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Chapter 8

Wave energy

By Les Duckers

8.1 Introduction

The possibility of extracting energy from ocean waves has intrigued people for centuries. However, although there are concepts over 200 years old, it was only in the latter half of the twentieth century that viable schemes began to emerge. In general, these modern wave energy conversion schemes have few environmental drawbacks, and the prospects that some of them may make a significant energy contribution are promising. In fact, in areas of the world where the wave climate is energetic and where conventional energy sources are expensive, such as remote islands, some of these schemes are already competitive. By 2020 it is expected that a number of commercial schemes will be in operation around the world, and as experience is gained costs are expected to fall.

The total wave energy resource is large, however estimates of its magnitude vary widely as the oceans have not been fully monitored over a long enough time period to establish a reasonable value. Moreover, even if a reasonable value could be determined there are difficult questions about how much of the resource is economically viable given the limitations of location and technology.

Nonetheless, it is clear that wave energy could make a major contribution to meeting world energy needs in a sustainable way. The World Energy Council has estimated the exploitable worldwide resource to be 2000 TWh per year if all potential improvements to existing devices are realized (WEC, 2010). Therefore for some countries – the UK is one example – wave energy offers a very large potential resource to be tapped. Thorpe estimates that between 15 and 20% of current UK electrical demand could be met from marine energy sources (Thorpe, 2003).

Technological developments could enable wave energy to fulfil this promise. A number of shore-mounted, near-shore and offshore prototypes are already planned or in operation. Refinements of these prototype designs could open up the possibility of harvesting vast quantities of energy from the oceans, particularly from floating offshore wave farms, consisting of tens or hundreds of devices.

The European Ocean Energy Association's ocean energy roadmap (EU-OEA, 2010) provides a set of steps which, once implemented, would facilitate exploitation of the vast European ocean energy resource and enable the realization of 3.6 GW of installed capacity by 2020, and close to 188 GW by 2050 (these figures encompassing both the wave devices of this chapter and the tidal technologies of Chapter 6).

History

Following the UK 'energy crisis' of 1973 and Stephen Salter's landmark paper (Salter, 1974) a large number of device concepts were invented, mathematically modelled and experimentally tested, with support from commercial sponsors and the former UK Department of Energy. Unfortunately, insufficient time and money was allocated to bring the various concepts and associated technologies to maturity, and in 1982, the Department of Energy scaled down the UK wave energy programme (Ross, 1995).

Some of the research teams involved were, however, able to sustain a minimal effort on wave energy projects. In 1989 a 75 kW prototype oscillating water column (OWC) wave energy converter was installed on Islay in Scotland. This had been fully funded by the Department of Energy following a recommendation that small-scale devices should be investigated as a source of energy for islands and remote communities where diesel normally provided the main energy source (ETSU, 1985).

Meanwhile, during this period of reduced funding in the UK, a number of other countries, notably Norway and Japan, increased their research and development wave energy programmes. With hydroelectric schemes supplying virtually all of its electricity, Norway had little immediate domestic need for wave energy, but it was keen to develop an export market for wave energy technology. In contrast, Japan did require more energy sources, but its wave climate is very modest.

Japan has conducted a substantial wave energy research programme, with many teams working on a variety of projects (see Section 8.5 for details of the Whale, BBDB and Pendulor). The late wave energy pioneer Yoshio Masuda, who began work in Japan in the 1940s, is generally considered to be the inventor of the oscillating water column (see below) and is often described as the 'father' of wave energy. He was the inspiration behind the Kaimei, the first large floating wave power station. Further details can be found in Miyazaki (1991); Miyazaki and Hotta (1991); Kondo (1993) and ISOPE (2002).

In the 1990s there was a revival of awareness of the potential of wave energy amongst politicians and others in a number of countries. In particular, a European Union initiative was launched (Caratti et al., 1993), which provided funding for a small number of projects and led to the formation of a European Wave Energy Thematic Network. Between 1992 and 2002, Thorpe carried out several surveys for the UK Department of Trade and Industry (DTI) and, by looking at the main types of device, he estimated the electricity generation costs to be around 5p per kWh (in 2001 prices), based on an annual practical wave resource of 30 TWh (Thorpe, 1992; 1998; 2001).

Over the years 2001–2011 there has been substantial UK investment in wave energy technology, both from commercial investors and from the government. Two marine energy centres have been established, in Scotland and Cornwall, and these centres offer facilities for developers to test their pilot schemes. There has been considerable growth in interest in wave energy, especially in Scotland and Ireland, where the most significant wave energy resources in the British Isles exist.

International interest in wave energy has also grown in the last 10 years with developments in India, China, the United States, Japan, Korea, South Africa, Australia, and the EU amongst others. An extensive list of wave devices and developments can be found in Chapter 14 by Thorpe in the 2010 World Energy Council survey (WEC, 2010).

8.2 Introductory case studies

The case studies presented in this section provide some insight into the nature of waves and of schemes designed to harness wave energy.

The TAPCHAN device is particularly valuable in that it incorporates an element of storage, and the oscillating water column (OWC) concept is important because it has been deployed in a number of countries and represents the most common form of wave energy converter deployed to date, probably because of its simplicity and robustness.

Shoreline prototypes are generally of the oscillating water column type. They are often regarded as easier to construct and maintain than offshore devices, but, in practice, each shore-mounted device may have to be purpose-built to exactly fit the specified location, whereas offshore devices can potentially be built in production facilities in large numbers. This should eventually lead to high-volume, high-quality, low-cost fabrication and assembled structures could be towed out in calm conditions for deployment in wave farms. By using an area of ocean a few kilometres or more offshore as a wave farm, it should be possible to deploy a large array of wave energy converters and hence capture large quantities of energy, which could then be transmitted back to shore via subsea electrical cables. Offshore devices can harvest greater amounts of energy, as the waves in deep water have a greater power density than those in the shallower water near to land.

TAPCHAN

In 1985 a 350 kW prototype TAPCHAN wave energy converter, built by the company Norwave, commenced operation on a small Norwegian island some 40 km north-west of Bergen.

The name 'TAPCHAN' comes from the 'TAPered CHANnel' design of the scheme (Figure 8.1). The first, and so far only, example had a channel with a 40 metre wide horn-shaped collector. Waves entering the collector fed into the wide end of the tapered, upward sloping channel, where they then propagated towards the narrow end with increasing wave height. The channel walls on the prototype were 10 m high (from 7 m below sea level to 3 m above) and 170 m long. Because the waves were forced into an ever-narrowing channel, their height became amplified until the crests spilled over the walls into the reservoir at a level of 3 m above the mean sea level. The kinetic energy in the waves was thus converted into potential energy, and this was subsequently converted into electricity by allowing the water in the reservoir to return to the sea via a low-head Kaplan turbine system (see Chapter 5 for details of the Kaplan turbine). This powered a 350 kW generator that delivered electricity into the Norwegian grid.

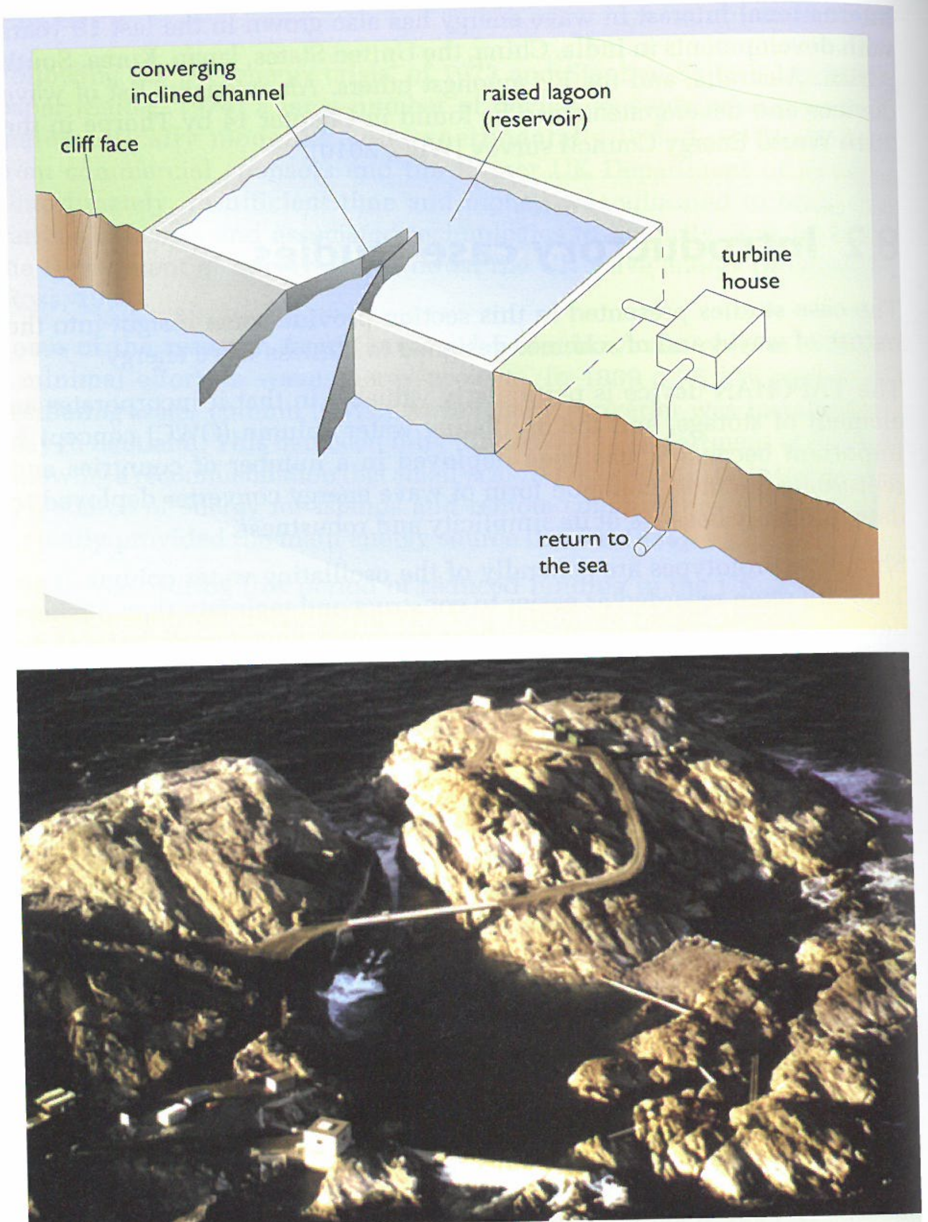


Figure 8.1 (a) The tapered channel (TAPCHAN) wave energy conversion device. (b) Aerial photograph of the Norwegian TAPCHAN: water is entering the reservoir in the centre of the image, where the channel device can just be seen between the cliff walls

The TAPCHAN concept is simple. With very few moving parts, its maintenance costs should be low and its reliability high. The storage reservoir also helps to smooth the electrical output. We shall see in Section 8.3 that ocean waves have a random nature and so most wave energy converters produce a fluctuating power output. In contrast, a TAPCHAN device 'collects' waves in the reservoir, and so the output from the Kaplan turbine is dependent on the relatively steady difference in water levels between the reservoir and the sea. A TAPCHAN device therefore has an integral storage capacity which is generally not found in other wave energy converters.

In the 1990s Norwave considered methods for reducing the cost of construction of future TAPCHANs. Among those methods is a scheme for wave prediction, to allow the Kaplan turbine to run at a greater output for some short time before the arrival of a number of large waves. This reduces the level of water in the reservoir and so makes room for those large waves. This technique may permit the designers to build schemes with smaller reservoirs and hence reduce the construction costs. A second cost-reduction method that has been proposed is to fabricate a shorter channel, and this was tried out on the existing prototype at Bergen by reducing the length of the existing channel. Unfortunately, there were some technical difficulties with the dynamiting of the concrete channel, and the ensuing commercial problems have meant that this prototype is no longer in operation (Petroncini and Yemm, 2000).

Perhaps more than other wave energy systems, the TAPCHAN approach can only be used in very particular places: to be effective it requires a good wave climate (i.e. high average wave energy, with persistent waves); deep water close to shore; a small tidal range (less than 1.0 m), otherwise the low-head hydro system cannot function properly for 24 hours a day (this therefore excludes most of the UK south of the Shetland Isles); and a convenient and cheap means of constructing the reservoir, which usually requires a natural feature of the coastline.

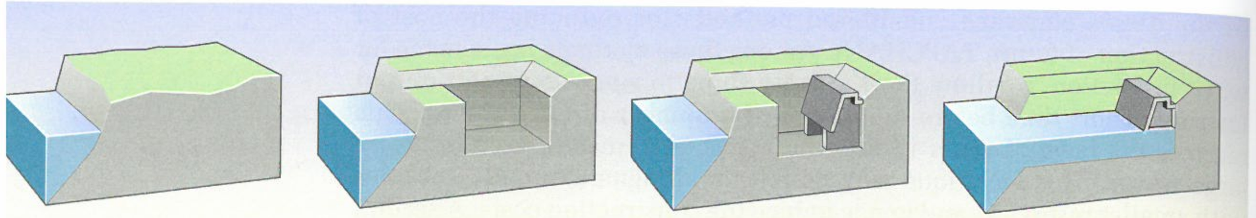
The Islay shoreline oscillating water columns

In the mid-1980s Queen's University, Belfast, (QUB) worked on the development of a shoreline oscillating water column (OWC) device. After surveying several Scottish islands, the island of Islay was chosen for their first OWC scheme, which was installed in a natural gully in1989. It supplied the local grid with electricity on an intermittent basis from a 75 kW generator from 1991 until it was decommissioned in 1999.

The approach was to develop a device which could be built cheaply on islands using locally available technology and plant. The main part of the OWC consisted of a closed wedge-shaped chamber, made from modular pre-fabricated concrete components, which was placed above the natural gulley. This chamber sloped down to below the sea surface and wave motion drove the water column thus trapped within the lower part of the chamber up and down like a huge piston. A cylindrical tube connected to the atmosphere allowed air to be thus expelled and drawn into the chamber. On its way to and from the atmosphere the air drove a Wells turbine (see Box 8.3), which was directly coupled to an electrical generator.

With experience gained from this natural gully project the team from QUB then collaborated with Wavegen of Inverness to develop what they referred to as a 'designer gully' OWC to overcome some of the limitations of the first Islay project. The principal modifications applied to the second Islay OWC, called LIMPET (Land Installed Marine Powered Energy Transformer), were in the construction method and the shape of the oscillating column.

The designer gully was excavated behind a natural rock wall, which was only removed at the end of the installation (Figure 8.2). As regards the water column, the chamber in the first Islay OWC had a horizontal floor at right angles to the back wall, causing turbulence and consequent loss of energy



gure 8.2 Construction sequence used by Queen's University and Wavegen for the 'designer gully' LIMPET OWC

within the chamber itself so, in order to improve the flow of water into and out of the oscillating chamber, the main part of the chamber of the designer gully OWC was built at a slope so as to efficiently change the water motion from horizontal to vertical and vice versa (Figure 8.3).

