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9: ECONOMICS OF WAVE POWER

George Hageman [1]

Abstract

Although wave power has not yet moved into the commercial marketplace, it is much closer now than it was ten years ago. Within the last decade, several full-scale prototypes and demonstration plants have been built, ranging in size from 20 kWe to 500 kWe, and most of these are still operating. In the economic evaluation presented herein, levelized energy costs are computed for land-based, caisson-based, and offshore wave power plant designs derived from this recent experience.

Land-based Tapered Channel technology, developed in Norway, is on the verge of commercialization, with orders placed for two small plants in Australia and Indonesia. Japanese caisson-based systems are expected to enter the Pacific island market during the next five years. The development of offshore wave power is less advanced. Without long-term demonstration, private financing of an offshore project is unlikely, due to large uncertainties in absorber fabrication cost, plant maintenance requirements, component durability, and wave energy absorption efficiency.

For plant sizes of 30 MWe or less, the projected cost of wave-generated electricity is lower than that for other ocean energy technologies. At this scale, wave power is also less expensive than small hydropower or diesel generation. Where demand growth is sufficiently high to warrant construction of a coal-fired plant, however, wave power loses its competitiveness with fossil fuels, although it remains the least costly ocean energy option for all but the largest tidal power plants.

Several co-products enhance wave power's economic appeal, including seawater pumping for aquaculture, fresh water production by direct reverse osmosis, and breakwater protection. The case is made that for island applications, fresh water may be more valuable than electricity, in terms of both market size and energy impact.

Given a scenario of commercial success in island markets, long-term demonstration of offshore components and systems, and the development of an onshore infrastructure for the storage and distribution of hydrogen, wave power can ultimately supply a large fraction of global demand for electricity, heating, and transportation fuel.

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Introduction

As of this writing, there is less than half a megawatt of grid-connected wave generating capacity operating worldwide, distributed among five demonstration plants. These are not commercial projects, however, in the sense that their construction and operation is supported entirely by revenue from the sale of electricity. All have received financial assistance from national, regional, or local governments, as well as private-industry funding from within the developing companies.

This chapter is divided into six text sections. The first section describes the methodology used to estimate energy costs, and the next section presents results for land-based, caisson-based, and offshore power plant designs. Capital cost is the most important component of any wave energy economic assessment, and its breakdown is analyzed in the third section. The fourth section describes the economic risks likely to be encountered in the development of a wave power project and how they can be reduced. The fifth section reviews various wave energy applications and outlines alternative market development scenarios. The last section compares the life-cycle cost of wave power with that of other energy technologies, drawing on examples from the southwest Pacific Ocean, Hawaii, northern California, and the United Kingdom.

Economic Assessment Methodology

Levelized energy costs were computed using financial parameters specified in the Electric Power Research Institute Technical Assessment Guide (EPRI TAG™; parameter values are given in the Appendix at the end of this chapter). These reflect the life-cycle costs that would be experienced by a regulated, investor-owned utility in the United States. It should be noted, however, that the first commercial wave power plants probably will be financed as independent projects, where the owner/operator sells power to a utility. There is no standard formula for computing energy costs in such cases, because of the wide variability in project financing schemes. For example, the plant may be sold to the utility after an initial period of successful operation under a power-purchase agreement, but well before the end of its service life. Under these circumstances, a single levelized energy cost would be difficult to define.

Nevertheless, a standard formula is required if economic comparisons are to reflect differences in technology cost-effectiveness rather than differences in accounting methods, financing schemes, or government monetary policies. The EPRI TAG™ was chosen because it has been developed for just this type of analysis and is well documented (Electric Power Research Institute, 1987).

Capital and operating cost estimates originating outside the United States were converted to U.S. dollars using the exchange rate in effect at the time the original estimate was made (see Appendix). All original-year costs were escalated to 1990 at an annual inflation rate of 6%.

Where capital cost breakdowns were available, absorber structure typically accounted for the largest share of the plant's direct cost. It was also evident that concrete and steel fabrication costs varied significantly from country to country. In order to more clearly reveal economic trends related to the efficient use of structure, a standard set of unit fabrication costs was developed. These costs are thought to be typical of small U.S. fabrication yards, and are given in the Appendix.

Levelized Energy Costs

It is significant that the five demonstration plants now operating are all land- or caisson-based systems. Floating devices are less well-developed, and as a result, assessments of their economic feasibility are less certain.

On the other hand, the cost and performance of land- and caisson-based systems are more sensitive to local site conditions. The cost of site preparation for a Tapered Channel power plant or land-based oscillating water column depends greatly on shoreline geology and topography. To the extent that cast-in-place concrete construction is required, the economic feasibility of these schemes also depends on the local availability of aggregate material. Likewise, the cost of a wave energy breakwater is influenced by the need for seafloor foundation leveling, as well as the local availability of suitable rock for a rubble mound on which the caissons would rest.

The sheltering effect of coastal features, such as headlands and peninsulas, and the effects of wave refraction and shoaling are much greater nearshore than offshore. Consequently, the performance of land- or caisson-based systems for a given deep-water wave resource is highly dependent on the exact coastal location of the plant.

Therefore, while cost and performance projections for land- and caisson-based wave power plants draw on greater experience, they are also more site-specific. Projections for offshore systems are less certain, but are more generally applicable for a given regional wave climate.

Land- and Caisson-Based Systems

As previously mentioned, less than half a megawatt of grid-connected wave generating capacity is operating worldwide. This is overwhelmingly dominated by a 350 kWe Tapered Channel plant at Toftestallen, on the North Sea coast of Norway, which has been operating continuously since the third quarter of 1986. Developed by Norwave A.S., this demonstration plant has survived several severe storms, including one which destroyed a nearby cliff-based oscillating water column system.

Norwave is the only company that can be said to have realistic prospects for commercial wave power development in the near-future. Based on the proven durability of the Toftestallen project, orders have been placed for two 1.5 MWe plants:

one on the south coast of Java, in Indonesia, and the other on King Island, in Bass Strait, just north of Tasmania.

Cost and performance projections for three Tapered Channel projects are given in Table 1. The following comments are based on telephone conversations with Even Mehlum (1990), a founder and principle owner of Norwave A.S.

The reservoir for the Toftestallen demonstration was built by damming two small inlets to the island's interior bay (Figure 1). A collector channel, 2-3 m wide and 7 m deep, was mined into the rock at the head of a natural gully. The gully is 60 m wide at its entrance and funnels waves into the collector channel, which leads to the converter. The concrete walls of the converter are formed to a height 3 m above sea level, and as waves travel along its 60 m length, they spill water over its sides and into the reservoir. Water then drains back to the sea through a Kaplan turbine/generator.

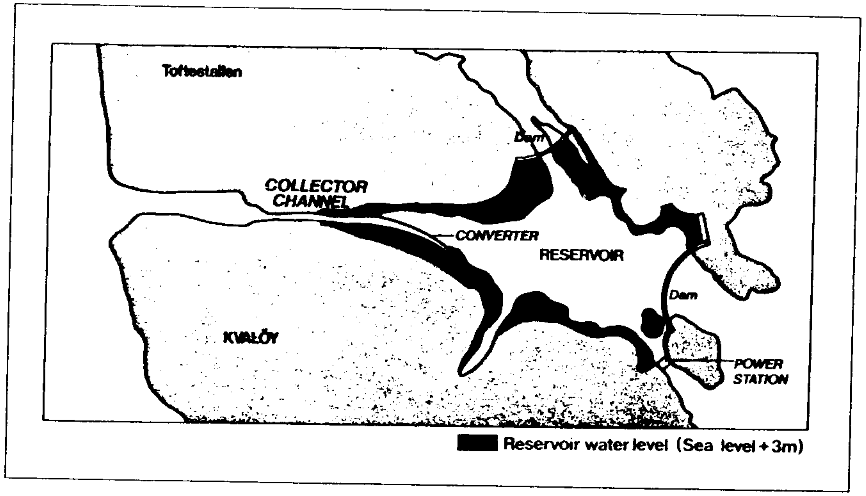


FIGURE 1. Tapered Channel demonstration plant. (Modified after JEFFREYS, 1985.)

The plant's annual output given in Table 1 is based on a projected wave energy resource of 25 kW/m, whereas the incident wave power measured at Toftestallen during the past five years has averaged only 7 kW/m. It should also be noted that the projected capital cost is based on an identical plant built at the same site, incorporating "lessons learned" during the construction of the demonstration plant and not requiring extensive monitoring instrumentation.

The purpose of the Toftestallen project was to verify wave/channel hydrodynamic performance rather than optimize electric power generation. In order to keep costs down, a 350 kWe generator was used, even though it is much smaller than optimal for this size reservoir in the projected wave climate.

TABLE 1. Cost and performance of Tapered Channel power plants. [a]

Location:	Toftestallen (Norway)	Java (Indonesia)	King Island (Australia)
Average wave power:	25 kW/m	20-25 kW/m	30-32 kW/m
Collector opening width:	55 m	unknown	unknown
Reservoir surface area:	5,500 m^2	8,100^2	unknown
Plant capacity:	0.35 MWe	1.5 MWe	1.5 MWe
Annual output:	1.7 GWh	10 GWh	9 GWh
Capacity factor:	25%	76%	68%
Initial investment:	$3,560/kWe	$2,000/kWe	$3,290-3,840/kWe
Annual O&M cost:	$18/kWe	$33/kWe	$33/kWe
Cost of energy:	8.0 ¢/kWh	3.6 ¢/kWh	6.2-7.2 ¢/kWh

[a] A plant service life of 40 years and a construction time of one year was used for all projects. Costs are in 1990 constant dollars. See Appendix for financial parameters and currency exchange rates. (Data from NORWEGIAN ROYAL MINISTRY OF PETROLEUM AND ENERGY, 1987; MEHLUM, 1990.)

The Java plant best represents the relationship between generator capacity, plant output, and reservoir size. Its capital cost is less than two-thirds that of the King Island project, even though both plants have the same generation capacity. This is largely due to the remoteness of the King Island site, which requires the construction of a 5 km access road and overland transmission line.

Given the more energetic wave climate at King Island, Norwave expects a higher capacity factor there, but the plant's annual output is limited by the small size of the island's utility grid. This emphasizes the importance of accurate demand forecasting; no matter how cost-effective a wave energy device is at a given site, the project won't be economically feasible if there isn't sufficient demand for the generated electricity.

Norwave projects a 40-year service life for its Tapered Channel power plants, which are quite similar to long-lived, conventional, hydroelectric plants. Construction of the 1.5 MWe projects is expected to take 12 to 18 months.

Turning next to caisson-based systems, Table 2 presents cost and performance data for three oscillating water column (OWC) designs, and one pivoting flap system. The Toftestallen and Tongatapu projects were based on stand-alone caissons. In the two Japanese designs, however, the caissons are placed next to one another, forming a continuous breakwater.

TABLE 2. Cost and performance of caisson-based wave power plants. [a]

Device:	Double-Acting MOWC	Double-Acting MOWC	Single-Acting OWC	Pivoting Flap
Developer:	Kvaemer Brug A/S	Kvaemer Brug A/S	Takenaka Corporation	Muroran Institute of Technology
Location:	Toftestallen (Norway)	Tongatapu (Tonga)	Kashima Port (Japan)	Muroran Port (Japan)
Water depth:	seaside cliff	reef crest	4.5 m	5 m
Average H_S:	unknown	unknown	1.4 m	2.0 m
Average T_S:	unknown	unknown	8 sec	6 sec
Average wave power:	15 kW/m	21 kW/m	unknown	11 kW/m
Caisson width:	10 m	18 m	7 m	25 m
Number of caissons:	one	four	20	10
Plant capacity:	0.5 MWe	2 MWe	1.5 MWe	1.5 MWe
Annual output:	0.64 GWh	5.8 GWh	4.1 GWh	6.9 GWh
Capacity factor:	15%	33%	31%	53%
Initial investment:	$1,610/kWe	$4,490/kWe	$7,320/kWe	$7,030/kWe
Re-investment:	none	none	none	$2,560/kWe every 15 yr
Annual O&M cost:	$16-32/kWe	$45-90/kWe	$57/kWe	$70/kWe
Plant service life:	25 yr	25 yr	25 yr	45 yr
Cost of energy:	16-17 ¢/kWh	19-21 ¢/kWh	33 ¢/kWh	20 ¢/kWh

[a] A construction time of one year was used for all projects. Costs are in 1990 constant dollars. See Appendix for financial parameters and currency exchange rates. (Data from BONKE AND AMBLI, 1987; TOMMERBAKKE, 1988A; WATABE AND KONDO, 1989; CHINO, NISHIHARA, AND NAKAKUKI, 1989.)

The largest wave power plant built to date was developed by Kvaerner-Brug A/S, a large Norwegian hydropower company. Kvaerner Brug's caisson design consists of a rectangular capture chamber, and a harbor formed by extending the side walls of the chamber in a seaward direction. Hydrodynamic interaction between the harbor and capture chamber causes the OWC to have several natural frequencies, and this concept is referred to as a multi-resonant oscillating water column, or MOWC.

A 500 kWe demonstration plant based on this concept was built at Toftestallen, alongside Norwave's Tapered Channel project. The turbine was a monoplane Wells design. The resonant harbor was excavated out of the island's cliff wall (Figure 2).

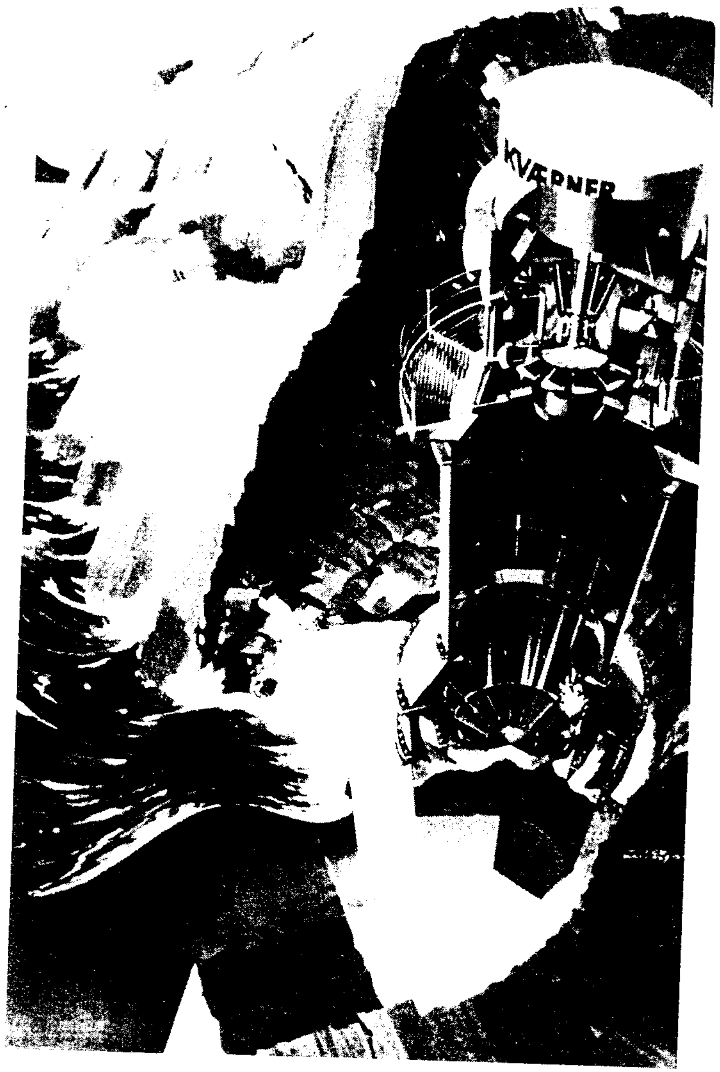


FIGURE 2. MOWC demonstration plant at Toftestallen. (Courtesy of Kvaerner Brug A/S.)

From November 1985 until December 1986, electric power was generated only when personnel were present to run tests and conduct measurements. The plant began fully automatic operation in January 1987, running for two years until it was destroyed by a severe storm in January 1989 (Reuter News Service, 1989).

As with Norwave, Kvaerner Brug's Toftestallen cost estimate is based on an identical plant built at the same site rather than the actual cost of the demonstration plant itself. Also note that the 15 kW/m resource for Kvaerner Brug's performance estimate is based on the average incident wave power *when plant output was measured*, and so does not represent an annual average. While Norwave's turbine/generator was undersized for the reservoir at Toftestallen, Kvaerner Brug's 500 kWe unit was too large for a 10 m caisson, which accounts for its projected low capacity factor (Tommerbakke, 1988b).

Kvaerner Brug also developed a commercial plant design for the south Pacific Kingdom of Tonga. This project, now abandoned, better represents the relationship between turbine/generator capacity and capture chamber size. The plant's capacity factor more than doubles, but the larger capture chamber involves a considerably higher concrete fabrication cost. The resonant harbor would have been formed as part of the caisson, and the reef crest site at Tongatapu would have involved more excavation than was required at Toftestallen (Figure 3).

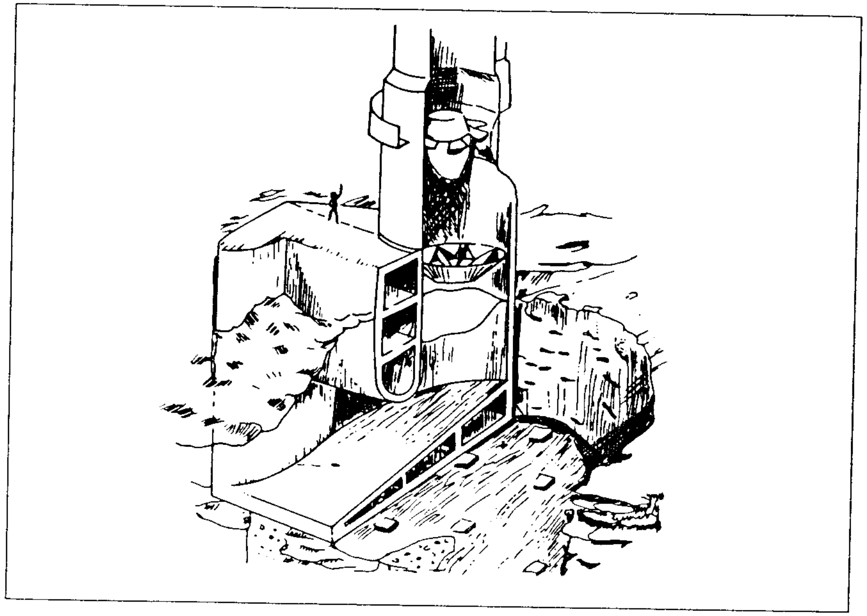


FIGURE 3. Caisson-based MOWC design developed by Kvaerner Brug for Tongatapu. Each caisson houses a 500 kWe Wells turbine/generator. (From STEEN, 1985.)

Kvaerner-Brug's MOWC is double-acting, in that the Wells turbine absorbs energy from both the rise and fall of the oscillating water column. A single-acting OWC device, which absorbs energy only from the water column's rise, has been developed by Takenaka Corporation in Japan. It consists of relatively narrow caissons which act as capture chambers. Output from several caissons is manifolded into a high-pressure air tank, which drives a conventional impulse turbine. Air is drawn into the caissons through check valves as the water column falls. When the water column rises, the air is directed to the manifold through a different set of check valves (Figure 4).

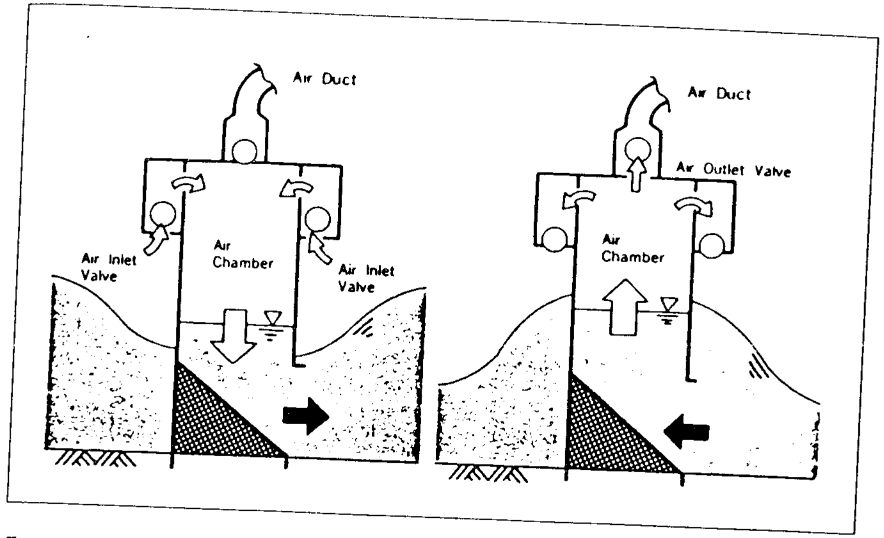


FIGURE 4. Takenaka Corporation's single-acting OWC concept (Modified after CHINO, NISHIHARA, AND NAKAKUKI, 1989.)

A 30 kWe demonstration plant has been operating at Kujukuri, on Japan's Pacific Ocean coast, since March 1988 (Chino, Nishihara, and Nakakuki, 1989). Ten steel caissons, 2.1 m in diameter and 11.8 m high, are connected by an 0.8 m diameter duct to an onshore cylindrical air tank. The air tank floats in a ground tank of water and can be weighted with ballast, such that it sinks deeper into the ground tank, increasing the pressure against which the OWC units must work. The compressed air drives a radial flow turbine/generator, which powers a seawater pump for a nearby flatfish aquaculture pond.

Based on their operating experience with this plant, Takenaka Corporation has developed a conceptual design for a 1.5 MWe plant at Kashima Port (Figure 5). It should be noted that their capital cost estimate does not include fabrication of the wave-absorbing caissons, which is assumed to have been financed by some other source for shore or harbor protection.

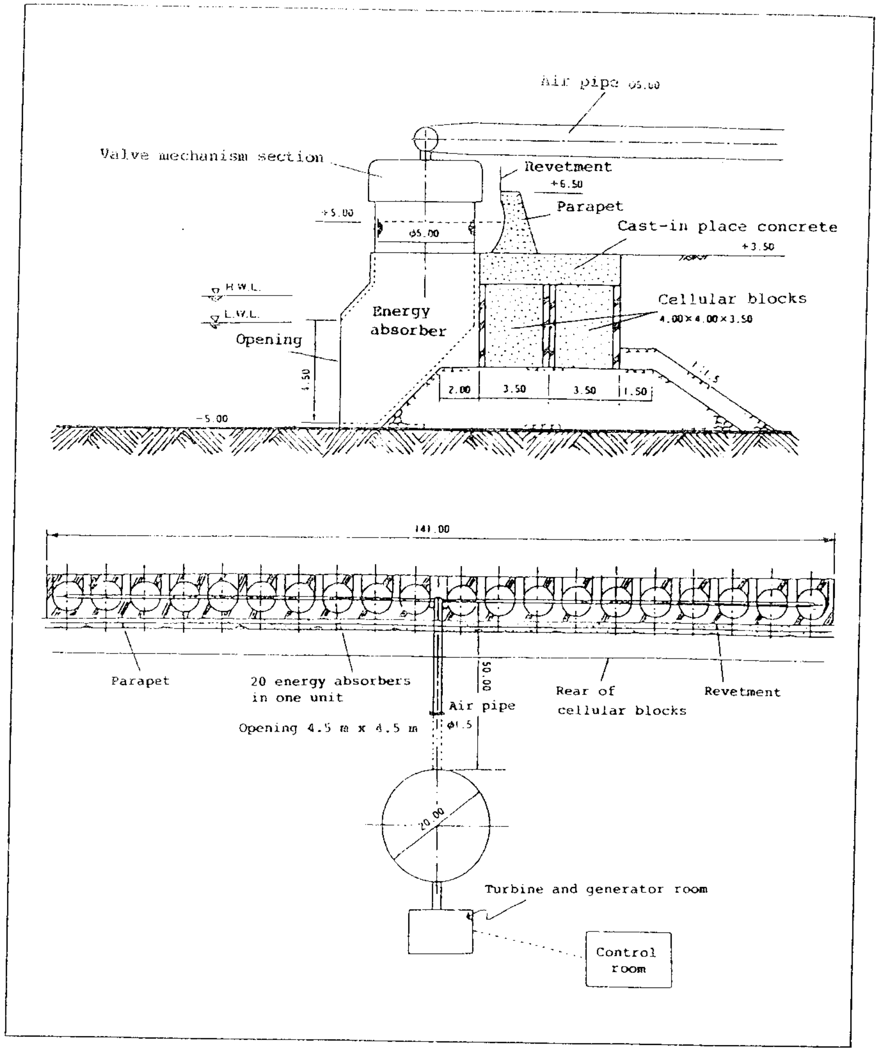


FIGURE 5. Conceptual design of a 1.5 MWe single-acting OWC plant, developed by Takenaka Corporation for Kashima Port. (From CHINO, NISHIHARA, AND NAKAKUKI, 1989.)

For over a decade, the Muroran Institute of Technology has developed a caisson-based pivoting flap device, which it calls the Pendulor System. The Pendulor itself is a stiffened steel plate that hangs down from the roof of a capture chamber. Unlike fixed OWC systems, where the capture chamber extends below the sea surface, the Pendulor System capture chamber is entirely open to the sea (Figure 6).

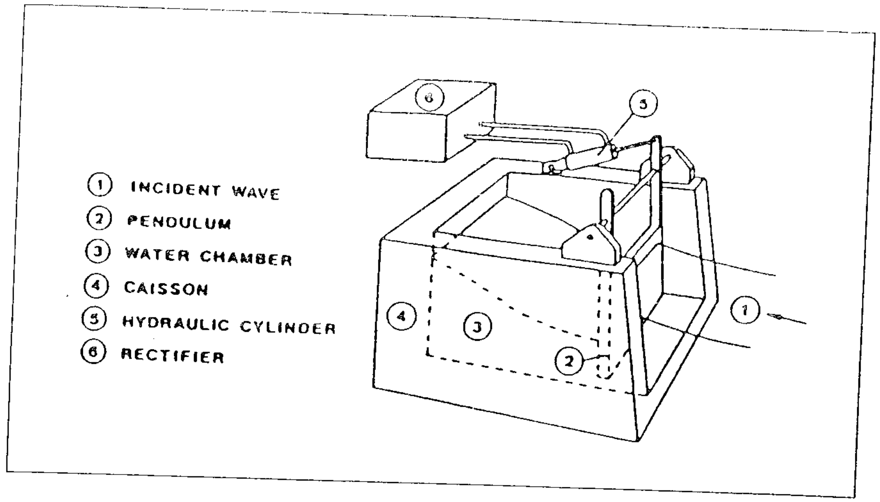


FIGURE 6. Caisson-based pivoting flap concept developed by Muroran Institute of Technology. (From KONDO AND WATABE, 1990.)

Incident waves interact with waves reflected off the back of the chamber to create a standing wave. The Pendulor is positioned at the node of this standing wave, where horizontal forces are at a maximum. As the Pendulor swings in response to these surge forces, it drives a double-acting hydraulic cylinder, which in turn drives a pair of hydraulic motors coupled to an electric generator.

In April 1983, a 5 kW (hydraulic motor rating) prototype was installed at Muroran Port, on the south coast of Hokkaido. The prototype caisson is sited in front of an existing seawall, in a water depth that ranges from 2.5 m at low tide to 4 m at high tide. Two capture chambers have been built into the caisson, but only one has been fitted with a Pendulor.

Twenty months after its installation, the Pendulor was bent during a severe storm, and the shock absorbers for the end-stops, which prevent over-stroking of the cylinder, had to be redesigned. A new Pendulor was installed in November 1985, and the prototype has survived several severe storms since then, without damage.

A small Pendulor System that generates electric power was deployed in 1981. Rated at 20 kWe, this unit is used to heat the public bath of a fishing cooperative at Mashike Harbor, on Hokkaido's west coast (Kuroi, 1983). Unfortunately, its Pendulor was also damaged by a storm, just three months after installation. It was replaced by a shorter Pendulor in 1983, which left a considerable gap at the bottom of the capture chamber. While this has prevented further damage, it has also lowered the system's conversion efficiency (Watabe, 1990). Nevertheless, the plant continues to operate.

Based on their experience with these two systems, Watabe and Kondo (1989) have developed a conceptual design for a 1.5 MWe plant at Muroran Port (Figure 7). Unlike Takenaka Corporation, their projected initial capital investment does include the caissons, and these account for 75% of the total plant cost.

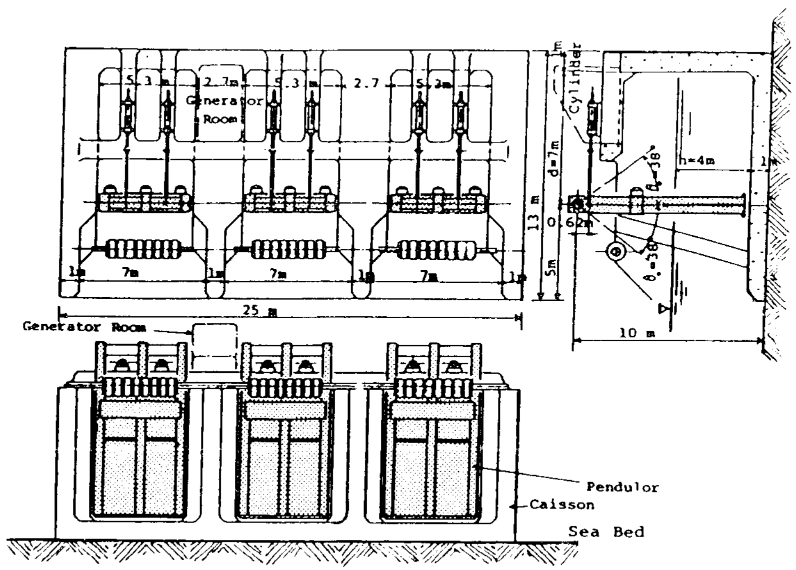


FIGURE 7. Caisson-based pivoting flap design. Each caisson contains three Pendulors, which drive a 150 kWe power conversion system. (Modified after KONDO AND WATABE, 1989.)

Watabe and Kondo (1989) project a 50-year service life for the breakwater caissons, but only a 15-year life for the balance of the plant. A 45-year plant life was used in Table 2, because it would not be cost-effective to replace balance-of-plant components at the end of the 45th year, for only five more years of caisson life.

Although incident wave power estimates were not published in the Takenaka design study, some inferences can be made by comparing wave statistics between Muroran Port and Kashima Port. Incident wave power is directly proportional to the square of significant wave height (H_S), multiplied by significant wave period (T_S). Thus, incident wave power at Kashima Port is about 35% less than that at Muroran Port, while Takenaka Corporation's proposed breakwater length is 45% shorter. If both plants were equally efficient, then the annual electricity output of Takenaka Corporation's design should be only about 2.5 GWh (65% x 55% x 6.9 GWh), but at 4.1 GWh, it is considerably higher.

This suggests that Takenaka Corporation's OWC is more efficient than Muroran Institute's pivoting flap. At $7,030/kWe, it is also much more expensive. Apart from the breakwater caissons, Muroran's balance-of-plant cost is only $2,560/kWe. If caisson fabrication and deployment can be financed by some other source (as has been assumed by Takenaka Corporation), and all other parameters in Table 2 remain the same, then the levelized energy cost at Muroran Port would be only 9.2 ¢/kWh over the 15-year service life of the balance-of-plant components.

In passing, it should be noted that annual O&M costs for the Kvaerner Brug designs were estimated by the developers to be 1-2% of initial investment. Muroran Institute of Technology uses a 1% estimate, whereas Takenaka Corporation has projected O&M costs on the more accurate basis of annual materials and labor requirements.

Offshore Systems

There has been much less full-scale experience with floating wave energy devices than with land- or caisson-based systems. The specially built ship, *Kaimei*, was deployed twice in the Sea of Japan, to test various pneumatic turbines (used in OWC systems and the SEA Clam). Electricity was landed ashore from only a single 125 kWe turbine/generator, however, and this only for four months during the winter of 1978-79 (Ishii, et al., 1982). Two heaving buoy systems have also been grid-connected for a period of months: a 30 kWe Swedish system in 1983-84, and a 45 kWe Danish system in the spring of 1990.

Within the past five years, detailed economic feasibility studies are available for only three offshore devices that have been tested outside the laboratory wave tank:

- A 12.5 MWe circular-spine SEA Clam design, developed as part of the United Kingdom's wave energy program, for the Outer Hebrides Islands off Scotland's northwest coast (Bellamy, 1992).

- A 30 MWe heaving buoy design, based on the Swedish hose pump concept. The economic feasibility of this design has been studied for an offshore site at Half Moon Bay, just south of San Francisco, California (SEASUN Power Systems, 1991), and for a location off Makapuu Point, on the east coast of Oahu, Hawaii (SEASUN Power Systems, 1992).

- A 740 MWe central station design, based on the Danish heaving buoy system, developed by Kim Nielsen. This design was prepared for a North Sea site off the coast of Denmark (B. Hojlund Rasmussen, 1988).

None of the above designs have been considered for actual deployment. They originally were prepared simply to provide an indication of economic feasibility. Each design is described briefly and illustrated in the following pages.

The circular SEA Clam design consists of five 2.5 MWe modules. Each module has a toroidal hull, 60 m in diameter and 8 m deep, assembled from twelve concrete sections (Figure 8). Bags from adjacent sections communicate with each other via metal ductwork. Ten 250 kWe Wells turbine/generators are placed in-line with the ductwork, and the entire air system is maintained at a pressure of 15 kPa (2 psi).

FIGURE 8. Circular SEA Clam design - concrete hull. (Courtesy of Sea Energy Associates, Ltd.)

The Swedish heaving buoy design consists of three star-shaped clusters of buoys, with six collecting lines per star, and ten buoys per collecting line (Figure 9). Each buoy has a diameter of 16-17 m. The buoys are spaced on 30 m centers, giving each star a total diameter of about 600 m. The underwater habitat at the center of each star houses a 10 MWe Pelton turbine/generator. The three stars are linked by a three-phase AC cable, which transmits power to shore at 35 kV.

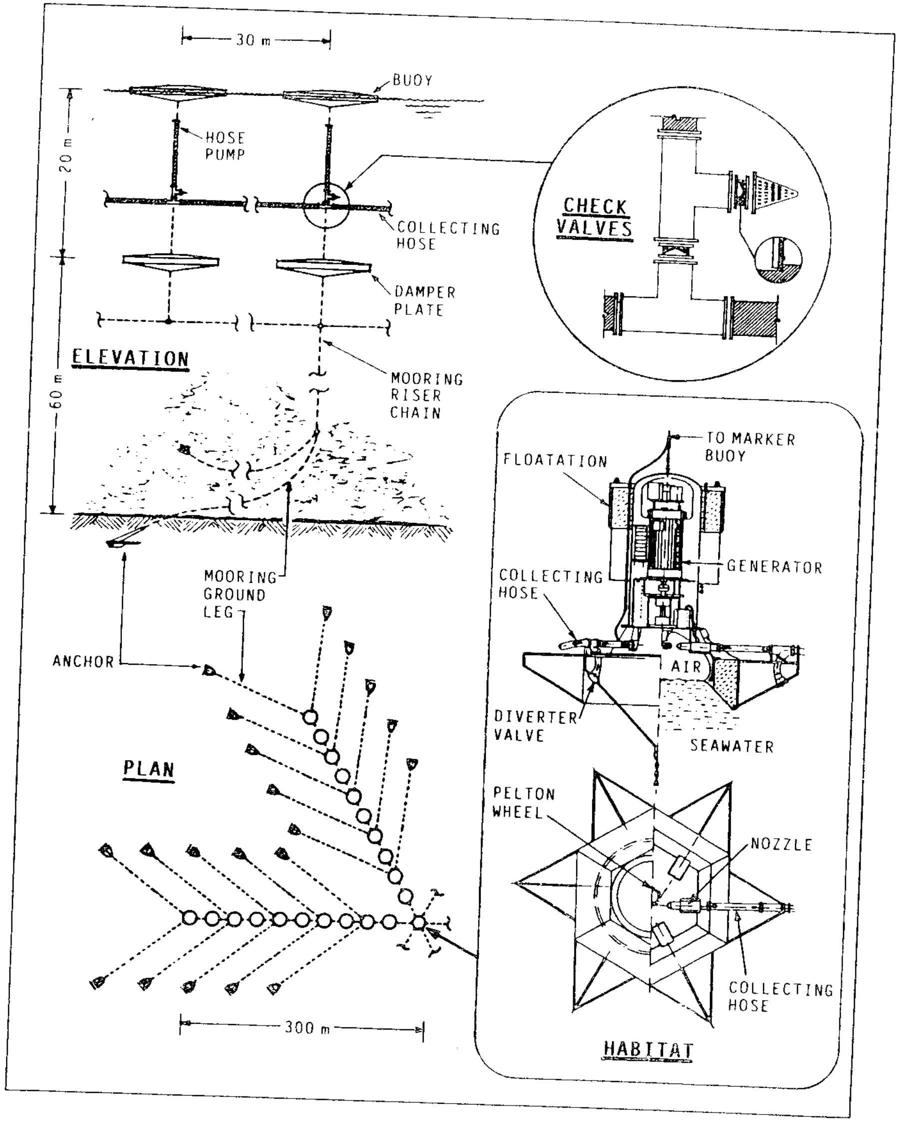


FIGURE 9. Swedish heaving buoy design. (Habitat detail courtesy of Technocean AB.)

In the Danish heaving buoy system, each converter consists of a 10 m diameter buoy tethered to a concrete piston. The piston is contained within a reinforced concrete cylinder, which is part of a circular deadweight anchor (Figure 10).

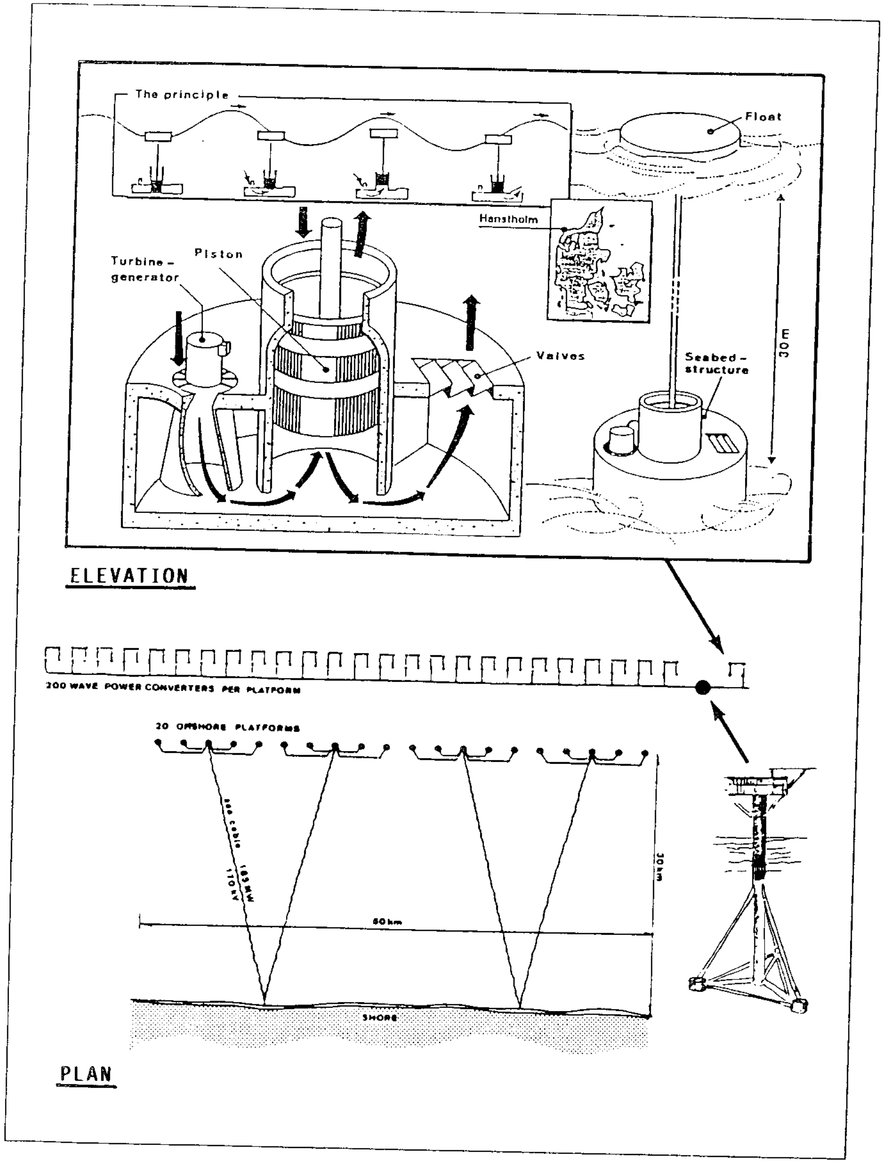


FIGURE 10. Danish heaving buoy design. (Elevation courtesy of Danish Wave Power, Aps; plan modified after B. HOJLUND RASMUSSEN, 1988.)

A 185 kWe Flygt submersible turbine/generator is mounted on the anchor, such that when the buoy heaves up on a wave crest, the piston draws water through the turbine into the anchor base. When the piston drops down in a wave trough, water returns to the sea through a one-way flap valve in the anchor wall. The electrical output from 200 modules is transmitted at 3 kV to a fixed platform, and the output of twenty such platforms is then transmitted to shore at 170 kV.

Cost and performance projections for the four different offshore designs are compiled in Table 3. An analysis of these results is presented following the table.

TABLE 3. Cost and performance of offshore wave power plants. [a]

Device:	Circular SEA Clam	Swedish Heaving Buoy	Swedish Heaving Buoy	Danish Heaving Buoy
Location:	Lewis (Scotland)	Half Moon Bay (California)	Makapuu Point (Oahu, Hawaii)	Hanstholm (Denmark)
Distance offshore:	5 km	24 km	10 km	30 km
Water depth:	80 m	80 m	80 m	30 m
Average H_S:	unknown	2.0 m	1.9 m	unknown
Average T_P:	unknown	10.8 sec	8.2 sec	unknown
Average wave power:	52 kW/m	25 kW/m	15 kW/m	9.1 kW/m
Absorber width:	60 m	17 m	16 m	10 m
Number of absorbers:	five	180	180	4000
Plant capacity:	12.5 MWe	30 MWe	30 MWe	740 MWe
Annual output:	27.9 GWh	76.3 GWh	111 GWh	870 GWh
Capacity factor:	25%	29%	42%	13%
Initial investment:	$2,210/kWe	$2,100/kWe	$1,970/kWe	$1,790/kWe
Re-investment:	none	$143/kWe	$173/kWe	none
Annual O&M cost:	$88/kWe	$84/kWe	$79/kWe	$10/kWe
Plant service life:	25 yr	30 yr	30 yr	20 yr
Construction time:	1 yr	1 yr	1 yr	5-10 yr
Cost of energy:	15 ¢/kWh	13 ¢/kWh	8.6 ¢/kWh	22-26 ¢/kWh

[a] Costs are in 1990 constant dollars. See Appendix for financial parameters and currency exchange rates. (Data from BELLAMY, 1992; SEASUN POWER SYSTEMS, 1991; SEASUN POWER SYSTEMS, 1992; B. HOJLUND RASMUSSEN, 1988.)

Comparison of the two Swedish heaving buoy designs reveals several interesting features. Oahu's island shelf is much narrower than the continental shelf off Half Moon Bay, and only a 10 km power cable is required to reach the 80 m depth contour. Smaller diameter buoys are optimal in the shorter period waves off Makapuu Point, which represents an even bigger cost saving. On the other hand, offshore deployment equipment is expected to be more costly in Hawaii, which results in a higher re-investment for periodic replacement of hose pumps, collecting lines, and mooring hardware. The initial capital investment, however, is less, as higher deployment costs are more than offset by lower power cable and buoy fabrication costs.

The 30 MWe reference design has a much greater capacity factor in Hawaii than off northern California. This is because the buoys are more efficient absorbers in shorter period waves, which are predominant along Hawaiian island coasts exposed to northeast trade winds. On the other hand, the wave energy resource off northern California is dominated by long-period swell, in which buoy performance is much poorer. Off Makapuu Point, the average wave energy absorption efficiency is 43%, compared with only 17% off Half Moon Bay. Trade wind waves are also more persistent than swell generated by winter storms in the north Pacific, which further accounts for the higher capacity factor in Hawaii.

Only the Swedish heaving buoy designs account for re-investment in capital equipment, yet both of the other systems will have periodic capital expenses. The submersible Flygt turbine/generators of the Danish heaving buoy system will require overhaul once every 3 to 5 years (Nielsen and Scholten, 1990). While the cost of overhaul parts may not be significant, the mobilization and deployment of offshore equipment to accomplish this work could be considerable. Similar considerations hold for periodic replacement of the SEA Clam's flexible bags, and if these cannot be changed at sea, then the Clam hull will require dry-docking, in addition to the offshore equipment spread for retrieving and re-deploying the unit.

The service lives listed in Table 3 are those projected by the developers. The Danish heaving buoy design, however, should be able to realize the same 25- to 30-year service life projected for other offshore systems. A short service life, coupled with a long build-out time, contribute significantly to the higher cost of energy for this design. The relatively poor wave energy resource off Hanstholm is also an important factor.

Annual operation and maintenance (O&M) costs for the Swedish heaving buoy designs were estimated as 4% of initial capital investment, based on offshore oil and gas industry experience. The annual O&M cost for the SEA Clam was developed from a line-item estimate, and works out, coincidentally, to be 4% of the capital cost.

Estimating O&M cost as a simple percentage of initial capital investment is not nearly as accurate as a line-item estimate. Furthermore, in the words of Stephen Salter (1988), "it predicts exactly the wrong outcome of spending money to reduce maintenance costs". Long-term ocean testing is required in order to truly understand the inspection, maintenance, and repair requirements of offshore wave power plants.

Capital Cost Analysis

As with other renewable energy systems, the cost of wave-generated electricity is dominated by fixed charges associated with a high initial capital investment. Capital cost breakdowns are available for four of the systems described above, and these are presented in Figure 11. Each capital cost center is reviewed below.

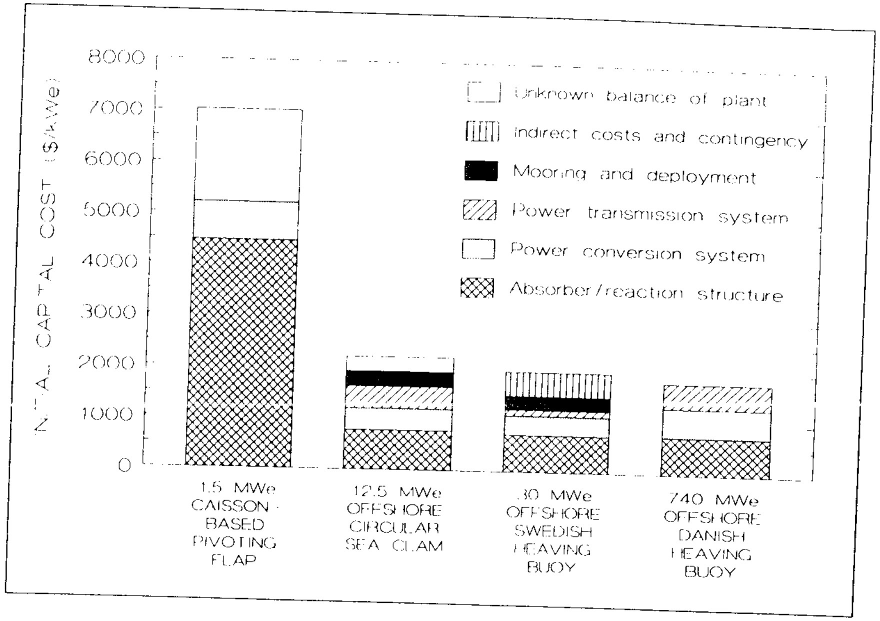


FIGURE 11. Capital cost breakdowns for four wave power plant designs. (Data from WATABE AND KONDO, 1989; BELLAMY, 1992; SEASUN POWER SYSTEMS, 1992; B. HOJLUND RASMUSSEN, 1988.)

In all designs, fabrication of absorber and reaction structures is the single biggest capital cost, ranging from 35% to 64% of the total investment. It should be noted that the original Danish cost estimate for buoys and gravity bases included the cost of deploying these structures. In this analysis, however, the absorber/reaction structure cost is based on a standard schedule of material fabrication costs, given in the Appendix. It was not possible to determine what part of the original Danish estimate was due to deployment, which is why it is missing from the breakdown in Figure 11.

The mechanical and electrical plant that converts absorber forces and motions into fluid power and thence to electric power, accounts for 19% to 32% of the capital cost of the three offshore systems, but only 10% for the caisson-based pivoting flap. This suggests that the power conversion system for this design may be undersized, as further evidenced by its high capacity factor in a relatively low-energy wave climate.

Sea-to-shore transmission costs are 20% or less for the smaller offshore systems. By comparison, the large central station design of the Danish heaving buoy system incorporates twenty fixed platforms as part of its transmission scheme, which accounts for 27% of the capital cost of that design.

Mooring and deployment account for 13% of the capital cost in the SEA Clam design and 14% in the Swedish heaving buoy system. As mentioned above, it was not possible to break out this cost center from the Danish heaving buoy design. Deployment costs were also not specifically accounted for in the caisson-based pivoting flap design. It should be noted that deployment of offshore wave power plants is likely to be more weather sensitive than it is for caisson-based systems. In the Swedish heaving buoy designs, a 30% "waiting-on-weather" contingency was applied to all buoy and habitat deployment activities.

Of the three offshore systems, only the Swedish heaving buoy design is known to account for indirect costs. These include land-based general facilities (office building, shop, warehouse, and associated utilities; does not include buoy fabrication yard, which is accounted for in absorber/reaction structure cost center), field engineering, and home office fees. Indirect costs were estimated to be 20% of the direct cost.

The cost breakdown given by Watabe and Kondo (1989) for the caisson-based pivoting flap was not fully detailed. Only 74% of the initial capital investment could be associated with a specific cost center; the remainder is presumably distributed among the other categories indicated in Figure 11, and may contain some power conversion equipment as well (only the hydraulic cylinders and motor/generators were broken out in the cited study). It should be further noted that the cost of absorber/reaction structure for this design covers only the concrete caisson. Therefore, the Pendulors are also in the "unknown" balance-of-plant category, but should not account for more than 5% of the total capital cost, based on the amount of steel involved.

Project Development Risks

Specific risks associated with the development of a wave power project are associated with uncertainties in capital and operating costs, as well as device performance projections. These risks can be quantified and compared in terms of their impact on the levelized cost of energy.

Uncertainties in equipment costs, energy absorption efficiency, and incident wave power have a direct and obvious impact on the cost of energy. Safety-related risks have a less obvious impact, but can be quantified in the same terms. For example, one of the risks associated with the deployment of offshore wave energy systems is that a device might break free of its mooring and become a drifting navigation hazard. To minimize this risk, the mooring can be substantially over-designed, and chain can be periodically replaced at an interval that is shorter than standard offshore practice. Both of these risk-reduction measures will increase the cost of energy.

To exemplify project development risks for an offshore wave power plant, a cost-of-energy sensitivity analysis was performed on the 30 MWe reference design developed for Makapuu Point (SEASUN Power Systems, 1992).

Uncertainty bands were estimated for eight cost and performance parameters. In order to determine which uncertainties were most significant, each of the parameters was varied from the reference case, one at a time. The results of this sensitivity analysis are presented in Figure 12. The basis for each uncertainty band is described below.

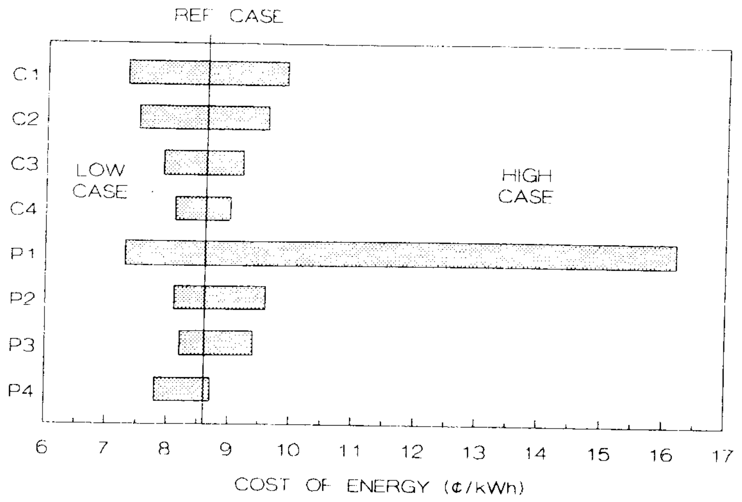
Cost Uncertainties

Buoy Fabrication Cost. The low case is based on a 1986 estimate for ferrocement construction, derived from the scantlings of a prototype tank landing craft (LCT) built and successfully tested by the U.S. Navy in 1945. The high case is based on a 1988 estimate for thin-wall reinforced concrete construction. The difference between the two estimates reflects very different construction methods: use of floating forms and shotcrete laminating in the low case; conventional land-based concrete work in the high case. The reference case was simply chosen as the midpoint between these two estimates (both escalated at an annual inflation rate of 6% to 1990). Of the four cost uncertainties evaluated in this study, buoy fabrication has the biggest impact on the cost of energy, ± 1.3 ¢/kWh.

Operating and Maintenance Cost. Marine tanker terminals are the offshore structures that are most similar to floating wave power plants, and for which there is any sort of long-term operational history. Like wave power plants, they are unmanned facilities and must maintain a high availability. The reference case is based on the annual maintenance cost (expressed as a percentage of capital cost) for Exxon's Tembungo Field Single Anchor Leg Mooring, located 93 km offshore Sabba, East Malaysia, in 91 m water depth (Gruy, et al., 1980). Projecting O&M in this manner is not nearly as accurate as a line item estimate, but the latter could not be developed within the resource constraints of the cited study (SEASUN Power Systems, 1992). Therefore, this parameter has a large uncertainty band and a significant impact on the cost of energy, ranging from -1.1 to +1.0 ¢/kWh.

Indirect Costs. The cost of land-based general facilities (defined on the previous page) are expected to range from 3% to 15% of the direct cost, while field engineering and home office fees are expected to range from 7% to 15% of the direct cost (Electric Power Research Institute, 1986). The uncertainty band represents the combined additive range of these estimates, with the reference case as the mid-point.

Deployment Cost. Mobilization and demobilization charges, as well as lease rates for offshore equipment, are expected to be higher in Hawaii than in the San Francisco Bay area. Relative to the Half Moon Bay Design (SEASUN Power Systems, 1991), the deployment cost for Hawaii was assumed to be the same in the low case, 50% higher in the reference case, and double in the high case.



COST UNCERTAINTIES	LOW CASE	REF CASE	HIGH CASE
C1 Buoy fabrication cost ($/m^2)	200	300	400
C2 Annual O&M cost (% of initial investment)	2	4	6
C3 Indirect costs (% of direct cost)	10	20	30
C4 Deployment cost (% relative to San Francisco Bay area cost)	100	150	200
PERFORMANCE UNCERTAINTIES			
P1 Wave energy absorption efficiency	upper bound	best fit	lower bound
P2 Hose pump service life (yr)	10	6	3
P3 Annual availability (%)	95	90	80
P4 Average wave power (kW/m) (time period of data set)	15.9 (1982)	15.0 (1982-89)	13.7 (1984)

FIGURE 12. Cost-of-energy sensitivity analysis for 30 MWe reference design of Swedish heaving buoy system off Makapuu Point. (From SEASUN POWER SYSTEMS, 1992.)

Performance Uncertainties

Wave Energy Absorption Efficiency. There is a large amount of scatter in the projected absorption efficiency of heaving buoy/hose pump modules in random waves. For a 16-meter diameter buoy in wavelengths typical of the dominant wave period off Makapuu Point the scatter in absorption efficiency data ranges from 25% to 65%. Of all project development risks, this one has the greatest impact on the cost of energy, ranging from -1.3 to +7.6 ¢/kWh.

Hose Pump Service Life. The reference case is based on the developers' estimate of 6 years (Svensson, 1985), which was derived from accelerated testing of laboratory-scale prototype hoses. The low case is based on a different set of laboratory tests, conducted by the Harwell Laboratory of the Energy Technology Support Unit in the United Kingdom to evaluate the fatigue characteristics of a polymer tube spring for mooring the submerged Bristol Cylinder wave energy device. Although developed independently of the Swedish hose pump, and for different purposes, the British tube spring is identical to the hose pump in form and function. The Harwell tests indicated a service life in excess of 25 years (Davidson, 1983). Other plant components (connecting hoses subject to bending, upper mooring chain and fittings) are not expected to last this long, however, and would have to be replaced more frequently, incurring the same buoy retrieval and re deployment costs. Therefore, the low case assumes that the hose pumps, together with these other components, would be replaced at 10-year intervals.

The high case is based on the experience of offshore tanker terminals, where underbuoy hoses have demonstrated a service life of 3-4 years. These hoses are never in tension, but are subject to continual bending. They also carry petroleum products rather than seawater. Nevertheless, they are the only large-diameter submerged hoses for which there is any operational history in the offshore marine environment.

Annual Maintenance Availability. The reported availability of turbo-generating machinery in tidal power plants is 96-98% (Carmichael, Adams, and Glucksman, 1986; Rice and Baker, 1987), and that for offshore tanker terminals is 93-96% (Gruy, et al., 1980; Versluis, 1980). Taken together, these give a total availability of 89% to 94% for the underwater habitat and turbine/generator.

Results from the British wave energy program suggested that the annual availability of a wave power plant off the northwest coast of Scotland would be 80% to 90%, based on a variety of devices under consideration at that time. These estimates were derived with a fairly sophisticated computer model that probably represents the best theoretical research in this area (Taylor, 1982).

The reference case approximates the worst reported availability from tidal power/offshore terminal experience, which is similar to the best wave power simulations. The low case approximates the best reported tidal/offshore experience. The high case was based on the worst reported wave power simulations.

Wave Energy Resource. The wave data record from offshore Makapuu Point is one of the longest and most complete in Hawaii. Even so, it covers only five complete years and may not represent the long-term wave climate over a 30-year project life. To assess the consequences of this uncertainty, the most and least energetic individual years were used for the low-cost and high-cost cases, respectively.

A similar analysis for the Half Moon Bay design indicated that during the 1981-86 time period, wave energy levels in the north Pacific Ocean were lowest in 1985 and greatest in 1983, an intense "El Nino" year when winter storms devastated much of the California coast (Seymour, 1983). Unfortunately, the wave record from offshore Makapuu Point contains major data gaps during these two extreme years. Of the remaining five years for which seasonally complete records do exist, there is relatively little year-to-year variability. Consequently, the cost-of-energy impact of this parameter is low at Makapuu Point, ranging from -0.8 to +0.1 ¢/kWh. Generally speaking, however, use of only a single year's wave data to forecast device performance entails much greater economic risk than indicated by this particular case.

Several measures can be taken to reduce the uncertainty in cost-of-energy projections, thereby lowering overall project development risk:

- More detailed design work would increase the accuracy of component capital costs. Where a cost uncertainty has an especially large impact on the cost of energy (e.g. buoy fabrication), it may be worthwhile to build a prototype component, which would give a firmer basis for estimating mass-production costs.
- Ocean testing of full-scale prototypes in a wide variety of sea states would reduce the uncertainty in projections of wave energy absorption efficiency, which is the single biggest project development risk.
- Longer-term ocean tests (on the order of years) are required to reduce uncertainties associated with operating and maintenance costs, the required frequency of re-investment in replacement equipment, and annual maintenance availability.

Over-estimation of incident wave power also represents a significant project development risk, and there are several examples of wave energy prototypes that did not perform well due to poor understanding of the local resource. For most projects, only a few years of site-specific measured wave data will be available, and an assessment should be made as to how well those years represent the long-term wave climate. A rough estimate can be obtained by statistical analysis of shipboard observations, which have been archived for well over twenty years in most parts of the world. A more accurate assessment requires a long-term numerical wave hindcast, which has become increasingly affordable in recent years with the development of high-performance desk-top computers and computationally efficient wave hindcasting models (for example, see Earle, 1989).

Wave Energy Markets and Co-Products

Two applications of wave energy conversion are distributed generation, to meet local demands on the coast, and central stations, designed to export bulk power inland to the main utility grid. Distributed generation plants are likely to be deployed before central stations, and their commercial appeal can be enhanced by a variety of co-products. In the long term, wave power may find application in current proposals for the offshore utilization of sea space. Various market development scenarios are outlined in the last part of this section.

Distributed Generation

Distributed generation is defined as a wave power plant designed to meet the electric power demands of a coastal load center. An alternating-current (AC) submarine power cable would be landed into an existing coastal substation, and the necessary transformers and switchgear would be provided to connect to the local distribution system. Export of power inland would be incidental only to variations in local demand, and it is assumed that the installed wave generating capacity would be sufficiently small so as not to require any reinforcement of existing onshore transmission lines.

Coastal towns in high latitudes seldom require summer air-conditioning, and where natural gas service is not available for winter heating, the seasonal variation in electricity demand is well-matched to that of the wave energy resource. The remoteness of the coast also makes it attractive for "mini-utilities", whereby winter peak load growth is met by building small, local wave power plants rather than additional transmission lines from the inland grid. A survey of coastal substations in northern California suggests that the useful size of such a wave power plant would range from one to ten megawatts (SEASUN Power Systems, 1991). It should be noted that these comments apply to large mainland utility grids; for many island applications, plant sizes on the order of tens to hundreds of kilowatts would be more appropriate.

In addition to meeting coastal load growth, a few megawatts of distributed wave generation capacity may benefit the regional transmission network by providing grid stability and voltage support, particularly in remote coastal areas with load centers at the end of a long transmission circuit. A recent study by Pacific Gas and Electric Company has suggested that small-scale photovoltaic (PV) plants would provide avoided-cost benefits to the local distribution system comparable to the value of the PV plant itself (Shugar, 1990). There is every reason to believe that a small wave power plant could provide the same benefits.

As important as distributed wave generation may be at the local or regional level, its impact on an entire grid may be insignificant. For industrialized countries, any significant development of the wave energy resource probably will require the deployment of central generating stations.

Central Station Generation

A major consideration for central station applications is inland transmission of the power once it lands ashore. A second consideration is managing the power so it can be most effectively combined with other generating plant.

In many regions of the world, good wave energy resources are located along coastal stretches that are relatively unpopulated and remote from main-grid load centers (examples include northern California and the northwest coast of Scotland). Even where a utility grid extends to such a coastal area, it is usually not designed to handle large amounts of power. Therefore inland export of wave power from coastal substations via existing transmission lines is likely to be severely limited.

Another possible inland route for wave power is surplus transmission capacity at thermal power plants located on the coast for access to cooling water; however, these plants may be far removed from the best wave energy resources. Furthermore, much of the surplus may be unavailable, due to other utility requirements for these lines.

Therefore, substantial development of the wave energy resource for bulk power generation will require reinforcement or extension of the onshore utility grid. Recent studies in the United Kingdom suggest that for a 2,000 MWe wave power station off the Outer Hebrides Islands, reinforcement of the onshore grid will be as expensive, if not more, than sea-to-shore power transmission (Thorpe, 1992)

Once the power reaches the central grid, there are further difficulties. Although waves are more persistent than the winds that generate them, output from a wave power plant can fall below rated capacity at irregular intervals lasting from a few hours to a number of days. Assume for a moment that the cost of energy from a central wave power station was comparable to that from thermal plant, and that the latter was used to make up for hourly or daily shortfalls in wave power. It is not practical to start up and shut down large coal-fired plants over this time scale. Either smaller gas- or oil-fired plants (which have higher energy costs than coal) must be available, or a large coal-fired plant would have to be kept on part load (spinning reserve), which is relatively inefficient. Alternatively, one could integrate long-term energy storage, such as an onshore pumped hydro station, with the wave power plant.

Modern wave forecasting models exist that can predict wave conditions 24 to 48 hours in advance with reasonable accuracy, easing the dispatch problem. This does not eliminate the need, however, for back-up generation or long-term energy storage.

Siting two or three smaller wave power plants at widely spaced intervals will provide a greater level of firm capacity than siting the same amount of wave generating plant in one location. Another way to increase wave power's baseload capacity contribution is to deploy more absorbers per unit generator rating. While this would be economical if the absorbers were a small part of total plant cost, this is not the case with the present state of the art, as shown in Figure 12.

A possibly more effective use of central station wave power would be the production of hydrogen as a winter heating fuel. This provides a good match to seasonal demand, eliminates the dispatchability problem, and avoids the environmental and economic costs of reinforcing or extending the onshore utility grid. Furthermore, a recent study by Pacific Gas and Electric Company suggests that hydrogen for heating is a more economical carrier of renewable energy than either hydrogen in fuel cells or electric power transmission with pumped storage (Braun, Suchard, and Martin, 1990). Only where no storage is required, as with naturally dispatchable photovoltaic plant, does electric power transmission become the more economical alternative. Wave energy processes must be proven in distributed generation applications, however, before central station applications (electricity or hydrogen) can become a reality.

Wave Energy Co-Products

A variety of products can be generated by wave energy systems, incidental to the generation of electricity, including:

- Seawater renewal for closed-pond aquaculture
- Fresh water for household use, livestock watering, and crop irrigation
- Breakwater protection for ports and harbors

Co-product potential varies among different wave energy technologies, depending on whether they are fixed or floating devices, and whether their working fluid is air, hydraulic oil, or seawater. Some devices could be modified to generate electricity and all three co-products in a single plant. For example, the closed-circuit hydraulic system of a caisson-based pivoting flap could be replaced with a high-pressure seawater system. Some of the pumped seawater could be diverted to onshore aquaculture ponds, while the rest would enter a reverse osmosis (RO) module. At a seawater pressure of 800 psi (5.5 MPa), only 20% of this flow would pass through the RO membrane as fresh water; the remainder could be discharged through a Pelton turbine to generate electricity. Such a system, however, is now a matter of speculation. The following text describes co-product applications that have been studied for state-of-the-art wave energy devices.

Aquaculture. The reservoir of a Tapered Channel power plant does not provide long-term storage, but smooths the input from one high-energy wave group to the next. The reservoir at Toftestallen has an area of 5,500 m^2, while the 350 kWe turbine/generator has an operating head of 3 m and a flow rate of 14 to 16 m/sec (Norwegian Royal Ministry of Petroleum and Energy, 1987). Assuming a turbine/generator efficiency of 90%, the upper meter of the reservoir is replaced once every six minutes, which represents a tremendous rate of seawater renewal. The Crown Agents of London have estimated that the value of fish farmed in a Tapered Channel reservoir "may cover all capital costs of wave collectors, converters and basin" (Mehlum, et al., 1990).

Deep oceanic water is cold, nutrient-rich, and relatively pathogen-free, which makes it an ideal resource for aquaculture, providing ease of temperature regulation, enhanced productivity, and reduced exposure to infection. Its use for open-ocean aquaculture has been proposed in connection with ocean thermal energy conversion (OTEC), but wave-powered pumps also have been proposed for the same purpose (Liu and Chen, 1991).

Fresh Water. Although the vast majority of wave energy systems are designed for electric power generation, a heaving buoy device (DELBUOY) was developed by researchers at the University of Delaware for the desalination of seawater by reverse osmosis. Since 1982, an evolving series of full-scale prototypes has been deployed off the southwest coast of Puerto Rico, producing fresh water at a continuous rate of 950 liters (250 gallons) per day from a single buoy (Hicks, Pleass, and Mitcheson, 1988).

DELBUOY consists of a 2.1 m diameter buoy tethered to a seafloor anchor by a single-acting hydraulic cylinder, which has a bore diameter of 4 cm. This gives a pressure amplification ratio of approximately 2750:1, such that relatively small waves can generate pump pressures as high as 5.5 MPa (800 psi). