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An Overview of Wave Energy Technologies: Status, Performance and Costs

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1 INTRODUCTION

Wave energy can be considered as a concentrated form of solar energy. Winds, generated by the differential heating of the earth, pass over open bodies of water, transferring some of their energy to form waves. The amount of energy transferred, and hence the size of the resulting waves, depends on the wind speed, the length of time for which the wind blows and the distance over which it blows (the fetch). The useful world-wide resource has been estimated at
> 2 TW (WEC, 1993). The UK is particularly well situated, being at the end of a long, stormy fetch (the Atlantic) as can be seen from Figure 1. Only the southern parts of South America and the Antipodes have a more energetic wave climate, due to the circumpolar storms near the Antarctic.

2 WAVE ENERGY IN THE UK

Work on wave energy within the UK began in the early 1970s with a report from the Central Policy Review Staff, which identified the Government's responsibility to assess a wide range of possible energy options to ensure security of energy supplies. The UK Department of Energy (DEn) funded extensive research into wave energy during the period 1974 to 1983 under its Wave Energy Programme. The programme objectives were to establish the feasibility of extracting energy from ocean waves and to estimate the cost of energy if used on a large scale to supply UK needs. The latter objective was addressed by setting a design aim to establish a 2 GW wave power station situated off South Uist in the Outer Hebrides of Scotland. During the course of the programme a large number of devices were considered but found to be uneconomic (ETSU, 1985). With hindsight, the objective of that programme was over ambitious and resulted in massive devices, with corresponding high capital and generating costs.

Following the conclusion of that programme in the early 1980s, the Department of Trade and Industry (DTI) continued to support R&D on smaller devices that were potentially more economic. This allowed wave energy to be developed in a more systematic way. A number of different devices benefited from this: the PS Frog, Circular SEA Clam; the Solo Duck and Shoreline OWC (Thorpe, 1992). As a consequence, a 75 kW OWC device was installed and tested on the island of Islay in Scotland (Whittaker *et al*, 1995). This device provided a large amount of useful information during its service life, which will benefit the design of future shoreline OWCs. However, an independent review showed that, despite improvements in the technology, electricity from wave energy was still too expensive (Thorpe, 1992).
In more recent years, industry (both within the UK and overseas), some Governments and the European Commission have undertaken considerable work on wave energy and have produced a number of new device designs, as well as modifications of existing designs. A recent evaluation of the current status of wave energy (Thorpe, 1999) concluded that the economics of wave energy had improved, so that several devices now had estimated generating costs of about 5 p/kWh (at 8% discount rate), with the potential for even lower generating costs in the future.

As a result of a recent review of renewables based on these values (and other factors – e.g. OST, 99), the UK Energy Minister (John Battle) announced that the Government was launching a new wave power programme (see http://pipe.ccta.gov.uk/coi/coipress.nsf).

There are other signs of the improvements in the prospects for wave, including:
- A report from the Marine Technology Foresight Panel (OST, 1999), that was supportive of the development of wave energy (and other offshore renewables) in the UK.
- The formation of a Scottish Commission to promote the development of a wave energy industry in Scotland;

- The formation of an Implementing Agreement on wave energy within the International Energy Agency;
- The inclusion of wave energy for the first time in the Scottish Renewables Order (SRO3). This has resulted in three devices being successful in the application, as described in other papers in this seminar.

3 TECHNICAL STATUS OF WAVE ENERGY

There is a large amount of ongoing work on wave energy schemes, which cannot be done justice in a brief overview. For ease of presentation, the activities will be divided between the technologies suitable for deployment on the shoreline, near the shore and offshore.

3.1 Shoreline Devices

These devices are fixed to or embedded in the shoreline itself, which has the advantage of easier maintenance and/or installation. In addition these would not require deep water moorings or long lengths of underwater electrical cable. However, they would experience a much less powerful wave regime. This could be partially compensated by natural energy concentration ("hot spots"). The deployment of such schemes could be limited by requirements for shoreline geology, tidal range, preservation of coastal scenery, etc.

One major class of shoreline device is the oscillating water column (OWC). One version of this (the Limpet – see below) has been shown schematically in Figure 2. It consists of a partially submerged, hollow structure, which is open to the sea below the water line. This structure encloses a column of air on top of a column of water. As waves impinge upon the device they cause the water column to rise and fall, which alternatively compresses and depressurises the air column. If this trapped air is allowed to flow to and from the atmosphere via a turbine, energy can be extracted from the system and used to generate electricity. Because of the oscillation in air flow, OWCs normally use Wells turbines to power the electricity generators. These turbines have the property of turning in the same direction regardless of which way the air is flowing.

A number of OWC devices have been installed world-wide (e.g. China, India, Japan, Norway, Scotland), with several commercial schemes currently being built:

- The European Pilot Plant on the island of Pico in the Azores. This plant will be used to test various technologies associated with OWCs (e.g. different types of turbines, see http://www.mech.ed.ac.uk/research/wavepower/vpt.htm) but it also supplies electricity to the local grid (see http://www.adi.pt/superval.uk/fichas/ficha422.html; Falcão, 1998 and this Seminar);
- The Wavegen Limpet on Islay, which uses a novel construction method to reduce construction costs (Figure 2). This device was successful in bidding for inclusion in SRO3 (see Thomson – this Seminar);
- The Energetech OWC in Australia. This uses a novel, variable pitch turbine (potentially with a higher conversion efficiency than the Wells) and a parabolic wall behind the OWC to focus the wave energy on the OEC collector (Figure 3), leading to potentially significant improvements in the economics of OWCs. This scheme already has a power purchase agreement with the local utility and construction is about to begin (see Rudge's poster session at this Seminar).