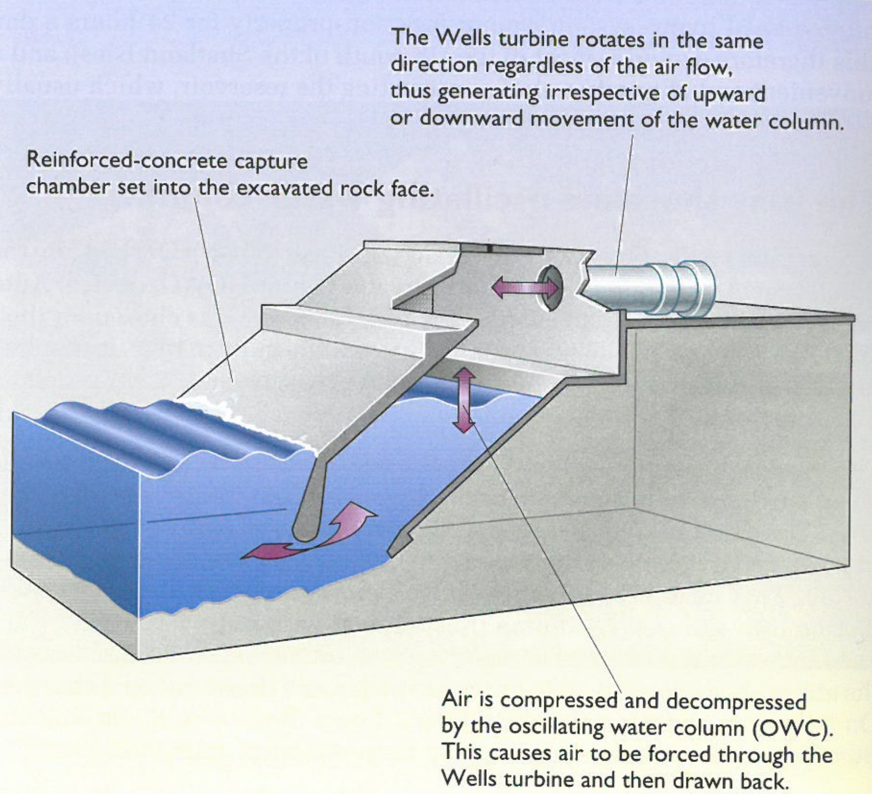
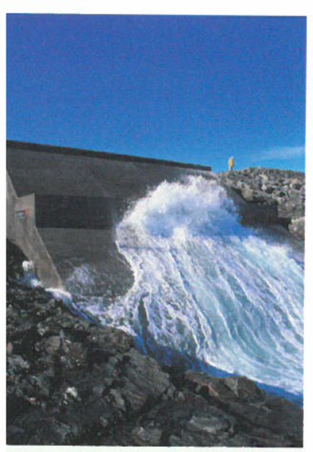


Figure 8.3 Outline of the LIMPET device on Islay



ıre 8.4 Photograph of the PET OWC device

Construction of LIMPET was completed in September 2000, and Figure 8.4 shows the finished structure, consisting of a rectangular sloping chamber which ducts the airflow through two contra-rotating Wells turbines. Each turbine is coupled to a 250 kW induction generator, giving the device a 500 kW maximum power output. Details of the first year of operation of LIMPET can be found in Boake et al. (2002). LIMPET has now accumulated many thousands of hours of operation, in more than ten years, and is used by Wavegen as a test bed for air turbines.

8.3 Physical principles of wave energy

Ocean waves are generated by wind passing over long stretches of water (known as 'fetches'). The precise mechanisms involved in the interaction between the wind and the surface of the sea are complex and not yet completely understood, but three main processes appear to be involved.

(1) Initially, air flowing over the sea exerts a tangential stress on the water surface, resulting in the formation and growth of waves.

(2) Turbulent air flow close to the water surface creates rapidly varying shear stresses and pressure fluctuations. Where these oscillations are in phase with existing waves, further wave development occurs.

(3) Finally, when waves have reached a certain size, the wind can exert a stronger force on the upwind face of the wave, causing additional wave growth.

Because the wind is originally derived from solar energy we may consider the energy in ocean waves to be a stored, moderately high-density form of solar energy. Solar power levels, which are typically of the order of 100 W m^{-2} (mean value), can be eventually transformed into waves with power levels of over 100 kW per metre of crest length. Note that these power levels are reported in different units, one *per square metre*, and the other *per metre of crest length*. This is because the nature of waves makes it impossible to refer to power per unit area: we have to consider that the wave action takes place throughout the depth of water, and so we consider the power passing through a *1 metre wide slice of water*. We cannot therefore directly compare solar and wave power densities, but can state that the solar to wind to wave sequence gradually concentrates the power density.

A simple, 'regular' wave can be characterized by its wavelength, λ; height, H; and period, T (see Box 8.1). Waves of greater height contain more energy per metre of crest length than small waves. It is usual to quantify the power of waves rather than their energy content.

BOX 8.1 Wave characteristics and wave power

The shape of a typical wave is described as **sinusoidal** (that is, it has the form of a mathematical sine function). The difference in height between peaks and troughs is known as the **height**, H, and the distance between successive peaks (or troughs) of the wave is known as the **wavelength**, λ.

Suppose that the peaks and troughs of the wave move across the surface of the sea with a velocity, v. The time in seconds taken for successive peaks (or troughs) to pass a given fixed point is known as the **period**, T. The **frequency**, f, of the wave describes the number of peak-to-peak (or trough-to-trough) oscillations of the wave surface per second, as seen by a fixed observer, and is the reciprocal of the period. That is, $f = 1/T$.

If a wave is travelling at velocity v past a given fixed point, it will travel a distance equal to its wavelength λ in a time equal to the wave period T. So the velocity v is equal to the wavelength λ divided by the period T, i.e.:

$$v = \lambda/T$$

The power, P, of an idealized ocean wave is approximately equal to the square of the height, H (metres), multiplied by the wave period, T (seconds). The expression is:

$$P = \frac{\rho g^2 H^2 T}{32\pi} \text{ W m}^{-1}$$

or (approximately) in kW m^{-1}, $P \approx H^2 T$ kW m^{-1}

where ρ is the density of water and g is the acceleration due to gravity.

Deep water waves

In terms of wave propagation, water is considered to be 'deep' when the water depth is greater than about half of the wavelength λ. The velocity of a deep-water ocean wave can be shown to be proportional to the period as follows:

$$v = gT/2\pi$$

This leads to the useful approximation that the velocity in metres per second is about 1.5 times the wave period in seconds.

An interesting consequence of this result is that in the deep ocean the long waves travel faster than the shorter waves. This is referred to as 'dispersion', a unique feature of deep water waves which can lead to dangerous and hard to predict combinations of wave crests. Long waves can catch up with preceding shorter waves creating large combined waves where they meet.

If both the above relationships hold, we can find the deep water wavelength, λ, for any given wave period:

$$\lambda = gT^2/2\pi$$

Intermediate depth waves

As the water becomes shallower, the properties of the waves become increasingly dominated by water depth. When waves reach shallow water, their properties are completely governed by the water depth, but in intermediate depths (i.e. between $d = \lambda/2$ and $d = \lambda/4$) the properties of the waves will be influenced by both the water depth d and wave period T.

Shallow water waves

As waves approach the shore, the seabed starts to have an effect on their velocity, and it can be shown that if the water depth d is less than a quarter of the wavelength, the velocity is given by:

$$v = \sqrt{g(d)}$$

In other words, the velocity under these conditions is equal to roughly three times the square root of the water depth d – it no longer depends on the wave period.

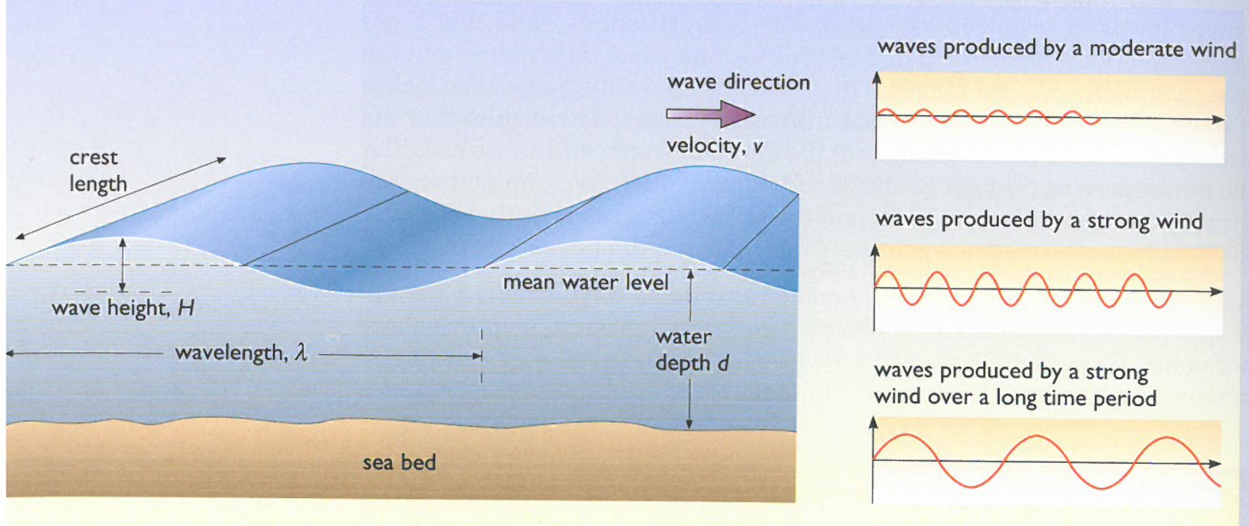


Figure 8.5 Characteristics of an idealized wave

Waves located within, or close to, the areas where they are generated are sometimes referred to as a 'wind sea'. When winds change in strength and direction, the resulting wave patterns can become quite complex. Waves can travel out of these areas with minimal loss of energy to produce 'swell waves' at great distances from their area of origin. As waves travel, there is a systematic tendency for periods and wavelengths to increase, and so swell seas are typically made up of relatively long period waves. The height and steepness of the waves generated by any wind field depends upon three factors: the wind speed; its duration; and the fetch, i.e. the distance over which wind energy is transferred into the ocean to form waves. When a steady wind has blown for a sufficient time over a long enough fetch, the waves are referred to as constituting a fully developed sea.

The UK is well situated to make use of wave energy because it lies at the end of a long fetch (the Atlantic Ocean) with the prevailing wind blowing towards it. The UK's western approaches have therefore been of most interest to wave energy engineers and developers. Although often stormy, the fetches in the North Sea are relatively short and so the wave power densities are generally smaller than those of the Atlantic Ocean.

Typical sea state

A typical sea state is actually composed of many individual components, each of which is like the idealized wave described in Box 8.1. Each wave has its own properties, i.e. its own period, height and direction. It is the combination of these waves that we observe when we view the surface of the sea, and the total power in each metre of wave front of this irregular sea is of course the sum of the powers of all the components. It is obviously impossible to measure all the heights and periods independently, so an averaging process is used to estimate the total power, as follows.

(1) By deploying a wave-rider buoy it is possible to record the variation in surface level during some chosen period of time. (Satellites are also used to detect wave heights.)

(2) The average water height will always be zero, since the average value also defines the zero value, but we can obtain a meaningful figure by calculating the significant wave height, H_s. This is defined as 4 × the *root mean square* of the water elevation – i.e. the instantaneous elevations are first squared, making all of the values positive, then the mean over a number of waves is calculated, then the significant wave height is calculated as four times the square root of the mean. The **significant wave height** is approximately equal to the average of the highest one-third of the waves (which generally corresponds to the estimation of height made by eye, since the smaller waves tend not to be noticed).

(3) The **zero-up-crossing period** T_z (or in abbreviated form, the zero-crossing period) is defined as the average time – counted over ten crossings or more to get a reasonable average – between upward movements of the surface through the mean level. (Note that including the downward movements would give the half-period.)

The **energy period**, T_e, is more useful to us as it characterizes the energy in the waves, whereas T_z represents all of the content of the waves including very small components which have negligible energy. The energy period is slightly longer than the zero-up-crossing period: $T_e \sim 1.12T_z$.

(4) For a typical irregular sea, it can then be shown (the derivation lies outside the scope of this book) that the average total power in one metre of wave crest can be approximated by $P = 0.5H_s^2T_e$ where P is in units of kW per metre length of wave crest. The approximation $P = 0.5H_s^2T_e$ is commonly used.

Figure 8.6(a) illustrates a typical wave record and shows the significant wave height and zero-crossing period. Figure 8.6(b) shows two further wave records for the same location, recorded on different days.

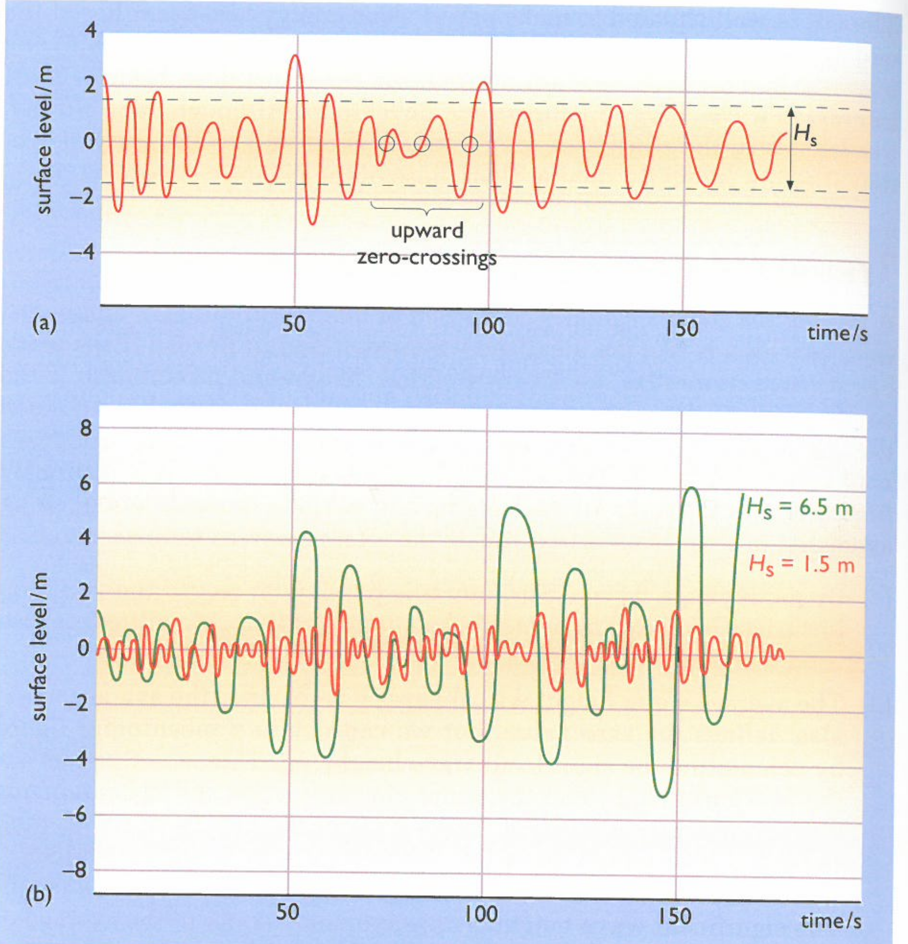


Figure 8.6 (a) A typical wave record. In this example the significant wave height H_s = 3 m (from −1.5m to +1.5m). Successive upward movements of the surface are indicated with small circles. In this case there are 15 crossings in 150 seconds, so T_z = 10 seconds. Then T_e = 11.2 seconds. From this, $P = 0.5\ (3^2 \times 11.2)$ kW m^{-1} = 50.4 kW m^{-1} (b) Two further wave records are shown here for the same location but represent recordings taken on different days

Variations in the wave power at a given location

Sea level recordings made at different times or dates will of course differ, leading to different values of H_s and T_e. Suppose that each recording represents a time period of one-thousandth of a year or 8.76 hours. If we record the sea states at our chosen location over a whole year, characterizing each of them by their values of H_s and T_e, we can build up a statistical picture of the distribution of wave conditions at our chosen location. This picture, or scatter diagram, gives the relative occurrences in parts per 1000 of the contributions of H_s and T_e. The example of a scatter diagram shown in Figure 8.7 is for the north Atlantic and shows that the waves at this location have a high average power density. In water 100 m deep at South Uist (Hebrides, Scotland), for example, the annual average might typically

