# Wave Power

## Surveillance study of the development

Elforsk rapport 11:02

Per Holmberg, Magnus Andersson, Björn Bolund, Kerstin Strandanger

May 2011

ELFORSK

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# Foreword

Wave Power is a renewable energy resource with a large potential worldwide and in particular Europe's Atlantic facing coast. However, the technology has not yet reached a commercial maturity comparable to, for example wind power. There is still a lot of necessary research and development to be done before wave power will be commercially competitive with wind power or power from bio-energy.

In order to monitor the development state of the sector, Elforsk has carried out a project during 2010 describing state of the art for wave power with two newsletters and the current report.

The project has been focused on the waters with conditions of interest for Swedish Power utilities.

The project has been financed by Vattenfall AB, Statkraft Development AS, E.ON Värmekraft Sverige AB, Svenska Kraftnät (Swedish national grid) and Skellefteå Kraft AB.

The report is elaborated and written by Vattenfall Research and Development AB. Input from steering group members Jørgen Ranum Krokstad, Harald Rikheim at Statkraft is greatly acknowledged.

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# Summary

Ocean energy is a so far untapped source of renewable energy. Of the various ways to harvest energy from the ocean the largest potential is found in the waves. The global resource according to IEA is somewhere between 8 000 – 80 000 TWh.

The theoretical resource of Nordic countries varies substantially. Norway with its long and exposed West Coast has been estimated to have an offshore theoretical resource of about 600 TWh. Much lower is the Danish theoretical resource estimated at 30 TWh while the Swedish resource is likely to be even lower although no thorough estimate has been made. How much of the theoretical resource that can be seen as practical potential depends on a number of factors but is likely to be in the 10-20 % range.

There are a wide variety of technology solutions being proposed for harvesting wave energy. No technology has yet come out as a clear winner and in all likelihood there will be scope for several technologies, especially as there is not a "one size fits all" solution. Instead local conditions such as water depth and wave climate (i.e. wave height and period) will determine what is the best technology for a given site.

Today there are more than 50 concepts actively being developed in generally small, one-product companies. It has been estimated that costs to get from idea to a full scale MW size prototype is on the order of SEK300 m. The funding for the full scale prototype is proving to be a major barrier for many developers.

The cost of a full-scale prototype is reported to be around SEK70 000-100 000 per kW according to recent British surveys. For a first 10 MW farm the investment cost has been estimated to be around SEK500-600 million (SEK50-60 000 per kW). With realistic although as yet not verified assumptions on performance, life length and O&M costs the associated cost of electricity is approximately SEK4,5 per kWh. The estimated cost for the 10 MW Sotenäs wave power farm is, however, much lower than the British estimates.

Wave power is generally expected to have low environmental impact. However, as with all new technologies the burden of proof lies with the technology. Thus the consenting process is conservative and the initial wave power projects will have ambitious environmental monitoring programs associated with them.

Looking towards the future there is little experience with full-scale devices. However, there are about a dozen projects on-going or planned for 2011 that will be very important for the future of wave power. Assuming success to a sufficient degree as well as continued public funding multi unit farms can be expected around 2015 with utility scale farms (~50-100 MW) somewhere after 2020.

However, to be commercially competitive, wave power must be able to generate electricity at an acceptable cost. If offshore wind power is used as benchmark this means a cost reduction to about a third (SEK 1,5 per kWh) of the estimated cost of the first 10 MW wave farm.

# Sammanfattning

Havsenergi är en ännu så länge outnyttjad resurs av förnybar energi. Av de olika möjligheterna att utvinna energi ur haven har vågkraft den största potentialen. Den globala potentialen har av IEA uppskattats till mellan 8 000 och 80 000 TWh.

Den teoretiska potentialen i de nordiska länderna varierar avsevärt. För Norge med sin långa och exponerade västkust har den teoretiska potentialen uppskattats till 600 TWh. Betydligt lägre är den danska som har uppskattats till 30 TWh. Någon detaljerad uppskattning av den svenska potentialen har inte gjorts men den är sannolikt lägre än den danska. Hur mycket av den teoretiska potentialen som skulle kunna utnyttjas i praktiken beror på ett antal faktorer men är sannolikt i storleksordningen 10-20%.

Det finns ett stort antal föreslagna tekniklösningar för att utvinna vågkraft. Ingen teknik framstår i nuläget som klar vinnare och det kommer med stor sannolikhet att finnas utrymme för ett flertal tekniker, särskilt eftersom det inte finns någon universalteknik som passar alla förutsättningar. Faktorer som t ex vågklimat och vattendjup är avgörande för vilken teknik som är bäst lämpad för en given plats.

Mer än 50 vågkraftskoncept utvecklas för närvarande aktivt, oftast i små bolag med vågkraft som enda verksamhet. Kostnaden för att komma från idé till en fullskaleprototyp i MW storlek har uppskattats till i storleksordningen 300 miljoner kr. I synnerhet har finansieringen av själva fullskaleprototypen blivit ett stort hinder för många utvecklare.

Kostnaden för en fullskaleprototyp ligger enligt uppgift i dag på 70 000-100 000 kr/kW enligt nyligen publicerade brittiska sammanställningar. En första 10 MW farm bedöms kosta 500-600 miljoner (50 000-60 000 kr/kW). Med realistiska men ännu icke verifierade antaganden på prestanda, livslängd och D&U kostnader fås en produktionskostnad på 4,5 kr/kWh. De uppskattade kostnaderna för den planerade 10 MW vågkraftsfarmen vid Sotenäs på den svenska västkusten är dock mycket lägre än de brittiska siffrorna.

Vågkraft förväntas ha små miljömässiga konsekvenser men som för alla nya tekniker ligger dock bevisbördan på tekniken. Detta har medfört att, åtminstone för de första vågkraftprojekten, myndigheterna har ställt krav på omfattande miljöuppföljning.

För framtidsutsikterna för vågkraft är fortfarande det faktum att det finns få erfarenheter från drift av fullskaleenheter en tröskel. Dock är ett dussintal vågkraftsprojekt i fullskala planerade eller påbörjade under 2011. Dessa är mycket viktiga för vågkraftens framtid. Är dessa framgångsrika kan de först 5-10 MW farmerna förväntas runt 2015 och farmer i kommersiell storlek (~50-100 MW) någon gång efter 2020.

För att bli kommersiellt gångbar måste vågkraften dock kunna producera el till en konkurrenskraftig kostnad. Om havsbaserad vindkraft används som referens måste kostnaden för vågkraft sänkas med två tredjedelar från den uppskattade produktionskostnaden för en första 10 MW farm, dvs från 4,5 kr/kWh till 1,5 kr kWh.

# Content

# 1 Introduction

## 1.1 Why wave power

Ocean energy is so far an untapped source of renewable energy. There are various ways in which electricity can be generated by ocean energy such as using the energy in tidal streams, temperature difference between surface and deep water or the energy released when freshwater meets saline seawater. However, the largest potential for electricity from the oceans is by using the energy in the waves. The theoretical global wave resource, according to IEA[1], is between 8 000 - 80 000 TWh. Even if only a fraction of this can be utilized it will mean a substantial contribution to global electricity supply (approx. 20 000 TWh 2008).

Wave power is expected to have low environmental and visual impact although this will need to be verified.

Wave energy is a variable resource and one obvious question is, how does its generation compares with other intermittent renewable energy resources? The variability of the UK wave energy resource has been studied[2] and some key findings were:

- Wave energy is highly seasonal with up to seven times more energy available during winter months than during summer months
- At high wave energy sites, there is a high degree of persistence - the most likely output the next hour is that being delivered during the previous hour
- Diversification of wave power generating capacity between a range of high energy sites (i.e. sites in the North as well as in the South West) is effective of further reducing variability, particularly during winter

Waves are correlated with wind but with time lag at the same location in confined waters such as the North Sea. Comparing simultaneous wind and wave measurements at Vattenfall's Horns Reef off shore wind farm on the Danish West Coast shows a time lag of 3-4 hours for waves in comparison with wind. Sites on west coasts exposed to open oceans will primarily have wave energy from swells with longer duration and less correlation to the local wind conditions.

The correlation of power output between large off shore wind farms in the North Sea and hypothetical wave power farms at e.g. high energy sites on West Coasts of Scotland and Ireland is yet to be studied.

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[1] http://www.iea-oceans.org/_fich/6/Poster_Ocean_Energy.pdf

[2] http://www.carbontrust.co.uk/SiteCollectionDocuments/Various/Emerging%20technologies/Technology%20Directory/Marine/Other%20topics/ECI%20variability_uk_marine_energy_resources.pdf

Pro’s and con’s of co-locating wind and wave power has to be further studied. One factor speaking against co-location is the fact that good sites for off shore wind power are sites with as little waves as possible, still with a good wind resource. It is therefore doubtful if wind and wave will be installed at the same sites.

# 2 Wave energy characteristics

## 2.1 What are waves?

To describe ocean waves, a few words about the physical setting is in order. In oceanography it is common to talk about one ocean, since in fact, there is only one ocean and many processes therein are connected. The ocean covers approximately 70 % of the surface of the earth, and the typical depths are 3 – 4 km. The minimum width of the Atlantic is approximately 1500 km so the horizontal dimensions are much greater than the vertical, i.e., most ocean basins are in fact rather shallow given their scale. This is one explanation to why horizontal ocean currents have much higher velocities than vertical.

Even though the ocean has been studied for more than a century this part of the earth is still rather unknown, e.g. there is no theory that fully describes how waves are generated by winds. The sun and the atmosphere drive, directly or indirectly almost all dynamical processes in the ocean. The unbalance in the heat exchange between the ocean and the atmosphere leads to winds, which in turn generates waves. When modelling waves it is therefore important to include the cross coupling between the ocean and the atmosphere.

The waves seen on the ocean surface are called ocean surface waves, or wind waves, and there are different classes or types of ocean surface waves, swells and wind seas. The latter are waves created or affected by a local wind system, whilst swells generally can be described as the waves seen after the wind has ceased to blow or waves large enough to not be affected by local wind systems. The waves seen in the oceans are often combinations of wind seas and swells, i.e. super positions of everything from small ripples to large swells. The size of the swells depends on the strength of the wind and the fetch, which is the distance over that the wind has built up the swells.

## 2.2 Characteristics of waves

If one zooms in from a birds-eye view of the ocean, and focus is put on a propagating wave or a group of waves, it can be seen how an individual wave appears in the beginning of the wave train and travels to the front of the wave train, where it dies out. What actually is seen is the difference between the speed that a particular phase of the wave propagates with and the speed that the wave group propagates with i.e., the difference between phase and group velocity. However, when looking at shallow water waves this phenomenon is not as apparent. Linear wave theory explains that as waves propagate into shallow water the frequency, or the period, remains constant but the wavelength changes. The dispersion relation describes the interrelation between different wave parameters such as wavelength, frequency etc. and it looks different for deep- and shallow-water waves. With help of the dispersion relation it can be shown that the phase velocity is twice the group velocity in deep waters whereas they are identical in shallow waters. It might not come as a surprise, but waves behave in other words differently in deep and shallow waters. Since the periods remain constant while the wavelengths decrease when the wave travels into the near shore, individual wave crests stack up, causing the wave heights to increase, and this can lead to wave breaking and white water.

If the focus is put on a single particle in a wind wave it will be noticed that its orbital motion changes as the water depth decreases. In deep-water waves the particle paths are circular and the orbits are closed. As depth decreases, the sea floor begins to influence the waves. Deep water is often defined as water depths greater than half a wavelength, i.e., the definition of deep water depends on the length of the waves. In shallow water, the orbital motion becomes disrupted due to the influence of the sea floor. The particles in motion do not return to their original position, instead is the position shifted a distance usually referred to as the Stokes drift. The circular particle paths in deep waters become elliptical in shallow waters.

However, in wave energy, particle paths and very detailed information about the waves are generally not of the greatest concern. Of greater interest are the sea states (typically a 1-3 h condition), which usually are described by statistical parameters. A wave buoy is the most common equipment used for measuring waves, and this device records the elevation of the sea surface. By using this information (the wave elevations) together with the sampling frequency the power spectral density function can be established for a given data set. This function is commonly referred to as the wave spectrum and it is derived by Fourier transformation of the time traces of wave elevations. The wave spectrum holds all information needed to derive parameters such as:

- The significant wave height, Hs
- The average wave height of the wave height set comprising the one-third highest waves
- Peak wave height, Hpeak
- The highest wave height in the set
- The zero-crossing period, Tz
- The average time between two successive crossing of the mean water level in the upward direction
- The wave energy period, Te
- The wave period that corresponds with the energy transported by the waves.
- The peak wave period, Tp
- The longest period in the set

The significant wave height is a historic measure, said to be used by fishermen for describing the sea. Today when the wave height is derived to represent a certain sea state, it is the zero-moment wave height (Hm0) that is calculated. This wave height is not exactly the same as the historic definition of the Hs. It is however common to use the two terms as if they were interchangeable, even though the two parameters are slightly different. The Hm0 is derived through the following expression.

$$H_{m0} = 4\sqrt{m_0}$$

where *m0* is derived through

$$m_n = \int_0^n f^n S(f)df$$

where *f* is the frequency and *S(f)* is the spectral density function. The wave energy period, *Te*, is also derived trough spectral moments,

$$T_e = \frac{m_{-1}}{m_0}$$

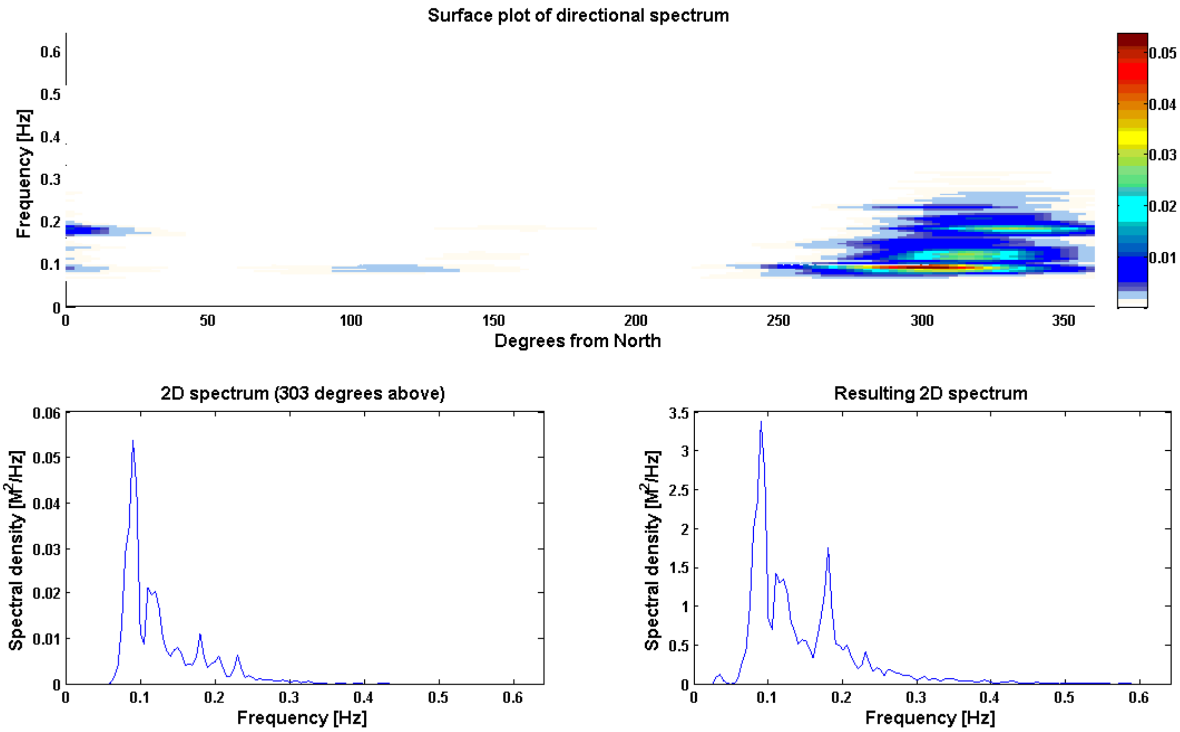


**Figure 2.1 Anticlockwise from top: Surface plot of directional spectrum – 2D spectrum from directional spectrum (303 degrees) – Resulting 2D spectrum of the whole 3D spectrum.**

Figure 2.1 shows various spectra from a buoy off the Norwegian coast. From the 2D spectrum in the lower right corner e.g. the Hs can be calculated to 1.71 m.

Once the Hm0 (or Hs) and Te have been calculated, the energy flux per meter wave front, also referred to as the wave climate (J), can be established with the following formula valid for deep waters.

$$J = \frac{\rho g^2}{64\pi} T_e H_{m0}^2 = kT_e H_{m0}^2 \text{ [kW/m]}$$

However, when the 2D spectrum is used for deriving various statistical parameters the directional information about the sea state is obviously lost, and sea states are rarely perfectly unidirectional. As mentioned earlier in this chapter, waves seen on the ocean surface are as a result of different weather systems. An oceanic swell might enter from one direction, whilst the wind in a local weather system might create waves with a completely other direction. The result is a crossed sea with waves traveling in different directions, and for e.g. WEC stability reasons etc. this could be of utmost importance.

When the waves travel into the nearshore one need to take notice of the changing physical setting. As mentioned, the sea floor influences the waves, resulting in the particle paths becoming more elliptical. In the shallow water regime the linear theory is no longer valid and a more complex non-linear theory is needed to describe the waves. The non-linear wave theory will not be presented here, instead it is concluded that waves loose energy as they travel into shallower water due to sea-floor interactions and that the surge component of the particle motion increases relatively.