The other main shoreline/near shore devices are:

- The TAPCHAN, which comprises a gradually narrowing channel typically 3 to 5 m above mean water level (Figure 4). Waves enter the wide end of the channel and, as they propagate down the narrowing channel, their height is amplified until the wave crests spill over the walls to the reservoir, which is raised above sea level. The water in the reservoir returns to the sea via a conventional low head turbine, which generates a stable output due to the storage effects of the reservoir. A demonstration device was built in 1985 at Toftesfallen, in Norway and discussions have taken place for the construction of a 1.1 MW scheme at Baron, Java (contact - per.stephansen@indonor.no).
- The Pendulor, which consists of a rectangular box, which is open to the sea at one end (Figure 5). A pendulum flap is hinged over this opening, so that the actions of the waves cause it to swing back and forth. This motion is then used to power a hydraulic pump and generator. Several small schemes (≥ 5 kW) have been built in Japan and there are plans to develop a larger plant (Osanai *et al*, 1995; Watabe *et al*, 1995).

A considerable amount of work has been done on all these devices, which are coming to the end of their R&D phase, being ready for commercial demonstration (Thorpe, 1999). This is exemplified by the inclusion of the Limpet in SRO3 and the awarding of a power purchase agreement to Energetech for their OWC. However, there is scope for further improvements (e.g. variable pitch turbines, use of valves to improve capture efficiency).

Compared to the multi-megawatt devices developed in the old UK WEP, these devices are much smaller, being rated at (typically) up to 500 kW.

3.2 Near Shore Devices

The main prototype device for moderate water depths (i.e. < 20 m) is the OSPREY developed by Wavegen (Figure 6). This is a 2 MW OWC, with provision for inclusion of a 1.5 MW wind turbine. Since there could be environmental objections to large farms of wind or wave energy devices close to the shore, this system aims to maximise the amount of energy produced from a given amount of near shore area. A prototype device with a steel body failed during problems in installation was near Dounreay (Scotland) in 1996. A new concrete-based design has been developed for deployment in 2000. Again, a considerable amount of work has been done on this device, which is coming to the end of its R&D phase, being ready for commercial demonstration. However, further improvements continue to be made, particularly concerning reductions in civil construction costs (Thorpe, 1999).

3.3 Offshore Devices

This class of device exploits the more powerful wave regimes available in deep water (> 40 m depth) before energy dissipation mechanisms have had a significant effect. In order to extract the maximum amount of energy from the waves, the devices need to be at or near the surface (i.e. floating) and so they usually require flexible moorings and electrical transmission cables. There are many different types of offshore device, each with its own pros and cons.

In contrast to the large devices developed in the UK wave energy programme (ETSU, 1985), early overseas devices concentrated on small, float-based schemes, where the heave of the float was used to pump sea water to drive a motor or a turbine wheel (Figure 7). In these cases the pump could be a conventional one (as in the case of the DWP – Nielsen *et al*, 1995) or a hosepump (a reinforced rubber tube whose inner volume changes with the amount of extension - see http://www4.tripnet.se/technocean/). In comparison to the multi-megawatt designs of the early UK programme, these overseas devices were rated at a few tens of kilowatts each (although they could be deployed in arrays with a greater output).

More recent designs for offshore devices have also concentrated on small, modular devices. Some of the promising ones are shown in Figure 8.

- **The McCabe Wave Pump.** This device consists of three narrow (4 m wide) rectangular steel pontoons, which are hinged together across their beam. These pontoons are aligned so that their longitudinal direction heads into the incoming waves and they can move relative to each other in the waves. The essential aspect of the scheme is the damper plate attached to the central pontoon; this increases the inertia of the central pontoon (by effectively adding mass), ensuring that it stays relative still. Therefore, the fore and aft pontoons move in relation to the central pontoon by pitching about the hinges. Energy is extracted from the rotation about the hinge points by linear hydraulic rams mounted between the central and two outer pontoons near the hinges. Control of the characteristics of the hydraulic system allows the device to be tuned to the prevailing sea state and so optimise energy capture. This energy can be used in two ways: to provide electricity by driving an hydraulic motor attached to a generator, with a rating of ~ 400 kW; to produce potable water by supplying pressurised sea water to a reverse osmosis plant. A 40 m long prototype of this device was deployed off the coast of Kilbaha, County Clare, Ireland and a commercial demonstration scheme is currently being built.

- **The OPT WEC.** The Wave Energy Converter developed by Ocean Power Technology (OPT WEC) in the USA consists of a simple and ingenious mechanical system to drive the generators using mechanical force developed by the wave energy converter. It has very efficient power conversion electronics to optimise the generated electricity. The generators and electronics are housed in a watertight compartment, in marine proven ocean-going buoys. The system employs standard marine grade power cabling and grid connection hardware and software, and a combination of mooring chains and anchors are used for positioning. Underwater hubs and electrical power cables are used for interconnection and transmission to the shore. The OPT system has been extensively tested at a large scale in the Eastern Atlantic and the first commercial schemes are about to be built in Australia and in the Pacific, with a number of other schemes in the pipeline.

- **The Pelamis.** The Pelamis device is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. The wave induced motion of these joints is resisted by hydraulic rams which pump high pressure oil through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. A novel joint configuration is used to induce a tuneable, cross-coupled resonant response, which greatly increases power capture in small seas and control of the restraint applied to the joints allows tuning to the particular sea state. A device is being developed for SRO3, which is rated at 375kW and is 130 m long and 3.5 m in diameter (see http://www.oceanpd.com/ and Yemm – this Seminar).

- **The Archimedes Wave Swing**. This consists of a cylindrical, air filled chamber (the “Floater”), which can move vertically with respect to the cylindrical “Basement”, which is fixed to the sea bed. The air within the 10m – 20m diameter Floater ensures buoyancy. However, a wave passing over the top of the device, alternatively pressurises and depressurises the air within the Floater, changing this buoyancy. This causes the Floater to move up and down with respect to the Basement and it is this relative motion that is used to produce energy. The design for a 2 MW Pilot scheme is currently being finalised (see van Breugel – this Seminar).

