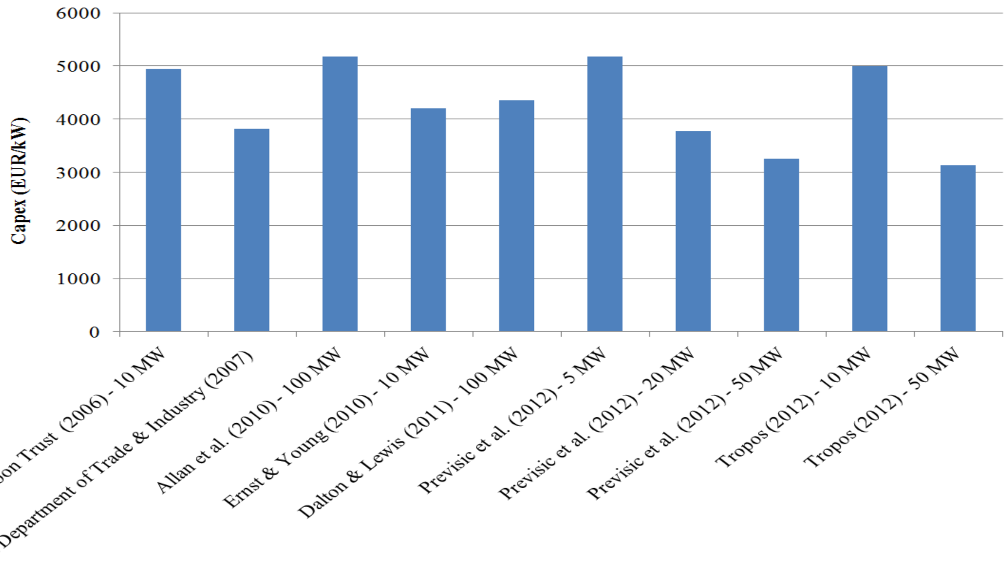


Figure 6.8 *- CAPEX of WECs based on different sources.*

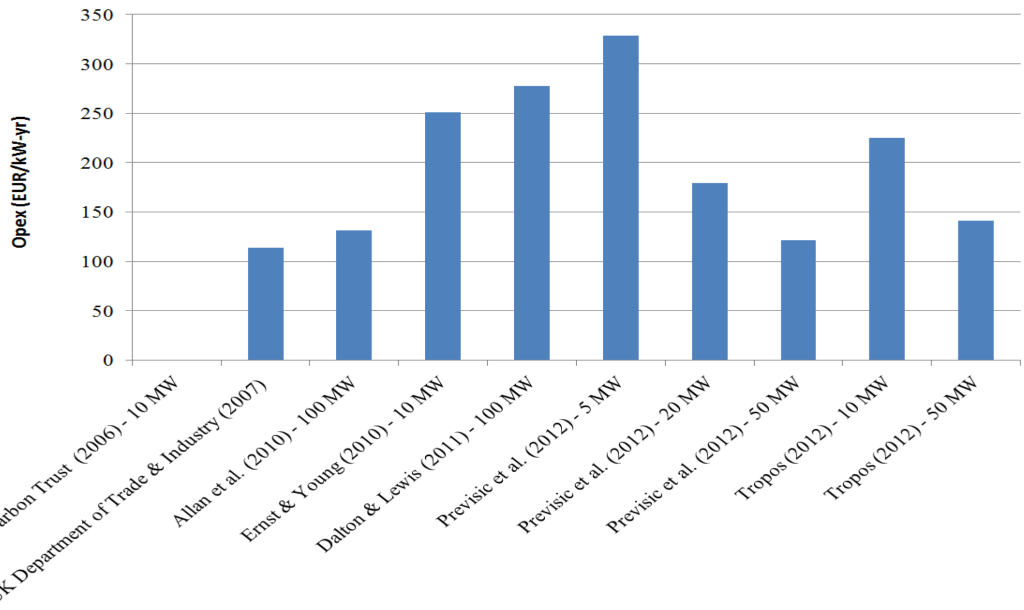


Figure 6.9 *- OPEX of WECs based on different sources.*

The technologies which have reached to the higher stages of the development programme are currently focusing on cost of energy reductions. The price of generating electricity through wave energy is presently too high compared with other renewable energy and conventional energy technologies.

General reduction in cost as a function of the increase of the technology deployment can be well described using learning curves. These curves are usually used to estimate future costs of energy based on historical costs for the particular energy generation technology. Figure 6.10 shows the installed cost per MW of installed capacity as a function of the cumulatively deployed capacity for three different technology sectors (gas turbines, windmills, photovoltaic). The learning rates of e.g. wind energy can also be applied to the wave energy. However, they cannot be applied with greater certainty due to the different scaling laws and resources. Furthermore, WECs have not yet commercialized. There are currently several different technology options at different stages of development program, and it is still not clear which technologies will stand out from this competition, indicating that learning rate reductions may take longer to realize when measured against cumulative industry capacity. Therefore, a caution should be taken whilst applying the known learning rates.

More detailed information about learning rates and future cost calculations can be found in Previsic (2012) and SI OCEAN (2013).

6.3 Key activities for cost reductions

Whilst in short term, capital investment is needed to support the deployment of the first arrays of WECs, in long-term device affordability will determine the economics of the project (SI OCEAN, 2012). An affordable WEC requires innovation and cost reductions. The Carbon Trust Accelerating Marine Energy report (Carbon Trust, 2011) and the Marine Energy TINA report (Low Carbon Innovation Coordination Group, 2012) have highlighted the role that innovation could play in order to reduce the technology and development costs.

Carbon Trust (2011) has defined clear pathways for future cost of energy (CoE) reductions in order to make marine energy competitive with other forms of renewable energy technologies by the mid-2020s. Recently, SI OCEAN (2013) stated that CoE of marine energy devices can reduce with scale and volume (i.e. up-scaling, number of devices, scale of production, and scale of engineering support), with experience (learning by doing) and through innovation (radical changes in design or development process). All of these offer significant opportunities for cost reduction. Based on the recent literature, table 6.1 is compiled, which shows the areas of innovation having the most potential for CoE reductions.

In figure 6.11, the cost of marine energy technology is anticipated to reduce to a stage at which commercialization could occur (Point 1). Following on from commercialization, three scenarios are shown:

A. No further cost reductions are seen once the technology has entered a commercial phase
B. Costs are estimated to reduce with learning rates similar to that anticipated by the offshore wind sector through learning-by-doing mechanisms
C. Costs are estimated to reduce through both learning-by-doing and technological innovation, whereby an improved cost reduction pathway can be achieved.

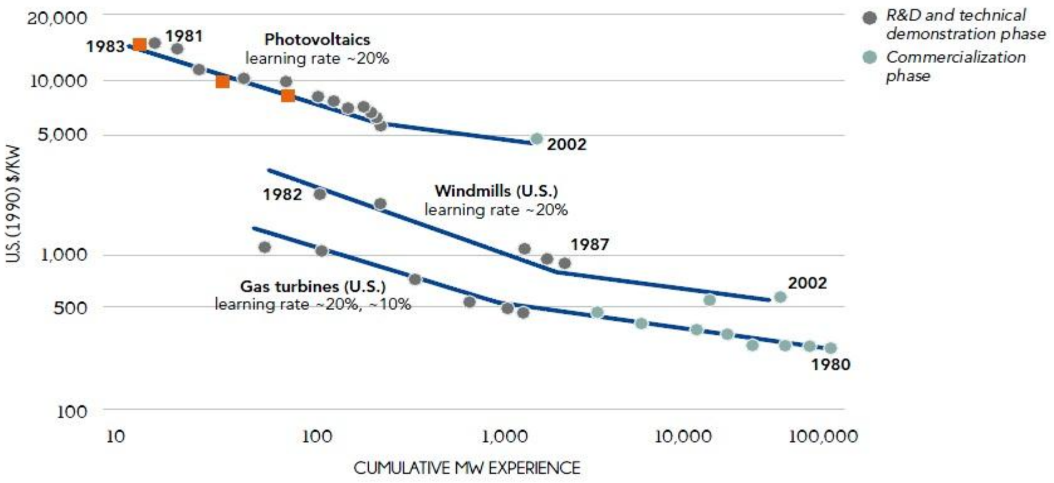


Figure 6.10 *- Learning rates of different technologies (IEA-OES, 2012).*

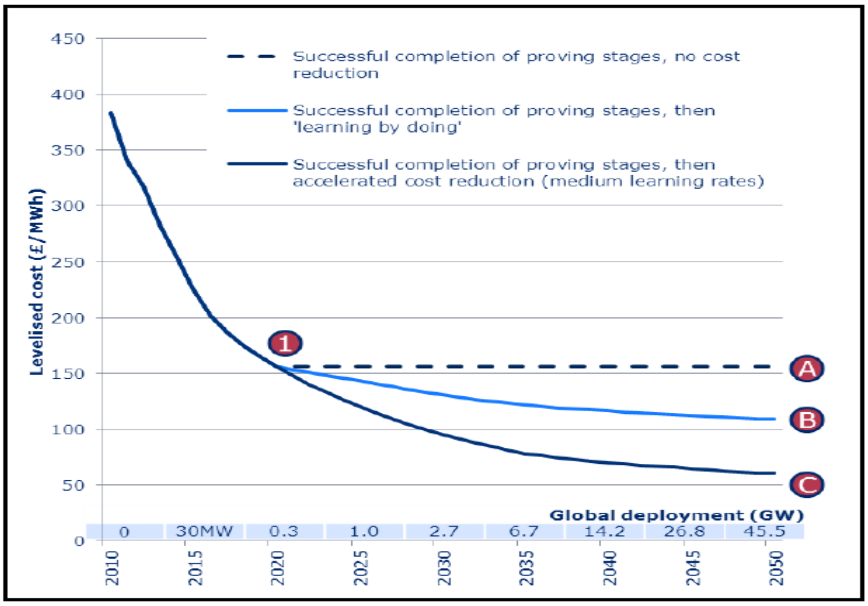


Figure 6.11 *- Potential Impact of Innovation on Levelised Costs - Medium global deployment (Low Carbon Innovation Coordination Group, 2012).*

Focus area	CAPEX reduction	Expected impact	OPEX reduction	Challenge
Structure and prime mover	Material optimization Up-scaling of devices Standardization Batch and serial production Reduced over-engineering Regional manufacturing	Geometry optimization Optimization of array layout Increased energy capture with higher reliability Reduced costs for foundation/mooring		Steel price
Power Take-Off (PTO)	Improved power electronics Improved hydraulic system Alternative/improved PTOs Condition monitoring	Improved control systems and algorithms (software) Increased energy capture with higher reliability Improvement in met-ocean forecasting Drive train optimization Improved power electronics Array yield optimization	Modular subsystems	
Foundation and moorings	Improved moorings Improved foundations Improved piling technique Cost-effective anchors for all seabed conditions Standardization	Deep water installation technique Reduced costs for foundation/mooring		Steel price
Grid Connection	Increasing use of off-shore umbilical/wet-mate connectors Subsea hubs Array electrical system optimization (transforms etc.) Off-shore grid optimization Standardization of the design of cables	Optimized subsea transmission to reduce losses	Improved connection and disconnection technique	Further development and diffusion of submarine HVDC interconnectors
Installation	Specialist vessels Optimization of vessel use Modularization of subsystems Improvements in metocean forecasting Fast deployment and other economic installation methods Subsea and seabed drilling technique Improved ROV and autonomous devices Lessons from off-shore wind Learning by doing	Faster deployment with cheaper vessels		Oil price
Operation & Maintenance		Real-time condition monitoring of WEC operating characteristics More efficient O&M planning Improved availability through: Intelligent predictive maintenance Techniques to reduce weather dependency	Increased reliability Modular components Simpler access Specialist vessels Far offshore O&M strategy Intelligent predictive maintenance Improved ROV and autonomous devices Improved condition monitoring technology	

Table 6.1 *- Cost reduction improvements*
(Carbon trust, 2011; Re-Vision 2012; SI OCEAN 2013, Wave and Tidal energy UK 2013, IEA-OES, 2013).

7 Evaluation of WECs

7.1 Introduction

As it is documented by Chapter 2 and by the Appendix to D3.3.2, there are a number of WEC concepts available nowadays and the selection of the most promising ones for installation at a given location may be difficult.

Therefore the aim of this Chapter is to propose an objective procedure for the evaluation of WECs. This procedure consists of two steps: a pre-screening phase and a ranking phase.

The pre-screening phase is a “go/no-go” option based on the technical information available for a given WEC and the development stage of its technology.

The ranking phase consists of scoring the WEC performance based on selected criteria that account for technological and non-technological issues relevant to installation, operation and maintenance.

Specific objectives of this Chapter are (i) to identify key criteria and sub-criteria for the evaluation process, (ii) to provide the users with indication of the most promising concepts at present, (iii) to discuss the key challenges of WEC installation in multi-purpose solutions.

7.2 Description of the assessment methodology

7.2.1 1st stage: Initial screening

In the first step, the available WECs –already identified and listed in Appendix to D3.3.2- are examined considering the following two issues:

- level of details of the available information regarding the general features and specifically the power production of the WEC, also as a function of the local wave climate conditions;
- development stage of the WEC technology, following the five-stage approach described in Sub-Section 2.2.4; specifically the WECs selected for Step 2 have to be at least at Stage 3.

The purpose of this screening phase is discarding the concepts whose information and development stage are insufficient to assure a feasible installation and to allow exportability to other sites/climate conditions. Therefore after an extensive literature review, only few WECs (11) at present can be retained for Step 2 (see for details the Appendix to D3.3.2). These WECs are Pelamis, Oyster, Dexa, Wave Dragon, OE Buoy, Wave Bob, Drakoo, Seabased, Aws II, PowerBuoy, Wavestar.

7.2.2 2nd stage: Ranking

In the second step, WECs are evaluated against selected criteria that have to be comprehensive of the WEC characteristics and impact during life-cycle.

Four key criteria have been selected and for each specific sub-criteria have been identified to allow an easier judgement.

Experts / users of the methodology should provide scores for each sub-criteria, then the score of each criteria is determined as the average of the scores attached to the sub-criteria without any weight. The scores range from 1 to 5, where 1=best solution, lowest impact, best performance, etc; and 5=worst solution, highest impact, worst performance, etc.

The overall score for each WEC is evaluated as the sum of the scores computed for each of the the four key criteria without including any weight. The ranking is finally performed by ordering the WECs from the most successful (lowest score) to the less successful (highest score).

A further development of this methodology can be to add weights to each criteria depending on the background of the users completing the evaluation procedure or depending on the relevance assigned by local stakeholders to the different criteria.

In the following, the criteria and sub-criteria used in table 7.1 are described.

1. Maturity of technology.

This criteria is aiming at better characterising and assessing the technological development and advances. Specific sub-criteria include:

- Meaningful levels of power generation and hours, so that capacity factor projections are credible enough;
- Reliability, in terms of operation at nearly prototype scale, reported failures of the system under ordinary and extreme waves, robustness of the technology;
- Performance, considering the average and peak device efficiency and the limitations of power production (mild conditions, heavy storms);
- Technological innovations such as use of different materials, device power capture improvements, minimization of loads, etc.

2. Environmental impact

This criteria is aiming at quantifying the impact on the environment based on the type of the installation, on the WEC design and on the requirements for operation.

- Use of marine space: the larger the minimum space required for a feasible installation (from an energetic point of view) the higher the chance to create conflict of uses (with maritime routes, fishing , protected areas, etc.);
- Foundation type: foundations placed in sandy sea-beds affect the benthic communities, and therefore fixed foundations have general greater impact (larger areas, installations buried in the bottom) rather than anchoring points for floating installations;
- Materials: the inclusion of new surfaces usually attract new habitats therefore increasing biodiversity; however bio-fouling on WECs may be undesirable for a number of reasons (maintenance of hinges, increased friction and draft) and therefore require toxic paintings;
- Impacts on native habitats and species: the larger the space occupied by each WEC, the larger the area where light conditions and therefore water oxygenation may be affected;
- Impact on the coast: the larger the wave absorption and the closer to the coast, the greater may be the impact on the coast due to reduced incident wave height and diffraction effects, that can in turns affect sediment transport patterns;
- Inclusion of exposed components/parts: the design of the WEC may include parts such as floaters (in the Wavestar), reflectors (in the Wave Dragon), etc. that may directly or indirectly interact with the fauna, i.e. since they are a directly exposed at the wave action, they may be broken and produce debris drifted in the sea;
- Noise/Vibration during operation: the type of power take off (for instance, turbines instead of electromagnetic PTO) and the relative movements of components may generate noise and vibration and affect birds, mammals, etc.;
- Aesthetic impact: submerged or floating devices that consist of parts with low crest freeboard do not affect the visual impact even when placed near-shore, on the contrary WECs with emerged components may be visible also when they are not installed on-shore;
- Maintenance: the environmental impact induced by maintenance operation can be assessed considering the following issues:
    - a- Transportation: the expected frequency of maintenance and therefore the effects induced by the dedicated boat trips;
    - b- Fouling: the required type of periodic treatments to keep fouling under control;
    - c- Material durability: the need of specific treatments and/or the impact of corroded and abraded material in the water.

3. Risks

- Geotechnical failure: fixed foundations can be unstable due to soil liquefaction; of course also anchors are exposed at this same risk, but since are multiple they lead to a lower risk of malfunctioning of the whole installation;

- Hazard for maritime activities: WECs that have emerged parts or that can produce debris may constitute an hazard for navigation;
- Moorings: the design of mooring systems is still one of the major technical challenges and many failures have been already reported for different WECs;
- PTO type: the risk of failure of PTO in some cases is documented, and is usually higher for turbines and hydraulic systems rather than electro-magnetic ones;
- Survivability mode: the chance to put the device in survivability mode significantly reduces some of the failure risks listed above (i.e. PTO, maritime activities, moorings); as a minimum the survivability mode consists of stopping the energy absorption and the power production during extreme storms, and may be substantially improved if the floating device is submerged during these storms, thanks to GPS controlled buoyant bodies;
- Modularity of the structure/s: devices that consist of modular structures (i) are usually less fragile than rigid structures, and (ii) thanks to the presence of many modules can at least partially assure the installation functionality.

4. Costs

- Installation depth: with increasing the installation depth, the device exposure to extreme wave loads increases and the distance of the device from the shore increases, therefore both installation and maintenance costs increase;
- Weight: the costs of the material can be considered proportional to the weight of the device and fixed components;
- Power take off:
  - a- Power take off type: hydraulic PTO systems have lower costs than innovative concepts;
  - b- Power transfer to shore: standing-alone solutions where the generated power is locally stored or used for other purposes are cheaper than transferring the power to shore, due to the cost of cables;
- Mechanical complexity of overall system: the costs can be reduced if the WEC is composed of simple and modular structures; it would be ideal if at least some of the components can be found in the market and do not have to be specifically designed and produced;
- Maintenance:
  - a- Offshore accessibility: an important factor to be considered is if maintenance can be performed with standard transports;
  - b- Cost-effective materials: durable materials require less frequent treatments or substitution and therefore are cheaper for maintenance purposes;
- Moorings: in case moorings are present, the cost is related to the type of mooring scheme, to the material of the mooring lines, to the installation depth and therefore mooring line length;
- Installation/maintenance methods requirements: installation/maintenance of devices placed on the sea bed and completely submerged requires higher costs than in case of floating WECs; WECs that require to be dismounted and maintained on-shore have also higher costs than WECs that may be maintained in-situ.

Identification of promising wave energy converters - Ranking (1-5, from best to worst)

											
Selection Criteria	**PELAMIS**	**OYSTER**	**WAVE STAR**	**WAVE DRAGON**	**DEXA WAVE**	**OPT POWERBUOY**	**DRAKOO**	**SEABASED**	**AWS - III**	**WAVEBOB**	**OE Buoy**
Maturity of Technology											
Have completed meaningful levels of power generation and hours, can therefore give credible capacity factor projections?	1.33	2.33	1.67	2.00	5.00	1.50	3.00	3.00	3.50	3.00	3.00
Reliability	2.00	2.67	2.00	2.33	3.67	2.00	3.00	3.00	3.00	3.00	2.50
Performance	2.33	3.67	2.00	2.67	4.00	2.50	2.50	3.50	3.50	3.00	3.00
Performed technology innovations for reduced cost of energy (different materials, device power capture improvements, minimizing loads, etc.)	2.67	2.67	2.33	3.33	2.67	3.00	3.50	3.00	2.50	3.50	4.00
TOTAL	**2.08**	**2.83**	**2.00**	**2.58**	**3.83**	**2.25**	**3.00**	**3.13**	**3.13**	**3.13**	**3.13**
Environmental impact											
Use of marine space:	2.00	3.67	3.33	4.33	1.67	2.50	2.00	1.00	3.00	1.50	2.00
Foundation type (moorings….fixed):	1.33	4.33	3.00	2.00	1.33	2.00	2.50	3.00	2.00	1.50	1.50
Materials (including need of toxic paintings):	3.67	3.67	2.67	3.67	2.33	3.50	3.50	2.00	4.00	3.50	4.00
Impacts on native habitats and species:	1.33	4.67	3.67	2.00	1.67	1.50	3.50	2.50	2.00	1.00	2.50
Impact on the coast:	1.33	3.33	2.67	2.00	1.33	1.50	3.50	2.00	2.50	1.50	2.00
Inclusion of exposed components/parts:	2.33	2.00	2.67	2.33	2.00	2.50	1.50	2.00	1.50	2.50	2.00
Noise/Vibration during operation:	2.00	3.00	3.33	3.67	2.00	2.50	3.50	2.00	2.50	3.00	3.50
Aesthetic impact:	2.00	1.67	3.67	2.33	2.67	2.50	4.50	2.00	1.00	2.00	2.00
Maintenance:	3.67	3.78	3.00	3.78	2.67	3.50	3.00	2.83	3.33	3.50	3.50
Transportation:	*3.67*	*4.33*	*3.00*	*4.00*	*2.67*	*4.00*	*1.50*	*3.00*	*4.00*	*4.00*	*3.00*
Fouling:	*3.33*	*3.67*	*3.00*	*3.67*	*3.00*	*2.50*	*3.50*	*2.00*	*2.50*	*2.50*	*3.50*
Material durability	*4.00*	*3.33*	*3.00*	*3.67*	*2.33*	*4.00*	*4.00*	*3.50*	*3.50*	*4.00*	*4.00*
TOTAL	**2.19**	**3.35**	**3.11**	**2.90**	**1.96**	**2.44**	**3.06**	**2.15**	**2.43**	**2.22**	**2.68**
Risks											
Geotechnical failure	2.00	3.00	4.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Hazard for maritime activities (submergence and debris)	2.00	1.00	3.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Moorings	4.00	1.00	1.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
PTO type	1.67	1.00	2.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Survivability mode	1.67	1.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Modularity of the structure/s	1.33	4.00	1.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
TOTAL	**2.11**	**1.83**	**2.00**	**3.33**	**3.33**	**3.33**	**3.33**	**3.33**	**3.33**	**3.33**	**3.33**
Costs											
Installation depth	3.33	2.00	3.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Weight (device and fixed components)	2.67	4.00	5.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
PTO	3.50	1.50	3.00	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
Power take off type:	*2.67*	*1.00*	*3.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*
Power transfer to shore	*4.33*	*2.00*	*3.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*
Mechanical complexity of overall system	3.00	3.00	2.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Maintenance	3.50	4.50	3.00	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
Offshore accesibility	*3.00*	*5.00*	*3.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*
Cost-effective materials (durability)	*4.00*	*4.00*	*3.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*	*5.00*
Moorings	4.00	1.00	1.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Installation/maintenance methods requirements	2.33	5.00	3.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
TOTAL	**3.19**	**3.00**	**2.86**	**4.14**	**4.14**	**4.14**	**4.14**	**4.14**	**4.14**	**4.14**	**4.14**

	PELAMIS	**OYSTER**	**WAVE STAR**	**WAVE DRAGON**	**DEXA WAVE**	**OPT POWERBUOY**	**DRAKOO**	**SEABASED**	**AWS - III**	**WAVEBOB**	**OE Buoy**
TOTAL SCORES	**9.57**	**11.01**	**9.97**	**12.96**	**13.27**	**12.17**	**13.53**	**12.75**	**13.03**	**12.82**	**13.28**

Table 7.1 - *Evaluation of selected WECs – Step 2 of the assessment methodology.*

7.2.3 Application of the procedure

It is worthy to remark that the procedure for WEC selection and the ranking obtained in table 7.1 do not consider any specific installation site but have been performed under the assumption of keeping constant the undefined location of installation.

In real conditions, the procedure has to be applied considering the local wave climate, the characteristics of the seabed, the bathymetry and therefore the average distance from shore, the preliminary design of the array (at least in terms of wave park area and expected energy production), the type of energy storage/transfer solution, etc. This will allow an objective selection of the preferred solution/s for a given area. Of course the ranking does not take into account the existing local regulations and laws that may possibly furthermore restrict the selected WECs.

7.3 Integration with other technologies

With solar, wind, and wave energy resources, many coastal areas of the world will be able to use resource diversity to reduce the variability of renewable power and lower the system integration costs of renewables. Before looking forward to where the offshore renewable energy sectors are heading in the future, it is important to consider where the sectors are now.

For the offshore wind sector, there is currently approximately 4GW installed capacity in Europe, and over 100GW in the planning pipeline for 2020. In comparison, for the ocean energy sector (wave and tidal stream), no commercial farm scale deployments currently exist, and the amount of capacity in the pipeline for Europe by 2020 is approximately 2GW. It is clear that the ocean energy sector is at an earlier stage of development than the offshore wind sector and a deployment timeline for the two sectors is shown in figure 7.1 (ORECCA, 2011).

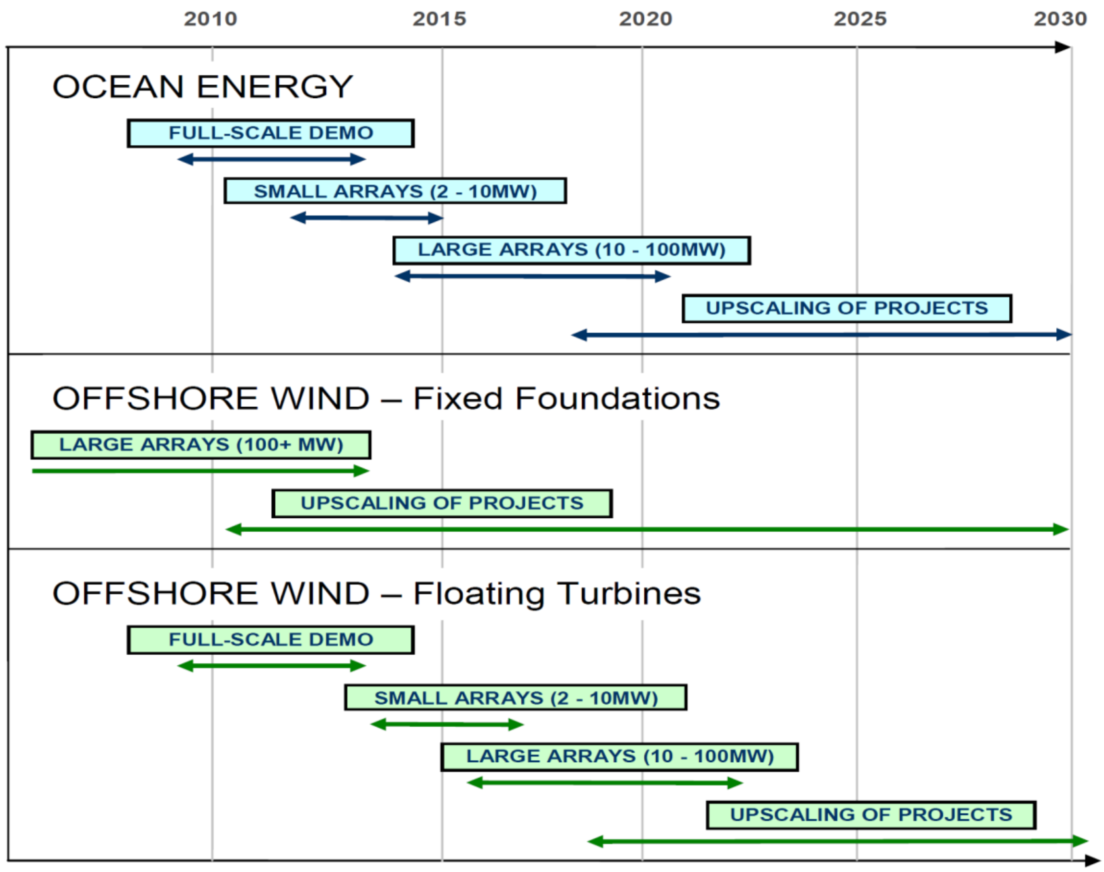


Figure 7.1 *- Projected deployment timelines for the ocean energy (wave and tidal stream) and offshore wind sectors. From ORECCA (2011).*

The following principal areas have been identified where immediate technical synergy opportunities exist among the offshore wind, wave and tidal energy sectors (ORECCA, 2011):

- Foundations: common foundation types to be used.
- Array layout: sharing of lessons learnt for effective array design.
- Mooring/fixed connection points: common mooring/fixed connection points to be used.
- Grid connection and integration.
- Power take off: common power take off technologies to be used.
- O&M: sharing of lessons learnt for effective design and technology development to reduce the need (and associated cost) for O&M (remote monitoring is a good example of this).

Combining renewable energy resources with low temporal correlations showed to

- reduce the aggregate power output variability of renewables (Wan et al., 2003),
- reduce the operational requirement for reserve and regulating power (Holttinen, 2005), and
- reduce the requirement for generation capacity to maintain power system reliability (Wangdee et al., 2006).

The areas where exploitable tidal resources exist are relatively limited in number but show high energy densities. Analysis revealed that tidal stream resources make the smallest contribution to the total offshore natural resource in Europe. Therefore, focusing on areas of wind and wave combined resource is the most important overlap among the three technologies in terms of exploiting combined resources.

A modeling study carried out by Stoutenburg et al. (2006) on the combination of wave and wind farms along the California coast showed that in this case:

- combined farms would provide a greater power capacity factor than farms exploiting waves only (see Fig. 6.2).
- combined farms would have less than 100 h of no power output per year, compared to over 1000 h for offshore wind or over 200 h for wave farms alone (see Fig.s 6.2 - 6.3).

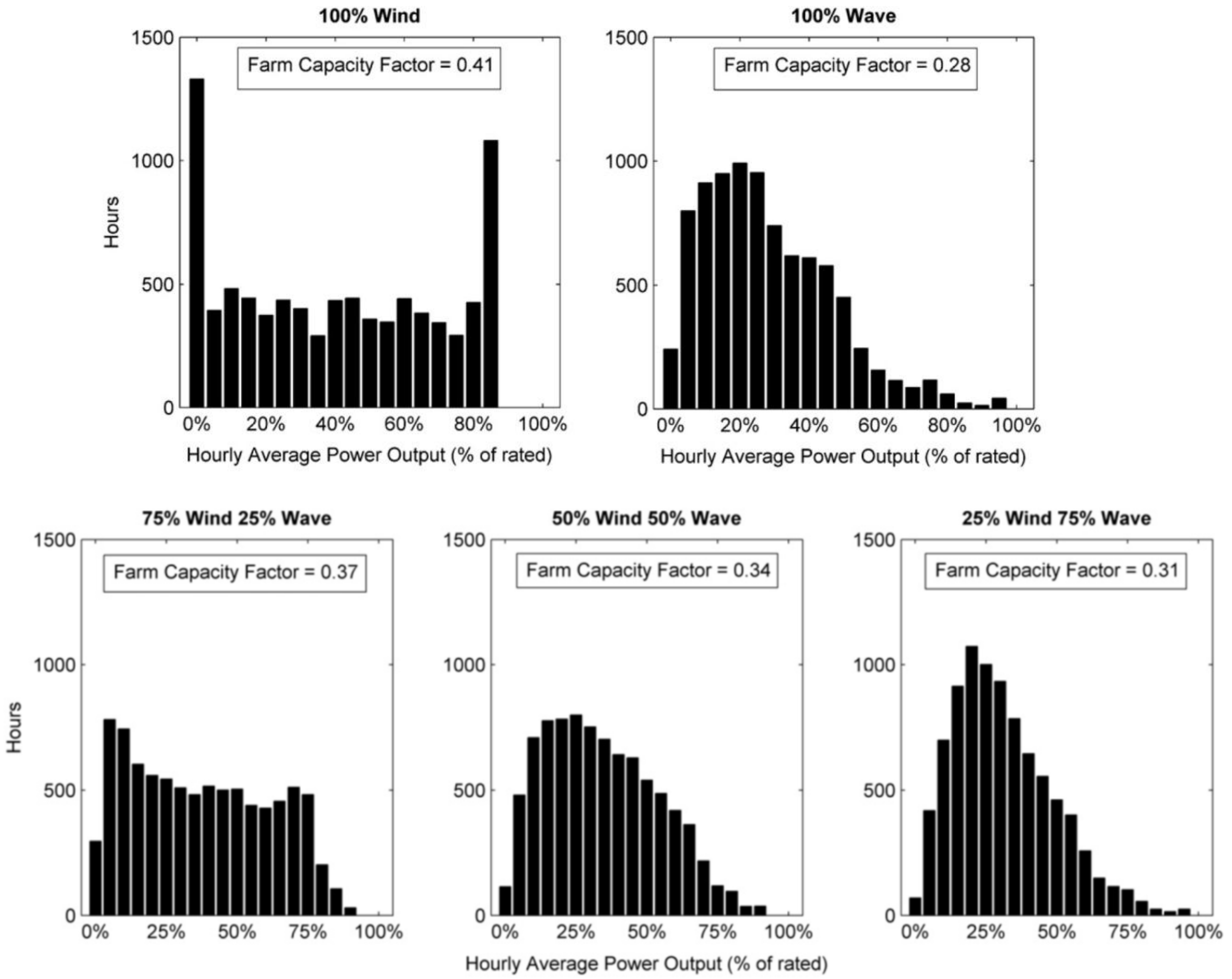


***Figure 7.2** – Histogram of hourly average power output as a percentage of rated power for a wind farm, a wave farm and three mixes of combined wind and wave energy farms at buoy 30 off Cape Mendocino (delivered power after losses). From Stoutenburg et al. (2006).*

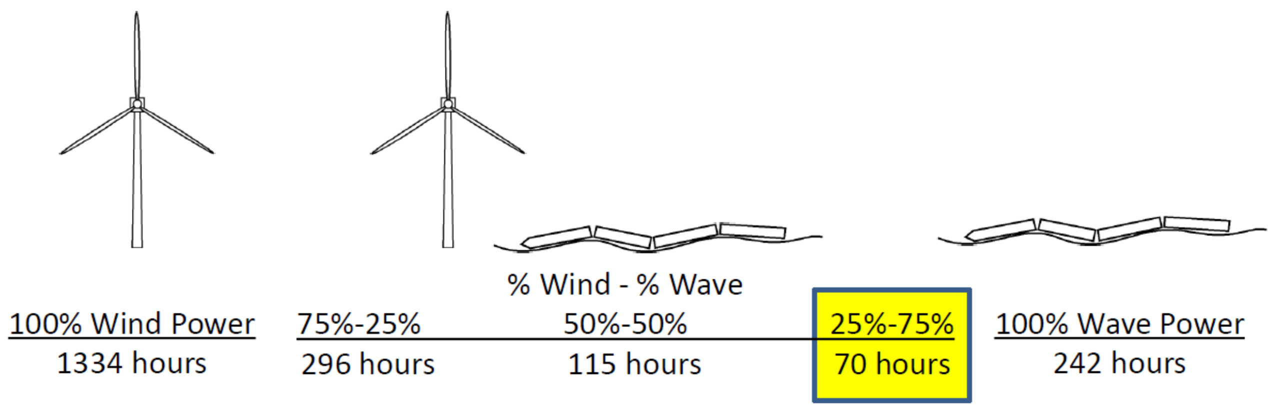


***Figure 7.3** – Number of no-power-output hours for different combinations of wind and wave farms along the California coastline. From Stoutenburg et al. (2006).*

8 Final remarks

This document provides a comprehensive overview of the present technology development level of WECs and of the many concepts available. The number of patents is continuously growing and therefore new emerging concepts might not have been included in this literature review.

The key main activities (ORECCA, 2011) identified to be the top priorities for the exploitation and commercialisation of WECs are

- 1st generation device and array trials;
- performance data collection;
- installation methods;
- recovery methods;
- cost effective O&M techniques;
- 2nd generation device development;
- control systems;
- energy conversion systems (PTO);
- foundations and mooring systems;
- wet HV connectors;
- performance guidelines/specifications;
- design of installation tools;
- device modelling tools;
- array design and modelling tools;
- resource analysis tools; and
- reliability modelling tools.

The high priority of so many technology related activities is illustrative of the fact that the wave energy sector is at an earlier stage of maturity than the offshore wind sector, no significant deployments beyond full scale prototype testing currently exist, and there is relatively little design consensus around the best technologies to move the sector forwards.

It is moreover desirable the development of synergies with other technologies for energy extraction and/or with other off-shore installations and activities, such as gas platforms, aquaculture, fish farms and transportation. Despite the current immaturity of combined platforms as a concept, co-location of devices can realise significant benefits with respect to infrastructure. The most attractive combined natural resource in existence in Europe is combined wind and wave resource, and this presents a large opportunity. There are two principal benefits of co-locating devices:

- joint utilisation of a single electrical infrastructure (which will allow cost reductions and smoothing of power output from the combined farm);
- potential joint utilisation of O&M teams, vessels and infrastructures.

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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*

Appendix A

Deliverable: D3.3.2	
Nature of the Deliverable:	Report
Due date of the Deliverable:	31.12.2013
Actual Submission Date:	
Dissemination Level:	Confidential
Contributors:	Kaan Koca, Andreas Kortenhaus, LWI
Work Task Leader Responsible:	Barbara Zanuttigh, **UNIBO**
Work Package Leader Responsible:	Inigo Losada, **UC**
Reviewed by:	-

Version	Date	Revised Pages	Description of Changes
1.0	17.12.2013	-	1st Draft released
1.1			
1.2			

Table of contents

11 Introduction

12 Wave energy converters

12.1 Methodology of collating WEC information

Various methods have been used to identify all relevant WECs currently under development.

These methods are (Fig. A.1):

- Review of the European Marine Energy Centre (EMEC) (http://www.emec.org.uk/marine-energy/wave-developers/) the US Department of Energy (DOE) (http://en.openei.org/wiki/Marine_and_Hydrokinetic_Technology_Database) and the International Energy Agency's Implementing agreement on Ocean Energy Systems (IEA-OES) (http://www.ocean-energy-systems.org/) websites.
- Review of each technology developer's websites.
- Review of other internet resources such as technology websites, energy news, and video sharing sites (e.g. YouTube, Vimeo, etc.)
- Review of the most recent (2009-2013) renewable energy related reports, journal papers and conference proceedings.

While reviewing these resources, so-called '*inactive criteria*' have been created. *Inactive criteria* are criteria which define a WEC to be no longer actively developed and consist of:

- WECs discontinued their development probably because of the technical and economical reasons.
- WECs whose websites have not been updated over the last three years.
- WECs that are at their first thinking stage and their proof of operation has yet to be proven.

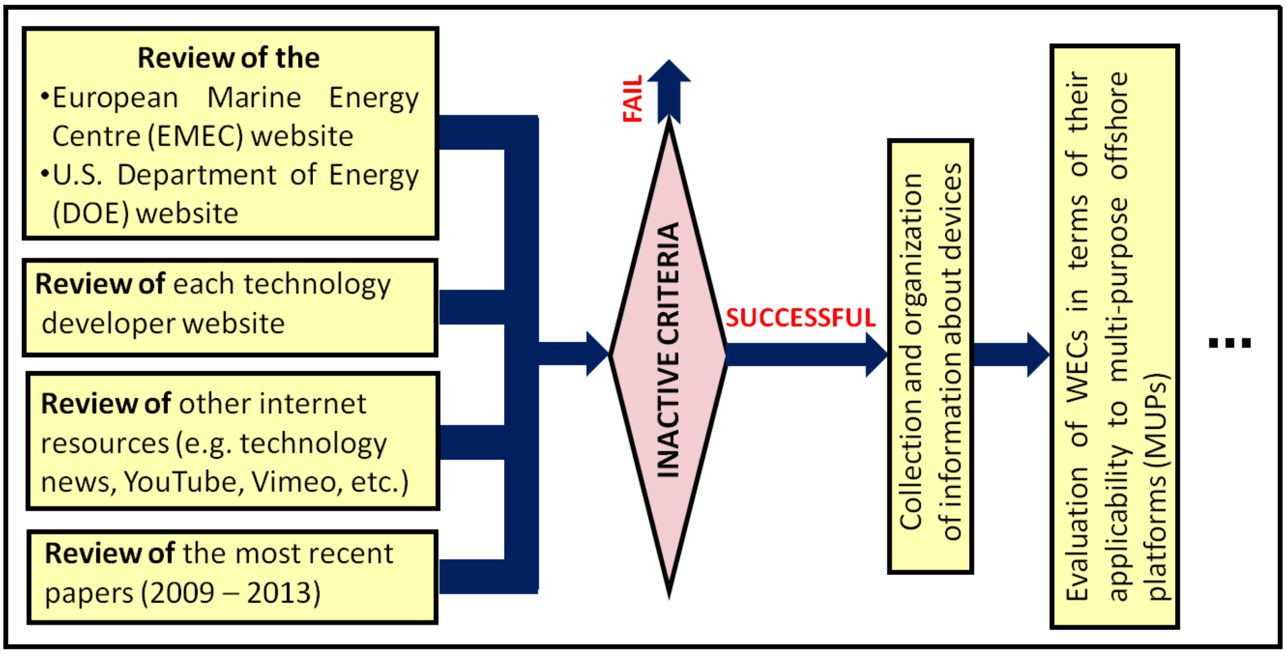


Fig. A. 1: Methodology of collating information

12.2 WEC project components

Ocean energy conversion devices possess many common sub-systems, even though individual WECs vary from developer to developer. Carbon Trust (2011) considered these common systems as: Structure and prime mover, foundations and moorings, Power take-off (PTO), Control, installation, connection, and operation and maintenance (O&M) (SI OCEAN, 2012).

Table A. 1 provides an overview of the key components and cost centres that need to be considered in wave energy projects. These components are also considered as the main components in which innovation should be done for the acceleration of marine energy.

Table A. 1: Key components and cost centres of WEC projects (Carbon Trust, 2011; SI OCEAN, 2012).

Component	Description
Structure and Prime Mover	The physical structure of the device which captures energy and the main interface between the resource and the PTO system. Even though steel is generally used, developers have drawn their attention to alternative materials in search of cost reductions. The Prime movers such as turbine blades are made of composite materials.
Support structures and moorings	Support structures and mooring are used to keep WECs in position. This includes pile-mounted or gravity base support structures and floating support structures which consist of slack or tight mooring systems. These topics are discussed in sections 5.1 and 5.2 of the main document.
Power take-off (PTO)	PTO systems are used to convert the mechanical energy extracted from the waves into a useful form, generally electricity. Several PTO system options exist including mechanical, hydraulic, or direct-drive permanent magnet generators. These are discussed in greater detail in Khan and Bhuyan (2009) and in Chapter 3 of the main document.
Control	Systems and software to safeguard the device and optimize the performance under a range of operating conditions. Control systems may adjust certain parameters of the device autonomously in order to ensure favourable operation.
Installation	The method of installing the structure and device at its power generating location. This includes all vessels and ancillary equipment needed to fully deploy and ocean energy device.
Connection	The cables and electrical infrastructure for connecting the power output from the device to the electricity network. In order to export the generated electricity to the grid, power conditioning systems and transformers will be needed, which provide a grid code compliant electrical output.
O&M	Periodic repair and reconditioning work will be required on all ocean energy devices. As well as the physical maintenance of mechanical and electrical components within the device, operation and maintenance will also have to consider access to the device, and device retrieval.

Following these definitions, a range of WEC technology types are discussed below which were used to collect information about the global WEC developments in section 2.4.

12.3 WEC technology types

Wave energy converters (WECs) can be classified in several ways: according to conversion principle, according to location, according to directional characteristics, and according to power take-off (PTO) system. However, classification is mostly done based on the conversion principle proposed by Falcão (2010), who categorize the devices into three main categories: oscillating water column, overtopping devices, and wave-activated bodies. Wave-activated bodies can be further divided into four sub-categories: heaving buoys, pitch/surge devices, surge/heave/pitch devices and yaw/heave devices. Fig. A.2 shows the motion of a wave activated body in six degrees of freedom.

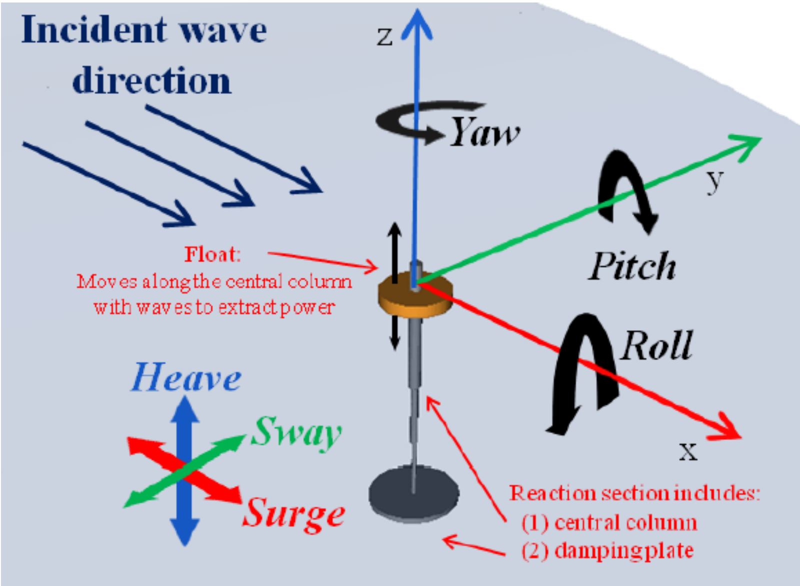


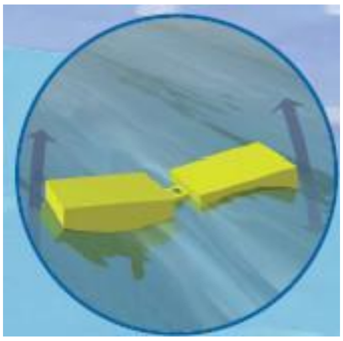
Fig. A. 2: Motion of a wave activated body in six degree of freedom (6DoF) (Li & Yu, 2012)

In this report, WECs are categorized according to EMEC (http://www.emec.org.uk/marine-energy/wave-devices/), where the following notation (Table 2) is used.

Table A. 2: Notation used for WEC types in this report.

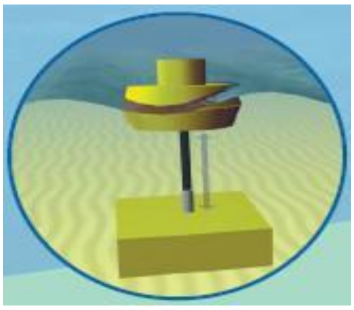
Type of device	Notation
Attenuator	1
Point absorber	2
Oscillating Wave Surge Converter (OWSC)	3
Oscillating Water Column	4
Overtopping/Terminator	5
Submerged pressure differential	6
Bulge wave	7
Rotating Mass	8
Other	9

12.3.1 **Attenuator (1)**



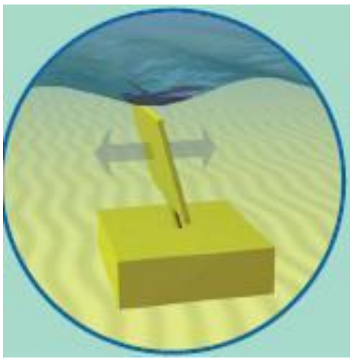
An attenuator is a floating device which operates parallel with predominant wave direction and rides the waves. These devices capture energy from the relative motion of the two arms as the wave passes them. An example of an attenuator is the Pelamis developed by Pelamis Wave Power.

12.3.2 **Point absorber (2)**



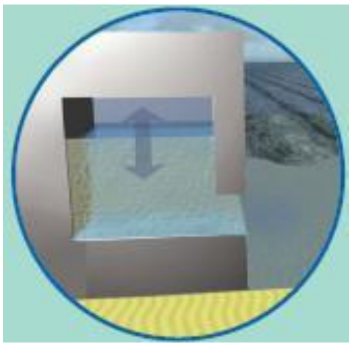
Point absorber is a wave energy device which has small dimensions compared to the incident wave length, and can absorb energy from all directions. It generally consists of two separate parts: a lower part which is attached to the seafloor, and a float which oscillates with the waves. The resultant relative motion between two parts is used to generate electricity via a PTO system. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors. An example of an point absorber is Powerbuoy developed by Ocean Power Technology.

12.3.3 **Oscillating Wave Surge Converter (OSWC) (3)**



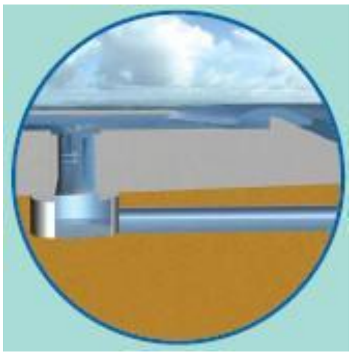
Oscillating wave surge converters exploits energy from wave surges and the movement of water particles within them. The arm oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves. These devices are designed to be deployed in shallower water to take advantage of the wave motion there. An example of this device is Oyster developed by AquaMarine Power.

12.3.4 **Oscillating Water Column (OWC) (4)**



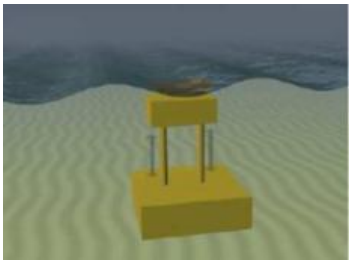
An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine is used to generate electricity. The turbine is designed so that the blades turn the same direction regardless of the air flow direction. An example of this device is GreenWave developed by Oceanlinx.

12.3.5 **Overtopping (5)**



Overtopping devices capture water as waves break into a storage reservoir. The water is then returned to the sea passing through a conventional low-head turbine which generates power. An overtopping device may use 'collectors' to concentrate the wave energy. An example of this device is Wave Dragon developed by Wave Dragon A/S.

12.3.6 **Submerged pressure differential (6)**

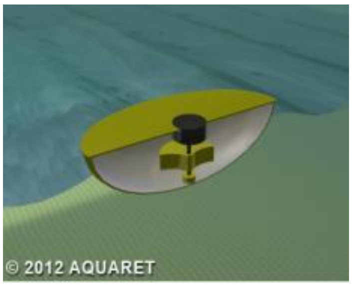


This is a submerged device typically located near shore and attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential which causes the device to rise and fall with the waves. An example of the submerged pressure differential device is Archimedes Wave Swing (AWS) developed by AWS Ocean Energy.

12.3.7 **Bulge Wave (7)**

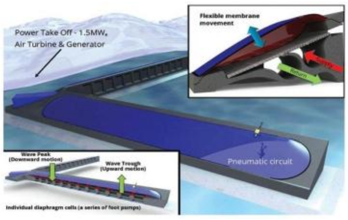
Bulge wave technology consists of a rubber tube filled with water, moored to the seabed heading into the waves. The water enters through the stern and the passing wave causes pressure variations along the length of the tube, creating a 'bulge'. As the bulge travels through the tube it grows, gathering energy which can be used to drive a standard low-head turbine located at the bow, where the water then returns to the sea. An example of this device is Anaconda developed by Checkmate Sea Energy UK Ltd.

12.3.8 **Rotating mass (8)**



Two forms of rotation are used to capture energy by the movement of the device heaving and swaying in the waves. This motion drives either an eccentric weight or a gyroscope causes precession. In both cases the movement is attached to an electric generator inside the device. An example of this device is Wello Penguin developed by Wello Ltd.

12.3.9 **Other (9)**



There are further devices with either a unique or different design as compared to the more established types of technology. An example of this device is Bombora developed by Bombora Wave Power. The Bombora device extracts energy by utilizing a low-cost, flexible membrane system. The membrane directly transfers the wave energy to pressurized air within the device.