## 2.3 Wave energy absorption

In wave energy, the term absorption refers to the conversion of the incoming wave energy flux to mechanical power. Wave energy absorption is best explained by considering the example given in Falnes et al[3] (1978), reproduced here in Figure 2.2. Figure 2.2a shows an undisturbed incident wave. Curve b shows the wave radiation pattern by a wave energy converter oscillating in heave while curve c shows the wave radiation patter by a wave energy converter oscillating in surge. Curve d shows the resultant wave field after the superposition of all three waves, curves a, b and c. It can be seen that in order to absorb a wave it is necessary to generate a wave. Hence the paradoxical statement “that to destroy a wave means to absorb a wave”

[3] Falnes, J and Budal, K: Wave-power conversion by point absorbers. Norwegian Maritime Research, Vol.6, No.4, pp.2-11 (1978)

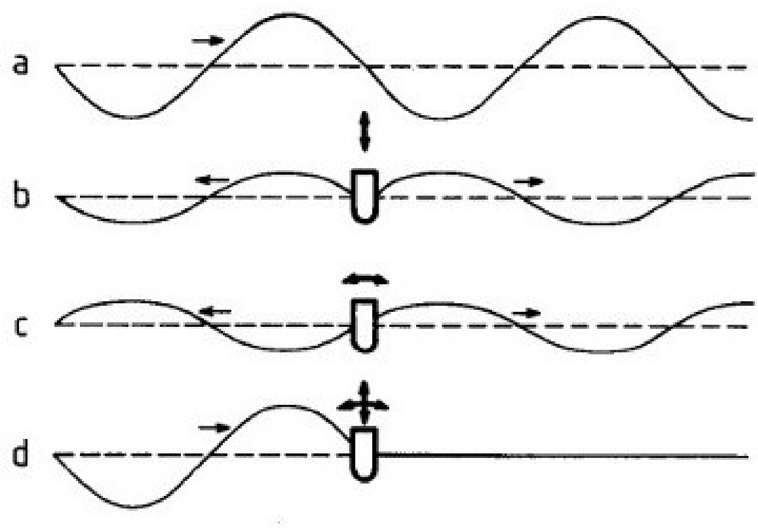


**Figure 2.2: Wave absorption of a wave energy converter operating in heave and surge (Falnes et al 1978)**

Most wave energy converters are designed to have a relative motion between two or more bodies induced by the interaction with the waves. The relative motion or the wave-induced mechanical power is what drives the power train, usually referred to as the Power-Take-Off (PTO), and ultimately the generator. As discussed earlier in this article, the wave energy flux is dependent on two parameters, the wave height and wave period. Most wave energy devices are designed to perform at their best for certain, and often quite narrow, frequency ranges i.e. for a certain range of wave periods, and this range should obviously be chosen so that it corresponds well with the most occurring wave periods at the envisaged site. However, the wave energy converter will still be able to produce energy, although not as much in waves of other frequencies. The full frequency range that the converter can produce in is called the bandwidth of the machine. Wave energy converters are in other words designed to operate in certain wave climates or sea-states, and most of the device developers today have machines designed for Atlantic conditions where the wave energy potential is the greatest. There are some developers however, that aim to provide niche markets with wave energy converters designed for low- to moderate-energy seas. The mechanism by which these WECs are designed for certain sea-states is achieved via control, WEC shape and tuning.

Machines designed for large ocean swells will experience large forces and low velocities compared to moderate wind driven sea states. Such big-wave machines require larger masses and more inertia to produce power instead of just surfing the waves (the Pelamis is a good example of a machine designed for Atlantic swells). However, if such a WEC would be deployed in a low-, or moderate wind driven waves it would more or less just sit still in the water. In these types of waves it is instead preferable to have smaller and lighter devices that can utilise the velocity of the motion. The wave conditions do not only set the size of the WEC, it also determines the characteristics of the PTO. Machines working in ocean swells needs PTOs that are able to cope with the large, but slow, forces associated with such waves, e.g. hydraulic systems have these qualities. In smaller wind driven waves a directly driven system, e.g. linear generator, is to prefer as it responds to velocity changes more rapidly.

In order to maximise economic returns, all wave energy converters try to absorb as much of the incoming wave energy as they can, convert this to electrical power and sell this as energy in the form of MWh. The amount of energy that can be absorbed from a wave is regulated by the control regime. The control in wave energy devices can be classified into three categories; geometry control, PTO control and power regulation. All wave energy developers consider these three different stages in conjunction.

Geometric control alters the shape, added-mass, damping, centre of gravity, buoyancy, mass etc. of the device in order to change the response characteristics of the device.

PTO control of the device is implemented to maximise absorption force compared to incident wave force. Many wave energy developers implement a PTO using a single damping coefficient, often referred to as real control. This is the simplest form of control to carry out as it only involves a force that is proportional to a damping coefficient times a velocity. A more evolved type of control system is that of reactive control. Here two or more coefficients are used in the PTO, generally spring-damping coefficients. Using this type of control it is possible to get both the absorption force and wave excitation force in phase for one chosen frequency. This is analogous to complex conjugate control used in the electrical industry. In theory, this is very easy to implement but in order to execute it in a physical WEC, it requires more complex and expensive components and a power take off that can both produce and consume power. Another type of control is that of latching. Here the WEC is held (latched) in position at both the trough and peak of a wave and released at a time in order to achieve maximum power absorption.

To summarize, latching control aims to control the phase that the device oscillates with, whilst in reactive control both the phase and the amplitude of the oscillations are controlled. The difference between latching and reactive control is that the device itself has to arrive at the holding position in latching control, whilst in reactive control the PTO is allowed to function as a motor and drive the device to the optimal holding position.

Power regulation control refers to the quality and quantity of the delivered electricity. This form of control can include power smoothing via energy storage, control of the voltage and frequency.

**Tuning**

Tuning can be described as a means of changing the machine’s behavior on a transient basis so that it suits the incoming sea state. This is usually achieved by optimizing one of the control strategies for certain wave climates. Geometric control is chosen and set at the design stage of the WEC and thus cannot be readily tuned. PTO control, sometimes referred to as mechanical control, can be changed on a regular basis and the control parameters can be optimized or tuned for the occurring sea state. For example in low energy sea states, it might be more beneficial to have a low damping setting to achieve more relative motion in the device and conversely in more energetic seas, increased damping will result in more power absorption. Tuning can in other words be fixed (geometric control) or active (PTO control). Active tuning obviously requires information of the current sea state in order to do the suitable adjustments. This information could come from the machine itself or through communication with a nearby wave buoy.

## 2.4 Wave energy potential in the Nordic countries and British Isles

Wave resource and wave power potential are generally rather poorly investigated in all countries. This could be due both to the inherent complexity to compute them, especially as the amount of data is limited, as well as the ambiguity of the results. How to determine wave resources for a given point or area is described in Appendix 1.

There is no absolute level of wave resource as it varies with time and distances from shore. Waves are primarily created in the open ocean and travel with small energy loss until nearing the shore, where energy is lost through friction against the sea floor and breaking. Thus the incoming hydrodynamic power flux can be expressed as contour lines starting off shore with gradually lower levels when nearing the shore. This can be seen in Figure 2.3 from the Irish Wave Energy Atlas[4]. Typically the **theoretical resource** refers to the power flux crossing a line sufficiently offshore to be unaffected by the bottom.

The power flux or wave climate is usually expressed as the annual mean power per meter wave front and is a function of significant wave height and wave period. If for example a contour line of constant power flux is followed the theoretical resource will be the length of contour line times the power flux and annual hours. Alternatives may be, following a depth contour line or a line of constant distance from the shore. However it has to be kept in mind that every reference line will give a different theoretical resource.

The **wave power potential** is then how much of the theoretical resource that can be extracted from a technical point of view including wave power plant characteristics. Various restrictions such as natural protection areas and shipping lanes and physical restraints such as maximum water depths or distance from shore need to be accounted for.

Looking at the Nordic countries and British Isles the level of knowledge around wave resources and wave power potential varies considerably.

The most ambitious attempt to determine the wave resource and wave power potential has been made in Ireland[5]. The theoretical wave resource offshore was estimated to approximately 500 TWh along the 70 kW/h contour line. The wave power potential has then been estimated by deploying a hypothetical double line of Pelamis wave converters resulting in a wave power potential of 28 TWh. After reduction for protected areas etc the net potential was found to

[4] Marine Institute/Sustainable Energy Ireland "Accessible Wave Energy Resource Atlas: Ireland:2005" available at http://www.seai.ie/
[5] Ibid

be 21 TWh. Here some comments can be made; firstly the power curve used was for the now defunct P1 version of the Pelamis and a better performance should be expected for a new and optimized version and secondly that there is no reason that it should be just two lines of wave energy converters if the wave resource after passing through them is high enough.

In Norway an investigation of marine energy resources[6] determined the offshore wave resource to be about 600 TWh. A rough estimate of the wave power potential has also been made in the report. It assumes that the same percentage of the wave power resource as the Norwegian hydro power resource is possible to develop, i.e. 25 %, and that the wave power conversion efficiency is between 10 and 25 %, thus arriving at a wave power potential of 12-30 TWh.

No recent estimates have been made in the UK; a twenty-year old study[7] (ETSU 1992) gives an offshore wave power resource of 6-700 TWh for the UK. A UK wave power potential of 50 TWh is quoted in a number of official publications including e.g. the 2010 Marine Action plan, although details on how this figure is derived are unknown.

The Danish wave resource is found on the west coast of Jutland and estimated to be 30 TWh offshore[8]. The maximum offshore power flux is around 15-20 kW/m and a wave power potential of 5 TWh is given as “feasible”.

There has not been any study of the Swedish wave energy resource and consequently wave energy potential. However, the best conditions in Sweden are found on the West Coast north of Gothenburg where the offshore power flux is around 5 kW/m. Multiplying this with 150 km stretch between Gothenburg and the Norwegian border gives a theoretical resource of 6 TWh. There is also a wave resource in the Baltic Sea but with lower power fluxes. A study[9] has estimated the total Baltic Sea resource to 56 TWh of which some would be included in a Swedish wave energy resource. However, the methodology used in this study differs from the others studies and results are not comparable.

[6] Enova 2007, “Potensialstudie av havenergi i Norge” available at http://www.enova.no/

[7] Whittaker, T. J. T. and Mollison, D. (1992). Kirk McClure Morton (Consulting Engineers), An assessment of the UK shoreline and nearshore wave power resource, Report No. ETSU-WV-1683. Energy Technology Support Unit Harwell, 152 pages

[8] Energistyrelsen, Elkraftsystem and Eltra, 2005 ”Bøljekraftstrategi – Strategi for forskning og udveckling” available at http://www.ens.dk/

[9] Henfridsson et al. 2007 ”Wave energy potential in the Baltic Sea and the Danish part of the North Sea, with some reflections on the Skagerrak”, Renewable Energy 32 (12), pp 2069-2084

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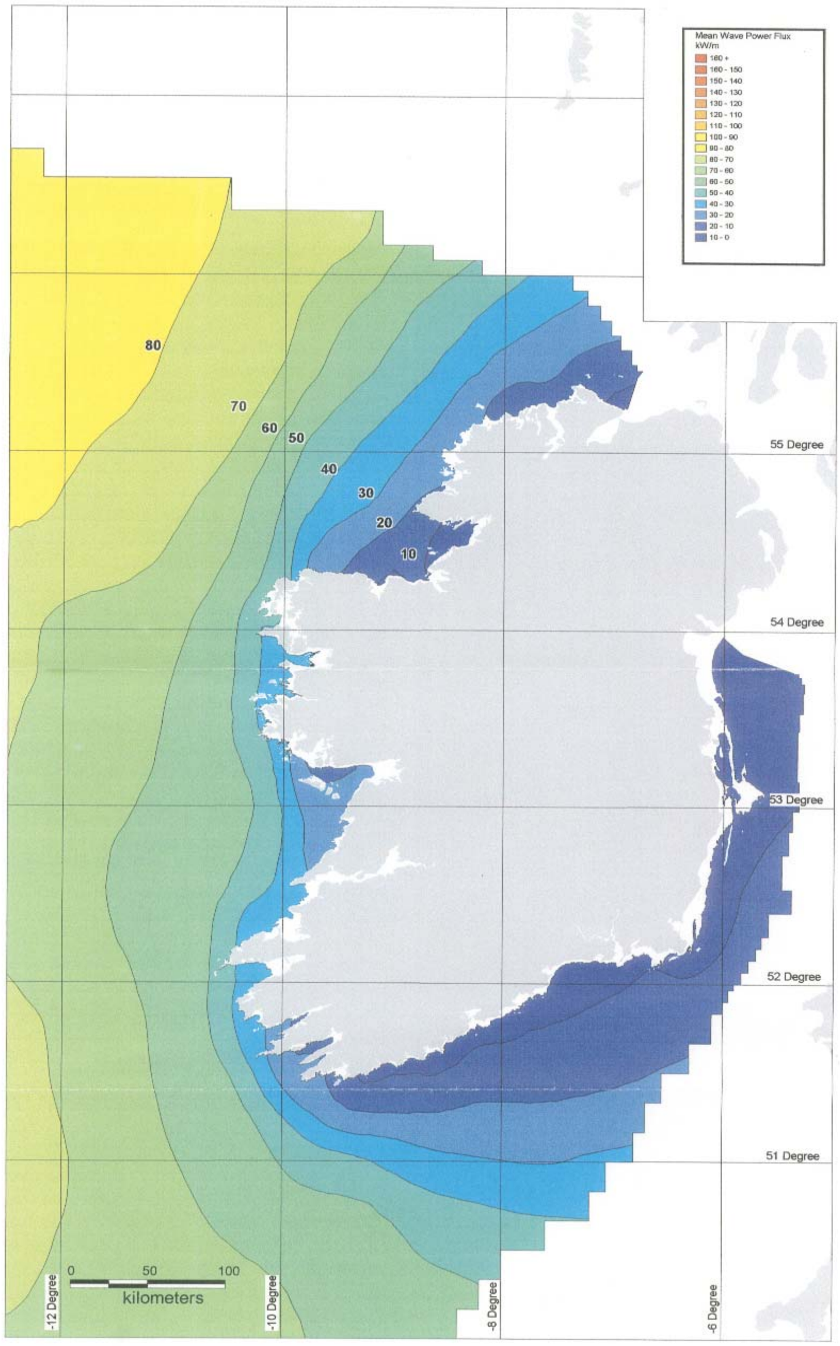



ESB International
Environmental Services 2005

Fig No. 5 Mean Annual Theoretical Wave Power Flux kW/m

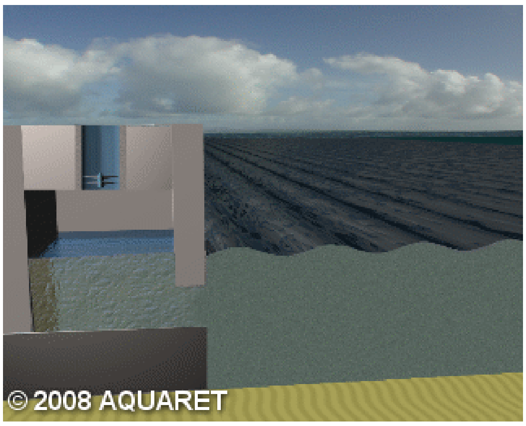
**Figure 2.3 (Marine Institute/SEI 2005)**

# 3 Wave power technology

There are several different concepts for extracting energy from the waves. The harvesting mechanism for most concepts can be categorised into one of six different methods, Oscillating Water Column, Attenuator, Point Absorber, Submerged Pressure Differential, Oscillating Surge Converter or Overtopping Devices (sometimes referred to as Terminator). The various concepts referred to in the text are shown in Appendix 2. The illustrations come from www.aquaret.com[10] and are also available as animations there.

## 3.1 Oscillating Water Column (OWC)

An OWC is an air chamber that is open to the sea at the bottom and has an air outlet through a turbine at the top. As waves impact the device, the water level inside the chamber rises and falls, compressing and expanding the air and driving it through the air turbine. Since the air direction reverses halfway through each wave, a method of rectifying the airflow is required. This can be done either by using multiple turbines or by using a self-rectifying turbine that spins in only one direction regardless of the direction of airflow (usually Wells turbine). OWC concepts exists for both off shore and shoreline sites




The size of the air filled chamber influences the ideal wave climate for the OWC. By varying the length, width and depth of the air chamber an OWC can be designed to match most wave climates, where the length of the device has the largest impact on suitable wave climate. However, for larger size installations (hundreds of kW) a relatively energetic wave climate is needed. OWC are suitable for shoreline installations, like the Limpet (Wavegen demonstrator) plant, where mooring is not an issue and maintenance is more available and cheaper as compared to offshore installations. Offshore OWCs (like Oceanlinx and OE buoy) are usually catenary moored devices, much like a ship. There are also some ideas about building to integrate OWC in offshore wind turbine foundations, whether this is feasible is unclear. Depending on device energy absorption, wave to air, is usually 10-30%.

The PTO systems used for OWCs are air turbines (usually Wells turbines) coupled to a rotating generator. The Wells turbine is self-rectifying but suffers from high noise levels and has a narrow bandwidth. Depending on working conditions efficiencies for the turbine is in the range of 40%-70%. The

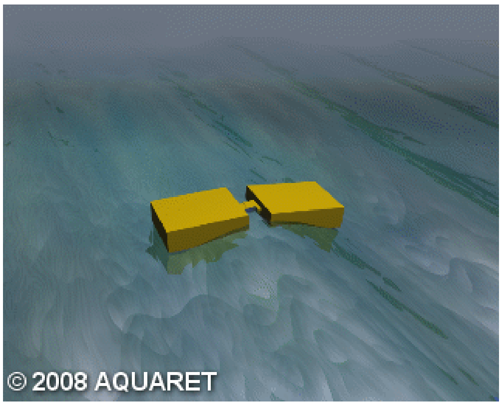
[10] Aquatic Renewable Energy Technologies (Aqua-RET) is an e-learning tool promoting aquatic renewable technologies. It is an EU-funded Leonardo da Vinci project.

efficiency of the generator is usually 85-95% depending on load and generator type. This type of PTO system cannot utilize active control to increase absorption but there exists some other ideas, so far untested in reality, of PTOs for OWCs that may be able to utilize active control.

## 3.2 Attenuator

Attenuators are floating devices aligned to the direction of the incident waves. Energy is extracted as waves pass along the length of the device. These types of devices are typically long multi-segment structures. Each segment is a floating pontoon joined together by a joint allowing the segments to move (usually pitch and yaw). Their relative motion, concentrated at the joints between segments, is used to pressurise a hydraulic piston that drives fluid through a motor, which turns a coupled generator. Attenuators must be aligned (to some extent) with the direction of the incident wave. This is usually achieved by a mooring system attached to the front of the device. The mooring system needs to allow the attenuator to move and slack moored or catenary moored systems are common.

The length of an attenuator segment should be smaller than ¼ of the wavelength otherwise the segment will notably start counteracting itself. An attenuator can therefore be designed to suit specific wave climates ranging from small to large waves. Pelamis for example is, due to its size, most suited to relatively long waves $T_e$>7s with good performance for energetic north Atlantic sea.