The status of these designs is slightly less advanced than that for OWCs. However, several devices have been tested in the sea at near full size (e.g. the OPT WEC and the McCabe Wave Pump) and so are ready for commercial demonstration. All these devices will continue to benefit from ongoing R&D.

3.4 Other Activities

3.4.1 The European Wave Energy Programme

The main areas of activity of this programme include (Russel and Diamantaras, 1995):

- A computerised European wave energy atlas (see http://www.ineti.pt/ite/weratlas);
- Evaluation of offshore wave energy converters;
- Evaluation of power take-off turbines;
- Design of shoreline OWC on the island of Pico in the Azores;
- Evaluation of a novel wave energy conversion system.

3.4.2 The Indian Wave Energy Programme

The Indian wave energy programme started in 1983 at the Institute of Technology, Madras (Ravindran *et al*, 1995 and http://www.niot.ernet.in/ocean-energy.html) and has concentrated almost exclusively on the OWC concept. A 150 kW prototype OWC with harbour walls was built onto the breakwater of the Vizhinjam Fisheries Harbour, near Trivandrum in India. Following the successful testing of this, it is proposed to build a commercial scheme of 10 caissons, each 21 m wide, at Thangassery, on the west coast of India. Each caisson will have two power modules, both with a 55 kW rating, leading to an overall rating of 1.1 MW. These caissons will be spaced at an optimum distance apart, in order to increase their overall capture efficiency to above that of a single caisson.

3.4.3 The Japanese Wave Energy Programme

The most important aspect of this programme is that it has focused on construction and deployment of prototype devices, described above (primarily OWCs and Pendulors). As a result, hundreds of OWC devices have been installed in navigation buoys, which require no external power source. A new step is the recent deployment of a floating OWC called the “Mighty Whale” (see http://gk2.jamstec.go.jp/jamstec/myt.html and Figure 9).

3.4.4 Activities in Korea

Baek Jae Engineering have designed a prototype wind-wave energy scheme, which has many novel features, in particular a floating, lattice structure fabricated from plastics and composites (Figure 10). The new aspects of the design are intended to reduce the overall capital cost of the scheme by minimising the non-productive wave loading on the device. The design is at an early stage of development. Baek Jae Engineering are continuing to develop the design and are intending to progress to testing a prototype in the near future.

3.4.5 Other Activities

There is considerable ongoing work elsewhere, but details are not easily available, for instance:

- **Norway**: development of the ConWEC wave energy device (contact uraa@online.no);
- **Sweden**: development of the IPS buoy and hosepump devices (see http://www.phys.ntnu.no/glos/grupper/stralbol/bolgegrp-e.html);
- **Denmark**: a Government sponsored programme to develop wave energy (see http://www.waveenergy.dk/).
- **USA**: development of numerous designs (e.g. http://www.owec.com).
- **International**: a production of a state-of-the-art overview of wave energy, supported by JAMSTEC and probably to be called “Ocean-Wave Energy: The Resource and Its Utilization”.

4 COMMERCIAL STATUS OF WAVE ENERGY

4.1 Predicted Generating Costs

The assessment of the commercial prospects for wave energy has been a hotly debated field. There are a number of historic reasons for this but, perhaps, there is one underlying cause: until the technology matures, estimates of the cost of power from wave energy devices *"represent a snapshot of the status and costs of the designs at (the current) stages of their development"* (Thorpe, 1992).
That review found support for this proposition, with the predicted generating costs of several devices being reduced by factors of two or more as part of the review activities.

The electricity costs of a number of devices have been evaluated more recently using the same peer-reviewed methodology developed for the last UK review of wave energy (Thorpe, 1999). The resulting costs have been plotted in Figures 11 and 12 against the year in which the design of device was completed. These figures show that there have been significant improvements in the predicted generating costs of devices, so that there are now several with costs of about
5 p/kWh (= US 8 ¢/kWh) or less at 8% discount rate (if the devices achieve their anticipated performance). This indicates that, if these devices can be successfully built and operated, wave energy is already economically competitive in niche markets such as supplying electricity to isolated communities that are not connected to the grid. Furthermore, wave energy has good prospects of being commercially competitive with conventional large-scale power generation (e.g. coal) following further R&D.

It should be emphasised that the predicted costs of generation for the most recent devices are for sites chosen by the device designers. Hence, having different wave power levels and transmission distances, the predicted costs of the devices cannot be compared directly with each other. Instead, these costs should be taken as indicative only.

In addition:

- These costs assume serial production and, as such, they are not expected to be achieved for several years;
- There is uncertainty attached to these costs, which can be overcome only by gaining actual construction and in-service experience.
- Several of the design teams claim lower costs than those presented, for instance the Hosepump is claimed to have generating costs of 2.4 - 4 p/kWh (Eurowave, 1997).
- Some designs such as the McCabe Wave Pump offer the chance for value added performance by providing desalinated water through reverse osmosis at economic rates. This would open up a new large and important market for wave energy.

4.2 The UK Market

The deployment of commercial-sized wave energy devices in the UK is expected in the next few years; the deployment of schemes beyond this date will depend on the technical performance and reliability of these first commercial schemes. On a longer timescale (e.g. 2010 and beyond) the prospects could also be influenced by the deployment of new devices currently being researched. The potential contribution to UK generation from wave energy is
~ 50 TWh/year. However, taking economic factors into account, the likely contribution is reduced to 30 TWh/year, corresponding to 1/10th of current UK electricity demand and a capital investment of ~£ 10 billion. However, it should be emphasised that this market penetration would be accomplished only in scenarios favouring the deployment of renewables (DTI, 1999) and providing wave energy devices do achieve their predicted costs and performance.

4.3 Export Potential

There are well advanced plans to increase the wave energy capacity in the rest of the world to nearly 6 MW in the next few years. Further predictions for future world-wide capacity are, at present, speculative but several companies have plans for the deployment of several MWs per year in the period 2000-2005, with increasing deployment thereafter.