12.4 List of global wave energy converter developments

Table 3 and Table 4 show the individual WEC developments around the world. Table 3 shows the types and development status of the WECs based on the explained types in section 2.3 and five-stage approach (see section 2.2.2 in the main document), respectively whilst Table 4 presents a brief overview of these devices.

Table A. 3: List of global WEC developments (as of 03.02.2013)

Item	Country	Company	Technology	Website	Contact	Type	Status
1	Australia	Oceanlinx	greenWave	http://www.oceanlinx.com	info@oceanlinx.com	4	4
2	Australia	Oceanlinx	BlueWave	http://www.oceanlinx.com	info@oceanlinx.com	4	4
3	Australia	Oceanlinx	OgWave	http://www.oceanlinx.com	info@oceanlinx.com	4	3
4	Australia	Biopowersystem	bioWave	http://www.biopowersystems.com/	http://www.biopowersystems.com/contact-us.html	3	3
5	Australia	Carnegie wave energy Limited	CETO	http://www.carnegiewave.com/	enquiries@carnegiewave.com	6	4
6	Australia	Wave Rider Energy	Wave Rider	http://www.waveriderenergy.com.au/	http://www.waveriderenergy.com.au/Contact_Us.html	2	3
7	Australia	Bomborawavepower	Bombora	http://www.bomborawavepower.com.au/	http://www.bomborawavepower.com.au/contact	9	1
8	Australia	Ocean Power Technologies Australasia	OPT Powerbuoy	http://optaustralasia.com.au/	info@optaustralasia.com.au	2	4
9	Australia	AquaGEN Technologies	SurgeDrive	http://www.aquagen.com.au/	info@aquagen.com.au	2	3
10	Australia	Protean Energy	Protean Energy Conversion Platform	http://www.proteanenergy.com/	http://www.proteanenergy.com/about-us/corporate-directory.html	2	3
11	Australia	Proteus Wave Power P/L	Proteus wave energy harvester	http://www.proteuswave.com/	info@proteuswave.com	1	3
12	Belgium	University of Ghent	FlanSea	http://www.ugent.be/en	fiers.hubert@deme.be	2	3
13	Belgium	Laminaria Bvba	Laminaria WEC	http://www.laminaria.be/	info@laminaria.be	9	1
14	Brazil	Seahorse Wave Energy	Coppe	http://seahorseenergy.com.br/	segen@lts.coppe.ufrj.br	2	3
15	Canada	Solar Inspired Energy Inc	SIE-CAT Wave Energy Accumulator	http://www.wave-energy-accumulator.com/	http://www.wave-energy-accumulator.com/index.php?option=com_contact&view=contact&id=2&Itemid=93	2	1
16	Canada/USA	WaveBerg Development Limited	Waveberg	http://waveberg.com/	http://waveberg.com/wavenergy/contact.htm	1	3
17	Canada	Seawood Designs Inc.	SurfPower	http://www.surfpower.ca/	**seawood@shaw.ca**	2	2
18	Canada	Wave Energy Technologies Inc.	WET EnGen	http://www.waveenergytech.com/wetEnGen.aspx	info@waveenergytech.com	2	3
19	Canada	Finavera AquaEnergy	AquaBuOY	http://finavera.com/	info@finavera.com	2	3
20	Chile	Etymol Wave Power	Etymol	http://www.etymol.com	contacto@etymol.com	9	1
21	China	Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences	Floating Duck WEC	http://english.giec.cas.cn	youyg@ms.giec.ac.cn	2	3
22	China	Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences	Sharp Eagle No.1	htp://english.giec.cas.cn	web@ms.giec.ac.cn	9	3
23	China	Motor Waves	Motor waves	http://www.motorwavegroup.com	gambarota@motorwavegroup.com	2	2
24	Denmark	Wave Dragon	Wave Dragon	www.wavedragon.net	hcs@wavedragon.net	5	3
25	Denmark	Waveplane A/S	Wave Plane	http://www.waveplane.com/	es@asolutioninvent.com	5	3
26	Denmark	WavePiston	Wave Piston	www.wavepiston.dk	http://www.wavepiston.dk/contact.html	1	2
27	Denmark	Wave Star Energy ApS	Wave Star	http://wavestarenergy.com/	lma@wavestarenergy.com	2	4

Item	Country	Company	Technology	Website	Contact	Type	Status
28	Denmark	WEPTOS A/S	WEPTOS	http://www.weptos.com/	weptos@weptos.com	9	2
29	Denmark	Leancon Wave Energy	Multi Absorbing Wave Energy Convertor (MAWEC)	http://www.leancon.com/	kdr@leancon.dk	4	3
30	Denmark	Floating Power Plant	Poseidon's Organ	http://www.floatingpowerplant.com/	info@floatingpowerplant.com	1	4
31	Denmark	DEXA WAVE Energy Aps	Dexa Wave Converter	http://www.dexawave.com/	info@dexawave.com	1	3
32	Denmark	Resen Energy	LOPF wave energy buoys	http://www.resenwaves.com	prs@resen.dk	2	2
33	Denmark	Waveenergyfyn	Crestwing	http://www.Waveenergyfyn.dk	crestwing@gmail.com	9	3
34	Finland	Wello Ltd.	Wello Penguin	http://www.wello.eu/	http://www.wello.eu/contact.php	8	4
35	Finland	AW-Energy Oy	WaveRoller	http://aw-energy.com/	info@aw-energy.com	3	4
36	France	Ecole Centrale de Nantes	SeaREV	http://www.ec-nantes.fr/	Alain.Clement@ec-nantes.fr	2	2
37	France	Hydrocap Energy	SeaCap	http://www.hydrocap.com/en	**seacap@hydrocap.com**	2	1
38	France	Kneider	Wave energy propulsion	http://kneider.voila.net/	kneider@yahoo.com	9	1
39	France	D2M	Bilboquet	http://www.polemerpaca.com/Ressources-energetiques-marines/Energies-marines-renouvelables/BILBOQUET /	dominique.kervazo@pole-mer-bretagne.com	2	No info
40	France	Saipem SA	Swell Barge	http://www.saipem-sa.com/	stephane.anres@saipem-sa.com	9	1
41	France	SBM Offshore	S3 Standing Wave Tube Electro Active Polymer	http://www.sbmoffshore.com/	Philippe.Jean@sbmoffshore.com	9	2
42	Germany	Nemos GmbH	Nemos	http://www.nemos.org/	info@nemos.org	2	1
43	Greece	Daedulus Informatics and technology partner	Wave Energy Conversion Activator (WECA)	http://www.daedalus.gr	daedalushq@mail.daedalus.gr	4	1
44	India	Gp. Capt. S.M Ghouse.	Free Floating Wave Energy Converter	http://www.linkedin.com/pub/gp-capt-sm-ghouse-retd/2b/19/5a2	pselvam@iitm.ac.in	1	1
45	Ireland	Sea Power Ltd.	Sea Power Platform	http://www.seapower.ie/	ben.wrafter@seapower.ie	1	2
46	Ireland	Jospa Ltd.	Irish Tube Compressor (ITC)	http://www.jospa.ie/	info@jospa.ie	9	1
47	Ireland	Limerick Wave Ltd	Limerick	http://www.limerickwave.com/	limerickwave@gmail.com	9	1
48	Ireland	Blue Power	No name yet	http://www.bluepower.ie/aboutus.html	damien.browne@bluepower.ie	2	1
49	Ireland	Ocean Energy Ltd.	OE Buoy	http://www.oceanenergy.ie/	info@oceanenergy.ie	4	3
50	Ireland	WaveBob	Wavebob	http://www.wavebob.com/	franc.mouwen@wavebob.com	1	3
51	Israel	S.D.E. Ltd	Sea Wave Power Plant	http://www.sde.co.il/	abe@shani.net.il	9	4
52	Israel	Eco Wave Power	Wave Clapper/Power wing	http://www.ecowavepower.com	info@ecowavepower.com	2	3
53	Italy	Politecnico di Torino		http://www.polito.it/?lang=en	giuliana.mattiazzo@polito.it	2	3
54	Italy	Wave Energy.it s.r.l.	REWEC3	www.wavenergy.it/	boccotti@unirc.it	4	3
55	Italy	WEMPower Engineering Office	Wave Energy Module-	http://www.wempower.it/	info@wempower.it	2	2

Item	Country	Company	Technology	Website	Contact	Type	Status
			WEM				
56	Japan	Nihon University Mitsubishi Heavy Toa Corporation Saga University	Multi-resonant OWC	http://www.engan.esst.kyushu-u.ac.jp/~JapanKorea/material/Nagata.pdf	ikoma.tomoki@nihon-u.ac.jp	4	1
57	Japan	Gyrodynamics Corporation Tottori University Hitachi Zosen Corporation	Wave power generation by using gyroscopic moment	http://www.tottori-u.ac.jp/dd.aspx?menuid=2828	h-kanki@gyrodynamic.co.jp	2	3
58	Japan	Mitsui Engineering & Shipbuilding Co. ltd. Power Buoy of Ocean Power Technologies Inc. University of Tokyo	Japanese type power buoy	http://phx.corporate-ir.net/phoenix.zhtml?c=155437&p=irol-newsArticle&ID=1747988&highlight	http://www.mes.co.jp/english/contact.html	2	2
59	Japan	Yamaguchi University CTI Engineering Co. Ltd	Float-counterweight type WEC	http://www.civil.yamaguchi-u.ac.jp/?page_id=1575&lang=en	taneura@ctie.co.jp	2	3
60	Japan	Nihon Univ. Wits, Chiba Science Institute	Improved buoy-mounted EPAM power	http://www.nihon-u.ac.jp/intldiv/en/	ikoma.tomoki@nihon-u.ac.jp	2	3
61	Japan	Kyushu University	MC-OWC	http://hyoka.ofc.kyushu-u.ac.jp/search/details/K001265/announceList.html	yasuzawa@nams.kyushu-u.ac.jp	4	1
62	Japan	Saga University Akishima Laboratories (Mitsui Zosen)	Backward Bent Duct Buoy	http://www.saga-u.ac.jp/english/	imai@ioes.saga-u.ac.jp	4	2
63	Japan	Saga University	FPWEC	http://www.saga-u.ac.jp/english/		3	2
64	Korea	KEPRI, MKE	Variable Liquid Column Oscillator	http://www.kepri.re.kr/	chobh@kepri.re.kr	1	2
65	Korea	MOREI, MLTM	Pendulum WEC	http://www.kiost.ac/kordi_web/main/main.jsp	imai@ioes.saga-u.ac.jp	3	2
66	Korea	Yonsei University MKE	AWS type with linear generator	http://www.yonsei.ac.kr/eng/	casfirsear@yonsei.ac.kr	6	2
67	Korea	Syarense Energy, MKE	WEC for horizontal wave force			3	1
68	Korea	KORDI, MLTM	Yongsoo OWC	www.kordi.re.kr	kyhong@moeri.re.kr	4	3
69	Korea	KMU, MKE	Cross-Flow Hydraulic Turbine	http://english.hhu.ac.kr/english/main/		5	No info
70	Korea	Gyeongju Univ., MKE	Resonant Vertical Oscillator	http://www.gju.ac.kr/english/index.jsp		2	No info
71	Netherland	OceanMill /formerly Ecofys	Wave Rotor	https://sites.google.com/site/oceanmilltest/	oceanmill@xs4all.nl	9	3
72	New Zealand-USA	Wave energy Technology	WET-NZ	http://www.wavenergy.co.nz/	enquiries@powerprojects.co.nz	2	3
73	Norway	Euro Wave Energy	Cape Verde	http://www.eurowaveenergy.com/	http://www.eurowaveenergy.com/contact/	2	Concept
74	Norway	Euro Wave Energy	Flexible drive line	http://www.eurowaveenergy.com/	http://www.eurowaveenergy.com/contact/	2	Concept
75	Norway	Euro Wave Energy	Vertical	http://www.eurowaveenergy.com/	http://www.eurowaveenergy.com/contact/	2	Concept

Item	Country	Company	Technology	Website	Contact	Type	Status
			running rod				
76	Norway	Intentium AS	OWEP/ Intentium	http://www.intentium.com/	http://www.intentium.com/contact/index.html	2	1
77	Norway-UK	Fred Olsen Ltd.	BOLT Lifesaver	http://www.boltwavepower.com/	http://www.boltwavepower.com/contact	2	3
78	Norway	Langlee Wave Power	Langle E1-E2	http://www.langlee.no	Julius@langlee.no	3	2
79	Norway	OWWE – INNOVAKO	OWWE-Rig	http://www.owwe.net/	http://www.owwe.net/?o=contact	5	1
80	Norway	OWWE – INNOVAKO	Wave Pump-Rig	http://www.owwe.net/	http://www.owwe.net/?o=contact	2	Concept
81	Norway	Pelagic Power AS	W2POWER	http://www.pelagicpower.no/	hanssen@1-tech.net	2	2
82	Norway	Pontoon Power AS	Pontoon power converter	http://www.pontoon.no/	http://www.pontoon.no/Contact.html	2	2
83	Norway	Purenco AS	Winch operated buoy	http://www.straumekraft.no/	gam@purenco.com	2	3
84	Norway	OWC Power AS	The OWC Power	http://www.owcpower.com/	anders.torud@straumgroup.com	4	1
85	Norway	Wave Energy AS	Seawave slot-cone generator	http://www.waveenergy.no/	monika.bakke@waveenergy.no	5	2
86	Portugal	Kymaner	Kymaner OWC	http://www.kymaner.com/	info@kymaner.com	4	2
87	Portugal	WavEC	PICO OWC	http://www.pico-owc.net/	mail@wavec.org	4	4
88	Portugal	Sea for life Lda.	Wave Energy Gravitational Absorber – WEGA	http://www.seaforlife.com/	seaforlife@seaforlife.com	2	1
89	Portugal	ReefPower Energy	SPIDER RP05	http://en.reefpower.com.pt/	geral@reefpower.com.pt	2	1
90	Russia	Applied Technologies Company Ltd (ATC)	Float Wave Electric Power Station (FWEPS)	http://www.atecom.ru/	atecom@atecom.ru	9	2
91	Singapore	Hann-Ocean	Drakoo	http://www.hann-ocean.com/	http://www.hann-ocean.com/contact-us/	4	3
92	South Africa	Stellenbosch University	Stellenbosch Wave Energy Converter (ShoreSWEC)	http://www.crses.sun.ac.za/	wikus@sun.ac.za	4	1
93	Spain	Hidroflot S.A. Ocean Electric Inc.	Hidroflot	http://www.hidroflot.com/	hidroflot@hidroflot.com	2	2
94	Spain	OCEANTEC Energias Marinas S.L.	Oceantech	http://www.oceantecenergy.com/	bdemiguel@oceantecenergy.com	1	3
95	Spain	PIPO systems SL	APC-PISYS	http://www.piposystems.com/	info@piposystems.com	2	3
96	Spain	Abencis Seapower	Marine pump	http://www.abencis.com/energia-marina.php	http://www.abencis.com/contacto.php	9	3
97	Spain	GM Renovables	(J+B) 2B wave	http://gmrenovables.com/	info@gmrenovables.com	9	3
98	Spain	EVE – Ente Vasco de la Energia	Mutriku OWC plant	http://www.eve.es/index.aspx	http://www.eve.es/Contacto.aspx	4	5
99	Spain	Sendekia S.L.	SDK Wave turbine	http://www.sdkmarine.com/	info@sendekia.com	4	1
100	Spain	University of Santiago de Compostela	WaveCat	http://www.usc.es/en/index.html	gregorio.iglesias@usc.es	5	1
101	Sweden	CorPower Ocean AB	Corpower	http://www.corpowerocean.com/	patrik@corpowerocean.com	2	1
102	Sweden	Ocean Harvesting Technologies AB	Ocean Harvester	www.oceanharvesting.com	mikael.sidenmark@oceanharvesting.com	2	2
103	Sweden	Waves4Power	WaveEL	http://www.waves4power.com/	http://www.waves4power.com/contact/	2	3
104	Sweden	Seabased AB	Seabased	http://www.seabased.com/index.php?Itemid=56	info@seabased.com	2	4
105	Sweden	Vigor Wave Energy	Vigor	http://www.vigorwaveenergy.com/	http://www.vigorwaveenergy.com/contact	7	2

Item	Country	Company	Technology	Website	Contact	Type	Status
		AB					
106	Turkey	Avium A.Ş.	Yeti Cluster system	http://www.avium.com.tr/	info@avium.com.tr	9	3
107	UK	AlbaTERN Ltd.	SQUID	http://albatern.co.uk/	info@albatern.co.uk	2	3
108	UK	Wavewinder	Wave Winder	http://www.wavewinder.co.uk/	http://www.wavewinder.co.uk/contact_wavewinder_renewable_energy_investment_partner_opportunity	9	1
109	UK	Aquamarine Power	Oyster 800	http://www.aquamarinepower.com/	martin.mcadam@aquamanriepower.com	3	4
110	UK	AWS Ocean Energy	Archimedes Wave Swing (AWS- III)	http://www.awsocean.com/	info@awsocean.com	6	3
111	UK	Checkmate Sea Energy UK Ltd.	Anaconda	http://www.checkmateseaenergy.com/	http://www.checkmateseaenergy.com/contact/	7	2
112	UK	Seatricity Ltd	Seatricity	http://www.seatricity.net/	http://www.seatricity.net/content/contacts	2	4
113	UK	Ecotricity Group Limited	Searaser	http://www.ecotricity.co.uk/	home@ecotricity.co.uk	2	3
114	UK	Ecotricity Group Limited	Snapper	http://www.ecotricity.co.uk/	paul.mckeever@narec.co.uk	2	2
115	UK	Trident Energy	Powerpod	http://www.tridentenergy.co.uk/	http://www.tridentenergy.co.uk/contact/	2	2
116	UK	Sperboy /Embley Energy	Sperboy	http://www.sperboy.com/	info@sperboy.com	4	3
117	UK	Green Ocean Energy Ltd.	Wave Treader / Ocean Treader	http://www.greenoceanenergy.com/	info@greenoceanenergy.com	1	2
118	UK	Ocean Navitas	Aegir Dynamo	http://www.ntu.ac.uk/	business.info@ntu.ac.uk	2	1
119	UK	Offshore Wave Energy Ltd.	OWEL	http://www.owel.co.uk/	nminns@owel.co.uk	9	2
120	UK	Voith Hydro Wavegen Ltd.	Limpet OWC	http://www.wavegen.co.uk/	t.whittaker@qub.ac.uk	4	4
121	UK	Pelamis Wave Power	Pelamis	http://www.pelamiswave.com/	http://www.pelamiswave.com/contact-us	1	5?
122	UK	Nodding Beam Ltd.	Nodding Beam = Power	http://www.noddingbeam.com/	info@noddingbeam.com	9	Concept
123	UK	Lancaster University	Wraspa	http://www.engineering.lancs.ac.uk/	g.aggidis@lancaster.ac.uk	3	2
124	USA	Atargis Energy Corporation	Cycloidal Wave Energy Converter	www.atargis.com/	http://www.atargis.com/Contact_Us.php/	9	2
125	USA	Atmocean, Inc.	OHS	http://www.atmocean.com/	atmocean.information@gmail.com	2	3
126	USA	Ocean Energy Industries. Inc.	WaveSurfer	http://www.oceanenergyindustries.com	info@oceanenergyindustries.com	2	4??
127	USA	OWECO Ocean Wave Energy Company	OWEC – Ocean Wave Energy Converter	http://www.owec.com	foerd@owec.com	2	2
128	USA	Resolute Marine Energy, Inc.	SurgeWEC	www.resolutemarine.com	contactus@resolutemarine.com	3	3
129	USA	AeroVironment (INC)	Sub Surface Wave Buoy	http://www.avinc.com/engineering/marine_energy/	zambranot@avinc.com	6	3
130	USA	Independent Natural Resources	Seadog Pump	http://inri.us/	seadog@inri.us	2	3
131	USA	Ocean Energy Ltd.	Wave Catcher	http://www.offshoreislandslimited.com	sales@offshoreislandslimited.com	9	No info
132	USA	Sara Ltd	MWEC	http://www.sara.com/	http://www.sara.com/SARA/contact_sara.html	2	1
133	USA	Able Technologies L.L.C.	Electricity generating wave pipe EGWaP	http://www.abletechnologiesllc.com/	srutta@yahoo.com	2	1
134	USA	Colombia Power Technologies	SeaRay	http://www.columbiapwr.com/	info@columbiapwr.com	2	3

Item	Country	Company	Technology	Website	Contact	Type	Status
135	USA	Steven Institute of Technology Seahorse Power LLC	Wave Energy Harvesting Device (WEHD)	http://www.stevens.edu/seahorsepower/index.html	mraftery@stevens.edu	2	1
136	USA	SRI International	ETWAM	http://www.sri.com/	roy.kornbluh@sri.com	2	3
137	USA	Ecomerit Technologies	Centipod	http://www.ecomerittech.com/	wfegarsky@ecomerittech.com	2	concept
138	USA	Floating Inc.	OOES's Rho-Cee	www.floatinc.org/	projects1@floatinc.com	4	2
139	USA	Kinetic Wave Power	PowerGin	http://www.kineticwavepower.com/	info@kineticwavepower.com	5	2
140	USA	Spindrift Energy	Spindrift	http://www.spindriftenergy.com/	http://www.spindriftenergy.com/get-in-touch.html	2	2
141	USA	Neptune Wave Power	Model 3.0/3.1	http://www.neptunewavepower.com/	http://www.neptunewavepower.com/index.php/contact/	2	3
142	USA	M3Wave Energy Systems LLC	DMP	http://www.m3wave.com/	mike@m3wave.com	6	1
143	USA	Navatak Ltd.	Navatek	http://www.navatekltd.com/	schmicker@navatekltd.com	2	1
144	USA	Aqua Magnetics Inc.	Ocean Swell Wave Energy Conversion - OSWEC	www.amioceanpower.com	jrick@amioceanpower.com	2	1
145	USA	Ocean Motion International	OMI Combined energy system	http://www.oceanmotion.ws/	omi4us@aol.com	2	1
146	USA	Grays Harbor Ocean Energy	Titan Platform	http://www.graysharboroceanenergy.com/	http://www.graysharboroceanenergy.com/contact.htm	4	1
147	USA	Green Wave Energy Corp.	Bottom wave generator	http://greenwaveenergycorp.com/	info@greenwaveenergycorp.com	2	3

Table A. 4: Global wave energy converter developments

Nr.	**Company**	**Technology**	**Description**	**Resources**
1	Oceanlinx	greenWave	The greenWAVE device is a single oscillating water column that has been designed specifically for shallow water application. It is made from steel reinforced concrete and located in approximately 10m of water and then mounted onto the seabed. The top of the device also extends above sea level. This is where the AirWave turbine and electrical control systems are housed. The only moving part of the device is the airWAVE turbine which is stationed out of harm's way above the waterline.	http://www.oceanlinx.com/technology/products/greenwave http://phys.org/news/2013-11-oceanlinx-celebrates-wave-power-australia.html
2	Oceanlinx	BlueWave	The blueWAVE device is a cluster of 6 oscillating water columns that has been designed specifically for deep water application. It is an anchored floating device fabricated from steel and is deployed in approximately 40-80m of water. The top of each of the 6 devices also extends above sea level. This is where the airWAVE turbine and electrical control systems are housed. The only moving part of the device is the airWAVE turbine which is stationed out of harm's way above the waterline. The unit can be dedicated to the production of electricity, desalinated seawater, or both. Additionally it can be incorporated in a sea wall or breakwater structure which in turn can further reduce the cost of the unit.	http://www.oceanlinx.com/technology/products/bluewave

3	Oceanlinx	OgWave	The OgWAVE is a special application of Oceanlinx technology, capable of connecting with oil and gas platforms, as well as installations in more remote areas. It is an anchored floating device made from steel and is located in approximately 40-80m. It is capable of connecting with oil and gas platforms as well as installations in more remote areas. The unit can be dedicated to the production of electricity, desalinated seawater, or both.	http://www.oceanlinx.com/technology/products/ogwave-2
4	Biopower system	bioWave	The bioWAVETM is mounted on the seafloor, with a pivot near the bottom. The array of buoyant floats, or "blades", interacts with the rising and falling sea surface (potential energy) and the sub-surface back-and-forth water movement (kinetic energy). As a result, the pivoting structure sways back-and-forth in tune with the waves, and the energy contained in this motion is converted to electricity by an onboard self-contained power conversion module, called O-DriveTM. The O-DriveTM contains a hydraulic system that converts the mechanical energy from this motion into fluid pressure, which is used to spin a generator. Power is then delivered to shore by a subsea cable.	http://www.biopowersystems.com/
5	Carnegie wave energy Limited	CETO	CETO is a fully submerged wave driven pump based technology. The Buoyant Actuator is attached to the pump via a tether, and the entire system is moored to the seabed. The Buoyant Actuators movements in harmony with the motion of the passing waves, drives the pumps which in turn pressurise water that is delivered ashore via a subsea pipeline. On shore the high pressure fluid then powers an “off the shelf” turbine, producing zero-emission, 100% renewable electricity. The high-pressure water can also be used to supply a reverse osmosis desalination plant, replacing greenhouse gas emitting electrically driven pumps usually required for such plants.	http://www.sut.org.au/perth/perth_events/sut_carnegie_evening%20141009.pdf; http://www.carnegiewave.com/files/reports/2011/06_CETO_Development_Pathway.pdf

6	Wave Rider Energy	Wave Rider	The Wave Rider is made up of an open steel truss with numerous buoyancy pontoons that keeps the structure afloat. Along the length of the structure, a series of below surface buoys are fitted that move up and down as a wave passes. This movement causes the rotation of an axle on top of the structure that is connected via a chain system, which in turn drives various generators that convert the mechanical energy into electrical energy.	http://www.waveriderenergy.com.au/
7	Bombora wavepower	Bombora	Bombora's device operates much like a series of foot pumps, pressurising air into a common manifold system to a drive turbine and generator. As the wave passes over the device, it impresses upon the membrane (and individual diaphragm cells underneath) to create a sequence of positive system pressures in areas under the wave peak and negative system pressures in areas below the wave trough. These positive and negative pressures provide a pressure differential across the turbine and ultimately generate flow around the close loop circuit following a 'source and sink' principle. Check valves are introduced between the diaphragm cells to control the flow in one direction.	http://www.bomborawavepower.com.au/
8	Ocean Power Technologies Australasia	OPT Powerbuoy	OPT's PowerBuoy wave generation system uses a "smart," oceangoing buoy to capture and convert wave energy into low-cost, clean electricity. The rising and falling of the waves offshore causes the buoy to move freely up and down. The resultant mechanical stroking is converted via a sophisticated power take-off to drive an electrical generator. The generated wave power is transmitted ashore via an underwater power cable.	http://www.oceanpowertechnologies.com/PDF/OPT_Mark%203_Sept2013.pdf http://www.oceanpowertechnologies.com/PDF/Reedsport%20OPT_Newsletter_Sep_2011.pdf

9	AquaGEN Technologies	SurgeDrive	SurgeDrive is an innovative wave power technology which harnesses the energy of ocean waves to produce electricity or desalinated water. As waves pass the buoyancy units of a SurgeDrive® wave farm, they move in oscillation and the system transfers the pure wave forces out of the water, via tension transfer elements. From there, the energy conversion module is able to use these forces to generate electricity or desalinated water, using an innovative mixture of design and 'off the shelf' components. This dramatically simplifies the capture of wave energy because most components are above water and underwater components are minimised and simplified. This leads to a significant reduction in capital expenditure (less expensive, corrosion resistant materials required), maintenance whilst also enabling the flexibility for the system to not only survive storms but to continue to generate during them.	http://www.aquagen.com.au/
10	Protean Energy	Protean Energy Conversion Platform	In brief the Protean technology comprises a large surface located buoy, approximately 15-feet wide, complementary to this surface buoy is a subsea weight used in mooring and energy conversion. The surface buoy is connected with multiple cables to the subsea weight and seafloor mooring. The wave energy conversion is done inside the surface buoy through a simple, robust and effective mechanical system which converts the movement of the surface buoy directly into a usable form, such as electricity or desalinated water. Protean™ Wave Energy technology – a modular system that has at its core a wave energy converter with the capacity to integrate further modules such as wind energy and desalination.	http://www.proteanenergy.com/
11	Proteus Wave Power P/L	Proteus wave energy harvester	The platform for the superior technology is an articulating pontoon device that is robust enough to withstand the extremely harsh environment of the ocean. Units consist of long, curved floating pontoon structures.	http://www.proteuswave.com/

12	University of Ghent	FlanSea	The FlanSea wave energy converter is based on the so-called "point absorber" technology. These point absorbers keep track of and react in synchronization with wave motions, whereby their movements relative to the seafloor as a fixed point of reference can be converted to electrical power. The generator will be mounted on/inside the buoy itself. Moreover, inside the buoy there is a winch with a cable wind around it. The other, far end, of the cable is fixed into the seafloor. The buoy will use the rising and falling motions of the waves to wind or unwind the cable on the winch, thus producing electrical power. FlanSea is specifically designed for low to moderate wave climate conditions found on sheltered seas,	http://www.flansea.eu/ http://www.flansea.ugent.be/12-Powerpoint%20Persmoment%2023april2013.pdf http://www.flansea.ugent.be/10-Press%20Release%20Wave%20Pioneer.pdf http://www.belspo.be/belspo/ssd/science/Reports/BOREAS%20Finaal_rapport_ML.pdf
13	Laminaria Bvba	Laminaria WEC	The Laminaria constitutes a vertical surface which must interact with the horizontally travelling wave energy. As a result, the upper section will move more than the lower one, creating a change angle between the two sections. This changing angle is used to extract energy from the waves.	http://www.laminaria.be/
14	Seahorse Wave Energy	Coppe	The project calls for the construction of 20 modules, with a capacity of generating 500 KW. In this first stage two modules of the wave energy plant have already been installed. The two modules are composed of large mechanical arms. At the tip of each arm, there is a float in contact with the sea. As waves hit the floats, the structure (mechanical arms and floats) rise and lower. The continuous movement of the floats and arms activate hydraulic pumps, which propels sweet water enclosed in a closed circuit (with no contact with the environment), to circulate in a high pressure environment. This sweet water under pressure goes to an accumulator, which in turn has water and air compressed in a hyperbaric chamber (which is the main component of the system). From the Hyperbaric chamber an extremely narrow conductor (like a venture channel), makes the water reach high pressures, which is then expelled in a water jet equivalent to a 500 meter waterfall similar to a big hydroelectric dam. This water jet moves a hydraulic turbine, which is connected to a generator, which in turn produces electric energy.	http://seahorseenergy.com.br/

15	Solar Inspired Energy Inc	SIE-CAT Wave Energy Accumulator	Ocean swell and wave energy is captured by using ocean surface buoys connected to pistons within cylinders which are secured to the ocean floor. The air is compressed within the cylinders and then recompressed in series stages of other buoys and cylinders to create a reservoir storage tank of very high pressure compressed air. The high pressure compressed air can be stored indefinitely and used to operate pneumatic motors and/or actuators to propel machinery which require large amounts of energy to operate.	http://www.wave-energy-accumulator.com/
16	WaveBerg Development Limited	Waveberg	Waveberg is an asymmetrical series of hinged floats driving pumps, which pressurize seawater for delivery to shore via flexible pipes. The overall triangular shape in plan view assures each portion of the device receives fresh wave crest.	http://waveberg.com/
17	Seawood Designs Inc.	SurfPower	A patented near-shore wave energy conversion system with unique buoyant wings each coupled to a seawater pump that anchors the assembly to the seabed. The long aYesis of the pontoon automatically aligns itself with the crest of oncoming waves, irrespective of the wave direction. The seawater piston pump is unlike any other in that it discharges pressurized seawater through a hollow rod to a collection main located on the sea bed. The buoyant wings are actively controlled responding to changing sea conditions on a wave by wave basis. Pressurized seawater delivered by a number of buoyant wings is collected by a seabed main and delivered onshore to operate a conventional pelton turbine generator set delivering electrical energy directly to the grid.	http://www.surfpower.ca/
18	Wave Energy Technologies Inc.	WET EnGen	The system's main feature is its "Smart Float", the float moves up and down a rigid spar witch is at a 45° incline. The float is connected to a synthetic cable witch drives a shaft via a capstan. The rotational energy of the shaft can be used to generate electricity through a generator or to drive a high pressure pump in order to desalinate water.The spar is moored at a single point; this allows it to align itself with the incoming waves.	http://www.waveenergytech.com/wetEnGen.aspx

19	Finavera AquaEnergy	AquaBuOY	The AquaBuoy uses a cylindrical buoy as a displacer within which the impulse turbine and generator is housed. The reactor is a water mass underneath the buoy which is enclosed by a long vertical cylinder. A large neutrally buoyant disk inside the cylinder is used to drive the house pump (A hose pump is a soft rubber tube with a spiral steel cord inside the tube wall, If the tube is stretched the cord contracts the tube, thereby decreasing it's inside volume.). As the passing waves causes the device to move up and down the disk stays relatively still, this cases the upper or lower pipe respectively to stretch (thereby decreasing its displacement volume) thereby pumping the water into a high pressure accumulator. The water is fed from the accumulator to a turbine that in turn drives a generator. The electricity will be fed to shore through a cable.	http://finavera.com/
20	Etymol Wave Power	Etymol	Each ETYMOL converter has several opening and closing gates, which produce a water flow that enters into a high pressure chamber through the open gates toward a low pressure chamber where the water flow goes out across the output gates. This flow is used to move a marine turbine which is connected to a compressor that feeds a pneumatic accumulator to store the energy produced. This energy storage as pressurized air in this component drives a synchronous turbo generator that provides electrical power to the grid.	http://www.etymol.com/010_DOCUMENTOS/ETYMOL%20Brochure%202013%20-%20English.pdf
21	Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences	Floating Duck WEC	This 100KW Floating Buoy Duck WEC applies the multi-level hydraulic power generation system, which enables the WEC to operate under different wave conditions. Specifically speaking, the WEC contains two sets of engine sets, the 30KW engine and 70KW engine, both of which will choose to operate or not based on the wave size. The 30KW engine sets starts to work in small waves, while the 70KW ones in medium waves, and the 100KW with two sets working together in strong waves. This equipment is conducive to lowering costs and raising convectoring efficiency, which contributes to further development of wave energy.	http://english.giec.cas.cn http://english.giec.cas.cn/rh/rp/201304/t20130428_101448.html
22	Guangzhou Institute of Energy	Sharp Eagle No.1	The light wave energy absorber was specially designed, with its motion track mostly matching that of wave, thus absorbing the incident wave to the maximum while	http://english.giec.cas.cn http://english.giec.cas.cn/rh/rp/201301/t20130110_97942.html

	Conversion, Chinese Academy of Sciences		reducing the reflected wave to the minimum. Based on intensive research programme, it was decided that the equipment that would be put on sea would combine the light wave energy absorber and sub-merged ship.	
23	Motor Waves	Motor waves	MotorWave is composed of modules made of 2 floats. The up and down are transferred to a central shaft that combines energy of all modules. Transformation is made by hydraulic converting into compressed air.	http://www.motorwavegroup.com
24	Wave Dragon	Wave Dragon	The Wave Dragon is a floating slack-moored wave energy converter of the overtopping type. It basically consists of two wave reflectors focusing the waves towards a ramp. Behind the ramp there is a large reservoir where the water that runs up the ramp is collected and temporarily stored. The water leaves the reservoir through hydro turbines that utilise the head between the level of the reservoir and the sea level.	http://www.icoe2012dublin.com/ICOE_2012/downloads/papers/day1/1.1%20Wave%20Energy%20Convertors/Erik%20Friis-Madsen%20-%20WaveDragon.pdf http://www.wavedragon.net/index.php?option=com_content&task=view&id=4&Itemid=35
25	Waveplane A/S	Wave Plane	The WavePlane is an overtopping device. The V-shaped artificial beach is designed to slow the bottom of the wave down and thus making them break and overtop into the device reservoir.	http://www.waveplane.com/
26	WavePiston	Wave Piston	The WavePiston concept comprises an elongated floating structure whereupon horizontally moving vertical wings are mounted. Due to the horizontal component of the 2D water movement the vertical wings are forced to move, thus enabling eYestraction of energy. In the real system the power take-off system is envisioned to be hydraulic, using the surrounding sea water as the medium.	www.wavepiston.dk
27	Wave Star Energy ApS	Wave Star	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. Waves run the length of the machine, lifting 20 floats in turn. Powering the motor and generator in this way enables continuous energy production and a smooth output.	http://wavestarenergy.com/concept http://vbn.aau.dk/files/55762154/Performance_Evaluation_of_the_Wavestar_Prototype.pdf

28	WEPTOS A/S	WEPTOS	WEPTOS employs a well-known and effective method in order to extract wave energy in a completely new and innovative manner. Through its floating angular construction, the wave energy converter is able to regulate the wave energy input and reduce the impact during rough weather conditions. The V-shaped structure absorbs the wave energy through a line of rotors, which each of them transmits the energy to a common axle, directly attached to a generator. This way, an even energy generation throughout the wave duration follows, enabling for other known generator solutions to be applied.	http://www.weptos.com/wp-content/uploads/2012/07/OMAE2012-83751-WEPTOS-Paper.pdf; http://vbn.aau.dk/files/70080263/Performance_Evaluation_of_Wave_Energy_Converters.pdf
29	Leancon Wave Energy	Multi Absorbing Wave Energy Convertor (MAWEC)	LEANCON Wave Energy has developed a new Multi Absorbing Wave Energy Converter (MAWEC) which differentiates from other known wave energy converters (WEC) in the world, as it uses the suck forces to be held down. Hereby it can be made with low weight which reduces the material costs. The WEC is an off shore OWC type that preferably uses a special designed displacement turbine as power take off (PTO), but a traditional air turbine can also be used.	http://www.leancon.com/
30	Floating Power Plant	Poseidon's Organ	Poseidon's floating hybrid energy system - for deep sea deployment - is based on a wave energy plant that serves as a floating platform for offshore wind turbines. Poseidon utilizes and absorbs the energy from the waves, reducing the height of the waves and creating calm waters behind the front of the plant, making the platform easily accessible (acting as a floating breakwater)	http://www.floatingpowerplant.com/
31	DEXA WAVE Energy Aps	DEXA Wave Converter	The DEXA converter is inspired by the wave extraction system as developed and [patented] in 1980 by the famous inventor Sir Christopher Cockerell. The Cockerell Raft consisted of two buoyant pontoons, hinged together, and dampened with a hydraulic power take-off system. DEXA reconfigured and simplified the basic construction of the Cockerell Raft, and only adopted the use of two pontoons and a hydraulic system. The two floaters are ideally distant 1/2 wavelength.	http://www.dexawave.com/converters.html http://www.sciencedirect.com/science/article/pii/S0378383912001809 http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/258.pdf

32	Resen Energy	LOPF wave energy buoys	The wave energy buoy is patented and is a very simple device: that is, a horseshoe shaped float with a lever in the centre section that is anchored to the ocean floor. It activates as a wave lifts or pushes the buoy. The end of the lever that is anchored to the ocean floor cannot move up as waves lift the buoy, causing a gearboxes and generator, fastened on the lever, to activate as the buoy moves up and the other end of the lever, which is fixed to the seabed, remains at a fixed elevation. The gearboxes and generator are integrated within the hinge in the buoy.	http://www.resenwaves.com
33	Waveenergyfyn	Crestwing	The Crestwing operates on the surface of the ocean and has two pontoons which are fixed with hinges and the mechanical power take-off system is located above the hinge (PTO). During the up and down movement of the pontoons the potential atmospheric pressure will be utilized through the PTO system which generates electricity by a generator.	http://www.Waveenergyfyn.dk
34	Wello Ltd.	Wello Penguin	The Wello Penguin is fully sealed floating generator platform with all moving parts inside the platform. The Penguin vessels float on water and capture kinetic energy, which is then directly turned into electrical power. The Penguin is designed to be simple, reliable and extremely durable in order to withstand the harsh conditions of the ocean environment. The outer structure is made of tough, recyclable materials.	http://www.wello.eu/index.php; http://www.vegvesen.no/_attachment/329472/binary/575592
35	AW-Energy Oy	WaveRoller	WaveRoller is a device that converts ocean waves to energy and electricity. As the WaveRoller unit (panel) moves and absorbs the energy from ocean waves, the hydraulic piston pumps attached to the panel pump the hydraulic fluids inside a closed hydraulic circuit. All the elements of the hydraulic circuit are enclosed inside a hermetic structure inside the device and are not exposed to the marine environment. To maximize the energy that WaveRoller panel can absorb from the waves, the device is installed under water at depths of approximately 8 – 20 meters, where the wave surge is most powerful. The panel spans almost the entire depth of the water column from the sea bed without breaking the surface. This ensures that the panel does not protrude onto the seascape and prevents the creation of material inefficiencies that would put additional load on the structure.	http://aw-energy.com/

36	Ecole Centrale de Nantes	SeaREV	The SEAREV wave energy converter is a floating device enclosing a heavy horizontal axis wheel serving as an internal gravity reference. The centre of gravity of the wheel being off-centered, this component behaves mechanically like a pendulum. The rotational motion of this pendular wheel relative to the hull activates an hydraulic Power Take Off (PTO) which, in turn, set an electric generator into motion.	http://192.107.92.31/test/owemes/29.pdf
37	Hydrocap Energy	SeaCap	Seacap is a wave energy converter combined with a fixed platform; it is composed of oscillating buoys guided around fixed poles embedded to the seafloor. The energy capture developed by the alternative heave vertical displacement is done in both directions.	http://www.hydrocap.com/en
38	Kneider	Wave energy propulsion	With inspiration from pursuing wave propulsion came from observing powered flight, the developer has designed a wave energy propulsion technology in which the forward motion of the engine is converted to vertical lift by the airfoil shape of the wings plus, during takeoff, the added topside curve of downward-tilted flaps . This converts forward motion to vertical lift. Designer set out to reverse the principle by converting vertical motion to horizontal push.	http://kneider.voila.net/ http://energiesdelamer.blogspot.de/2008/08/un-procd-de-propulsion-navale-nergie.html http://pesn.com/2005/09/21/9600154_Kneider_Wave_Energy/
39	D2M	Bilboquet		http://www.polemerpaca.com/Ressources-energetiques-marines/Energies-marines-renouvelables/BILBOQUET /
40	Saipem SA	Swell Barge	Swell Barge is a large scale barge equipped with several underwater resonators whose number and locations are optimized according to the site conditions. This innovative wave energy converter has been invented and specifically developed for deepwater applications in order to generate several MWs depending on the wave conditions. The system is passive with a large response spectrum. It is simple, robust and easy to maintain with conventional offshore means. The dimensions of the barge can be adapted to both directional and non-directional wave conditions.	http://www.saipem-sa.com/ http://www.onepetro.org/mslib/servlet/onepetropreview?id=OTC-23253-MS
41	SBM Offshore	S3 Standing Wave Tube Electro Active	Floating under the ocean surface, the S3 amplifies pressure waves similarly to a Ruben's tube. Only made of elastomers, the system is entirely flexible, environmentally friendly and silent. Thanks to a multimodal resonant behavior, the S3 is capable of efficiently harvesting wave	http://www.sbmoffshore.com/ http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1312500

		Polymer	energy from a wide range of wave periods, naturally smoothing the irregularities of ocean wave amplitudes and periods. In the S3 system, Electro Active Polymer (EAP) generators are distributed along an elastomeric tube over several wave lengths, they convert wave induced deformations directly into electricity. The output is high voltage multiphase Direct Current with low ripple.	
42	Nemos GmbH	Nemos	The NEMOS-system consists of an elongated floating body which is braced by three cables to the ocean floor. It is excited by the movement of waves and transmits mechanical energy by cable to a generator, which is positioned protected from sea water at the tower of a wind turbine. New to Peckolt´s development primarily are the trajectory of the floating body (different arcs) and the control strategy. Due to that up to 80% of the incoming wave energy can be used to drive electric generators. Conventional systems with vertical movement only are well below 50% efficency. With a change in the wave direction the orientation of the body also changes by a self-employed patented system. For protection from extreme wave loads in heavy storms, the system can be lowered to a depth of calmer water.	http://www.nemos.org/ http://www.ijern.com/images/February-2013/24.pdf http://www.youtube.com/watch?v=MENEAaedw9E
43	Daedulus Informatics and technology partner	Wave Energy Conversion Activator (WECA)	The original full-scale model WECA design proposed is made of steel, so as to be suitable for mounting on the run up wall of breakwaters or other rigid or floating structures. It serves the purpose of absorbing most of the energy of the impacting waves and turn it into compressed air (subsequently converted into electric power or other form of work).Emphasis is given to the development dynamics concerning the behaviour of a hydrodynamic phenomenon, resembling a virtual “Wedge” of kinetic energy rushing into the WECA’s interior chamber. The codename nomenclature used for this phenomenon is C.M.W. (Critical Momentum Wedge principle).	http://www.daedalus.gr http://www.daedalus.gr/jsauxilpublic/Wave%20Energy%20Technology%20-%20The%20WECA%20Device%20%28full%29.pdf
44	Gp. Capt. S.M Ghouse.	Free Floating Wave Energy Converter	The Free Floating Wave Energy Converter (FFWEC) concept consists of an ‘Inlet’ with a hollow flexible pipe attached to it, and an ‘Outlet, or coupling at its tail end. The device floats on the ocean surface, adapting to the waveform, generally facing towards the oncoming waves and it is suitably moored. The ‘Inlet’ is a rigid pipe attached to one or more number of buoys. It ingests ‘slugs’	http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6058258&tag=1

			of air and water sequentially, synchronous with the waves. The air and water slugs get trapped in the crests and troughs respectively. The wave propagation pushes the slugs of air and water through the length of the "Flexible pipe". The flexible pipe behaves as a 'U' tube manometer creates a continuous flow and pressure of air and water. The developed pressure could be utilized to drive conventional generators on the shore.	
45	Sea Power Ltd.	Sea Power Platform	The **Sea Power Platform** Wave Conversion Device consists of a floating central inertial body about which are fitted power-producing floating bodies connected to the central body via the power take-off and damping system. The device consists of 2 pontoons- the Main pontoon and the Forward pontoon. The pontoon floats are manufactured in concrete and are thus very low cost.	http://www.seapower.ie/ http://www.seapower.ie/our-technology/
46	Jospa Ltd.	Irish Tube Compressor (ITC)	The concept uses slugs of air and water in a tube to generate electricity from waves. Starting energy is continuously needed to bring the water slugs up to the necessary speed to enter the tube. Jospa's analogy is to consider a surfer. If he/she is travelling at a speed close to that of the wave, the surfer will 'catch the wave' and be carried forward. But if the speed is insufficient the wave will simply sweep by. The electrical induction motor is another analogy. It must run just slightly slower than the electromagnetic waves in the windings to apply power.	http://www.jospa.ie/ http://www.jospa.ie/early-tests.html
47	Limerick Wave Ltd	Limerick	This technology puts mechanical reciprocating motion into a flywheel which is used to turn the rotor in a generator and produce electricity.	http://www.limerickwave.com/ http://www.youtube.com/watch?v=uz9fadpr7to
48	Blue Power	No specific name found	The process involves converting the linear heaving motion of a wave energy buoy into rotational kinetic energy using our innovative linear/rotary gear box. The gear box drives a flywheel which then drives a standard Permanent Magnet electric generator.	http://www.bluepower.ie/aboutus.html
49	Ocean Energy Ltd.	OE Buoy	The buoy uses the oscillating wave coulomb principal to generate electricity. The up and down motion caused by the passing waves forces the air; that is trapped inside the chambers; to drive turbines (Self rectifying turbines are used in order to harness the up and down motion of the waves; these turbines will spin in one direction no matter what direction the air flows). The turbines are connected to generators in order to generate	http://www.oceanenergy.ie/oe-technology/platform.html http://www.westwave.ie/wp-content/uploads/downloads/2011/12/WestWave-Supply-Chain-Report-Rev5.pdf

			electricity.	
50	WaveBob	Wavebob	The Wavebob is an axi-symmetric, self-reacting point absorber, primarily operating in the heave mode. It is specifically designed to recover useful power from ocean wave energy, and to be deployed in large arrays offshore. It incorporates a number of highly innovative features, protected by a series of World patents that have been assigned to the Company. A full-scale, pre-commercial, grid-connected Wavebob WEC will be deployed off the coast of Portugal.	http://www.westwave.ie/wp-content/uploads/downloads/2011/12/WestWave-Supply-Chain-Report-Rev5.pdf http://www.wavebob.com/
51	S.D.E. Ltd	Sea Wave Power Plant	Buoyant metal plates are attached to a wall (it can for instance be attached to a breakwater). These plates use the up and down motion of the swell to drive hydraulic rams. The high pressure oil is used to drive hydraulic motors, the motors in turn drives generators in order to generate electricity.	http://www.sde.co.il/ http://en.wikipedia.org/wiki/SDE_Sea_Waves_Power_Plant
52	Eco Wave Power	Wave Clapper/Power wing	The EWP convertors draw energy from wave power throughout uniquely shaped buoys, "The Wave Clapper" and the "Power Wing" that rise and fall with the up and down motion, lifting force, change of water level, hydraulic air lock, and incident flux of waves. The motion of the floats is then delivered to shore by a subsea cable. The Shore- located, machinery room"/hydro pneumatic system (located on land, just like a regular power station), converts the energy from this motion into fluid pressure, which is used to spin a generator, producing electricity.	http://www.ecowavepower.com/technology/the-solution/ http://www.youtube.com/watch?v=TUE2ycjHk94
53	Politecnico di Torino	ISWEC	ISWEC is a gyroscopic energy conversion device, floating on a hull designed ad-hoc to guarantee stability and an optimum synchronization to the wave length of the installation site.	http://www.waveforenergy.com/index.php?option=com_content&view=article&id=8&Itemid=141 http://www.youtube.com/watch?v=P9xgSTK-1cw
54	Wave Energy.it s.r.l.	REWEC3	A Resonant Wave Energy converter (REWEC3, called also U-OWC, or J-OWC) is an advanced device to produce electrical power from ocean waves. It belongs to the family of Oscillating Water Colums (OWC) devices and it has the	http://www.owemes.org/owemesphp/documents/marexmed/OWC-Mediterranean%20Sea.pdf http://www.wavenergy.it/documents/leaflet_weavenergy%20GB.pdf

			dramatic advantage to obtain an impressive natural resonance without any further device for phase control	https://www.see.ed.ac.uk/~shs/Wave%20Energy/EWTEC%202009/EWTEC%202009%20%28D%29/papers/181.pdf
55	WEMPoWer Engineering Office	Wave Energy Module-WEM	**WEM** (Wave Energy Module), protected by international patent, is a modular system that was designed to extract energy from the waves of the sea. Each module has a central steel structure with arms to which six floating devices of 1.000 kg each (they are partially filled with water) are attached. Together, they form a **spider-like structure**. Inside the central structure, there is a 7 nominal kilowatt generator. The structure is placed at a mid-sea level (taking the tides into account) and attached (or anchored) to the bottom of the sea as to ensure resistance against currents or storms. The floating devices transfer their energy to a device found within the central structure during the descending phase of the waves and through the arms. At this point, the device transmits impulses to a generator, thus producing **electrical energy**.	http://www.wempower.it/en/wem-wave-energy/
56	Nihon University, Mitsubishi Heavy, Tao Corporation, Saga University	Multi-resonant OWC (PW-OWC)	An artificial harbor surrounded by projecting walls is installed. The type is called as PW-OWC in this paper. Standing waves occur in the artificial harbor, the absorbing device consequently has a resonance frequency differing from that of OWC. From the effect, the system is able to absorb wave power in very wide range of the wave frequency.	http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1786711 http://www.mhi.co.jp/en/technology/review/pdf/494/494052.pdf
57	Gyrodynamics Corporation, Tottori University Hitachi Zosen Corporation	Wave power generation by using gyroscopic moment	This gyroscopic wave power generation system is a pure rotational mechanical system that does not use conventional air turbines, and is housed on a unique floating platform ("float"). In particular, its outstanding feature is that it utilizes the gyroscopic (spinning) effect. A motor is used to turn a 1-meter -diameter steel disc ("flywheel") inside the apparatus, and when the rolling action of waves against the float tilts it at an angle, the gyroscopic effect causes the disc to rotate longitudinally. This energy turns a generator and produce electricity.	http://www.youtube.com/watch?v=czs6MXQGop4 https://www.see.ed.ac.uk/~shs/Wave%20Energy/EWTEC%202009/EWTEC%202009%20%28D%29/papers/159.pdf http://www.osaka.cci.or.jp/gcp/e/list/pdf/e_gyrodynamics.pdf http://e-book.lib.sjtu.edu.cn/isope2010/data/papers/10YK-02Nagata.pdf
58	Mitsui Engineering & Shipbuilding Co. ltd.	Japanese type power buoy	The system will be an adaption of the OPT Buoy technology to Japanese wave conditions. It is expected that many enhancements to the system will be made, and the device will be commercial in Japan.	http://phx.corporate-ir.net/phoenix.zhtml?c=155437&p=irol-newsArticle&ID=1747988&highlight