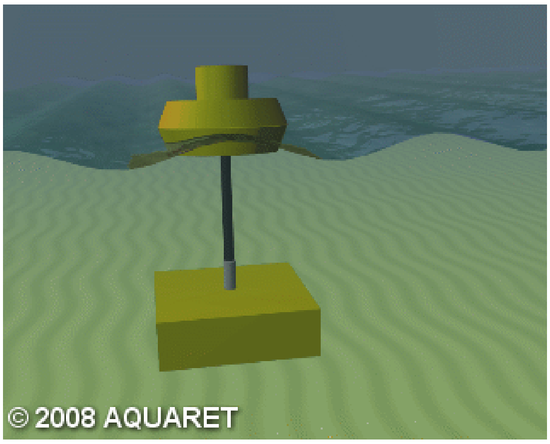



The PTO systems for attenuators are hydraulic. The hydraulic systems then drive an electric generator. The wave power device is then connected to shore via a sub sea power cable. Since attenuators are moving, the cable connection needs a smooth transition as not to be worn out by fatigue. The hydraulic system can utilize active control to increase the energy absorption. Without active control energy absorption is generally less than 20%. Active control can double or triple the absorption, how much remains to be seen. Hydraulic efficiency is 40-80% depending on technique. Simple "off-the-shelf" hydraulic systems have efficiencies of around 40-50 % while more advanced systems can today reach 60-65 %. According to developers of hydraulic systems efficiencies up to 75-80% are feasible in the near future. Generator efficiency is 85-98%.

## 3.3 Point Absorber

A point absorber is a buoy (displacer) floating on the water surface that is referenced to a fixed system, either a large inertial body (reactor) or a damper by wires or by a stiff connection. The point absorber motion is due to the heave displacement caused by a passing wave and the relative heave motion between the two bodies is used to extract power. The PTO of such systems is often hydraulic due to the high forces and slow motion, but concepts using linear generators exist.

Point absorber devices can be designed to work at near shore and off shore sites and at most sea states. A small (1-5 m diameter) and light (<5 tonnes) buoy like the one used in the Seabased concept has high absorption for small and high waves (short $T_e$ and high $H_s$) and is ideal for North Sea climates. As waves becomes longer ($T_e$ increase) absorption starts to drop and for systems without active control absorption is only a few percent for long waves like Atlantic swell ($T_e$>12s). Active control can be used (like Wavestar) to tune a small buoy into higher absorption even for longer waves although how much is yet unknown. Heavy (100s of tonnes) and big (10-25m) point absorbers like Wavebob are more suited to long waves (>7s). A point absorber can be designed for short or long wave periods and by using active control a single point absorber can be designed to match most sea states. The diameter of a point absorber should be less than 1/6 of the wavelength otherwise it will notably start counteracting itself. For systems without active control absorption is usually 10-30%. Active control has shown absorption of 40%-50% for specific wave climates.



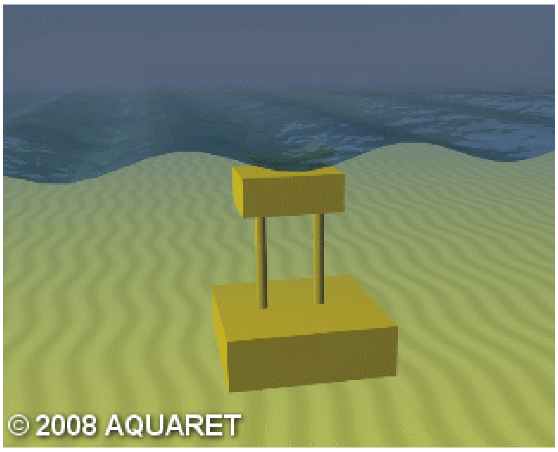

Point absorbers have the largest variety of PTO:s even if hydraulic is the most common. Again, simple hydraulic systems have shown efficiencies around 40-50% while more advanced systems can today reach 60-65%. Hydraulic developers claim that efficiencies up to 75-80% might be possible in near future. The hydraulic system is coupled to a rotating generator with an efficiency of 85-98%. Direct drive linear generators are represented (Seabased) as well as different mechanical arrangements/gearboxes to convert the linear motion to rotating motion. Examples are Rack and pinion (Aegir Dynamo) and wire to winch (Straumekraft) coupled to a generator. PTO efficiency for linear generators depends on design and load conditions but ranges from 60%-85%. Mechanical gearbox arrangements are fairly efficient, 80-90%, coupled to a rotating generator with 85-98% efficiency. There are, however reliability and life length issues yet to be proven for the mechanical solutions.

Point absorbers are often associated with some mechanical protection against high waves such as end stops or removing the absorber from the sea surface (WaveStar). Life length and long term functionality of these protection systems is unknown and their influences on the survivability of the devices. As with attenuators mooring and cable connection are areas that need careful attention.

## 3.4 Pressure Differential

A pressure differential type of device is similar to a point absorber, but here the wave causes an air filled body to change volume when the water presses against a membrane or, if the body is submerged, the pressure differential of successive crests and troughs induces the body to rise and fall. When the body is submerged the height of water above the body increases as a crests passes overhead thus pushing the body downwards. As a crest passes over the device, the water pressure is reduced and the body rises again due to its own buoyancy. Electricity is generated by the relative movement of the body (displacer) to the reactor as with the point absorber concept.

Submerged devices are acting on the pressure difference under a wave and these types of machines needs to have the body relatively close to the surface. Again the size of the body determines a suitable wave climate. For large units (hundreds of kW) the built in inertia and added mass requires a relatively energetic sea state 15-20kW/m to start generating (CETO), limiting these type of devices to more energetic seas.




The PTO for CETO is water hydraulics feeding pressurised water ashore (50%-90% efficient) to a hydroelectric station with turbine efficiency of 80%-90% and generator efficiency of 85%-98%. Other PTOs could be used however with the under water location in mind it is preferable to keep it as simple as possible.

Devices where a membrane causes a volume change typically contains several air filled bodies creating a pressure difference between them. Energy is extracted with an air turbine (similar to OWCs) when the air tries to stabilize the pressure between two bodies (AWS/Coventry Clam[11]).

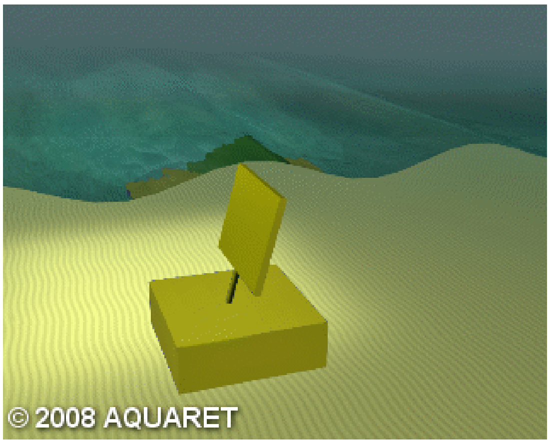
There are no publicly available data for absorption efficiency while the PTO efficiency should be on the same order as for the similar system in OWCs.

## 3.5 Oscillating Surge Converter

An oscillating surge converter extracts energy from wave surge. As waves approach more shallow water, the circular movement of water particles becomes more elliptic and water movement closer to the sea bed becomes a back and forth motion. Oscillating wave surge converters use this oscillating back and forth motion to extract energy. Devices are generally secured to the seabed at shallow waters (<20m) although some concepts of offshore floating surge converters exist. A hinged displacer moves back and forth with the

[11] The Archimedes Wave Swing was a well-known submerged concept, however some years ago AWS ltd took the decision to scrap this design. It has since then been working on a new design based on a 70ties concept called the Coventry Clam.

oscillating water movement, with energy being extracted via hydraulic energy converters secured to the fixed component.

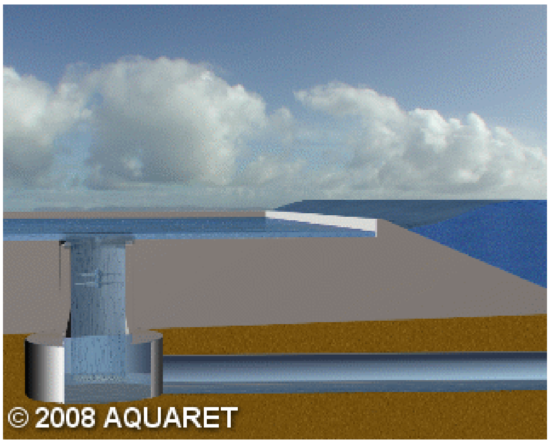



Oscillating surge converter concepts are well designed to survive extreme wave climate since they are often standing on the seabed with a flap that is not floating on the surface. The flap follows the natural surge movement making the design simple, but it also makes it difficult to apply any active control to optimize absorption. Instead this needs to be handled in the design. Looking at large designs (hundreds of kW) this type of devices seems to be suited best for wave periods longer than 7s. Floating "OSCs" like the Langlee device are very large since they need to be ½ wavelength long to even out forces. Absorption depends strongly on wavelength and sea state but for Atlantic sea conditions an average absorption is 20-45%. Geometric design of the flap also influences the absorption and it remains to be seen how much the absorption can be increased by this measure.

The PTOs used in oscillating surge converters are hydraulic. Devices secured to the seabed are fixed and some of those concepts (Oyster) pump water ashore to a hydroelectric station. Pumping water result in efficiencies of 50%-90%, turbine efficiency at 80%-90% and generator efficiency of 85%-98%.

## 3.6 Overtopping Devices

Overtopping devices use reflector arms and/or sloped surfaces to drive the waves to a reservoir of stored seawater. The difference in water head is then used to drive low head turbines. An advantage for overtopping devices is that the turbine technology is well understood and used in hydropower. These devices are often large installations and can be placed on the shoreline as well as offshore.




Limiting sea conditions are set by the design itself and by the low head turbine used (Usually Kaplan type with lower limit of 1m). The reservoir is typically built up in several stages/heights to extract more energy from higher waves.

Floating devices need to be stable in the water but also be able to adjust to different wave heights. Too low in the water means that waves will pass right over while too high will stop waves before. The solutions to this vary; the Wave Dragon uses sheer mass to stay in place while changing height through an air cushion, WavePlane uses a so called heave plate (a flat plate rigidly fixed to the surface part located sufficiently deep to be under the wave action) while different wave heights are handled by inlets at several heights. These devices are often catenary moored to withstand the forces exerted on it. These kinds of devices are often large, heavy and designed for moderate to high wave climates.

The PTO is, as mentioned, always a low head turbine (Kaplan type) coupled to a generator. Turbine efficiency can go up to 90% and generator efficiency is 85-98%. Overall wave to wire efficiency has been reported to be 18-20 %.

## 3.7 Summary

The table below summaries where the six basic principles are suitable.

| | **Onshore** | **North Sea** | **Atlantic** |
|---|---|---|---|
| **OWC** | Suitable, Concepts exist | Concepts exist | Suitable, several concepts exist |
| **Attenuator** | | Concepts exist | Suitable, concepts exist |
| **Point Absorber** | | Suitable, Concepts exist | Suitable, Concepts exist |
| **Submerged Pressure Differential** | | | Possible, Concepts exist |
| **Oscillating Surge Converter** | | Possible, concept exits | Suitable, Concepts exist |
| **Overtopping Devices** | Suitable, Concepts exist | Suitable, Concepts exist | Suitable |

# 4 Wave power development and the utility perspective

## 4.1 Overview

There are around 50 to 100 wave power concepts actively being developed, i.e. RD&D being carried out on a daily basis in an associated company. The majority are however at an early phase (see Ch.4.2) and have so far not encountered the major economic and technological hurdles. Furthermore these companies are small with more or less strained economics, which makes the day-to-day struggle more important than the longer view. However understandable this is, it means that that the system perspective is somewhat neglected and to be blunt some wave power developers have rather vague insight in large-scale power generation.

Utility scale wave power would mean large farms (100 MW+) in order to be meaningful and, in all probability, to be economically viable. Thus from a utility perspective wave power devices need to be able to be installed and connected to the grid in large numbers, be able to be maintained and have an acceptable economic performance.

This chapter will look at issues of interest from a utility perspective. The following section will however briefly discuss the various development stages of wave power concept to give a background of the challenges for the wave power developers.

## 4.2 Development stages

There are several ways to categorize the development stages of new technologies e.g. NASA uses a measure called TRL, Technology Readiness Levels, that consists of nine different development levels with defined technical milestones. Another measure developed specifically for the marine energy sector is the Irish Ocean Energy development and evaluation protocol with five levels including indicative costs for each step.

The wave energy sector is often compared to the wind energy sector, and especially the offshore wind energy sector. It is often heard that wave energy, in terms of technological maturity, is some ten to fifteen years behind the wind sector. Indeed there are many similarities between offshore wind and wave energy, but there are also some fundamental differences. Whilst wind energy converters have been developed as an onshore technology that has been applied to the offshore, most wave energy converters are developed for offshore operations from the start. Being offshore increases the obstacles that must be overcome (e.g. survivability) and the wind energy sector could prove the technology onshore before taking the step offshore whereas the wave energy sector must face all challenges associated with being at sea with the first prototypes.

Furthermore, there is a fundamental difference in how a wind turbine harvests the energy compared to a wave energy converter that influence the development process. A wind turbine's capacity to produce power is very much determined by the area swept by the turbine. The ability to produce power for a wave energy converter is strongly connected to the weight of the device than, for example, the water-plane area. Wind turbines have been able to grow from rather small devices rated in the tens of kW, to the multi-MW machines in a commercial arena. The same site used for a small-scale wind turbine some 15-20 years ago can today be used for large-scale wind energy generation. However for wave power the cost of offshore works (e.g. sub sea cabling or piling) would be prohibitive for small-scale units. Furthermore, since mass and inertia are such central factors in wave energy there is no point in deploying and connecting a scaled wave energy converter in EMEC or WaveHub, the two currently operational marine energy test centres with sub sea electrical infrastructure installed, since such a device would be too light and only produce trivial data. Indeed, there are test zones in Europe for scaled devices e.g. the Irish test zone in Galway bay, but all these sites lack a grid connection. To get offshore experience and results wave energy developers are more or less required to go to full scale.

A simplified description of the development process for wave energy converters is given in Figure 4.1, and the different stages are described in more detail below.

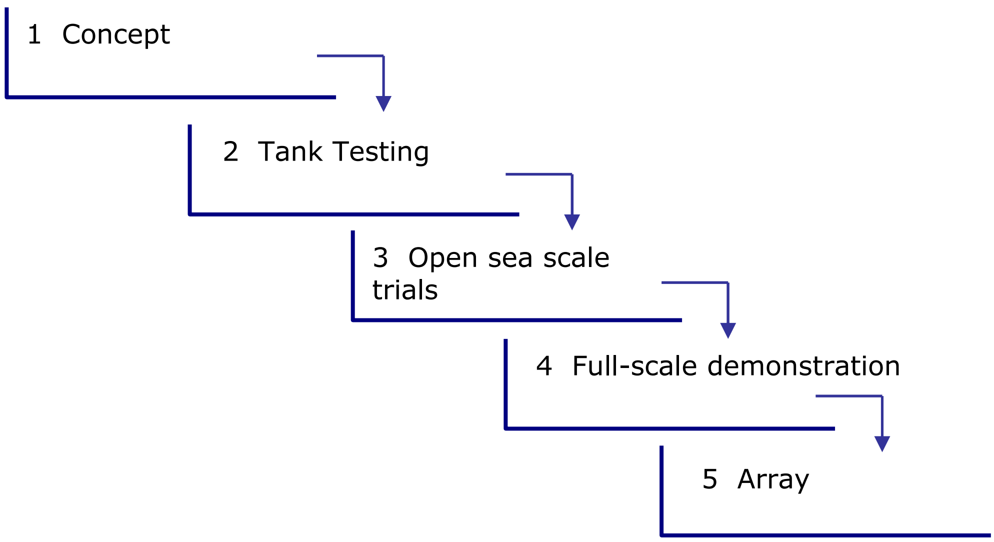



**Figure 4.1: The different stages in the development process of wave energy technology simplified.**

1. **Concept:** A drawing table phase where the initial design is established. This phase usually includes numerical modelling for early validation of the wave energy concept.

2. **Tank testing:** Experiment in ocean wave basins is a cost effective way to do tests on a design. Testing in this protected environment has many other advantages compared to real sea testing, e.g. accessibility to workshops, safety, and most importantly the sea states can be chosen. The freedom to choose the sea state is essential for comparative tests since different designs can be tested in identical conditions and also for survivability tests. Suitable scale versions are typically around 1:15$^{th}$ to 1:20$^{th}$ scale for power tests and possibly smaller for survival tests. Tank testing campaigns can also be performed in later stages of the development process to given guidance results in case of e.g. a design change is called for. Many WEC developers rely much on simulation tools, which often are produced in-house, and tank-testing results are important to validate numerically derived results. Hence are tank experiments important in order to develop not only the device itself, but also numerical tools.
3. **Open sea scale trials:** At one point it is necessary to bring the design out in the real sea. Although modern wave basins can create very realistic environments they cannot fully capture the complexity of the real sea. In this step a scaled device is used in order to give information about e.g. deployment strategy and real sea performance that ultimately will baseline the decision to go to full scale.
4. **Full-scale demonstration:** The focus in this stage is set on verifying the concept in full scale in real operational conditions. One of the main constraints for a successful full-scale demonstration is the economical resources required. This is further discussed later in this section.
5. **Array:** Once the wave energy converter is demonstrated array operation is the last and ultimate step to take in order to show that the wave concept is a viable technology for commercial energy production.

Today there are several wave energy converter developers somewhere around stages 3 and 4, but no developer has really showed continuous array operation i.e. stage 5. Obviously the further the developers reach in the development process, the higher the cost get for taking another step, and this is often a restricting factor. Figure 4.2 below shows indicative costs for taking a device from the concept stage to a full-scale grid connected MW-sized device based on estimates from several developers[12] (also showing the actual funding sources).