An assessment of the likely markets has been made, taking into account competing sources of electricity (Thorpe, 1999). This indicated that, if the wave energy devices performed as predicted, then their economic contribution would be > 2000 TWh/year. This would correspond to an investment of over £ 500 billion.

5 OTHER FACTORS

5.1 Environmental Impacts

All forms of electricity generation have an impact upon the environment but it is generally perceived that wave power is less environmentally degrading than some other forms of power generation, especially in relation to atmospheric emissions. An evaluation of the life cycle emissions associated with wave energy and other conventional power stations (Figure 13) supports this view (Thorpe, 1999). Many of the potential impacts would be site specific and could not be evaluated until a location for the wave energy scheme is chosen. However, the potential impacts (listed in Table 1) should be considered.

Table 1 Summary of Potential Impacts of Wave Energy

Environmental Effect	Size
Construction/maintenance sites	S
Recreation	S
Coastal erosion	S-M
Sedimentary flow patterns	S
Navigation hazard	S
Fish & marine biota	S
Acoustic noise	S
Endangered species	S
Device/mooring damage	S-M

Key: S - small, M - medium, L - large

5.2 Institutional Factors

There are significant difficulties faced by these early projects.

- **Planning and Consent**. An extensive and expensive consultation process is needed in the UK, because of a plethora of statutory bodies that have an involvement in the coastline. The costs and delays involved cannot easily be accommodated by the small companies building wave energy devices. In other countries, this process is much more streamlined.
- **Grid Connection**. Good locations for wave energy devices are often situated near the end of the distribution grid and any would-be developers will have to pay grid connection charges. The limited experience to date in this area indicates that, in some countries, such charges can be very high, representing a major cost centre that lies outside the control of the developers.
- **Design and operation**. Wave energy devices run the risk of being put in the same category as offshore oil production platforms (with regards to factors of safety in their design and operation). These are designed and operated with a view to their (generally) high levels of manning and the dangerous nature of the products that they handle. Therefore, the level of conservatism in design codes and health and safety procedures might not be appropriate to a wave energy device.
- **Other Factors.** The Marine Technology Foresight Panel recently issued the results of a review of offshore energy (both hydrocarbons and renewables – OST, 1999). This laid out a programme for development of wave energy (*inter alia*) and made several recommendations.

6 SUMMARY

Wave energy has advanced significantly in the past five years. Much of this work has been undertaken by SMEs. In addition, there has been support from national and international bodies. As a result, some wave energy devices are at the end of their R&D phase (although improvements continue) and several are currently being deployed (or will be deployed in the next few years). Some devices are already competitive in niche markets; other devices require further R&D to achieve this. If current work is successful, then wave energy could make a substantial contribution to global electricity supply (with reductions in greenhouse and acid gas emissions) and supply of potable water. However, the priority for wave energy is to demonstrate the survivability and reliability of the first devices in order to overcome the credibility problems resulting from the early days of development.

The views expressed in this paper are those of the author and do not necessarily represent those of any organisation with which he may be associated. The data presented is drawn from the author’s own researches, supplemented by published information.

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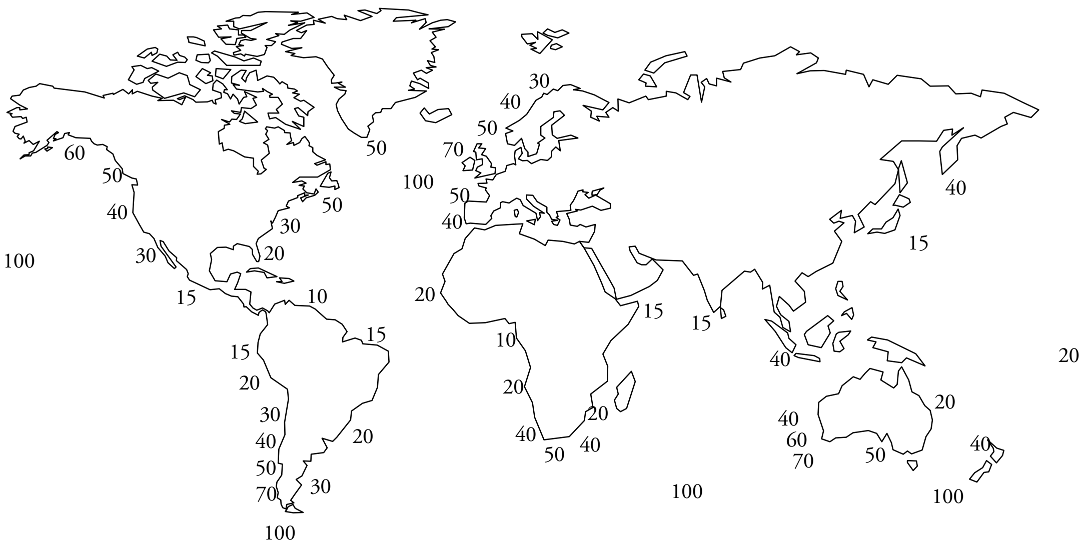
Figure 1 Approximate Global Distribution of Wave Power Levels