	Power Buoy of Ocean Power Technologies Inc. University of Tokyo			
59	Yamaguchi University, CTI Engineering Co. Ltd	Float-counterweight type WEC	This device mainly consists of a float, counterweight, and cable, driving pulley, ratchet, gearbox and generator. The mechanism of energy transfer is basically the conversion of the heaving of the float mass into a rotational motion of the shaft connected to the electric generator. The ratchet mechanism converts the bi-directional rotation of the driving pulley into a unidirectional rotation of the shaft which is then accelerated by gearbox.	http://www.civil.yamaguchi-u.ac.jp/?page_id=1575&lang=en http://e-book.lib.sjtu.edu.cn/isope2010/data/papers/10YK-02Nagata.pdf
60	Nihon Univ. Wits, Chiba Science Institute	Improved buoy-mounted EPAM power	The system is improved version of the EPAM technology which has been developed by SRI International company.	http://www.nihon-u.ac.jp/intldiv/en/ http://juser.fz-juelich.de/record/135442/files/HP3a_pp_Chi_Chiba.pdf
61	Kyushu University	MC-OWC		http://hyoka.ofc.kyushu-u.ac.jp/search/details/K001265/announceList.html
62	Saga University, Akishima Laboratories (Mitsui Zosen)	Backward Bent Duct Buoy	A BBDB consists of an L-shaped duct, a buoyancy module, an air chamber, a turbine and a generator. Water comes into the duct through a rear opening and pushes the air in the air chamber. This high-pressure air turns a turbine, generating electricity.	http://www.saga-u.ac.jp/english/ http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/159.pdf http://www.ioes.saga-u.ac.jp/archive/15-6.pdf
63	Saga University	FPWEC	FPWEC is a floating type pendulum wave energy converter with a rotary vane pump as the power take-off system.	http://www.saga-u.ac.jp/english/ http://www.isope.org/publications/proceedings/ISOPE/ISOPE%202011/data/papers/11YK-03Toyota.pdf http://www.isope.org/publications/proceedings/ISOPE/ISOPE%202013/papers/vol1/13TU-01Toyota.pdf http://kaken.nii.ac.jp/pdf/2011/seika/C-19/17201/21560834seika.pdf

64	KEPRI, MKE	Variable Liquid Column Oscillator	A variable liquid column oscillator using wave energy comprises: a variable liquid column body having a U-shaped tube comprising a horizontal tube and vertical tubes communicating with each other through the horizontal tube, and air chambers connected to the vertical tubes, the air chambers being isolated from each other about an isolation plate; an air tube to connect the air chambers to each other; control valves mounted on the air tube; pressure transformers connected to the air chambers, respectively, and a level transformer connected to one of the vertical tubes; and a controller to which the control valves, the pressure transformers, and the level transformer are connected.	http://www.kepri.re.kr/ http://www.isope.org/publications/proceedings/isope/isope%202010/data/papers/10SWH-07Yang.pdf http://www.google.com/patents/US20110031747
65	MOREI, MLTM	Pendulum WEC		http://www.kiost.ac/kordi_web/main/main.jsp
66	Yonsei University , MKE	AWS type with linear generator		http://www.yonsei.ac.kr/eng/
67	Syarense Energy, MKE	WEC for horizontal wave force		
68	KORDI, MLTM	Yongsoo OWC		www.kordi.re.kr
69	KMU, MKE	Cross-Flow Hydraulic Turbine		http://english.hhu.ac.kr/english/main/ http://www.pivlab.net/upload_file/Korea%20Perspective.pdf
70	Gyeongju Univ., MKE	Resonant Vertical Oscillator		http://www.gju.ac.kr/english/index.jsp

71	OceanMill /formerly Ecofys	Wave Rotor	The Wave Rotor Turbine has ingeniously combined two different turbine types on a single axis of rotation. The Wave Rotor is able to convert not only tidal current power, but also wave power into a rotation of vertical axis of the turbine. The latter is possible because waves are made up of circulating water particles. In order to tap the kinetic energy in waves, the following two rotors are combined: a Darrieus rotor with more or less vertical (or slanted) rotor blades and a Wells rotor which has horizontal radial blades.	https://sites.google.com/site/oceanmilltest/
72	Wave energy Technolog y	WET-NZ	The WET-NZ device is a point absorber that has been designed to eYestract as much energy as possible from all types of motion. The device is floating but the majority of it is submerged so that as much of it as possible interacts directly with the passing waves. There are three main components: (i) the power pod, which contains all of the power conversion equipment, (ii) The hull, which is flooded with seawater to add mass to the system, and (iii) The float, which pivots about a single axle between the hull and the power pod at the waterline. Because of its mass, the hull does not move vertically to track the wave profile, but can still capture surge and pitch motions. This allows the float to be excited by both vertical and horizontal motions of the waves and to rotate about the pivot, thereby creating relative motion between the two parts. By opposing this differential movement, work can be done and energy extracted	http://www.wavenergy.co.nz/ http://www.youtube.com/watch?v=397QGcRIqLY http://mhk.pnnl.gov/wiki/index.php/Wave_Energy_Technology_NZ
73	Euro Wave Energy	Cape Verde	The Cape Verde-version (floating absorber) is inspired by Cape Verde, where such an installation might be highly valuable (e.g. to power desalination plants). It is best suited for areas with minor, local electricity needs. No more information.	http://www.eurowaveenergy.com/ http://www.eurowaveenergy.com/working-principle/ http://www.eurowaveenergy.com/cape-verde-version/
74	Euro Wave Energy	Flexible drive line	The purpose of this model (floating absorber) is to make a smaller version of the other two versions. Hence, the use of a running rod became impractical. This version is highly flexible and is best suited for small and medium-sized devices. The main module can be placed subsea or onshore. No more information.	http://www.eurowaveenergy.com/ http://www.eurowaveenergy.com/working-principle/ http://www.eurowaveenergy.com/flexible-drive-line/
75	Euro Wave Energy	Vertical running rod	The patent with vertical running rod (floating absorber) is best suited for large installations and can be used with one or two absorbers. The version with two absorbers, which is	http://www.eurowaveenergy.com/ http://www.eurowaveenergy.com/working-principle/ http://www.eurowaveenergy.com/vertical-running-rod-2/

			shown in the animation, is best suited for areas where the waves move in the same direction over larger periods	
76	Intentium AS	IOWEP	The **IOWEP concept** is characterized by a long float moored to a front buoy and stabilized with its longest side normal to the incoming and dominant wave front. The float is further connected to a double-acting water pump with a buoyancy controlled water anchor, attached at the lower end. The full scale PTO has analogy with hydro power, and consists of accumulator, water turbine and generator.	http://www.intentium.com/ http://www.youtube.com/watch?v=fq3aLbpxYCU http://www.fp7-marinet.eu/access_user-projects_OWEP.htm http://www.proexca.es/Portals/0/Documents/Informacion/OtrasPonencias/Noruega/Intentium.pdf l
77	Fred Olsen Ltd.	BOLT Lifesaver	Lifesaver" is a point absorber WEC, capturing the energy of waves and converting it into clean, sustainable electricity, and features: (i) Up to five independently operating power take-off units (PTO), each moored independently to the sea bed. Each PTO has an installed (nameplate) capacity of 80 kW. (ii) An all electric power conversion system (iii) A patented drive train solution. BOLT technology is a wave energy converter (WEC) designed to produce electric power at a cost that is competitive to power produced by offshore wind installations. The design philosophy behind BOLT is reducing the cost of material, construction, installation and maintenance associated with WECs. The key technology driver: to energy BOLT for the most frequent sea states and designed to survive the more challenging ones.	http://www.boltwavepower.com/ http://www.youtube.com/watch?v=ZWa-Te7oxgI http://www.all-energy.co.uk/__novadocuments/30236?v=635059632173100000 http://www.mdpi.com/2076-3417/3/2/420
78	Langlee Wave Power	Langle E1-E2	Langle wave energy converter is a floating steel structure with lightweight wings that swing with the waves and generate power which is sent to the grid by an electric cable. A unique mooring design based on tried and tested fish farming technology allows easy installation, whether for a single unit or linked array which can provide several megawatts of wave power.	http://www.langlee.no http://www.youtube.com/watch?v=qSQ5t8I9kro http://vbn.aau.dk/files/70080263/Performance_Evaluation_of_Wave_Energy_Converters.pdf http://www.isope.org/publications/proceedings/isope/isope%202010/data/papers/10JPK-01Pecher.pdf
79	OWWE – INNOVAKO	OWWE-Rig	The main structure is a float with several basins. The float can be trimmed and the height above sea desired the water pressure at the turbines. OWWE-Rig is an overtopping technology as Wave Dragon. It can be equipped with hinged walls to make it more efficient. OWWE-Rig is constructed as a hybrid wind and wave energy converter. A 1:20 scale model was made in 2005. In search of funding the company participates at conferences.	http://www.owwe.net/

80	OWWE – INNOVAKO	Wave Pump-Rig	It uses the technology developed by Floating Inc, called Pneumatically Stabilized Platform. All cylinders are open to the sea and when air moves freely from cylinder to cylinder only the wave pump take energy from the waves.	http://www.owwe.net/
81	Pelagic Power AS	W2POWER	W2Power is the first practical solution for combined extraction of Wind & Wave energy off-shore. It combines state-of-the-art offshore wind turbines and an innovative, robust wave energy conversion technology on a single, light-weight floating platform. W2Power is designed from first principles as a true hybrid wind & wave energy conversion plant. Two corners of the triangle support one wind turbine each. The third corner houses the power take-off for the patented wave energy conversion system, using a conventional Pelton turbine driven by three lines of wave-actuated hydraulic pumps mounted on the platform's sides.	http://www.pelagicpower.no/ http://www.youtube.com/watch?v=Nym7_EIKSq8
82	Pontoon Power AS	Pontoon power converter	The Pontoon Power Converter (PPC) is a floating wave energy converter based on working pontoons, hydraulic pumping cylinders, hydroelectric turbine and generator mounted on a patent pending ballasting and load-bearing structure, with slack moorings suitable for a wide range of water depths and many offshore locations.	http://www.pontoon.no/ http://www.youtube.com/watch?v=OkpCDJSmPIM http://www.youtube.com/watch?v=Ca0GOMigZZI http://www.cdti.es/recursos/doc/eventosCDTI/Seminario%20hispanonoruego%2012%20abril%202012/Presentaciones/38517_2342342012113644.pdf
83	Purenco AS	Winch operated buoy	A design of a winch based wave energy absorbing buoy, where a self-tightening winch, mounted on or otherwise connected to the buoy, serves as anchoring system, and at the same time provide energy absorption. The system also comprises an overload protection strategy based on the simple principle of not letting more energy into the system than the system itself can handle. The self-tightening-mechanism of the winch is furthermore integrated in the energy-conversion and power-take-off system, which helps to lower the design costs of the wave power plant.	http://www.straumekraft.no/ http://www.google.com/patents/EP2347120A2
84	OWC Power AS	The OWC Power	In a wave power converter based on the OWC principle, the waves pushes a water column up and down in an oscillation chamber. The oscillating water column pushes air in front of it causing air to flow back and forth through an air turbine. The turbine rotates in the same direction independent of the direction of the airflow. Thereby the oscillating wave movement is converted into a continuous rotating motion, which drives a standard electric generator.	http://www.owcpower.com/ http://www.owcpower.com/index.php?parent=0&groupid=193

85	Wave Energy AS	Seawave slot-cone generator	SSG is a wave energy converter based on the wave overtopping principle utilizing a total of three reservoirs placed on top of each other, in which the potential energy of the incoming wave will be stored. The water captured in the reservoirs will then run through the multi-stage turbine. This turbine has the advantage of utilizing different heights of water head on a common turbine wheel. The multi-stage technology will minimize the number of start/stop sequences on the turbine, even if only one water reservoir is supplying water to the turbine, resulting in a high degree of utilization.	http://www.mdpi.com/1996-1073/6/3/1344
86	Kymaner	KymanOS OWC	KymanOS® stands for Kymaner OffShore and is inspired in the Greek word for Ocean, the source of energy it is meant to explore. KymanOS® System has no moving parts in addition to the turbine and has a design that prevents the movement of salt water vapor in the turbines and abduction pipes.	http://www.kymaner.com/
87	WavEC	PICO OWC	The plant is operated by WavEC since 2004 and is the oldest wave energy plant in Europe. Furthermore it is the only one open for training, innovation, research and demonstration. A large number of researchers of several nationalities visit Pico plant every year.	http://www.pico-owc.net/
88	Sea for life Lda.	Wave Energy Gravitational Absorber – WEGA	The Wave Energy Gravitational Absorber (WEGA) device is an articulated suspended body, semi-submerged, attached to a mount structure that oscillates in an elliptical orbit with the passage of the waves. The articulated body attaches to the mount structure through a rotary head which allows it to adapt to the direction wave propagation.	http://www.seaforlife.com/
89	ReefPower Energy	SPIDER RP05	The equipment is composed by a series of organs that have been planned to guarantee a good performance in extracting energy from the sea in variable conditions, including hurricanes. The SPIDER RP05 is a device that works offshore over 40 meters of depth, which has an innovative structure and requires a minimum depth of only 4 meters.	http://en.reefpower.com.pt/ http://www.youtube.com/watch?v=GM0OhZC82D4

90	Applied Technologies Company Ltd (ATC)	Float Wave Electric Power Station (FWEPS)	The FWEPS concept uses the advanced approach when the process of energy conversion is based on efficient interaction of wave energy source and oscillatory loading mechanism intrinsic for the case. The module of FWEPS is a vertically oriented, oblong axisymmetrical capsule-float located on sea surface. Inside the capsule there are a mechanical converter consisting of an oscillatory system and drive; an electric generator and energy accumulator. Under waves effect the capsule-float and inner oscillatory system of a mechanical converter are in continuous oscillatory motion, while the drive engaged with the system provides a continuous spin-up of an electric generator. Owing to its peculiarity, the device is matchable with outer wave space that gives the most effective mode for energy taking-off and sustainable operation at varying wave harsh conditions. Depending on the mission it is possible to develop both a single modular FWEPS for output power up to 50 Kw and multi-modular plant designed for the total electric power of the order of some dozens of megawatts.	http://www.atecom.ru/
91	Hann-Ocean	Drakoo	The working principle of Drakoo (Dragon King of Ocean), being a twin-chamber oscillating water column system, is to transform waves into a continuous water flow which drives a hydro turbine generator. Firstly, an incoming wave increases the inlet chamber's water level, and a transfer of water from the inlet to the outlet chamber occurs. Secondly, once the water level outside the device falls, both chambers' water levels also fall, again leading to a flow from the inlet to the outlet chamber. The two-step action of the water columns occur continuously in waves. Meanwhile, the checkerboard valves regulate the water flow. The water flow is nearly constant and one-directional resulting in smooth rotation of the hydro turbine which in turn generates stable electricity efficiently. The Drakoo working principle has been proven with various scale models in lab tests and sea trials. A twin-chamber wave energy convertor (WEC) "Drakoo" (Dragon King of Ocean) that allows for low cost electricity generation from all waves scales (0.2m – 5.5m) and hence very suitable for both shallow water and deep seas deployment.	http://www.hann-ocean.com/products/drakoo-wave-energy-converter/features-benefits/ http://www.hann-ocean.com/wp-content/uploads/2012/12/Drakoo-B-e-brochure.pdf

92	Stellenbosch University	Stellenbosch Wave Energy Converter (ShoreSWEC)	The SWEC is fully submerged and founded on the sea floor making it a robust structure with very few moving parts large research project was completed by the Ocean Energy Research Group at Stellenbosch in the seventies and early eighties to investigate the possibility of exploiting tidal, wave and sea current resources around the South African coastline. This work culminated in the Stellenbosch Wave Energy Converter (or SWEC). At this time this research is taken forward after the filing of a patent for a Shore-SWEC. This SWEC adaptation is named the ShoreSWEC and comprise of a series of hollow, steel reinforced concrete chambers with openings below the water surface to allow wave driven flow to enter and exit the chambers. A linear generator for wave energy conversion was also developed in the Department of Electrical and Electronic Engineering at Stellenbosch University.	http://www.crses.sun.ac.za/
93	Hidroflot S.A., Ocean Electric Inc.	Hidroflot	The floating structure works semi submerged and is composed for 16 columns joined in a net. This floating structure is anchored on sea bed by chains. Due his physical characteristics it has a great stability over the sea. The floating buoys are moved vertically by waves at long of columns. The movement of buoys tows a mechanical dispositive to activate a power generator	http://www.hidroflot.com/ http://www.youtube.com/watch?v=zP4e3pPPiaE
94	OCEANTEC Energias Marinas S.L.	Oceantech	Oceantec patented a new, worldwide, marine energy converter technology. **Floating body** oscillates due to wave excitation in its main DOF: pitch. **Mooring system** allows the body to weathervane so that it is faced to the predominant wave propagation direction. Main advantage: capture system **completely encapsulated** free of contact with sea water. A **flywheel** continuously spins under the action of an electric motor (Z). The pitching motion of the WEC caused by wave action is transformed into an **alternating precession** in the longitudinal hull axis (X). A coupling device transforms this precession into an unidirectional rotation of higher frequency that is used to feed a **conventional electric generator.**	http://www.oceantecenergy.com/ http://www.oceantecenergy.com/technology/in-company-developments/
95	PIPO systems SL	APC-PISYS	The APC-PISYS system is comprised of a series of submerged buoys of variable internal pressure that are connected individually to another buoy on the surface. It is a physically adaptive system that can react to external	http://www.piposystems.com/ http://www.piposystems.com/sistemaapspisys_en.html http://www.youtube.com/watch?v=EPxNMkIeKrc

			stimuli and respond to any situation that threatens its stability.	
96	Abencis Seapower	Marine pump		http://www.abencis.com/energia-marina.php
97	GM Renovables	(J+B) 2B wave		http://gmrenovables.com/ http://gmrenovables.com/paginas/producto.html
98	EVE – Ente Vasco de la Energia	Mutriku OWC plant	It is the same machine concept operating at LIMPET (Islay, Scotland). This plant contains 16 turbines and was the first commercially sold and operated wave energy plant in the world and the only multi-unit plant operating in the world.	http://www.eve.es/index.aspx
99	Sendekia S.L.	SDK Wave turbine	The company has designed an energy power generator, consisting of a hydraulic turbine immersed in water within a resonance chamber. This device can produce energy integrated in breakwaters or floating like a buoy.	http://www.sdkmarine.com/ https://www.youtube.com/watch?v=xiV2QKv9D4w&feature=player_embedded
100	University of Santiago de Compostela	WaveCat	WaveCat is an offshore floating WEC whose principle of operation is oblique wave overtopping. It consists of two hulls, like a catamaran (hence its name). Unlike a catamaran, however, the hulls are not parallel but converging, forming a wedge in the plan view; they are joined at the stern by a hinge, which allows the angle between them to be varied depending on the sea state.	http://www.usc.es/en/index.html http://www.sciencedirect.com/science/article/pii/S0951833912000640 http://www.ep.liu.se/ecp/057/vol9/002/ecp57vol9_002.pdf
101	CorPower Ocean AB	Corpower	The compact WEC systems are of the point absorber type, with a buoy on the ocean surface absorbing energy from waves. The WEC is located at a depth between the surface and sea bottom where it is protected from rough seas. Force is transferred to the WEC by a buoy tether, and it is moored to the sea bed. Flexible connection points automatically minimize harmful lateral forces on the WEC. The WEC has a unique Power Take-Off (PTO) design that combines the high load capabilities from hydraulics with the efficiency of a direct mechanical drive. Temporary energy storage is provided by a two-step approach, smoothing the electrical power output compared to the power profile of typical ocean waves and minimizing the cost of electronic components. The system has been designed for low inertia and high structural efficiency, allowing the use of active phase control to optimize power absorption.	http://www.corpowerocean.com/ http://www.diva-portal.org/smash/get/diva2:666775/FULLTEXT01.pdf

102	Ocean Harvesting Technologies AB	Ocean Harvester	The Ocean Harvester captures energy from the rise of each wave with the use of a winch system, which provides sufficient length of stroke for the largest wave on the selected site. A patented mechanical PTO with a counterweight efficiently converts the highly fluctuating energy that is absorbed from the waves into a smooth power and force through system. This way the PTO and power electronics can be sized for the average energy instead of the peak energy. The key advantage with this is considerable reduction in the cost of the PTO, as well as high efficiency and load factor of the generator and power electronics, all together resulting in low cost of energy.	http://www.vegvesen.no/_attachment/329472/binary/575592
103	Waves4Power	WaveEL	The WaveEL works by principle of a two body oscillating system. The buoy with the characteristic long vertical acceleration tube below and the water column in the tube. The movement of the water column is dampened by a water piston which is connected to a hydraulic piston in a cylinder. By loading the hydraulic piston the relative motion between the wave induced heave of the buoy/tube and the large water mass – that is still and not affected by the wave motion – is dampened and a gigantic hydraulic pump is created which pumps oil to a hydraulic motor which in turn rotates a generator. The WaveEL-buoy is free floating and can be moored to a floating or fixed structure as long as the water depth is sufficient for the acceleration tube.	http://www.waves4power.com/
104	Seabased AB	Seabased	Seabased's wave power technology utilizes the water motion in waves to directly drive the wave power plants. The active element is a unique directly driven permanent magnet linear generator. The generator is specially designed to take advantage of the slow movement of the waves that is transferred to it via a buoy (point absorber) on the ocean surface. The buoy action is transferred directly to the generator with no intermediate mechanical gearing since the generator is optimized to output high power even at slow speeds. The movement of the waves (about 15 wave cycles/min) causes the translator (corresponding to the swiftly turning rotor of a conventional generator) to move up and down within the stator, thus converting the kinetic energy of the wave to electric energy. Very powerful neodymium-iron-boron	http://www.seabased.com/en/technology/seabased-wave-energy http://www.diva-portal.org/smash/get/diva2:414885/FULLTEXT01.pdf http://scitation.aip.org/content/aip/journal/jap/102/8/10.1063/1.2801002

			magnets are mounted on the translator. They create an alternating magnetic field which penetrates the stator windings. The stroke length of the translator is limited by end stops at the top and bottom.	
105	Vigor Wave Energy AB	Vigor	Vigor uses the seawater as mechanical parts that create a pressure difference and a flow. In this way Vigor converts the energy with a minimum use of material. Many relative low costs hoses can be connected to the same conversion point making the Vigor technology very cost efficient. The Vigor Wave Energy onverter is flexible; reacts against itself and don't use a fixed reference frame such as the ocean floor. This is a large advantage in extreme wave climate and limits the strains that drag forces etc. can give rise to. This means that Vigor follows the movement and works with the waves instead of working against the waves.	http://www.vigorwaveenergy.com/
106	Avium A.Ş.	Yeti Cluster system	YETI CLUSTER unit absorbs wave energy from all directions and works on the basis of, among others, negative. Such feature, in combination with having a simple self adjusting variable damping / active control (PTO) system on board (used for varying the damping in line with the encountered wave excitation force thus causing/keeping the unit conversion responsive) is enabling it to harness in-coming irregular wave energy efficiently and economically both in low and high energy density areas of deployment.	http://www.avium.com.tr/
107	AlbaTERN Ltd.	SQUID	A central buoyant "absorber" is filled with water so that it sits just below the surface. The absorber is moved by the passing waves, and the relative motion between the absorber and the link arms is used to pump hydraulic fluid through a generator, producing electricity.	http://albatern.co.uk/
108	Wavewinder	Wave Winder	See http://www.g1jbg.co.uk/pdf/avowave.pdf	http://www.wavewinder.co.uk/ http://www.youtube.com/watch?v=DT537G53fn0 http://www.youtube.com/watch?v=GmFj0OXCX7E http://www.g1jbg.co.uk/pdf/avowave.pdf
109	Aquamarine Power	Oyster 800	Oyster wave power technology captures energy in nearshore waves and converts it into clean sustainable electricity. Essentially Oyster is a wave-powered pump that pushes high pressure water to drive an onshore hydroelectric turbine.	http://www.aquamarinepower.com/technology/how-oyster-wave-power-works/ http://www.westwave.ie/wp-content/uploads/downloads/2011/12/WestWave-Supply-Chain-Report-Rev5.pdf

110	AWS Ocean Energy	Archimedes Wave Swing (AWS- III)	The AWS-III is a multi-cell array of flexible membrane absorbers that convert wave power to pneumatic power through compression of air within each cell. The cells are inter-connected, thus allowing interchange of air between cells in anti-phase. Turbine-generator sets are provided to convert the pneumatic power to electricity.	http://www.awsocean.com/technology.aspx?ln=1 http://www.google.com/patents/US20110185721?printsec=description&dq=2011/0185721&ei=xXMvT9XpO8jO2gXynamFDw http://www.wavec.org/content/files/02_GrahamBibby_AWS.pdf
111	Checkmate Sea Energy UK Ltd.	Anaconda	The system essentially consists of a rubber tube filled with water, which is placed in the sea. Both ends of this rubber tube are sealed and it is anchored with its head to the waves. It is squeezed or enlarged locally by waves causing pressure variations along its length. As a wave passes, the bulge tube is lifted with the surrounding water and causes a bulge wave to be excited, which passes down the tube's diameter like a pulse in an artery, gathering energy from the sea wave as it goes. Continuous energy gathering results from resonance between the bulge wave and the sea wave. Energy from the sea wave is stored in the rubber as it stretches. The bulge wave travels just in front of the wave rather like a surfer, picking up energy as it progressively increases in size. At the end of the tube the bulge wave energy surge drives a turbine.	http://www.checkmateseaenergy.com
112	Seatricity Ltd	Seatricity	Arrays of buoy actuated reciprocating pumps produce high pressure seawater which is then transmitted ashore by pipeline. Once ashore the pressurised sea water is used to drive a standard hydroelectric turbine to produce electricity. This pressurised sea water can also be used for directly producing fresh water by the reverse osmosis desalination process. Both fresh water and electricity can be produced simultaneously.	http://www.seatricity.net/
113	Ecotricity Group Limited	Searaser	Searaser pumps seawater using a vertical piston between two buoys – one on the surface of the water – the other suspended underwater and tethered to a weight on the seabed. As the ocean swell moves, the buoys move up-and-down and the piston pumps pressurized seawater through pipes to an onshore turbine. This produces electricity. Searaser units could also supply energy on-demand by pumping seawater into a coastal reservoir, with a hydropower turbine, solving renewable energy's problem of fluctuating output.	http://www.ecotricity.co.uk/
114	Ecotricity Group	Snapper	The device works like a typical linear generator in which a set of magnets mounted in a translator is moved up and	http://www.ecotricity.co.uk/ http://www.snapperfp7.eu/snapper-s-background

	Limited		down inside multiple coils of wire of an armature. However, there is a crucial difference with Snapper: alongside the armature coils is a second set of magnets of alternating polarity.	http://www.youtube.com/watch?v=fUIzUNwE-AY http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/259.pdf http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5674966&tag=1
115	Trident Energy	Powerpod	PowerPod is a modular unit containing a number of our patented linear generators. PowerPod is a generic and scalable power take-off solution with multiple applications in offshore wind, wave and tidal energy generation. The linear generators convert the movement directly into electricity without additional gearboxes or hydraulics.	http://www.tridentenergy.co.uk/
116	Sperboy /Embley Energy	Sperboy	The SPERBOY is based on the 'oscillating water column' principle. As the buoy moves up and down on the waves, air is displaced from a chamber within the buoy, which then drives turbine-generators situated on top. Maintenance requirements are kept to a minimum due to a limited number of moving parts, which are located above the sea's surface making them more easily accessible. The planned design will use advanced laminated concrete in its construction and has a 40-50 year life expectancy.	http://www.sperboy.com/
117	Green Ocean Energy Ltd.	Wave Treader / Ocean Treader	Comprised of two pontoons at the fore and aft and a spar buoy in the centre. As waves pass along the device, first the fore pontoon lifts and falls, then the spar buoy, and then the aft pontoon, respectively. The relative motion is harvested by hydraulic cylinders that pump fluid hydraulic motors and an electric generator.	http://www.greenoceanenergy.com/
118	Ocean Navitas	Aegir Dynamo	The Aegir Dynamos' two major components are the buoyant base (that is anchored by three cables) and the float that moves up and down with the swell. The linear motion between the float and the base is converted into angular momentum (the details of this conversion process is unknown to the author). The angular motion is then used to drive the generator that is sealed inside the central column.	http://www.ntu.ac.uk/

119	Offshore Wave Energy Ltd.	OWEL	The WEC is a horizontally floating duct which is made up of several sections which together forms one large system. The height of the duct, at the entrance, will be equal to the average wave amplitude and the length will be determined by the average wave length. The fact that the system consists of several sections and that it is length is longer than the average wave length, will allow it to be stable. The anchoring system allows the WEC to align itself with the incoming waves. The incoming waves trap air against the top of the ducts. The air gets compressed more and more as the waves moves forward into the ducts because the ducts are narrower at the rear. The air is collected in a chamber before it is forced to flow through a turbine at the rear that in turn drives a generator. The prevailing energy in the waves is dispersed by the baffle at the rear in order to prevent them from reflecting back into the duct.	http://www.owel.co.uk/
120	Voith Hydro Wavegen Ltd.	Limpet OWC	The LIMPET 500 (Land Installed Marine Pneumatic Energy Transformer – 500kW) is an OWC built into the shoreline near Portnahaven, on the island of Islay off the west coast of Scotland. This project is similar to the Pico project in Portugal.	http://mhk.pnnl.gov/wiki/images/2/25/Islay_LIMPET_Report.pdf; http://web.sbe.hw.ac.uk/staffprofiles/bdgsa/shsg/Documents/2004sem/limpet.PDF
121	Pelamis Wave Power	Pelamis	Pelamis is a semi-submerged wave energy converter consisting of individual tubular sections, each linked to neighbouring segments by universal joints. Motion is induced in each section as a wave passes down the length of the device; movement between neighbouring segments will be resisted by hydraulic rams, which pump hydraulic fluid through pressure smoothing accumulators then on to a hydraulic motor. This motor is connected to a generator.	http://www.pelamiswave.com/pelamis-technology http://www.pelamiswave.com/upload/document/PWP-brochure-online.pdf http://www.pelamiswave.com/upload/document/PWP-brochure-online.pdf
122	Nodding Beam Ltd.	Nodding Beam = Power	Nodding Beam = Power is a wave energy conversion system that utilizes the simple concept of a nodding beam, typically used to pump oil, and linear generators that are mounted on a robust concrete barge to convert energy directly from ocean waves into electricity.	http://www.noddingbeam.com/
123	Lancaster University	Wraspa	The WRASPA, or Wave-driven Resonant, Arcuate-action, Surging Power Absorber, is a hinged device which operates in Pitch-Surge. It is envisaged that the device will operate in water depths of 20-50m. The device has been the subject of a joint research programme of design optimization, funded by the Joule Centre in Manchester, and conducted by Lancaster and Manchester Metropolitan	http://www.engineering.lancs.ac.uk/ \ http://www.youtube.com/watch?v=q68XnBnI90o

			Universities. We are now working to build a consortium to take forward the development of this device, so that it can be demonstrated at full scale. Current work centres around further improvements in collector shape and further developments of the novel control system for power conversion.	
124	Atargis Energy Corporation	Cycloidal Wave Energy Converter	Two hydrofoils that rotate around a shaft with the wave crests and operated under feedback control achieve wave termination To convert waves into useful electrical energy, the CycWEC must synchronize with ocean waves, perfectly cancelling the wave by producing an anti-wave 180 degrees out of phase. In doing so, the CycWEC extracts the ocean energy to drive a shaft on a generator, converting the wave power into electrical power.	www.atargis.com/
125	Atmocean, Inc.	OHS	Arrays of (point-absorbing) buoys producing pressurized seawater, conveyed using seafloor hydraulic transmission line to onshore conversion/generation. The arrays are positioned offshore in water depths of 20m (minimum required) to 100m (preferred maximum due to mooring cable cost). "Slack" or catenary array moorings attach each end to the seafloor. With this architecture, undersea operations are not required during deployment - a major cost savings - and tidal changes have no effect on the pumping action of the buoys, as each pump adjusts to changing ocean depth. For other systems using direct bolt-down of each device, tidal change is a major issue.	http://www.atmocean.com/ http://www.youtube.com/watch?v=qAm-8G1EMyw&feature=youtu.be http://www.youtube.com/watch?v=v-xRlGAgy9Q&feature=youtu.be
126	Ocean Energy Industries. Inc.	WaveSurfer	WaveSurfer (Patent pending) is a reliable, inexpensive and efficient off-shore system, "point absorber" that can be installed on different depths by mooring. WaveSurfer consists of two bodies, a buoyant body that floats on the surface of water and a submerged body suspended from the buoyant body. The submerged body consists of electric generators and horizontally-aligned rotors.	http://www.oceanenergyindustries.com
127	OWECO Ocean Wave Energy Company	OWEC – Ocean Wave Energy Converter	All three OWEC models have a very similar working principal. The whole structure is submerged, except for the buoy that is partially submerged. A damping plate is used to resist movement of the base, thereby allowing the buoy to move relative to the base. The relative motion between the base and buoy is either directly converted into electricity by means of a linear generator, or by using an intermediate stage to convert the horizontal motion into	http://www.owec.com

			rotational motion before it's used to drive a generator.	
128	Resolute Marine Energy, Inc.	SurgeWEC	Resolute's SurgeWEC consists of a paddle hinged at the bottom where it is attached to electricity-generating equipment and a heavy metal frame that can be anchored to the seabed. Pushed by each passing wave, the paddle swings toward the shore, then back again, returning to an upright position like a swinging door turned on its side. The mechanical energy of the paddle's movements drives a pump, which transmits hydraulic power to a generator, which in turn converts it to electricity to be delivered to shore.	www.resolutemarine.com
129	AeroViro nment (INC)	Sub Surface Wave Buoy	Anchored to the sea floor and floating beneath the surface, its turbine generates clean energy as the float moves horizontally through the water, responding to pressure changes from passing waves. Unobtrusive, silent and reliable, it is an attractive alternative to other ocean-energy devices.	http://www.avinc.com/engineering /marine_energy/
130	Independe nt Natural Resources	Seadog Pump	A buoyancy block, inside of a chamber, is used to drive a piston pump. The pump pumps seawater (under high pressure) to the shore where it is used to drive a hydroelectric system in order to generate electricity or to desalinate seawater.	http://inri.us/
131	Ocean Energy Ltd.	Wave Catcher	It is a long surface buoy cylinder that is lifted by each passing wave. As the cylinder is lifted, it pulls on its anchor lines, which, in turn, pulls on a support pulley. This support pulley turns the generator's rotor and flywheel. The generator's flywheel keeps the rotor turning until the next wave lifts up the cylinder and the anchor line once again turns the pulley. The cylinder will also be lifted by waves from all directions. As a result, the anchor cables at each end of the buoy may either pull together or at slightly different times. The gears, the pulleys, the rotor and flywheel are turned when the anchor cable's tension is high. The uni-direction pulley's re-coil spring re-winds the anchor cable back around the pulley, when the buoy moves	http://www.offshoreislandslimited.com

			down with the trough of the wave and the anchor cable tension is low.	
132	Sara Ltd	MWEC		http://www.sara.com/
133	Able Technologies L.L.C.	Electricity generating wave pipe EGWaP	The device produces electrical or other types of energy using ocean waves and a hollow pipe (tube or container) system with an internal float that uses a counter weight to work gears that turn a generator.	http://www.abletechnologiesllc.com/
134	Colombia Power Technologies	StingRay	The SeaRay is a point absorber designed to convert heave and surge wave energy directly into rotary motion in order to harness twice the energy of a point absorber operating solely in heave. The SeaRay is a direct drive linear generator made up three moving bodies: a forward float, aft float, and spar. The forward float is connected to the starboard side generator, and the aft float is connected to the port side generator. The floats are designed to rotate up and down with the oncoming waves, relative to the center spar, which is moored in such a way that it stays relatively stationary in the vertical motion. The aft and forward floats have approximately a 90° max range of motion centered about the horizontal axis, but typically move up to 10°-15° off axis during normal operation.	http://www.columbiapwr.com/
135	Steven Institute of Technology, Seahorse Power LLC	Wave Energy Harvesting Device (WEHD)		http://www.stevens.edu/seahorsepower/index.html http://www.stevens.edu/seahorsepower/video/index.php http://www.slideshare.net/ProvostStaff/seahorse-power http://www.youtube.com/watch?v=GyXk8TSI40Y
136	SRI International	EPAM	SRI's wave-powered generators can be deployed on existing ocean buoys that use batteries as their energy source. SRI's new generator utilizes patented electroactive polymer artificial muscle (EPAM™) technology, and offers a renewable method to continually power ocean buoys. SRI will use instrumentation that allows remote monitoring of the generator's output energy as well as wave height and buoy motion.	http://www.sri.com/ http://www.youtube.com/watch?v=ePOB8pUXhBg http://www.sri.com/newsroom/press-releases/novel-wave-powered-generators-deployed-sea-trials-florida-coast http://juser.fz-juelich.de/record/135442/files/HP3a_pp_Chi_Chiba.pdf
137	Ecomerit Technologies	Centipod	Centipod technology is designed to harness the power available from waves, in a similar way as the Wavestar does. The multi-megawatt Centipod system is based on a stable floating platform, which is actively yawed to wave	http://www.ecomerittech.com/

			front exposure. As waves travel across the Centipod, pods rise and fall, generating electricity.	
138	Floating Inc.	OOES's Rho-Cee	The system is able to exploit the renewable resources of the oceans (wind, wave and ocean currents) in the same structure. The system is accommodated on a preferably very large pneumatically stabilized platform (PSP). The Rho-Cee, as Float Inc. has named their wave energy converter system, is a large, floating OWC to be moored in deep water and resonant across a selected frequency band. By means of impedance matching, highly efficient wave energy absorption is demonstrably achieved. The Rho-Cee is integrated with Float's PSP to take advantage of controllable stability, load capacity and the deck area that it provides. An array of wind turbines similar to onshore ones is also deployed.	www.floatinc.org/
139	Kinetic Wave Power	PowerGin	A typical PowerGin™ has rotors that are 80 - 100 feet long and 10 feet in diameter. The size is somewhat dictated by the wave period and energy output specification. Wave energy is focused by the wave ramp and the rotors and is funneled into the "buckets" called energy capture units on the ramp side of the rotor. In the case of smaller wave states; the water moving up the wave ramp artificially becomes a larger wave and crests to help fill the buckets. The buckets are mounted in a dense spiral pattern around the perimeter similar to hydro electric turbine blades which provide a high surface area to catch wave energy. As the buckets on the ramp side of the rotor fill with wave water, the rotors begin to turn. Water is emptied out of the bucket instantaneously when it is submerged under the water by a patented gravity driven flap on the bottom. The flap slams shut in one direction and opens in the other. The two rotors rotate in opposite directions which maintain balance and continuous rotary power flow.	http://www.kineticwavepower.com/

140	Spindrift Energy	Spindrift	A Spindrift device is a buoy, rigidly attached to its submerged venturi tube. As the buoy moves up-and-down, the attached submerged venturi tube moves up-and-down. They move as a single unit. The surplus pressure of the water in the advancing end of the tube is converted into additional speed and kinetic energy as it moves through the narrowing channel of the venturi tube. When the water reaches the narrowest portion of the venturi tube, i.e. the "throat", its speed, and its kinetic energy, have been significantly increased at the expense of the surplus water pressure. This accelerated water then drives a hydrokinetic turbine located in the throat of the venturi tube.	http://www.spindriftenergy.com/
141	Neptune Wave Power	Model 3.0/3.1	Neptune Wave Power's technology is a "point absorber" Wave Energy Conversion Device ('WECD'). The floating and securely moored offshore buoy reacts to the vertical surge and irregular movement of waves causing a horizontal pendulum within it to rotate. The rotational energy of this pendulum, through a proprietary internal drive system, is directed to an on board electric generator. Power generated is fed to the utility grid via an underwater cable system at an interconnect point.	http://www.neptunewavepower.com/
142	M3Wave Energy Systems LLC	DMP	The Delos-Reyes Morrow Pressure Device, or DMP, is an innovative new approach to the concept of extracting energy from the ocean. Originally developed in 1991, the DMP is being commercialized by M3 Wave Energy Systems LLC in the Pacific Northwest region of the United States. The DMP operates beneath the surface of the ocean, avoiding many of the issues inherent with surface-based systems like ocean power buoys, ocean wind farms, and floating PV. Submerged operation reduces the impact on commercial navigation, recreation, fisheries, marine animals, aesthetics, and sea birds. Residing under the surface also protects the DMP from some of the harsh apsects of the ocean environment- wind loading, inclement weather, rogue waves, UV damage, etc. Additional benefits include tow-to-site self-deploying and recovery capability, enhanced power source security, and stealthy power generation potential for military applications. The DMP is a hybrid of conventional ocean wave energy converter technologies, merging proven aspects of pressure	http://www.m3wave.com/ http://www.youtube.com/watch?v=3j3pnHSExME

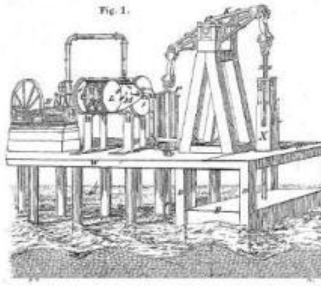
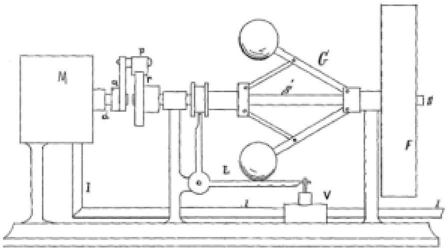
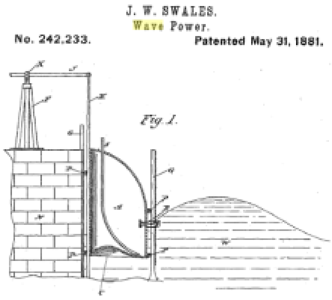
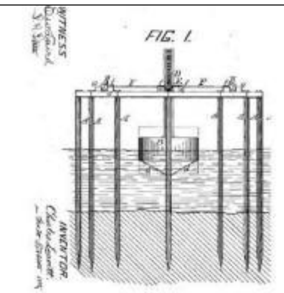
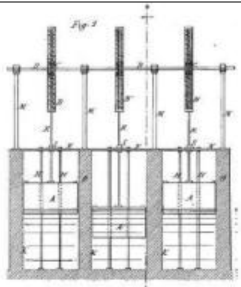
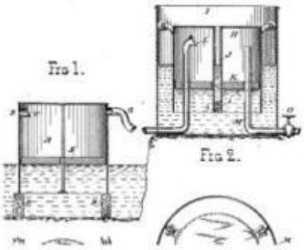
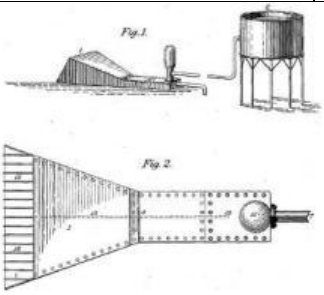
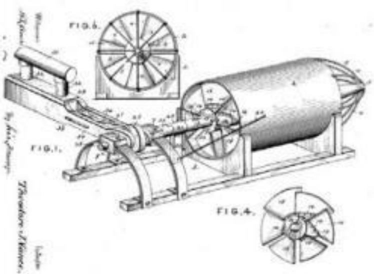
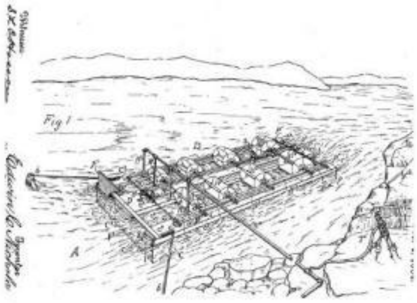
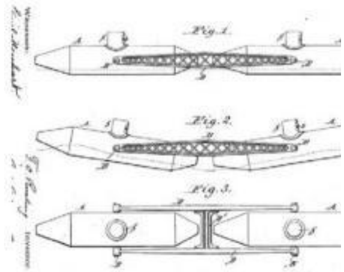
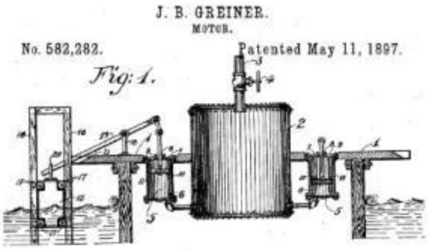
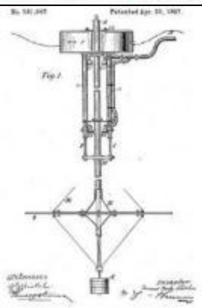
			transient converters with OAC and OWC systems in a simple, easy-to-manufacture, and highly robust device.	
143	Navatak Ltd.	Navatek	The Navatek WEC was developed using in-house expertise gained through a decade of research into the design, construction and at-sea testing of advanced ship hull prototypes for the Office of Naval Research and other customers. The same sophisticated hydrodynamics/motions tools used to design ship hulls with reduced motions were applied in reverse to develop a WEC with enhanced motions for greater energy capture. In March 2007, Navatek tank-tested at Offshore Model Basin, Escondido, CA a small-scale, 8-foot model of its WEC device equipped with a Navatek-designed power take-off device. Design goals were achieved. In December, 2008 Navatek received a U.S Patent on its invention. Navatek is currently looking at system aspects of proposed energy farms using this WEC device, together with novel concepts for associated energy storage.	http://www.navatekltd.com/ http://www.navatekltd.com/waveenergy.html
144	Aqua Magnetics Inc.	Ocean Swell Wave Energy Conversion - OSWEC	The Generator housing moves up and down with the motion of the Buoy on the ocean's surface while the Damping Plates hold the Generator Coil in a stable position. The relative motion between the magnetic field in the generator housing and Generator Coil creates an electric voltage in the Generator Coil.	www.amioceanpower.com
145	Ocean Motion Internatio nal	OMI Combined energy system	The Combined Energy System CES consists of four sub system components a seawater wave pump a hydro turbine electric generator a reverse osmosis filtration unit and an electrolysis hydrogen generation unit The CES is designed to operate on a large offshore platform which is essentially a modified version of a standard modular offshore drilling unit The system produces potable water electricity and hydrogen which is delivered to shore through service piping and cabling The OMI WavePump is technically described as a mass displacement wave energy conversion device The patented seawater pump and heart of the CES is an innovative design which uses a small number of simple moving components for minimal maintenance and wear The hydro turbine electric generator is driven by the output of multiple WavePumps which provide a constant flow of high volume high pressure seawater .	http://www.oceanmotion.ws/

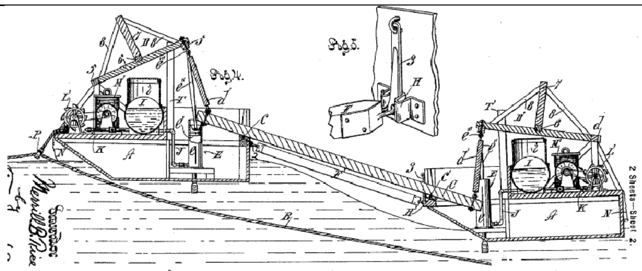
146	Grays Harbor Ocean Energy	Titan Platform	Titan platform consists of a three-legged jack-up support structure that floats to site with the turbine pre-installed at the energy. The platform supports a wind turbine and OWCs that are integrated into the legs of the platform. The power from the wind turbine and wave energy converters is transmitted from the platform to shore by a cable buried about 3 feet below the seabed and under the beach.	http://www.graysharboroceanenergy.com/
147	Green Wave Energy Corp.	Bottom wave generator	Their turbine consists of nothing more than a structurally reinforced fiberglass cylinder with a large propeller (or impeller) inside that's connected to an electric generator. No oil or hydraulics are involved. The The turbine is vertically anchored into a fixed spot (outside the breakers in a location predetermined based on local stakeholders' recommendations) with just its top peeking out of the water. The generator is also easily connected to other Green Wave turbines that make up the power plant, or the substation nearby on land. The generator's production relies on the water rising and falling inside the cylinder, to turn the propeller and generate electricity.	http://greenwaveenergycorp.com/

12.5 List of patents

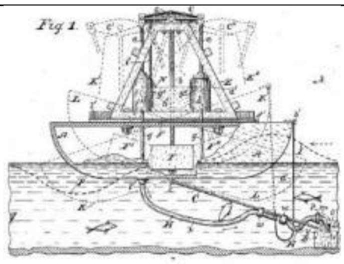
Table A.5 presents a list of WEC patents. It should be noted that this list is not exhaustive.