[12] ”Channelling the Energy” 2010, http://www.bwea.com/pdf/marine/RenewableUK_MarineReport_Channeling-the-energy.pdf

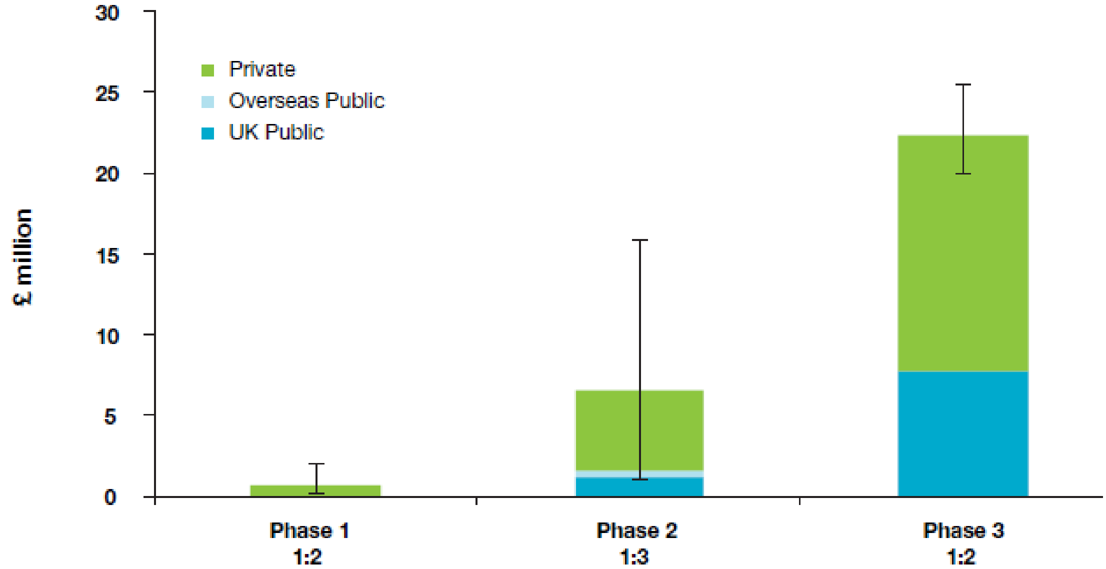



**Figure 4.2: Cost levels for taking a technology from concept to full-scale demonstration. Phase 1: Concept design & tank testing. Phase 2: Open sea scale trials. Phase 3: Full-scale grid connected prototype.**

Figure 4.2 covers development stages 1-4 described above in this section, Phase 1 in the Figure 4.2 includes both development stage 1 and 2.

Many wave developers gets stuck in phase 2, Figure 4.2 offers an explanation to this. It is not necessarily the technological maturity of the technology that is the toughest hurdle in order to prove the technology in full scale, in many cases it can be the ability of the developing company to attract the required funding that proves an even bigger challenge.

## 4.3 Economics

The current cost of wave power is high as we are looking at the first of kind prototypes. There is only some fragmentary information about actual costs. For example at ICOE in Bilbao the presenter from Aquamarine Ltd announced that the current installed cost of the Oyster wave power device was around SEK 80 000/kW. The cost of the 10 MW Sotenäs wave farm to be installed at the Swedish West Coast has according to the Annual Report[13] of Seabased AB been estimated to SEK259 million. This figure is about half of the corresponding investment costs for a 10 MW wave farm given in the British surveys presented later in this section.

[13] http://www.seabased.com/pdf/SEA_redovisning_2009.pdf

There are two recent public surveys of wave power costs, Renewable UK's publication "Channelling the Energy"[14] and DECC's (UK Department of Energy and Climate Change) "Cost of and financial support for wave, tidal stream and tidal range generation in the UK"[15]. In both report costs for wave power are presented based on information from developers and utilities that are active in the wave power sector. As both reports are based on similar sources the figures are in general agreement. As the DECC report is more extensive the figures below are from this source.

The current installed capital cost (CAPEX) for a single machine is given as a range of £6–8,5 million per MW (SEK70 000-100 000 per kW). However more interesting is what the cost of a first 10 MW farm would be.

For a developer's first 10 MW the presented average CAPEX is £49 million (approx. SEK550 million or SEK55 000/kW) with a spread of £4,1-5,7 million. The operational expenditure (OPEX) is given as £2,9 million per year (approx. SEK35 million per year) with a spread of £2,4-3,5 million per year.

With an assumed capacity factor[16] of 33 %, a life length of 20 years and an IRR of 12 % this translates to a cost of electricity of £400 per MWh (approximately SEK4,5 per kWh). (It can be noted that with 33% capacity factor the OPEX translates to slightly more than SEK1 per kWh.)

It is not clearly stated what is included in these costs or not and there will obviously be variations depending on technology and site. In the former case there may be trade-offs between CAPEX and OPEX for example.

## 4.4 Performance

The performance of wave power plants is, at least in theory, described by a capacity factor analogous with wind turbines. This is defined as the annual produced power divided by the theoretical maximum (rated power times annual hours).

There are no published results from real sea tests, therfore estimates of capacity factors are somewhat speculative at this stage. In "Channelling the Energy" industry estimates of the capacity factor is in the range of 30-35 % and this level is probably necessary for wave power to be viable. However a few comments about performance and the capacity factor needs to be made:

- The performance of a wave power plant is usually very dependent on the wave climate at the actual site. Wave power concepts are typically designed for optimum performance at the prevailing wave conditions of the site. Installing the same wave power plant at a site with very

[14] "Channelling the Energy" 2010, http://www.bwea.com/pdf/marine/RenewableUK_MarineReport_Channeling-the-energy.pdf

[15] "Cost of and financial support for wave, tidal stream and tidal range generation in the UK", 2010 http://www.decc.gov.uk/assets/decc/What%20we%20do/UK%20energy%20supply/Energy%20mix/Renewable%20energy/explained/wave_tidal/798-cost-of-and-finacial-support-for-wave-tidal-strea.pdf

[16] Average output as percentage of rated power on annual basis

different wave conditions can result in poor performance. An example of this can be found in a study by Dalton et. al.[17], where the performance of the Pelamis wave energy converter was investigated for a number of sites, see Figure 4.3. (The data used for the performance of the Pelamis was from simulations of old and now defunct P1 design and should only be seen as indicative.) The Pelamis is designed for Atlantic swells and as can be seen from the results give a good performance in such (Ireland). However when gradually moving towards smaller waves the performance deteriorates.

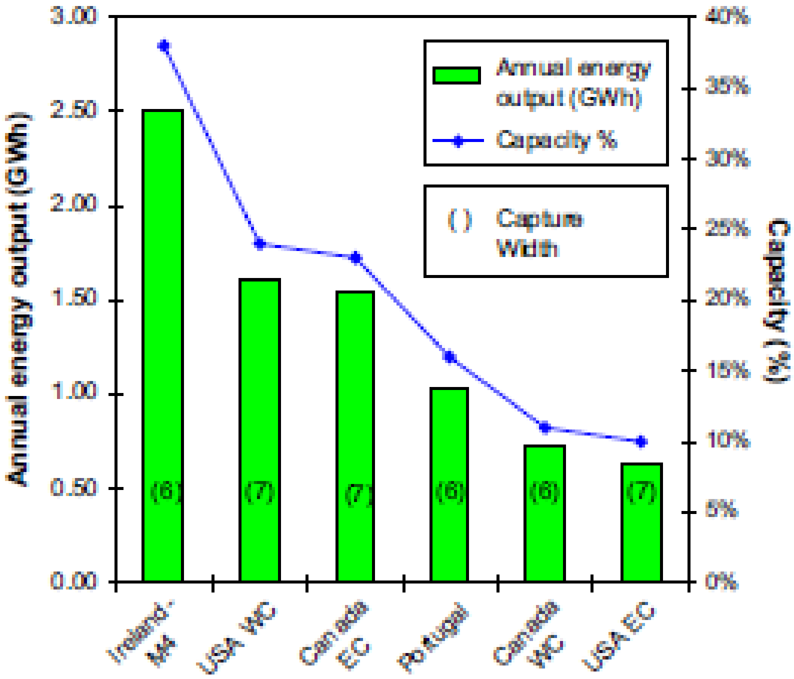



Figure 4.3 Annual energy output and capacity factor for a Pelamis P1 750 kW wave power converter at 6 different sites (from Dalton. Et. al.)

- There will be a continuous improvement of wave power plant performance by e.g. more sophisticated control algorithms or improved geometrical design as experience is gained.
- The capacity factor is not in itself the whole answer. For example down rating the generator will result in a higher capacity factor but will only mean a small cost reduction. Furthermore there may be scope for low cost concepts with a moderate performance. All in all the only true measure is the cost of produced electricity.

[17] Dalton G.J., Alcorn R. and Lewis T.. "Case study feasibility analysis of the Pelamis wave energy converter in Ireland, Portugal and North America", Renewable Energy 35 (2010) pp 443-445

## 4.5 Installation

Installation of wave power plants differs significantly between shallow water and deep-water devices.

Shallow water devices such as the Oyster or WaveStar are bottom mounted and needs to be firmly anchored to seabed with piling. Currently these concepts needs to be barged and lifted in place although it should be possible in the future to float them in place and ballast them down. In the case of Oyster and CETO who needs to transport pressurized water to turbines there is a need for high pressure piping that in the case of at least Oyster is installed by horizontal drilling.

Deep water devices such as the Pelamis will be towed to the site. The major installation work is anchoring and installation of sub-sea electrical equipment, primarily sub-sea cable to shore. There are several options for anchoring; dead weight, suction, drag, plate and piling. Loads and type of bottom determine which anchoring type that can be used. For an extensive review of anchoring see "Advanced Anchoring and Mooring Study"[18].

## 4.6 Operation and maintenance

In general wave power plants will have an onboard control system and will be able to run autonomously to a large degree. Overall control and supervision will be done from shore. Communication is primarily done by coaxial fibres in the sub-sea cable. However there will also be a need for wireless communication in case of failures in fibre connection. In most, if not all, concepts there is also need for power supply for running the control system and other critical equipment during periods when the wave power plant for some reason is not generating power.

Maintenance will be more or less problematic for wave power plants due to accessibility. Massive devices such as the proposed full-scale versions Wave Dragon or Floating Platform can probably be accessed from the leeward side in fairly high waves. Shallow water devices such as the Oyster or the CETO have a large part of their components on shore while the Wave Star is fixed structure with accessibility similar to off shore wind turbines.

For floating deep-water devices such as the Pelamis, OPT's Power Boy or WaveBob options are more limited. Maintenance at sea is not realistic as these devices are cramped with (probably) limited internal accessibility and not least with regard to safety issues. Pelamis plans to tow in their device and do maintenance at the quayside. To facilitate this Pelamis has developed a "quick release" mechanism that allows disconnection of the device in 1,5 hours and up to 1,5 m wave height.

However, maintenance will be problematic when, for example access may be impossible for weeks or even months during large parts of the year. Thus wave power plants must be designed with as little maintenance needs as possible including possible critical failures. This may include minimizing the

[18] http://www.oregonwave.org/wp-content/uploads/Anchor-and-Mooring-Study_FINAL-mod-051010.pdf

number of moving parts, redundancies for critical components and using subdivisions that at least allows part load operation.

Wave power devices are generally stated to be designed for a 20-25 year life span with typically mid-life refit, although this obviously remains to be verified.

## 4.7 Grid connection

The grid connection of wave power plants will typically be the responsibility of the owner and operator, e.g. utilities. For shallow water wave power devices this should not pose any problems as they either have electricity generation on shore or it is located in such shallow water that a platform containing electrical equipment easily could be built.

For floating deep water wave power plants the situation is more difficult especially when looking at larger farms.

For a single floating wave power plant electrical power will be transported to shore with a so called riser cable to the sea floor where it is joined to a sub-sea cable going to shore. In order to be able to remove the wave power plant for maintenance or repairs there must be a possibility to disconnect the plant. There are two alternatives for this, wet-mate or dry-mate connectors, that can be located anywhere between the wave power plant and the sub-sea cable. Dry-mate connectors are a standard connection within a waterproof container. It is available for all voltages and relatively inexpensive, the drawback is that connection/disconnection must be carried out onboard a vessel and is time consuming. Wet-mate connectors are basically plugs where the holes in the female part are oil filled and covered by rubber diaphragms. Connection/disconnection can thus be made underwater; the drawback is high cost and that they currently only is available up to 6,6 kV although an 11 kV connector is under development.

Moving on to multiple units there is a need to connect them to the same sub-cable. This can be done in two ways; either by connecting them in series on the surface through so-called jumper cables or underwater through a series of junctions or a single junction box. The surface option is probably the simplest but has never been tried and there will be severe strains on the jumper cables. A drawback to this solution is that if the wave power plant with the connection to sub-sea cable needs to be removed the whole string needs to be shut down. A junction box has been developed for the Wave Hub test site that consists of busbars within a dry atmosphere. While it is possible to install active components e.g. circuit breakers within the junction box the risk of failure and subsequent complex retrieval operation has to be valued against the advantages. Without circuit breakers in the junction box for the whole farm needs to be closed down during the removal or installation of one device.

With large deep water arrays the problem of voltage levels and capacity of sub-sea cables arises. It is possible to have transformers up to medium voltage (33 kV) within a MW-sized wave power plant. However, if wet-mate connectors are used (as in e.g. Pelamis) the voltage level is restricted to 6,6 kV possibly increasing to 11 kV. With existing sub-sea cable dimensions and up to a distance of 20 km the power that can be transmitted is approximately; 6,6 kV 5 MW, 11 kV 10 MW, 33 kV 25 MW (Vattenfall estimates).

Thus for 100+ MW arrays a high voltage solution similar to large offshore wind farms are needed. However, at water depths of 50 m or more bottom fixed surface platforms of the offshore wind farm type seems at least difficult if possible at all. Other solutions could be floating or sub-sea high voltage transformers although these remain to be developed (there exists a couple of prototype high voltage sub-sea transformers for the oil and gas industry but designed for much deeper water and with cost as a low priority).

## 4.8 Environmental effects from wave energy

One of the attractions of wave power as renewable energy source is that only minor environmental effects are expected. Both positive and negative environmental effects are possible. At present there are no large-scale commercial wave energy parks and only a few full-scale tests and demonstration projects to draw experience from. The knowledge on environmental impacts from wave energy establishments is therefore very limited, and to a large extent built on speculations on probable effects or on assumptions that the impacts may be similar to the impact of other industrial offshore activities.

### What is the probable environmental impact?

Wave power installations have potential to affect both the physical, biological and human environment. Effects on coastal processes, marine mammals, seabirds, fishery and shipping and navigation have been highlighted. Coastal processes may be affected because of changes in wave and current regimes due to presence and operation of wave power device. For marine mammals there is a risk of entanglement, entrapment and collision from presence and operation of wave energy converters, mooring lines and maintenance vessels. Fishery could be negatively affected because wave farm areas become restricted areas for fishing. The negative effects from wave energy on the environment are expected to be dependent of the geographical size of the wave farms.

Some of the potential environmental effects should be unique for wave energy installations and some are expected to resemble effects from other industrial offshore activities such as wind farms and subsea transmission links. A specific negative effect of wave energy farms during construction, operation and decommission is generation of underwater noise that may disturb marine organisms. Electro Magnetic Fields (EMF) generated by subsea cables is not an environmental risk that is unique for wave energy farms. Effects of construction work of wave energy devices and transmission cables on marine organisms are activities that also are not unique for wave power installations. Environmental effects of EMF from subsea cables for wave energy farms and construction work for wave energy devices and subsea cables should be similar as for wind farms and subsea transmission links.

There are also possible positive environmental effects of wave power. The main driver for the wave energy development is to combat climate change by introducing low-emitting energy sources. Wave energy is expected to have significantly lower $CO_2$ emissions than the current energy mix in a global perspective. Wave energy farms may function as artificial reefs (AR) or Marine Protected Areas (MPA), which should enhance local abundance of fish and invertebrates. It is also possible that surface-oriented wave energy devices (i.e. buoys, supporting structures) may function as Fish Aggregation Devices (FAD) for pelagic fish.

### How to get knowledge?

The potential impact of wave energy is in many cases generic e.g. studies carried out in one site may be used to judge impact on the marine environment in other sites. A cost-effective strategy to increase knowledge about environmental effects from wave power is collaboration in Joint Industry Monitoring Programmes (JIMP). Another opportunity is compilation of knowledge about environmental effects on marine organisms from other industrial offshore projects such as offshore wind, oil and gas and subsea cables where some of the environmental impact is expected to resemble the possible impact from wave energy installations.

| Environmental/acceptance topics | Example of Key concerns, based on the Scottish Strategic Environmental Assessment[19] |
|---|---|
| Marine birds | Disturbance during installation<br>Noise during installation and operation<br>Risk of collision with devices during foraging<br>Risks due to contamination of water<br>Displacement<br>Risk of increased mink predation |
| Marine Mammals | Disturbance during installation<br>Noise during installation and operation<br>Risk of collision with devices during feeding and migration<br>Risks of accidental contamination of water<br>Barriers to movement due to avoidance reactions |
| Benthic ecology | Increased suspended sediment from seabed disturbance during device installation and cable trenching<br>Risk of smothering from seabed disturbance<br>Accidental contamination from device failures and collisions |

[19] http://www.seaenergyscotland.net/public_docs/ER_NTS_FINAL_MAR07.pdf

| | |
|---|---|
| | Changes in tidal flow and wave regime due to device presence and operation<br>Substratum loss, caused by attaching devices to the seabed |
| Fish and shellfish | Risk of smothering from seabed disturbance<br>Noise during installation<br>Risk of collision with devices<br>Accidental contamination from device failures and collisions<br>Habitat exclusion due to presence of devices<br>Substratum loss, caused by attaching devices to the seabed |
| Commercial fisheries | Direct disturbance of fishing grounds during installation of devices attached to the seabed and during cable trenching<br>Temporary and long-term displacement from traditional fishing grounds<br>See key concerns for fish and shellfish above |
| Shipping and navigation | Displaced/increased shipping density<br>Reductions in the safety of navigation<br>Risk of collision with installation vessels and equipment and operational devices |
| Water quality | Risk for accidental contamination, e.g. in case of collision |
| Geology and energy extraction | Changes in coastal processes due to energy extraction |
| Electric and magnetic fields | Interference with prey location and mate detection by marine species<br>Barriers to migration for EMF-sensitive species |

## 4.9 Wave energy and environmental consent processes

Issues relating to legislation, policies and acceptance are factors of great importance for the success of a wave energy development project. On the one hand, national energy policies and physical planning may promote the use of renewable energy, and therefore encourage the deployment. On the other hand protective environmental legislation, complicated and time consuming consent processes and other stakeholders' interest in the use and protection of sea zones may limit the possibilities for wave energy development.

The currently existing wave farms are mostly small and mainly intended for research and development. It must therefore be emphasised that the environmental legislation in most countries has not yet been applied or adapted to large scale commercial wave farms.

### Time and resources

Establishment of wave energy farms will require consent from the authorities. There are examples of early consent processes requiring more than 25 permits and contacts with ten public departments[20].

The time consumption of the consenting process varies greatly, both within and between countries, depending both on the type of process, on the sensitivity of the selected location and the stakeholders' opinions. In the UK, data collection and consultations are extensive parts of the consenting process. Consultations are held with a wide group of stakeholders and data collection requirements of up to 2 years must be expected. The actual application process thereafter is expected to last approximately 8-9 months[21].