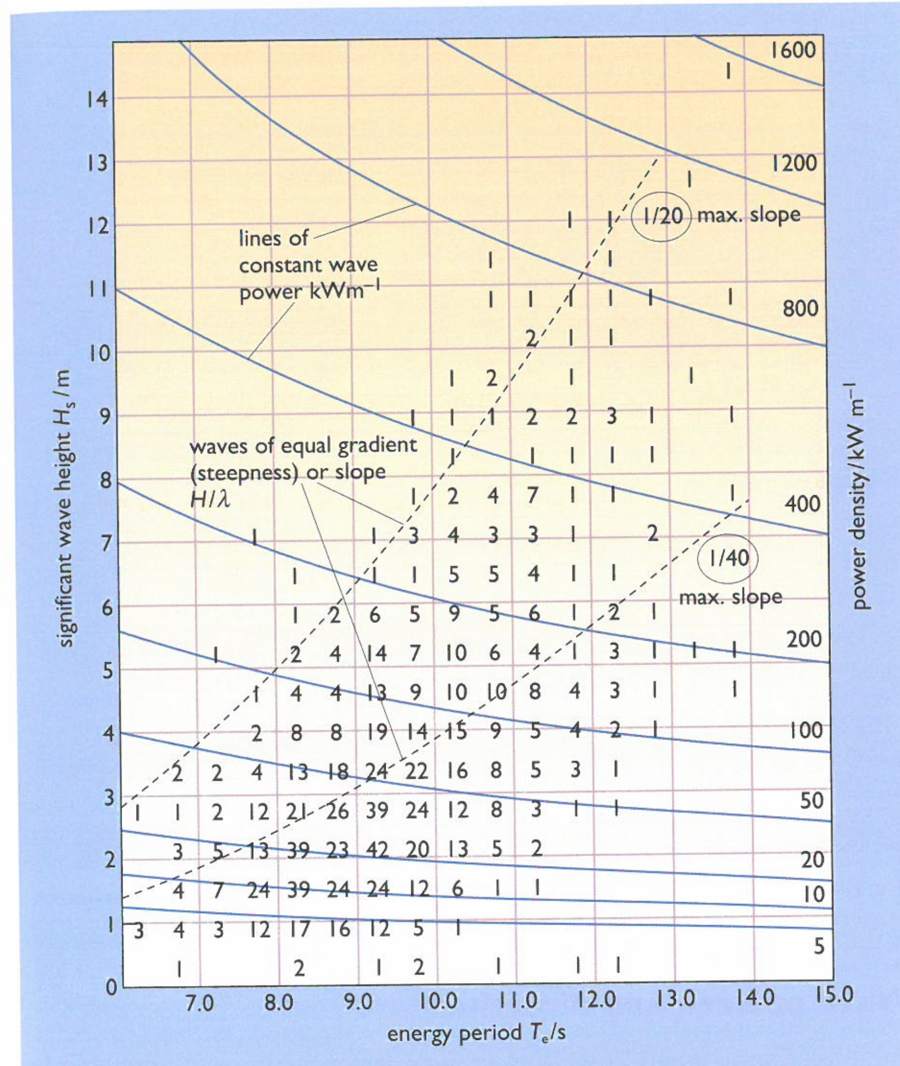
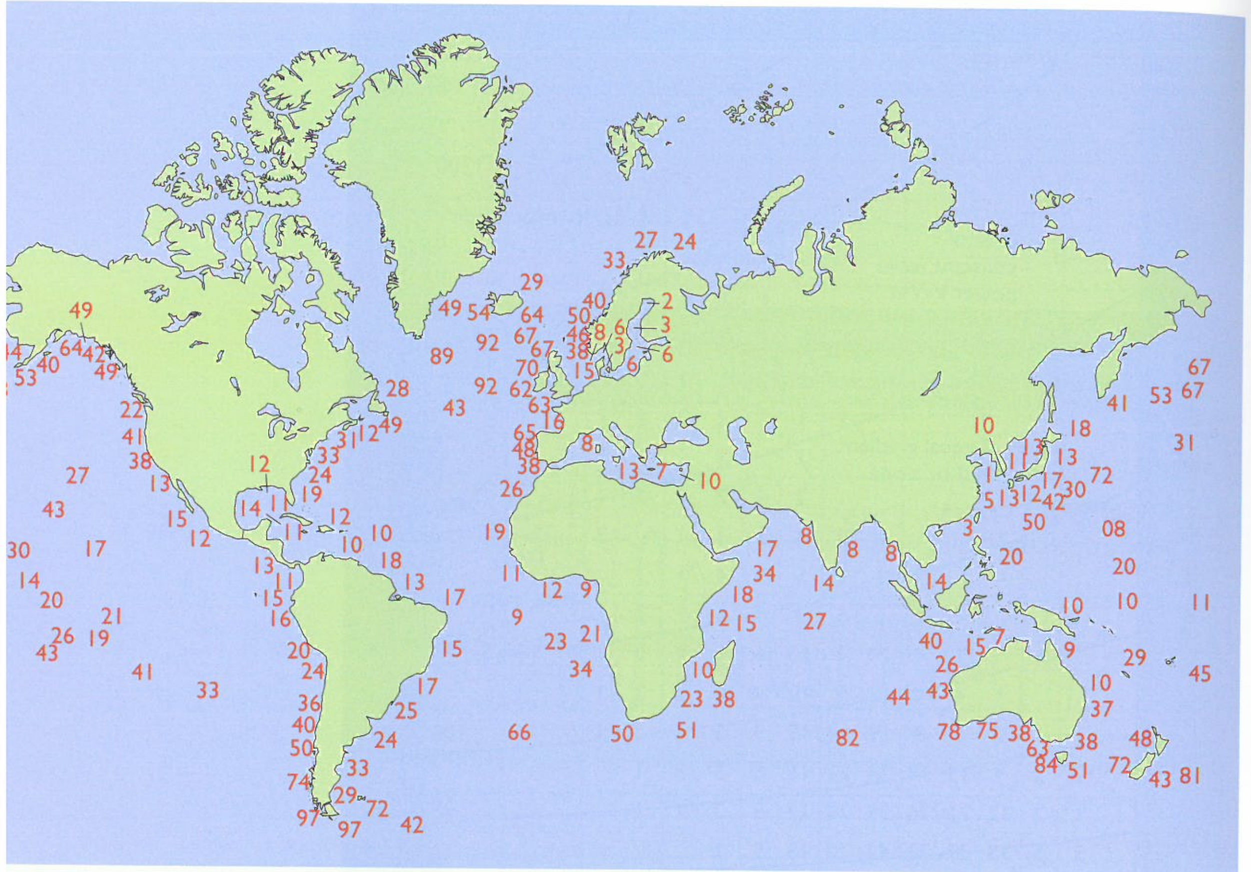


Figure 8.7 Scatter diagram of significant wave height (H_s) against energy period (T_e) for 58°N 19°W in the middle of the north Atlantic. The numbers on the graph denote the average number of occurrences of each combination of H_s and T_e in each set of one thousand 8.76 hour-long measurements made over one year. The most frequent occurrences are at H_s ~ 2 m, T_e ~ 9 s

be around 70 kW m^{-1} (or 613 000 kWh m^{-1} per year), whereas closer to shore where the depth is 40 m, the corresponding figure might be around 50 kW m^{-1} (or 438 000 kWh m^{-1} per year). These figures indicate that the north Atlantic is indeed a valuable wave energy resource.

Figure 8.8 shows estimates of the average wave power density at various locations around the world. The areas of the world which are subjected to regular wind fluxes are those with the largest wave energy resource. South westerly winds are common in the Atlantic Ocean, and often travel substantial distances, transferring energy into the water to form the large waves which arrive off the European coastline.



ure 8.8 Annual average wave power in kilowatts per metre (kW m^{-1}) of crest length, for various locations around the world. ırce: adapted from Claeson, 1987)

Wave pattern and direction

The direction of waves travelling in deep water is obviously dictated by the direction of the wind generating them. Waves can travel vast distances across open water without much loss of energy. At any given location we can therefore expect to observe waves arriving from different sources, and hence different directions. For example, we might see waves approaching us from the south-west which were produced by the winds over the mid-Atlantic, but at the same time find that some waves have been generated by storm conditions to the south and east of our position. It is easy to imagine that the resulting wave pattern will be complex, and indeed such patterns are commonly observed. (Figure 8.9a).

A representation of the annual average power as a function of direction at a given location can be given by a 'directional rose' (Figure 8.9b).

What happens beneath the surface?

The surface profile of the ocean is the obvious evidence for the existence of waves, but we also need to understand the sub-surface nature of waves if we are to design schemes to capture energy from them (Figure 8.10).

Waves are composed of orbiting particles of water. Near to the surface, these orbits are the same size as the wave height, but the orbits decrease

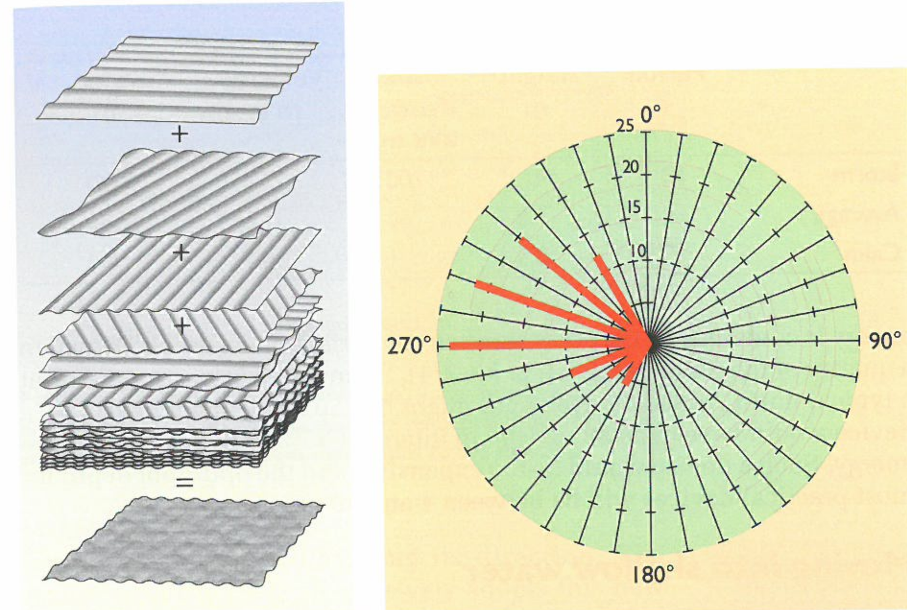


Figure 8.9 (a) The development of a complex sea – wave components produced by different weather conditions in different distant geographical areas arrive and combine in the local area (source: adapted from Claeson, 1987) (b) A directional rose for waves. The length of the line in each sector represents the average annual power in that sector. In this case most of the waves are coming from the west (source: Thorpe, 1999)

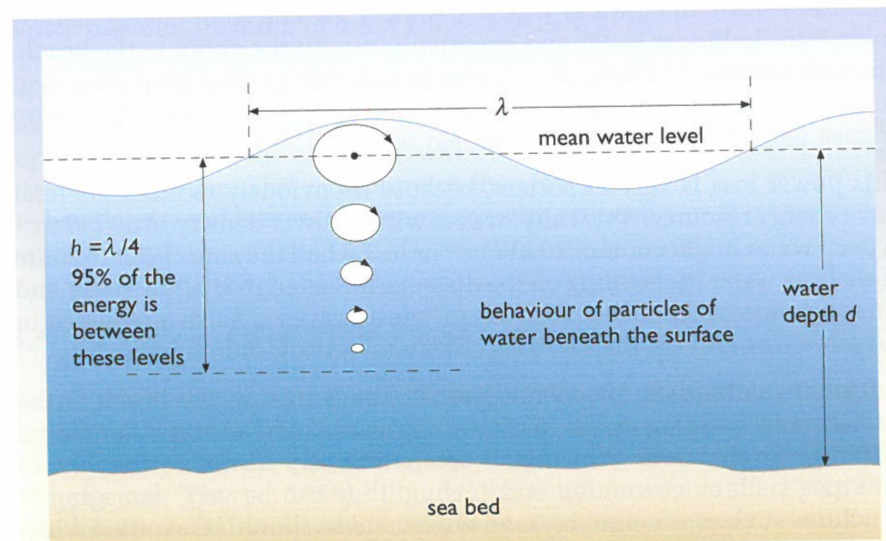


Figure 8.10 Behaviour of particles of water beneath the surface

in size as we go deeper below the surface. The size of orbits decreases exponentially with depth.

To capture the maximum energy from a wave we could try to construct a device that was deep enough to intercept all of the orbiting parts of that wave. But this would be impractical and uneconomic, since the lowest orbits actually contain very little energy. In deciding how deep a structure to extract wave energy should be, it is useful to know that 95% of the wave

Table 8.1 North Atlantic offshore wave conditions

	Period/ s	Height/ m	Power density/ kW m^{-1}	Velocity/ m s^{-1}	Wavelength/ m
Storm	14	14	1700	23	320
Average	9	3.5	60	15	150
Calm	5.5	0.5	1	9	50

energy is contained in the layer between the surface and a depth h equal to a quarter of the wavelength λ (i.e. $h = \lambda/4$). From Table 8.1 we can see that a typical north Atlantic wavelength might be 150 m, which tells us that a device would have to be 38 m deep to intercept 95% of the incident wave energy. Such a device would be too expensive, and the optimum depth for most practical devices will be between 4 and 10 m.

Moving into shallow water

There are a few areas in the world where the shoreline is formed by a steep cliff which drops into reasonably deep water. These are the areas most suitable for shore-mounted wave energy converters because the incident waves have a high power density. However, for most of the coastlines around the world the near-shore water is quite shallow. Due to the frictional coupling between the water particles at the greatest depths with the seabed, deep water waves gradually give up their energy as they move into shallower water and eventually run up the shore to the beach. The frictional effect becomes significant when the water depth is less than quarter of a wavelength, and the power loss can be tens of watts per metre of crest length for every metre travelled in-shore.

This power loss is very important, because it obviously reduces the total wave energy resource. Typically, waves with a power density of 50 kW m^{-1} in deep water might contain 20 kW m^{-1} or less when they are closer to shore in shallow water (depending on the distance travelled in shallow water and the roughness of the seabed). However, storm waves are also attenuated in the same way and are therefore less likely to destroy shoreline devices.

A further mechanism for energy loss as waves run up the beach is the formation of breaking waves, which are turbulent and energy-dissipating. Although such waves ('breakers') are potentially desirable for leisure activities such as swimming and surfing, they can be very damaging to structures such as wave energy converters, and so should be avoided when choosing suitable locations.

Refraction

As ocean waves approach the shore they will usually be entering shallower water and, as we saw in Box 8.1, the velocity of the waves then becomes governed by the water depth. Shallower water means lower wave velocity. This in turn leads to **refraction** (change of wave direction due to change of wave velocity).

Imagine that a wave crest approaches shallow water at an angle, so that one end of the crest reaches the shallow water first. This part then moves more

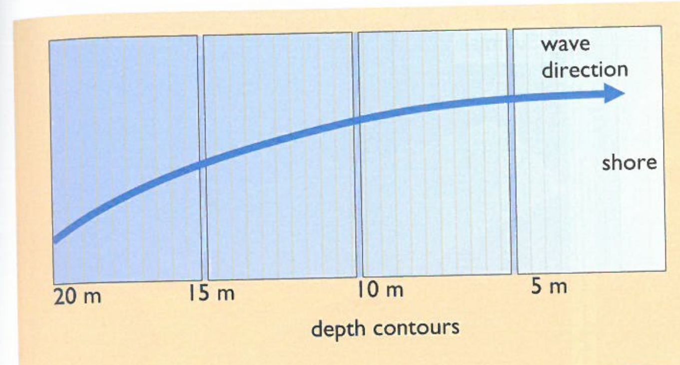


Figure 8.11 As waves travel from deep water into shallow water their velocity reduces and the resulting refraction generally causes waves to approach a beach at right-angles to the shore

slowly than the rest, changing its direction. The remainder of the crest progressively adopts this new direction as its velocity is also reduced on entering the shallow water. The effect of refraction, caused by the reducing depth and hence velocity, is gradually to change the direction of the crest to be roughly parallel with the shore (Figure 8.11).

Knowledge of the depth contours around a coast allows the identification of areas where waves will be concentrated, and are thus the most cost-effective for wave energy developments. Consider a shoreline with headlands (Figure 8.12) – notice how the varying water depth, as shown by the contours (white lines), causes refraction to occur. This concentrates the waves onto the headlands, and leaves the other areas with reduced wave density.

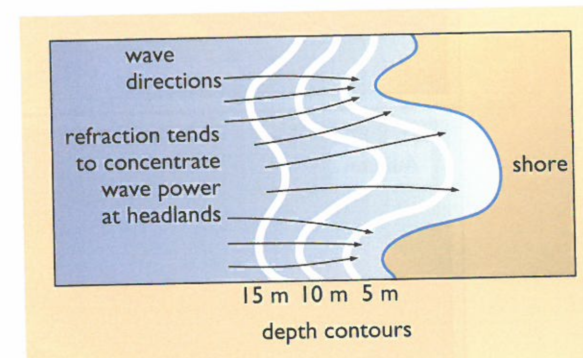


Figure 8.12 Concentration effects of refraction around a shoreline with headlands

8.4 Wave energy resources

Wave power resources (the annual average kW per metre of crest length) around the world were shown in Figure 8.8. As already mentioned, the World Energy Council has estimated a total worldwide resource of 2 000 TWh per year (Thorpe, 1999), although this estimate might in fact prove to be rather conservative as others have suggested higher figures.

Regarding the UK, Thorpe (2003) estimated that the total annual average wave energy along the north and west side of the United Kingdom (i.e. from the south-west approaches to Shetland) ranges from 100 to 140 TWh per year at the near shore to about 600 to 700 TWh per year in deep water. Figure 8.13 shows the seasonal variation in significant wave height, a measure of the available resource, in British waters (BERR, 2008). The variation is quite marked, with a greater resource being available, on average, during the winter months, coinciding with the highest demand for energy. The proportion of this resource that could actually be harnessed to produce electrical power depends, of course, on various practical and technical constraints.

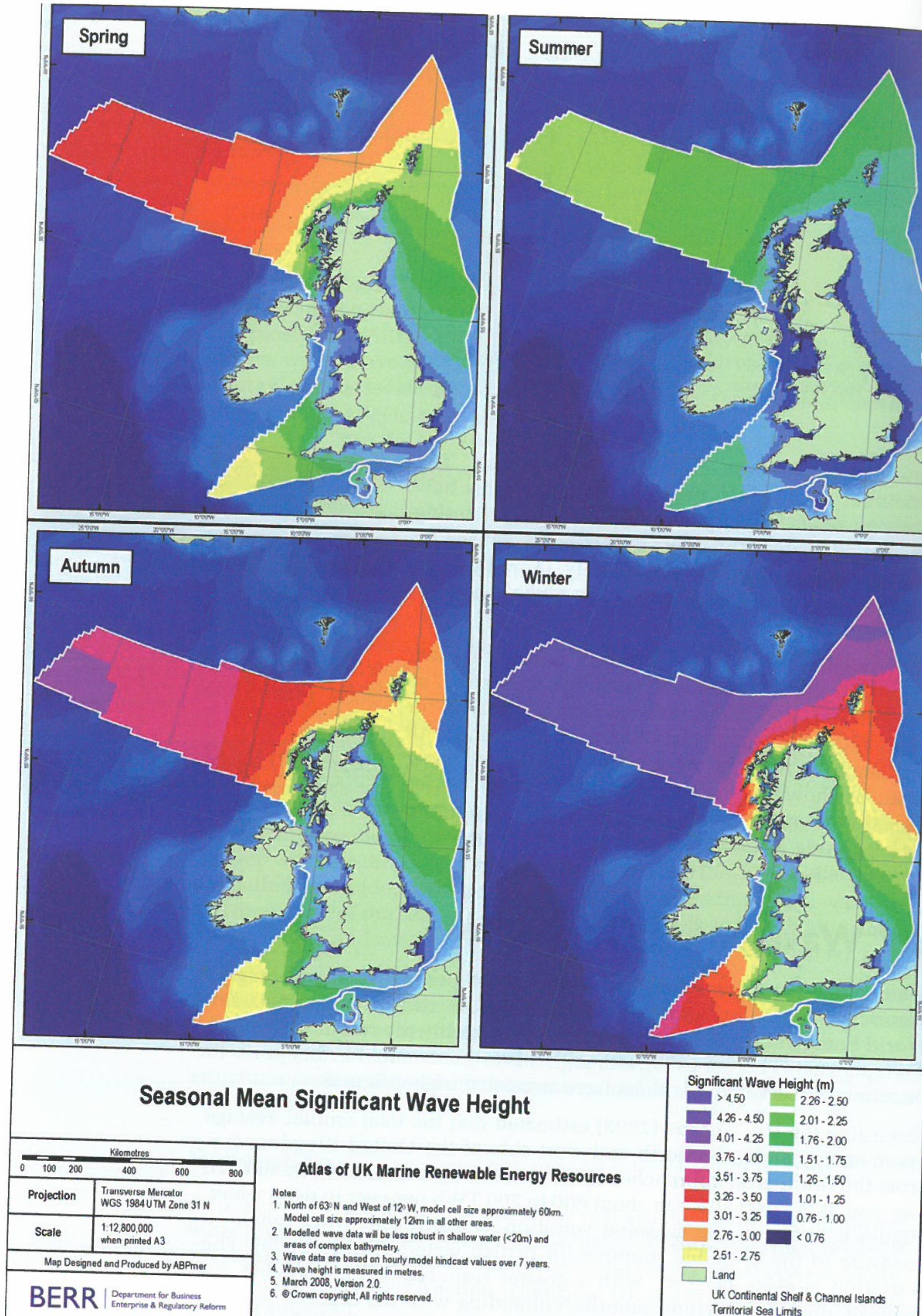


Figure 8.13 Seasonal variation in significant wave height around the UK (source: BERR, 2008)

Thorpe (1992) estimated that the technical resource (i.e. the resource technically available regardless of cost, see Chpater 10) is between 7 GW and 10 GW annual average power, which is equivalent to 61 to 87 TWh per year, depending on the water depth. In comparison, total UK annual electricity production in 2010 was approximately 360 TWh. Table 8.2 gives a breakdown of the resource at different water depths.

Table 8.2 The natural and technical wave energy resource for the north and west side of the UK

Water depth/m	Average natural resource		Average technical resource	
	GW	TWh per year	GW	TWh per year
100	80	700	10	87
40	45	394	10	87
20	36	315	7	61
Shoreline	30	262	0.2[1]	1.75

[1] The technical shoreline resource is very dependent on details of the local shoreline structure, for example the nature and shape of the rock formations and of gullies and beaches.
Source: Thorpe 1992, 2001

8.5 Wave energy technology

In order to capture energy from sea waves it is necessary to intercept the waves with a structure that will react in an appropriate manner to the forces applied to it by the waves. In the case of a shore-mounted device, like TAPCHAN and most OWC devices, the structure is firmly fixed to the seabed, and the waves make water move in a useful way. For other types of device some part of the structure may be fixed, perhaps anchored to the seabed, but another part may be a float which moves in response to the waves by pulling against the anchor. In this case the relative motion between the anchor and the float provides the opportunity to extract energy.

Very loosely tethered floating structures can also be employed, but a stable frame of reference must still be established so that the 'active' part of the device moves relative to the main structure. This can be achieved by taking advantage of inertia, or by making the main structure so large that it spans several wave crests and hence remains reasonably stable in most sea states.

A body in the sea subject to waves can respond via six types of movement. These are sway, roll and yaw, which are not generally harnessed in wave energy conversion technology, and heave, surge and pitch (Figure 8.14), which are harnessed to varying degrees in most wave energy converters. these three modes of movement can be defined as follows:

- pitch – waves cause the device, or part of it to rotate about its axis
- heave – waves cause the device to rise and fall vertically
- surge – waves cause the device to move horizontally backwards and forwards.

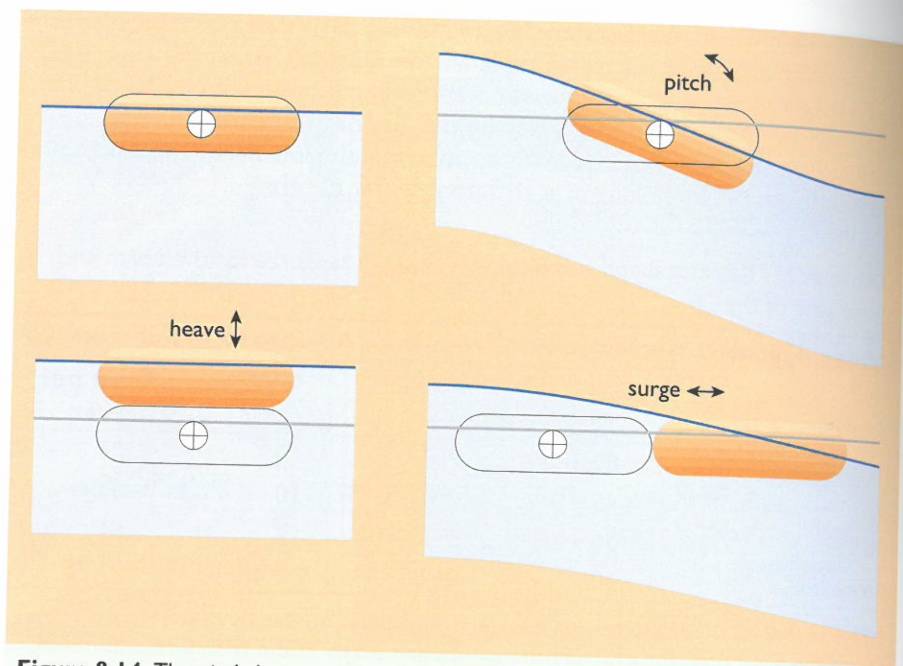


Figure 8.14 The pitch, heave and surge responses of a floating object to incident waves

It is easy to imagine a heaving device, rising and falling with the waves, but such devices have too high a natural frequency to be particularly effective (see the subsection on multi-resonant OWCs for more details). Surge devices tend to have low natural frequency and so can respond to a wide range of wave frequencies. Theoretically, surging motions are twice as energetic as heaving ones, thus making it preferable to harness the surge component of waves (see for example Salter and Lin (1995)).

Economics demands that a device should survive at sea for at least five years. During that time some of its components will have to execute 15 to 30 million cycles, placing severe constraints on material selection and strain levels. A structure designed to operate at a particular design wave power density will also have to endure storms with power densities ten to thirty times higher than the design value.

The physical size of the structure of a wave energy converter is a critical factor in determining its performance. The appropriate size can be estimated by considering the volume of water involved in the upper particle orbits in a wave. In most circumstances a wave energy converter will have to have a swept volume which is similar to this volume of water in order to capture all of the energy contained in the wave. A variety of wave energy concepts are discussed below. The precise physical size and shape of each device will be governed by its mode of operation, but as a rough guide the swept volume must be of the order of several tens of cubic metres per metre of device width. A device with a swept volume much smaller than this would have a limitation on the total energy that it could capture from each typical wave cycle: although it might still be capable of capturing most of the energy from small waves it would be restricted in its response to larger waves, thereby reducing its overall efficiency.

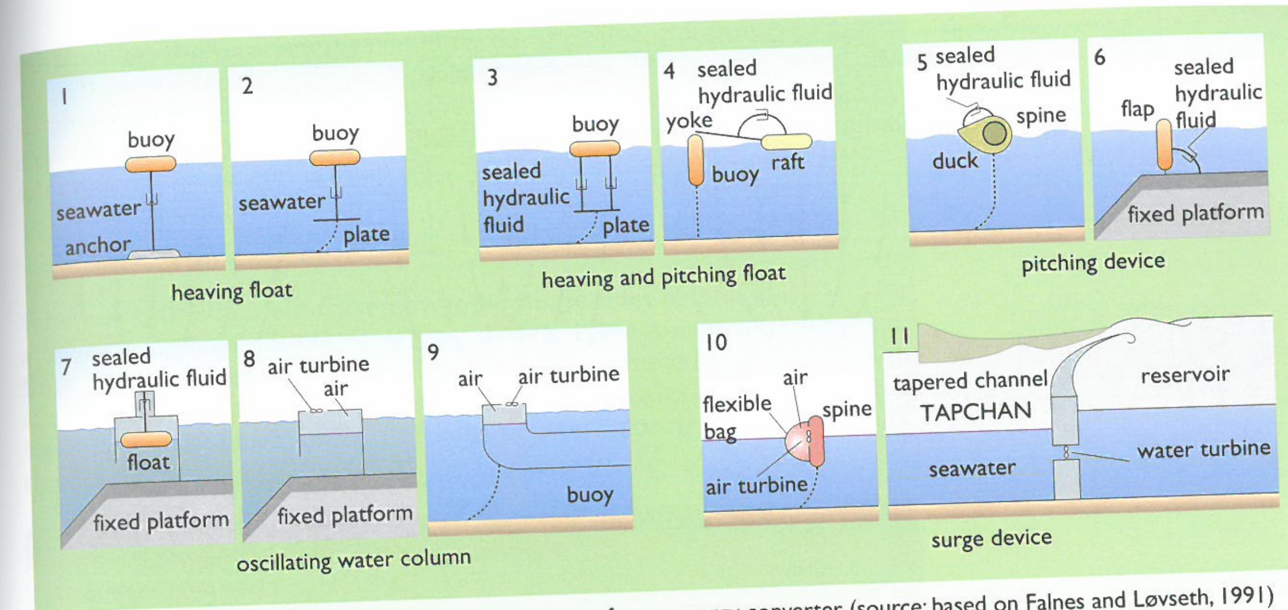


Figure 8.15 Schematic representation of various types of wave energy converter (source: based on Falnes and Løvseth, 1991)

There are many different configurations of wave energy converter, and a number of ways of classifying them have been proposed. One approach is to classify by mode of operation (Figure 8.15).

Another approach is to consider the device location (Figure 8.16) – here the three general classifications are:

- fixed to the seabed, generally in shallow water (eg TAPCHAN)
- tethered in intermediate depths (eg Oyster)
- floating offshore in deep water (eg AWS-III).

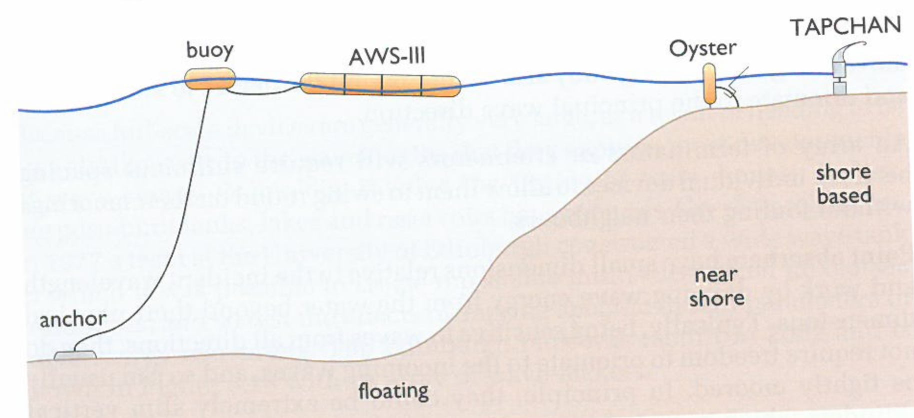


Figure 8.16 Classification of wave energy converters according to location

Alternatively the geometry and orientation of the wave energy converter may be used (Figure 8.17). Here the options are:

- terminators
- attenuators
- point absorbers.

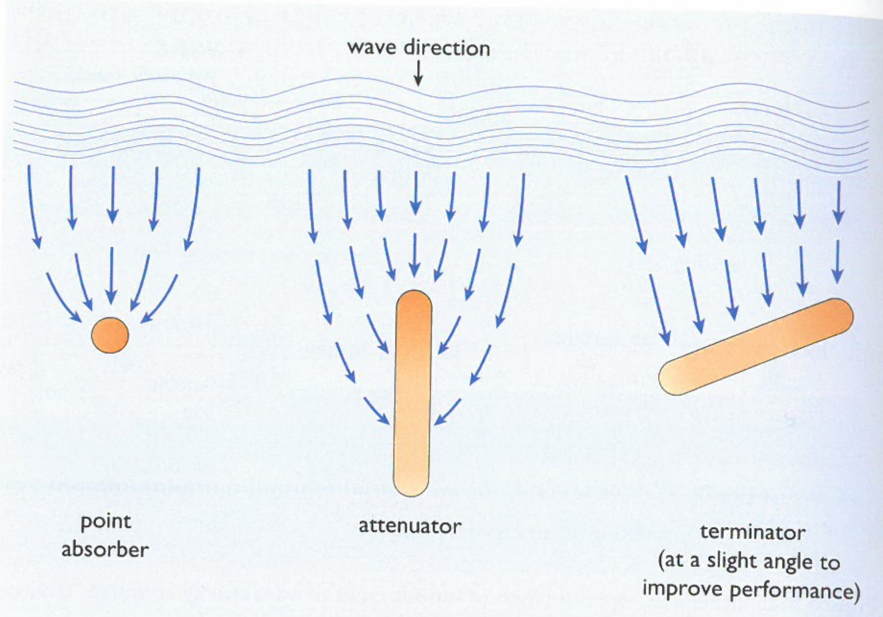


Figure 8.17 Classification of wave energy converters according to size and orientation

Terminator devices have their principal axis parallel (or almost parallel, since a slight angle helps to increase the stability of the whole body) to the incident wave front, and they physically intercept the waves. Depending on the depth, a 300 m long device in a wave climate of 60 kW per metre thus intercepts up to 300 × 60 kW = 18 000 kW. Typically 1/3 of this might be converted into electricity (i.e. 6 000 kW). The terminator might be moored to a leading buoy and anchor, which allows the terminator to pivot as the wave direction changes.

Attenuators have their principal axis perpendicular to the wave front, so that wave energy is gradually drawn in towards the device as the waves move along it. A leading buoy and anchor permit the device to swing round and orientate to the principal wave direction.

An array of terminators or attenuators will require sufficient spacing between individual devices to allow them to swing round on their moorings without fouling their neighbours.

Point absorbers have small dimensions relative to the incident wavelength and work by drawing wave energy from the water beyond their physical dimensions. Typically, being sensitive to waves from all directions, they do not require freedom to orientate to the incoming waves, and so can usually be tightly moored. In principle, they could be extremely slim vertical cylinders which execute large vertical excursions in response to incident waves, but in practice the hardware involved tends to mean that they are a few metres in diameter and absorb energy from perhaps twice their own width. Tethered buoy systems, for example, act as point absorbers.

Point absorber theory (Budal and Falnes, 1975), which is derived from radio antenna theory, suggests that if the body is assumed to be small with respect to the wavelength, the power it may absorb is related, not to the size of the body, but to the wavelength. Therefore, point absorber theory offers the wave energy converter designer the opportunity to create a small device capable of absorbing large amounts of energy from outside its physical bounds. Theoretically the maximum power, P_{max}, absorbed by a perfect point absorber is determined by the mode (heaving or surging) in which it oscillates, and is given by:

$$P_{max} = \varepsilon\left(\frac{\lambda}{2\pi}\right)P_i$$

Where P_i is the incident wave power per metre crest length, and ε is 1 for a heaving device and 2 for a surging device. It is important to note that, from this equation, a body oscillating in surge is theoretically capable of absorbing twice the power of that of a body oscillating in heave, and that for both this could be several times the power incident upon the width of the device.

BOX 8.2 Point absorbers in practice

In theory a perfect wave energy point absorber responding to a heaving motion could capture the energy from a wave front with a length equal to $\lambda/2\pi$ metres. For example, a wave with a period of 6 seconds would have a wavelength of between 56 m and 72 m, depending on whether the water is deep or shallow, and so a perfect (1 m wide) point absorber would absorb the energy from a width of between about 9 m and 12 m). In reality, however, the capture width is much less due to the limitations of the vertical amplitude of the motion of the absorber.

The mathematical explanation of this is outlined by Nielsen and Plum (2000) who go on to report experimental results. These devices are said to have a **capture width ratio**, i.e. the ratio of apparent diameter to physical diameter, greater than 1. Figures 8.25, 8.26 and 8.27 later in the chapter show examples of float systems working off a heaving motion. The concept of **latching**, or holding the float under water for a second or so before allowing it to follow the wave, has been developed to maximize the energy capture by permitting a large amplitude of motion of the float, which is needed for optimal performance (Falnes and Lillebekken, 2003; Falnes, 2011).

Because full-scale devices are generally very large, as a result of needing to be on a similar scale to the wavelengths that they capture, most developments of wave energy technology involve the testing of scale models. Indoor, purpose-built tanks, lakes and reservoirs have been used by research teams. In 1977 a team at the University of Edinburgh constructed a wide wave tank in which it was possible to create repeatable multi-directional mixed-sea conditions, and so test the effects of varying specific design parameters of wave energy converters. The Edinburgh tank was rebuilt in 2002 and is shown in Figure 8.18 with its array of wave-makers.

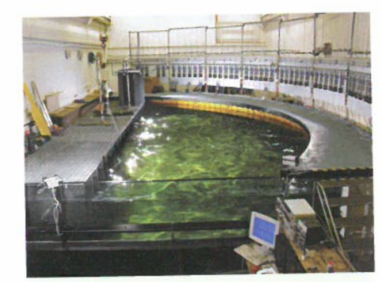
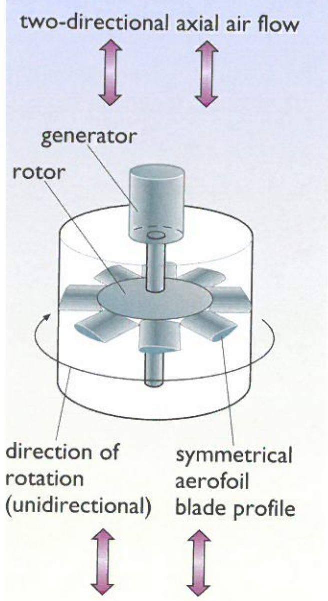


Figure 8.18 The Edinburgh wave tank (28 m long)

Fixed devices

Fixed seabed and shore-mounted devices are usually terminators, and these have been the most common types of wave energy converter to have been tested as prototypes at sea. Having a fixed frame of reference, being closer to a grid, and with good access for maintenance purposes, they have obvious advantages over floating devices. In addition, the seabed attenuates storm waves which could otherwise destroy the device and turbine.



gure 8.19 The Wells turbine

However, such devices have the disadvantage that they generally operate in shallow water and hence at lower wave power levels. Another drawback of shore-mounted devices is that of geographical location – only a limited number of sites are suitable for deployment: to optimize output, they need to be positioned in an area of small tidal range, otherwise their performance may be adversely affected. It is also worth noting that mass production techniques are unlikely to be totally applicable to shore-mounted schemes, as site-specific requirements will demand a tailored design for each device, thus adding to the production costs.

The majority of devices tested and planned are of the oscillating water column (OWC) type. In these devices, an air chamber pierces the surface of the water and the contained air is forced out of and then into the chamber by the approaching wave crests and troughs. On its passage from and to the chamber, the air passes through an air turbine (generally of the Wells type) which drives a generator and so produces electricity. The Wells turbine (Figure 8.19) is an axial-flow device which rotates in the same direction irrespective of the direction of airflow, and has aerodynamic characteristics particularly suitable for wave applications (Box 8.3). A very attractive feature of OWCs is that the cross-sectional area of the air turbine can be much smaller than the area of the moving water surface. This reduction in available area for airflow acts like gearing to increase the air velocity through the turbine such that it can operate at high speed.

BOX 8.3 The Wells turbine

The Wells air turbine, invented by Professor Alan Wells, is self-rectifying – that is to say, it can accept airflow in either axial direction. To achieve this, the aerofoil-shaped blade profile must be symmetric about the plane of rotation, untwisted and with zero pitch, i.e. the chord line must be in line with the plane of rotation. The vector diagrams in Figure 8.20 show how this occurs. Note that the diagrams are very much like those used in Chapter 7 to explain the properties of wind aerofoils. As the blade moves forward, the angle of attack, which is the angle between the relative airflow velocity and the blade velocity, is small and this produces a large lift force (L). The forward component of L provides the thrust which drives the blade forwards.

The Wells turbine operates in much the same way as would a horizontal-axis wind turbine with symmetrical, untwisted blades and with zero pitch angle. Consider the nearest blade with air flowing in an upward direction (Figure 8.20(a)). If we now work in the frame of reference of the blade – we do this by making the blade appear to be stationary to us (even though it is moving) by considering the blade velocity vector to be in the opposite direction to the blade's actual direction of movement – we get Figure 8.20(b). Note that because the blade chord is in line with the plane of rotation, the angle of attack α is the same as the relative wind angle ϕ referred to in Section 7.4 of Chapter 7.

If we now resolve these vectors we get Figure 8.20(c). From this diagram we can see that there will be a net forward force on the blade acting in the plane of rotation if ($L \sin \alpha$) – ($D \cos \alpha$) is greater than zero. The reaction components are of little interest but the rotor bearings must be capable of carrying these forces with minimal friction losses. If the net forward thrust is greater than zero, then the blade will be driven forwards and can usefully extract energy from the airflow. The shape of the blade is extremely important here since it will dictate the values of the lift and drag coefficients C_L and C_D (defined in Chapter 7, Section 7.4) and hence the magnitude of the forward thrust.

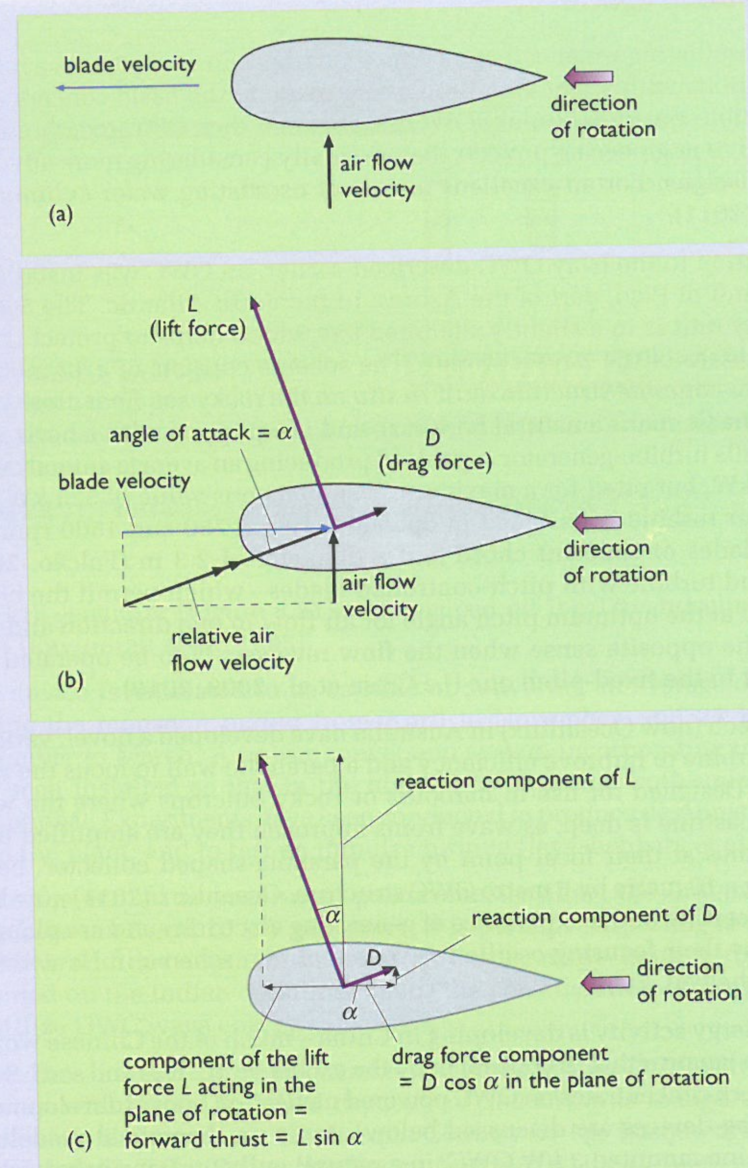


Figure 8.20 The Wells turbine (a) airflow and blade velocity; (b) relative air velocity and lift and drag forces; (c) forces in the plane of rotation

There is a linear relationship between airflow and pressure drop for the Wells turbine rotating at a constant speed. This means that the Wells turbine has a constant impedance to airflow. Careful choice of the design parameters ensures that this impedance matches the requirements of the wave climate at the chosen location. Impedance matching like this maximizes the transfer of energy from the wave to the generator. The Wells turbine is ideally suited to wave energy applications because of its constant impedance, whereas the impedance of a conventional air turbine varies with airflow. A conventional air turbine may have a superior peak efficiency, but a Wells turbine will perform well over a range of air flows giving it a better wave cycle efficiency. A further beneficial characteristic of the Wells turbine is that, at the sizes typically employed, it can rotate at high speed (1500–3000 rpm) so that the electrical generator can be attached directly to the shaft of the turbine, obviating the need for a gear box to raise the generator speed.

OWC-based devices

Fixed oscillating water column devices have been investigated in a number of locations with slight variations being made to the basic concept – this subsection considers bespoke OWC installations, then OWCs combined into other civil engineering projects, before finally considering more advanced OWC designs. For an excellent review of oscillating water columns see Heath (2011).

In addition to the Islay OWC described earlier, an OWC was installed on the island of Pico, part of the Azores, in the north Atlantic. The 500 kW capacity unit is in a slightly sheltered bay which helps to protect it from the excesses of the largest storms. The scheme consists of a 12 metre by 12 metre concrete structure built *in situ* on the rocky sea floor close to the shoreline (it spans a natural harbour), and is equipped with a horizontal-axis Wells turbine-generator capable of producing an average annual output of 124 kW, but rated for a maximum instantaneous value of 525 kW. The Wells air turbine is designed to operate between 750 and 1500 rpm, has eight blades of constant chord and a diameter of 2.3 m (Falcão, 2000). A second turbine with pitch-controlled blades , which permit the blades to be set at the optimum pitch angle for air flow in one direction and then set in the opposite sense when the flow reverses, is to be operated as a contrast to the fixed-pitch one (Le Crom et al., 2009, 2010).

Energetech (now Oceanlinx) in Australia have developed a novel, variable-pitch turbine to improve efficiency and a parabolic wall to focus the wave energy. Designed for use in harbours or rocky outcrops where the water at the coastline is deep, as wave fronts approach they are amplified up to three times at their focal point by the parabola-shaped collector, before entering a 10 metre by 8 metre OWC structure. Oceanlinx (2011) now have 5000 operating hours experience of generating electricity and are planning to deploy their focusing oscillating water column scheme in Hawaii (Gill and Rocheleau, 2009).

Wave energy activity is developing in China – much of the Chinese work is linked to Japan, either in concept or by the exchange of ideas and staff. Some of the work concentrates on OWC powered navigation buoys (developments in floating devices are discussed below), some on theoretical modelling. A shoreline mounted 3 kW OWC, in a natural gully on Dawanshan Island in the Pearl River, has been successful enough to warrant upgrading with a 20 kW turbine.

Harbour and breakwater schemes

When OWCs are incorporated into breakwaters, the double benefits of the breakwater – the provision of a harbour and the generation of electricity – mean that the function of electrical production does not have to justify the total capital cost, and so the generated cost of electricity may be more economically attractive.

Japanese developers have incorporated an OWC into a 20 m section of an extension to the harbour wall at Sakata, on the north-west coast of Japan. The unit was installed in 1989 and contains a Wells turbine rated at 60 kW.

In India, trials of a multi-resonant OWC device (see below), installed in a breakwater and employing a Wells turbine of 2 m in diameter, driving a

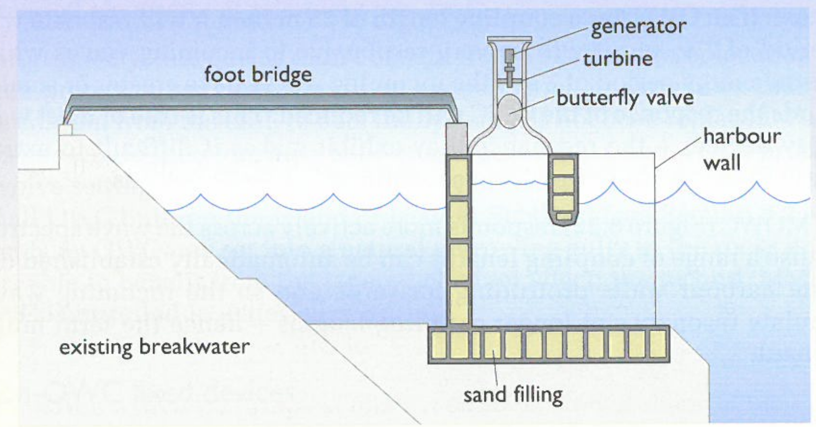


Figure 8.21 Cross-section through the Indian breakwater OWC

150 kW generator (Figure 8.21), commenced off the Trivandrum coast in 1991 (Ravindran et al., 1995).

The device is estimated to be capable of delivering an average of 75 kW during the monsoon period from April to November, and 25 kW from December to March. A power conversion system incorporating two units has been installed so that in the higher power period both units can be operational. Experiments have been conducted to produce desalinated water from the plant, and to test an impulse turbine (Jayashankara et al., 2009).

Since the annual average wave power density along the Indian coast is only between 5 and 10 kW per metre, it is perhaps surprising to see such research and development activity. However, many more harbours are planned on the Indian coastline, hence the consideration of the potential to utilize OWC wave energy converters.

Elsewhere, in July 2011 a 16 chamber, 16 Wells turbine OWC wave energy scheme with a total installed capacity of 300 kW was inaugurated in a breakwater in Mutriku in the Basque Country by the Basque utility Ente Vasco de la Energia. (Renewable Energy Focus, 2011). A Chinese team have also described a breakwater OWC design (Liu et al., 2009).

The multi-resonant OWC (MOWC)

Most wave energy devices are resonant systems – they have a natural resonance period or time over which they repeat their motion. This is just like the motion of a child on a swing who moves with a period of a few seconds. The period is dictated by the length of the swing's ropes – longer ropes give a longer period.

In the case of OWCs the natural period is governed by the length of water from the water or wave surface outside to the water surface inside the device. This can be termed the coupling length (l) and the arrangement behaves like a 'U' tube containing water. The period of oscillation (T) is given by:

$$T = \pi\sqrt{\frac{2l}{g}}$$

For example if $l = 25$ m then T is about 7 s. To put this into a wave energy context: if an OWC has a coupling length of 25 m then it will resonate with a period of 7 s, and it will be very responsive to incoming waves which have an energy period of 7 s. If the incoming waves have greater or smaller periods the response of the OWC will be reduced. This is true of most wave energy devices – the resonance they exhibit makes it difficult to extract energy from a wide range of wave conditions or wave periods.

The MOWC (Figure 8.22) responds more actively across the wave spectrum because a range of coupling lengths can be automatically established due to the harbour walls protruding forwards and so the incoming waves stimulate resonance at longer coupling lengths – hence the term multi-resonant.

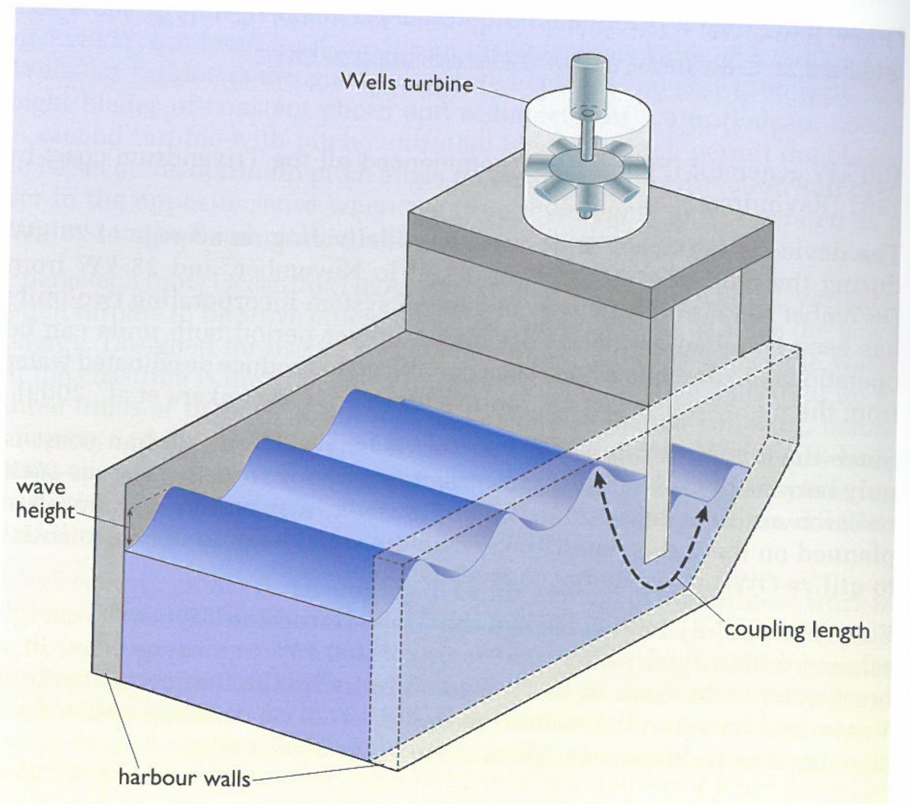


Figure 8.22 A multi-resonant oscillating water column

A multi-resonant oscillating water column (MOWC) was designed and manufactured in 1985 by Kvaerner Brug, and located on the same small Norwegian island as the TAPCHAN prototype. The chamber was set back into a cliff face, which falls vertically to a water depth of 60 m. This created two harbour walls at the entrance to the device, which (as detailed above) allowed the system to absorb energy over a wider range of wave periods. The oscillating airflow was fed through a 2 m diameter Wells turbine rotating within the speed range 1000–1500 rpm. The turbine was directly coupled to a 600 kW generator, and the output passed through a frequency converter

before being fed to the grid. The performance exceeded predictions and provided electricity at relatively low cost.

Unfortunately, this device didn't benefit from a shallow water location that often protects fixed OWCs and two severe storms in December 1988 tore the column from the cliff; to date the system has not been replaced. Future designs would therefore have to be much more robust, and would probably involve setting the column into the body of the cliff, as was done with the small OWC built on the island of Islay in Scotland (see Section 8.2 – the first Islay OWC was set into a natural narrowing gully in the rocks and so was able to benefit from the tapered channel effect; the second 'LIMPET' OWC is installed in a 'designer' gully).

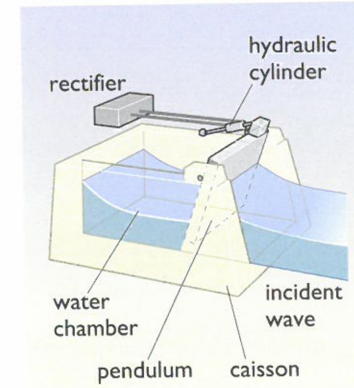


Figure 8.23 The Japanese Pendulor device

Non-OWC fixed devices

Other, non-OWC fixed device prototypes have also been tested in Japan and Scotland. A number have used a mechanical linkage between a moving component, such as a hinged flap, and the fixed part of the device. An example of this approach is the **Pendulor** (Figure 8.23).

The Pendulor is a paddle, hinged at the top, which is fitted one-quarter of a wavelength from the back wall of a caisson. This is at the first anti-node (i.e. the point of maximum amplitude of a series of waves) and so the paddle is subjected to the maximum possible wave movement (note that the paddle can be located at the anti-node for only one particular wavelength). In the regions of Japan where Pendulor devices have been tested, the seas generally have wavelengths close to the design wavelength for much of the year.

A push–pull hydraulic system converts the mechanical energy from the movement of the Pendulor paddle into electrical energy. Two prototypes with nominal power outputs of 5 kW have been operational on Hokkaido, Japan since the early 1980s. The Korean wave energy conversion study group (KORDI) started working on a Floating Pendulor Study in 2010 under a collaborative agreement with a Japanese research group with the intention of accelerating the development of this concept.

In Scotland a working prototype of the Oyster hinged scheme is being trialled. This device is designed to respond to surge forces. The first full-scale Oyster 1 wave power device (Figure 8.24) was installed at the European Marine Energy Centre (EMEC) in Orkney, Scotland in the summer of 2009 and was connected to the national grid in November 2009. At the time of writing Oyster 1 is undergoing sea trials to gather data to finalize the design of the next-generation devices, which are intended to consist of three linked wave power devices with an installed capacity of 2.3 MW. (Aquamarine Power, 2011a). Deployment of these commenced in 2011.

Figure 8.24 The 315 kW Oyster 1 in the factory

Tethered devices

Float systems, with the main body of the structure floating on the surface, but moored to the seabed via a pump, have attracted attention over the years, and are the subject of activity in some current projects. These can act as point absorbers which draw in energy from a greater sea width than their own physical diameter (see Box 8.2).

BOX 8.4 Support from EMEC and Wave Hub

The European Marine Energy Centre (EMEC) mentioned in Chapter 6, Box 6.6, helps to solve many of the problems that have dogged the construction of prototype wave-power generators in the past. For example, storm-proof moorings and armoured cables facilitate the simple and cheap installation and testing of new devices. Also EMEC can accommodate up to four machines at a time, so designers can directly compare devices under identical conditions, giving them a chance to spot small design 'tweaks' that will improve the efficiency of energy generation.

Another facility providing an infrastructure for the demonstration and proving of arrays of wave energy generation devices over a sustained period of time is the Wave Hub, a grid-connected offshore facility 16 kilometres off the north coast of Cornwall. It holds a 25 year lease on 8 sq km of seabed and can accommodate four separate wave energy schemes each with a capacity of 4–5 MW.

PowerBuoys

The wave energy converter termed 'PowerBuoy', developed by Ocean Power Technology (OPT), consists of a modular buoy-based system which drives generators using mechanical force developed by the vertical movement of the device. Each module is relatively small, permitting low-cost regular maintenance, leading to expected lifetimes of at least 30 years.

An early version of the PowerBuoy was deployed in December 2009 approximately 1.2 km off the coast of Oahu, Hawaii in a water depth of 30 m. To date, this device has operated and produced power from over 3 million power take-off cycles (one take-off cycle is the term for one operational cycle of one significant wave cycle) and 4400 hours of operation. This project is part of OPT's on-going programme with the US Navy to develop and test the PowerBuoy technology, and has contributed to the roll-out of OPT's next generation PB150 system, with a generating capacity of 150 kW, for the electrical utility markets. At the time of writing, the first PB150 device is being prepared for transit to a location off the coast of Inverness, Scotland, for planned ocean testing (OPT, 2011).

OPT has further plans for its devices. It is proposing to develop a commercial wave park in North America at Coos Bay, Oregon, and has signed an agreement to develop a wave-power station in Japan.

The Coos Bay park will be the largest wave energy project in the world on completion and may have a capacity of up to 100 MW. It is intended to be located approximately 4.3 km miles off the coast and will utilize another of OPT's next generation devices – PB500 PowerBuoys (which have a maximum sustained generating capacity of 500 kW). The wave park will consist of up to 200 of these PowerBuoys, 20 undersea substations, and a submarine cable to deliver the electricity generated from this wave park into the grid served by the Pacific Northwest Power Grid (OPT, 2011).

The Japanese development is expected to provide the groundwork for a larger commercial-scale wave-power plant with a capacity of 10 MW or more. The initial phase of the contract will see OPT work with the Japanese consortium of Idemitsu Kosan, Mitsui Engineering and Shipbuilding and Japan Wind Development to identify ideal sites for the demonstration power station, based on commercial potential. The consortium will then work with OPT to build up to three of its PowerBuoys for the demonstration plant (OPT, 2010).

Hose pump wave energy converter

The average wave power along the Swedish coast is about 0.57–1.1 GW, representing 3–7% of demand. In addition, however, the potential along the neighbouring Norwegian coast is put at around 3.0–3.5 GW, which could contribute some 12–15% of Sweden's electricity demand via the Nordic grid – hence Swedish interest in wave power. Both countries could exploit the Norwegian coastline wave resource.

The Hose Pump Wave Energy Converter was developed by Technocean in Sweden and was intended to pump sea water from an array of hose pumps fixed to the seabed (Figure 8.25). The hose pump consists of a reinforced vertical rubber cylinder, anchored to the seabed and attached to a float on the surface (thus it acts as both tether and pumping mechanism).

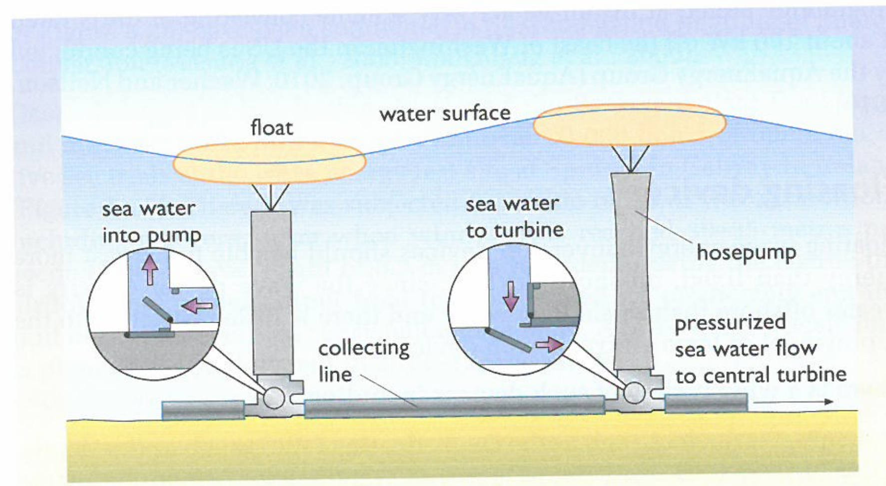


Figure 8.25 Swedish hose pump wave energy converter

The reinforcing cords in the hose are arranged at a carefully chosen angle to the main axis of the hose. As the buoy rises with a wave, the hose is stretched and the cord angle changes in such a way that it causes the internal volume of the hose to be reduced. This raises the pressure of the sea water contained within the hose. The sea water is then pumped out of the tube and up to a storage reservoir on land. A Pelton wheel (see Chapter 5, Section 5.8) extracts energy from the water as it is released from the reservoir back to sea. The tube is refilled with water via a non-return valve. The concept has not been exploited.

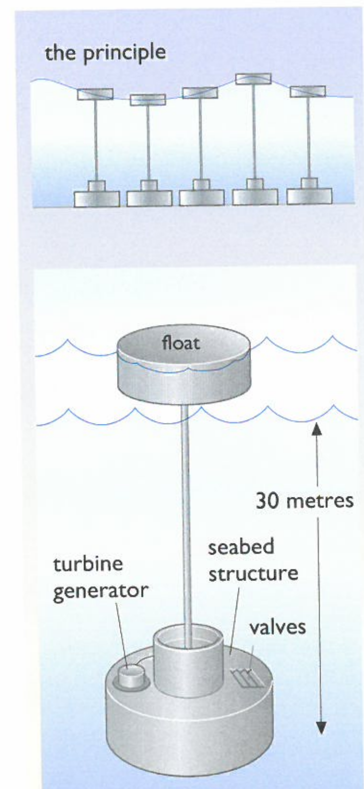


Figure 8.26 Tethered buoy wave energy converter

Danish research has been conducted in this area on a tethered buoy system where each buoy device contains a generator (Figure 8.26). The floating buoy responds to wave activity by pulling a piston in a seabed-mounted unit. This piston pumps water through a submerged turbine. An array of

Figure 8.27 The AquaBuoy system, based on the IPS and Hose Pump concepts

these buoys could be deployed and arranged to have an integrated output (Nielsen and Plum, 2000).

Interproject Service Convertor

The Interproject Service (IPS) Converter was developed by Interproject Service AB, Sweden, in the early 1980s and tested at a 1:10 scale in a lake and as a full-scale prototype at sea. It consists of a long buoy with a tube open at both ends, attached underneath. A piston inside the tube is linked to the buoy and power is extracted by the interaction of the buoy and the water in the tube. A new configuration developed at the University of Edinburgh, the sloped IPS, embodies a number of attractive features, particularly the additional energy capture yielded by operating at an angle to the vertical. By employing a hydraulic accumulator the device can effectively provide reasonably smooth output and so offers the prospect of a reliable source of power for small, isolated electricity networks or small islands (Salter and Lin, 1995).

The AquaBuoy system shown in Figure 8.27 is a development based on both the IPS and the hose pump wave energy converter. An experimental programme aimed at installing a 1 MW scheme consisting of units rated at about 100 kW off the coast of Washington in the US is being conducted by the AquaEnergy Group (AquaEnergy Group, 2010; Wacher and Neilson, 2010).

Floating devices

Floating wave energy conversion devices should be able to harvest more energy than fixed, on-shore devices, since the wave power density is greater offshore than in shallow water and there is little restriction to the deployment of large arrays of such devices.

There is a wide variety of such devices including:

- terminator devices such as the Duck, floating OWCs such as the Whale, OWEL and Backward Bent Duct Buoy (BBDB), and floating tapered channels (described as Floating Wave Power Vessels, FWPV)
- point absorbers such as the AWS-III
- attenuator devices such as the Pelamis.

Terminator devices

OWC-based devices

A number of floating OWC-based devices have been developed – the Kaimei, a converted barge fitted with a number of floating OWC devices and the first sea-going Wells turbine, was first tested in Japan in 1977 – as mentioned previously, this was the first large floating wave power station.

As mentioned earlier, China has an expanding interest in wave energy – numerous OWC-powered navigation buoys have been deployed and the BBDB concept, originally proposed by Masuda, has been tested at model scale (Masuda et al., 2000). Experiments on the BBDB concept (illustrated

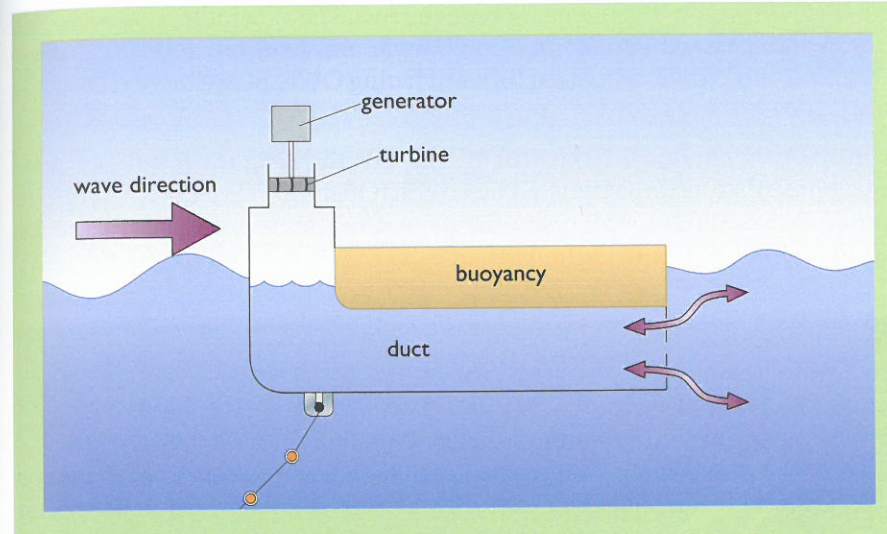


Figure 8.28 The Backward Bent Duct Buoy (BBDB)

in Figure 8.28) have been conducted at the Guangzhou Institute of Energy Conversion (Masuda et al., 2000; Xianguang et al., 2000).

Ocean Energy Ltd has further developed the Backward Bent Duct Buoy and a quarter scale hull has achieved over 20 000 hours of operation in live sea trials at the wave energy test site at Spiddal in Galway in Ireland (Figure 8.29). There it was subjected to a wide range of wave conditions including a severe storm when wind speeds reached 30–35 metres per second and a wave height of 8.2 m was recorded. During the testing the airflows and power output from the tests scaled up predictably and the hull behaviour was also consistent and reliable. A three-quarter scale unit is planned for deployment in 2011–12 (Heath, 2011).

Figure 8.29 Ocean Energy buoy with Wells turbine (courtesy of Ocean Energy)

Other variations on this theme include the Swan DK3, which is based on the L-shaped Backward Bent Duct Buoy (Meyer and Nielsen, 2000; IT Power, 2011) and the Whale, a floating forward facing OWC-based device (Washio et al., 2001).

A multi-cell version of the BBDB, the OWEL, (Figure 8.30) is under development by a consortium led by OWEL (Offshore Wave Energy Limited) and IT Power (2011) which should see a 45 m long pilot version with a rating of 500 kW tested at the Wave Hub site in Cornwall in 2013.

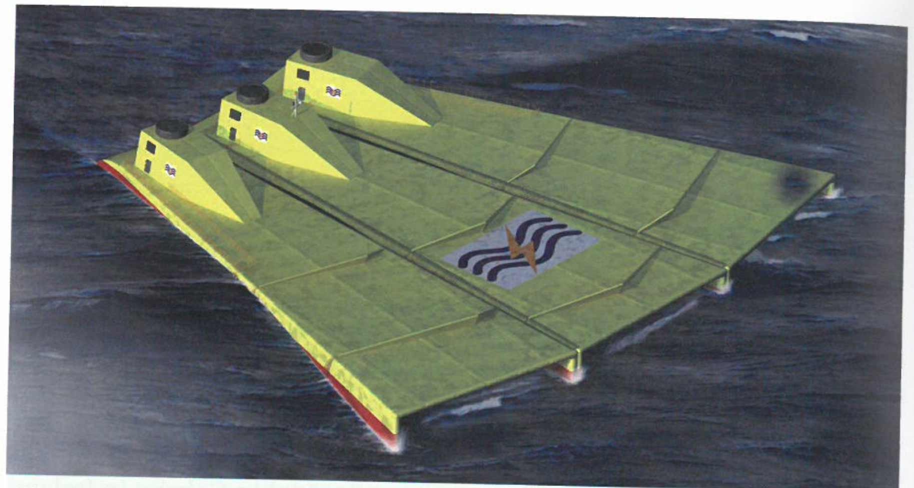


Figure 8.30 Artist's impression of OWEL (source: IT Power)

An alternative design of floating OWC has been developed by Oceanlinx. Their most recent OWC deployment involved its Mk3 floating device. The unit was a one-third scale demonstration version of a full scale 2.5 MW device. It was installed offshore from the eastern breakwater of Port Kembla Harbour from February to May 2010. The unit supplied electrical power directly into the local grid. It broke free of its moorings during a severe storm in May 2010, and ran up onto the beach.

Oceanlinx has now finalized the full-scale development of new shallow and deep water OWC designs, named greenWAVE and blueWAVE respectively. The greenWAVE unit is a single OWC chamber, fixed to the seabed in shallow water (Figure 8.31). In a good wave climate greenWAVE is rated at around 1 MW. The blueWAVE unit is a cluster of six OWC chambers, moored as a floating device in deeper water. Versions of both are expected to be rolled out in commercial operation over the next two years (Oceanlinx, 2011).

Floating wave power vessel (FWPV)

In 1992 Sea Power International installed a floating wave power vessel (FWPV) for testing off the west coast of Sweden. This steel vessel resembles a floating TAPCHAN in that waves run up a sloping ramp and are collected in a raised internal basin. The water flows from the basin back into the sea via low-head turbines. This device is not sensitive to tidal range, and by varying its ballast the device can be tuned to different wave heights.

Figure 8.31 Artist's impression of an Oceanlinx greenWAVE unit

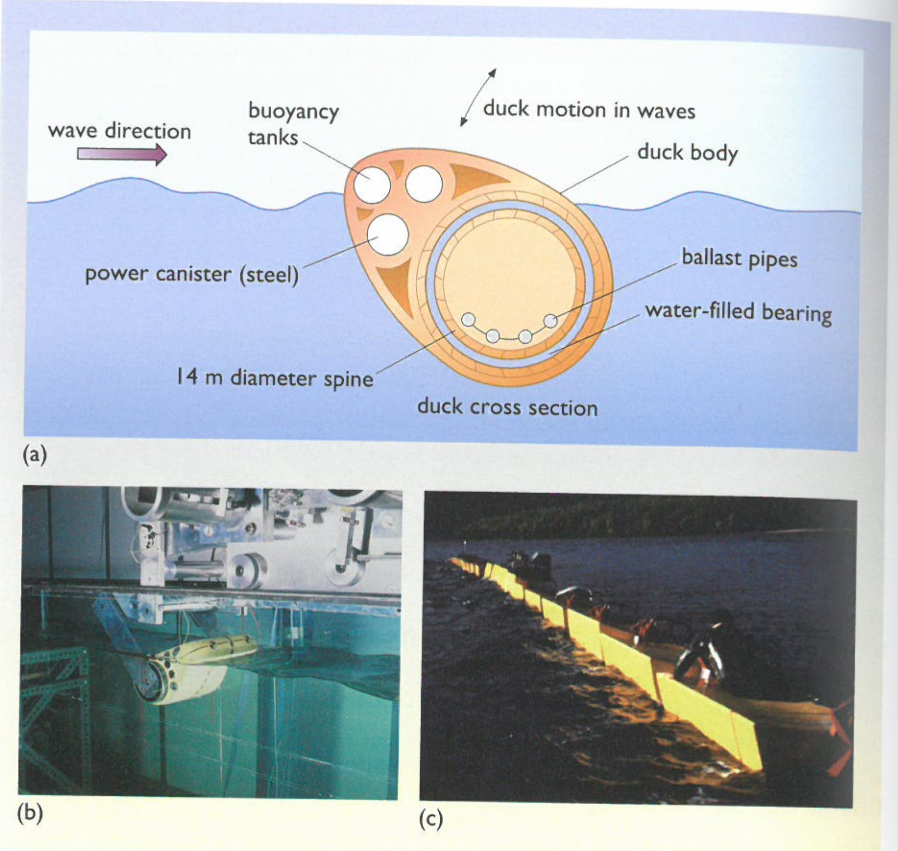
Subsequently, a pilot version based on ship construction was anchored in 50–80 m depth of water 500 m from the Shetland coast in 2002. This device was developed by the Swedish company Sea Power International as part of a Scottish government-backed scheme. It was designed to have a maximum power output of 1.5 MW, producing about 5.2 GWh per year (Lagström, 2000). The device functions by capturing the water from waves that run up its sloping front face. The captured water is returned to the sea via a standard Kaplan hydroelectric turbine (see Chapter 5). In many respects this device may be compared to a floating version of the TAPCHAN.

A Danish version of this floating TAPCHAN concept is the Wave Dragon. Again waves run up a tapered channel and a head of water collects in a reservoir – the water then returns to the sea via a set of simplified Kaplan hydroelectric turbines. A full-scale version was launched near to the University of Aalborg in March 2003, and this delivered its first power to the grid in June 2003. More turbines were installed at sea in September 2003, demonstrating that maintenance at sea is possible (Sorensen et al., 2003). A full scale 7 MW test scheme was designed for deployment in South Wales in 2011.

Another Danish device also uses water to directly drive turbines – the Waveplane is a wedge-shaped device which directs incoming waves of varying frequency into a trough in a spiral configuration, creating a vortex which is used to drive a turbine. Tests using a 1:5 scale model were conducted in Mariager Fjord in Jutland in 1999.

Duck

The Edinburgh Duck concept (Figure 8.32), conceived by Professor Stephen Salter at Edinburgh University in the 1970s, was originally envisaged as many cam-shaped bodies linked together on a long flexible floating spine which was to span several kilometres of the sea. The spine would be oriented almost parallel to the principal wave front, making the Duck largely a terminator. The Duck was designed to extract energy by pitching to match the orbital motion of the water particles, as discussed earlier. To generate power each cam-shaped body – or duck – either moves relative to the spine, producing high pressure in a hydraulic system, or drives a



(a)

(b) (c)

Figure 8.32 (a) The Edinburgh Duck wave energy converter; (b) Duck model being tested in a wave tank; (c) A scale model of the Duck being tested in Loch Ness, Scotland by Coventry University

set of gyroscopes mounted in the noses of the 'ducks'). This matching can be nearly 'perfect' at one wave frequency and the efficiency in long waves can be improved by control of the flexure of the spine through its joints. The concept is theoretically one of the most efficient of all wave energy schemes, but it is likely to take some years to fully develop the engineering necessary to utilize this concept at full scale. The control and engineering challenges of optimizing power conversion efficiency whilst producing steady electrical energy from a 'randomly' rocking body have been studied in great detail by Salter and his team.

Point absorber devices

AWS-III/Clam

AWS Ocean Energy have recently refined the key aspects of this technology, which initially appeared as the Circular Clam, developed at Coventry University in the UK in the 1980s.

AWS-III consists of twelve interconnected air chambers, or cells, arranged around the circumference of a toroid with Wells turbines in each cell. At full scale this would be 60 metres or so in diameter, and would be deployed

in deep water (40–100 m). Each cell is sealed against the sea by a flexible reinforced rubber diaphragm. Waves cause the movement of air between cells. Air, pushed from one cell by the incident wave, passes through at least one of the twelve Wells turbines on its way to fill other cells. As the air system is sealed, this flow of air will be reversed as the positions of wave crest and trough on the circle change. Figure 8.33 shows a 1:9 scale test conducted on Loch Ness, Scotland in 2010. After large-scale single cell proving tests, a pilot scheme is scheduled for 2011–12 (AWS, 2011).

Figure 8.33 AWS-III 1:9 scale test on Loch Ness

The important points about AWS-III are its omni-directional energy absorption and the highly sensitive diaphragms which accept energy from the surge motion of the waves. As pointed out earlier in this chapter, the surge component of waves can be twice as energetic as the heave.

Attenuator devices

Pelamis

The Pelamis, or 'sea snake', can trace some of its ancestry to the Edinburgh Duck; it consists of a number of floating cylindrical tubes, connected to each other by active joints. The tubes are arranged at a slight angle off the down-wave direction and so act as attenuator devices. The wave-induced heaving and swaying of the tubes is resisted by hydraulic rams that pump high-pressure oil through hydraulic motors via smoothing accumulators, and the hydraulic motors drive electrical generators to produce electricity.

The ability to withstand high wave power densities has been a key goal of the designers; the Pelamis is capable of inherent load shedding, which means that the spine is not subjected to the full structural loadings that would otherwise be imposed on it during a storm. As an attenuator it sits down the waves rather than across them – see Figure 8.34 – and so becomes detuned in long storm waves, where the waves are much longer than the device.

The prototype 750 kW devices are 150 m long, 3.5 m in diameter, and composed of five modular sections. To reduce risk, wherever possible use

Figure 8.34 The Pelamis P2

is made of existing technology that has been proven offshore. Three 750 kW devices were deployed 5 km into the Atlantic off northern Portugal in 2008. Pelamis P2 has been tested at the European Marine Energy Centre (EMEC), Orkney, Scotland, and the developers have secured the rights to develop several wave farms around Scotland which might give a total installed capacity of 50 MW (Yemm et al., 2012).

The McCabe wave pump

A 40 m long prototype of a device called the McCabe wave pump was deployed off the coast of Kilbaha in Ireland in 2004 (Figure 8.35). This device consists of three narrow rectangular steel pontoons, which are hinged together across their beam, which points into the incoming waves. The pontoons move relative to each other and energy is extracted from this motion by linear hydraulic rams mounted between the pontoons near the hinges. The output is intended for use in applications such as desalination, as well as electrical generation. Experimental and theoretical results of the motion of a McCabe wave pump have been reported by Kraemer et al. (2000) while Nolan et al. (2003) have modelled the power take-off system.

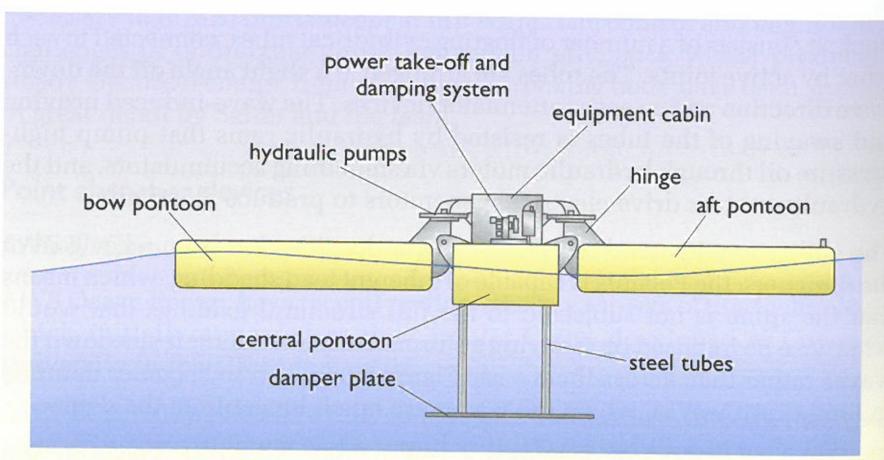


Figure 8.35 The McCabe wave pump – schematic showing operation

The Pitching and Surging FROG

The Pitching and Surging FROG, developed by Professor French and his colleagues at Lancaster University, is a reaction wave energy converter which achieves energy-absorbing behaviour by the movement of internal inertial mass (McCabe et al., 2003). Hence, it is a compact structure which does not require a large spine to provide a stable frame of reference (Figure 8.36).

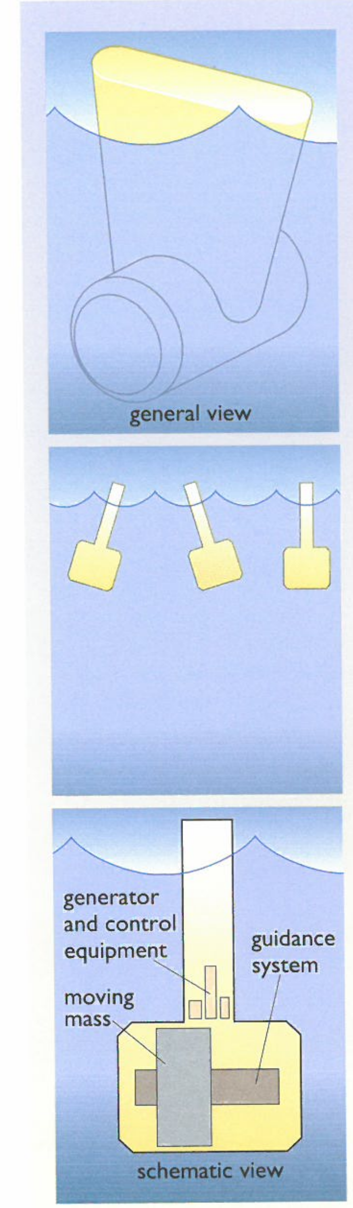


Figure 8.36 The Pitching and Surging FROG wave energy converter

8.6 Economics

Reducing operation and maintenance costs is the key to the successful economic implementation of wave energy stations. The *capital cost* per kW of establishing a wave-energy run power station is likely to be at least twice that of a conventional station running on fossil fuels; and the *capacity factor* is likely to be much lower than a conventional station due to the variability of the wave climate. Therefore, wave energy costs can only be competitive if the *running costs* are significantly below those for a conventional station. Naturally the 'fuel' or wave energy costs are zero, leaving the operation and maintenance costs as the determining factor. Schemes will therefore have to be reliable in their energy conversion and robust enough to survive the wave climate for many years. This means schemes designed for long lifetimes and with small numbers of moving parts (to minimize failures). The oscillating water columns and TAPCHAN schemes are good examples of what is required.

On the other hand the wave energy pioneer Stephen Salter has long argued against 'simplicity' and in favour, for instance, of sophisticated control and power conversion systems to maximize the useful energy that can be captured from the large and expensive structures that had traditionally been required to intercept the waves (Salter et al., 2002).

The UK Committee on Climate Change (CCC, 2011) has calculated the cost of electricity from a possible future (2030) 50 MW array of shoreline wave energy converters, with a capital cost of £2200 per kW and life expectancy of 40 years. Using a 10% discount rate and expressed in £(2010):

- for a low capacity factor (15%) the cost of electricity is 29.1p kWh^{-1}
- for a high capacity factor (22%) the cost of electricity is 19.9p kWh^{-1}.

As with the hydro and tidal plants discussed in Chapters 5 and 6 the discount rate used is an important factor, and is discussed further in Chapter 10 and Appendix B.

This illustrates the importance of achieving a high capacity factor – making as much use of the device as possible. The cost figures reported here are high and reflect the fact that the fixed devices cannot usually benefit from mass production as they would be purpose built for a specific location, and also that such devices would generally operate in shallow water where there is a much reduced wave energy climate.

The total capital investment required for wave energy schemes is dependent on overall average efficiencies and on location. Many of the devices detailed in this chapter have average efficiencies of around 30%. Frequency response characteristics and limitations of swept volume and survival when operating in very energetic seas are responsible for the generally low overall efficiency. At the time of writing, the capital cost is typically around £3000–£4500 per installed kW, although the cost of particular schemes may vary markedly from this.

Large schemes are technically demanding because of the high structural loads imposed by the north Atlantic wave climate. As time has passed there have been improvements in design, performance and construction techniques, together with rationalization of some of the problems and a move to smaller schemes. Smaller schemes are technically simpler and less financially risky, and hence the capital costs and insurance costs are reduced, with commensurate reduction in produced energy costs.

Wave energy technology has moved into the commercial world and several developers are already deploying prototypes and, in some cases, executing schemes generating electricity or desalinating sea water at favourable prices. Coupled with incentives for avoided carbon dioxide emissions, the economic prospects for commercial wave energy exploitation appear to be good.

As wave energy is considered to be environmentally benign (see below), if the technology can be successfully developed it is likely to become an attractive commercial and political proposition, and this should result in an extensive installation programme with wave farms deployed in many locations. The cost of such installations will certainly fall from current levels due to refinement to designs, making them more efficient, and to lower production costs when they are (where possible) mass produced.

8.7 Environmental impact

Wave energy converters may be among the most environmentally benign of energy technologies for the following reasons.

- They have little potential for chemical pollution. At most, they may contain some lubricating or hydraulic oil, which will be carefully sealed from the environment.
- They have little visual impact except where shore-mounted.
- Noise generation is likely to be low – generally lower than the noise of crashing waves (there might be low-frequency noise effects on cetaceans, but this has yet to be confirmed).
- They should present a small (though not insignificant) hazard to shipping.
- They should present no difficulties to migrating fish.
- Floating schemes, since they are incapable of extracting more than a small fraction of the energy of storms, will not significantly influence the coastal environment. Of course, a scheme such as a new breakwater incorporating a wave energy device will provide coastal protection, and may result in changes to the coastline. Concrete structures will need to be removed at the end of their operating life.
- Near-shore wave energy schemes will release (from, for example, construction and material transport) an estimated 11 g of CO_2, 0.03 g of SO_2 and 0.05 g of NO_x for each kWh of electricity generated (Thorpe, 1999), making them very attractive in comparison to the conventional UK electrical generating mix of coal, gas and nuclear plants (see Chapter 10). Thus wave energy can make a significant contribution in meeting climate change and acid rain targets.

8.8 Integration

The electrical output from a wave energy scheme can be used directly but it is much more likely that the electricity will be fed into a grid. The electrical issues associated with such schemes include variability of supply of electricity due to the nature of waves, phasing, power factor correction and transmission losses (Freris and Infield, 2008).

Wave energy for isolated communities

If the grid is small and serves a small, remote community, great care must be taken in integrating the electrical output from a wave energy scheme: the output from a wave energy scheme will vary with time (except in the case of units such as the TAPCHAN) and may cause voltage or frequency fluctuations. Energy storage or other methods of smoothing may thus be necessary.

Many small communities currently depend on diesel generators for their electricity. A diesel generator is best run at a constant output close to its design capacity – say 50 kW. Therefore, if a diesel unit is the sole source of electricity, the load from the grid should always be matched to 50 kW. Clearly, the consumers will cause the load to vary as they switch appliances on and off, so to allow for this, a 'dump' load can be incorporated into the system. The diesel output is directed to this dump load when the load on the grid falls – for instance at night when the demand is low, energy can be used for space heaters, freezers, water heaters or to drive washing machines, etc.

Similarly, the incorporation of a varying electrical output from a wave energy scheme into the grid can partially be accommodated by the use of such dump loads located in houses, schools, factories etc. to stabilize the grid (Figure 8.37).

By careful overall design of an integrated scheme, a remote community could enjoy significant gains in electricity supply from a wave energy scheme. If this produces most of the energy the reduction in diesel oil consumption would be substantial, and since it is costly to transport diesel oil to remote locations, the cost savings could be large. Ideally the diesel generator would be held in reserve and only brought into use when the wave activity is too low to meet demand. An energy storage system such

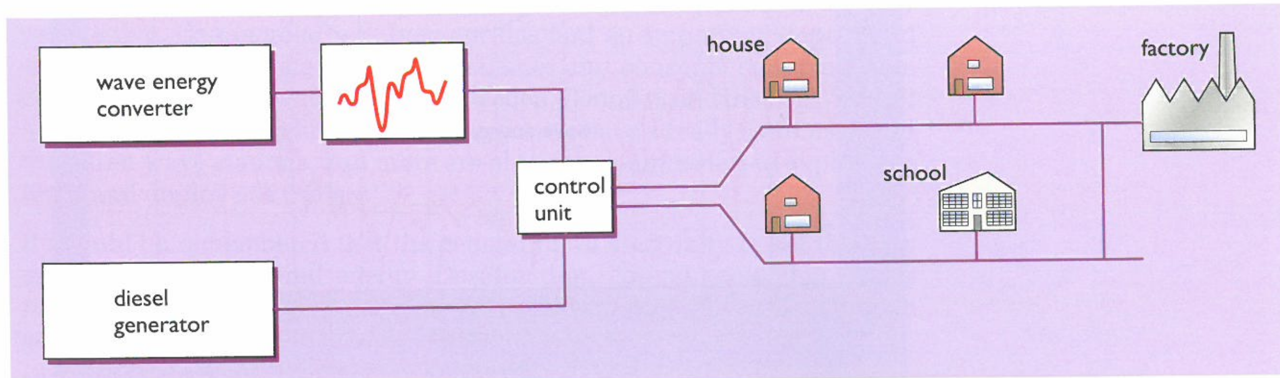


Figure 8.37 An integrated wave energy/diesel system

as batteries would be very useful in smoothing the supply and minimizing the call on the diesel generator.

Wave energy for large electricity grids

When the electrical outputs of several wave energy units are added together, the total output will be generally smoother than for a single unit. If we extend this to an array of several hundred floating devices, then the summed output will be smoother still. In addition, any fluctuations in output will be less important if the electricity is to be delivered to large national systems like those of the UK, where in most locations the grid is 'strong' enough to absorb contributions from a fluctuating source. Figure 8.38 illustrates a typical scheme.

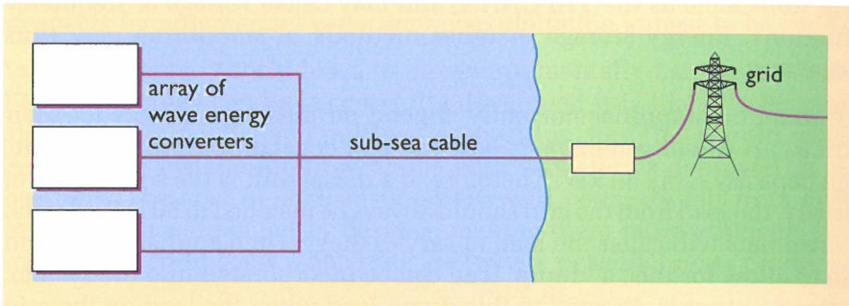


Figure 8.38 Electrical connections for an array of wave energy devices

Finally, although we have dwelt upon short-term fluctuations of seconds or minutes, the wave resource also varies on a day-to-day and season-by-season basis. For those countries in the north-east Atlantic such as the UK, Ireland, Spain and Norway, the seasonal variation shown in Figure 8.39 demonstrates that wave power output reaches a maximum in the bad weather of winter when the electrical demand is greatest (see for example, Rugbjerg et al., 2000 and Petroncini and Yemm, 2000).

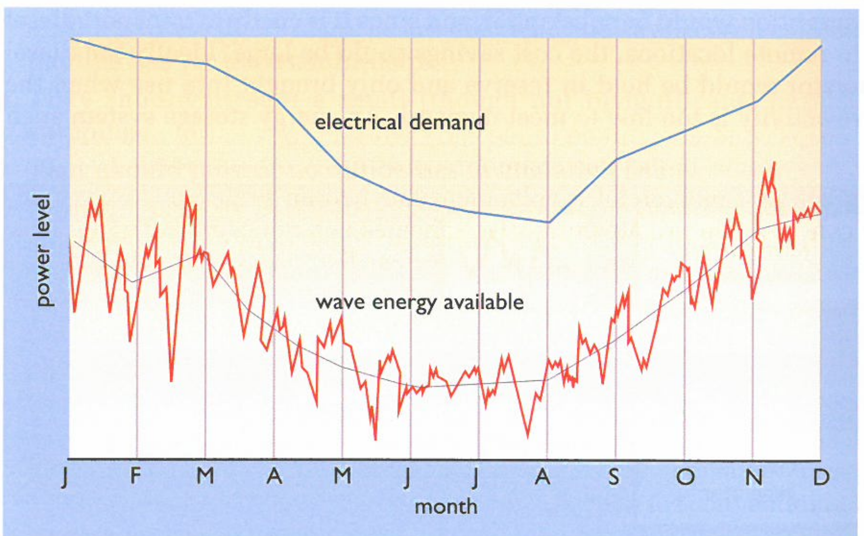


Figure 8.39 Seasonal availability of wave energy and electrical demand for the UK

8.9 Summary

The concept of extracting energy from ocean waves has intrigued people for centuries. The detailed understanding of waves, and of the energy that they contain, is complex, as is the description of a typical sea state which is composed of many waves, with different frequencies moving in different directions at different velocities. However, by developing wave theory even in a simple form we can build up a working knowledge which is suitable for designing wave energy converters.

There are some important outcomes from even a basic appreciation of waves – firstly that the world wave energy resource is extremely large (and even now has not yet been fully assessed). If only a small proportion of this could be harnessed it would make a major contribution to meeting the world's energy requirements.

The waves in deep water are very energy rich, but of course the conditions are difficult to operate in and so wave energy converters for this environment must be highly robust. As waves move towards the shore they lose some of their energy, and while the operating conditions are less strenuous, different technological challenges are raised in designing economic devices for capturing the wave energy. All told, there are over 1000 patents on wave energy devices, resulting in well over 100 wave energy projects – in this chapter a few have been reviewed as being representative of some of the more significant categories of wave energy converter shown in Figure 8.15.

In the UK, while the wave climate is conducive to wave power developments, the political climate has not always been so favourable. In the 1970s and 1980s the UK government's brief to wave energy teams was to design 2 GW schemes. In hindsight we can appreciate that this was remarkably ambitious – analogous to expecting someone to design a Boeing 747 in the early days of aviation without going through the evolution of the biplane, single seater monoplane, jet engine, etc. Attitudes are changing very quickly, however, prompted by the need to address global climate change, by the issue of long-term resource security of fossil fuel supplies and by the increasingly competitive economics of wave energy. Supporting this effort are the EMEC and Wave Hub test sites which have been established in Cornwall and the Orkneys respectively.

UK teams conducted much of the early work in the development of wave energy systems, but as this chapter records many other countries are now very active. Commercial involvement has had an important impact and we can now see private enterprise schemes and concepts emerging from countries such as Norway, Australia, Sweden, Denmark and the USA, as well as the UK. Across the globe, several companies have already commissioned their first wave stations, and more are obtaining permission to exploit sea areas and deploy sea trials.

It should be remembered that the generation of electricity is not the only option for the delivered energy. Desalination, coastal protection, water pumping, mariculture, mineral recovery from sea water and hydrogen generation are among the benefits being developed.

The cost of energy from the current generation of wave energy converters is high, but wave energy developers are confident that with time, experience and technological improvements costs will reduce, rendering wave energy an environmentally attractive and sustainable industry. Indeed some commentators have made the point that no other energy technology (coal, oil, nuclear, wind) has ever started commercial production from such a low unit cost as was initially expected of wave energy. If wave energy costs follow the example of wind power then rapid cost reductions can be expected (Aquamarine Power, 2011b).

The development of wave energy technologies has been a long process, but the economics of current designs are potentially attractive. Proving the long-term survival and cost effectiveness of designs as technologies mature should make the prospect of wave energy stations on a large scale a real possibility – we may well see such converters deployed in large numbers to harvest the considerable wave energy that is present at some locations.

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