Table A. 5: Patent list of WECs (after Alawa et al., 2009)

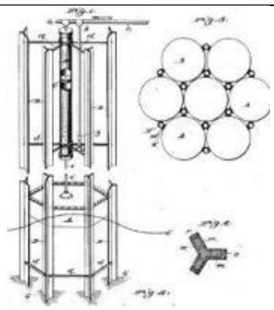
 Improvement in Wave Powers US Patent: 138,474, May, 1873 Inventor: Charles Buckner, CA, USA	 Wave Motor US Patent: 241,800, May, 1881 Inventor: George B. Grant, MA, USA	 Wave Power US Patent: 242,233, May 31, 1881 Inventor: John Swales, CA, USA
 Mechanism for Utilizing Wave Power US Patent: 321,229, June 1885 Inventor: Charles Leavitt, OH, USA	 Hydraulic Marine Motor US Patent: 366,768, June 1887 Inventor: Joseph Elias, SYRIA	 Surf-Power Machine US Patent: 416,972, December 1889 Inventor: Henry Thomas, CA, USA
 Apparatus for Utilizing the Force of W US Patent: 430,790, June 24, 189 Inventor: F. Starkenberg, MA, US.	 Water Motor US Patent: 507294, October 1893 Inventor: Theodore Vance MO, USA	 Apparatus for Generating Compressed Air US Patent: 530,118, December 1894 Inventor: Edwin C. Nichols, MS, USA
 Wave Motor US Patent: 541,631, June 25, 1895 Inventor: F. O. Rusling, NY, USA	 Motor (Wave) US Patent: 582,282, Nov. 20, 1896 Inventor: John Greiner, FL, USA	 Apparatus for Utilizing Power of Sea-Waves US Patent: 581,067, June 20, 1896 Inventor: Bernard Fletcher, London, England



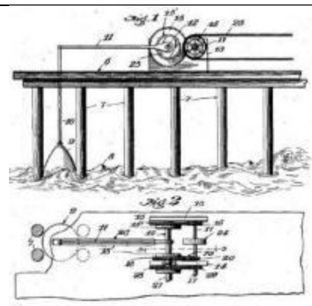
Wave Motor
US Patent: 632,826, September 1899
Inventor: Merrill B. Rice, CA, USA



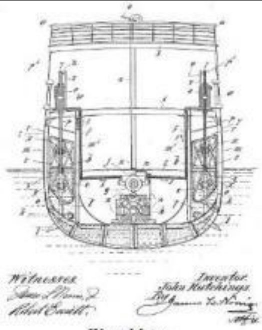
Wave Motor
US Patent: 656,645, August 1900
Inventor: George W. Hoff, NY, USA



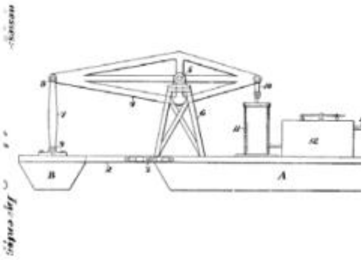
Wave-Motor
US Patent: 706620, August 1902
Inventor: Henry Williams, CA, USA



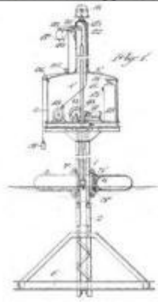
Wave Motor
US Patent: 791,366, May 1905
Inventor: Theodore Rapp, CA, USA



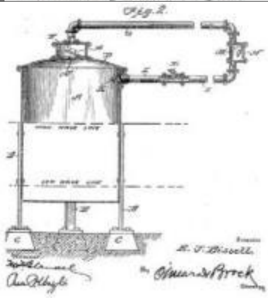
Wave Motor
U.S. Patent 787182, April 1905
John Hutchings, London, England



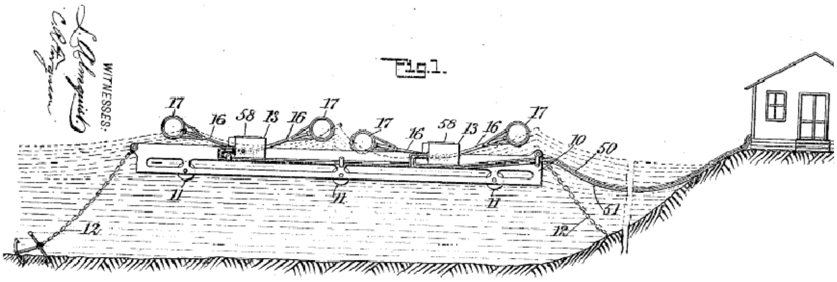
Wave Motor
US Patent: 816,934, Mar. 1906
Inventor: Charles Newell, CA, US



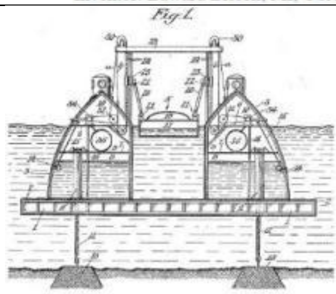
Wave Motor
US Patent: 852,232, April 1907
Inventor: Ernest Kohler, CA, USA



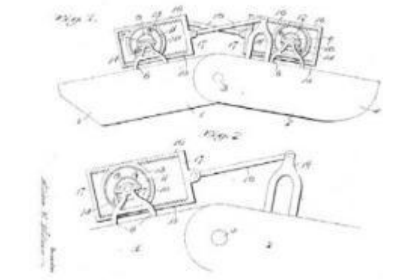
Wave Motor
US Patent: 875,042, Dec. 1907
Inventor: Edward Bissell, MI, USA



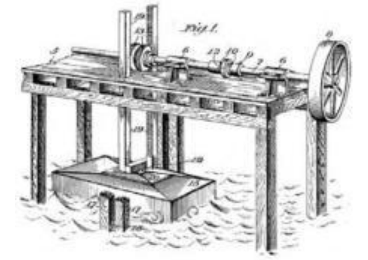
Wave Motor
US Patent: 855,258, May 28, 1907
Inventor: John W. Kealia, Territory of Hawaii



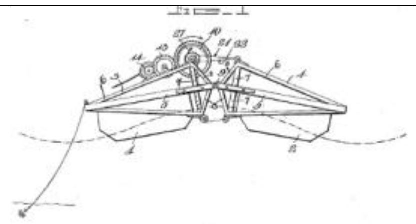
Wave Motor
US Patent: 879,992, February, 1908
Inventor: George Wilson, CA, USA



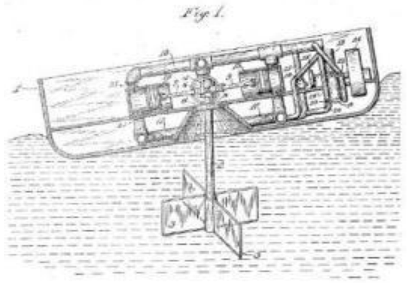
Wave Motor
US Patent 882,883, March 1908
Inventor: William Hillson, WI, USA



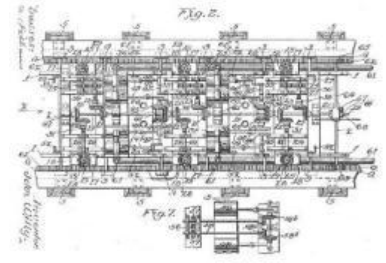
Wave Motor
US Patent: 884,080, April 1908
Inventor: George Fallis, CA, USA



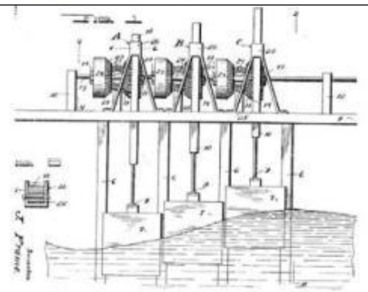
Wave Motor
US Patent: 917,411, April 1909
Inventor: Casella & Reynolds, CA, USA



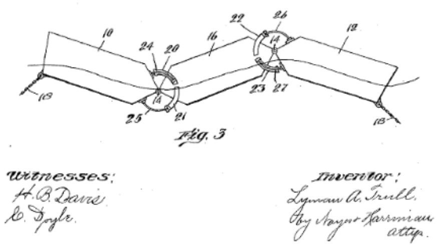
Wave-Motor
US Patent: 937,712, October 1909
Inventor: James D. McFarland, CA, USA



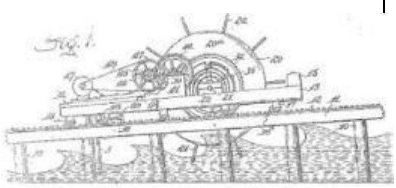
Mechanism for the obtainment of motive power from the waves of the ocean, lakes, or other large bodies of water
US Patent: 1,045,654, Nov. 1912
Inventor: John Willy, CA, USA



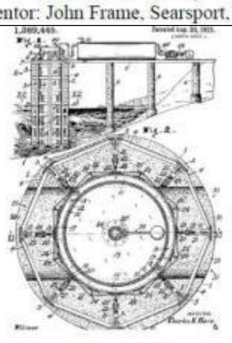
Wave Motor
US Patent: 1,061,061, May 1913
Inventor: John Frame, Searsport, ME



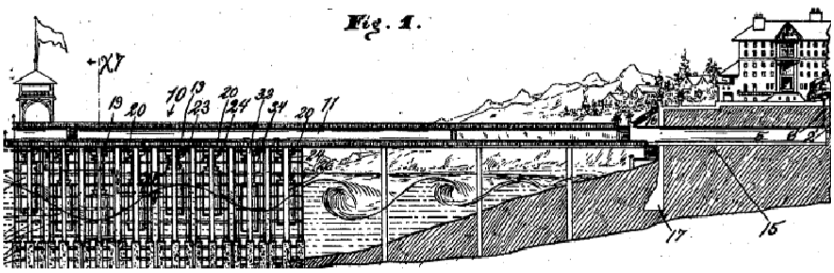
Wave Motion Motor
US Patent: 1,078,323, Nov. 11, 1913
Inventor: L. A. Trull, NH, USA



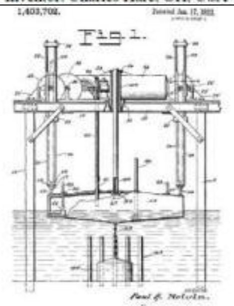
Wave Motor
US Patent 1,289,533, Dec. 31, 1918
Inventor: Benjamin H. Pelton, CA, USA



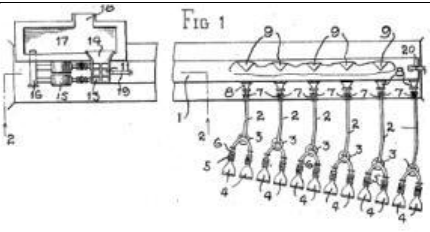
Ocean Compressed Air Power
US Patent: 1,389,445, Aug. 30, 1921
Inventor: Charles Hare, OH, USA



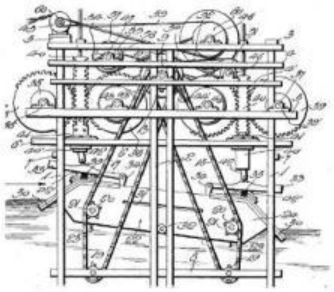
Ocean Compressed-Air Power
US Patent: 1,623,341, August, 17, 1921
Charles N. Hare, OH, USA



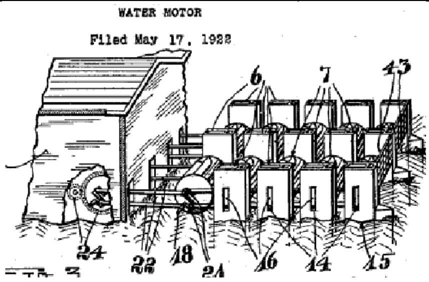
Water Motor
US Patent: 1,203,702, January 1922
Inventor: Paul Melvin, IL, USA



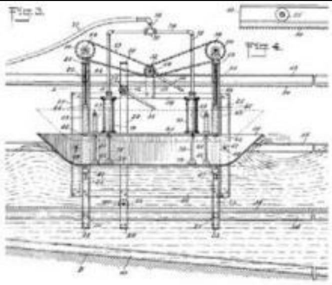
Method of and Apparatus for Obtaining Power from the Surf
US Patent: 1,418,680, June 1922
Inventor: William Scott, NJ, USA



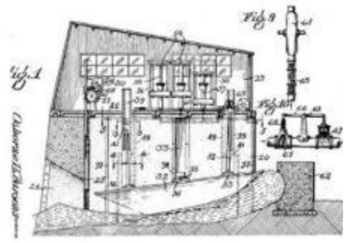
Wave Motor
US Patent: 1,471,222, October 1923
Inventor: William M. Taylor, VA, USA



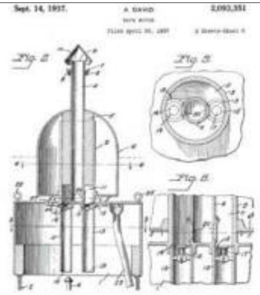
Water Motor
US Patent: 1,498,707, June 1924
Inventor: Frederick Wilcott, CA, USA



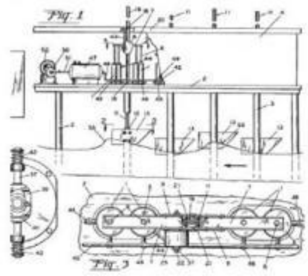
Wave Motor
US Patent: 1,647,025, June 7, 1927
Inventor: Ferdinand Stich, NY, USA



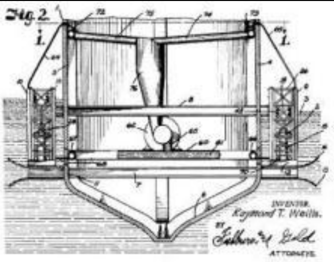
Wave Motor
US Patent: 1,930,958, October 17, 1933
Inventor: Osborne Parsons, Nova Scotia, Can



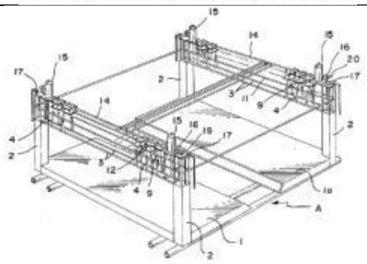
Wave Motor
US Patent: 2,093,351, Sept. 14, 1937
Inventor, Andrew David, Wash. DC, USA



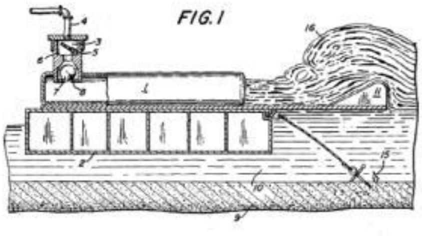
Ocean Wave Air Compressor
US Patent: 2,706,077, April 12, 1955
Inventor: Seral Searcy, OR, USA



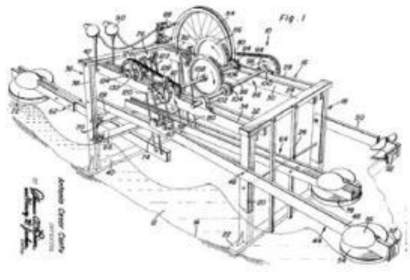
Buoy Motor
US Patent: 2,871,790, Feb. 3, 1959
Inventor: Raymond Weills, TX, USA



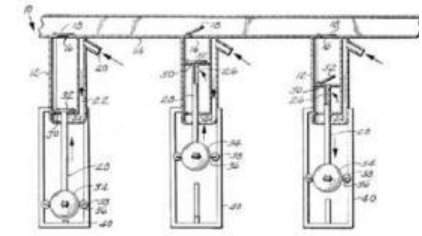
Wave Power Generator
US Patent: 5,499,889, March 19, 1966
Inventor: Myung-Shik Yim, Korea



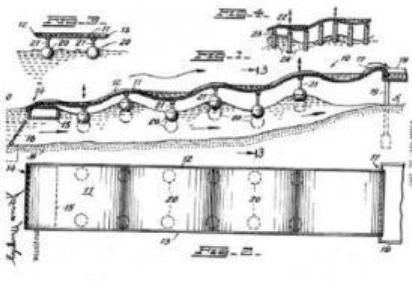
Air Compressors Utilizing the Kinetic and Potential Energy of Water Waves Common to Bodies of Water
US Patent: 3,149,776, Sept. 22, 1964
Inventor: William Parrish, CA, USA



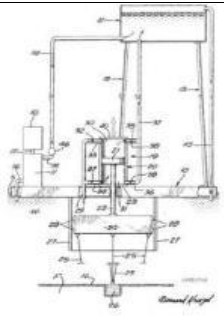
Ocean Wave Energy Generator
US Patent: 3,259,361, July 5, 1966
Antonio Cantu, Mexico



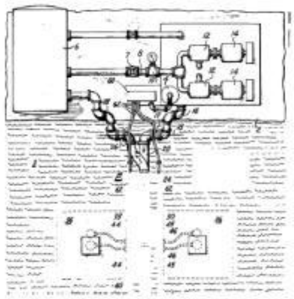
Ocean Powered Compressor
US Patent: 3,268,154, August 23, 1966
Inventor: Gyula Aranyi, PA, USA



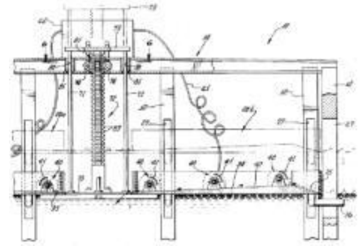
Wave Machine and Means for Raising Water
US Patent: 3,335,667, Aug. 15, 1967
Inventor: James Murphy, NY, USA



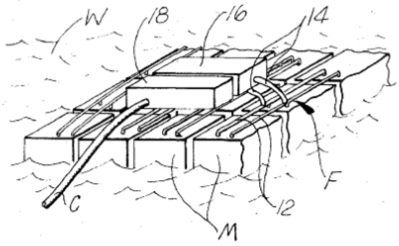
Power Generating System
US Patent: 3,487,228, Dec. 30, 1969
Bernard Kriegel, CA, USA



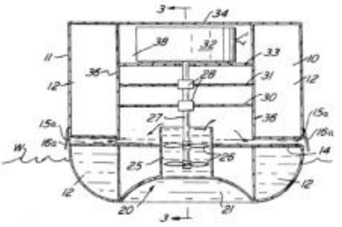
Wave Operated Power Apparatus
US Patent: 3,603,804, September 7, 1971
Inventor: Jesse Casey, AL, USA



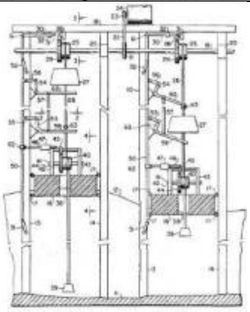
Electrical Power Plant Driven by
Ocean Waves and Tides
US Patent: 3,746,875, July 1973
Inventor: Joseph Donatelli, CA, USA



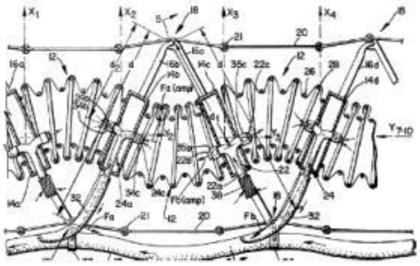
Conversion System for Providing Useful Energy
Water Surface Motion
US Patent: 3,758,788, Sept. 1973
Inventor: Dale Richeson, HI, USA



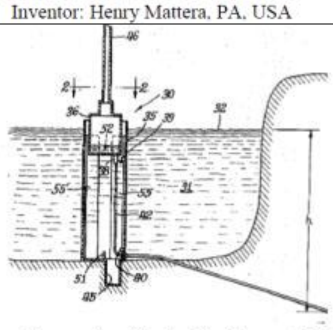
Wave Operated Power Plant
US Patent: 3,870,893, Mar. 11, 1975
Inventor: Henry Mattera, PA, USA



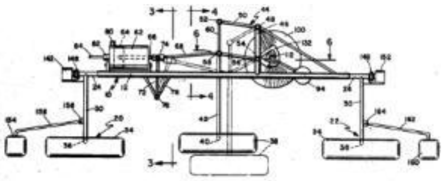
Wave Action Power Source
US Patent: 3,894,241, July 8, 1975
Inventor: Saul Kaplan, PA, USA



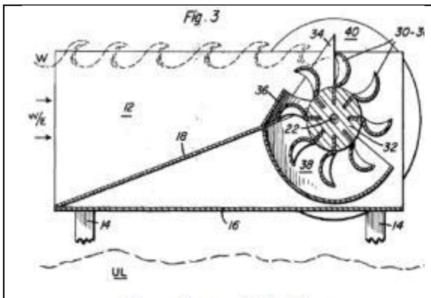
Water Action Powered Pump
US Patent: 3,961,863, June 8, 1976
Inventor: Lee Hooper III, FL, USA



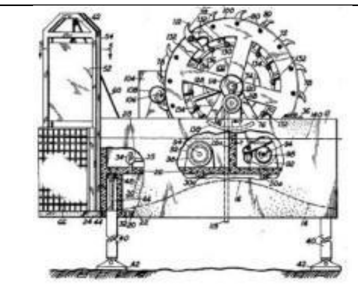
Energy Converting Hydraulic Buoyant Motor
US Patent: 3,961,479, June 8, 1976
Inventor: Ray C. Anderson, OK, USA



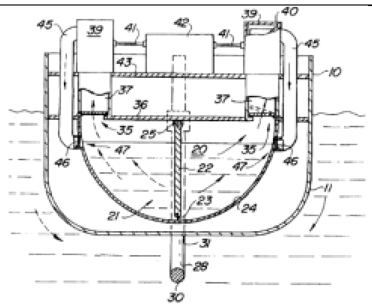
Power Generating Machine Actuated
by Ocean Swells
US Patent: 3,965,365, June 22, 1976
Inventor: Edward Parr, CA, USA



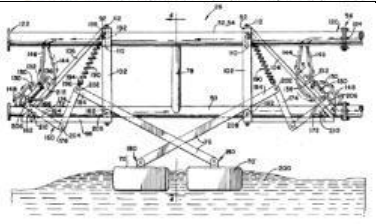
Wave Energy Machine
US Patent: 3,965,679, June 29, 1976
Inventor: Erasmus Paradiso, NY, USA



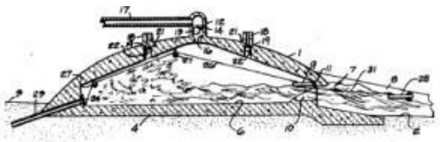
Wave and Current Operated Power Generating Device
US Patent: 4,001,596, Jan. 4, 1977
Inventor: Earl Kurtzbein, WA, USA



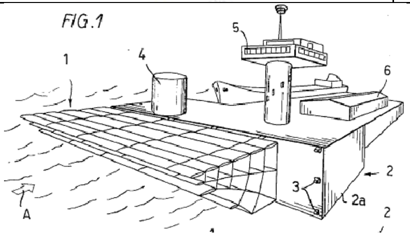
Wave Operated Power Plant
US Patent: 4,00,396, Feb. 22, 1977
Inventors: Mattera & Pitts, PA, USA



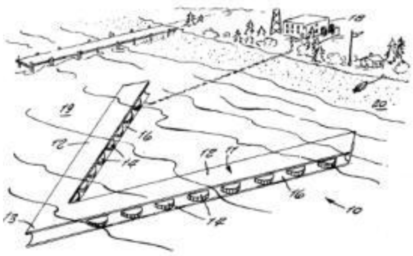
Wave Power Apparatus Supported by Floats in Water
US Patent: 4,013,382, Mar. 22, 1977
Inventor: Richard Diggs, MO, USA



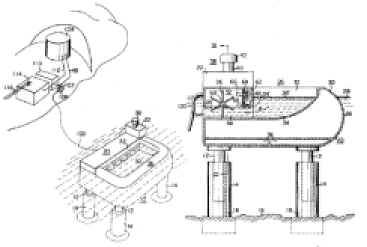
Shoreline Air Compressors wherein swell water pumps the air
US Patent 4,022,549, May 10, 1977
Inventor: Harold Gregg, CA, USA



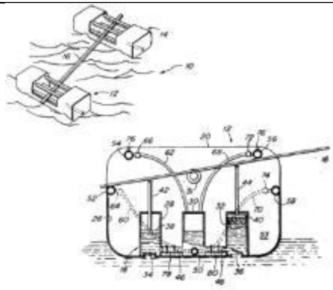
Wave Motor Comprised of a Submerged Floating Network of Chambers Formed by Walls Permitting Variable Geometry
US Patent: 4,036,563, July 1977
Inventor: Rolf Tornkvist, Finland



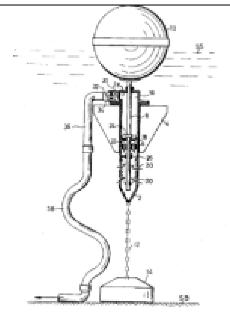
Ocean Tide and Wave Energy Converter
US Patent: 4,034,231, July 5, 1977
Inventor: John L. Conn, G. Spector, NY, USA



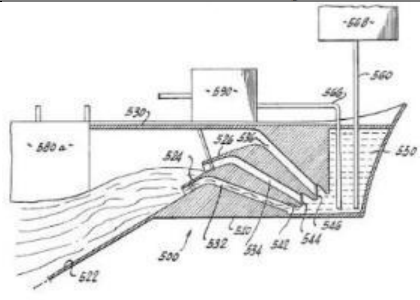
Transducer For Conversion of Sea Water Energy
US Patent: 4,060,344, Nov. 29, 1977
Inventor: Fumio Ootsu, Japan



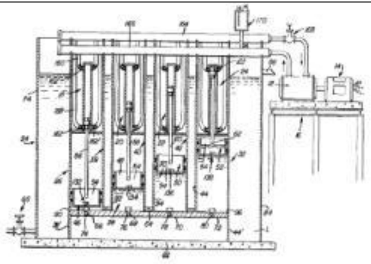
Dual Wave Motion Pump
US Patent: 4,076,464, Feb. 28, 1978
Inventor: Paul E. Pinney, NJ, USA



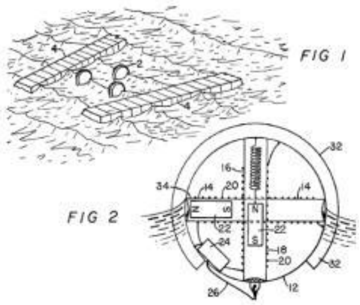
Wave Motor
US Patent: 4,076,463, Feb. 28, 1978
Inventor: Mordechai Welczer, Israel



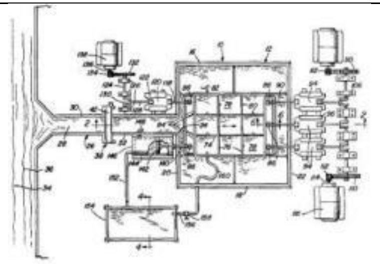
Sea Wave Energy Conversion
US Patent: 4,078,871, Mar. 14, 1978
Inventor: Clifford Perkins, CA, USA



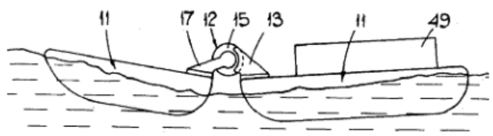
Apparatus and Method for Converting Hydrostatic Energy to Electrical Energy
US Patent: 4,083,186, April 11, 1978
Inventor: Andrew W. Jackson, AL, USA



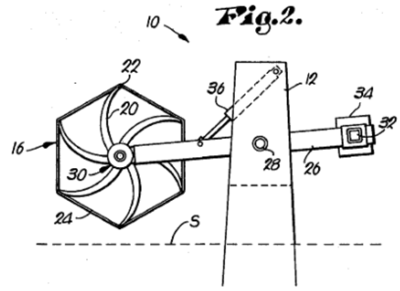
Wave Powered Electric Generator
US Patent: 4,110,630, Aug. 29, 1978
Inventor: Frank J. Hendel, CA, USA



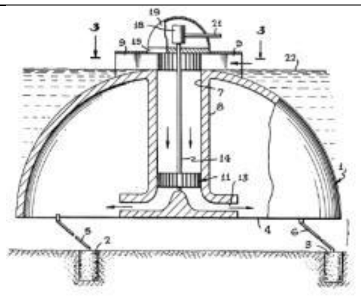
Wave Motor
US Patent: 4,108,579, August 1978
Inventor: Antero & Estrella Martinez
Dominican Republic



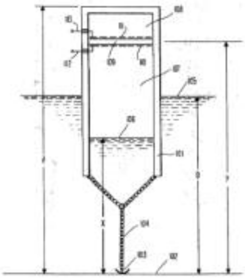
Energy Conversion Systems
US Patent: 4,118,932, Oct. 1978
Assignee: Lucas Industries, England



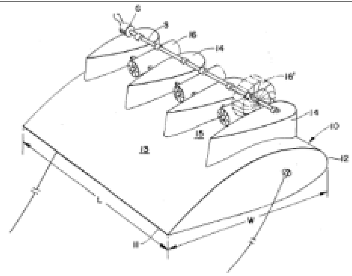
Oceanic Wave Powered Prime Mover
US Patent: 4,137,005, Jan.30, 1979
Inventor: Walter Comstock, KS, USA



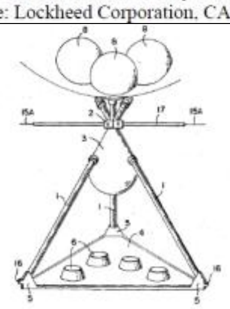
Wave Powered Motor
US Patent: 4,152,895, May 1979
Assignee: Lockheed Corporation, CA, USA



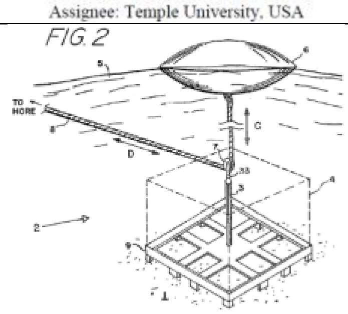
Process for Conversion of Ocean Wave Energy into Electric Power and Apparatus
US Patent: 4,178,517, Dec. 11, 1979
Assignee: Temple University, USA



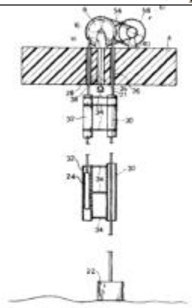
Method and Apparatus for obtaining useful work from Wave Energy
US Patent: 4,179,886, Dec. 25, 1979
Inventor: Juniro Tsubota, Japan



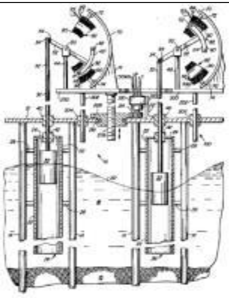
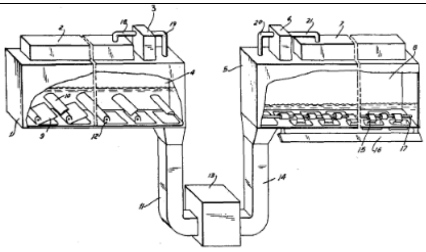
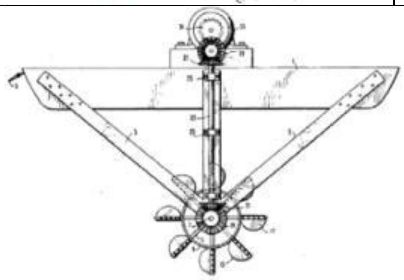
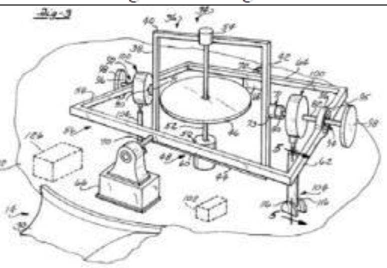
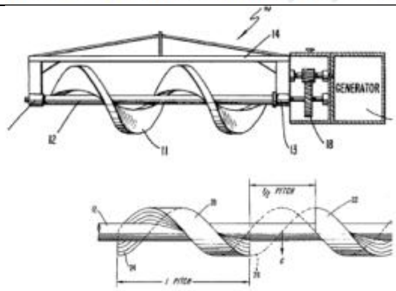
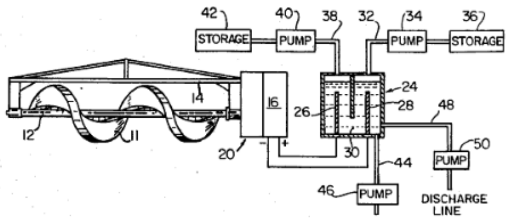
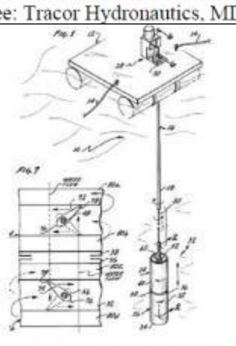
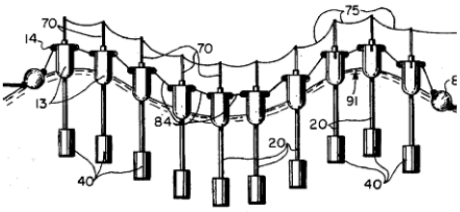
Ocean Wave Energy Converter
US Patent 4,232,230, June 14, 1980
Inventor: Foerd Ames, NY, USA

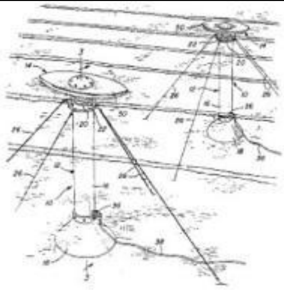


Wave Motion Apparatus
US Patent: 4,228,360, October 14, 1980
Inventor: Pablo Navarro, FL, USA

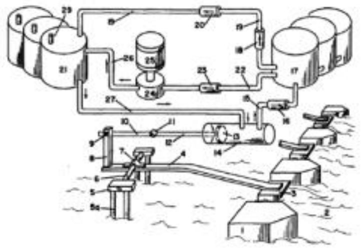


Device for Converting Sea Wave Energy into Electrical Energy
US Patent: 4,242,593, Dec. 30, 1980
Inventor: Quilico, & Troya, Italy

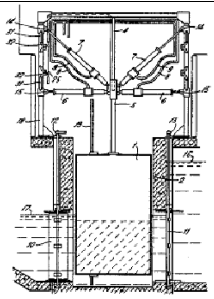
 Wave Operated Electrical Generation System US Patent: 4,260,901, April 7, 1981 Inventor: David Woodbridge, MD, USA	 Sea and Ocean Wave Energy Converter US Patent: 4,345,434, Aug. 24, 1982 Assignee: Institute Za Yadreni Izslednania I Yadrena Energetica – Bulgaria
 Ocean Wave Energy Converter US Patent: 4,359,868, Nov. 23, 1982 Inventor: David M. Slonim, FL, USA	 Mechanism for Generating Power from Wave Motion on a body of water US Patent: 4,352,023, Sept. 28, 1982 Inventors: H. and G. Sachs, MI, USA
 Wave Energy Converter US Patent: 4,412,417, Nov. 1983 Assignee: Tracor Hydronautics, MD, USA	 Apparatus for Storing the energy of Ocean Waves US Patent: 4,384,212, May 17, 1983 Assignee: Laitram Corp. LA, USA
 Apparatus for Harvesting Wave Energy US Patent: 4,462,211, July 31, 1984 Inventor: Hal Linderfelt, CA, USA	 FIG. 9. Wave Response Generator US Patent: 4,447,740, May 8, 1984 Inventor: Louis Heck, LA, USA



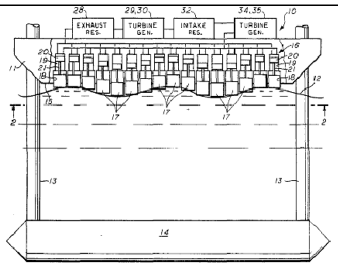
Wave Activated Generator
US Patent: 4,539,485, Sep. 3, 1985
Inventor: V. Neuenschwander, NM, USA



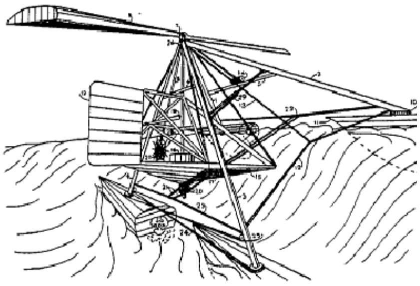
Method of Converting Ocean Energy Action Into Electrical Energy
US Patent: 4,454,429, June 12, 1984
Inventor: Frank Buonome, CT, USA



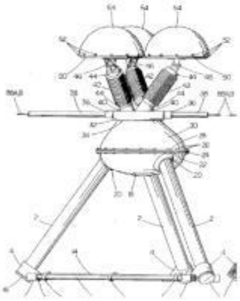
Water Engine
US Patent: 4,586,333, May 6, 1986
Assignee: Aur Hydropower, Ltd.



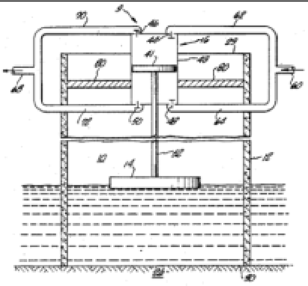
Wave Action Power Generator Platform
US Patent: 4,622,473, Nov. 1986
Inventor: Adolph Curry, AK, USA



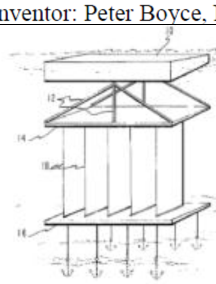
Ocean Wave Energy Converting Vessel
US Patent: 4,608,497, Aug. 26, 1986
Inventor: Peter Boyce, NJ, USA



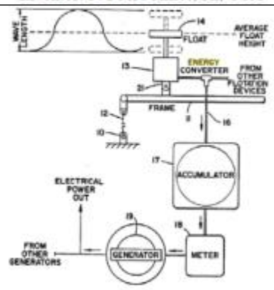
Ocean Wave Energy Converter
US Patent: 4,672,222, June 9, 1987
Inventor: P. Foerd Ames, RI, USA



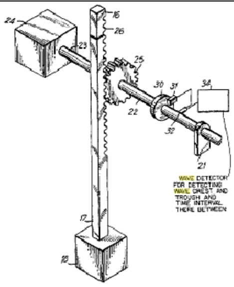
Wave Power Converter
US Patent: 4,698,969, October 13, 1987
Assignee: Wave Power Industries, CA, USA



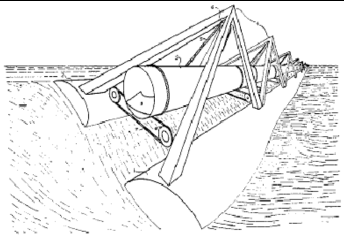
Ocean Wave Energy Conversion Using Piezoelectric Material Members
US Patent: 4,685,296, August 11, 1987
Inventor: Joseph Burns, NJ, USA



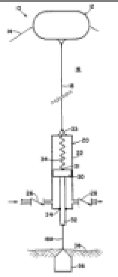
Wave Energy Engine
US Patent: 4,742,241, May 3, 1988
Inventor: Kenneth P. Melvin, CA, USA



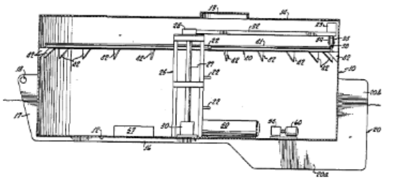
Ocean Wave Energy Device
US Patent: 4,599,858, July 15, 1988
Inventors: J. La Stella & Tornabene, NY, USA



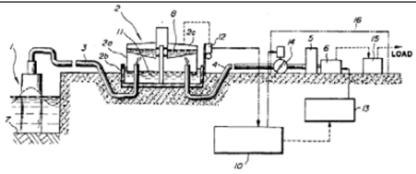
Ocean Wave Energy Extracting Erosion Reversal and Power Generation System
US Patent: 4,748,338, May 31, 1988
Inventor: Peter Boyce, NJ,



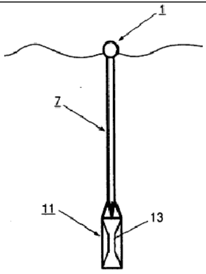
Float Type Wave Energy Extraction Apparatus and Method
US Patent: 4,754,157, June 28, 1988
Inventor: Tom Windle, OK, USA



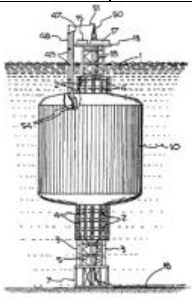
Wave Action Power Generator
US Patent: 4,843,250, June 27, 1989
Assignee: JSS Scientific Corp., CA, USA



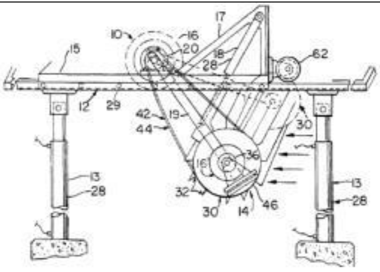
Method and Apparatus for Generating Electricity Using Wave Energy
US Patent: 5,027,000, June 25, 1991
Assignee: Takenaka Corp., Japan



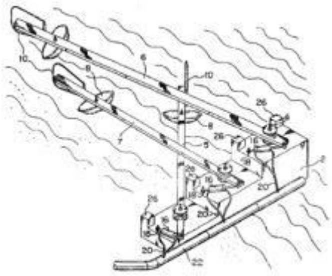
Ocean Wave Energy Conversion Device
US Patent: 5,136,173, August 1992
Assignee: Scientific Applications & Research Associates, Inc. CA, USA



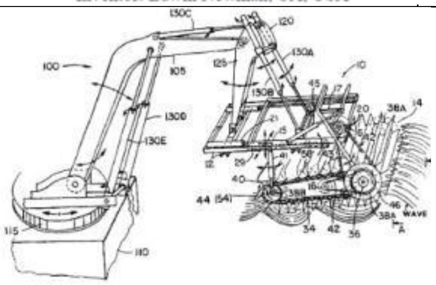
System for Undersea Wave generation of Electric Power
US Patent: 5,324,988, Jan. 28, 1994
Inventor: Edwin Newman, CA, USA



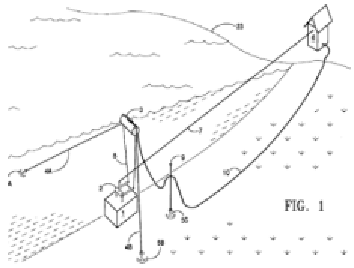
Equipment to Extract Ocean Wave Power
US Patent: 5,311,064, May 10, 1994
Inventor: Bogumil Kumbatovic, NY, USA



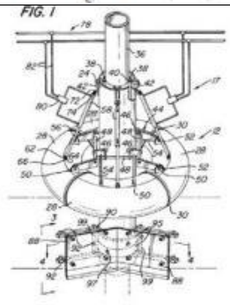
Ocean Wave Energy Conversion System
US Patent: 5,708,305, Jan 13, 1998
Inventor: Douglas Wolfe, VA, USA



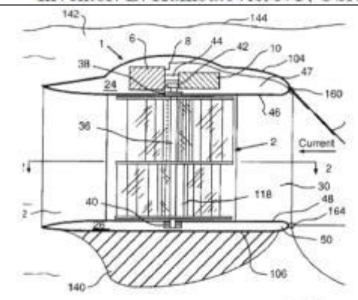
Equipment to extract ocean wave power
US Patent: 5,789,826, Aug. 4, 1998
Inventor: B. Kumbatovic, NY, USA



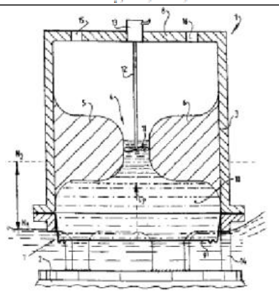
Ocean Wave Energy Conversion Device
US Patent: 5,808,368 , Sept. 15, 1998
Inventor: Clifford Brown
Washington, DC, USA



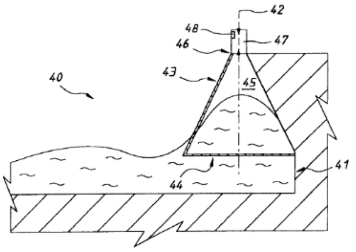
Wave Enhancer For A System For Producing Electricity From Ocean Waves
US Patent: 5,986,349, Nov. 16, 1999
Inventor: William Eberle, TX, USA



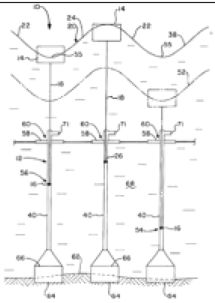
Submersible Apparatus for Generating Electricity
US Patent: 6,109,863, Aug. 29,2000
Inventor: Larry Milliken, PA, USA



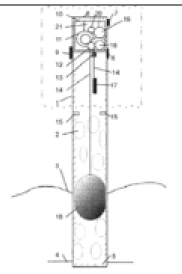
Apparatus for the Conversion of Energy from the Vertical Movement of Seawater
US Patent: 6,216,455 B1, Apr. 2001
Inventors: Doleh & Lock, Dubai, UAE



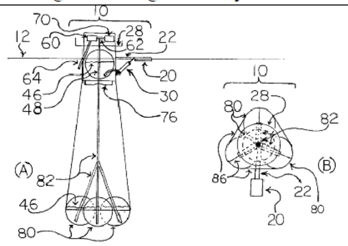
Ocean Wave Energy Extraction
US Patent: 6,360,534 B1, Mar. 26, 2002
Assignee: Energetech, Pty, Australia



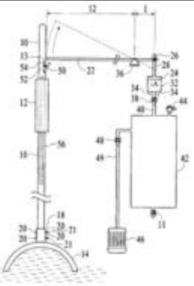
Hydro Electric Plant
US Patent: 6,388,342 B1, May 14, 2002
Inventor: Richard Vetterick Sr.& Jr. NY, USA



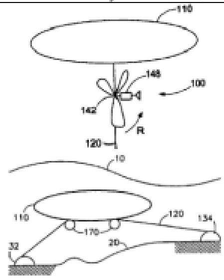
Able Technologies, LLC
Electricity Generating Wave Pipe
US Patent 6,476,512: Nov. 5, 2002
Inventor: Stanley Rutta, NJ, USA



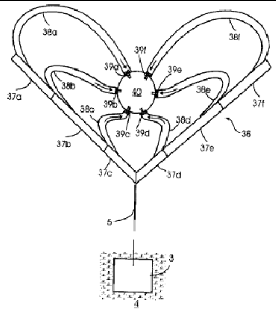
Ocean Wave Power Generator "Modular Power-Producing Network"
US Patent: 6,647,716 B2, Nov. 18, 2003
Inventor: Secil Boyd, HI, USA



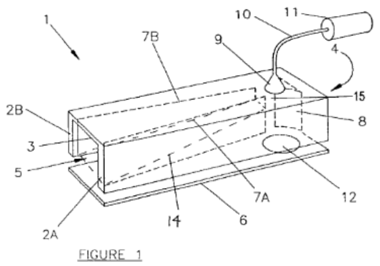
Tidal / Wave Compressed Air Electricity Generation
US Patent: 6,574,957 B2, June, 10, 2003
Inventor: Donald Brumfield, CA, USA



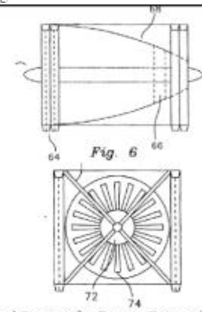
Method of and Apparatus for Wave Energy Conversion Using Float w/ Excess Buoyancy
US Patent 6,756,695 B2, June, 29, 2004
Assignee: Aerovironments Inc. CA, USA



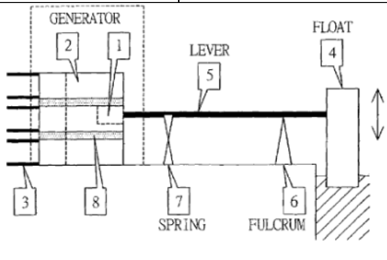
Plant for Utilizing the Energy In Sea Waves
US Patent: 6,527,504, B1, Mar. 4, 2005
Assignee: Waveplane Intl., Denmark



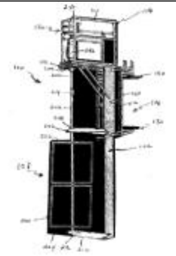
Apparatus for Deriving Energy from Waves
US Patent: 6,922,993 B2, Aug. 2, 2005
Inventor: John F. Kemp, England



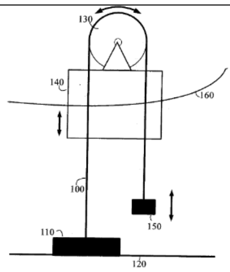
Machine and System for Power Generation through the movement of Water
US Patent 6,955,049 B2, Oct. 18, 2005
Inventor: Wayne F. Krouse, TX, USA



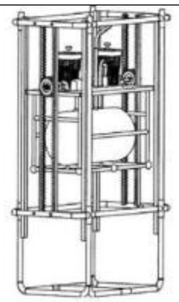
Apparatus For Converting Ocean Wave Energy Into Electric Power
US Patent: 7,012,340 B2, March 14,2006
Assignee: Kun Shan University, Taiwan



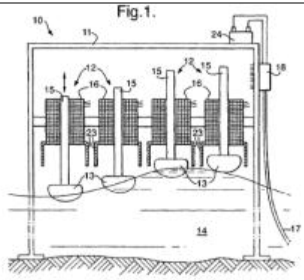
Single Sided Power Generator Support Frame
US Patent Ap.US2006/0251510 A1, Nov. 2006
Assignee: Verdant Power, VA, USA



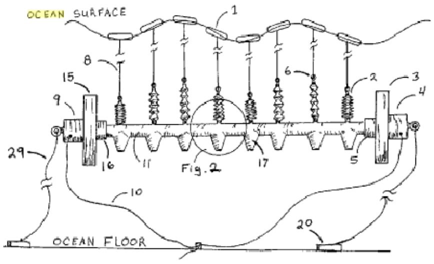
Method & Apparatus for Wave Energy Conversion floating pulley & Counterweight
US Patent Ap: US2007/0018458, Jan. 25, 2007
Inventor: Melaquinas Martinez, MA, USA



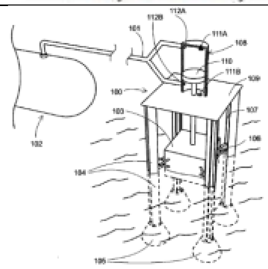
Integrated Ocean Wave Harness Unit
US Patent: US 2007/0089682 A1, Apr. 2007
Inventor: Reynaldo Mariansky CA, USA



Method of Operation for a Self Protecting Wave Energy Conversion Plant
US Patent: 7,242,106 B2, Jul. 10, 2007
Inventor: Hugh-Peter Kelly, Essex, GB, UK



Ocean Wave Energy Converter
US Patent: 7,245,041 B1, July, 17, 2007
Inventor: Chris Olson, TX, USA



Wave Power Generator
US Patent Ap. US2007/0130929A1
Inventors: Ghazi Khan, Shabnaz Khan
Lincoln, CA, USA

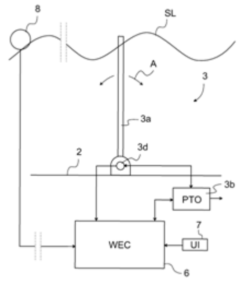
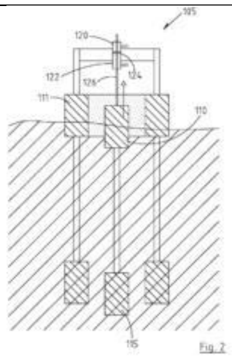


Fig. 2

Wave Energy Recovery System
PCT/FI2010/050255, October 6, 2011
Inventors: Matti Vuorinen, Erkki Kasanen, Hyvinkää (FI)



A Wave Energy Conversion System
US Patent 20120096846 A1,
April 26, 2012
Assignee: Wavebob Ltd., IE

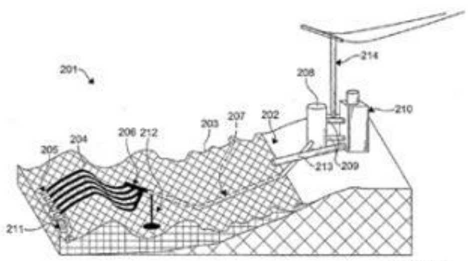


FIG. 2A

An Improved Free Floating Wave Energy Converter
PCT/IN2012/000510, January 31, 2013
Inventors: Mohammed Syed Ghouse, Hyderabad, IN

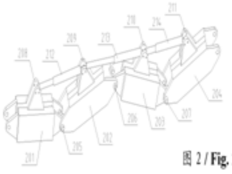
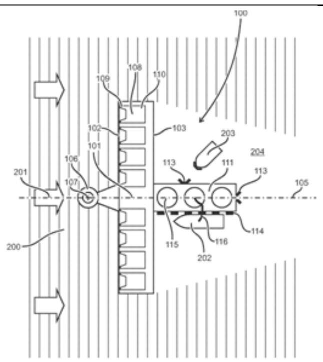
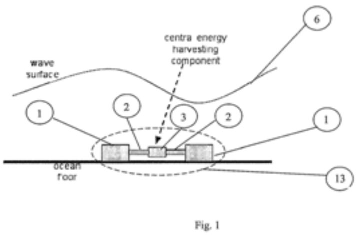


图 2 / Fig. 2

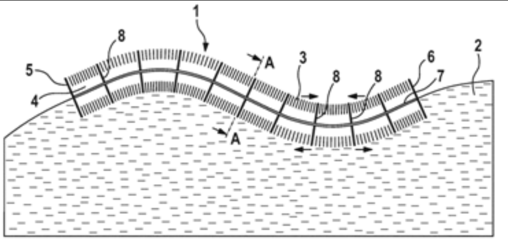
Floating Water Wave Energy Collecting and Transducing System
PCT/CN2012/076282,
January 31, 2013
Inventors: Wanzhang Dong, Guilin Wang, Beijing, CN



Off-shore Platform For Safe Transfer Of Personnel And Goods
PCT/DK2012/050263,
January 17, 2013
Assignee: FLOATING POWER PLANT A/S, DK



Submerged Wave Energy Converter
PCT/US2011/046222
February 7, 2013, US
Inventors: Michael Morrow, Michael Delos-Reyes, USA



Flexible Structure For Generating Electrical Energy From Wave Motions
PCT/EP2012/063888, February 7, 2013,
Inventors: Gabriele Michalke, Benjamin Hagemann, Matthias, Grauer, Istvan Denes, Stuttgart, DE

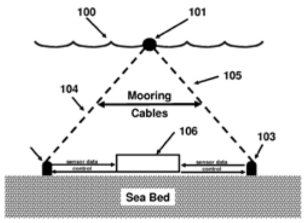
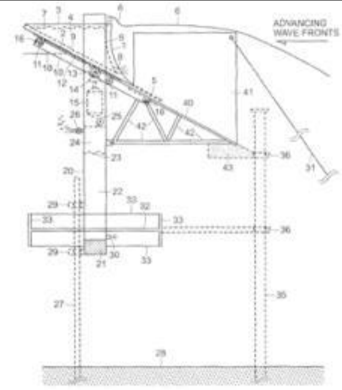
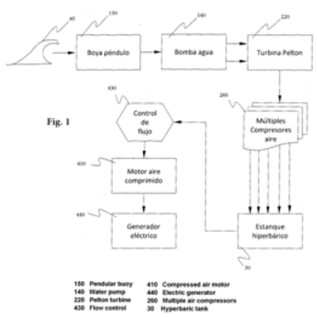


Fig. 1

Optimized Control OF Multiple-PTO Wave-Energy Converters
PCT/US2012/052357,
February 28, 2013,
Inventor: William, P. Staby, Jeffrey, T. Scruggs, Steve M. Lattanzio, USA



Submergible sloped absorption barrier wave energy converter
PCT/US2012/053590, March 7, 2013
Inventor: John, W. Rohrer, Portsmouth, USA



Wave-power Electricity Generation System
PCT/CL2012/000045, March 7, 2013
Inventor: Egaña Castillo, Eduardo Javier, CL

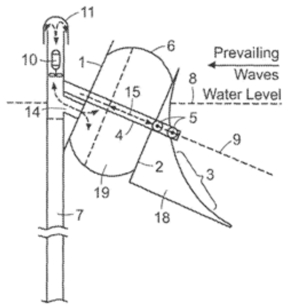


FIG. 7

Ocean Wave Energy Converter with Multiple Capture Modes
US Patent: US 2012/0032446 A1, March 07, 2013
Inventor: John W. Rohrer, USA

13 Wave energy test centers

Many facilities from small wave flumes to full scale test sites are required in order to successfully complete the structured development programme.