In Sweden, only one wave farm has been consented so far and there were no appeals to that consent. It took 8 months from the consent application (including EIA) was handed in to the Environmental court until the consent was given. It is however difficult to know if that is a typical process.

### "One stop shop" consenting

Introduction of "one-stop-shop" consenting processes, where all parts of the application, EIA and consent process can be handled through one authority is one strategy to avoid or at least reduce the complexity and waste of time and resources.

Scotland started working with a one stop shop approach in April 2010 with the newly formed authority Marine Scotland, which has been given responsibility to coordinate consents for wave, tidal and offshore wind energy applications.

In Ireland, consenting of construction and operation of wave farms is still spread among a number of authorities. It is currently the developer's responsibility to seek opinion and consent from all of these authorities. However, introduction of a one stop shop system is planned as one of the main tasks of the Ocean Energy Development Unit[20].

Denmark follows a one-stop-shop procedure in their regulatory framework for EIA and consent for offshore wind and ocean energy[22]. In Sweden, a number of authorities have to give consent for the establishment and operation of a wave farm, e.g. the Environmental court for consent according to the environmental act and the "Legal, financial and administrative services agency" for "Right of disposition" of the area. An electricity network concession is also required for grid connection and building permits may be required by the local authorities if the establishment takes place within the 12nm limit[23].

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[20] Dalton et al, *Non-technical barriers to wave energy development, comparing progress in Ireland and Europe*, 2009

[21] http://www.marinemanagement.org.uk/works/energy/documents/application_flowchart.pdf and http://www.scotland.gov.uk/Resource/Doc/295194/0096754.pdf

[22] Simas et al, *Review and Discussion of common environmental legislation for ocean energy schemes*, 2009

[23] MKB för Vågkraftspark i Sotenäs, Seabased Industry AB, 2009-10-26

In Norway, all generating facilities with a component over 1 000 Volt need consent according to the Energy act[24]. These consents are handled by the Norwegian Water Resources and Energy Directorate. An environmental impact assessment is required for production of electrical energy with an installed power of above 25 MW[25].

### Strategic Environmental Assessment

Strategic Environmental Assessment (SEA) is used to examine environmental effects when developing plans and programs, often on a national level. The existence of ocean energy plans or programmes based on SEAs is to facilitate an ocean energy development with careful consideration of environmental aspects from the start.

In Scotland, an SEA has been performed to assess, at the strategic level, the effects on the environment of meeting or exceeding an estimate of 1 300MW of marine renewable energy capacity around Scotland by 2020[26].

The Marine institute on Ireland is currently in the middle of an ocean energy SEA process. An environmental report has been completed and there is an ongoing consultation process until mid-January 2011[27].

In Norway, a process of identifying sea areas suitable for future development of offshore wind power has been initiated. The Norwegian government plans to continue the spatial planning process by initiating a strategic environmental assessment (SEA), probably during 2011. When this is completed, the Government will decide on opening sea areas for applications[28].

### National differences in consent processes

The differences in consent processes between different countries probably have historical background. In Ireland there have, up to now only been minor industrial offshore activities in need of consents and therefore coordination between authorities has not been needed. The massive plans in Scotland for development of offshore wind, wave and tidal farms have shown the need for a more coordinated consent process between authorities. In Sweden the development of hydro power in the last century has been a template for the current procedure of environmental consent processes, and in Denmark, the large wind energy establishment has driven the development.

It is not only the consent processes that differ between countries. The focus of the content and the requirements of baseline studies for the EIA process and monitoring program also differ. In Sweden one wave energy farm has been consented so far. The main topic of discussion in the Swedish consent process, both in stakeholder consultations and in the court judgement was the effects on commercial fishery, especially concerning the catch loss of

[24] http://www.nve.no/no/Konsesjoner/Andre-energianlegg/
[25] http://www.nve.no/Global/Konsesjonsveiledere/Vindkraft/Veileder5.pdf
[26] http://www.seaenergyscotland.net/public_docs/ER_NTS_FINAL_MAR07.pdf
[27] http://www.seai.ie/Renewables/Ocean_Energy/Offshore_Renewable_SEA/Environmental_Report/
[28] http://www.regjeringen.no/nb/dep/oed/aktuelt/taler_artikler/politisk_ledelse/taler-og-artikler-av-statssekretar-per-r/2010/offshore-renewable-energy-production--po.html?id=620419

Norwegian lobster in the closed off wave energy farm area. The baseline studies and investigations for the consented Swedish energy farm did not include any offshore surveys or investigations of birds, marine mammals or fish. When studying ongoing consent process in Scotland and Ireland, it is striking that the baseline study requirements are extensive, and with a focus on marine mammals and birds.

| | Scotland | England and Wales | Ireland | Denmark | Sweden | Norway |
|---|---|---|---|---|---|---|
| One-stop-shop procedure | Yes, through Marine Scotland | Yes, through the Marine Management Organisation | Planned | Yes | No | No information |
| Time consumption of application process* | ≈ 9 months | >8 months | Not known | Based on individual experience, >1 year | Based on single experience, 8 months | No information |
| Ocean Energy SEA performed | Yes | Planned | On-going | No information | No | Planned |
| Focus areas in stakeholder consultations | Birds and marine mammals, hydro dynamics, navigation | No information | Birds and marine mammals, hydro dynamics, navigation | No information | Fish and fishery | No information |

*After submission of the application

# 5 National programs and activities

## 5.1 Overview

The motivation for national programs for wave power (or to be more precise ocean energy thus including tidal power) is a combination of need for domestic renewable power and hope of a new industrial sector creating jobs as well as exports. Thus many countries are striving to become the “Denmark of wave power”. With this background the difference between the ambitious programs in the UK and Ireland compared to the low interest in Norway despite having similar wave energy resources.

Apart from the countries discussed in the following sections wave power programs exists in Spain and Portugal in Europe. The Spanish program is at the moment mainly an R&D program aimed at developing domestic concepts. Portugal has no domestic developers and is therefore trying to become a proving ground for wave energy power plants with measures such as dedicated areas for wave power, feed in tariff and investment in supporting facilities. France that has good wave and tidal power resources is for some reason only focused on the latter.

Outside of Europe it can be noted that USA somewhat belatedly has started to put a wave power program together. Canada has an ocean energy program although mainly focused on tidal power. There also wave power activities in Australia and New Zeeland.

## 5.2 Sweden

Sweden had a wave power R&D program in the late seventies that primarily led to two concepts being developed, the IPS-buoy and the Hose pump. The IPS-buoy has been resurrected as the WaveEl concept otherwise very little remains of the earlier activities.

At the moment Sweden does not have any national wave power program or targets for wave power. Wave power projects can apply for funding in competition with other renewable projects, the SEK 139 Million funding for the “Sotenäs wave power project” (see Chapter 6) is e.g. from a fund for large demonstration projects for renewable energy. The Swedish Energy Agency supports wave power research at Uppsala University and at the universities experimental site at Lysekil on the Swedish West Coast.

There is also a recent initiative to create an Ocean Energy Centre at Chalmers University of Technology in Gothenburg. The Centre will start its activities in 2011 and is organised under the department of Shipping and Maritime Technology. Funding is from regional authorities, utilities, technology developers and Chalmers.

## 5.3 Norway

Norway has no special policies or programs dedicated to ocean energy, but ocean energy is included in more general renewable energy policies and programs. The overall funding for renewable energy R&D made available through the Norwegian Research Council, Innovation Norway and ENOVA has increased significantly the last years. This has also resulted in increased funding for ocean energy projects as well, from research to prototypes and demonstration.

The research cluster in Trondheim, comprising of NTNU and SINTEF/MARINTEK, is active in ocean energy research. Some of the activities are; technology screening and verification, control systems, mooring, marine structures, safety, optimal design of devices and load modeling. MARINTEK's model tank is also used to test ocean energy devices.

Statkraft has an Ocean Energy Research program within wave and tidal energy in cooperation with NTNU, Marintek and Uppsala University in Sweden. The program funds a professorship, seven PhD students, a post doc. and four research projects. Thematically the program covers numerical classification of wave technologies, improved efficiency and optimised resource usage in wave energy arrays, modelling of wave energy, tidal devices in combined current and wave exposed areas, new design models for tidal devices and vertical tidal turbines. The program also has a substantial activity within environmental aspects of ocean energy.

## 5.4 Denmark

Denmark had a wave energy program 1997-2002 where DKr 40 Million was allocated towards development of concepts in a three- staged process. Some 40 ideas were initially screened of which 15 proceeded to tank tests and one (Wave Dragon) to pilot test in the open sea.

A Danish wave energy R&D strategy[29] was published in 2005 that acknowledged the potential contribution of wave power to the Danish electricity supply and gives recommendations on how R&D for wave power should proceed. However, it did not suggest that any funds or other targeted support measures should be allocated to wave power, instead leaving it to the market to carry the development further.

Out of the approximately DKr 80-100 million annually available for energy R&D it is estimated that about 5 % goes to wave energy. There is one major collaborative R&D project, "Structural design of wave energy devices" started in 2010 and involving a number of Danish and international partners. The project is led by Aalborg University with a budget of Dkr 20 Million from the Danish Agency for Science, Technology and Innovation and will run for five years. The Wave Energy Research Group at Alborg University is the centre for wave power R&D in Denmark.

[29] Energistyrelsen, Elkraftsystem and Eltra, 2005 "Bølјekraftstrategi – Strategi for forskning og udveckling" available at http://www.ens.dk/

## 5.5 UK/Scotland

Public funding and other support for marine energy in the UK exceed by certainty the rest of world put together. Marine energy funding is generally for both wave power and tidal power, currently split about 50/50. The Scottish government is self-governing in matters relating to renewable energy. Much of the marine energy resources are in Scotland, which in combination with employment issues, has led to some special Scottish initiatives regarding marine energy over and beyond the rest of the UK.

The UK has the best ocean energy resources in Europe while at the same time a huge demand for new renewable energy to fulfil its EU commitments. In the 2009 UK Renewable Energy Strategy £60 Million was allocated to the ocean energy sector for immediate use; see below. There is no firm target for marine energy but a figure of 1000-2000 MW deployed 2020 has been indicated.

There is a multitude of funding agencies and programs in the UK so only the major initiatives are described here:

- Three test facilities; NAREC (bench and tank testing), EMEC at the Orkney Islands (near shore testing of single wave and tidal devices) and the Wave Hub outside Cornwall (offshore for wave power arrays) has in total received ~£50-60 Million (of which £30 Million from the 2009 funds).
- Marine renewable proving fund (MRPF). £22 million (from 2009 funds) in capital grants for prototype testing allocated to 6 projects (2 wave and 4 tidal).
- Marine renewable deployment fund (MRDF). A 2005 fund of £42 Million so far unused but extended to 2011. The fund is to provide a combination of capital grants and feed-in tariffs. (Note: The combination of prerequisites to apply and support levels has made this fund unattractive and unless terms are changed likely to remain unused).
- A total of £12 Million for "collaborative RD&D to reduce costs and improve performance" administered by the Technology Strategy Board.

The Scottish government has, with its Wates and Waters funds, contributed another £20 Million towards prototype deployment. In addition the Scottish Government has announced the most spectacular support; the Saltire Price:

**The Saltire price**

The Saltire price is a competition open for wave and tidal projects. The winner is the project that generates most electricity during a rolling two-year period starting the latest 2015. The winner will get £10 Million but must generate more the lower qualifying limit of 100 GWh.

(Comment: It would need a 20 MW array to accomplish this and it is unlikely that such a project will commence within this time frame. An educated guess is that the date will be adjusted.)

## 5.6 Ireland

In the 2007 White Paper, "Delivering a sustainable energy future for Ireland", the Irish Government states that it intends to make Ireland a world leader for research, development and deployment of Ocean Energy technologies. Furthermore it sets the ambition to have 500 MW installed capacity by 2020.

The actual strategy had already been set out in the National Strategy for Ocean Energy (SEI/Marine institute, 2006) where development was set out in four stages:

Phase 1 (2005-2007) Offshore test facility for ¼ scale prototypes, enhanced research capability and funding.

Phase 2 (2008-2010) Support for pre-commercial single devices, development of a grid-connected offshore test site.

Phase 3 (2011-2015) Pre-commercial small array testing and evaluation.

Phase 4 (2016-) Strategies for commercial deployment of wave power technologies

Phase 1 was fulfilled with e.g. the Galway Bay test facility. For the 2008-2010 period the government allocated €27 Million and created a supervising authority, the Ocean Energy Development Unit (OEDU). The funds primarily allocated to support of device developers, development of the offshore test facility and enhancement at the primary R&D facility, Hydraulics and Maritime Research Centre, Cork.

At a glance the time schedule needs to be revised as test site (AMETS) is still at a planning stage and no pre-commercial devices have been deployed or even are planned.

## 5.7 Tariffs for wave power

As a new technology, wave power will be dependent on subsidies until the industry has reached a competitive level. At the earliest stage there will be a need for upfront capital through primarily capital grants to decrease risk. However, the most important support when moving from the earliest prototypes is feed-in tariffs or similar. The table below shows what electricity generated by wave power plants would receive today in the Nordic countries and the British Isles (shown in € for comparison)

| **Country** | **Electricity price** | **Comments** |
|---|---|---|
| UK (except Scotland) | ≥15 €cent/kWh | 2 ROC's* + whole sale price (~6€cent/kWh) |
| Scotland | ≥28 €cent/kWh | 5 ROC's* + whole sale price (~6€cent/kWh) |
| Ireland | 22 €cent/kWh | Feed-in tariff |
| Norway | 5 €cent/kWh | Whole sale price (~5 €cent/kWh) |
| Sweden | 8,5 €cent/kWh | Whole sale price (~5 €cent/kWh) + green certificate (~3,5 €cent/kWh) |
| Denmark | 8 €cent/kWh | Feed-in tariff |

*Renewable obligation certificate, floor price approximately 4,5 €cent/kWh although currently higher due to a deficit of certificates (2010 ~7 €cent/kWh)

The remuneration in Nordic countries is essentially without any reference to wave power (there is a mention in the Danish tariff system but the level shows that it is a token gesture).

The Scottish Government has used their prerogative to self determine renewable energy support. The level is based on the expected cost of wave power today and will be reviewed at certain intervals. However, existing plants will keep the level at their introduction, so called grandfathering. (Note: Tidal power receives 3 ROC's)

The UK support level is appreciated to be too low but is expected, at least initially, to be combined with capital support as well.

# 6 Wave power projects in the near future

There have so far been relatively few wave power demonstration projects at anything near full scale and grid connected. However, there are number of projects announced to be deployed the near future. In common all have been allocated large grants from public sources. As full-scale demonstrations needs substantial investments with uncertain returns a high degree of public funding at this stage is more or less a necessity. However, public funding sources are not inexhaustible and there is a possibility that the gap between developers will increase depending on who has received funding or not. Furthermore, it will be very important for the selected developers to be sufficiently successful otherwise there is a risk of waning interest from authorities.

The following table lists wave power devices at full or large scale and grid connected to be deployed 2010-2011.

| Device (Developer) | Rated power | Location year | Public funding | Public funding source | Operator |
|---|---|---|---|---|---|
| CETO (Carnegie Corp.) | 200 kW (to be expanded to 5 MW in Phase 2) | Australia 2010 (Phase 2 2011) | A$ 12 Million for Phase 2 | Western Australian government | Carnegie Corp. |
| Wavegen | 16x18,5 kW | Mutriku (breakwater), Spain 2010 | N/A (total project cost €6,5 Million + €2 Million for storm damages) | EU FP6, Regional authorities | Ente Vasco de la Energia |
| Powerbuoy (OPT) | 150 kW | EMEC, Scotland 2010 | £0,64 Million | Scottish government, WATES fund* | OPT |
| Pelamis P2 | 750 kW | EMEC, Scotland 2010 | £4,8 Million | British government, MRPF | E.oN |
| Seabased | 420x25 kW (Phase 1 42x25kW) | Sotenäs, Sweden, Phase1 2010-11 | SEK 139 Million | Swedish Energy Authority | Fortum |
| Oyster2 (Aquamarine) | 2,5 MW | EMEC, Scotland 2011 | £5,1 Million | British government, MRPF** | Aquamarine |

| | | | | | |
|---|---|---|---|---|---|
| Waveroller (AW energy) | 300 kW | Peniche, Portugal 2011 | €3 Million | EU FP7 | Consortium led by AW Energy |
| Powerbuoy (OPT) | 150 kW | Reedport OR, USA 2011 | $2 Million | US government, DOE | Local utilities |
| Pelamis P2 | 750 kW | EMEC, Scotland 2011 | £2 Million | Scottish government, WATES fund | Scottish Power |
| Wavebob | 250 kW | Tbd, Portugal 2011 | €5 Million | EU, FP7 | Consortium led by Wavebob |

* Wave and Tidal Energy Support Scheme (WATES), £10 Million allocated to wave and tidal projects. Now to be followed by the £12 Million WATERS fund.
** Marine Renewables Proving Fund (MRPF), a one-off £22 Million allocation shared by four tidal projects and the two wave projects above out of some 30 applicants.

At the close of 2010 the first Pelamis P2 is in place at EMEC while the Mutriuku project is on way although it has suffered storm damage. The CETO and Powerbuoy will be delayed until 2011 but are in the process of being built. The Seabased project has received an environmental permit and is understood to be waiting for a green light from the EU commission regarding the grant from the Swedish government. Thus no deployment has taken place yet.

Looking beyond 2011 plans tend to be more tentative, however one project merits mentioning. RWE npower plans to build a 4MW wave power station on the Scottish Island of Siadar to be in operation 2012 with a £6 Million grant from the Scottish government's WATERS fund. It will consist of 40 100 kW Wavegen turbines incorporated in a newly built breakwater.

# 7 Discussion and outlook

**The obvious question is if and when will wave power will become commercial as well as able to supply electricity in substantial quantities?**

To become commercial in a technical sense the technology needs to be proven, i.e. survivability, availability, O&M strategies, production etc must be verified. One measure of this is when wave power plant developers can give warranties on these properties (as well as having the financial resources to back them up which may be a bigger issue).

To become commercial in an economic sense the wave power plants must be able to produce electricity at a price acceptable to the market. An obvious benchmark in this case is offshore wind power whose cost of electricity is around SEK 1,5 per kWh[30] (including a 12% rate of return). If wave power cannot compete with offshore wind power it is difficult in the long run to see any future for wave power.