Wave power levels are approximate and given as kW/ m of wave front

Figure 2 Side View of the Limpet OWC

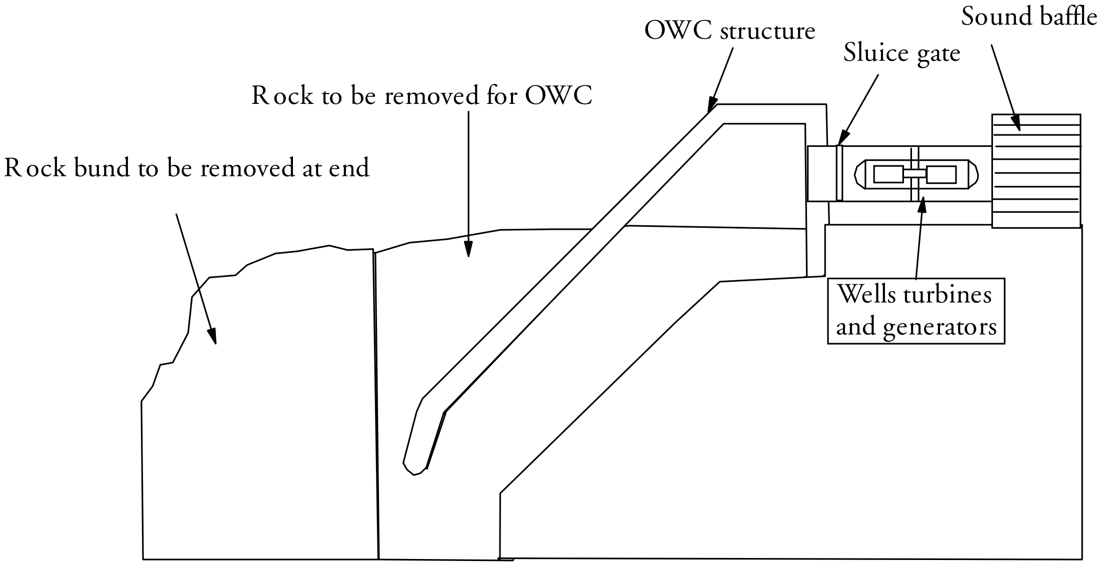
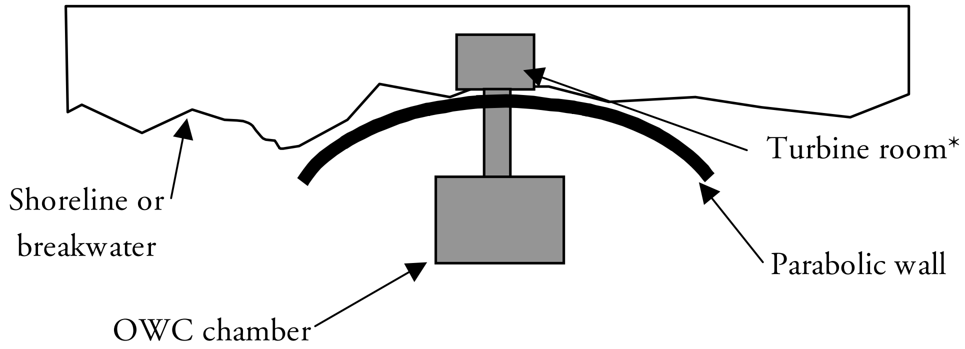