The purpose of wave energy test sites is to make this process technically and financially easier for device developers to conduct the extensive and expensive full scale testing of devices in real sea conditions. EU funded Waveplam (WAVEPLAM, 2009), SOWFIA project (SOWFIA, 2011) and EquiMar project (EquiMar, 2011a) provides a detailed overview of the test centres that are currently operational. Fig. A.3 shows the distribution of these centres across Europe. This is followed by the test site characteristics, as shown in Table (A.6-8). It should be noted that the centres are colour coded based on their scale. More detailed information about the wave energy test sites can be found in SOWFIA (2011) and EquiMar (2011a).

In addition to Europe, there are also other wave energy test sites worldwide. Northwest National Marine Renewable Energy Centre (NNMREC) of USA, which is based at Oregon State University has recently announced that Newport, Oregon will become home of the Pacific Marine Energy Centre (PMEC) (http://oregonstate.edu/ua/ncs/archives/2013/jan/newport-selected-home-pacific-marine-energy-center). PMES will be the first utility-scale grid connected test site in the USA.

As the cost of testing from small scale to full scale is increasingly expensive, MARINET network (http://www.fp7-marinet.eu/) has been created. MARINET is a European Commission-funded network of world-class marine renewable energy research centres that have come together in order to accelerate the development of marine renewable energy. The network initiative will run for four years until 2015. It was formed by the pioneering marine energy research centres in order to accelerate marine renewable R&D at all scales by giving free-of-charge access to the facilities for a period of time and conducting joint activities in parallel to standardise testing, improve testing capabilities and enhance training and networking. Table A.9 shows the list of facilities available within MARINET action. Further information on the MARINET program and the facilities can be found at MARINET website.

In order to accelerate the marine energy, a number of new facilities for scaled tank-testing stages of technology development are also being built. For example, FloWave TT (a subsidiary of the University of Edinburgh) is scheduled to complete construction of an onshore tank test facility in 2014 (Krohn et al., 2013). An agreement with EMEC was made on the sharing of site data to be able to replicate sea conditions in the tank. FloWave TT will allow wave energy concepts to be tested at a small scale, with representative site conditions.

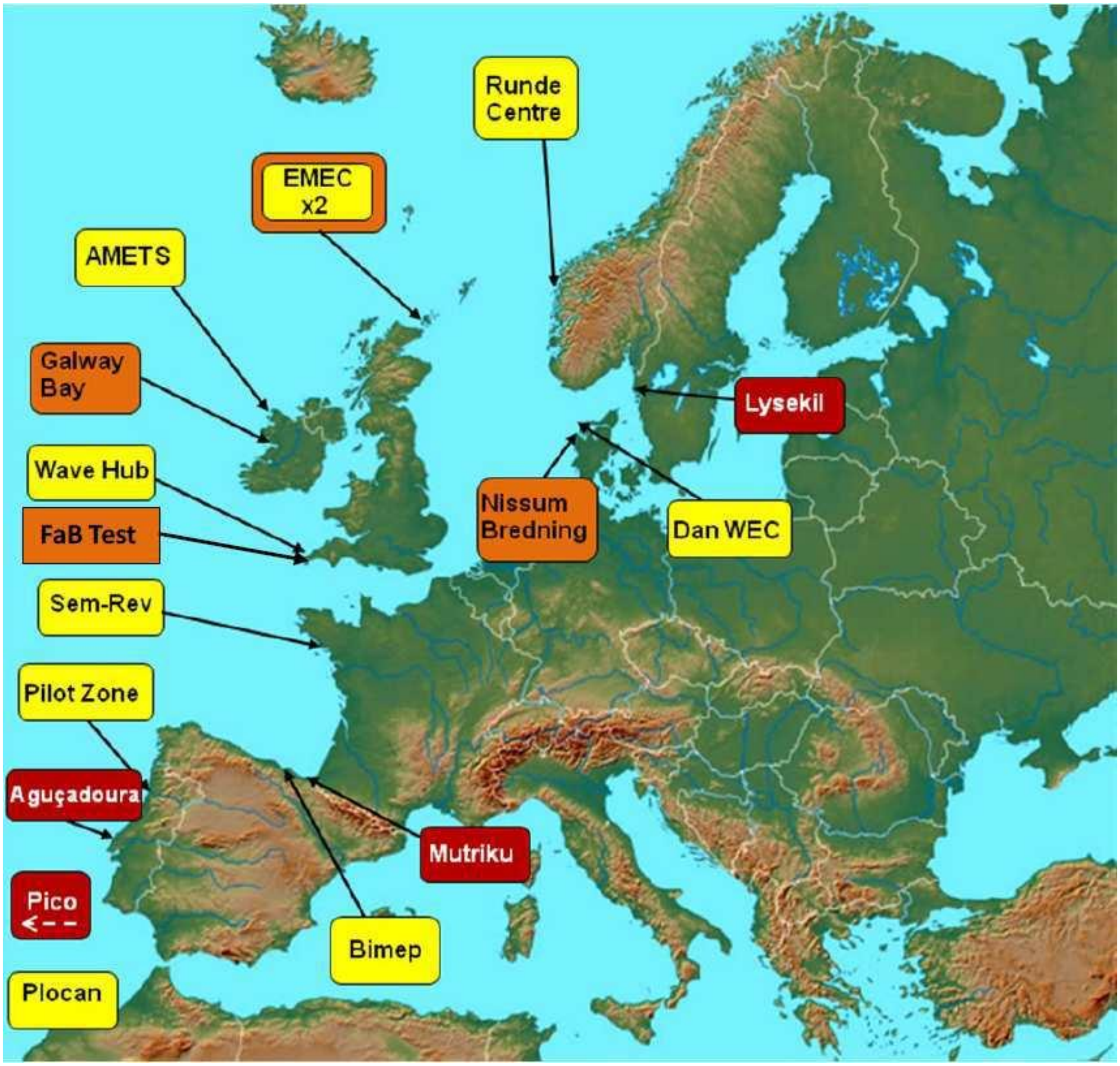


Fig. A. 3: Distribution of test centres across Europe (SOWFIA, 2011).

Table A. 6: Full scale test centres across Europe (After SOWFIA, 2011)

Country	Location	Name	Est'd	Seabed Area	Water Depth	Energy flux	Dist. To shore	Port/harbour Distance	Stage	Grid Connection
Denmark	Roshage Pier, Hanstholm	DanWEC	2009	1 km^2	12 m	5 kW/m	200 km	Hanstholm, 1.5 km	3/4	Yes
England	St. Ives Bay, Cornwall,	WaveHub	2010	8 km^2	50 – 65 m	~20 kW/m	16 km	Plymouth, 160 km Falmouth, 100 km St. Ives, 9 km	4/5	Yes, 33 kV
France	Le Croisic, Pays de la Loire	SEMREV	2007	1 km^2	35 – 40 m	14.5 kW/m	15 km	Le Croisic, 18 km	4/5	Yes, 20 kV
Ireland	Belmullet Co. Mayo	Atlantic Marine Energy Test Site (AMETS)	In planning since 2009	Area A: 10.5 km^2 Area B: 6.5 km^2	50 – 120 m	Area A: H_s= 2.5 m Area B: H_s= 3.2 m	7 km	Galway Ciry, 190 km Killybegs, 125 km	4/5	Yes, 10 kV planned
Norway	Runde Island, Runde, west Norway	Maren Test Site	2008		45 m	40 - 50 kW/m	400 m	25 km SW of Aalesund	3/4	Yes, 22 kV
Portugal	Figueria da Foz	Portuguese Pilot zone	2007	320 km^2	30 – 90 m	30 - 40 kW/m	5 – 8 km	Leixoes, 148 km Peniche, 63 km Fig. da Foz, 37 km	4	Yes
Scotland	Orkney	EMEC	2002	5 km^2	20 – 75 m	22 - 25 kW/m	1 – 2 km	Stromness, 8 km Kirkwall, 23 km Lyness, 20 km	4	Yes, 11 kV
Spain	Armintza, Basque Country	BIMEP	Operational by 2013	5.2 km^2	50 – 90 m	21 kW/m	1.7 km	Bilbao, 10 km	4/5	Yes, 13.2 kV
Spain	Canary Islands	Canary Islands Oceanic Platform: Plocan	Operational by 2014	40 km^2	30 – 1000 m	8 - 10 kW/m	1- 12 km	Las Palmas Port, 10 km Arigana Port, 21 km Talibarte Port, 8 km	3/5	Yes, 20 kV

Table A. 7: Large scale test centres across Europe (After SOWFIA, 2011)

Country	Location	Name	Est'd	Seabed Area	Water Depth	Energy flux	Dist. To shore	Port/harbour Distance	Stage	Grid Connection
Denmark	Nissum Bredning	Danish Benign Test Site	2000		4 – 8 m	H_s= 1.2 m	200 m	Thyboron, 7.5 km	3	Yes
Ireland	Spiddal, Co. Galway	Galway Bay	2006	0.37 km^2	21 – 24 m	3 kW/m	2.4 km	Killybegs, 200 km Foynes, 150 km Galway City, 15 km	3	No
Scotland	Orkney	EMEC –nursery	2011	0.36 km^2	21 – 25 m	H_s= 0.35 m	~500 m	Stromness, 8 km Kirkwall, 23 km Lyness, 20 km	3	No
England	Falmouth Bay, Cornwall	FaBTest	2011	2 km^2	20 – 50 m	In progress	3 – 5 km	Falmouth, 5 km	3	No

Table A. 8: Demonstration sites across Europe (After SOWFIA, 2011)

Country	Location	Name	Est'd	Seabed Area	Water Depth	Energy flux	Dist. To shore	Port/harbour Distance	Stage	Grid Connection
Portugal	Pico Is. Azores	Pico Test Plant	1999	--	~10 m	13.4 kW/m	--	Peniche, 1600 km Horta, 16 km	3/4	Yes, 15 kV
Portugal	Aquçadoura	Aquçadoura Wave Farm (shut downed in 2009)	2007		40 – 50 m	32 kW/m	5 km	Peniche, 240 km Leixoes, 32 km Monserrate, 25 km	5	Yes, 6.6 kV
Portugal	Peniche	Peniche Test Site	2007	2 km^2	15 – 20 m	30 kW/m	0.5 km	Peniche	3/4	No
Spain	Basque Country	Mutriku	2011	n/a	< 10 m	4.8 kW/m (summer) 18 kW/m (winter)	onshore	Mutriku	3/4	Yes, 296 kW (16 x 18.5 kW)
Sweden	Lysekil, near Gothenburg	Lysekil Wave Energy Research Site	2003	0.04 km^2	25 m	2.6±0.3 kW/m	2 km	Lysekil harbour, 10 km		Yes, 10 kV

Table A. 9: Wave R&D facilities available within MARINET action (http://www.fp7-marinet.eu/access_facilities-available_category-view.html)

Scale	Wave energy research facilities	Electrical / PTO / Material
Stage 1	Aalborg University – Deep Water Wave Basin Queens's University Belfast – Shallow Water Wave Tank University College Cork-HMRC – Ocean Wave Basin University of Edinburgh – Curved Wave Tank University of Strathclyde – Kelvin Hydrodynamics Laboratory	SINTEF – Renewable energy Lab – Smart grids TECNALIA – Electrical PTO Lab UCC-HMRC – Rotating Test Rig USTUTT – Turbine Test Rig
Stage 2	CNR – INSEAN – Wave Tank Ecole Centrale De Nantes-Hydrodynamic and Ocean Engineering Tank IFREMER – Deep Seawater Wave Tank IFREMER – Wave-Current Circulation Tank National Renewable Energy Centre Ltd. – Large Scale Wave Flume	DTU – Mechanical Test Facilities DTU – PowerLabDK IFREMER – Materials in Marine Environment Lab NAREC – CPTC Development Test Lab NAREC – Nautilus Rotary Test Rig
Stage 3	Aalborg University – Nissum Bredning Test Site European Marine Energy Ltd. – Nursery Wave Test Site Sustainable Energy Authority of Ireland – Galway Bay Test Site	UNEXE – South West Mooring Test Facility
Stage 4 **Stage 5**	EVE – Biscay Marine Platform Sustainable Energy Authority of Ireland – Belmullet Test Site	EVE – Mutriku OWC Plant FH_IWES – Offshore Field Test Facilities WaveC – OWC Pico

14 References

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.

Carbon Trust (2011): Accelerating marine energy: The potential for cost reduction - insights from the Carbon Trust Marine Energy Accelerator. Available at http://www.carbontrust.com/media/5675/ctc797.pdf.

EquiMar (2011a): Deliverable D4.3 test sites catalogue available at https://www.wiki.ed.ac.uk/download/attachments/9142387/Equimar+Test+Sites.pdf?version=1.

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Krohn, D.;Woods, M.;Adams, J.;Valpy, B.;Jones, F.; Gardner, P. (2013): Wave and tidal energy in the UK conquering challenges, generating growth. UK, available at http://www.renewableuk.com/en/publications/reports.cfm/wave-and-tidal-energy-in-the-uk-2013, 32 p.

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SI OCEAN (2012): Ocean Energy: State of the Art. Available at: http://si-ocean.eu/en/upload/docs/WP3/Technology%20Status%20Report_FV.pdf, 78 p.

SOWFIA (2011): Deliverable D.2.1 Catalogue of Wave Energy Test Centres available at http://sowfia.eu/fileadmin/sowfia_docs/documents/D2.1_Annex_Update_Sept_2012.pdf.

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.

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*

Appendix B

Deliverable: D3.3.2	
Nature of the Deliverable:	Report
Due date of the Deliverable:	31.12.2013
Actual Submission Date:	
Dissemination Level:	Confidential
Contributors:	Kaan Koca, Andreas Kortenhaus, LWI
Work Task Leader Responsible:	Barbara Zanuttigh, **UNIBO**
Work Package Leader Responsible:	Inigo Losada, **UC**
Reviewed by:	-

Version	Date	Revised Pages	Description of Changes
1.0	17.12.2013	-	1st Draft released
1.1			
1.2			

Table of contents

15 List of standards and regulations

American Petroleum Institute (API) guidelines and regulations	
Reference	**Title**
API 2F	Specification for Mooring Chain
API RP 2GEO	Geotechnical and Foundation Design Considerations
API RP 2A-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 station keeping systems for floating structures, 2005
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
API RP 95F	Interim Guidance for Gulf of Mexico MODU Mooring Practice – 2007 Hurricane Season, 2nd edition
API	Guide for the certification of offshore mooring chain
Det Norske Veritas	
Reference	**Title**
DNV OS C101	Design of offshore steel structures, general (LRFD method)
DNV RP B401	Cathodic protection design
DNV OS E301	Position Mooring, 2008
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
DNV – Carbon Trust	Guideline on design and operation of wave energy converters, 2005
DNV-OSS-312	Offshore Service Specification Certification of Tidal and Wave Energy Converters, October 2008
DNV-OS-J101	Design of offshore wind turbine structures
DNV-OS-J103	Design of Floating Wind Turbine Structures
International Organization for Standardization (ISO)	
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)

***Table B.1** - Standards, guidelines and regulations which are relevant to WECs (Alawa et al, 2009; Orecca, 2011c; Marina platform, 2012; EI, 2013).*
Part 1 – To be continued

International Organization for Standardization (ISO)	
Reference	**Title**
ISO 19902	Fixed steel offshore structures
ISO 19903	Fixed concrete offshore structures
BS ISO 19904-1	Floating Offshore Structures – Part 1: Monohulls, semi-submersibles and spars
ISO 19905	Site-specific assessment of mobile offshore units
ISO/TR 13637:1997	Petroleum and natural gas industries -- Mooring of mobile offshore drilling units (MODUS) -- Design and analysis
ISO 13819-1	Petroleum and natural gas industries - Offshore structures – Part 1: General requirements
BS-ISO-19901-7	Specific Requirements for Offshore Structures – Station keeping Systems for Floating Offshore Structures and Mobile Offshore Units
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
American Bureau of Shipping	
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)
ABS	Guide for building and classing floating offshore wind turbine installations
ABS	Guide for building and classing bottom founded offshore wind turbine installations
Bureau Veritas (BV)	
Reference	**Title**
BV NR 183	Towage at sea of vessels or floating units
BV NI 199	Cyclic fatigue of nodes and welded joints of offshore units
BV NR 216	Rules on materials and welding for the classification of marine units
BV NR 266	Survey of materials and equipment at works for the classification of ships and offshore units
BV NR 320	Certification scheme of materials and equipment for the classification of marine units
BV NI 422	Type approval of non-destructive testing equipment for the classification of ships and offshore units
BV NI 423	Corrosion protection of steel offshore units and installation
BV NR 426	Construction survey of steel structures of offshore units and installation
BV NI 432	Certification of fiber ropes for deepwater offshore services
BV NR 445	Rules for the classification of offshore units (offshore rules)
BV NR 580	Rules for the classification of floating establishments
BV NR 467	Rules for the classification of steel ships (ship rules)
BV NR 493	Classification of mooring systems for permanent offshore units

Table B.1 *- Standards, guidelines and regulations which are relevant to WECs (Alawa et al, 2009; Orecca, 2011c; Marina platform, 2012; EI, 2013).*
Part 2 – To be continued

Bureau Veritas (BV)	
Reference	**Title**
BV NR 494	Rules for the classification of offshore loading and offloading buoys
BV NI 534	Guidance note for the classification of self-evaluation units
BV NI 537	Guidelines for the design of the means of access for inspection, maintenance and operation of commercial ships
BV NI 539	Spectral fatigue analysis methodology for ships and offshore units
BV NR 546	Hull in composite materials and plywood, material approval, design principles, construction and survey
BV NR 578	Rules for the classification of Tension Leg Platforms
BV NI 198	Underwater welding – general information and recommendations
BV NI 409	Guidelines for corrosion protection of seawater ballast tanks and hold spaces
BV NR 476	Approval testing of welders
BV NR 480	Approval of the manufacturing process of metallic materials
BV NI 572	Classification of offshore floating wind turbines
Lloyd's Register	
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)
Lloyd's Register	Guidance on offshore wind farm certification (including floating offshore wind turbine)
National Association of Corrosion Engineering (NACE)	
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
Mineral Management Service (MMC)	
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

Table B.1 *- Standards, guidelines and regulations which are relevant to WECs (Alawa et al, 2009; Orecca, 2011c; Marina platform, 2012; EI, 2013).*

Part 3 – To be continued

Mineral Management Service (MMC)	
Reference	**Title**
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
Deutsche Institut für Normung (DIN)	
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
Canadian Standard Association (CSA)	
Reference	**Title**
CSA S471	General Requirements, Design Criteria, the Environment and Loads
CSA S474	Concrete Structures, Offshore Structures
CAN/CSA-ISO 19901-6-10	Petroleum and natural gas industries - Specific requirements for offshore structures - Part 6: Marine operations
HSE	
Reference	**Title**
HSE-OTO 2001/048	Floating Installations
British Standards Institution (BSI)	
Reference	**Title**
BS-ISO-19901-7	Specific Requirements for Offshore Structures – Station keeping Systems for Floating Offshore Structures and Mobile Offshore Units
Engineering Equipment & Materials Users (EEMUA)	
Reference	**Title**
EEMUA 158	Construction Specification for Fixed Offshore Structures in the North Sea
Germanischer Lloyd (GL)	
Reference	**Title**
GL	Guideline for the certification of ocean energy converters Part: 1: Ocean Current turbines
International Energy Agency (IEC)	
Reference	**Title**
IEC TC 114	Assessment of mooring systems for marine energy converters
IEC-61400-3	Design requirements for offshore wind turbines
European Marine Energy Centre (EMEC)	
Reference	**Title**
EMEC	Marine Renewable Energy Guides (series of 12 guidelines)

Table B.1 *- Standards, guidelines and regulations which are relevant to WECs (Alawa et al, 2009; Orecca, 2011c; Marina platform, 2012; EI, 2013).*
Part 4 – Finished

16 B. List of standards and regulations

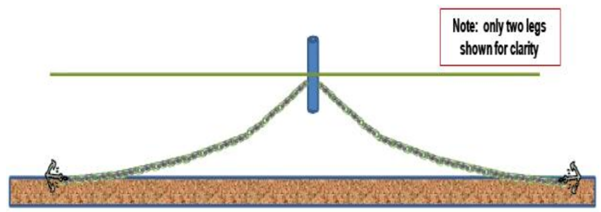
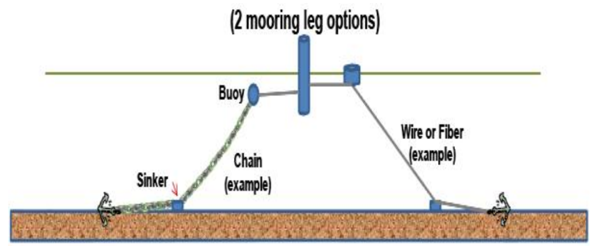
Configuration	Type	Description	Characteristics	Image	Suitability
SPREAD MOORING SYSTEM	Catenary mooring	Mooring lines hang directly from the WEC or from an intermediate surface buoy. Mooring lines are sufficient length/weight to create a near zero line angle at the seabed (in order to enable proper functioning of a drag anchor).	• Most used and simplest. • The horizontal restoring force comes from the weight of the mooring chain being lifted off the seafloor when loaded. • The footprint of this system is large. • WEC or an intermediate surface buoy must resist to the vertical loads • Simple to install but difficult to maintain pretension during life of the WEC. • Line contacts with the seabed can cause wear and may be environmentally unacceptable. • All anchor types can be considered depending primarily on seabed conditions only. • Can be very cost efficient depending on the water depth		High
	Multi-catenary mooring	Mooring lines can be constitued of various line types and include intermediate buoys and sinkers. Lines can arrive at various angles to the seabed.	• Intermediate surface and/or subsurface buoys can be used to limit vertical load at the WEC device. Sinkers can be used to shorten mooring scope. • The horizontal restoring force can come from the weights of line and sinkers being lifted off the seafloor and subsurface buoys being pulled down. • Mooring footprint can be reduced by introducing buoys and sinkers to create a multi-catenary shape. • Steeper line angles at seabed contact are possible. • Anchoring becomes more complicated to the potential need for resisting uplift loading. • Mooring can be tuned to maximize WEC performance.		High

***Table B.2** – Characteristics of possible WEC mooring configurations*
(after Harris et al., 2006; Sound & Sea Technology Engineering, 2009, etc.).
Part 1 – To be continued

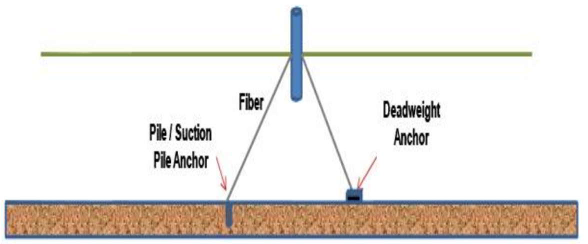
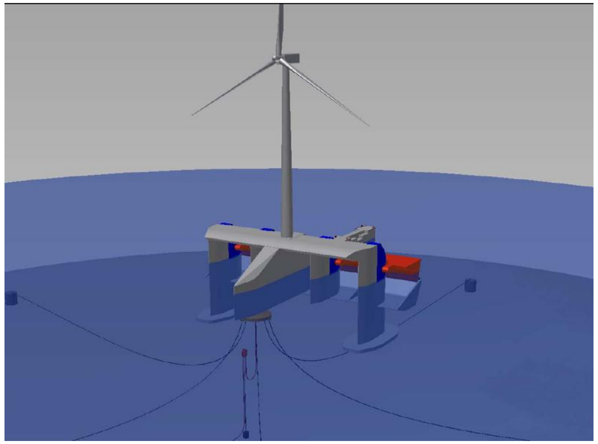
Configuration	Type	Description	Characteristics	Image	Suitability
SPREAD MOORING SYSTEM	Semi-taut spread mooring	Mooring lines arrive at an angle to the seabed. Vertical lines similar to those used with a Tension Leg Platform (TLP) are not considered practical in shallow water.	• Restoring force comes primarily from the elasticity of the mooring line. • High stretch synthetic lines would be required to accommodate tides and waves. • Anchors would be required to resist large vertical and lateral loads. • Anchoring becomes very complicated due to the need to the anchor to resist large vertical and horizontal loads. • The WEC would have to resist large vertical loads. • Installation and maintenance of taut moorings is complicated and costly.		Low
SINGLE POINT MOORING	Turret mooring	An internal or external catenary moored turret attached to a floating structure allows weathervane around the turret	• The turret is in its essence a buoy held in place by three or more mooring lines. The mooring lines are secured with anchors • The mooring would allow the WEC device to weathervane around the connection point. • This will require a large operational footprint and likely preclude use of this type of system when multiple WEC devices are employed in an energy farm. • It is generally suitable for harsh multi-directional environments. Therefore, it is suitable for North sea harsh conditions • The turret system provides a compact load and fluid-transfer system with a minimum number of anchor legs required. • Its design and fabrication requires specialized engineering and manufacturing techniques and knowledge	 Poseidon floating platform (source: http://mhk.pnnl.gov)	Low

***Table B.2** – Characteristics of possible WEC mooring configurations*
(after Harris et al., 2006; Sound & Sea Technology Engineering, 2009, etc.).
Part 2 – To be continued

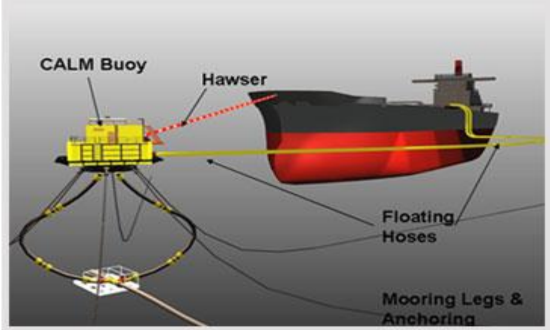
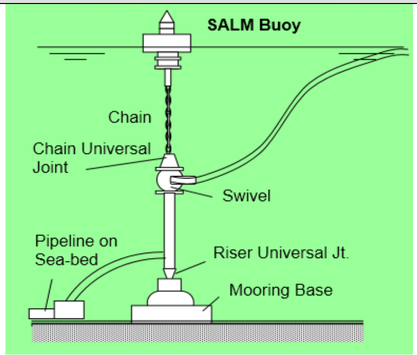
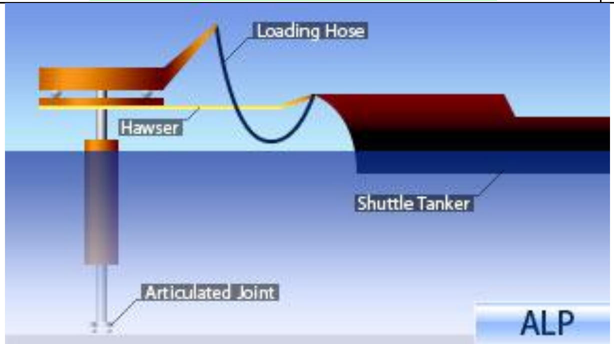
Configuration	Type	Description	Characteristics	Image	Suitability
SINGLE POINT MOORING	Catenary Anchor Leg Mooring (CALM)	The floating structure is moored with a catenary to a buoy and is able to weathervane around the moored buoy.	• Anchored by 4 or more chains extending in catenaries to anchor points • The primary benefit of a CALM Buoy over a SALM Buoy is ease of maintenance • Suitable for shallow and deep water • CALM buoys have been made with a rectangular vertical cross-section which has a relatively high drag resistance • Construction and installation are relatively fast and cheap		High
	Single Anchor Leg Mooring (SALM)	The floating structure is moored to a single anchored taut buoy and is able to weathervane around the moored buoy	• The anchor point may be gravity based or piled • The anchor leg is provided with a swivel which will allow the buoy to rotate according to pull and environmental conditions. • Suitable for shallow water • SALM may inherently lack redundancy so that a catastrophic failure is perhaps more likely than with a catenary moored turret based system		High
	Articulated Loading Column (ALC)	A moored floating structure can weathervane around a bottom hinged column, which has a swivel above the water line	• It has the swivels above the water • The tower system is more stable (statistically and dynamically) than SALM and CALM • In very deep water bending moments become large • An extra column joint can be introduced to reduce bending moments, thus lighter column can be used. The disadvantage doing so is the additional maintenance required and reliability is reduced caused by an extra joint		Medium

***Table B.2** – Characteristics of possible WEC mooring configurations*
(after Harris et al., 2006; Sound & Sea Technology Engineering, 2009, etc.).
Part 3 – To be continued

Configuration	Type	Description	Characteristics	Image	Suitability
SINGLE POINT MOORING	Single Point Mooring and Reservoir (SPAR)	A SPAR allows the storage of a medium (oil, hydrogen) and a floating structure to weathervane around a mooring point	• The mooring allows the WEC device to weathervane around the connection point.		Medium
	Fixed tower mooring	A fixed tower anchored into the seabed allows the moored floating structure to weathervane around the mooring point	• The mooring allows the WEC device to weathervane around the connection point. • They are suitable for applications in shallow and medium range water depths with high currents.		Medium
DYNAMIC POSITIONING	Active mooring	It consists of mooring lines which are spread around the floating structure.	• The inboard end of each mooring line is held by a servo controlled winch. • A central computer tensions or loosens the mooring lines in order to keep a fixed seabed position • Complicated • Suitable for harsh climate • Applicable in shallow and deep water • High capital expenditure - expensive • Represents high risk for long term applications		Low
	Propulsion	It consists of positioning a floating structure above a fixed seabed point by the use of propeller or thrusters	• Propeller or thrusters are controlled from a central computer • Complicated • Suitable for harsh climate • Applicable in shallow and deep water • High capital expenditure - expensive • Represents high risk for long term applications		Low

***Table B.2** – Characteristics of possible WEC mooring configurations*
(after Harris et al., 2006; Sound & Sea Technology Engineering, 2009, etc.).
Part 4 – Finished

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*

Current energy converters

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Reviewed by:	

Version	Date	Revised Pages	Description of Changes
1.0	16.12.2013	-	1st Draft released
1.1			
1.2			

Table of contents

1 Introduction

1.1 The MERMAID project

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.

The EU-funded MERMAID project was initiated in 2012 with duration of four years, and will continue until the end of 2015. The project is expected to develop novel, innovative and generic design concepts for a next generation offshore platforms for multiple use of ocean space including energy extraction, aquaculture and platform related transport**.** The project will give answer to the following questions: (i) What are the best practices to develop multi-use platforms?; (ii) what are the accumulated effects of multi-use platforms on the environment?; (iii) what are the best strategies for the installation, maintenance and operation of multi-use offshore platforms?; and (iv) what is the economical and environmental feasibility of multi-use offshore platforms

The one of the main objectives of the Mermaid project 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. An example of the envisioned combined usage of different facilities is shown in Fig. 1.

Fig. 1: Example of multi-use management of a wind farm. From left to right: diving (recreation), scientific studies, energy extraction facilities, aquaculture, fishing, tourism (http://www.mermaidproject.eu)

1.2 Work package 3: Development of renewable energy conversion from wind and waves

Work Package 3 (WP3) consists of development of renewable energy conversion from wind and waves. The main aim of WP 3 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.

As aforementioned, one of the objectives of the MERMAID is to integrate different energy conversion technologies into the same platform. The combination of these technologies might be a cost-effective solution whilst optimizing the use of ocean space and reducing the impact on the environment. To achieve this integration, existing and in-progress technologies of the different subsystems (Fig. 2) need to be reviewed and analyzed with high-level description data, bearing in mind the final aim of integration. Then, based on this information, combinations of different technologies can be examined for their integration on multi-use platforms (MUPs). In this regard, the MERMAID is seeking answers to the following questions: (i) What are the possible combinations of existing technologies together with large scale wind energy enabling sustainable growth in aquaculture?; (ii) which combination(s) can ensure cost-effective energy production with high performance in long term?

Fig. 1: Different subsystems of MUPs (Koca et al., 2013)

During the 3rd EU-Mermaid meeting in Santander, Spain, it has been discussed that the tidal energy converters (TECs) do not hold promise for EU Mermaid project purposes mainly due to the lack of tidal velocities in the four sites being investigated in the project. Therefore, this report will only presents a brief review of the TEC technologies.

1.3 Task 3.3: Energy converters

As aforementioned, review of energy converters has been organized into the tasks in Fig. 2.

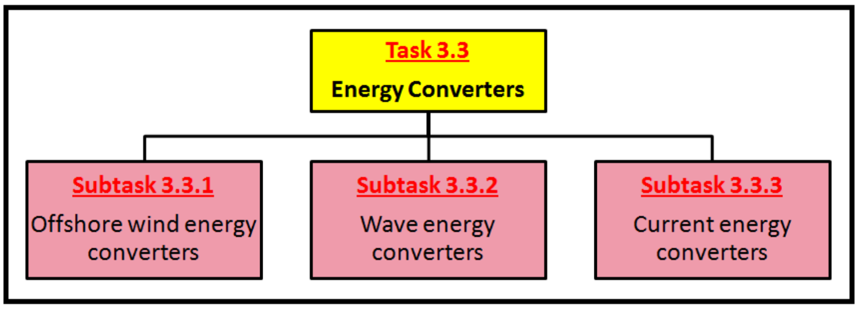


Fig. 2: Structure of work task 3.3

One of the aims of this task is to identify potential tidal energy converter concepts 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 MERMAID (2013a), *Deliverable D7.1 –Site specific conditions.*

1.4 Subtask 3.3.3: Current energy converters

The main goal of this subtask is to review of state of the art of TECs. As stated above, during the 3rd EU-Mermaid meeting in Santander, Spain, it has been discussed that TECs do not hold promise for Mermaid project purposes mainly due to the lack of tidal velocities in the four sites being investigated in the project. Therefore, this report focuses on a brief review of the TEC technologies.

1.5 The structure of the report

The structure of this report is as follows:

The report starts with the definitions on the tidal energy, including underlying physics, principles and tidal energy resource across Europe in sections 2.1, 2.2 and 2.3, respectively.

Section 3 presents methodology used during collating information on TEC technologies, and introduces types of TECs. An attempt is also made to summarize current stage of global tidal energy activities. This includes distribution of individual TEC developments, analysis based on technology type as well as distribution of current R&D.

In section 4, conclusion of this research is presented.

2 Tidal energy

The world energy consumption in 2010 was about 505 EJ. Until now about 85 % of the energy demand is covered by fossil energy source. As the world energy consumption is still rising with increasing population, it is inevitable to turn the focus towards renewable energies as the known fossil sources are finite. A promising potential source of renewable energy regarding reliability and predictability is tidal currents. The estimated energy of tidal currents is about 95-110 EJ, thereof 2/3 (69 EJ) in coastal areas (Oumeraci, 2010). Tidal energy is reliable as it is slightly influenced by short-term weather fluctuations and long-term climate changes. Most regions of the world have semi-diurnal tides (two high tides and two low tides per day) and they are predictable several years in advance. Despite these aspects, tidal energy is still very young.

2.1 Tidal energy physics

The word "tide" originated in the word "tyd", meaning "seasons" (of the moon). Actually the moon is the major component of low and high tide as there is gravitational pull on the world's ocean.

There are two theories in tide analysis: The theory of equilibrium of the tides (Newton) and the harmonic tide analysis (Laplace). The theory of Newton originates from 1686. It is based on the equilibrium of the gravitational pull and attractive forces between earth, moon and sun. At full and new moon, the earth, moon and sun are in line and add their gravitational pull (Fig. 3a). Consequently, the tides are higher (called spring tide). At half moon, the constellation of the earth-moon axis is at 90 degrees to the earth-sun axis, which is causing lower neap tides (Fig. 3b). The theory of Newton has still several limitations: The main problem of this theory is the assumption of a steady water cover without continents and isles. With this theory, the local forecast of tides is not possible.

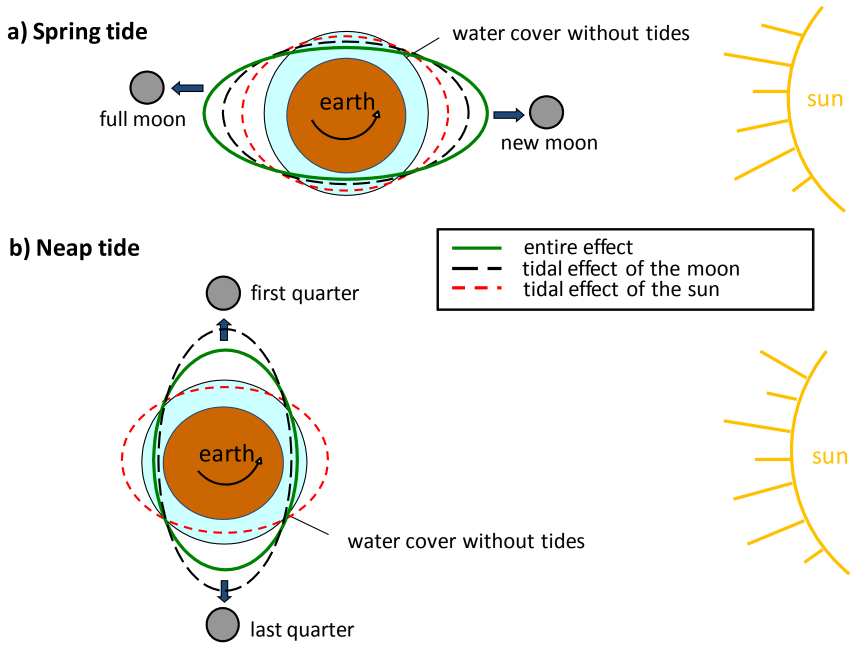


Fig. 3: Gravitational pull of sun and earth (Oumeraci, 2010)

The harmonic tide analysis is more complex. This theory regards gravitational forces of earth, moon and sun as well as topographic influences and resonance effects. The consideration of the local topography is the basis for local tide prediction. This theory was developed by Laplace and is still valid.

2.2 Principles of tidal energy

Tidal energy can be divided into two mutually depending energy types: tidal current and tidal range energy. Tidal range is the steady rise and fall of the water derived from the gravitational forces mentioned above. It is therefore potential energy. Tidal current energy is a result of the tidal rise and fall as the water has to flow between high and low tide. The movement is affected by seabed bathymetry and mostly horizontally. Current energy is kinetic energy.

To profit from the tidal range, a barrage system is necessary to store water. There is one station in France, where the estuary of the Rance River is separated from the Atlantic Ocean. A separation implicates a massive intervention into the ecosystem: the water flow is not steady anymore, silt deposits in front of the barrier and flora and migration of sea life is impeded.

Energy converters working with kinetic energy have lower economical effects as they do not dam a whole estuary and they can be bypassed. They need sites with currents but do not rely on estuaries so there is more flexibility in the location. Another advantage is the smaller size and less cost for single units than building a long dam. The first grid-connected array is the Paimpol-Brehat Tidal Farm, installed in France. At present, developing and using current energy converters is the favoured alternative. In this report, an attention is paid solely on tidal stream energy converters.

2.3 Tidal energy potential across Europe

This section gives a brief summary of the tidal range and tidal stream resources potential across the Europe. The distribution of tidal range and tidal stream resources in Europe is shown in Fig. 4. There is a noticeable accordance between maximal tidal range and maximal tidal stream potential. **Errore. L'origine riferimento non è stata trovata.** shows the combined locations of combined wind, waves and tidal resources potential. As seen in **Errore. L'origine riferimento non è stata trovata.** and **Errore. L'origine riferimento non è stata trovata.**, Great Britain has an abundance of marine energy resources. According to the Crown Estate report (Crown Estate, 2012), wave and tidal stream energy could provide 15-20 % of the UK's current electricity demand.

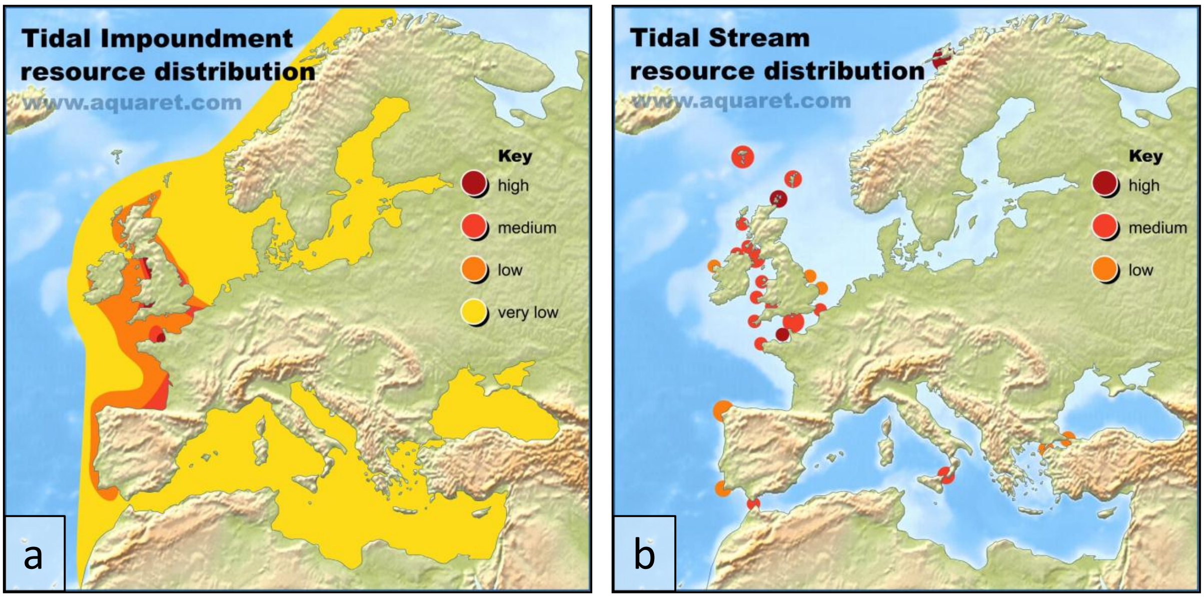


Fig. 4: Distribution of a) tidal range and b) tidal stream resources in Europe (www.aquaret.com)

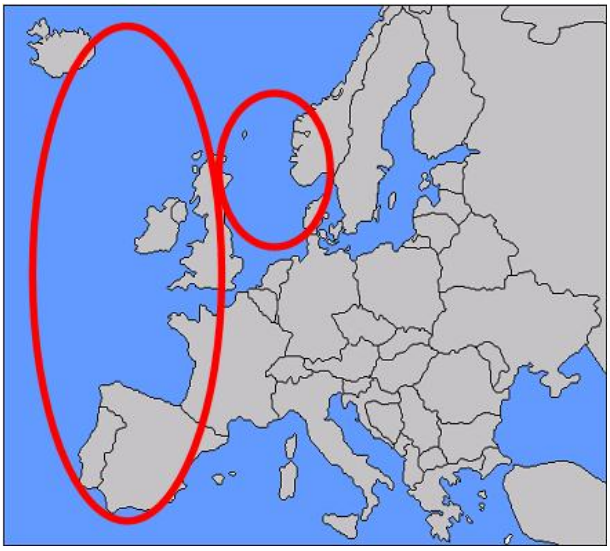


Fig. 5: Identified "hotspots" (combined wind, wave and tidal energy resources) (ORECCA, 2011)

This research will confine on tidal stream velocities, so the tidal range will be excluded in the following section. There are intense currents around Great Britain and Ireland, as mentioned. There are also some other places with intense currents, including the Strait of Gibraltar (the link between the Atlantic Ocean and the Mediterranean Sea), the Bosporus and Dardanelles (the link between the Black Sea and the Mediterranean Sea) and the Straits of Messina (between Italy and Sicily). The potential sites in Europe for electricity generation with tidal stream energy are presented in Table 1.

Table 1: List of potential sites in Europe for tidal stream generation (Hammons, 2011)

Area	Site name	Resource (TWh/a)
Pentland Firth	Pentland Skerries	3.9
	Stroma	2.8
	Duncans-by Head	2.0
	South Ronaldsay	1.5
	Hoy	1.4
Alderney	Casquets	1.7
	Race of Alderney	1.4
North Channel	Rathlin Island	0.9
	Mull of Galloway	0.8

The cut-in speed necessary for generating power are specified with 0.5-1.5 m/s (AECOM, 2011). Fig. 6 shows flow velocities around Great Britain. There are many places where the flow rate is more than 0.5 m/s and even several places with a flow rate of more than 1.5 m/s. Furthermore, some technologies have a lower cut-in speed (< 0.5 m/s) (the information sheets of the technologies can be found in the Appendix A).

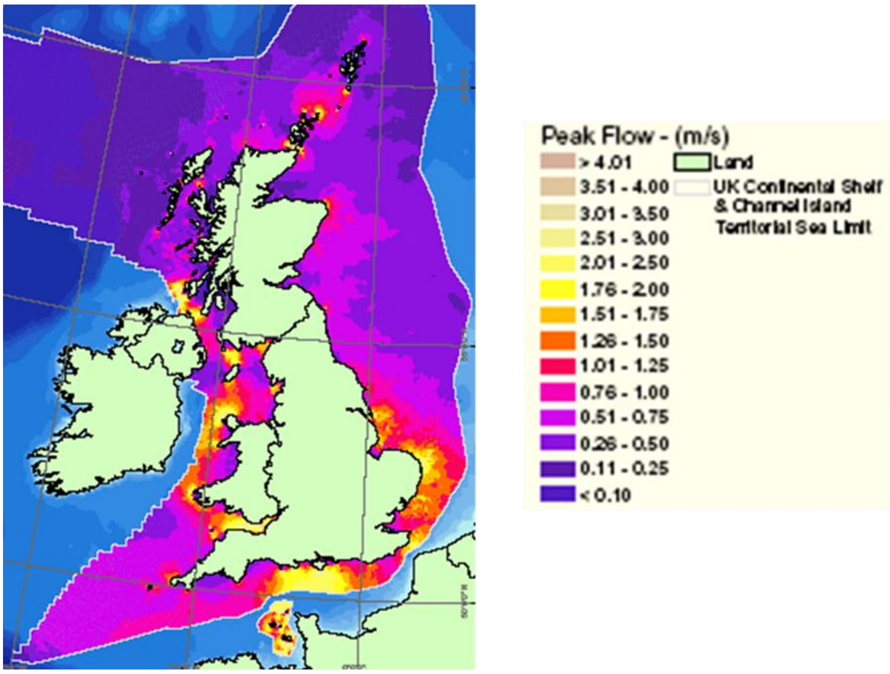


Fig. 6: Flow velocities around Great Britain (*Atlas of UK marine renewable energy resources, 2004 (www.engineering.lancs.ac.uk)*

3 Tidal energy converter development status

Due to increasing energy demand and climate change concerns, the need for renewable energy resources is becoming increasingly evident. Many efforts have been devoted to extract energy from renewable resources. Among them, marine current energy is considered as one of the most important marine renewable energy resources; however the technological development for its exploitation is yet at a very early stage. Research into tidal energy converters (TECs) has significantly increased in the past years in pursuit of finding energy alternatives to achieve renewable energy and CO_2 emission reduction targets. A wide diversity of TECs has been developed, tested and proposed with different rate of success. The tidal energy industry is currently making substantial progress towards commercialization. This has been highlighted by the recent surge in the installation of prototype devices at the European Marine Energy Centre (EMEC), to the point where the facility is fully booked. Furthermore, a number of projects have been recently approved such as the 10 MW Skerries Tidal Energy Array in Wales and the 100 MW OpenHydro Tidal Energy Array in Ireland, which are expected to enter commercial operation in 2015 and 2020, respectively.

3.1 Introduction

Tidal current energy technology is in still its infancy. There are several companies putting all their effort and time to the development of TECs. The technological and economical feasibility of these devices has not been proven yet, however, it is expected that the production costs will decrease as the technologies progress. This chapter gives an overview of the state of the art technologies of TECs.

3.2 Methodology of collating information

Various methods have been used to identify all relevant TECs currently under development. Fig. 7 shows the methodology of collecting information used during this research. While reviewing the literature, the so-called '*inactive criteria'* have been defined which identify a TEC to be no longer actively developed and consist of:

1) TECs discontinued their development probably because of technical and economical reasons;
2) TECs whose websites have not been updated over the last three years;
3) TECs that are at their first thinking stage and their workability have not yet been proven

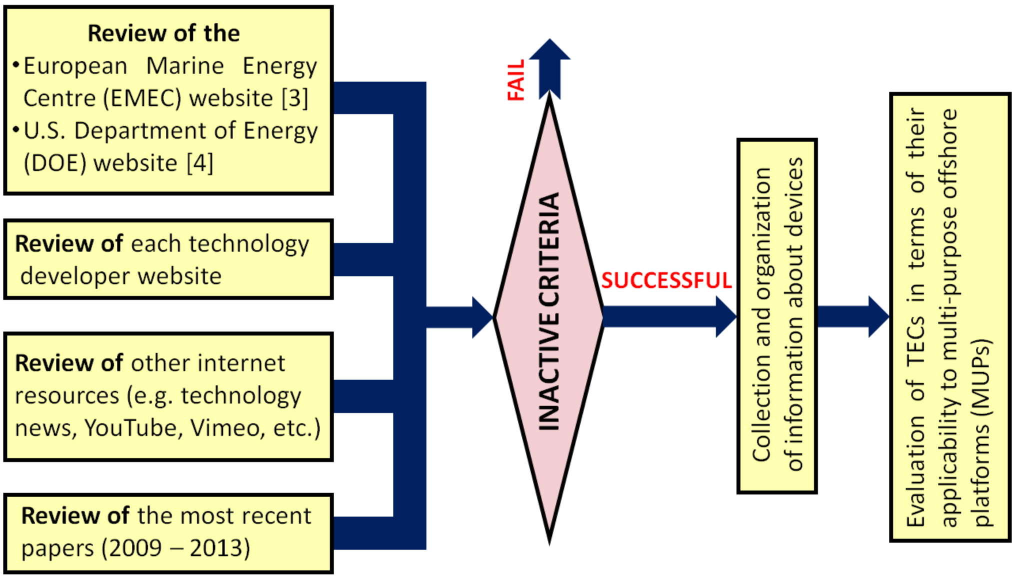


Fig. 7: Methodology of collating information

As a result, 64 individual TECs have been identified at different stages of development which operate with different principles. However, it should be noted that this list might not be exhaustive.

3.3 Classification of tidal current devices

The classification of TECs can be done in many ways, but there are three categories that are commonly used today. Conversion technology is considered as the main category in this classification.

3.3.1 Conversion technology

TECs demonstrate a wide range of conversion technologies. For example, in the review paper of Khan et al. (2009), 10 types of conversion technology were identified. In this report, tidal energy converters are categorized based on the available information given on the European Marine Energy Centre (EMEC) website.