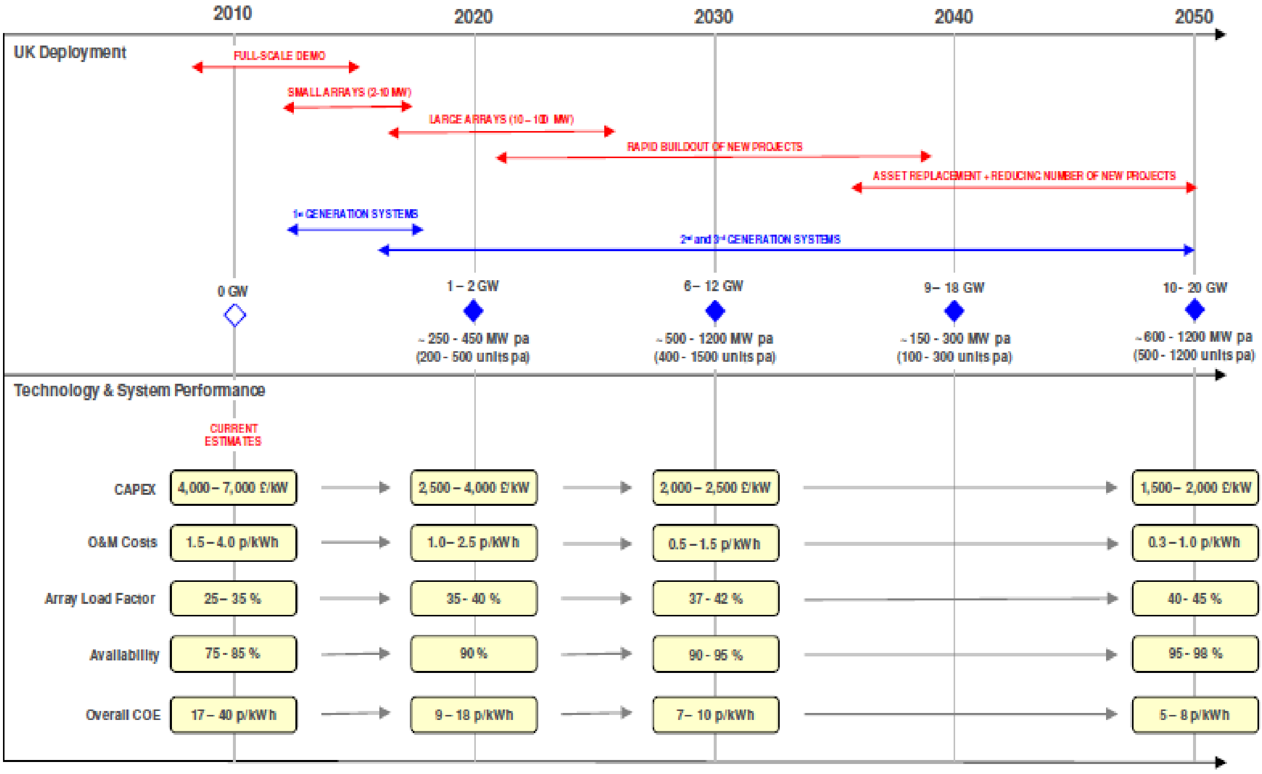
There have been various attempts to predict development and learning curves for wave power. An example of a best-case scenario can be seen on the following page where economic competitiveness (with offshore wind power) could be reached somewhere between 2020 and 2030.

However it must be stressed that this and similar scenarios are highly speculative or even idealized. It would involve very large investments even before 2020 with technology that is not yet proven or even tested to any degree in 2010.

Furthermore, the heterogeneous nature of the proposed wave power concepts raises the question to which extent a learning curve is valid for the sector as a whole. Looking at two of the most developed concepts, Pelamis and Oyster, it is difficult to see synergies between their respective developments. It may be that there will be individual learning curves for at least categories of wave energy concepts.

[30] Ernst & Young "Cost of and financial support of offshore wind" 2009, report for Department of Energy and Climate Change and available at www.decc.gov.uk

**Appendix 1 – UK Marine Energy Deployment Strategy and Technology Development Targets**




© The Energy Technologies Institute 2010

[31] UK Energy Research Centre and Energy Technologies Institute "Marine Energy Technology Roadmap" 2010 [www.eti.co.uk](http://www.eti.co.uk)

# Appendix 1

### How can the wave resource at a given location be determined?

The ultimate activity in order to establish the wave resource at a given location is to deploy a wave-measuring buoy on the site and let it measure the waves. This is however a time consuming action since several years of data is required to get a data set of significant sample size. If the information is more urgent, and there is no time to wait for a measuring campaign to finish, the wave resource can be estimated by way of numerical modelling.

### Different ways to measure waves

There are more ways than deploying buoys to measure waves. Acoustic instruments could be used or even satellites. The different methods are shortly described below.

Wave buoys

Wave buoys are the standard equipment for wave measurements, and they generally include an accelerometer and a GPS. The accuracy is fairly good; a typical buoy records wave heights and period with a few percents error margin and wave direction with a few degrees accuracy. The power supply is in most buoys today based on renewable energy, solar cells and back up batteries is the usual combination. The buoy registers samples of the wave elevation and directions and processes that information into directional spectrum, which is the ultimate wave data in order to describe a sea state. All other wave parameters can be derived from the directional spectrum. Directional spectra are composed of a wide range of frequencies and directions so these data sets become quite large. This spectral data is usually stored locally in the buoy and only statistical parameters, e.g. Hs, Hmax, Tp etc., are transmitted from the buoy. The detailed data can however be recovered, but that implies visiting the buoy on site.

Acoustic instruments

Acoustical instruments are deployed on the ocean floor and are mainly used for current measurements. These devices can however also generate detailed wave data (directional spectrum) e.g. by letting a vertical sound ray measure the distance to the water surface. The accuracy of these wave measurements is in the same range as those performed with wave buoys.

Satellites

Satellites are also used for measuring the waves. However, these measurements are not as detailed as those from buoys or acoustic instruments. What is actually measured is the scatter of a radar pulse that is sent down from the satellite. The form of the reflected pulse is used to determine the smoothness of the sea surface, which is proportional to the significant wave height. Since satellites are devices in orbits are only snapshots of the wave condition registered and this information is mostly used to improve e.g. forecasted wave data.

**Wave modelling**

Modelling waves is a quite tricky task since most of the processes that occur in the atmosphere and in the oceans are in some way interconnected. The flowchart below (Figure A.1) is an attempt to given an overview of the methodology behind wave modelling.

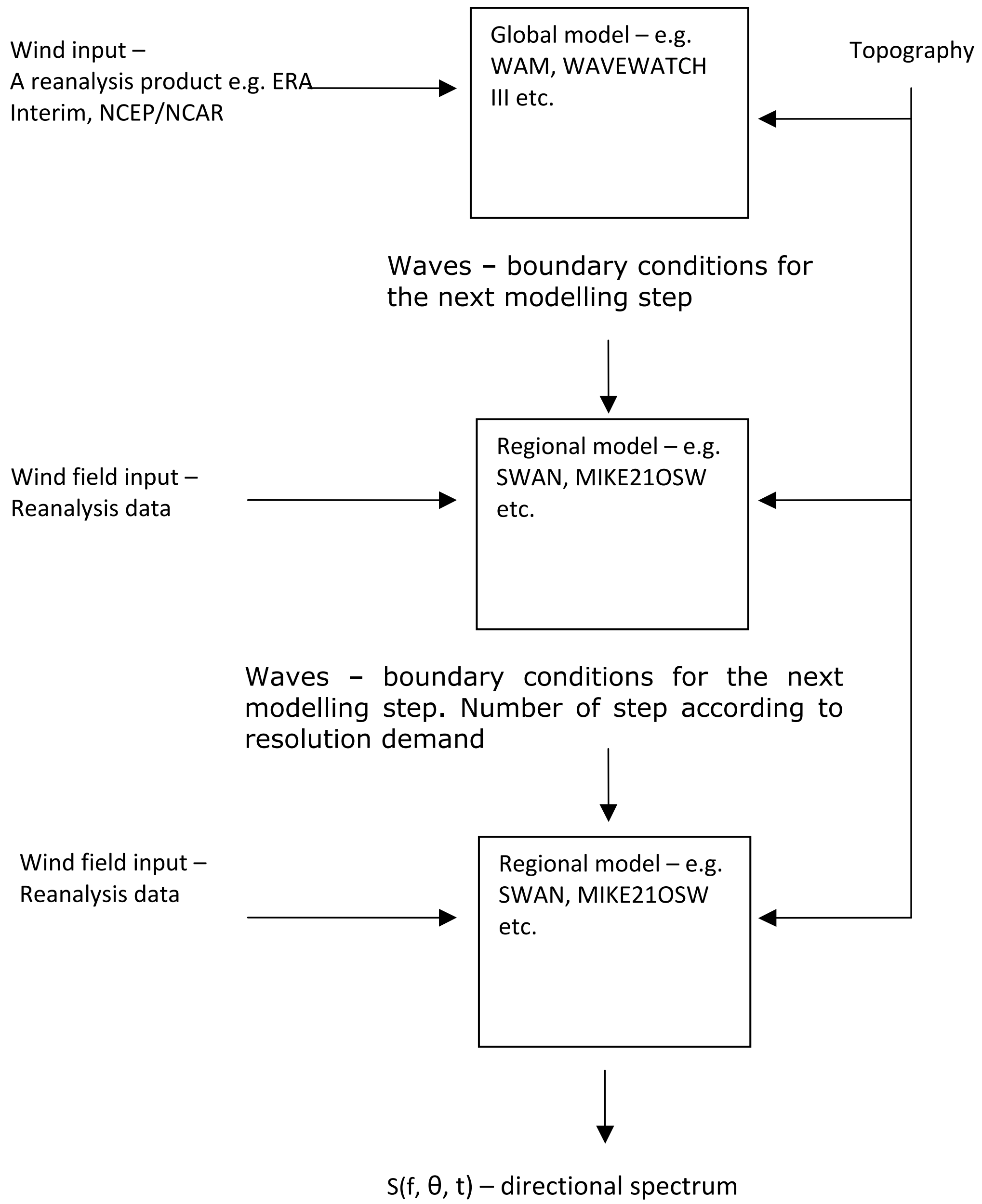


**Figure A.1: General description of the methodology behind wave modelling.**

### Global model

Even though only a site in e.g. the nearshore is of interest, a global wave model is needed in order to generate the boundary wave conditions needed as inputs to the regional wave model. This global model is fed with e.g. wind data, and since most of the grid points are deep-water locations the quality of the sea floor and depths data is not as crucial here as when the regional model is set up.

### Regional model

Once the boundary wave conditions are established, they are plugged into the regional model together with wind data for the region of interest. Since the running the model can be rather computation heavy, this step can be iterate in order to increases the spatial resolution. However, instead of using boundary conditions from a global model, the output wave data from the previous run with the regional model are used as inputs. With the approach briefly describe above time series of directional spectrum for the location of interest can modelled.

In wave energy, the power table has become the most common power transfer function, similar to the power curve used in wind energy. However, since the wave energy flux is determined from two parameters instead of one, as the case is in wind energy, a surface function or a table is needed to describe the energy conversion instead of a curve. The modelled spectra hold all information needed to create a scatter diagram (see fabricated example in Figure A.2), i.e. a bivariate occurrence table of Hs vs. Te for e.g. one year. Once the scatter diagram is generated it is simply a task of multiplying it with the power table, cell by cell, to get the annual energy production.

Example occurence table Hs/Tp

| Hs/Tp | 5,00 | 5,50 | 6,00 | 6,50 | 7,00 | 7,50 | 8,00 | 8,50 | 9,00 | 9,50 | 10,00 | 10,50 | 11,00 | 11,50 | 12,00 | 12,50 | 13,00 | 13,50 | 14,00 | 14,50 | 15,00 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0,50** | | | | | 0,03 | | | 0,06 | | 0,08 | 0,09 | | | 0,28 | 0,53 | | | | | | | 1,07 |
| **1,00** | 0,12 | 0,10 | 0,03 | 0,04 | 0,54 | 0,21 | 0,17 | 0,26 | 0,58 | 0,21 | 0,82 | 0,54 | 0,53 | 0,12 | 0,14 | | 0,12 | | | | | 4,53 |
| **1,50** | 0,15 | 0,36 | 0,21 | 0,24 | 0,57 | 0,96 | 1,24 | 1,34 | 1,21 | 1,03 | 0,82 | 0,56 | 0,32 | 0,14 | 0,12 | | | 0,03 | 0,04 | | | 9,34 |
| **2,00** | | 0,12 | 0,14 | 0,35 | 0,28 | 0,99 | 1,18 | 1,34 | 1,53 | 1,45 | 1,54 | 1,02 | 0,35 | 0,24 | 0,28 | 0,05 | 0,09 | | | | | 10,95 |
| **2,50** | | | | 0,12 | 0,51 | 0,78 | 1,14 | 1,34 | 1,85 | 2,01 | 1,75 | 0,86 | 0,73 | 0,64 | 0,31 | | | 0,05 | | | | 12,09 |
| **3,00** | | | | 0,40 | 0,12 | 0,78 | 1,06 | 1,08 | 1,58 | 2,21 | 1,86 | 1,34 | 1,31 | 0,65 | 0,32 | 0,18 | 0,05 | 0,06 | 0,05 | | | 13,05 |
| **3,50** | | | | | | 0,14 | 0,64 | 1,01 | 1,34 | 1,85 | 2,45 | 1,56 | 0,78 | 0,85 | 0,34 | | | 0,09 | | | | 11,05 |
| **4,00** | | | | | | | 0,05 | 0,32 | 0,87 | 1,06 | 2,06 | 1,65 | 1,24 | 0,60 | 0,61 | 0,09 | 0,05 | 0,03 | 0,07 | | | 8,70 |
| **4,50** | | | | | | | 0,05 | 0,23 | 0,69 | 1,06 | 2,02 | 1,94 | 1,06 | 1,21 | 0,41 | 0,23 | | | | | | 8,90 |
| **5,00** | | | | | | | | | 0,23 | 0,55 | 1,19 | 1,64 | 1,42 | 0,55 | 0,38 | 0,32 | 0,14 | 0,09 | 0,09 | | | 6,60 |
| **5,50** | | | | | | | | | | 0,23 | 0,55 | 0,86 | 1,31 | 0,75 | 0,28 | 0,18 | 0,05 | | | | | 4,21 |
| **6,00** | | | | | | | | | | | 0,05 | 0,55 | 0,83 | 0,69 | 0,46 | 0,23 | 0,14 | | | | | 2,95 |
| **6,50** | | | | | | | | | | | | 0,28 | 0,46 | 0,64 | 0,56 | 0,28 | 0,05 | 0,07 | | | | 2,34 |
| **7,00** | | | | | | | | | | | | 0,14 | 0,32 | 0,37 | 0,53 | 0,37 | 0,14 | 0,04 | | | | 1,91 |
| **7,50** | | | | | | | | | | | | | 0,09 | 0,23 | 0,46 | 0,23 | 0,18 | | | | | 1,19 |
| **8,00** | | | | | | | | | | | | | 0,05 | 0,14 | 0,18 | 0,14 | 0,09 | | | | | 0,60 |
| **8,50** | | | | | | | | | | | | | | | 0,09 | | 0,09 | | | | | 0,18 |
| **9,00** | | | | | | | | | | | | | | | | 0,05 | | 0,09 | | | | 0,14 |
| **9,50** | | | | | | | | | | | | | | | 0,03 | | | | | | | 0,03 |
| **10,00** | | | | | | | | | | | | | | | | | 0,04 | | | | | 0,04 |
| **10,50** | | | | | | | | | | | | | | | | | | 0,04 | 0,04 | | | 0,08 |
| **11,00** | | | | | | | | | | | | | | | | | | | 0,03 | | | 0,03 |
| **11,50** | | | | | | | | | | | | | | | | | | | | | | 0,00 |
| **12,00** | | | | | | | | | | | | | | | | | | | | | | 0,00 |
| **12,50** | | | | | | | | | | | | | | | | | | | | 0,02 | | 0,02 |
| **13,00** | | | | | | | | | | | | | | | | | | | | | | 0,00 |
| **13,50** | | | | | | | | | | | | | | | | | | | | | | 0,00 |
| **14,00** | | | | | | | | | | | | | | | | | | | | | | 0,00 |
| **14,50** | | | | | | | | | | | | | | | | | | | | | | 0,00 |
| | 0,27 | 0,58 | 0,38 | 1,15 | 2,05 | 3,86 | 5,53 | 6,98 | 9,88 | 11,74 | 15,20 | 12,94 | 10,80 | 8,10 | 6,03 | 2,35 | 1,23 | 0,59 | 0,32 | 0,02 | 0,00 | **100,00** |

**Figure A.2: Fabricated occurrence table**

# Appendix 2

List of devices mentioned in the report

| Name of Device | Country | www | Described in Newsletter 1 |
|---|---|---|---|
| Aegir Dynamo | UK | http://www.oceannavitas.com/ | |
| AWS | UK | http://www.awsocean.com/ | |
| CETO | Australia | http://www.carnegiecorp.com.au/ | X |
| Langlee | Norway | http://www.langlee.no/ | X |
| Oceanlinx | Australia | http://www.oceanlinx.com/ | X |
| OE Buoy | Ireland | http://www.oceanenergy.ie/ | |
| Pelamis | UK | http://www.pelamiswave.com/ | X |
| PowerBuoy | US/UK | http://www.oceanpowertechnologies.com/ | X |
| Seabased | Sweden | http://www.seabased.com/ | X |
| Straumekraft | Norway | http://www.straumekraft.no/ | |
| Wavebob | Ireland | http://www.wavebob.com/ | X |
| Wave Dragon | Denmark | http://www.wavedragon.net/ | X |
| WaveEl | Sweden | http://www.waves4power.com/ | X (as Bowec) |
| Wavegen | UK | http://www.wavegen.co.uk/ | X |
| WavePlane | Denmark | http://www.waveplane.com/ | X |
| WaveRoller | Finland | http://www.aw-energy.com/ | X |
| Wave Star | Denmark | http://www.wavestarenergy.com/ | X |

# Appendix 3

Newsletter 1 describing some of the current wave energy concepts

# The development of wave power

A NEWSLETTER FROM ELFORSK, ELECTRICITY AND HEAT PRODUCTION, NUMBER 1, SEPTEMBER 2010

Elforsk has started a project to follow up the development of wave power. The project will during 2010 result in two newsletters shortly describing the status of the area and a somewhat more comprehensive report describing the status of the technology and the various techniques under development.

The project is financed by E.on Värmekraft Sverige AB, Skellefteå Kraft AB, Statkraft Development AS, Svenska Kraftnät samt Vattenfall AB. Vattenfall Research and Development carries out the follow up and has also written this newsletter.

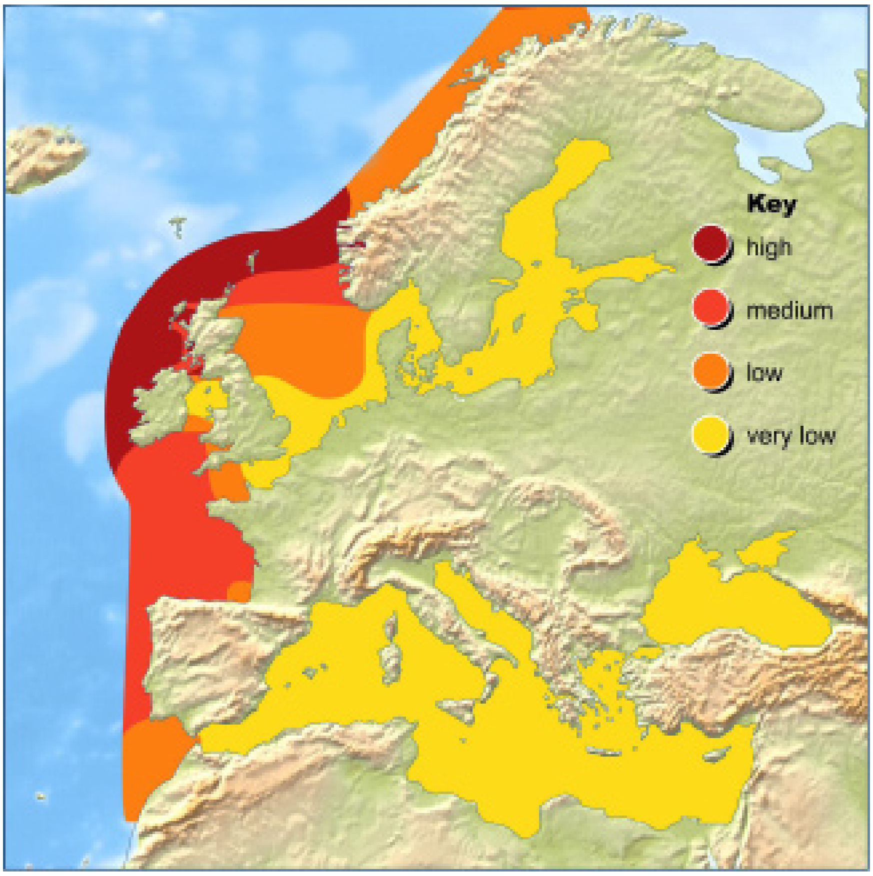
This first newsletter focuses on Nordic concepts but also give some background on the general state of development including leading (non-Nordic) concepts as well as recent important news.

A second newsletter will cover different national plans, economical support systems, permit processes and environmental issues.

*The editorial staff wishes a pleasant reading.*

Per Holmberg
Vattenfall Research and Development

## BACKGROUND




Source www.aquaret.com

Wave energy is widely seen as one of the next renewable energy sources to be commercially exploited. The European resource has been estimated to approximately 320 GW or 3000 TWh (http://www.wave-energy.net/Library/WaveEnergyBrochure.pdf). Even if only a fraction of this is technically and economically exploitable it could still substantially contribute to Europe's electricity generatioN. As can be seen from the figure the major potential is found in an arc from Portugal to southern Norway.

### General

The first real effort to develop wave power was made during the seventies after the oil crisis but petered out in the early eighties leaving mainly some fundamental theoretical work as legacy. The current development started around 1995 (in the UK) basically from scratch as only one or two wave power concepts can be traced back to the earlier era.

Wave power development is concentrated to Europe and to a lesser extent Australia. During the last couple of years some initiatives have been made in the U.S., however still at an early stage.

### National programs

Public funding is crucial for wave power development and is now gearing up from rather low levels. Funding is needed for all steps before a commercial level is reached including

- Basic R&D in universities and institutes
- Initial concept development
- Full scale prototypes
- Ocean test facilities
- Feed-in tariffs or similar of sufficient magnitude

UK is undoubtly the centre of gravity for wave energy development in Europe (as well as the world). The UK government funding exceeds the cumulative funding of the rest of Europe, including EU funds. Other European countries with wave power programs are Ireland, Portugal and Spain. Denmark had a fairly ambitious program between 2000-2003 that although terminated, left both know-how and some concepts still being developed. In the other Nordic countries there has been no recent wave power programs but individual projects have received funding.

### Development status

The front edge of development is now moving towards the first demonstrations of single full- scale wave power plants of which there will be some 5-10 within the next years. If sufficiently successful the first demonstration farms of 5-10 units each can be expected around 2015 and large- scale commercial farms around 2020.

## Device development - an overview

### Developers

There are probably some 50 to 100 concepts being actively developed, i.e. there is company formed around the concept and active development is taking place. With one or two exceptions the companies sole activity is wave power development and are small (from a few employees to the 60 or so of Pelamis and Ocean Power Technologies).

Also with one or two exceptions the developers are struggling financially. The main hurdle is going from basic development and scale tests to full-scale prototype. This stage typically involves costs in the SEK 50-100 million bracket with limited possibilities of positive financial return. Belatedly authorities have recognized this and funding for prototype development and deployment is increasingly available although by necessity for a small number of devices.

### Device rating and production

One reoccurring question is what kind of rated power we can expect for full scale, commercial wave power plants. The answer is complex as it is dependent and limited by a number of factors such as wave climate vs. optimum performance, water depth, ease of handling and economy of scale. As a rule of the thumb the optimum size for Atlantic open ocean waves will be around 1-2 MW for most free floating devices while moving to a less energetic wave climate, e.g. the North Sea will result in smaller devices. This also means that wave power converters will primarily be developed for a specific wave climate and not directly deployable in a different wave climate.

With regard to the production of the wave power converter the cost of produced electricity is in the end the determining factor rather than "efficiency" or similar. However, a capacity factor of 30-40 % (average in relation to rated power) has been generally quoted as both necessary and feasible to make wave power cost effective. Most wave power devices incorporate active control or tuning where somewhat simplified the device adapts to height and wavelength of the incoming waves in order to maximize wave energy absorption. This active control can mean 50 % or more absorption and is thus crucial for economy. However this part is probably the least developed part of wave energy converters and underlines the need for full-scale prototypes.

### Cost

The cost of electricity from wave power today cannot be stated with any degree of accuracy as life length, O&M costs etc are not verified. Furthermore few full-scale devices have been tested at all and then only for shorter periods. However the long-term goal stated by most developers is to be competitive with offshore wind power.

There are very few publicly available figures of what a wave power device costs today. ReNews names a rumored cost of £5 million for the Pelamis 750 kW P2 machine recently ordered from by Scottish Power. However, this figure by certainty includes costs of the development work.

### Survivability

Survivability is a critical and fundamental issue. The strategies for survivability varies from concept to concept but in general devices will go into a protective mode terminating generation and passively follow the waves. If possible critical components will be sheltered, e.g. the legs of Wavestar will be lifted out of the water or the swinging section of Aquamarine Power's concept Oyster ballasted down to the seafloor. However, in most cases structures have to be built to withstand the extreme forces.

Survivability has not been proved yet to a great extent in practice. Typically small-scale models have been tested in tanks successfully but mainly for single extreme waves, "the hundred-year wave". But how they withstand the pounding at full scale in real sea and successive storms is probably the most outstanding issue for wave power to be tested. However, there is obviously a reluctance to risk expensive prototypes in the worst conditions so it will be gradual process where tests are carried out at sites with challenging but still not the worst wave climate e.g. EMEC before moving out to the really rough sites.

### Operation & maintenance

O&M strategies vary from concept to concept. Pelamis for example plans to do all maintenance in harbor and has developed a mechanical and electric connection that can be released (or reconnected) in short time even in fairly high seas. Other developers plan to do maintenance at sea and/or to have as little need for maintenance as possible. Lack of real demonstrations makes it difficult to estimate costs today. However, to get acceptable O&M costs there will be necessary to have large farms in order to distribute costs for workboats and personnel.

## Test sites

Crucial for the development of wave power devices is localities to test them with existing framework permits, infrastructure (primarily grid connection), support resources etc.

There are a small number of test sites that has been used by individual developers although typically without grid connection. Examples of test sites in the Nordic countries are Islandsberg outside Lysekil (Seabased), Nissum Bredum and Hanstholm in Denmark and Risör in Norway. The only grid-connected site is Vattenfall's test site outside Runde in Norway (there is cable to shore at Islandsberg but it not connected to the grid).

The flagship test facility for wave power is the European Marine Energy Centre (EMEC) on Orkney, which has been in operation since 2004. It has four single device berths with grid connection and includes various support resources on shore e.g. data monitoring. EMEC is primarily designed for short term testing of prototypes.

The first real offshore test facility, Wavehub, is currently under construction off the north coast of Cornwall in the UK.

It will have four berths with grid connection of up to 4-5 MW each allowing for testing of small arrays. The publicly funded Wavehub is expected to be operational in 2010 or more probably 2011 at a total cost of £42 million.

A similar test facility is planned in Ireland called WETS (Wave Energy Test Site). The location outside Belmullet on the Irish west coast is probably among the most energetic wave power sites in Europe and will be a challenging test for wave power devices. WETS is planned to be in operation 2013-14. There also plans for more or less similar facilities in Portugal, Spain and France but yet unknown how firm they are.

In the Nordic countries there are suggestions in Denmark to make Hanstholm a test facility but with a lower ambition than e.g. the U.K. sites. Kvitsöy in Norway has also been suggested as a test site but lack of interest from the Norwegian authorities seems to have stopped this development. That there is interest for a test site in the Nordic countries can be concluded from several inquiries to use the Vattenfall site outside Runde.

## Wave power projects in the near future

There have so far been relatively few wave power demonstration projects at anything near full scale and grid connected. However, there are number of projects announced to be deployed the near future. With one exception they have in common that they have been allocated large grants from public sources. As full-scale demonstrations needs substantial investments with uncertain returns a high degree of public funding at this stage is more or less a necessity. However, public funding sources are not inexhaustible and there is a possibility that the gap between developers will increase depending on who has received funding or not. Furthermore, it will be very important for the selected developers to be sufficiently successful otherwise there is a risk of waning interest from authorities.

The following table lists wave power devices at full or large scale and grid connected to be deployed 2010-2011.

Looking beyond 2011 plans tend to be more tentative, however one project merits mentioning. RWE npower plans to build a 4MW wave power station on the Scottish Island of Siadar to be in operation 2012. It will consist of 40 100 kW Wavegen turbines incorporated in a newly built breakwater.

| Device | Rated power | Location year | Public funding | Public funding source | Operator |
|---|---|---|---|---|---|
| Oceanlinx | | Australia 2010 | - | - | Oceanlinx |
| CETO (Carnegie Corp.) | 200 kW (to be expanded to 5 MW in Phase 2) | Australia2010 (Phase 2 2011) | A$ 12 Million for Phase 2 | Western Australian government | Carnegie Corp. |
| Wavegen | 16x18,5 kW | Mutriku (breakwater), Spain 2010 | N/A (total project cost €6,5 Million + €2 Million for storm damages) | EU FP6, Regional authorities | Ente Vasco de la Energia |
| Powerbouy (OPT) | 150 kW | EMEC, Scotland 2010 | £0,64 Million | Scottish government, WATES fund* | OPT |
| Pelamis P2 | 750 kW | EMEC, Scotland 2010 | £4,8 Million | British government,MRPF | E.oN |
| Seabased | 420x25 kW (Phase 1 42x25kW) | Sotenäs, Sweden, Phase1 2010-11 | SEK 139 Million | Swedish Energy Agency | Seabased, Fortum |
| Oyster2 (Aquamarine) | 2,5 MW | EMEC, Scotland 2011 | £5,1 Million | British government, MRPF** | Aquamarine |
| Waveroller (AW energy) | 300 kW | Peniche, Portugal 2011 | €3 Million | EU FP7 | Consortium led by AW Energy |
| Powerbouy (OPT) | 150 kW | Reedport OR, USA 2011 | $2 Million | US government, DOE | Local utilities |
| Pelamis P2 | 750 kW | EMEC, Scotland 2011 | £2 Million | Scottish government, WATES fund | Scottish Power |
| Wavebob | 250 kW | Tbd, Portugal 2011 | €5 Million | EU, FP7 | Consortium led by Wavebob |

* Wave and Tidal Energy Support Scheme (WATES), £10 Million allocated to wave and tidal projects. Now to be followed by the £12 Million WATERS fund.
** Marine Renewables Proving Fund (MRPF), a one-off £22 Million allocation shared by four tidal projects and the two wave projects above out of some 30 applicants.

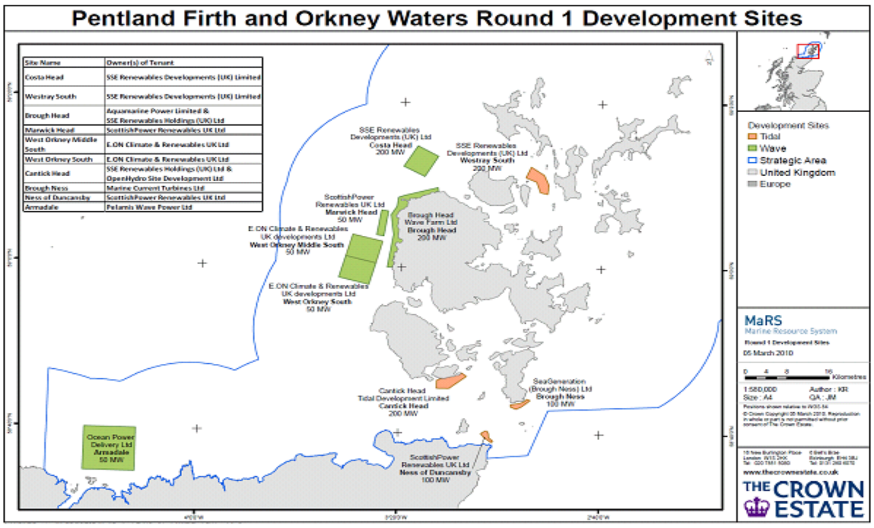
## First commercial wave power leases granted

A landmark was reached when in March 2010 the world's first commercial wave and tidal leases was granted in Scotland.

As new technologies there is an amount of uncertainness on behalf of authorities how to treat applications for marine energy. Thus only demonstration leases have been granted limited in time and size, for example a maximum of seven years and 10 MW in the UK. However the Pentland Firth and Orkney Waters Round 1 that was started in November 2008 has now resulted in the first long term leases of seafloor for wave and tidal energy in the world. New rounds are expected to follow for other Scottish waters.

A total of 1200 MW leases were granted out of which 600 MW was for wave power. Wave power leases were granted to the utilities Southern & Scottish Electric (200 + 200 MW), E.On (50 + 50 MW) and Scottish Power (50 MW) west of Orkney, see map. The wave power developer Pelamis got 50 MW site near the mainland.

The precise details around the leases are not known, e.g. how long time the leases can be kept without development, but the companies will now be able do enter the statutory consenting process with guaranteed access to the seafloor. It will however take time to develop these sites, as there currently does not exist any transmission capacity between Orkney and the mainland.



## Concepts

In the following a selection of concepts are presented. The thirteen Nordic concepts presented are the ones that to our knowledge are actively developed and in or near sea trials. A number of international concepts are also presented chosen by the criteria that they have full-scale (or near) grid connected sea trials on the way and in that respect can be seen as leading technologies.

There are also some well-known concepts that for various reasons does not fulfil the criteria above but motivates a brief comment.

Archimedes Wave Swing (AWS) is probably one of the most publicly known concepts due the demonstration of a 2 MW grid connected unit in Portugal 2004. AWS was originally developed in the Netherlands and it was the Dutch company that performed the Portugal demonstration. Immediately after the limitedly successful demonstration the IP and name was sold to interested parties in Scotland and a new company AWS Ocean Energy was created. This company has attracted substantial private funding but has kept its development very secret. It is known that the current version AWSIII has moved far from the original concept but essentially nothing is publicly known about the actual design. AWS Ocean Energy first stated that they would have a demonstrator ready in 2008 but this has moved every year and the current target is 2011.

Orecon had developed an offshore OWC design through tank and scale ocean tests phases and were on the stage to build a full-scale prototype. However, they failed to raise funds for this purpose and chose to close down the company in early 2010. It is not known what will happen with the IP.

Aquabouy had it is background in the Swedish IPS-buoy and hose pump concepts. After an U.S. sojourn it ended up in an Irish company, Finavera. However, in 2008 Finavera announced that they would not continue with the development of Aquabouy. The IPS-buoy part is now continued in the Swedish BOWEC project.

| Company | Name | Type | Stage | Capacity (full-scale) | Country |
|---|---|---|---|---|---|
| Seabased | Seabased WEC | Point absorber | Full-scale Demonstration | ~ 30-50 kW | |
| Ocean Harvesting Technologies | Ocean Harvester | Point absorber | 1:20 scale tank testing | 100+ kW | |
| Bohegg Engineering | Bowec | Point absorber | Unknown | Unknown | |
| AW Energy | WaveRoller | Oscillating wave surge converter | Demonstration | Unknown, 300 kW prototype planned | |
| Langlee Wave Power | Langlee E2 | Oscillating wave surge converter | 1:20 scale tank testing | 400 kW | |
| Fred Olsen | Bolt | Point absorber | Real sea test | 45 kW | |
| Wave Energy | Sea-wave Slot-cone Generator - SSG | Overtopping | 1:4 scale turbine tests | Unknown | |
| Pelagic Power | W2-POWER | Hybrid wave & wind power plant | 1:3 scale tests of wave PTO | Unknown | |
| DEXAWAVE | DEXAWAVE converter | Attenuator | 1:10 scale in real sea | 250 kW | |
| Wave Dragon | Wave Dragon | Overtopping | 1:4.5 scale in real sea | ~ 10 MW | |
| WavePlane | WavePlane | Overtopping | Interrupted full-scale test | Unknown | |
| Wave Star Energy | Wave Star | Multi point absorber | Section of WEC tested in real sea | Up to 6 MW | |
| Floating Power Plant | Floating Power Plant | Hybrid wave & wind power plant | Wave part tested in scale in real sea | Multi MW | |
| Pelamis Wave Power | P2 | Attenuator | Commercial sales | 750 kW | |
| Aquamarine power | Oyster | Oscillating wave surge converter | Full-scale demonstrator | 2,5 MW for three devices and one PTO | |
| Wavebob | Wavebob | Point absorber | 1:4 scale in real sea | 1-1,5 MW | |
| Ocean Power Technologies Ltd | Power Buoy | Point absorber | A 40 kW version has been tested in real sea | 150 kW under construction, 500 kW being designed | |
| Wavegen | Wavegen nearshore OWC | Oscillating water column | 500 kW land based machine on Islay | Individual turbines up to 100 kW | |
| Oceanlinx | Oceanlinx Mk3 | Oscillating water column | Pre-commercial Mk3 deployed in Feb 2010 | >2.5 MW | |
| Carnegie Wave Energy | CETO | Other | 200 kW demonstration under construction | Unknown, several units connect to one PTO | |

| Technology type | Working principle | Example WECs |
|---|---|---|
| Attenuator | Attenuators are often hinged multi body devices where different parts of the device experiences different phases of a wave. The reaction force is a buoyancy- vs. buoyancy force derived from the phase difference. | Pelamis, Dexa |
| Point Absorber | Point absorbers can look very different, but common is that they consists of two separate systems. One system usually riders the wave whilst the other supplies a reference to react against. The reference is in some cases a fixed point i.e. the seabed and in other cases inertia. The reaction force is either derived from buoyancy vs. fixed reference or buoyancy vs. inertia. | Seabased Wavebob |
| Oscillating Surge Wave Converter | An OSWC is typically a hinged flap type device standing on the bottom rather close to shore. In the nearshore the otherwise circular water particle orbit becomes elliptical and this horizontal wave motion component (surge) is utilised to move a flap back and forth. | WaveRoller, Oyster |
| Oscillating Water Column | An OWC uses an air chamber in which a water column oscillates up and down as the device interacts with the waves. This causes air to be pushed and pulled in and out of the air chamber and through a bidirectional air turbine. | Oceanlinx, Wavegen |
| Overtopping Devise | An overtopping device consists of three main parts – a collector, a reservoir, and a PTO. The collector is wider at the wave inlet and narrower at the reservoir – causing the waves to grow vertically. The waves overtop into the reservoir at the end of the collector, and the water is let back out to the sea again through low-head water turbines. | Wave Dragon, WavePlane |
| Submerged Pressure Differential | These devices are generally standing on the seabed. As the sea level varies the pressure on the device varies. One part of the machine oscillates as the pressure varies, whilst another part of the machine is still and the relative motion between the two machine parts is utilised for electricity generation by means of e.g. direct drive (linear generator) or hydraulics. | AWS |
| Other | Various other technologies have been proposed. None of these approaches to wave energy conversion has however advanced far in the development process to date. | CETO, Anaconda |
| **All** | Go to the EMEC website (http://www.emec.org.uk/wave_energy_devices.asp) to see animations of the different approaches to wave energy conversion | |

# Sweden

## Seabased

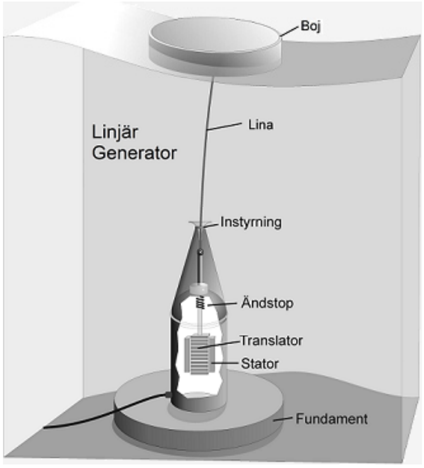
Seabased is a Swedish WEC developer based in Uppsala. The company is an offspring from research at Uppsala University.

Seabased is a two-body system; the reaction force between the gravity foundation and the buoyancy of the buoy drives the conversion to electric power, which is accomplished with a linear generator.

Several Seabased machines connect to an underwater substation, where electricity is converted, transformed, and carried to shore.

The technology has been tested since 2006 off the Swedish west coast as a part of a research programme at Uppsala University.

The company Seabased received a conditioned grant from the Swedish energy agency to demonstrate a 10 MW wave farm (420 converter units) off the Swedish west coast together with a commercial partner. The preferred partner is the Finnish.




## Ocean Harvester

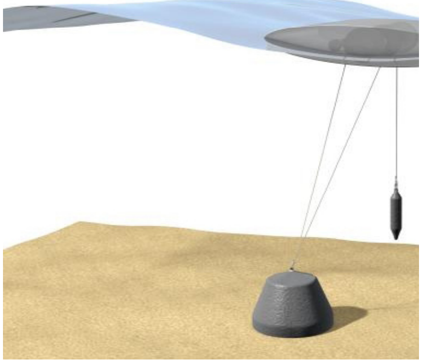
The Ocean Harvester is a WEC concept under development by company Ocean Harvesting Technologies.

The Ocean Harvester consists of a wave-riding buoy, a counter weight-anchor drum system, and a gravity foundation. The working principle of the machine is to both generate and store energy as the buoy is lifted by an incident wave. The stored energy in the counter weight is then used to generate electricity after a wave crest has passed.

The counter weight is also intended to be utilised for power smoothing purposes e.g. in the case when a wave group with large wave occur.

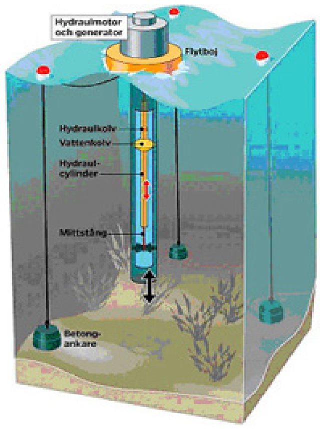
Parts of the Ocean Harvester system have been tested in 1:20 scale tank test, and the PTO has been tested in a dry test rig.

The development is supported by E.On Scandinavia.



## Bohegg Engineering

The design of the Bowec device originates from the IPS buoy and the work conducted on that device during the former Swedish wave energy programme in the 1970s.
Bowec is a two-body point absorber system with a hydraulic PTO.
Attached to the buoy is an acceleration tube, which is open at both ends allowing water to vertically move within the tube.
The relative motion between the water column and the buoy-tube systems creates a force on a water piston inside the tube.
The water piston is in turn connected to a hydraulic piston, which motion is either mechanically or hydraulically converted to a rotation for a generator.
Bohegg is currently building a scale demonstrator in Gothenburg.




# Finland

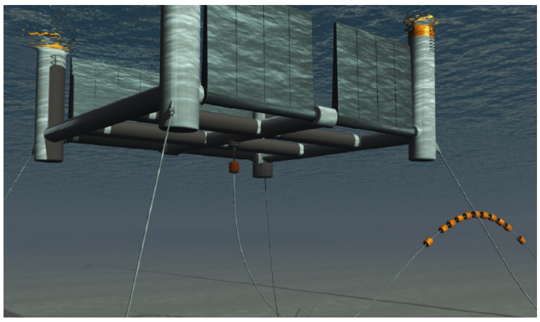
## AW Energy

The WaveRoller, under development by AW Energy, is a Oscillating Surge Wave Converter (OSWC) that is intended to be deployed nearshore.
The device is standing on the seabed, and thus not visible from shore.
The hinged flaps pumps hydraulic fluid, which in turn drives a hydraulic motor and a generator.
Each unit (flap) has its own motor-generator set, and the power is carried to shore as electricity.
The device has passed the proof of concept phase with demonstrations in both Portugal and at EMEC in Scotland.
The next step for AW Energy is to set up a full-scale demonstration plant and connect a wave farm to the grid.

# Norway

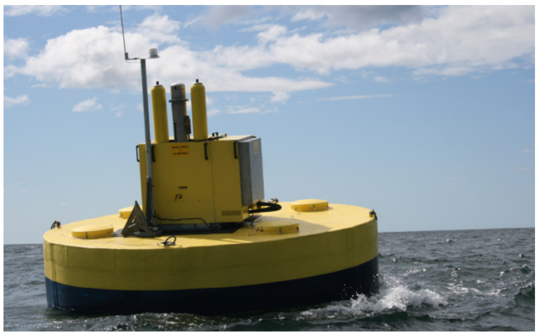
## Langlee Wave Power

The Langlee Wave Power concept, Langlee E2, is a floating OSWC envisaged to be operating in the nearshore.
The device is as most other OSWCs a hinged panel type device where the distance between the panels will be designed to be half the typical wavelength of the site. The panels at each end will then swing in opposite direction to minimise tension in the moorings.
The flaps pump hydraulic fluid that drives the PTOs, which are located in the pillars.
The concept has been tested in the Aalborg University, and the Trondheim University wave basins.



## Fred Olsen

The Fred Olsen has previously developed a multi point absorber rig called FO3. This project is however now terminated and the efforts are now focused on a single point absorber device called the Bolt.
The previous concept was left after refined calculations showed that the envisaged installed capacity of the FO3 was around 3 times too large.
Concerning this new Bolt device there is not much published and e.g. the PTO solution is therefore unknown to the author.
The 5,15 m in diameter and 1,45 m high buoy weights around 6 tonnes and will have a rated capacity of 45 kW.

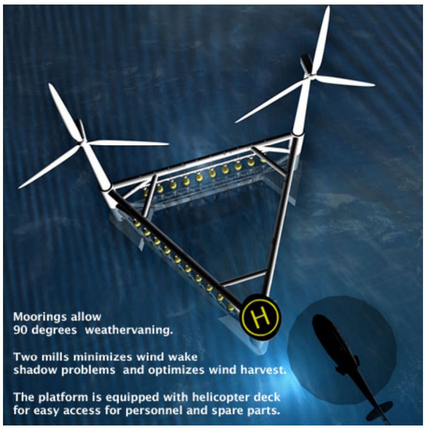


## Wave Energy

The Sea-wave Slot-cone Generator (SSG) is an overtopping concept proposed in three different WECs, one onshore, one breakwater, and one offshore device.
Depicted on the right hand side is the breakwater concept.
The company WAVEenergy is based outside Stavanger in Norway and was founded in 2004.
Since then the PTO technology has been tested in the company's in-house wave tank and at Aalborg University in Denmark.
Wave Energy is currently investigating potential sites suitable for full-scale demonstration of the breakwater concept.

## Pelagic Power

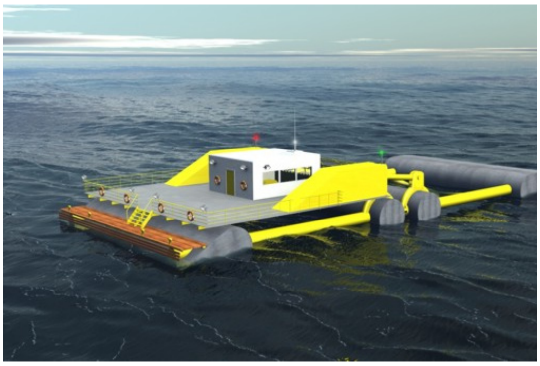
The Pelagic power W2-Power concept is a hybrid wave and wind energy converter.
The wave energy part of the machine is based on wave pumps that pump seawater to a water turbine.
The wave pump solution has been tested in 1:3 scale in real sea.
The full concept, with platform and wind turbines has not been subjected to scale tests to date.




# Denmark

## DEXA WAVE

The DEXA WEC is an attenuator device where different parts of the machine experiences different phases of the waves.
The relative motion between the two pontoons drives the hydraulic PTO.
A full-scale DEXA converter is envisaged to have a rated capacity of 250 kW.
The device has been subjected to sea trials in 1:10 scale in Limfjorden in northern Jutland.
The next step for DEXA is to test a 1:5 scale machine in real sea. This camping is planned for the fall of 2010.

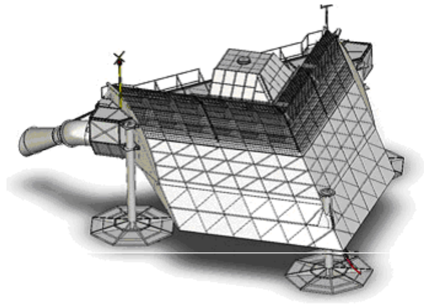


## Wave Dragon

The Danish Wave Dragon WEC is a large floating platform with two long arms in the front.
Together, the two arms serve as a collector for the water reservoir onboard the platform. The platform is trimmed to the actual wave height by an air cushion to maximise wave capture.
Once water has been collected in the onboard basin it is let out to the ocean through low head Kaplan turbines.
The Wave Dragon has been tested in 1:4,5 scale at the Danish wave energy test site in the Nissum Bredning. A full scale Wave Dragon is envisaged to have a rated capacity of around 10 MW.
In 2007 Wave Dragon had the permit as well as the funding (public and private) for a full-scale demonstrator in Wales. However, the unfortunate death of the owner of private partner company stopped project and Wave Dragon has since been looking for funding for the project, as far as known yet without success.

## Wave Plane

The Danish 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.
The device was built in full scale and deployed off the Danish west coast in February 2009.
Soon after the installation the mooring lines broke and the device was flushed up on the beach.
The status of the WavePlane concept at the moment is unclear to the author.



## Wave Star Energy

The Danish Wavestar is a multi point absorber with a hydraulic PTO above the water surface.
The platform is standing on the seabed and provides the reference for the buoys to react against.
In cases of harsh conditions the platform will be raised out of the water to protect the buoys and the machinery.
In September 2009 a section of a 1:2 scale machine including two buoys was deployed in Hanstholm, Denmark.
The only thing different between the machine in Hanstholm and a 1:2 scale machine is the length of the section and the number of buoys.

## Floating Power Plant

The Floating Power Plant is a hybrid wind and wave energy converter.
The wave energy part of the system consists of floats that pumps pressurised water to a water turbine.
The wind energy part of the system consists of standard wind turbines.
The Poseidon 37, the company's scale prototype has been tested in two separate trials. This prototype is 37 m wide, 25 m long, and 6 m high to deck. A full-scale floating power plant will be significantly larger.
In the second sea trial was three 11 kW wind turbines included.
The Danish research institute at Risø has confirmed the platform stability for mounting of wind turbines.

# Non-Nordic

## Pelamis Wave Power

Scottish Pelamis Wave Power develops an attenuator type WEC.
The current machine under development is the P2 WEC, which is considerably larger than the previous P1.
The P2 is 180 m long and approx 4 m wide, and the device will have a rated capacity of 750 kW.
The PTO is hydraulic, and individual PTOs are located at each joint of the machine.
The previous machine, the P1, was installed at EMEC and in Portugal was three P1 machines connected to the Portuguese national grid.
Pelamis is currently assembling a P2 machine for E.On that will be deployed at EMEC in the summer of 2010.
Scottish Power has also ordered a P2 for an EMEC installation, which will be constructed after the final assembly of the E.On machine.


## Aquamarine Power

Aquamarine Power, based in Edinburgh, develops an OSWC called Oyster.
The hinged flaps pumps seawater to an onshore PTO station, which much resembles a hydropower plant.
The WEC system is designed for nearshore installation where the horizontal component of the water particle motion is larger due to the shallower water depth.
The Oyster 1 is currently installed and tested at EMEC.
Aquamarine Power is currently developing the next generation Oyster, the Oyster 2.
The company plans to deploy three Oyster 2 units, connected to one PTO at EMEC 2011. This project is envisaged to have a rated capacity of 2.5 MW.

## Wavebob

The Irish Wavebob is a point absorber type WEC.
The working principle is to utilise the relative motion between to separate bodies.
One body, the Torus, rides the waves whilst the other, the Float-Neck-Tank (FNT), has a different wave activated response.
The inertia of the FNT is to a large extent derived by captured water, and the device will be tuned according to wave climate by means of venting water in and out of the FNT.
The PTO is based on hydraulics, and the envisaged nameplate capacity is 1,5 MW.
A 1:4 scale Wavebob has been subjected to two sea trials in Galway bay.
A part EU funded project aims to see a grid-connected scale Wavebob installed off the Portuguese coast during the course of year 2011.

## Ocean Power Technologies


Ocean Power Technologies (OPT) develops a point absorber called the Power Buoy rated 150 kW, OPT envisaged however higher capacity Power Buoys in the future.
The Power Buoy consists of two bodies, the buoy seen to the right that follows the waves, and a submerged body including a reaction plate.
The reaction plate, sometimes referred to as the heave plate, has the task to keep the submerged body as vertically still as possible, and thus creating a reference for the moving buoy.
The relative motion between the two parts of the machine is used in a hydraulic PTO to generate electricity.
OPT has also developed an Underwater Substation Pod (USP) that can aggregate electrical output from ten Power Buoys into a single transmission cable.
OPT plans on deploying one 150 kW Power Buoy at EMEC, and another 150 kW Power Buoy (the first of ten) at Reedsport, Oregon, during 2010.

## Wavegen

Wavegen is a wholly owned subsidiary of Voith Hydro that develops shoreline and nearshore OWCs.
The first LIMPET (Land Installed Marine Power Energy Transformer) plant on Isle of Islay is designed for annual average wave climates of 15 – 25 kW/m and has a nameplate capacity of 500 kW.
Wavegen and npower Renewables received consent in January 2009 to install 4 MW of OWC technology in a breakwater in the Siadar bay on the Isle of Lewis. The plant is planned to start operation in 2011.
Further, Wavegen is finalising a breakwater OWC WEC in Mutriku, Spain. This power plant consists of 16 turbines of each 18,5 kW (296 kW in total).

## Oceanlinx

Oceanlinx is an Australian developer of OWC type WECs.
The technology uses an Oceanlinx in-house developed turbine called the Denniss-Auld turbine.
The company has had three generations of their technology tested out at sea.
The Mk1 was deployed in 2005 and decommissioned in 2009.
The Mk2 was instrumented test unit that was in operation 2008 and 2009.
Just recently, in March 2010, Oceanlinx deployed their Mk3PC machine. This is a grid connected 3rd scale pre-commercial device.
Oceanlinx anticipates that a full-scale Mk3 WEC will have an installed capacity above 2,5 MW.

## Carnegie Wave Energy

The CETO wave energy system is quite different compared to most other wave energy technologies around.
This system consists of submerged water pumps (driven by the interactions with the ocean waves) that pumps pressurised seawater to land.
On land is the pressurised seawater used for both electricity generation (with a conventional Pelton wheel) and production of desalinated water (through reverse osmosis).
The CETO technology is currently demonstrated off the Garden Island in Western Australia.
The company Carnegie Wave Energy will own and operate all future CETO project on the southern hemisphere, and on the northern hemisphere will CETO projects be joint ventures with EDF Energies Nouvelles, a subsidiary of the French utility EDF.

Pelamis wave energy converter outside the Orkney Islands

Deployment of Seabased wave energy converter outside Runde, Norway. The linear generator is seen on the barge.

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