Figure 3 Outline of the Energetech OWC



* New design of variable pitch turbine

Figure 4 Outline of the TAPCHAN

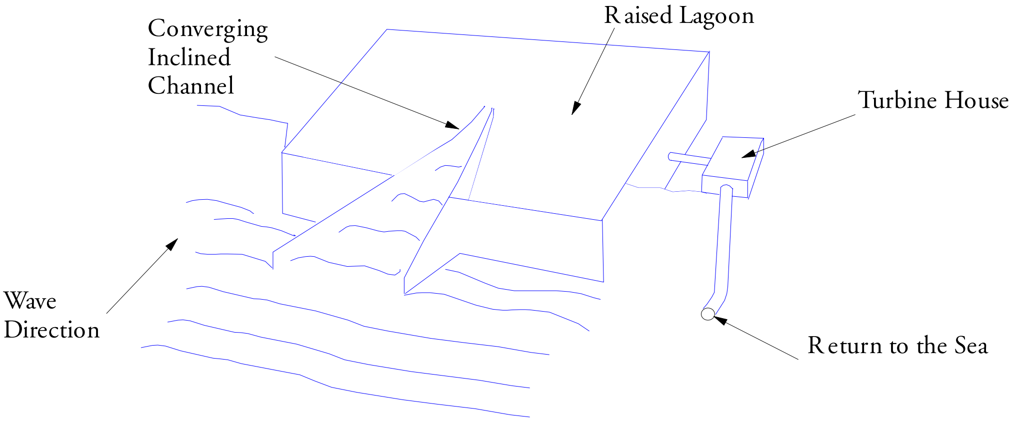


Figure 5 Outline of the Pendulor

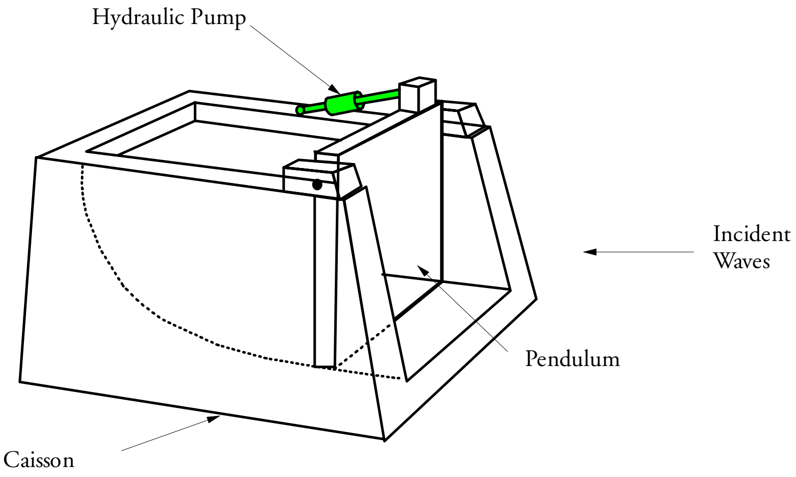


Figure 6 The OSPREY Wind-Wave Energy Device

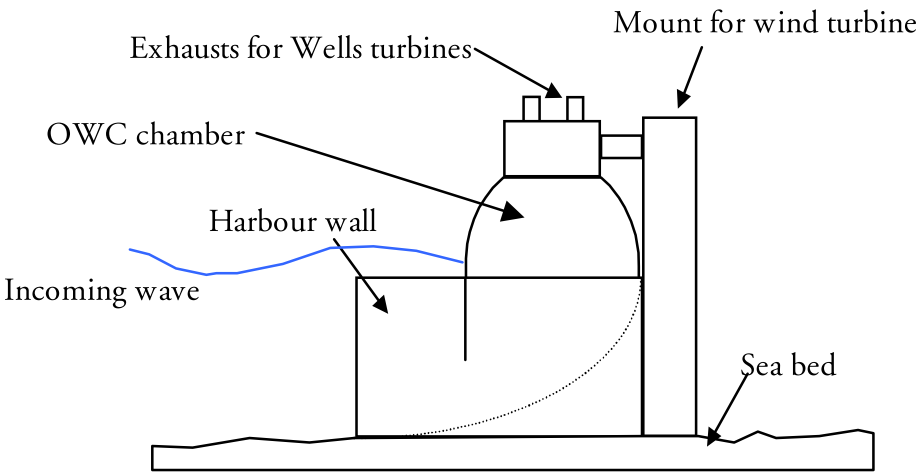


Figure 7 Early Offshore Wave Energy Devices

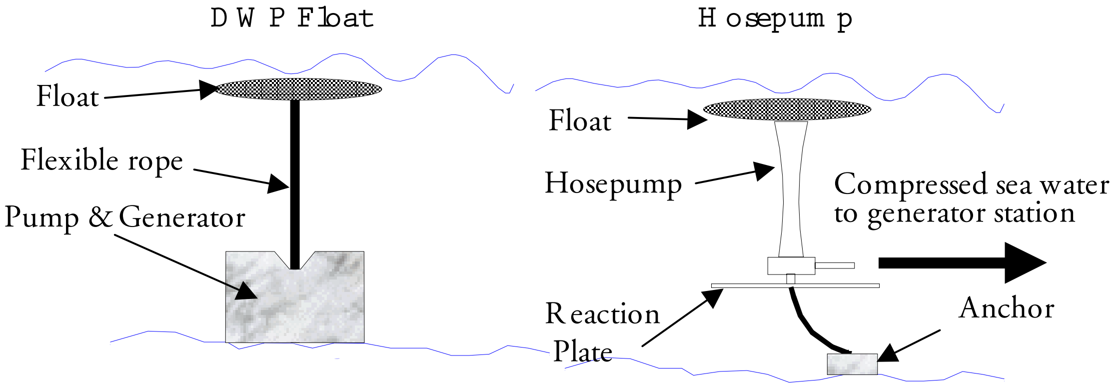
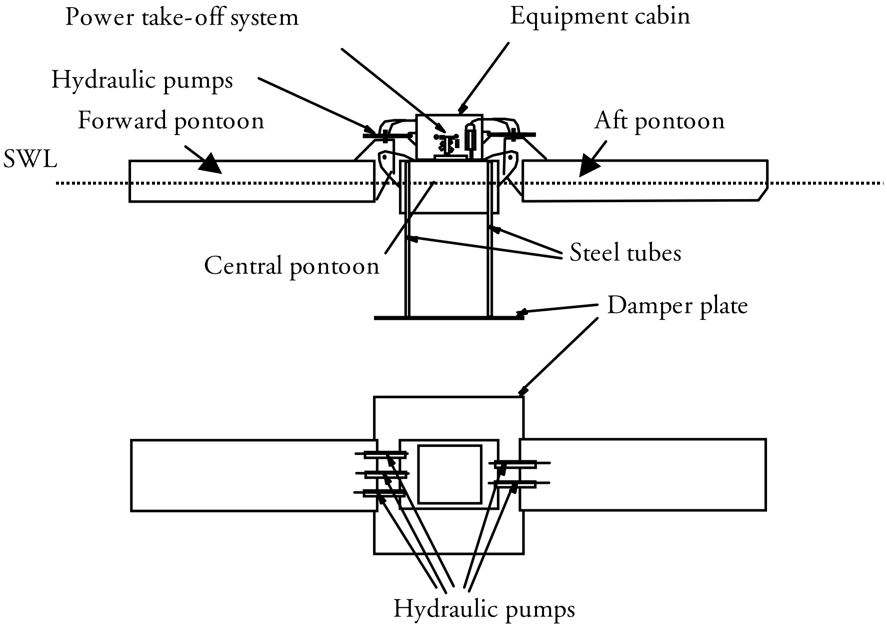


Figure 8 Promising Offshore Devices

The McCabe Wave Pump



The OPT WEC

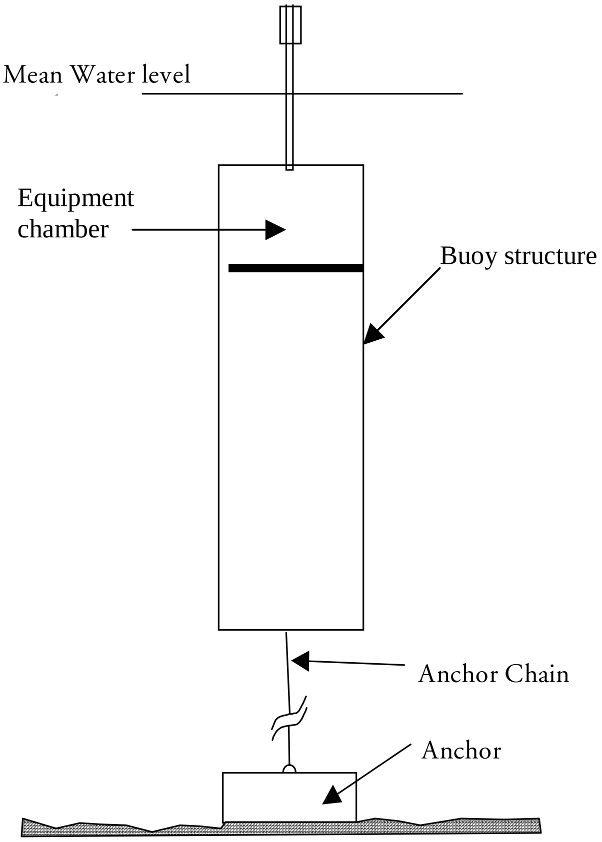
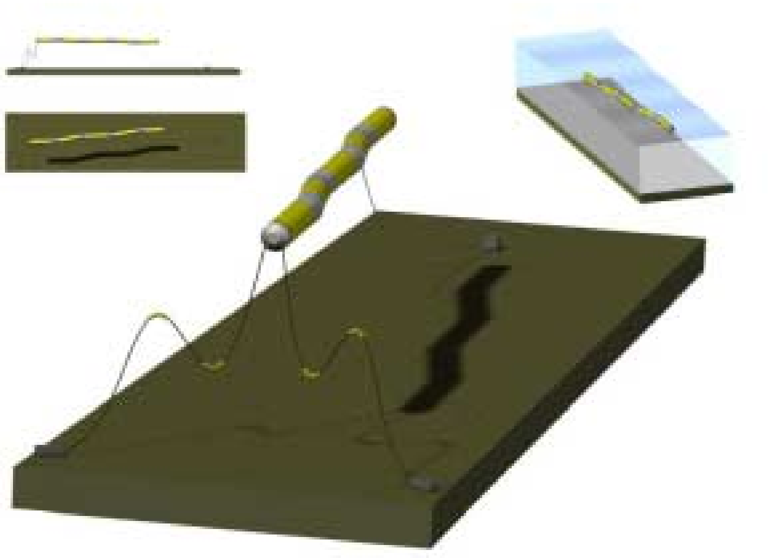
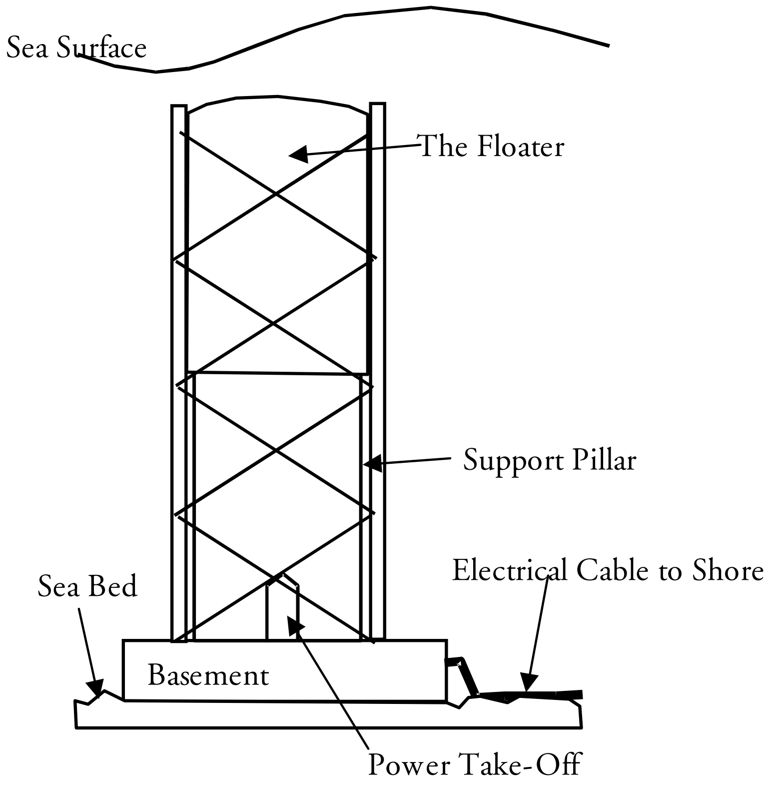


Figure 8 (continued) Promising Offshore Devices

The Pelamis



The Archimedes Wave Swing



9 The Japanese “Mighty Whale” OWC

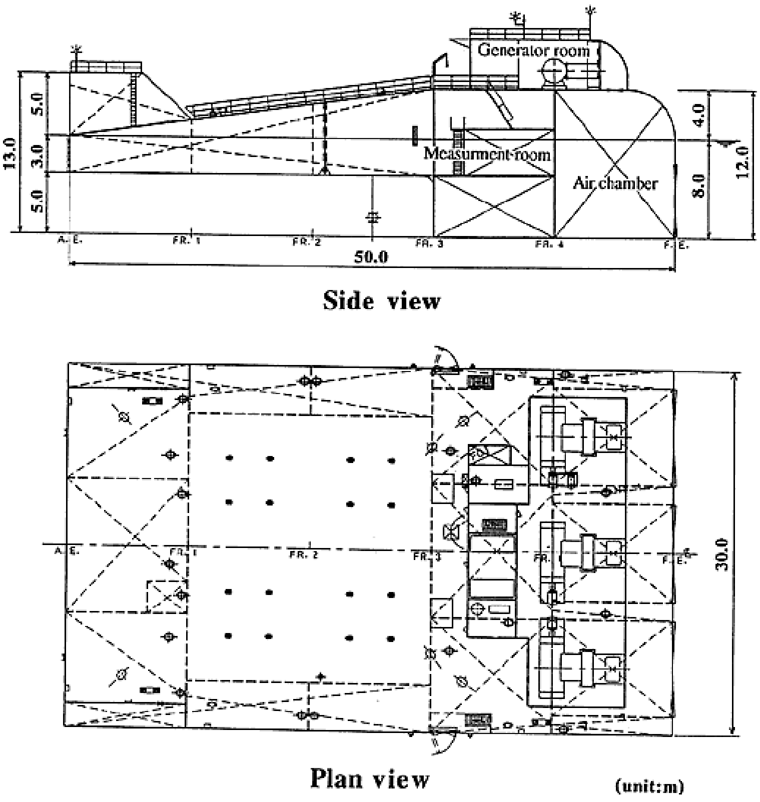


Figure 10 The Shim Wind-Wave Device

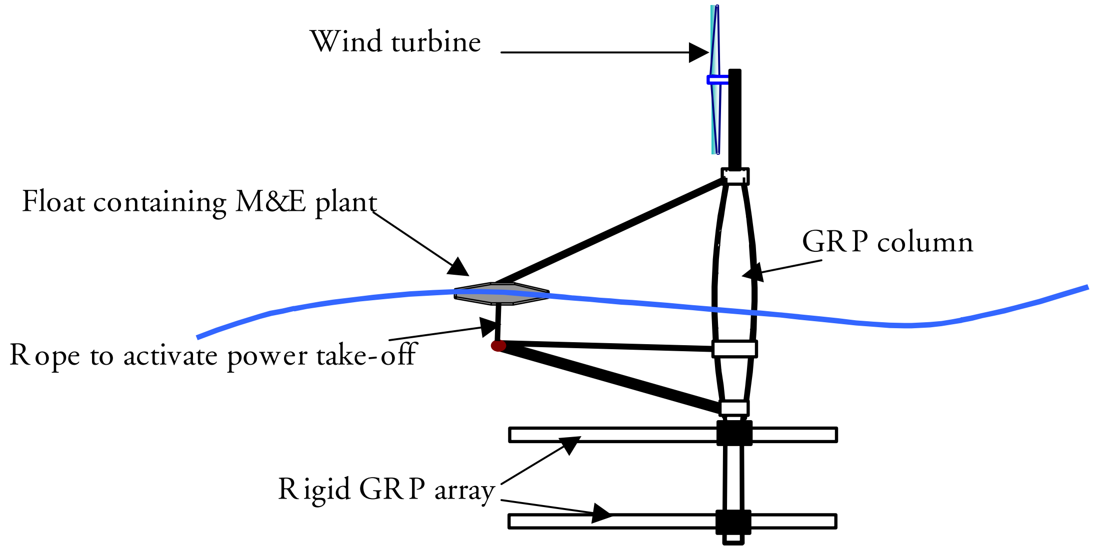
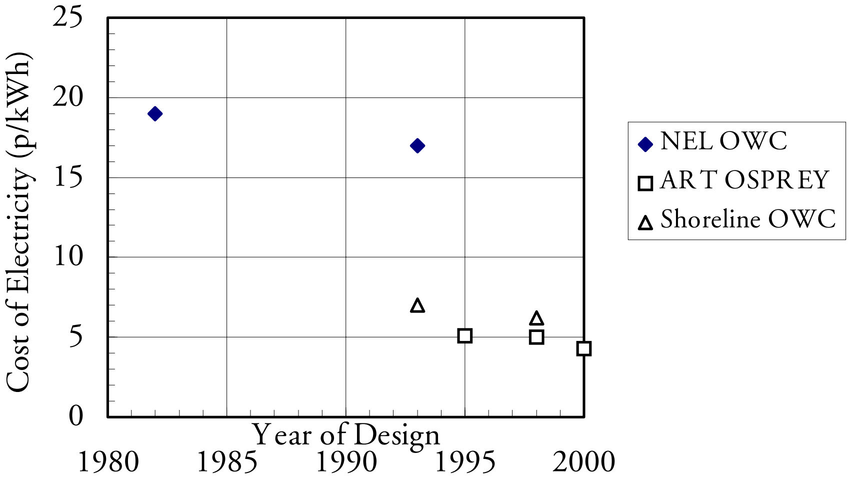
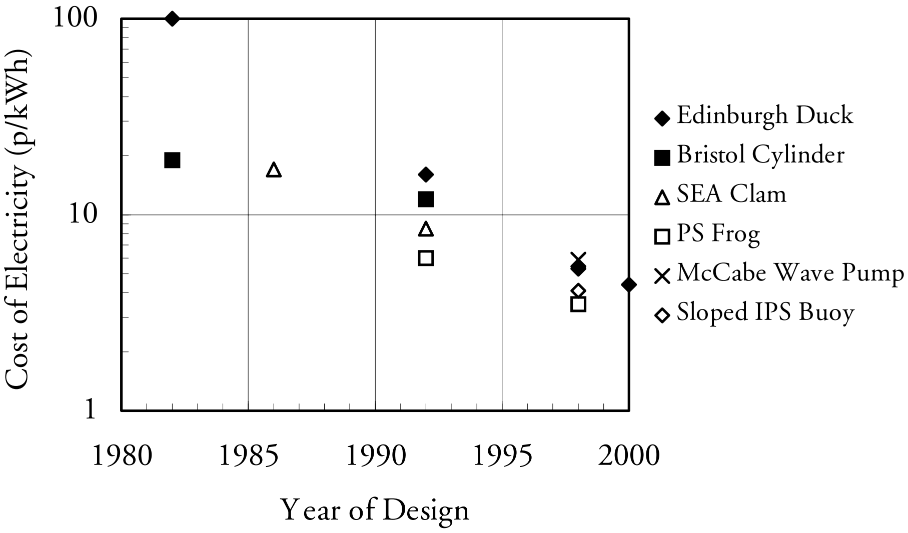


Figure 11 Evolution of Predicted Electricity Costs for OWCs*



Key. * at 8% discount rate.
Costs for year 2000 design incorporate improvements already quantified.

Figure 12 Evolution of Predicted Electricity Costs for Offshore Devices*



Key. * at 8% discount rate.
Costs for year 2000 design incorporate improvements already quantified.

Figure 13 Comparison of Life Cycle Emissions of CO_2