Horizontal axis turbines

Table 2 presents general characteristics of horizontal axis TECs.

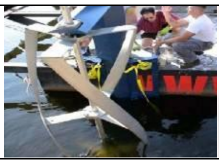
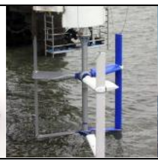
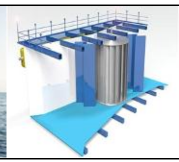
Table 2: Horizontal axis turbines (modified from Aquatera, 2012)

General Description
These devices extract energy from moving water in much the same way as wind turbines extract energy from moving air. The tidal stream causes the rotors to rotate around the horizontal axis and generate power. Support structures vary greatly: from seabed mounted gravity bases to moored floating structures. • Functional mode – blades rotating from 1 m/s to peak springs at varying rotational speeds (currently unknown) • Shut down mode - blades may be fixed or rotating freely • Power conversion method – gearbox to electrical • Typical power output – 1MW
Suitable Environmental Conditions
• **Water depth:** 15 – 80 m • **Resource:** < 1.5 m/s current speed with as little wave exposure as possible, linear flow ideal but uncommon • **Seabed type:** Not limited by seabed type but development areas are likely to be tidal swept bedrock (or other hard substrate) with no/little sediment cover. Smooth bedrock areas would be favored over rough areas with associated turbulence • **Coastal character:** Not limited by coastal character and development areas may be located near to coastlines of all types
Fixed components
• Support structures can be: gravity/deadweight anchors with mooring lines, gravity base structures, monopiles, as well as rock anchors with mooring lines. • More detailed information on these types of support structures and anchors can be found in D 3.3.2 (Offshore foundation technology) of the Mermaid project.
Footprint
• This is dependent on the type of moorings and support structure chosen. A gravity base will have a significantly smaller footprint that of a mooring array using gravity/rock anchors. • Monopile installations may penetrate the surface and floating structures will have the greatest surface footprint.


Vertical axis turbines

Table 3 presents general characteristics of horizontal axis TECs.

Table 3: Vertical axis turbines (modified from Aquatera, 2012)

General Description
These devices extract energy from the tides in a similar manner to the horizontal axis turbines; however the turbine is mounted on a vertical axis. The tidal stream causes the rotors to rotate around the vertical axis and generate power. Since the rotation is around the vertical axis, there is no need for a yaw mechanism to direct the turbine into the tidal stream. • Functional mode – blades rotating from 1 m/s to peak springs at varying rotational speeds (currently unknown) • Shut down mode - blades may be fixed or rotating freely • Power conversion method – gearbox to electrical • Typical power output – 1MW
Suitable Environmental Conditions
• **Water depth:** 5 – 80 m (can be used in shallower waters compared with horizontal axis turbines) • **Resource:** < 1.0 m/s current speed with as little wave exposure as possible, linear flow ideal but uncommon • **Seabed type:** Not limited by seabed type but development areas are likely to be tidal swept bedrock (or other hard substrate) with no/little sediment cover. Smooth bedrock areas would be favored over rough areas with associated turbulence • **Coastal character:** Not limited by coastal character and development areas may be located near to coastlines of all types
Fixed components
• Support structures can be: gravity/deadweight anchors with mooring lines, gravity base structures, monopiles, as well as rock anchors with mooring lines. • More detailed information on these types of support structures and anchors can be found in D 3.3.2 (Offshore foundation technology) of the Mermaid project.
Footprint
• This is dependent on the type of moorings and support structure chosen. A gravity base will have a significantly smaller footprint that of a mooring array using gravity/rock anchors. • Monopile installations may penetrate the surface and floating structures will have the greatest surface footprint.
    

Reciprocating hydrofoils

Table 4 presents general characteristics of reciprocating hydrofoils.

Table 4: Reciprocating hydrofoils (modified from Aquatera, 2012)

<table>
<tr><th>General Description</th></tr>
<tr><td>These devices have a hydrofoil attached to an oscillating arm. The tidal current flowing either side of a wing results in lift. This motion then drives fluid in a hydraulic system to be converted into electricity.

Functional mode – blades rotating from 1 m/s to peak springs
Shut down mode - hydrofoils may be locked or stalled
Gearbox – electrical
</td></tr>
<tr><th>Suitable Environmental Conditions</th></tr>
<tr><td>
Water depth: 5 – 80 m (can be used in shallower waters compared with horizontal axis turbines)
Resource: < 1.0 m/s current speed with as little wave exposure as possible, linear flow ideal but uncommon
Seabed type: Not limited by seabed type but development areas are likely to be tidal swept bedrock (or other hard substrate) with no/little sediment cover. Smooth bedrock areas would be favored over rough areas with associated turbulence
Coastal character: Not limited by coastal character and development areas may be located near to coastlines of all types
</td></tr>
<tr><th>Fixed components</th></tr>
<tr><td>
Support structures can be: gravity/deadweight anchors with mooring lines, gravity base structures, monopiles, as well as rock anchors with mooring lines.
More detailed information on these types of support structures and anchors can be found in D 3.3.2 (Offshore foundation technology) of the Mermaid project.
</td></tr>
<tr><th>Footprint</th></tr>
<tr><td>
This is dependent on the type of moorings and support structure chosen. A gravity base will have a significantly smaller footprint that of a mooring array using gravity/rock anchors.
Monopile installations may penetrate the surface and floating structures will have the greatest surface footprint.
</td></tr>
<tr><td></td></tr>
</table>

Venturi tube

Table 5 presents general characteristics of venturi type TECs.

Table 5: Venturi-type TECs (modified from Aquatera, 2012)

General Description
Venturi Effect devices house the device in a duct which concentrates the tidal flow passing through the turbine. The funnel-like collecting device sits submerged in the tidal current. The flow of water can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine.


Archimedes screw

Table 6 presents general characteristics of Archimedes' screw-type TECs.

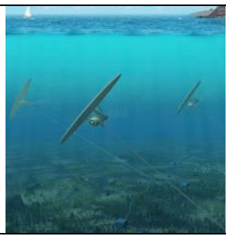
Table 6: Archimedes' screw

General Description
The Archimedes Screw is a helical corkscrew-shaped device (a helical surface surrounding a central cylindrical shaft). The device draws power from the tidal stream as the water moves up/through the spiral turning the turbines.


Tidal kite

Table 7 presents general characteristics of tidal kite TECs.

Table 7: Tidal kites

General Description
A tidal kite is tethered to the sea bed and carries a turbine below the wing. The kite 'flies' in the tidal stream, swooping in a figure-of-eight shape to increase the speed of the water flowing through the turbine.


Other designs

This covers those devices with a unique and very different design to the more well-established types of technology such as Aquascientific tidal turbine by the Tidal Sails AS and the VIVACE converter by University of Michigan (see Appendix A).

3.3.2 Power take-off system (PTO)

The devices which are described in section 3.3.1 require power-take off (PTO) systems to convert the kinetic energy into electricity. PTO system consists of a rotary generator, connected either directly or via a gearbox, or pressurized hydraulics (Khan and Bhuyan, 2009). The majority of the tidal devices are based on the horizontal axis turbines which operate in a very similar manner to that in horizontal axis wind turbines. Consequently, the generators are similar. PTO systems for wind turbines can be used for TEC generators. Some developers install the generators above the water surface. Maintenance costs and protection against corrosion can be reduced, but this will cause installation problems in greater water depths.

3.3.3 Foundation and mooring

The devices have to be fixed to the seabed in order to ensure their stability. The technique is divided into gravity base, pile mounted (with monopiles as the most common type) and floating devices, fixed with mooring lines. The type of foundation is depending from the current device and the site.

Seabed mounted or gravity base

Gravity base support structure (Fig. 8), as the name implies, uses their own weight to resist against the loads exerted by the superstructure as well as hydrodynamic loadings. It differs from the monopile in that it is not driven into the seabed, but rather sits 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). In modern wind engineering, they are used in shallow waters (with a maximum depth of 30 meters) (EON, 2012) and have proven to be cost effective (http://www.springerreference.com/docs/html/chapterdbid/332788.html, 2013). If the underlying soil layer has sufficient bearing and shear capacity, this type of foundations can be a convenient and cost effective solution.

They are also the most common foundation type for marine structures. Generally prefabricated concrete (either reinforced or pre-stressed) and steel can be used in construction of this kind of foundations (Gerwick, 2007).

Depending on site geologic conditions, this foundation may require significant seabed 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. Once leveled, there is the potential need for the addition of a stone bedding layer depending on the site conditions. Once the seabed preparation is done, the gravity base foundation can be correctly positioned and placed on the seabed (Lesny, 2010; http://www.springerreference.com/docs/html/chapterdbid/332788.html, 2013). Ballast material consisting of stones or other suitable material (concrete or other high density materials) is then filled inside the foundation to ensure final stability (http://www.springerreference.com/docs/html/chapterdbid/332788.html, 2013).

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 often a huge and massive structure. Therefore, installation process may result in special requirements such as installation vessel capacity or workspace size (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 support structures can be installed easier and much cheaper than known steel foundations as they do not require expensive jack up vessels, offshore cranes or hammers as stated by Wind Energy Update (http://social.windenergyupdate.com/operations-maintenance/gravity-base-foundations-building-advantages-and-new-innovation, 2013). However, it needs to sustain its development in order to move up the ladder (WEU, 2013). 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 also be avoided (http://social.windenergyupdate.com/operations-maintenance/gravity-base-foundations-building-advantages-and-new-innovation, 2013).

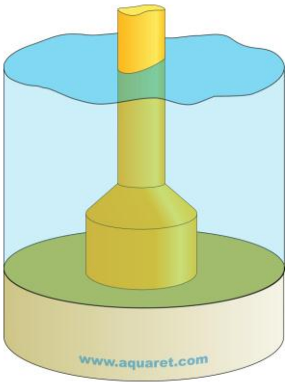


Fig. 8: Gravity base support structure (*http://www.aquaret.com*)

More information on the seabed mounted foundations can be found in D 3.3.1 (offshore technology) and D.3.3.2 (wave energy converters).

Pile mounted

There are several possibilities of pile mounting – using a monopile, a twin pile or a jacket with more than two piles (Fig. 9). The piles are usually made of steel and have a diameter of less than 6 m. Due to the offshore wind parks and other installed platforms e.g. for oil production, a lot of experience has been made during the last decades. The length of the piles is limited so the water depth of pile mounted devices which can be raised above the water surface is limited to around 35 m. Piles cannot be employed into deep soft sediments.

Monopile foundation solutions are based on design experience from the 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 for wind farm projects, particularly for the projects in the sandy North Sea seabed (EON, 2012).

At sites with high currents and high amount of sand movements, scour protection is of great importance. Therefore, many investigations have focused on scour problems around the monopile foundations. Suitable soil conditions for monopiles are sand and silt layers (http://www.springerreference.com/docs/html/chapterdbid/332788.html, 2013). 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 the superstructure size increases and site conditions become more challenging, which results in more weight. 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 (http://www.springerreference.com/docs/html/chapterdbid/332788.html, 2013; Teich, 2013).

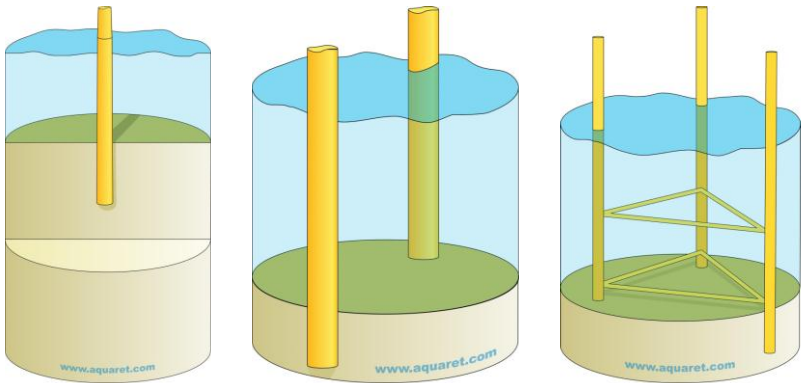


Fig. 9: From left to right: monopile, twin pile, pile jacket (here a tripod) (*http://www.aquaret.com*)

More information on the pile mounted foundations can be found in D 3.3.1 (offshore technology) and D.3.3.2 (wave energy converters).

Floating (with mooring lines)

The devices float either in the water or on the water surface. The mooring (Fig. 10) is made with mooring lines which can be rigid or flexible. With a flexible mooring, the devices are able to swing and can turn when the tide is changing direction, with a rigid mooring the devices are fixed and have a small leeway. The mooring can be fixed to the seabed or attached to other existing devices.

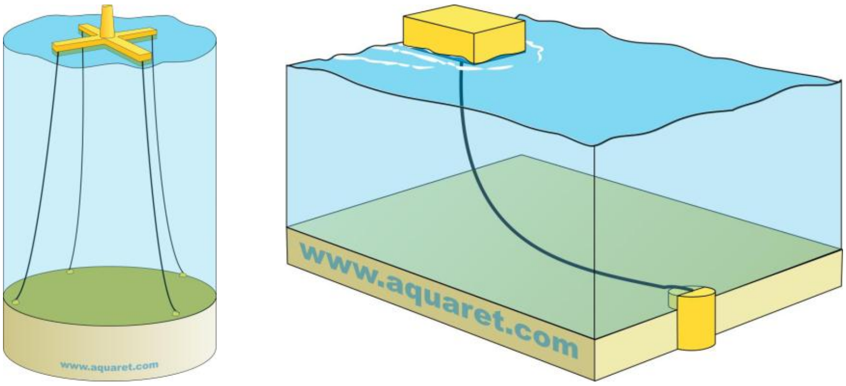


Fig. 10: Floating devices with mooring lines (*http://www.aquaret.com*)

More information on the mooring systems and mooring line types can be found in D 3.3.1 (offshore technology) and D.3.3.2 (wave energy converters).

3.4 Advantages and disadvantages

The development of TECs is still at an early stage. Costs for development, installation and maintenance are still very high and the conventional energy production is more profitable. Currently, many developers have been testing different concepts and have invented several technologies.

Using tidal currents as energy source has several advantages (http://www.thew2o.net/):

- The environmental impact is limited (minimal land use, no optical effect if fully submerged, no inhibiting of migratory paths and relatively silent);
- Nearly no extreme weather conditions at water depth of more than 20-30 m;
- Availability of tidal currents can be predicted accurately compared with the availability of wind;
- The density of sea water is more than 800 times higher than the density of air, so the velocity of the current does not have to be as fast as wind speed and the diameter of the rotors can be smaller than the diameter of wind turbines;
- Except for the production and installation of TECs, there is no production of greenhouse gases or other waste;
- The current energy is already present and available.

But there are also some difficulties considering TECs (http://www.ianswer4u.com/2012/02/tidal-energy-advan tages-and.html):

- As mentioned in Section **Errore. L'origine riferimento non è stata trovata.**, TECs cannot be located anywhere in the ocean;
- Each time the direction of tide is changing, no electricity can be generated. At locations with semidiurnal tides, this happens four times a day;
- TECs have to be designed to work bidirectional or have to be able to turn each time the tide changes direction;

- If the devices are fully submerged, the material and construction has to be protected against corrosion caused by the seawater;
- Divers are necessary for maintenance when the device cannot be raised to the surface.

3.5 Five-stage approach

There are several ways to categorize the development stages of emerging technologies. Many of these methods have been presented in D 3.3.2 (wave energy converters). In this report, five-stage development programme as described on the EMEC website (http://www.emec.org.uk/services/pathway-to-emec/technology-readiness-levels/) was used to categorize the devices.

Stage 1: Tidal-current energy conversion concept formulated
Stage 2: Intermediate scale subsystem testing, computational fluid dynamics, finite element analysis, dynamic analysis
Stage 3: Subsystem testing at large scale
Stage 4: Full-scale prototype tested at sea
Stage 5: Commercial demonstrator tested at sea for an extended period

3.6 Comparison of TECs

Tidal stream technology is still its infancy. Based on the available literature and recently held conferences, it has been observed that there are several companies worldwide spending all of their time and effort for further development of the TECs.

Harnessing tidal energy is a sector that is still under development. Research into tidal energy converters (TECs) has significantly increased in the past years in pursuit of finding energy alternatives to achieve renewable energy and CO_2 emission reduction targets. A wide diversity of TECs has been developed, tested and proposed with different rate of success. However, only a few technologies are currently generating electricity. Compared to wave energy, tidal energy is currently making substantial progress towards commercialization. This has been highlighted by the recent surge in the installation of prototype devices at the EMEC, to the point where the facility is fully booked. Irish company Open Hydro is currently installing the first commercial tidal farm in Brittany, France. It shall be fully operational in 2014 and consists of four 16 m tidal turbines generating 2 MW each (http://www.openhydro.com/news/010911.html). Furthermore, a number of projects have been approved recently such as the 10 MW Skerries tidal energy array in Ireland, which is expected to enter commercial operation in 2015, respectively (http://www.marineturbines.com/3/news/article/44/marine_current_turbines_kicks_off_first_tidal_array_for_wales).

3.6.1 Global status

The global distribution of the individual WEC R&D is shown in Fig. 11. As seen from the figure, the tidal energy sector is dominated by UK and USA with massive tidal stream energy resources to exploit and the experience/industrial base to develop devices.

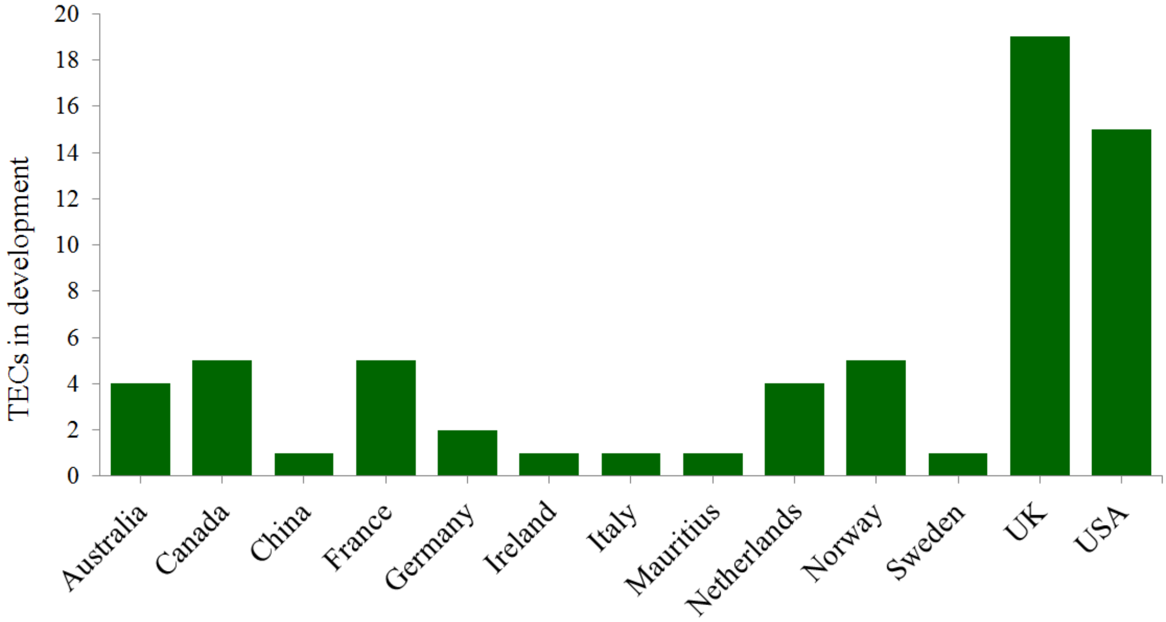


Fig. 11: Global status of TECs, demonstrating the high level of activity in the USA and the UK, relative to the rest of the world

3.6.2 Current trends in technology type

In this section, TECs currently under development have been analyzed to establish the current development of TECs with respect to technology type. Fig. 12 shows TECs based on the technology types described in section 3.3.1. It can be seen that there is a significant diversity in technology types, with the most common technology being the horizontal-axis turbines. This is followed by Venturi-type TECs and vertical-axis turbines. In most cases, a venturi-type TEC is also considered as a ducted horizontal axis turbine. A possible explanation for the convergence on horizontal-axis turbines is that the majority might have progressed research with horizontal axis turbines, which have been utilized for harnessing wind energy for several years. In fact, some of these devices look very similar with the only difference that horizontal axis TECs are submerged and have a different rotor diameter.

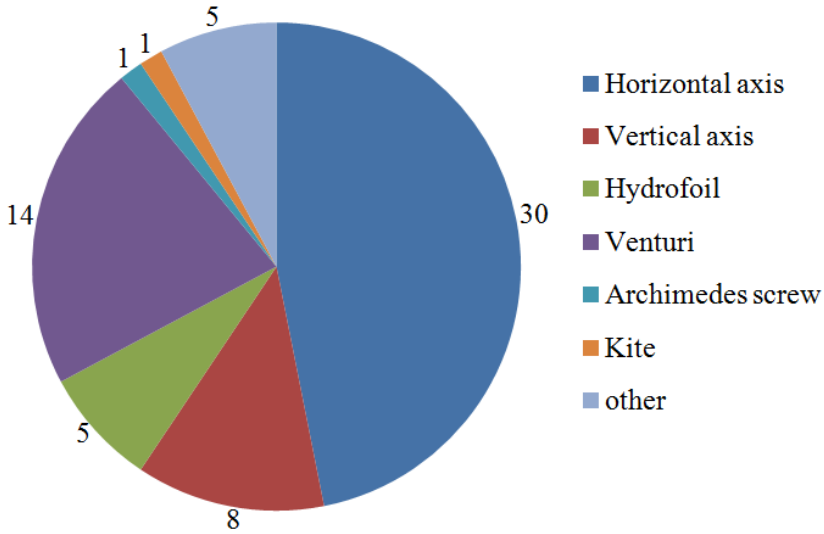


Fig. 12: Analysis of reported TECs currently under development based on technology type

As seen from Fig. 13, a variation is also observed for the support structure/anchoring of the TEC technologies. Many devices are planned to be seabed mounted or floating, but there exists devices which integrate different foundation types on it. The total number in the Fig. 13 is greater than the number of the devices since some devices employ multiple foundation options. To get an overview of the number of devices using several anchoring types, Table 8 is depicted which contains all variations of combined foundations with the number of the related devices. Possibility of having different feasible foundation types can improve the adaptation to the local environment; as different water depths and sea beds may require different foundation solutions. There are some devices which designed to be attached to existing platforms or bridge abutments to minimize construction costs.

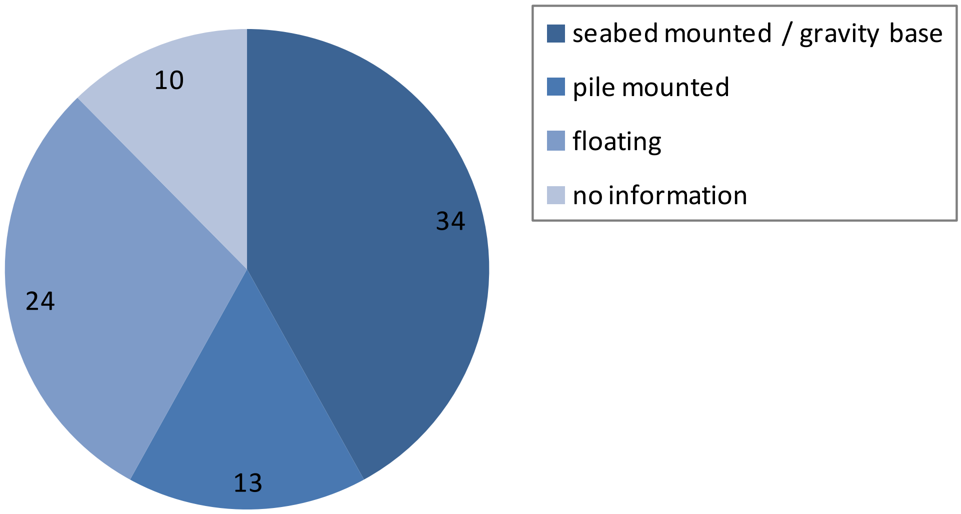


Fig. 13: Potential foundation of TECs

Table 8: Types of foundation and combination of foundations of TECs

Number of devices	seabed mounted / gravity base	pile mounted	floating
22	■		
5	■	■	
4	■		■
2	■	■	■
5		■	
1		■	■
16			■

Each anchoring option has its advantages and disadvantages. These are discussed in D 3.3.2 (offshore technology) in greater detail.

3.6.3 Current R&D status of devices according to five-staged approach

Fig. 14 shows the development stage of technologies currently under development (further information about the technologies can be found in the Appendix A). As seen in Fig. 14, there are a relatively high number of TEC technologies emerging whilst many TEC devices have progressed to more advanced stages. Considering the Stage 4 and 5, it can be said that the costs and performance of these devices has just started to be quantified with greater certainty. The developers must demonstrate not only that their devices will work in the real sea conditions, but also that the costs and performance meet their expectations and their investor's expectations (Carbon Trust, 2011). It seems that these devices are nowadays of particular importance since the proof of their performances and costs in Stage 4 and Stage 5 may increase the confidence in the industry, thus giving access the future investments in the tidal energy sector.

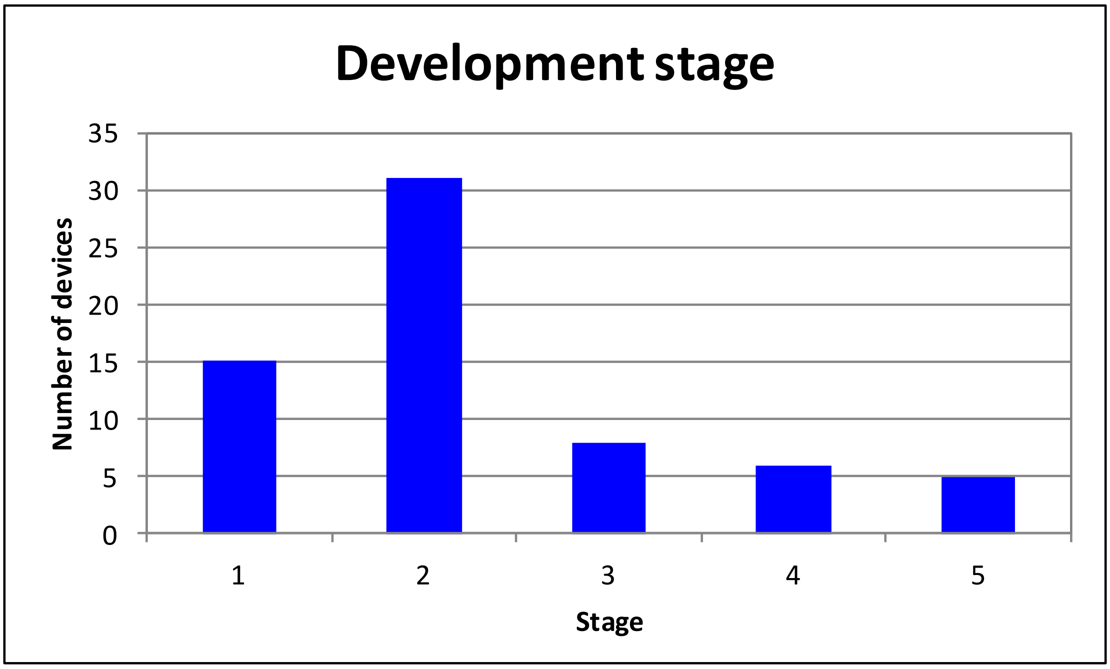


Fig. 14: Overview of the development stage of TEC, based on the EMEC categorization

In order to explore the distribution of R&D progress across the world, Fig. 15 is depicted. From the figure, the UK appears to have the most advanced TECs. Norway has also advanced technologies (Stage 4), but with a smaller pool of devices.

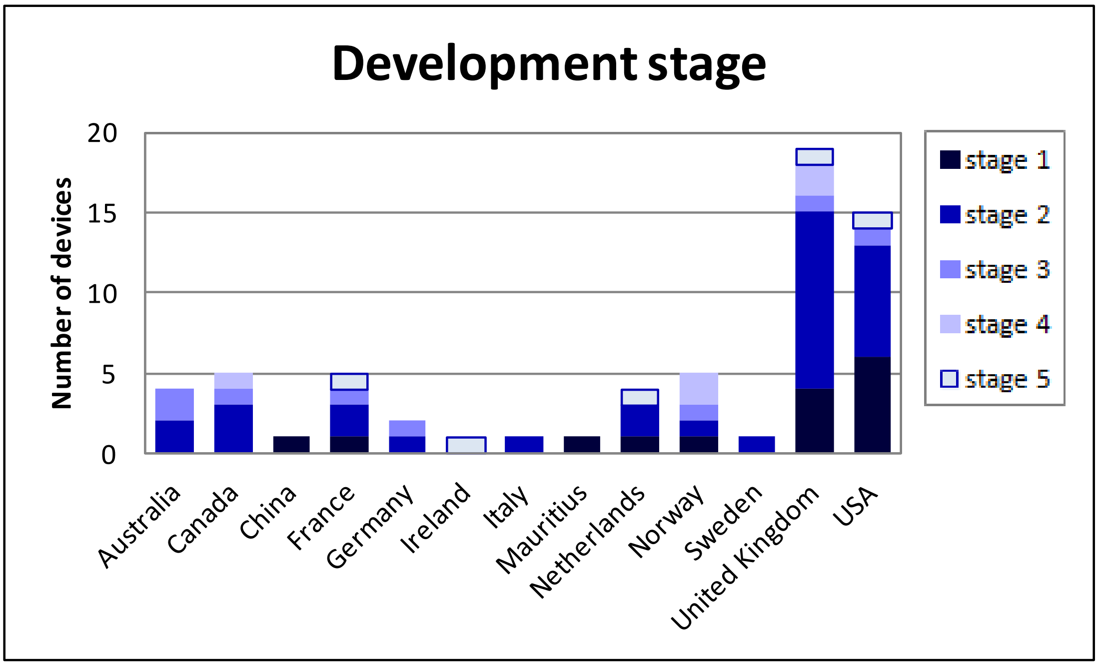


Fig. 15: Current development distribution worldwide based on the EMEC categorization

3.7 Identified synergies with 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.

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 Renewables 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.
Website: http://www.fp7-marinet.eu/

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.
Website: http://www.si-ocean.eu/en/

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.
Website: 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.
Website: 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.
Website: 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 performance of the Windfloat, 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.
Website: 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.
Website: http://www.marina-platform.info/

PolyWEC

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.
Website: http://www.polywec.org/

WECWakes

The WECwakes project is funded by the EU FP7 HYDRALAB IV programme, and is coordinated by Ghent University (Belgium, Prof. Peter Troch). The WECwakes project is testing record breaking array of wave energy converters: the largest array worldwide (25 individual WECs in an array set-up) is under testing in the DHI wave tank

Website:
http://www.ugent.be/ea/civil-engineering/en/research/coastal-bridges-roads/news-events/wecwakes-project.htm

GeoWave

GeoWAVE aims to address this immediate research need by providing a structure whereby industry specified research will be conducted on a new generation of offshore anchors and mooring components deemed to have the highest economical and technical merit for mooring wave energy devices. In so doing GeoWAVE will remove the technical and economical hurdle of mooring wave energy converters to the seabed so that widespread deployment on a commercial scale becomes viable, thereby providing new business opportunities for the SMEs.
Website: http://www.geowave-r4sme.eu/project.html

WAVEPORT (2009-2013)

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.
Website: http://www.fp7-waveport.eu/

The Shetland Project

Aegir Wave Power's immediate ambition is to develop and build a commercial wave farm off the southwest coast of Shetland, near St. Ninian's Isle. The proposed farm will likely consist of 10 Pelamis machines with a combined rated power of 10MW. The machines will be arranged in rows to form an array or wave farm. The wave farm will be connected back to the Shetland mainland via a subsea cable link.
Website: http://www.aegirwave.com/the-shetland-project.aspx

Pentland Orkney Wave Energy Resource (POWER) Ltd Project

The project will deliver the world's first large-scale, grid-connected demonstration of a wave energy farm with a total generation capacity of 28MW. If successful, it will comprise 10 nearshore Aquamarine Power Oyster devices and 24 offshore Pelamis machines within the Pentland Firth and Orkney waters leasing area, operating in multi-device array configurations.
Website:
http://www.segec.org.uk/projects/pentland-orkney-wave-energy-resource-%28power%29-ltd

EERA DTOC

EERA-DTOC stands for the European Energy Research Alliance - Design Tool for Offshore Wind Farm Cluster. The project is funded by the EU – Seventh Framework Programme (FP7) – and runs from January 2012 to June 2015. It is coordinated by the Technical University of Denmark - DTU Wind Energy. The EERA-DTOC project combines expertise to develop a multidisciplinary integrated software tool for an optimized design of offshore wind farms and clusters of wind farms.
Website: http://www.eera-dtoc.eu/

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.
Website: http://www.hyperwind.eu/

DeepWind

DeepWind is a 4 year project, funded by FP7 - Future Emerging Technologies. The project has the overall objective to explore the technologies needed for development of a new and simple floating offshore concept with a vertical axis rotor and a floating and rotating foundation. Additionally, the objective is to develop calculation and design tools for development and evaluation of very large wind turbines based on this concept. The project has officially started on October, 2010 and will run until September, 2014.
Website:
http://www.risoecampus.dtu.dk/Research/sustainable_energy/wind_energy/projects/VEA_DeepWind.aspx?sc_lang=en

TWENTIES

TWENTIES = Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions. The Twenties project aims at demonstrating by early 2014 through real life, large scale demonstrations, the benefits and impacts of several critical technologies required to improve the pan-European transmission network, thus giving Europe a capability of responding to the increasing share of renewable in its energy mix by 2020 and beyond while keeping its present level of reliability performance. This project is funded by the 7th Framework Programme of the European Commission. The project has officially started in April, 2010.
Website: http://www.twenties-project.eu/node/1

EquiMar

EquiMar involved about 60 scientists, developers, engineers and conservationists from 11 European countries working together to find ways to measure and compare the dozens of tidal and wave energy devices, proposed locations and management systems currently competing for funds, so governments can invest in the best ones and get marine energy on tap fast. The team has delivered a suite of “high level” protocols – general principles to allow fair comparison of marine energy converters testing and evaluation procedures. EquiMar protocols (read them here) cover site selection, device engineering design, scaling up designs, deployment of arrays, environmental impact on flora, fauna & landforms, and economic issues. The final EquiMar protocols establish a sound base for future marine energy standards currently being developed by IEC Technical Committee 114.
Website: http://www.equimar.org/

UPWIND

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 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.
Website: http://www.upwind.eu/

ORECCA – Offshore Renewable Energy Conversion Platforms

The objective of this project was 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 stimulated 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)
Website: http://www.orecca.eu/web/guest;jsessionid=60A614C5A41C67E83AC98FCF3831E88B

SEANERGY 2020

The objective of the SEANERGY 2020 project was 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.
Website: http://www.seanergy2020.eu/

7MW-WEC-BY-11

This action focused 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 was to introduce a new power class of large-scale Wind Energy Converters, the 7MW WEC, onto the market. The new 7MW WEC were to be designed and demonstrated at a large scale: eleven such WECs would be demonstrated in a 77 MW wind park close to Estinnes (Belgium).
Duration: 08/2008 - 08/2012 (48 months)
Website: http://cordis.europa.eu/projects/rcn/90994_en.html

SURGE

SURGE was an FP7 European collaborative demonstration project under grant agreement number 239496. The goal of the project was to build a grid connected wave energy converter in Portugal. The project started in October 2009 and it had a running period of three years including a one year of operation of the device. The Surge project aimed to access the WaveRoller device in a holistic manner and consequently, besides the performance, it included an environmental program in order to evaluate some of the environmental impacts.
Website: http://fp7-surge.com/

PROTEST - Procedures for TESTing and measuring wind energy systems

The objective of this pre-normative project was to set up a methodology that enables better specification of design loads for the mechanical components. The design loads 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 was 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)
Website: http://www.protest-fp7.eu/

RELIAWIND

RELIAWIND (Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation) 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)
Website: http://www.reliawind.eu/

NorthConnect

NorthConnect is a commercial Joint Venture (JV) established to develop, build, own and operate a High Voltage Direct Current (HVDC) 'interconnector'. The interconnector will provide an electricity transmission link between Scotland and Norway. The interconnector will allow electricity to be transmitted in either direction across the North Sea.
Website: http://www.northconnect.no/

TOPFARM

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)
Website:
http://cordis.europa.eu/projects/rcn/86364_en.html
http://www.risoecampus.dtu.dk/Research/sustainable_energy/wind_energy/projects/VEA_TOPFARM.aspx?sc_lang=en

OffshoreGrid

OffshoreGrid was a techno-economic study within the Intelligent Energy Europe programme. It developed a scientifically based view on an offshore grid in Northern Europe along with a suited regulatory framework considering technical, economic, policy and regulatory aspects. The project was targeted for European policy makers, industry, transmission system operators and regulators.
Website: http://www.offshoregrid.eu/

TradeWind

TradeWind was a European project funded under the EU's Intelligent Energy-Europe Programme. The project addressed one of the most challenging issues facing wind energy: its maximal and reliable integration in the Trans-European power markets.
Website: http://www.trade-wind.eu/

4 Conclusions

There is a high level of activity in tidal stream energy research. 64 individual TECs have been identified at different stages of development which operate with different principles. However, it should be noted that the list might not be exhaustive.

Compared to wave energy, tidal energy is currently making substantial progress towards commercialization. The most advanced TECs are now progressing towards multi-device array with multi-megawatts projects and thus are approaching nearing a commercially viable stage. Therefore, the techno-economical feasibility of these devices is yet to be proven. Irish company Open Hydro is currently installing the first commercial tidal farm in Brittany, France. It shall be fully operational in 2014 and consists of four 16 m tidal turbines generating 2 MW each. Furthermore, a number of projects have been approved recently such as the 10 MW Skerries tidal energy array in Ireland, which is expected to enter commercial operation in 2015.

Unlike the wave energy sector where it is still unclear which concept(s) will materialize in real business, there is a clear sign of consolidation in tidal energy sector on horizontal-axis turbines (~47%). However, there still exist many devices which are still at their early stages of development programme.

The greatest resource potential in Europe is accumulated around UK. France and Spain have also sufficient tidal resources in certain locations that TECs can operate efficiently.

For the EU MERMAID project purposes, it has been discussed during the project meetings that none of the four sites have sufficient tidal stream velocities which will favour TEC developments. The cut-in speed necessary for generating power are specified with 0.5-1.5 m/s (AECOM, 2011; Appendix A). D 7.1 – Site specific conditions (MERMAID, 2013a) has reported that the mean current velocities are generally below this range. For example, the currents are in order of 0.20-0.30 m/s in the Kriegers Flak Site (Baltic Sea), whilst they vary between 0 and 0.60 m/s in the Project Gemini Site (North Sea). The tidal current time series at Atlantic study site have also shown that 50% of the velocity data barely exceed 0.005 m/s, with magnitudes above 0.01 m/s have an occurrence rate of 20%. More information on the renewable energy resource characteristics can be found in D 7.1 of the Mermaid project. In order to see the most attractive functionalities at the Mermaid sites, Table 9 is herein recalled. As seen from the Table, none of the sites have considered tidal power as a promising alternative. Taking into account these reasons, no evaluation has been performed regarding the applicability of TECs for MUP purposes.

Table 9: Most attractive functionalities of the sites (MERMAID, 2013a; MERMAID, 2013b)

	North Sea Site: Gemini	**Baltic Sea Site: Kriegers Flak**	**Atlantic Sea Site: Ubiarco**	**Mediterranean Site: Acqua Alta**
Resource at site				
Expected annual wave power	10~15kW/m	None	32.7 kW/m	3 kW/m
Expected annual wind power	Annual average wind speeds of 10 m/s	297 W/m^2	100.6133 MW/m^2	4.54 m/s Limited
Expected annual tidal power	Very low	None	<0.1 W/m^2	None
Energy conversion				
Wind	Yes	Yes	Yes	Yes
Wave	Maybe	No	Yes	Yes
Tidal	No	No	No	No
Ecological				
Aquaculture	Yes	Yes	No (very difficult)	?
Mariculture	Yes – mussle seed collectors	Yes	No	Yes
Seaweed farming	Yes	Yes	No	?
Fish farming	Not yet	Yes	No	Yes
Potential MUP activities	Wind + wave (??) + shellfish aquaculture	Wind + aquaculture Wind + floating fish cages	Three floating wind turbine type + three WEC concepts	Two WEC concepts + wind Two WEC concepts + fish farm

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http://www.h2ocean-project.eu/
http://www.demowfloat.eu/
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http://www.offshoregrid.eu/
http://www.trade-wind.eu/

6 APPENDIX A

Table A.1 list of global TEC technologies

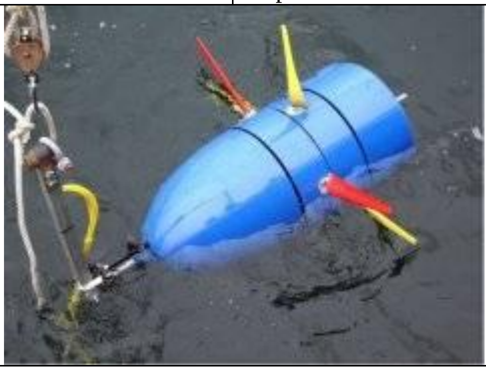
Item	Technology	Company	Country	Status	Technology type
1	Airborne	CoRMaT	Netherlands	2	Horizontal axis
2	Alstom (Tidal generation limited, UK)	Deep-Gen	France	3	Horizontal axis
3	Aquantis inc	C-plane	USA	1	Horizontal axis
4	Aquascientific	tidal turbine	United Kingdom	2	Other
5	Atlantis resources corporation	AR-1000	United Kingdom	3	Horizontal axis
6	Atlantis resources corporation	AS	United Kingdom	2	Venturi
7	Atlantis resources corporation	AN (Nereus)	United Kingdom	2	Hydrofoil
8	Atlantis resources corporation	AK-1000	United Kingdom	3	Horizontal axis
9	Atlantisstrom	Atlantisstrom	Germany	2	Horizontal axis
10	Balkee tide and wave electricity generator	TWPEG	Mauritius	1	Horizontal axis
11	BioPower Systems	bioStream	Australia	2	Hydrofoil
12	Blue Energy	Davis Hydro turbine / VAHT	Canada	2	Venturi
13	Bluewater	Bluetec	Netherlands	1	Both horizontal and vertical axis
14	Bourne Energy	CurrentStar	USA	1	Horizontal axis
15	Bourne Energy	TidalStar	USA	1	Horizontal axis
16	Cetus energy	Cetus turbine	Australia	2	Horizontal axis
17	Clean Current Power Systems Incorporated	Clean Current tidal turbine	Canada	2	Venturi
18	Current2Current	tidal turbine	United Kingdom	2	Venturi
19	Elemental energy technologies limited	SeaUrchin	Australia	3	Venturi
20	Flumill	Helix	Norway	3	Archimedes screw
21	Free flow power corporation	SmarTurbine	USA	2	Vertical axis
22	FreeFlow 69	Osprey	USA	2	Horizontal axis
23	GCK technology inc	Gorlov helical turbine	USA	1	Vertical axis
24	Hammerfest Strom AS	Hammerfest turbine (HS300, HS1000)	Norway	3	Horizontal axis
25	Harbin Engineering University (HEU)	Wanxiang vertical turbine	China	1	Vertical axis

26	Hydra tidal energy technology AS	Morild 2	Norway	3	Horizontal axis
27	Hydrocoil power inc	Hydrocoil	USA	4	Other
28	Hydro-gen	Hydro-gen	France	4	Other
29	Hydrokinetic laboratory	Hypeg	USA	1	Vertical axis
30	HydroVenturi Ltd	HydroVenturi	United Kingdom	1	Venturi
31	IHC Mervede (Ecofys)	Wave rotor	Netherlands	2	Vertical axis
32	Lunar Energy	Rotech tidal turbine (RTT)	United Kingdom	2	Venturi
33	Marine current turbines (MCT)	Strangford Lough SeaGen	United Kingdom	4	Horizontal axis
34	Mavi innovations	Mi2	Canada	2	Venturi
35	Minesto	Deep Gen	Sweden	2	Kite
36	Natural currents	Red hawk	USA	2	Horizontal axis
37	New energy corporation Inc	EnCurrent turbine	Canada	3	Vertical axis
38	Ocean energy company	Tidal defense and energy system (TIDES)	USA	2	Horizontal axis
39	Ocean flow energy, overberg ltd	Evopod	United Kingdom	2	Horizontal axis
40	Ocean renewable power company (ORPC)	TidGen / OCGen turbine generator unit (TGU)	USA	3	Horizontal axis
41	Offshore Islands ltd	Current catcher	USA	1	Horizontal axis
42	open hydro group ltd	Open-centre turbine (OCT)	Ireland	4	Venturi
43	Pôle Mer Bretagne	Blustream	France	1	Venturi
44	Pôle Mer Bretagne	Marenergie (=Sabella)	France	1	Venturi
45	Ponte di Archimede International S.p.A.	Enermar Kobold turbine	Italy	2	Vertical axis
46	Pulse generation ltd	Pulse generator / pulse stream	United Kingdom	2	Hydrofoil
47	Robert Gordon University	Sea Snail	United Kingdom	2	Hydrofoil
48	Rugged renewable	Savonius turbine	United Kingdom	1	Vertical axis
49	Sabella Energy	Sabella subsea tidal turbine	France	2	Horizontal axis
50	Scotrenewable	SR250 (SRTT)	United Kingdom	2	Horizontal axis
51	SMD Hydrovision	TidEL	United Kingdom	2	Horizontal axis
52	Statkraft Hydra Tidal Energy Technlogy (HTET)	Statkraft tidal turbine	Norway	1	Horizontal axis
53	Swanturbines	Swanturbine	United Kingdom	2	Horizontal axis
54	Teamwork Technology BV	Tocardo	Netherlands	4	Horizontal axis

55	The Engineering Business ltd	Stingray	United Kingdom	1	Hydrofoil
56	Tidal energy pty ltd	Davidson Hill Venturi (DHV) turbine	Australia	2	Venturi
57	Tidal energy systems corporations	Foil rotor III	USA	1	Venturi
58	Tidal Hydraulic Generators ltd (THGL)	Tidal stream generator (DeltaStream)	United Kingdom	1	Horizontal axis
59	Tidal Sails AS	tidal sails AS	Norway	1	Other
60	TidalStream	Triton	United Kingdom	2	Horizontal axis
61	UEK Systems	UEK turbine (underwater electric kite)	USA	2	Venturi
62	Verdant power LLC	Free flow / Kinetic Hydropower System (KHPS)	USA, Canada	3	Horizontal axis
63	Voith Hydro	HyTide	Germany	2	Horizontal axis
64	Vortex hydro energy	VIVACE (vortex induced vibrations aquatic clean energy)	USA	2	Other

Table A.2: Technology sheets

TECHNOLOGY PROFILE	
Technology name:	CoRMaT
Developer	(Nautricity Ltd,) Airborne
Country:	(UK,) NL
Website:	http://www.airborne.nl/



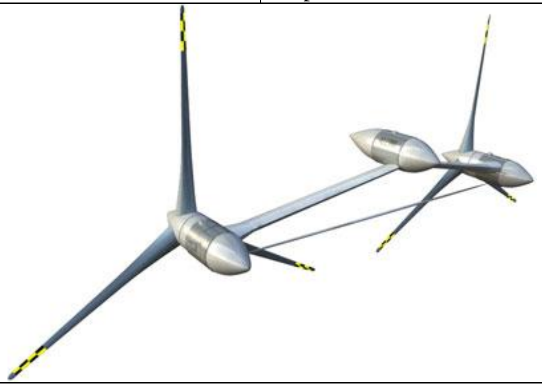
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	permanent magnet generator
Brief description:	
Mooring / anchoring / foundation:	moored
Required water depth (m):	8-500 m
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

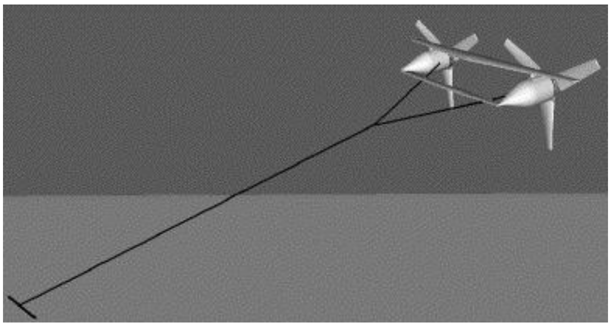
REMARKS

The CoRMat employs two closely spaced contra rotating rotors, driving a contra rotating electrical generator. The first rotor has three blades rotating in a clockwise direction while the second rotor, located directly behind the first, has four blades rotating in an anti-clockwise direction. The turbine directly drives a flooded, permanent magnet, contra-rotating generator, without a gearbox. The flooded generator is cooled passively by the water, eliminating parasitic energy losses associated with gearbox driven water tight active oil based gearbox-generator cooling systems and power absorbing shaft seals.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Aquantis C-plane
Developer	Aquantis Inc.
Country:	USA
Website:	http://www.ecomerittech.com/aquantis.php



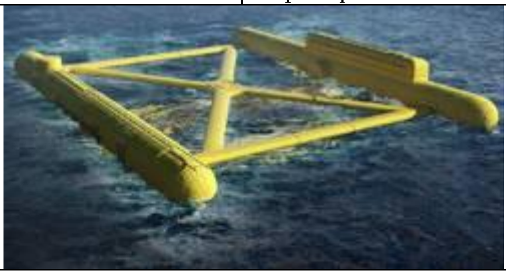


DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	Multi-blade
Mooring / anchoring / foundation:	tethered
Required water depth (m):	
Dimensions of full prototype (mxm):	Diameter 30 m
Weight (ton):	
Current stage:	Stage 1
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The Aquantis Current Plane ("C-Plane™") technology is a marine current turbine designed to extract the kinetic energy from the flow and is capable of achieving reliable, competitively priced, base-load power generation. The technology is suitable for both steady marine currents and tidal currents, although there are system differences and specific arraying and deployment requirements for each. Aquantis is designed to harness the energy from the Gulf Stream and other steady marine currents around the world. Aquantis deployment is projected to be cost-competitive with thermal power generation when CO_2 emissions and other environmental costs are accounted for.

Current speed (m/s)	Electric power output (kW)
2.5	750

TECHNOLOGY PROFILE	
Technology name:	Aquascientific tidal turbine
Developer	Aquascientific
Country:	UK
Website:	http://aquascientific2.moonfruit.com/#
	

DEVICE SPECIFICATIONS	
Operating principle:	other
Operating position:	
Power take-off system:	
Brief description:	Small scale prototype experimental trials in wind tunnel confirmed power extraction. Water flow trials are underway
Mooring / anchoring / foundation:	gravity base, other options are currently being explored
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS
Turbine is positioned by anchoring and cabling. Energy extraction from flow that is transverse to the rotation axis. Turbines utilize both lift and drag.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	AR-1000
Developer	Atlantis resources corporation
Country:	UK
Website:	www.atlantisresourcescorporation.com
	

DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	nearshore
Power take-off system:	mechanical drive
Brief description:	Bi-directional blades
Mooring / anchoring / foundation:	seabed-anchored (monopile)
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 4 / 5 Deployed and commissioned at the EMEC facility during 2011 (full scale), in 2012 tests at Narec
Future targets:	
References:	http://www.orecca.eu http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The AR series turbines are commercial scale Horizontal Axis Turbines designed for open ocean deployment in the harshest environments on the planet. AR turbines feature a single rotor set with highly efficient fixed pitch blades. The AR turbine is rotated as required with each tidal exchange using the on board yaw system. This is done in the slack period between tides and fixed in place for the optimal heading for the next tide. AR turbines are rated at 1MW @ 2.65m/s of water flow velocity. The AR-1000, the first of the AR series, was successfully deployed and commissioned at the EMEC facility during the summer of 2011

Current speed (m/s)	Electric power output (kW)
2.65	1000s

TECHNOLOGY PROFILE	
Technology name:	AS
Developer	Atlantis resources corporation
Country:	UK
Website:	www.atlantisresourcescorporation.com

DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	
Power take-off system:	
Brief description:	mono-directional blades
Mooring / anchoring / foundation:	
Required water depth (m):	>25
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 AS-400 tow-tested in 2008
Future targets:	
References:	http://peswiki.com/index.php/Directory:Atlantis_Resources_Corporation_--_Nereus_and_Solon_Tidal_Turbines http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

AS series turbines are ducted Horizontal Axis Turbines (HAT) suitable for deployment with mono-directional blades in river environments and bi-directional blades in diurnal tidal locations. AS turbines feature a unique swept back blade design and control system to optimize turbine efficiency across flow velocity distributions. The AS-400™, the first of the AS series, has been designed from first principles using extensive computer modelling and following tow-testing in August 2008, is recognized as the world's most efficient water-to-wire turbine as verified by Black & Veatch.

Current speed (m/s)	Electric power output (kW)
2.6	100
2.6	500
2.6	1000

TECHNOLOGY PROFILE	
Technology name:	AN (Nereus)
Developer	Atlantis resources corporation
Country:	UK
Website:	www.atlantisresourcescorporation.com

DEVICE SPECIFICATIONS	
Operating principle:	Hydrofoil
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	pile mounted
Required water depth (m):	<25
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 AN-400 tow-tested in 2008
Future targets:	
References:	http://peswiki.com/index.php/Directory:Atlantis_Resources_Corporation_--_Nereus_and_Solon_Tidal_Turbines http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The AN400™ is a 400kW shallow water hydro kinetic turbine which has been extensively operated at an open ocean, grid connected test facility located at San Remo, Australia. The AN400 turbine uses Aquafoils™ to capture the kinetic energy present in the flow of water which drives a chain drive system powering 2 X 75kW induction generators. The system has 220o yaw capability, vertical recovery for maintenance and cleaning, and the system is fully autonomous and can be remotely controlled via internet connection. The converter and PLC/power conditioning/control systems are located on top of a surface piercing pylon. The turbine is robust and can withstand water flow containing significant debris. It is fully scalable and has been developed over a 6 year period with multiple tow-testing and continual optimisation.

Current speed (m/s)	Electric power output (kW)
	2 x 75
1-5	

TECHNOLOGY PROFILE	
Technology name:	AK1000
Developer	Atlantis resources corporation
Country:	UK
Website:	www.atlantisresourcescorporation.com

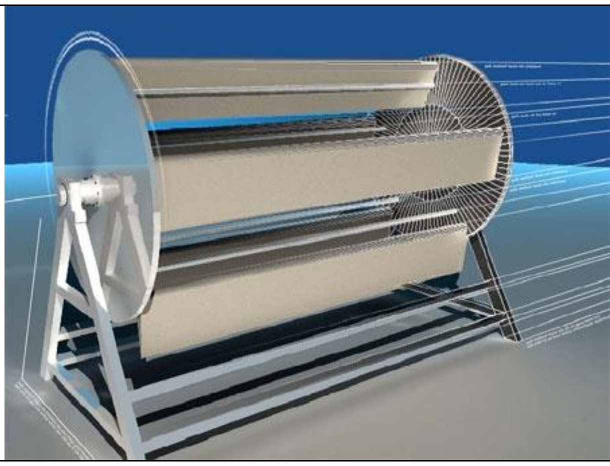
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis
Operating position:	
Power take-off system:	
Brief description:	18 m diameter
Mooring / anchoring / foundation:	seabed mounted
Required water depth (m):	
Dimensions of full prototype (mxm):	Stands at 22.5 m height
Weight (ton):	1300
Current stage:	Stage 4 / 5 Prototype installed in Orkney (2010)
Future targets:	
References:	http://www.bbc.co.uk/news/uk-scotland-highlands-islands-10942856

REMARKS

The AK-1000 turbine is a Horizontal Axis Turbine (HAT) designed for open ocean deployment in the harshest environments on the planet. Atlantis AK series turbines feature a unique twin rotor set with fixed pitch blades eliminating the requirement for sub-sea nacelle rotation to improve operational reliability. The AK-1000 turbine is rated at 1MW @ 2.6m/s and has been designed for cost efficient open ocean nacelle retrieval.

Current speed (m/s)	Electric power output (kW)
2.65	1000

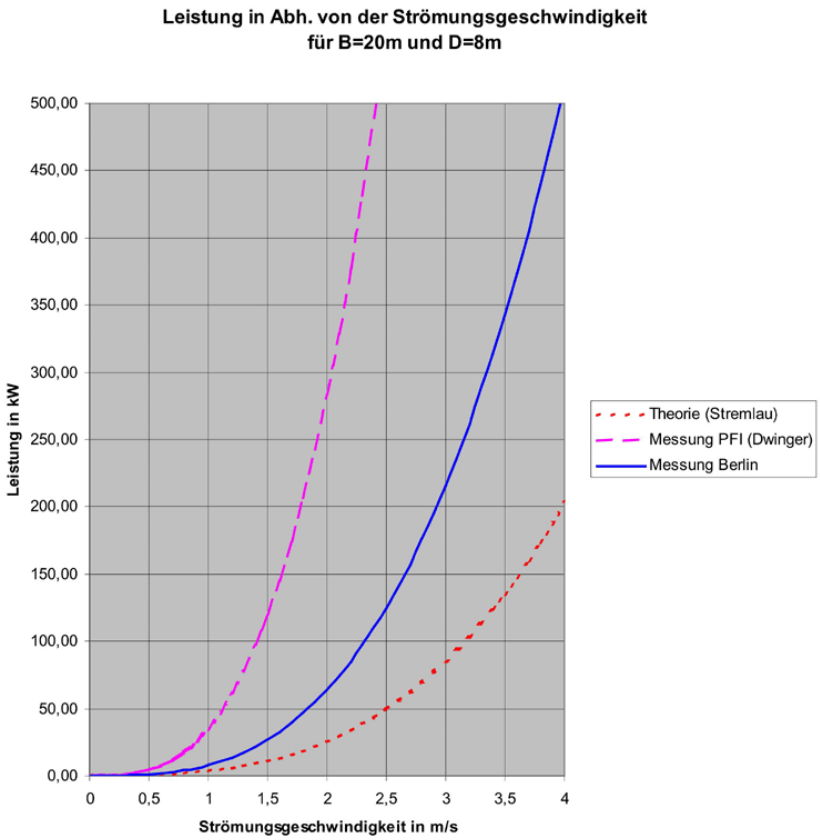
TECHNOLOGY PROFILE	
Technology name:	Atlantisstrom
Developer	Atlantisstrom
Country:	Germany
Website:	http://www.atlantisstrom.de/



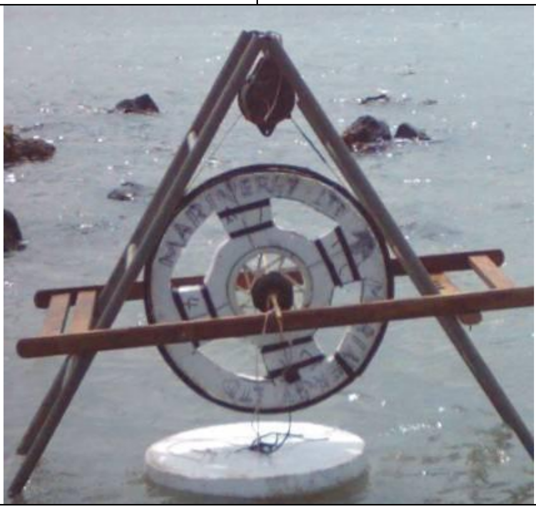
DEVICE SPECIFICATIONS	
Operating principle:	transverse horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	10m diameter, fully submerged, 5 fins
Mooring / anchoring / foundation:	seabed mounted
Required water depth (m):	>15m
Weight (ton):	
Description of model prototypes:	1:10 scale prototype tested
Current stage:	Stage 2 1:10 scale prototype tested
Future targets:	
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

Current speed (m/s)	Electric power output (kW)
	300

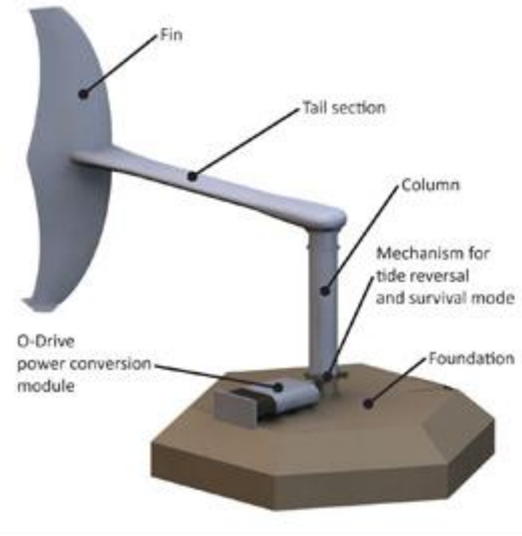


Source: http://www.atlantisstrom.de/projektbeschreibung.html

TECHNOLOGY PROFILE	
Technology name:	TWPEG
Developer	Balkee tide and wave electricity generator
Country:	Mauritius
Website:	
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1
Future targets:	
References:	http://peswiki.com/index.php/Directory:Balkee_Tide_and_Wave_Electricity_Generator
REMARKS	

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	bioStream
Developer	BioPower Systems
Country:	Australia
Website:	http://www.biopowersystems.com/



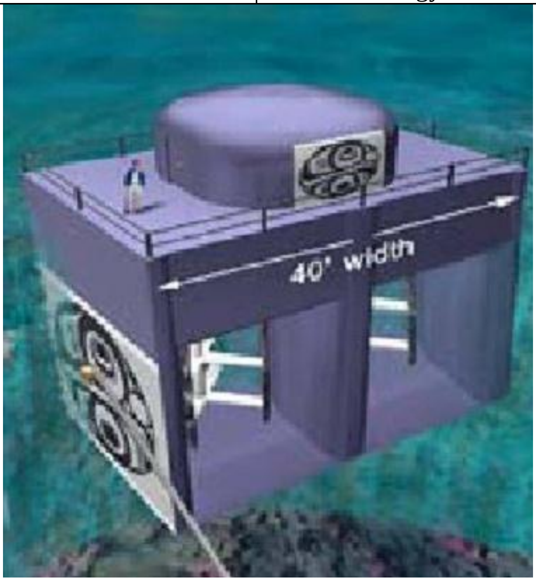
DEVICE SPECIFICATIONS	
Operating principle:	oscillating hydrofoil
Operating position:	
Power take-off system:	
Brief description:	vertical-hydrofoil version of the Stingray
Mooring / anchoring / foundation:	gravity base
Required water depth (m):	30-50
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 250 kW project in development
Future targets:	1 MW commercial scale
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

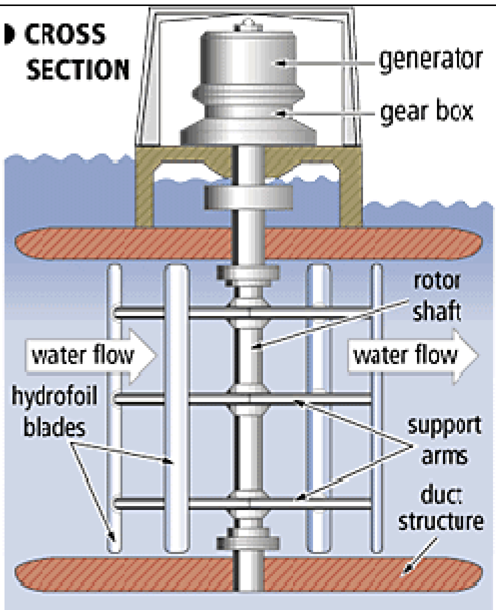
REMARKS

The bioSTREAM is an oscillating hydrofoil based on the highly efficient propulsion of Thunniform-mode swimming species, such as shark, tuna, and mackerel. The bioSTREAM mimics the shape and motion characteristics of these species, but is a fixed device in a moving stream. In this configuration the propulsion mechanism is reversed, and the energy in the passing flow is used to drive the device motion against the resisting torque of an electrical generator. Due to the single point of rotation, this device can align with the flow in any direction and can assume a streamlined configuration to avoid excess loading in extreme conditions. Systems are being developed for 250 kW, 500 kW, and 1 MW capacities to match conditions in various locations.

Current speed (m/s)	Electric power output (kW)
>2.5 m/s	

TECHNOLOGY PROFILE	
Technology name:	Davis Hydro turbine / VAHT (Vertical axis hydro turbine)
Developer	Blue Energy
Country:	Canada
Website:	www.bluenergy.com





DEVICE SPECIFICATIONS	
Operating principle:	Venturi (vertical axis)
Operating position:	offshore
Power take-off system:	mechanical
Brief description:	4 fixed hydrofoil blades, turbine mounted in a concrete marine caisson anchoring the unit to the ocean floor; gearbox and generator above the rotor above the surface
Mooring / anchoring / foundation:	gravity base
Required water depth (m):	up to 50m
Dimensions of full prototype (mxm):	10m diameter, base of the caisson 17m wide and 10.5m long, height ranging from 10 to 20m
Weight (ton):	
Current stage:	Stage 2 homepage updated in Jan 2012
Future targets:	
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://canmetenergy.nrcan.gc.ca/sites/canmetenergy.nrcan.gc.ca/files/files/pubs/CanadianTechnologyDeveloper2010update_eng.pdf http://peswiki.com/index.php/Directory:Blue_Energy http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

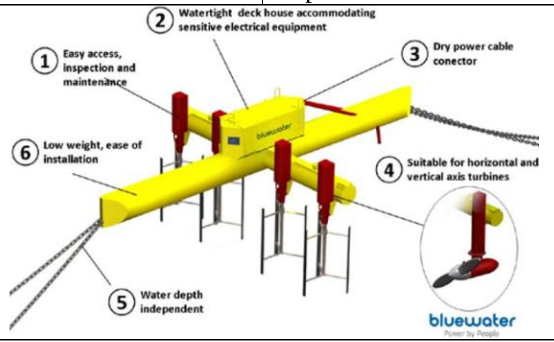
The Blue Energy Ocean Turbine acts as a highly efficient underwater vertical-axis windmill. Four fixed hydrofoil blades of the turbine are connected to a rotor that drives an integrated gearbox and electrical generator assembly. The turbine is mounted in a durable concrete marine caisson that anchors the unit to the ocean floor; and the structure directs flow through the turbine further concentrating the resource supporting the coupler, gearbox, and generator above the rotor. These sit above the surface of the water and are readily accessible for maintenance and repair. The hydrofoil blades employ a hydrodynamic lift principal that causes the turbine foils to move proportionately faster than the speed of the surrounding water. Computer optimized cross-flow design ensures that the rotation of the turbine is unidirectional on both the ebb and flow of the tide.

Current speed (m/s)	**Electric power output (kW)**
7.2-7.7	5000-10000

PARAMETER	**SPECIFICATION**	
Rated capacity	1MW@5 m/s	3MW@5 m/s
Rotor diameter	10 m	10 m
Rotor height	3.6 m	10.4 m
RPM	5.5@ 1 m/s - 28.6@ 5 m/s	5.5@ 1 m/s - 28.6@ 5 m/s
Tip speed	14.5 m/s	14.5 m/s
Drive train efficiency	Direct drive, no drive train	Direct drive, no drive train
Protective inlet screen	No	No
Total height	6.6 m	13.4 m
Total length	14 m	14 m
Total width	11 m	11 m
System weight	n/a	n/a

Source:
http://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=24&ved=0CFQQFjADOBQ&url=http%3A%2F%2Fcanmetenergy.nrcan.gc.ca%2Fsites%2Fcanmetenergy.nrcan.gc.ca%2Ffiles%2Ffiles%2Fpubs%2FCanadianTechnologyDeveloper2010update_eng.pdf&ei=Um9VUY7KFM_WsgaA_4C4Bg&usg=AFQjCNGVUyVoYsrpLinh2SyWxmTtkody3w&bvm=bv.44442042,d.Yms
(Canadian technology developer 2010)

TECHNOLOGY PROFILE	
Technology name:	Bluetec
Developer	Bluewater
Country:	Netherlands
Website:	http://www.bluewater.com/bluetec/



DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine/vertical axis turbine
Operating position:	
Power take-off system:	
Brief description:	floating, mooring lines
Mooring / anchoring / foundation:	floating
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1 homepage (technology) updated in August 2011
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The Bluetec platform is a unified floating support structure which can hold any type of turbines in any water depth. It offers waterproof housing for vulnerable systems above the waterline unique in the tidal industry. Power cables are connected dry rather than under water, reducing risks and costs significantly. The Bluetec structure is much lighter than the gravity based designs, requiring less tonnage steel per MW. The device itself is floating and therefore installation can be executed with widely available vessels, without the need for expensive floating cranes or jack-ups.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Currentstar
Developer	Bourne Energy
Country:	USA
Website:	http://www.bourneenergy.com/

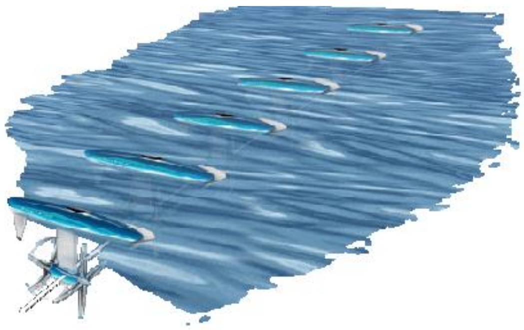
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	power cartridge - micro generator system
Brief description:	
Mooring / anchoring / foundation:	floating
Required water depth (m):	
Dimensions of full prototype (mxm):	length 30.5 m, width 30.5 m, height above water line 3.65 m
Weight (ton):	
Current stage:	Stage 1 homepage updated in October 2011
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

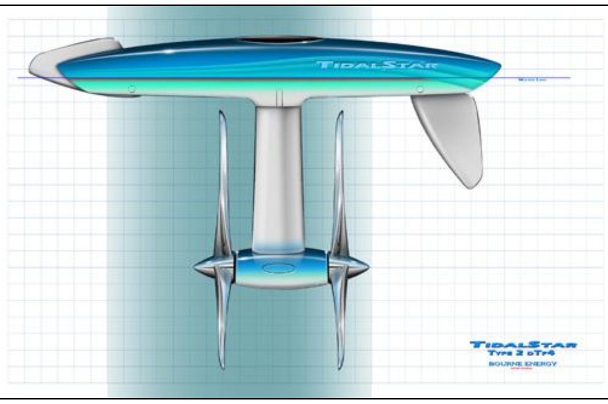
REMARKS

The CurrentStar series is designed to harness the enormous potential source of clean energy in ocean currents. Ocean currents flow at all depths in the ocean but the strongest usually occur in the upper layer.

Current speed (m/s)	Electric power output (kW)
	50

TECHNOLOGY PROFILE	
Technology name:	TidalStar
Developer	Bourne Energy
Country:	USA
Website:	http://www.bourneenergy.com/

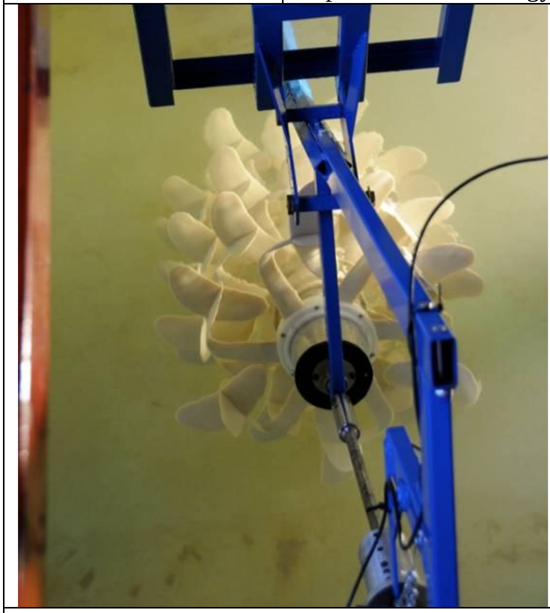




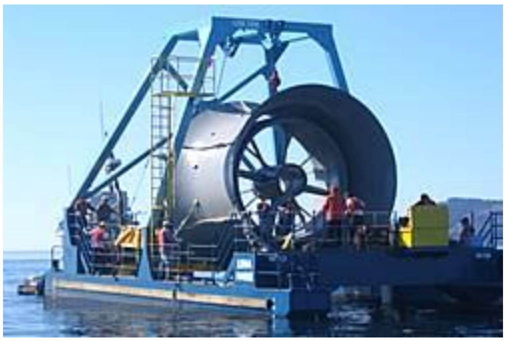
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	power cartridge - micro generator system
Brief description:	a pair of contra-rotating blades, on in front of the other length 6 m, width 6 m, height above water line 1 m
Mooring / anchoring / foundation:	floating pontoon
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1 homepage updated in October 2011
Future targets:	
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS
The horizontal axis TidalStar device uses a bidirectional twin rotor turbine to produce approximately 50 kW at peak capacity in both ebb and flood tides.

Current speed (m/s)	Electric power output (kW)
	50kW

TECHNOLOGY PROFILE	
Technology name:	Cetus turbine
Developer	Cetus energy
Country:	Australia
Website:	http://www.cetusenergy.com.au/
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	
REMARKS	
At the centre of the Cetus technology is the Cetus Blade. The technology is the only turbine able to convert chaotic energy input to uniform torque output allowing the turbine to continue rotating in the same direction irrespective of the direction of flow. It is a fully patented blade, coupled with a unique flexible operating dynamic, which allows it to capture energy flows from any direction, at any speed.	

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Clean Current tidal turbine
Developer	Clean Current Power Systems Incorporated
Country:	Canada
Website:	http://www.cleancurrent.com
	

DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	nearshore
Power take-off system:	permanent magnet generator, direct drive
Brief description:	Wells turbine for use in bidirectional flows, direct drive, variable speed, 5 blades
Mooring / anchoring / foundation:	pile mounted or gravity base (depending on sites)
Required water depth (m):	min. 5.5-13.0 (depending on the model) up to 20m
Dimensions of full prototype (mxm):	4 different models (diameter 3.5-10.0m)
Weight (ton):	
Current stage:	Stage 3 full scale (installed 2006)
Future targets:	
References:	ocean energy global technology development status (2009) http://www.orecca.eu Canadian technology developer 2010 http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

starts at 1m/s and stops on a declining tide at about 0.75m/s
Clean Current's tidal turbine generator is a bi-directional ducted horizontal axis turbine with a direct drive variable speed permanent magnet generator. Operability is enhanced by a simple design that has one moving part - the rotor assembly that contains the blades. There is no drive shaft and no gearbox. The bearing seals will be replaced every 5 years and the generator will be overhauled every 10 years. The service life of the a service life of turbine generator is 25-30 years

* **Current speed (m/s)**	**Electric power output (kW)**
3.0	65 (3.5m diameter)
3.0	125 (5m diameter)
3.0	285 (7.5m diameter)
3.0	500 (10m diameter)

TECHNOLOGY PROFILE	
Technology name:	Tidal turbine
Developer	Current2Current
Country:	UK
Website:	http://www.current2current.com/CURRENT2CURRENT_new_site/Home.html

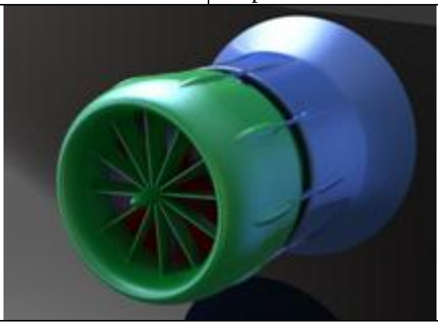
DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech http://www.aberdeenrenewables.com/members/complete-a-z-index/current2current/

REMARKS

The design of the SPG leverages water flows in varying scenarios to generate electricity. While the focus of the C2C deployments is ocean currents, the SPG works in a bi-directional manner. Therefore, the SPG can be deployed to generate electricity from tidal differential/tidal streams. In areas where currents and tidal differential/streams converge, the SPG with remote control and telemetry systems will track the water velocity. In this manner, the SPG can be maneuver in three dimensions to optimize water flow. Each “tube” of the catamaran is approximately 150 feet in length. The inner tube contains the electronic components and the outer tube is the rotating impeller system, comprising a generator with a four-blade turbine, which measures approximately 100 feet in diameter. The total area covered by each SPG is about the size of a football field.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	SeaUrchin
Developer	Elemental energy technologies limited
Country:	Australia
Website:	http://www.eettidal.com/

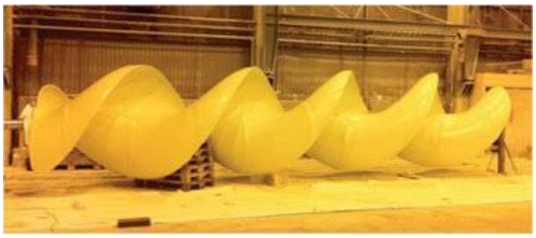


DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine/Venturi
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 3
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

A revolutionary vortex reaction turbine (branded the SeaUrchin), an advanced third generation marine turbine technology capable of delivering inexpensive, small to large scale, baseload or predictable electricity by harnessing the kinetic energy of free-flowing ocean currents, tides and rivers.

Current speed (m/s)	Electric power output (kW)
1.5	2

TECHNOLOGY PROFILE	
Technology name:	Helix
Developer	Flumill
Country:	Norway
Website:	http://www.flumill.com/
	
DEVICE SPECIFICATIONS	
Operating principle:	Archimedes screw
Operating position:	
Power take-off system:	
Brief description:	counter rotating helixes
Mooring / anchoring / foundation:	pile or gravity based
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 3
Future targets:	
References:	
REMARKS	
The top fin controls the operational angle and stability of the Flumill System.The fin connects the two turbines and supports the upper bearings. Controlling the operational angle of the helix during operation (between 25 and 50 degrees), the fin has no moving parts, is buoyant and made from PVC foam with an outer composite material layer. The shape of the top fin will be optimized with respect to the sites.	

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Osprey
Developer	FreeFlow 69
Country:	USA
Website:	http://www.freeflow69.com/
	
DEVICE SPECIFICATIONS	
Operating principle:	vertical axis turbine
Operating position:	
Power take-off system:	
Brief description:	30ft aluminium catamaran
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	http://pesn.com/2007/08/17/9500490_FreeFlow69/ http://peswiki.com/index.php/Directory:FreeFlow_69 http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
The Osprey is a vertical axis turbine mounted to the bottom of a 30' aluminium catamaran test rig float.	

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	SmarTurbine
Developer	Free flow power corporation
Country:	USA
Website:	http://free-flow-power.com/
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	bottom-mounted on pylons, suspended freom the surface on floating mounts, attached to bridge abutments or deployed in fields
Required water depth (m):	>3 m
Dimensions of full prototype (mxm):	diameter 2.25 m (shroud 3 m), length 4 m, width 3 m, height 3 m
Weight (ton):	3.04
Current stage:	Stage 2
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
SmarTurbine has a 2.25 meter rotor (3 meter outer diameter including shroud), a single moving part (the rotor) with no gearbox or chemical lubricants, and generates 10 kW in flows of 2.25 meters per second.	

Current speed (m/s)	Electric power output (kW)
2.25	10
max 5	

No information on homepage, no actual information with google

TECHNOLOGY PROFILE	
Technology name:	Gorlov helical turbine
Developer	GCK Technology Inc
Country:	USA
Website:	http://www.gcktechnology.com/GCK/pg2.html
	

DEVICE SPECIFICATIONS	
Operating principle:	vertical axis turbine
Operating position:	
Power take-off system:	unspecified
Brief description:	twisted blades (reducing the amount of vibrations) capture up to 35% of the energy of the water flowing through it
Mooring / anchoring / foundation:	
Required water depth (m):	1 MW planned
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1 no updates found since 2001
Future targets:	
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The Gorlov Helical Turbine (GHT) evolved from the Darrieus turbine design, which was altered to have helical blades/foils. In the GHTs design, the blades are twisted about the axis, so that there is always a foil section at every possible angle of attack. The optimal placement and angle of the blades allow the GHT to operate under a lift-based principle

Current speed (m/s)	Electric power output (kW)
1.5	0.8 kW prototype
	5 kW prototype

TECHNOLOGY PROFILE	
Technology name:	Andritz Hammerfest-turbine (HS300, HS1000)
Developer	Hammerfest Strom AS
Country:	Norway
Website:	http://www.hammerfeststrom.com

DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	nearshore
Power take-off system:	induction, mechanical drive
Brief description:	3-bladed, pitch control, fully submerged, ~10rpm
Mooring / anchoring / foundation:	seabed-anchored (gravity foundation)
Required water depth (m):	35-100m
Dimensions of full prototype (mxm):	
Weight (ton):	~130t nacelle ~150t substructure
Current stage:	Stage 4 / 5 full-scale prototype HS1000 in Orkney (2012)
Future targets:	pre-commercial array in Sound of Islay
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://inhabitat.com/worlds-first-tidal-farm-successfully-installs-100-foot-subsea-turbine/

REMARKS

HS1000 rotor diameter 21m, 1,000kW
HS300 rotor diameter 20m, 300kW

* Current speed (m/s)	Electric power output (kW)
	300 HS300
	1,000 HS1000
2.5	

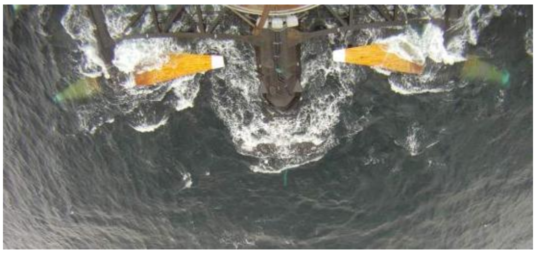
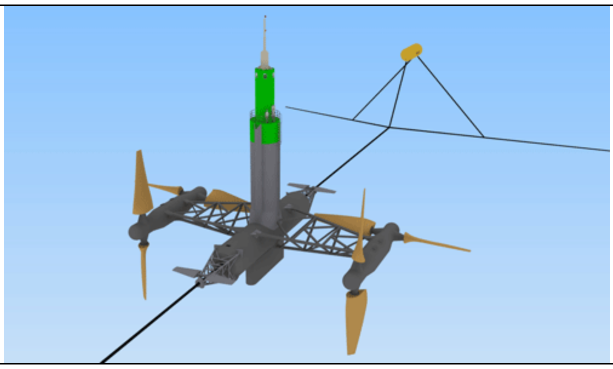
TECHNOLOGY PROFILE	
Technology name:	Wanxiang vertical turbine
Developer	Harbin Engineering University (HEU)
Country:	China
Website:	http://mhk.pnnl.gov/wiki/index.php/Wanxiang_II

DEVICE SPECIFICATIONS	
Operating principle:	vertical axis turbine
Operating position:	
Power take-off system:	unspecified
Brief description:	2 vertical axis turbines, Wanxiang 2: generators and electronics mounted above the waterline
Mooring / anchoring / foundation:	Wanxiang 1 small floating barge Wanxiang 2 gravity-based anchoring
Required water depth (m):	40-70m
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1 no updates found since 2009
Future targets:	
References:	ocean energy global technology development status (2009) http://mhk.pnnl.gov/wiki/index.php/Overview_of_ocean_renewable_energy_in_China

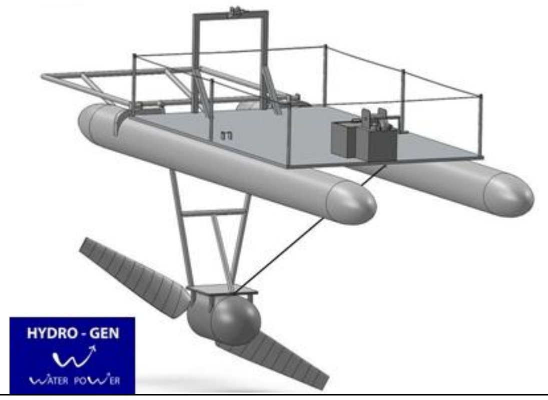
REMARKS

Current speed (m/s)	Electric power output (kW)
2.0-2.5	5-20kW Wanxiang 1
	40kW capacity Wanxiang 2

TECHNOLOGY PROFILE	
Technology name:	Morild 2
Developer	Hydra tidal energy technology AS
Country:	Norway
Website:	http://www.hydratidal.info/#!technology

	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	offshore
Power take-off system:	mechanical
Brief description:	2 pairs of contra-rotating axial flow rotors, turbines and generators under water, brought to the surface for maintenance, 8 blades
Mooring / anchoring / foundation:	floating, tethered
Required water depth (m):	
Dimensions of full prototype (mxm):	23 diameter
Weight (ton):	
Current stage:	Stage 4 / 5 full scale
Future targets:	
References:	http://www.norwegen.no/News_and_events/germany/business/WeltgroBte-schwimmende-Gezeitenkraftwerk-in-Norwegen-geoffnetdoc/ http://www.forskningsradet.no/en/Newsarticle/Laminated_wood_to_be_used_for_offshore_turbine_blades/1253954822447 http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
A unique and patented floating tidal power plant - Prototype has an installed effect of 1,5 MW - Turbine diameter of 23 meters - Each turbine is pitchable - 4 turbines with a total of 8 turbine blades - Unique wooden turbine blades - The MORILD II can be anchored at different depths, thus it can be positioned in spots with ideal tidal stream conditions - The plant carries a sea vessel verification, and is both towable and dockable - The floating installation enables maintenance in surface position, and on site - The MORILD II will be remotely operated, and has on-shore surveillance systems - Technology patented for all relevant territories The Morild power plant is a floating, moored construction based on the same principle as horizontal axis wind turbines. The plant has 4 two-blade underwater turbines and can utilize the energy potential in tidal and ocean currents. The 4 turbines transmit power via hydraulic transmission to 2 synchronous generators. Can be pitched 180 degrees to utilize energy in both directions. A cable from the transformer on the prototype to shore transfers energy.	

Current speed (m/s)	Electric power output (kW)
	1,500

TECHNOLOGY PROFILE	
Technology name:	hydro-gen
Developer	hydro-gen water power
Country:	France
Website:	http://www.hydro-gen.fr/
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	floating
Power take-off system:	
Brief description:	90 % composite material and aluminium
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	20 kW: 6.20 x 3.20 x 3.20
Weight (ton)::	20 kW: 0.6
Current stage:	Stage 5
Future targets:	
References:	
REMARKS	

Current speed (m/s)	Electric power output (kW)
	10-100
>0.3	
<3.5	

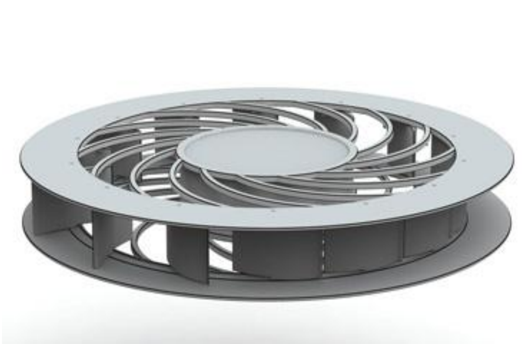
TECHNOLOGY PROFILE	
Technology name:	hydrocoil
Developer	hydrocoil power, inc
Country:	USA
Website:	http://www.hydrocoilpower.com/
	

DEVICE SPECIFICATIONS	
Operating principle:	Archimedes screw
Operating position:	Floating, suspended from buoy, bottom-mounted, attached in a hydrodynamic pod or recessed into the hull, or tethered to a surface or a submerged vessel
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	3-point slack (seabed mounted, floating, placed onto existing devices)
Required water depth (m):	
Dimensions of full prototype (mxm):	different types (scalable)
Weight (ton):	
Current stage:	Stage 5
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

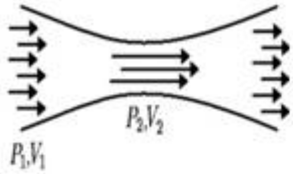
The HydroCoil device is set inside of a molded plastic cylinder six inches in diameter, to produce hydro electric power at low cost and with high efficiency in places with low head and low water flow. The unit’s coiled vane sequentially slows the water, thereby extracting more energy.

Current speed (m/s)	Electric power output (kW)
	2

TECHNOLOGY PROFILE	
Technology name:	hypeg
Developer	hydrokinetic laboratory
Country:	USA
Website:	http://www.hklabllc.com/
	
DEVICE SPECIFICATIONS	
Operating principle:	vertical axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	gravity base with built-in mooring spikes in the legs
Required water depth (m):	>40
Dimensions of full prototype (mxm):	length / width 50 m, height 20 m
Weight (ton):	
Current stage:	Stage 1
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
Their Hydro-kinetically Powered Electrical Generators (HyPEGs) converts the unimpeded flow and the massive current of large, deep rivers and ocean currents into useful electrical power on a large scale -- 4 to 8MW each. This innovative system design approach is viable because of the unique power head, cup design, and location in which the unit is placed. Unlike conventional turbine-type or propeller type current generators being tested today, HyPEGs can operate in fairly shallow rivers, since they rotate in the horizontal plane, rather than the vertical. Turbine/propeller type generators can only operate in water that is sufficiently deep that it is not a hazard to navigation - worse, they are greatly limited in power output due to a limited-sized power head. Once a suitable location is found, a HyPEG can be made in any diameter, and are limited only by their side-to-side clearance. Additionally, they need far less support structure than vertical generators	

Current speed (m/s)	**Electric power output (kW)**
	4000-8000
>5	

TECHNOLOGY PROFILE	
Technology name:	HydroVenturi
Developer	HydroVenturi Ltd
Country:	UK
Website:	http://www.hydroventuri.com/



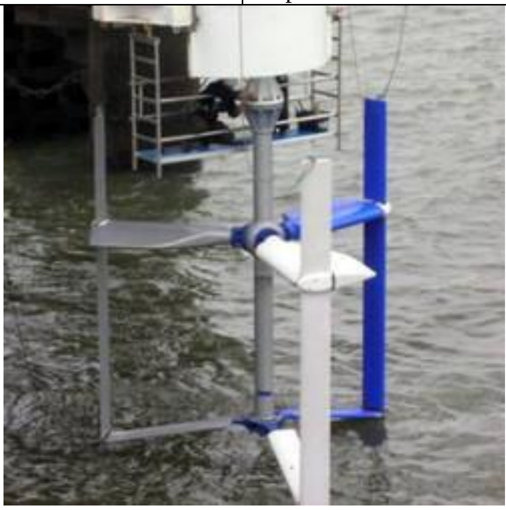
DEVICE SPECIFICATIONS	
Operating principle:	other tidal, Venturi
Operating position:	onshore
Power take-off system:	unspecified
Brief description:	accelerating water through a narrow opening, decreasing the pressure and pulling water from the surface into the chamber, using the movement to power an onshore turbine - no moving parts underwater
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1 no actual information found
Future targets:	
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/information.aspx?type=tech&id=52669fd6-13c8-40ec-8ec6-18f56c9bd9b3

REMARKS

HydroVenturi marine system a submarine Venturi is used to accelerate the water and create a subsequent pressure drop which can be made to drive a turbine. This design does not require impounding large bodies of water to extract energy economically, nor does it require submarine turbines or submarine moving or electrical parts. Expensive maintenance operations that typically arise when complex mechanical systems are submerged in a marine or river environment can thus be avoided. This is expected significantly to reduce total system lifecycle costs and eventually enable HydroVenturi to generate electricity at costs competitive with fossil fuels, with low recurring maintenance or fuel costs.

Current speed (m/s)	Electric power output (kW)
	150kW prototype

TECHNOLOGY PROFILE	
Technology name:	wave rotor
Developer	Ecofys (since 2012 IHC Mervede)
Country:	Netherlands
Website:	http://www.ihcbeaverdredgers.com/



DEVICE SPECIFICATIONS	
Operating principle:	vertical axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	pile-mounted
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 1:2 model
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The Wave Rotor uses a combined Darrieus-Wells rotor, which is contained on the same vertical axis of rotation. These are respectively omni- and bi-directional rotors that can operate in currents of changing directions. The Wave Rotor is mounted on a platform to allow for the capture of wave energy from circulating water particles created by local currents. Since it uses two types of rotor on a single axis of rotation it is able to convert not only tidal currents, but also waves into electricity.

Current speed (m/s)	Electric power output (kW)
	30 kW

TECHNOLOGY PROFILE	
Technology name:	Rotech tidal turbine (RTT)
Developer	Lunar Energy
Country:	UK
Website:	www.lunarenergy.co.uk

DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	offshore
Power take-off system:	pressurized hydraulic
Brief description:	bi-directional, symmetrical venturi duct,
Mooring / anchoring / foundation:	gravity base, no oder little seabed preparation
Required water depth (m):	>40m
Dimensions of full prototype (mxm):	duct diameter 15m, duct length 19.2m, turbine diameter 11.5m
Weight (ton):	600
Current stage:	Stage 2 1:20 scale prototype tested, full-scale testing
Future targets:	full scale
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

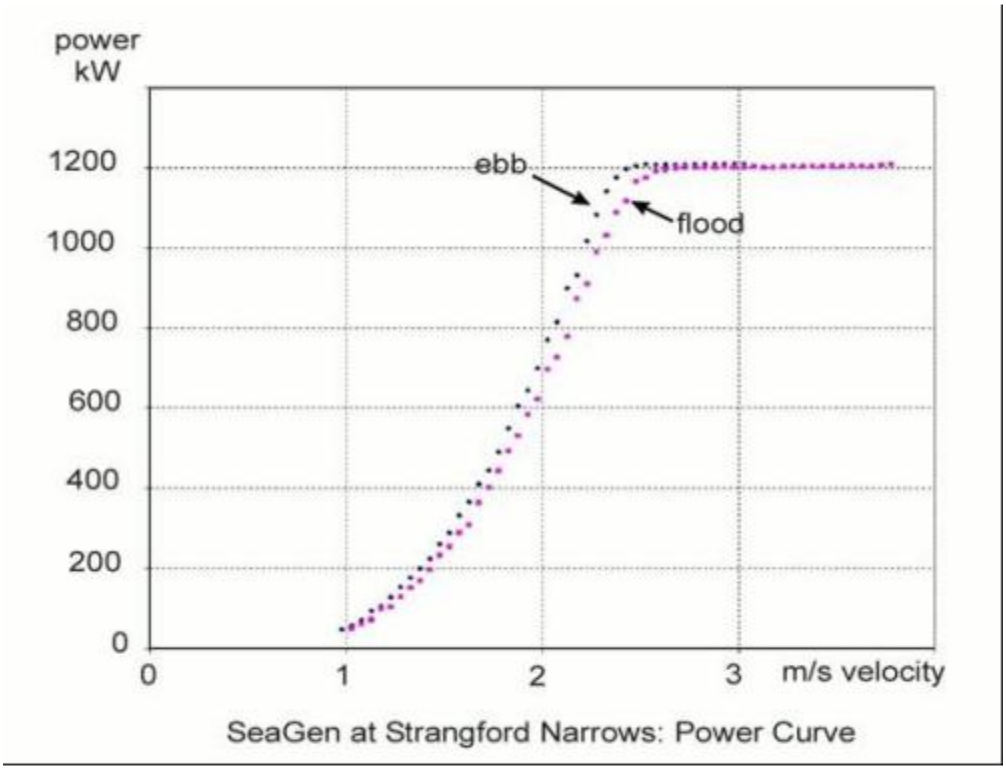
The Rotech Tidal Turbine (RTT) is a bi-directional horizontal axis turbine housed in a symmetrical venturi duct. The Venturi duct draws the existing ocean currents into the RTT in order to capture and convert energy into electricity. Use of a gravity foundation will allow the RTT to be deployed quickly with little or no seabed preparation at depths in excess of 40 meters. This gives the RTT a distinct advantage over most of its competitors and opens up a potential energy resource that is five times the size of that available to companies using pile foundations.

* Current speed (m/s)	Electric power output (kW)
	1,000 target

TECHNOLOGY PROFILE	
Technology name:	Strangford Lough SeaGen
Developer	Marine Current Turbines (MCT)
Country:	UK (Northern Ireland)
Website:	http://www.seageneration.co.uk/ http://www.marineturbines.com
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	nearshore
Power take-off system:	induction generator, mechanical drive
Brief description:	2 rotors, 16 m and 27 t each (2 x 0.6 MW) 14.3 cycles per minute
Mooring / anchoring / foundation:	monopile mounted into seabed
Required water depth (m):	working at 24-28.3 m suitable up to 38m
Dimensions of full prototype (mxm):	150 t, width 29 m + 2 x 1/2 rotors, monopile diameter: 3 m, height: 40.7 m above ground
Weight (ton):	500
Current stage:	Stage 5 operational
Future targets:	SeaGen S Nk2 rotor diameter 20m, rated power 2MW
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://peswiki.com/index.php/Directory:Marine_Current_Turbines_Ltd http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	

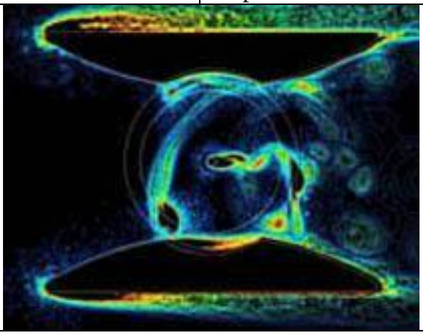
- Based on Seaflow (pilot): 300 kW, 1 rotor
- First commercial scale device
- Average peak effiency: 40-45%
- Actual electric power output: 1,200 kW at 2.4 m/s, target: 1,500 kW

* **Current speed (m/s)**	**Electric power output (kW)**
2.4	1,200
	1,500 target



Source:
http://www.marineturbines.com/3/news/article/38/dnv_confirms_seagen_s_powerful_performance_

Technology name:	Mi2
Developer	Mavi innovations
Country:	Canada
Website:	http://www.mavi-innovations.ca



DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	
Power take-off system:	permanent magnet generator - dependent on the application
Brief description:	either floating platforms, installed directly on the seabed or installed into existing civil infrastructures
Mooring / anchoring / foundation:	depending
Required water depth (m):	>8 m
Dimensions of full prototype (mxm):	
Weight (ton)::	
Current stage:	Stage 2
Future targets:	
References:	Canadian technology developer 2010 http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	

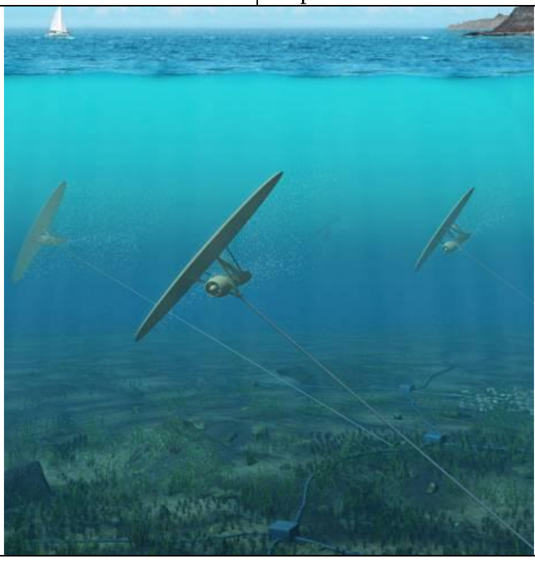
Table 2 Specifications of the Mi3 device

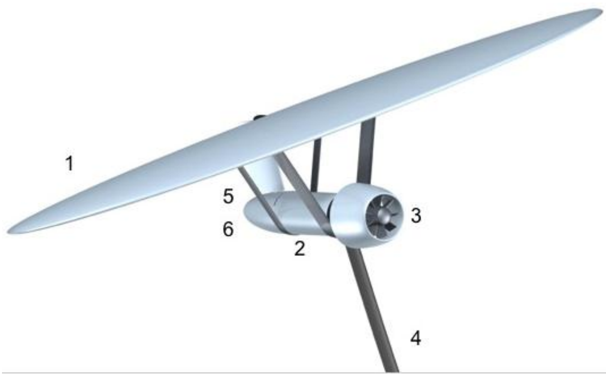
PARAMETER	SPECIFICATION
Rotor diameter	3 m
Swept area	9 m (based on rotor, i.e. excluding ducting)
RPM	0 - 75
Tip speed	2.25-3.25
Cut-in speed	1.0 knot
Protective rotor screen	Optional
Drive train efficiency	90-95%
Rated capacity	50 kW in 3m/s
System Weight (in air)	15 tonnes (excluding mooring system)

Source:
http://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=24&ved=0CFQQFjADOBQ&url=http%3A%2F%

2Fcanmetenergy.nrcan.gc.ca%2Fsites%2Fcanmetenergy.nrcan.gc.ca%2Ffiles%2Ffiles%2Fpubs%2FCanadianTechnologyDeveloper2010update_eng.pdf&ei=Um9VUY7KFM_WsgaA_4C4Bg&usg=AFQjCNGVUyVoYsrpLinh2SyWxmTtkody3w&bvm=bv.44442042,d.Yms (Canadian technology developer 2010)

TECHNOLOGY PROFILE	
Technology name:	Deep Green
Developer	Minesto
Country:	Sweden
Website:	http://www.minesto.com/deepgreentechnology/





DEVICE SPECIFICATIONS	
Operating principle:	kite
Operating position:	
Power take-off system:	
Current stage:	Stage 2
Future targets:	
References:	http://www.good.is/posts/deep-green-kite-based-tidal-power/ http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

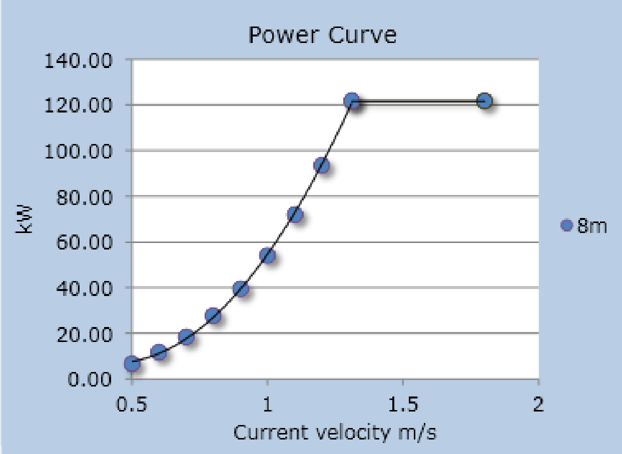
REMARKS

You tether this kite-like apparatus to the ocean floor, at a depth of anywhere from 60 to 150 meters. Then, as a tide or current pushes against the kite, it moves from side to side because its wings create a lift force. As it moves, water flows through a turbine in the kite. And because it's moving, the velocity of the flow of water through the turbine can be 10 times the surrounding stream flow, according to Minesto.

The kite consists of a wing (1), which carries a nacelle (2) and turbine (3), which is direct coupled to a generator inside the nacelle. The wing is attached to the seabed by struts and a tether (4). The tether accommodates power cables to shore but also cables for communication. By means of a rudder (5) and servo system in the rear cone (6) of the nacelle and a control system the kite is steered in a predestinated trajectory. The tether attaches the kite to a swivel mounted on a foundation at the seabed.

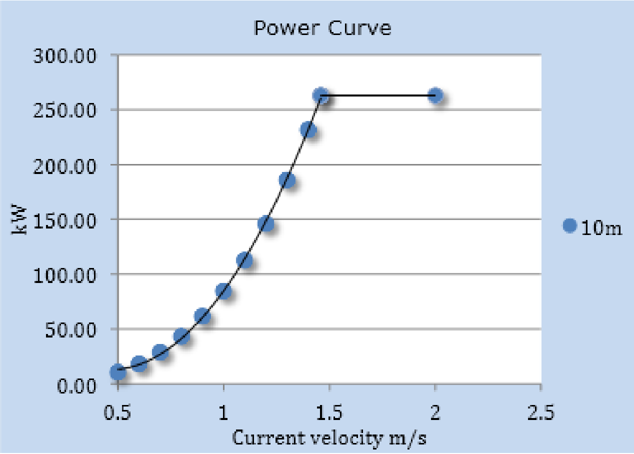
DG8:

Wing Span	8m
Rated Power (@m/s)	120 kW@1.3
Tether Length	60-80m
Depth	50-65m
Desired Speed	1.2-1.8 m/s
Lower/Upper Cut off current	0.5/2.5 m/s
Weight	2 tons
Devices/km²	50
Clearance (tip to surface)	7.5-10m
Rotor diameter	0.67m
Swept area	888m²
Nacelle diameter	0.5m
Nacelle length	3m
Nacelle weight	1.2 tons



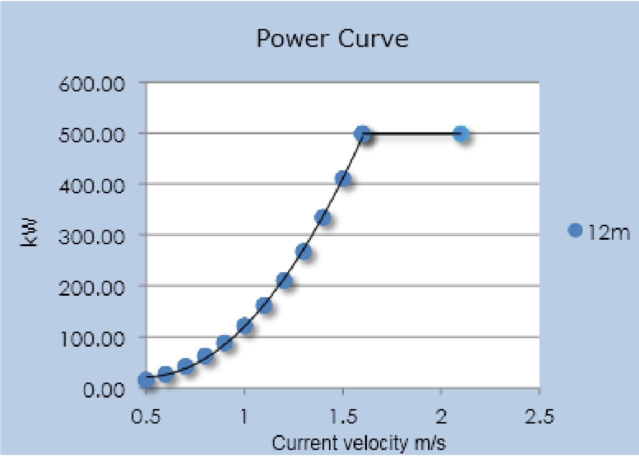
DG10:

Wing Span	10m
Rated Power (@m/s)	220kW @1.4
Tether Length	75-100m
Depth	60-80m
Desired Speed	1.4-2 m/s
Lower/Upper Cut off current	0.5/2.5 m/s
Weight	4 tons
Devices/km²	30
Clearance (tip to surface)	9.5-12.5m
Rotor diameter	0.83m
Swept area	1400m²
Nacelle diameter	0.625m
Nacelle length	3.75m
Nacelle weight	2.3 tons



DG12:

Wing Span	12m
Rated Power	500 kW
Tether Length	85-120m
Depth	75-100m
Desired Speed	1.4-2.2 m/s
Lower/Upper Cut off current	0.5/2.5 m/s
Weight	7 tons
Devices/km²	25
Clearance (tip to surface)	12-16m
Rotor diameter	1m
Swept area	2000m²
Nacelle diameter	0.75m
Nacelle length	4.5m
Nacelle weight	4 tons

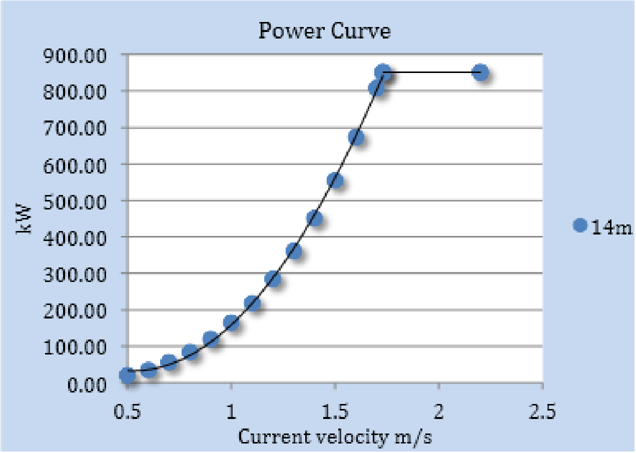


DG14:

- **Wing Span** 14m
- **Rated Power (@m/s)** 850 kW@1.7
- **Tether Length** 110-140m
- **Depth** 90-120m
- **Desired Speed** 1.4-2.2 m/s
- **Lower/Upper Cut off current** 0.5/2.5 m/s
- **Weight** 11 tons

- **Devices/km^2** 16
- **Clearance (tip to surface)** 14-18m

- **Rotor diameter** 1.15m
- **Swept area** 2700m^2
- **Nacelle diameter** 0.875m
- **Nacelle length** 5.25m
- **Nacelle weight** 6.35 tons



TECHNOLOGY PROFILE	
Technology name:	Red Hawk
Developer	Natural currents
Country:	USA
Website:	http://www.naturalcurrents.com/

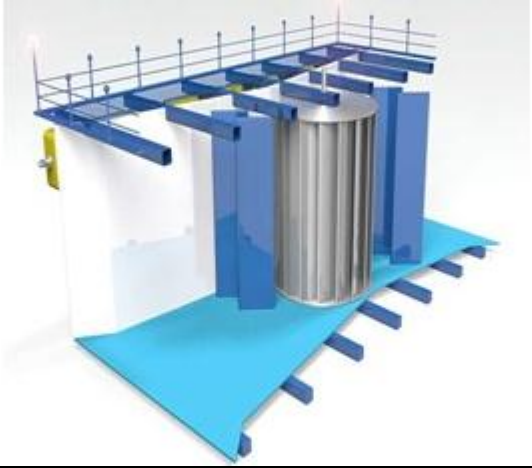
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	less than 5 meters required
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

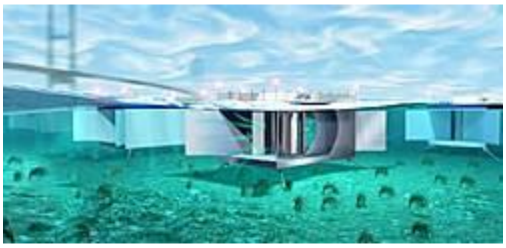
REMARKS

The RED HAWK device is a horizontal axis tidal turbine. The RED HAWK tidal turbine transforms the lateral motion of water currents into electric power. This systems produces 3-phase power for net metering or direct inter-connection. Single unit or array systems are excellent for marinas, shoreline infrastructure and community development projects. Larger-scale systems are currently in development.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Neptune Proteus tidal power pontoon (NP1000)
Developer	Neptune Renewable Energy
Country:	UK
Website:	http://www.neptunerenewableenergy.com/





DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	
Power take-off system:	unspecified
Brief description:	turbine mounted underneath a barge, gearbox and generator mounted on top of the barge 1:100 scale prototype has been tested, 1:10 scale prototype in progress
Mooring / anchoring / foundation:	designed for quick mooring - floating
Required water depth (m):	
Dimensions of full prototype (mxm):	4x4m vertical axis turbine, duct 8x13m
Weight of the super structure (ton):	
Current stage:	Stage 2
Future targets:	no future, Neptune renewable energy goes into liquidation
References:	ocean energy global technology development status (2009) http://www.greencarcongress.com/2007/09/new-tidal-power.html

REMARKS

The Neptune Proteus Tidal Power Pontoon consists of a 6m x 6m vertical axis crossflow turbine mounted within a patented, symmetrical diffuser duct and beneath a very simple steel deck and buoyancy packages. The Neptune Proteus is designed for estuarine sites, which can exhibit powerful currents yet have lower access, cabling and maintenance costs than offshore environments. The vertical shaft connects to the gearbox and generator/alternator, located on the top of the pontoon with associated valves and electrical processing and control machinery. The power pontoon is easily moored in the free stream, thus minimizing environmental impact and operates just as efficiently in both flood and ebb currents. The rotor is maintained at optimal power outputs by sets of computer-controlled shutters within the duct. Theoretical work on 1/10th, 1/40th and 1/100th scale laboratory experiments suggest an overall efficiency of greater than 45%.

Current speed (m/s)	Electric power output (kW)

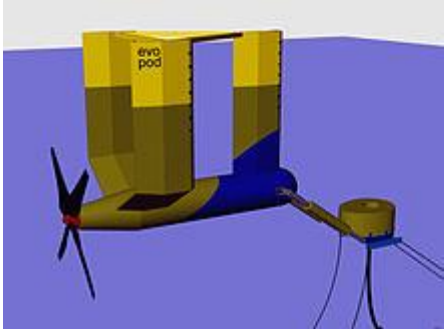
TECHNOLOGY PROFILE	
Technology name:	EnCurrent turbine
Developer	New Energy Corporation Inc
Country:	Canada
Website:	www.newenergycorp.ca
	
DEVICE SPECIFICATIONS	
Operating principle:	vertical axis turbine, cross-flow
Operating position:	
Power take-off system:	permanent magnet generator
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	different types; diameter 1.52-4.83m
Weight (ton):	
Current stage:	Stage 4 5 kW operational 125 kW under development 250 kW under development, diameter 7.6 m since 2010 no updates found
Future targets:	
References:	ocean energy global technology development status (2009) Canadian technology status report 2010 http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
based on Darrieus wind turbine turbine rotates in the same direction regardless of the direction of the water current captures between 35-40% of the energy in moving water low-flow 25kW design: cut-in speed 1.0m/s, 2.4m/s rated capacity, requires larger rotor design standard design: cut-in speed 1.5m/s, 2.4m/s rated capacity [2010]	

Current speed (m/s)	Electric power output (kW)
3	25
2.4	25

Parameter	Specification (Non-Ducted)			
Turbine Size	5 kW	10 kW	25 kW	Low-flow 25 kW
Rotor height	0.76 m	1.52 m	1.70 m	2.41 m
Rotor Diameter	1.52 m	1.52 m	3.40 m	4.83 m
Rated capacity	5 kW	10 kW	25 kW	25 kW
Water Velocity @ Rated Capacity	3 m/s	3 m/s	3 m/s	2.4 m/s
RPM	90	90	40	25
Cut-in speed	1.5 m/s	1.5 m/s	1.5 m/s	1.0 m/s
System height	2.25 m	3.24 m	4.24 m	5.41 m
System weight (in air)	340 kg	640 kg	1910 kg	2665 kg

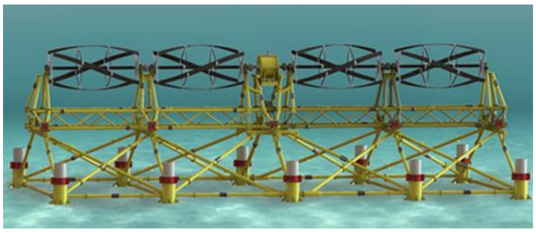
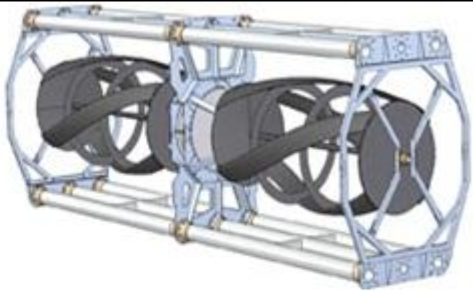
Source: http://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=6&cad=rja&ved=0CGEQFjAF&url=http%3A%2F%2Fcanmetenergy.nrcan.gc.ca%2Fsites%2Fcanmetenergy.nrcan.gc.ca%2Ffiles%2Ffiles%2Fpubs%2FCanadianTechnologyDeveloper2010update_eng.pdf&ei=FEitUMC7K9HHtAaL64HICg&usg=AFQjCNGVUyVoYsrpLinh2SyWxmTtkody3w

TECHNOLOGY PROFILE	
Technology name:	Evopod
Developer	Ocean Flow Energy, Overberg Ltd
Country:	UK
Website:	www.oceanflowenergy.com



DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	offshore
Power take-off system:	permanent magnet generator, mechanical
Brief description:	semi-submerged, floating, tethered, turbine, automatically aligns itself with the current direction
Mooring / anchoring / foundation:	Mooring lines
Required water depth (m):	up to 60m
Dimensions of full prototype (mxm):	15m diameter
Weight (ton):	
Current stage:	Stage 2 developing 1:4 scale prototype (37 kW) 1:10 scale
Future targets:	
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://en.wikipedia.org/wiki/Evopod http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	

* Current speed (m/s)	Electric power output (kW)
	1,500 target
up to 6m/s	

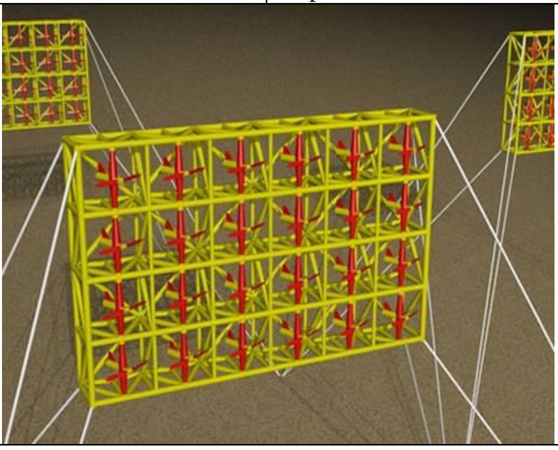
TECHNOLOGY PROFILE	
Technology name:	TidGen / OCGen turbine generatur unit (TGU)
Developer	Ocean renewable power company (ORPC)
Country:	USA
Website:	http://www.orpc.co/
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis
Operating position:	
Power take-off system:	Permanent magnet generator
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	15-30
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 3
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
The OCGen turbine-generator unit (TGU) is unidirectional regardless of current flow direction. Two cross flow turbines drive a permanent magnet generator on a single shaft. OCGen modules contain the ballast/buoyancy tanks and power electronics/control system allowing for easier installation. The OCGen TGU can be stacked either horizontally or vertically to form arrays	

Current speed (m/s)	Electric power output (kW)
	180

TECHNOLOGY PROFILE	
Technology name:	Tidal defense and energy system (TIDES)
Developer	Oceana energy company
Country:	USA
Website:	http://www.oceanaenergy.com/
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	Gravity base, 3-point stack, or catamaran
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
The Tidal Defense and Energy System (TIDES) power generation platform includes a horizontal axis turbine. The TIDES device has a free-scaling range of motion and can manipulate the size and shape of its hydro blades to vary the ratio of freely flowing water-to-water contact over its blade surfaces. In 2006, Oceana entered into a Cooperative Research & Development Agreement (CRADA) with the U.S. Navy to utilize its Naval Surface Warfare Center, Carderock Division's engineering facilities and expertise to develop and test TIDES.	

Current speed (m/s)	**Electric power output (kW)**

TECHNOLOGY PROFILE	
Technology name:	Current catcher
Developer	Offshore Islands Ltd
Country:	USA
Website:	http://www.offshoreislandslimited.com/



DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	8 blade turbine
Mooring / anchoring / foundation:	fixed to the seabed or moored
Required water depth (m):	shallow water depth to deep water depth
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech http://www.marineenergycorp.com/

REMARKS

The “Current Catcher”© harnesses the power and fluctuations of the ocean’s currents to generate energy. It uses cones to increase the velocity of the ocean current and to direct it to the turbine blades to maximize the production of energy, which, in turn, is transferred through electrical swivels. The “Current Catcher”© uses conventional low-cost steel tubular frames. These frames can support both ocean and tidal current power generators rigidly fixed to the seabed or moored to the seabed.

Current speed (m/s)	Electric power output (kW)

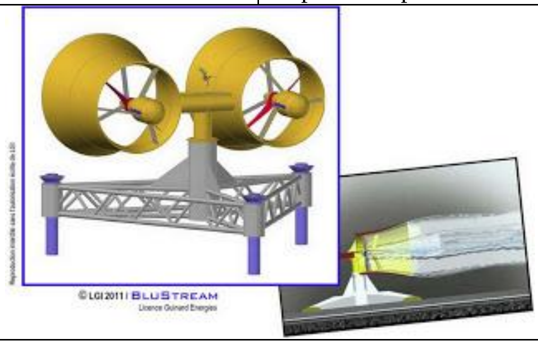
TECHNOLOGY PROFILE	
Technology name:	Open-centre turbine (OCT)
Developer	Open Hydro Group Ltd
Country:	Ireland
Website:	www.openhydro.com

DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	nearshore
Power take-off system:	permanent magnet generator, direct drive
Brief description:	open-centre, rim-generator style tidal turbine, slow-moving rotors, 2 counter-rotating fixed-pitch rotors, 16 blades, fully submerged 16 m diameter
Mooring / anchoring / foundation:	twin pile permanently anchored to the seafloor
Required water depth (m):	not stated
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 5 full scale (2007)
Future targets:	array
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The Open-Centre Turbine is designed to be deployed directly on the seabed. The Open-Centre Turbine is a horizontal axis turbine with a direct-drive, permanent magnetic generator that has a slow-moving rotor and lubricant-free operation, which decreases maintenance and minimizes risk to marine life.

* Current speed (m/s)	Electric power output (kW)
	5.6kW prototype
	500kW
	1,000 target

TECHNOLOGY PROFILE	
Technology name:	blustream
Developer	Pôle Mer Bretagne
Country:	France
Website:	http://www.pole-mer-bretagne.com/marine-energy-resources-en.php
	
DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 small scale tests
Future targets:	full-size prototype
References:	http://energiesdelamer.blogspot.de/2011/06/blustream-une-hydrolienne-francaise.html
REMARKS	

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Marenergie
Developer	Pole Mer Bretagne
Country:	France
Website:	http://www.pole-mer-bretagne.com/marenergie.php
	
DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	
Power take-off system:	unspecified
Brief description:	
Mooring / anchoring / foundation:	seabed-anchored
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1
Future targets:	install a 200 kW hydrogenerator
References:	ocean energy global technology development status (2009)
REMARKS	

Current speed (m/s)	Electric power output (kW)
	200kW (prototype)

TECHNOLOGY PROFILE	
Technology name:	Enermar Kobold turbine
Developer	Ponte di Archimede International S.p.A.
Country:	Italy
Website:	www.pontediarchimede.it

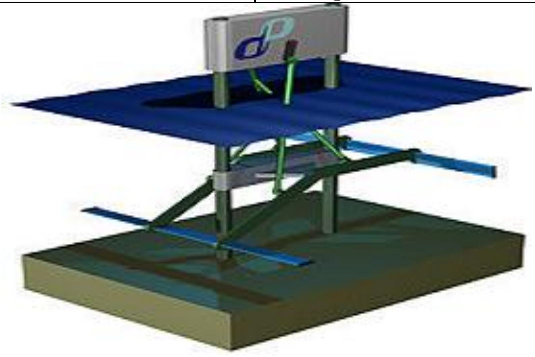
DEVICE SPECIFICATIONS	
Operating principle:	vertical axis / crossflow turbine
Operating position:	offshore
Power take-off system:	induction generator, mechanical
Brief description:	3 blades, unidirectional, mounted on a cylindrical floating platform, passive blade pitch control system (2 balancing masses for each blade)
Mooring / anchoring / foundation:	floating, tethered
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 6m diameter
Future targets:	full scale
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The Enermar (Kobold turbine) is a unidirectional vertical axis turbine with a high starting torque that permits spontaneous starting even under intense conditions without the need of an ignition device. The turbine has a passive blade pitch control system, which is made up of two balancing masses for each blade, which allows the turbine blades center of gravity to be altered as well as the pitch in order to improve rotor performance.

Current speed (m/s)	Electric power output (kW)
2.0	25 prototype
	130
	250 target

TECHNOLOGY PROFILE	
Technology name:	Pulse generator / pulse stream
Developer	Pulse Generation Ltd
Country:	UK
Website:	www.pulsetidal.co.uk



DEVICE SPECIFICATIONS	
Operating principle:	oscillating hydrofoil
Operating position:	nearshore
Power take-off system:	permanent magnet generator, mechanical drive
Brief description:	2 hydrofoils oscillating up and down with a variable stroke width to use the full depth during the tidal cycle
Mooring / anchoring / foundation:	anchored to the seabed (concrete foundation)
Required water depth (m):	shallow water
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 small-scale prototype tested
Future targets:	full-scale demonstration device off Lynmouth in Devon
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://www.pulsegeneration.co.uk/ http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The 100kW Humber prototype system uses tidal streams to oscillate horizontal blades rather than extracting energy in the same way as a wind turbine through rotary blades. This mode of operation is the key to the device's unique access to shallow water and has so far shown that it can harness enough energy to power 70 homes. The device is connected to the national grid through nearby industrial process plant Millennium Inorganic Chemicals and Ethernet connected through neighbouring resin manufacturing company Cray Valley

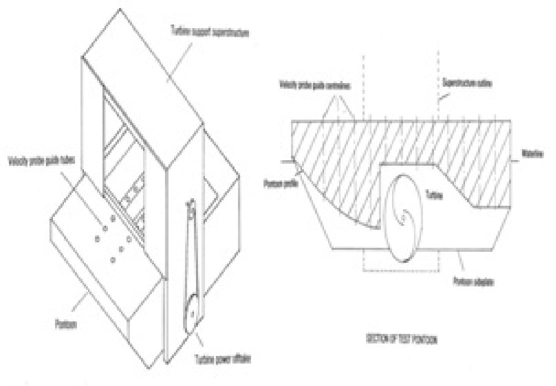
Current speed (m/s)	Electric power output (kW)
	100 prototype (not fully submerged)
	1,200 target

TECHNOLOGY PROFILE	
Technology name:	Sea Snail
Developer	Robert Gordon University
Country:	UK
Website:	http://www4.rgu.ac.uk/cree/general/page.cfm?pge=10769

DEVICE SPECIFICATIONS	
Operating principle:	hydrofoil
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 small-scale prototype tested
Future targets:	
References:	ocean energy global technology development status (2009)
REMARKS	

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	savonius turbine
Developer	rugged renewables
Country:	UK
Website:	http://www.narec.co.uk/



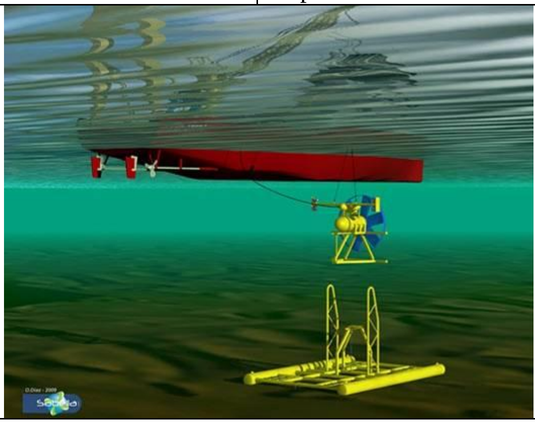
DEVICE SPECIFICATIONS	
Operating principle:	axial flow turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1
Future targets:	
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The large blade area of the Savonious Turbine allows for low blade loading, which eases the mechanical design. The low speed in relation to flow speed ensures minimal environmental disturbance. The output characteristic is peaked with a maximum free running speed at a tip speed ratio of about 1.5. Hence a 'runaway' Savonius freewheeling in a fast flow current is quite tame and over speed protection is not required. Since the turbine is unidirectional, it does not require an alignment system. The turbine is capable of extracting energy from flow which is fluctuating rapidly in speed and direction. The swept area is rectangular in shape, fitting it for applications unsuitable for propeller turbines.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Sabella subsea tidal turbine
Developer	Sabella Energy
Country:	France
Website:	http://www.sabella.fr/



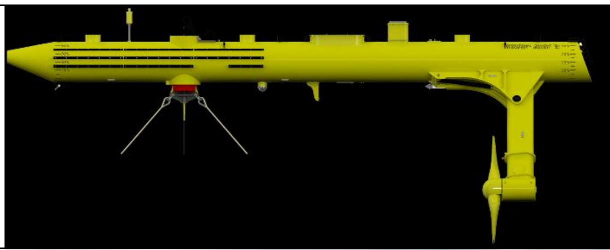
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	gravity base or anchored
Required water depth (m):	
Dimensions of full prototype (mxm):	3 m diameter
Weight (ton):	
Current stage:	Stage 2
Future targets:	tests in Rome
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

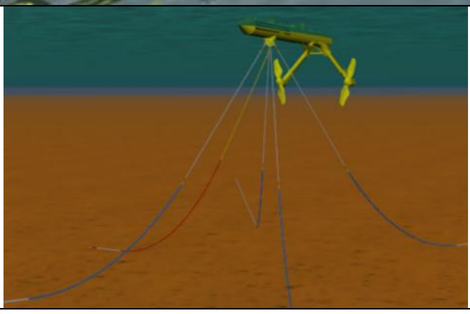
REMARKS

It is characterised by a turbine configuration on the seafloor, without impinging on the surface. These turbines are stabilised by gravity and/or are anchored according to the nature of the seafloor. They are pre-orientated in the direction of the tidal currents, and the profile of their symmetrical blades helps to capture the ebb and flow. The rotor activated, at slow speeds (10 to 15 rpm), by the tides powers a generator, which exports the electricity produced to the coast via a submarine cable anchored and embedded at its landfall.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	SR250 (SRTT)
Developer	Scotrenewables
Country:	UK
Website:	http://www.scotrenewables.com





DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	nearshore
Power take-off system:	mechanical
Brief description:	2 contra-rotating turbines, 1 on either side of the pontoon (on a nacelle), fixed rotor blades
Mooring / anchoring / foundation:	floating pontoon + tethered
Required water depth (m):	>25m
Dimensions of full prototype (mxm):	33m long, diameter 2.3, counter-rotating rotors diameter 8m
Weight (ton):	
Current stage:	Stage 3 SR250: full scale prototype (250 kW)
Future targets:	SR2000 (2 MW at 3 m/s)
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

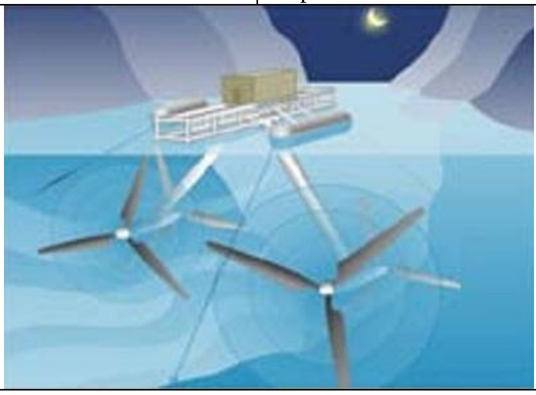
a free-floating rotor-based tidal current energy converter. The concept in its present configuration involves dual counter-rotating horizontal axis rotors driving generators within sub-surface nacelles, each suspended from separate keel and rotor arm sections attached to a single surface-piercing cylindrical buoyancy tube. The device is anchored to the seabed via a yoke arrangement. A separate flexible power and control umbilical line connects the device to a subsea junction box. The rotor arm sections are hinged to allow each two-bladed rotor to be retracted so as to be parallel with the longitudinal axis of the buoyancy tube, giving the system a transport draught of less than 4.5m at full-scale to facilitate towing the device into harbors for maintenance.

* Current speed (m/s)	Electric power output (kW)
	250 full-scale prototype
3	2,000 target

TECHNOLOGY PROFILE	
Technology name:	TidEL
Developer	SMD Hydrovision
Country:	UK
Website:	http://smd.co.uk/products/renewables/design-development.htm
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	unspecified
Brief description:	a pair of fixed-pitch turbines mounted on a central boom, contra-rotating
Mooring / anchoring / foundation:	anchored to the seafloor via mooring lines (allowing it to float at any depth and rotate to face any direction)
Required water depth (m):	>30m
Dimensions of full prototype (mxm):	15m diameter
Weight (ton):	
Current stage:	Stage 2 1:10 scale tested
Future targets:	full scale prototype
References:	ocean energy global technology development status (2009) http://www.nature.com/news/1998/040322/full/news040322-7.html http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
Peak velocity of 9 knots or more The TidEl device consists of twin horizontal axis turbines. The device is moored to the sea floor, but the twin turbines are free to move and change direction in accordance with the tide. As of 2005, the company had completed construction on a 1:10 scale model, which has since undergone tank testing.	

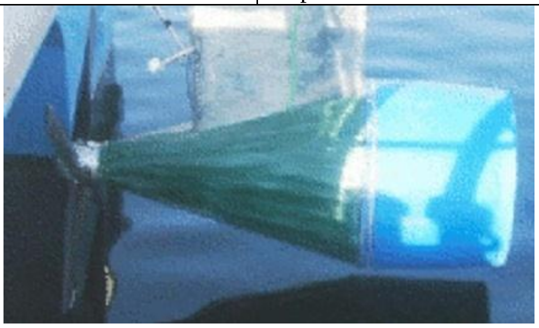
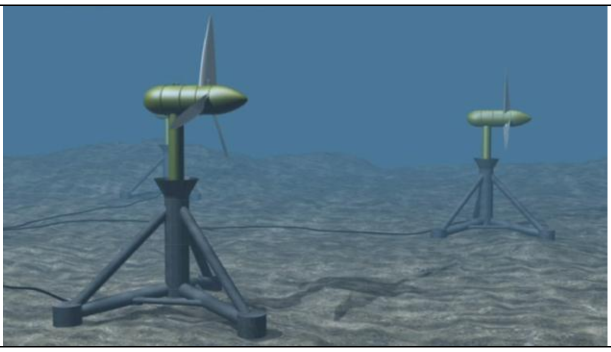
* Current speed (m/s)	Electric power output (kW)
	2x500 (full scale)

TECHNOLOGY PROFILE	
Technology name:	Statkraft tidal turbine
Developer	Statkraft, Hydra Tidal Energy Technology (HTET)
Country:	Norway
Website:	http://www.statkraft.com/presscentre/press-releases/2009/statkraft-takes-pole.aspx



DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	unspecified
Brief description:	2 turbines on each pod (2 pods), contra-rotating
Mooring / anchoring / foundation:	floating platform, anchored in a tidal channel
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1 prototype planned (no information since 2009)
Future targets:	
References:	ocean energy global technology development status (2009)
REMARKS	

Current speed (m/s)	Electric power output (kW)
	1MW planned

TECHNOLOGY PROFILE	
Technology name:	Swanturbine
Developer	Swanturbines
Country:	UK
Website:	http://swanturbines.co.uk
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	nearshore
Power take-off system:	direct drive
Brief description:	fixed-pitch blades, low-speed generator, possibility to be raised up out of the water for maintenance
Mooring / anchoring / foundation:	gravity base
Required water depth (m):	designed for both shallow and deep water
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 1:3 scale prototype 300 kW prototype tested
Future targets:	full scale
References:	ocean energy global technology development status (2009) http://www.orecca.eu http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
The Swanturbine was designed to allow for simple installation and maintenance retrieval in both shallow and deep water. The device has a gearless low speed generator with only one moving part in the drivetrain, which offers high efficiency over a range of speeds with minimal maintenance demands through the use of novel structural and electromagnetic topologies. A simple, robust and serviceable 360 degree yawing mechanism is used to allow the device to maximize flow capture.	

* Current speed (m/s)	Electric power output (kW)
	300
	1,800 target

TECHNOLOGY PROFILE	
Technology name:	Tocardo
Developer	Teamwork Technology BV
Country:	Netherlands
Website:	http://www.tocardo.com/ http://www.teamwork.nl/

DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	offshore (designed for mounting in the outflow sluices of storm protection barrages)
Power take-off system:	permanent magnet generator, mechanical drive
Brief description:	2-bladed, fixed-pitch turbine, variable-speed turbine
Mooring / anchoring / foundation:	bottom mounted, installed underneath floating platforms or installed at existing structures
Required water depth (m):	minimum: 4m
Dimensions of full prototype (mxm):	various sizes and installed capacities
Weight (ton):	
Current stage:	Stage 5 T50 up to 50kW T150 up to 150kW T500 up to 500kW T1000 up to 1000kW 1/5 scale 2.8m diameter rotor (2006)
Future targets:	
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The Tocardo Aqua 2800 is a direct-drive generator that eliminates the need for a gearbox. The device also has intelligent speed tuning (stall control), which eliminates the need for expensive and vulnerable pitching mechanisms, while matching the device to a wide range of tidal stream variations.

* Current speed (m/s)	Electric power output (kW)
3.2	35kW (prototype)
>2.0	

TECHNOLOGY PROFILE	
Technology name:	Stingray
Developer	The Engineering Business Ltd (now IHC Mervede)
Country:	UK
Website:	http://www.engb.com/

DEVICE SPECIFICATIONS	
Operating principle:	oscillating hydrofoil
Operating position:	
Power take-off system:	pressurized hydraulics
Brief description:	hydrofoil is attached by an arm to the base, allows the hydrofoil to move vertically
Mooring / anchoring / foundation:	fixed seabed-anchored base
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 1 no longer developed
Future targets:	none
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

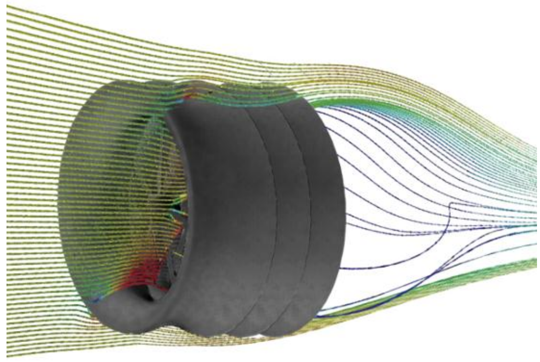
REMARKS

The Stingray consists of a hydroplane with an attack angle correctly positioned relative to the approaching water stream. The flow of the current causes the supporting arm to oscillate, which in turn forces hydraulic cylinders to extend and retract. This produces high pressure oil which is used to drive a generator.

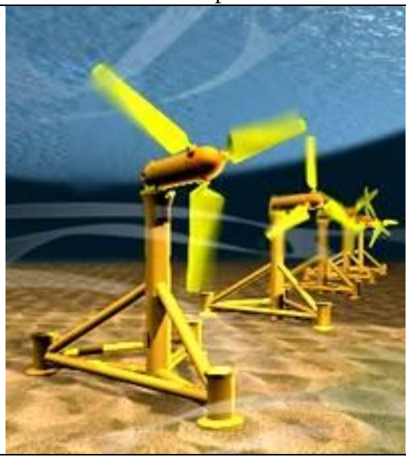
Current speed (m/s)	Electric power output (kW)
2	less than 40-50kW

TECHNOLOGY PROFILE	
Technology name:	Davidson-Hill Venturi (DHV) turbine
Developer	tidal energy pty ltd
Country:	Australia
Website:	http://tidalenergy.net.au/
	
DEVICE SPECIFICATIONS	
Operating principle:	Venturi (Davidson-Hill Venturi Turbine)
Operating position:	
Power take-off system:	
Brief description:	
Mooring / anchoring / foundation:	Mounted on the sea bed, on a monopole, slung under a pontoon, or made buoyant (like a kite underwater)
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 3 Commercial scale up (2005)
Future targets:	
References:	http://peswiki.com/index.php/Directory:Davidson_Hill_Venturi_by_Tidal_Energy_Pty_Ltd http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
A Patented tidal stream turbine invented by Aaron Davidson and Craig Hill of Tidal Energy Pty Ltd uses a venturi shaped shroud to increases the turbine efficiency as much as 3.84 times compared to the same turbine without the shroud, making this "a world leading if not world best design". The venturi not the turbine is the key component of the Davidson-Hill design as the venturi creates a vortex of low pressure behind the turbine - drawing the flow across the turbine. This increased flow allows the turbine to operate at higher efficencies then it would otherwise be capable of without the venturi and producing more power. The venturi can be designed to fit almost any type of turbine. It can also be integrated or "retro fitted to wind turbines", the company's early commercialisation niche is on fast flowing water currents such as tides, ocean currents, and run-of-the-river. The technology has a multitude of applications.	

Turbine Size	Water Speed 2m/s	Water Speed 3m/s	Water Speed 4m/s	Water Speed 5m/s	Water Speed 6m/s
1.5 m rotor	4.6 kW	15 kW	35 kW	70 kW	120 kW
2.4 m rotor	10 kW	40 kW	90 kW	180 kW	300 kW
5 m rotor	50 kW	170 kW	400 kW	800 kW	1.35 MW
7 m rotor	100 kW	340 kW	800 kW	1.6 MW	2.7 MW
10 m rotor	200 kW	680 kW	1.6 MW	3.2 MW	5.5 MW

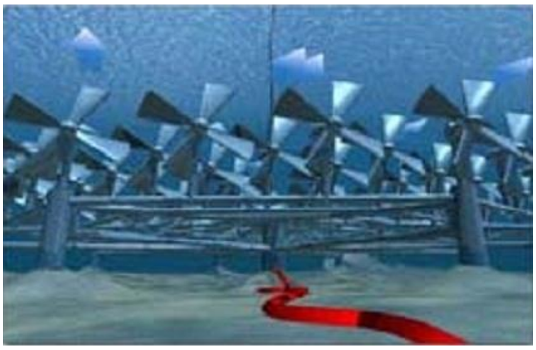
TECHNOLOGY PROFILE	
Technology name:	Foil rotor III
Developer	Tidal energy systems corporation
Country:	USA
Website:	http://www.tidalesystems.com/
	
DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	
Power take-off system:	permanent magnet alternator turbine
Brief description:	
Mooring / anchoring / foundation:	pivot-pilling mounted, can be mounted to a land-based hoist, bridge, seawall or floating structure
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 Construction of 1:15-scale model: Foil Rotor III, construction of full-scale turbine (Foil Rotor III)
Future targets:	Testing of full-scale model Development of turbine arrays
References:	
REMARKS	

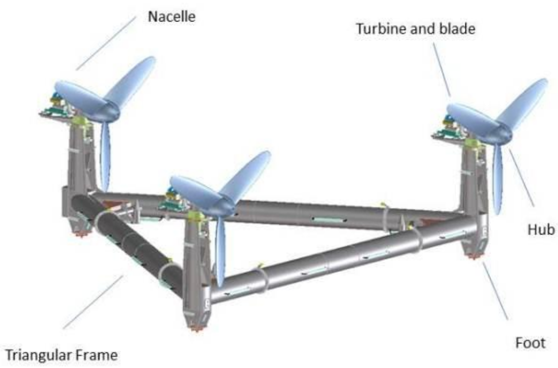
Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	Deep-Gen
Developer	Tidal generation limited (in 2013 acquired by Alstom, France)
Country:	UK
Website:	http://www.tidalgeneration.co.uk/ , http://www.alstom.com/power/
	
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	
Brief description:	18 m rotor diameter, 3 pitchable blades, 21 m long turbine, 135 tonnes (without seabed support structure), turbine width 2.6 to 3.5 m, turbine height 5 m, rotating nacelle (with every tide)
Mooring / anchoring / foundation:	seabed mounted
Required water depth (m):	35-80 m
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 3 1 MW unit at European Marine Energy Centre
Future targets:	deploy demonstration arrays as a precursor to full commercial production
References:	http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech
REMARKS	
The DEEP-Gen 1 MW fully submerged tidal turbine best exploits resources in depths > 30m. The horizontal axis turbine is inexpensive to construct and easy to install due to the lightweight (80 tons/MW) support structure; allows rapid removal and replacement of powertrains, enabling safe maintenance in a dry environment; and is located out of the wave zone for improved survivability.	

Current speed (m/s)	Electric power output (kW)
cut-in: 1	
rated power: 2.7	
maximum operating: 3.4	

TECHNOLOGY PROFILE	
Technology name:	Tidal stream generator (DeltaStream)
Developer	Tidal Hydraulic Generators Ltd (THGL)
Country:	UK
Website:	http://www.tidalenergyltd.com/





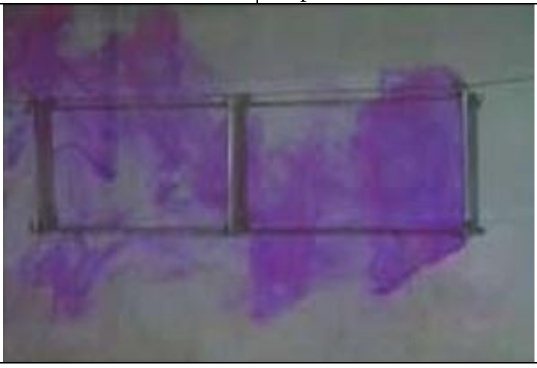
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	nearshore
Power take-off system:	pressurized hydraulics
Brief description:	array of turbines, 2 small horizonta-axis rotors, low centre of gravity, fixed pitch blades, 6 m diameter
Mooring / anchoring / foundation:	gravity base
Required water depth (m):	>12 m
Dimensions of full prototype (mxm):	Diameter 15 m
Weight (ton):	
Current stage:	Stage 1
Future targets:	full scale develop a 10MW commercial array project at St Davids Head in Pembrokeshire
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The DeltaStream device is a nominal 1.2MW unit which sits on the seabed without the need for a positive anchoring system, generating electricity from three separate horizontal axis turbines mounted on a common frame. The use of three turbines on a single, circa 30m wide, triangular frame produces a low center of gravity enabling the device to satisfy its structural stability requirements including the avoidance of overturning and sliding. The device utilizes fixed pitch blades designed to maximize the energy extracted from the tidal flow distribution at the deployment site. A mechanical yaw system allows the nacelles to oscillate by a control system, which is programmed to seek the optimum flow. The rotors extract the energy from the water flow at an elevation of between approximately 5-20m above the seabed (assuming a 15m rotor diameter).

Current speed (m/s)	Electric power output (kW)
	3
	1,200 target

TECHNOLOGY PROFILE	
Technology name:	tidal sails AS
Developer	Tidal Sails AS
Country:	Norway
Website:	http://tidalsails.com/

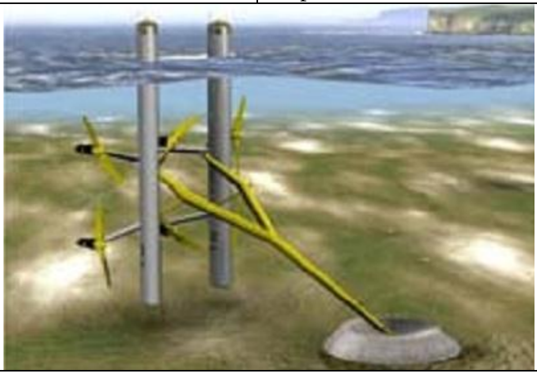


DEVICE SPECIFICATIONS	
Operating principle:	
Operating position:	
Power take-off system:	unspecified
Brief description:	based on a series of stacked sails
Mooring / anchoring / foundation:	
Required water depth (m):	
Dimensions of full prototype (mxm):	25m (planned)
Weight (ton):	
Current stage:	Stage 2 small scale demonstrator in Norway, 28 kW
Future targets:	full scale system with 2-10 MW
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

The sails, attached to two wire ropes, travel in a triangular pattern driving large sheaves which in turn drive a generator. In general linearly moving sails have great extraction efficiency, thus resulting in significant cost reductions. The technology may be applied in different settings protected by several patents worldwide.

Current speed (m/s)	Electric power output (kW)

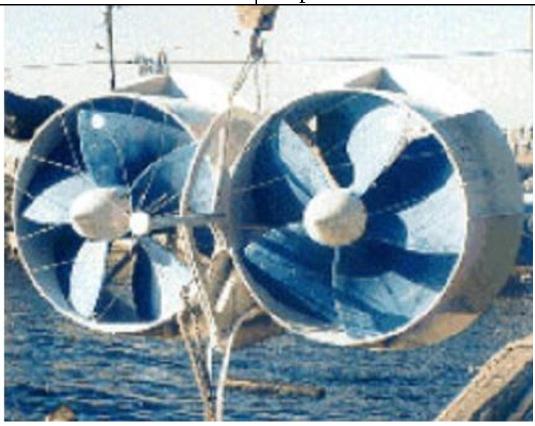
TECHNOLOGY PROFILE	
Technology name:	Triton
Developer	TidalStream
Country:	UK
Website:	http://www.tidalstream.co.uk/
	

DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	offshore
Power take-off system:	unspecified
Brief description:	3-6 turbines (contra-rotating), is allowed to swivel around the joint both vertically and horizontally
Mooring / anchoring / foundation:	buoyant system, boom attached to an anchored base on the seabed (gravity base, pinned frame or monopile)
Required water depth (m):	up to 90m (depending on system)
Dimensions of full prototype (mxm):	20m diameter rotors
Weight (ton):	
Current stage:	Stage 2 Triton 6 1:23 (2009) Triton 3 1:23 (rotor diameter 2 m) (2010-2011)
Future targets:	
References:	ocean energy global technology development status (2009)

REMARKS
can be floated into place

Current speed (m/s)	Electric power output (kW)
	1,000-2,000 target

TECHNOLOGY PROFILE	
Technology name:	UEK turbine (underwater electric kite)
Developer	UEK Systems
Country:	USA
Website:	http://www.uekus.com/



DEVICE SPECIFICATIONS	
Operating principle:	Venturi
Operating position:	designed for rivers and tidal streams
Power take-off system:	unspecified generator
Brief description:	a pair of contra-rotating, ducted turbines, using buoyancy control to operate at varying heights, 3 m diameter
Mooring / anchoring / foundation:	no need to fix the device to the seabed
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 project on Zambezi river (2007) no information since 2011
Future targets:	
References:	ocean energy global technology development status (2009) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

last update of homepage in August 2010
units from 3 ft diameter to 22 ft diameter
The UEK Dual Hydroturbine System is designed to operate as a 'Stand Alone' facility installed in a current of four knots or better. The twin UEK System design can accommodate velocities from four knots up to eight knots. The device is optimally designed to address current speeds of five knots (approx. <2.5m/sec.). Various other applications of the UEK Systems (Ocean, Tidal, and River) include, control of anoxic water; reverse osmosis fresh water systems; irrigation projects; hydrogen produced by electrolysis; hydraulic driven power systems for logging and mining operations.

* Current speed (m/s)	Electric power output (kW)
2.5	90 kW

TECHNOLOGY PROFILE	
Technology name:	Free flow / Kinetic Hydropower System (KHPS)
Developer	Verdant Power LLC
Country:	USA, Canada
Website:	www.verdantpower.com

DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	East River New York, nearshore
Power take-off system:	induction generator, mechanical drive
Brief description:	5 m diameter, fixed-pitch, three-bladed, ~35 rpm, fully submerged
Mooring / anchoring / foundation:	seabed-anchored (monopile mounted)
Required water depth (m):	at least 9 m, <40-50m
Dimensions of full prototype (mxm):	6 m height, 4.82 m length
Weight (ton):	system weight: 3.629 t
Current stage:	Stage 4 / 5 full-scale
Future targets:	full-scale
References:	ocean energy global technology development status (2009) http://peswiki.com/index.php/Directory:Verdant_Power http://www.nature.com/news/2004/040809/full/news040809-17.html http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS
requires a peak water velocity of 2m/s

* Current speed (m/s)	Electric power output (kW)
2.1	35
	1,000 target

PARAMETER	SPECIFICATION
Rotor diameter	5 meters (16.4 feet)
Swept area	19.6 m2
RPM	Approx. 35
Tip speed	Approx. 9 m/s
Cut-in speed	Approx. 0.8 m/s
Protective rotor screen	No
Drive train efficiency	Approx. 86%
Rated capacity	35 kW @ 2.1 m/s
Total height (to top of rotor)	6 m
Total length	4.82 m
System Weight (in air)	Approx. 3,629 kg

Canadian technology developer 210

TECHNOLOGY PROFILE	
Technology name:	HyTide
Developer	Voith Hydro
Country:	Germany
Website:	http://voith.com/en/index.html

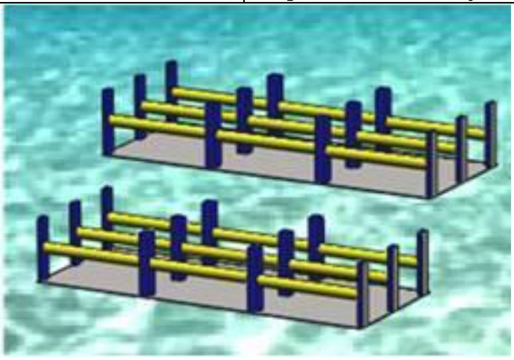
DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	nearshore
Power take-off system:	permanent magnet generator, direct drive
Brief description:	fully submerged, 3 fixed-pitch blades
Mooring / anchoring / foundation:	gravity base foundation or monopile
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 3 1/3 scale prototype in Korea since 2011: 110 kW at current speed of 2.9 m/s, diameter 5.3 m; full-scale prototype in Scotland (European Marine Energy Center): 1 MW at current speed of 2.9 m/s, diameter 16 m
Future targets:	full scale
References:	http://www.orecca.eu http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

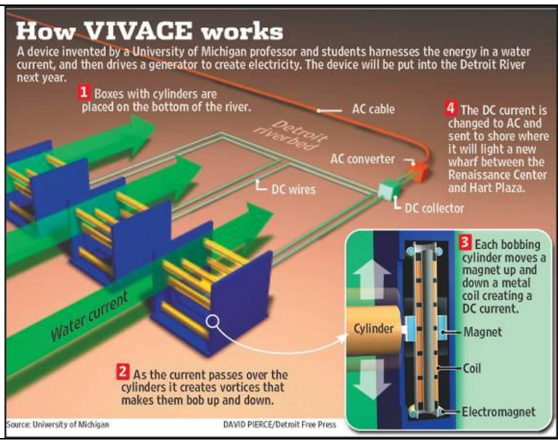
REMARKS

hyTide is a horizontal axis tidal turbine optimized for reliability and low maintenance costs. Voith Hydro therefore develops innovative tidal power stations that do not utilize the water storage but, similar to wind power stations, exploit the kinetic energy of the current and are operated fully under water. For this purpose, up to three turbines, each with a nominal power of 1 MW, are installed within a bridge-like structure. These turbines can be rotated around their horizontal axis, which allows them to make optimum use of the water and its flow direction, which changes every six hours.

Current speed (m/s)	Electric power output (kW)
	110
	1,000 target

TECHNOLOGY PROFILE	
Technology name:	VIVACE (vortex induced vibrations aquatic clean energy)
Developer	vortex hydro energy
Country:	USA
Website:	http://www.vortexhydroenergy.com/





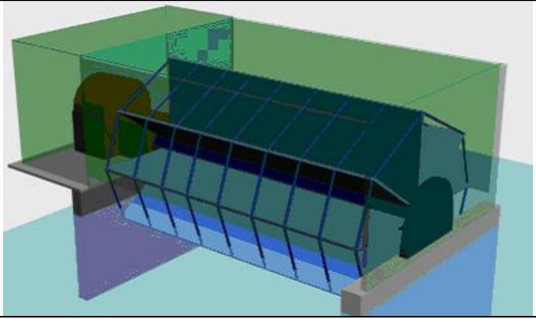
DEVICE SPECIFICATIONS	
Operating principle:	other (see figure)
Operating position:	
Power take-off system:	electromagnet
Brief description:	
Mooring / anchoring / foundation:	seabed mounted / gravity base
Required water depth (m):	
Dimensions of full prototype (mxm):	
Weight (ton):	
Current stage:	Stage 2 Prototype at the University of Michigan
Future targets:	
References:	http://peswiki.com/index.php/Directory:Vortex-Induced_Vibrations_for_Aquatic_Clean_Energy_%28VIVACE%29 http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS

- Can work in currents of less than 2 knots but can also handle high-speed currents
- Highly scalable
- VIVACE is based on the extensively studied phenomenon of Vortex Induced Vibrations (VIV), which was first observed 500 years ago by Leonardo DaVinci in the form of “Aeolian Tones.” For decades, engineers have been trying to prevent VIV from damaging offshore equipment and structures. By maximizing and exploiting VIV rather than spoiling and preventing it, VIVACE takes this ‘problem’ and transforms it into a valuable resource for mankind. Vortex Induced Vibrations (VIV) result from vortices forming and shedding on the downstream side of a bluff body in a current. Vortex shedding alternates from one side to the other, thereby creating a vibration or oscillation. The VIV phenomenon is non-linear, which means it can produce useful energy at high efficiency over a wide range of current speeds.

Current speed (m/s)	Electric power output (kW)

TECHNOLOGY PROFILE	
Technology name:	WWTurbine
Developer	Water Wall Turbine Inc.
Country:	Canada
Website:	www.wwturbine.com



DEVICE SPECIFICATIONS	
Operating principle:	horizontal axis turbine
Operating position:	
Power take-off system:	unspecified
Brief description:	semi-submerged
Mooring / anchoring / foundation:	designing fixed and floating installations
Required water depth (m):	various sizes and installed capacities
Dimensions of full prototype (mxm):	various sizes and installed capacities
Weight (ton):	
Current stage:	Stage 2
Future targets:	
References:	ocean energy global technology development status (2009) Canadian technology status report (2010) http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech

REMARKS
less than 50% submerged RPM: 1-50 cut-in speed: ~1.5 m/s rated capacity: 2.5 MW @ 5.5 m/s

Current speed (m/s)	Electric power output (kW)
	1,000-10,000
5.5	2,500

Stages (http://www.emec.org.uk/services/pathway-to-emec/technology-readiness-levels/)

Stage 1 Tidal-current energy conversion concept formulated

Stage 2 Intermediate scale subsystem testing, Computational Fluid Dynamics, Finite Element Analysis, Dynamic Analysis

Stage 3 Subsystem testing at large scale

Stage 4 Full-scale prototype tested at sea

Stage 5 Commercial demonstrator tested at sea for an extended period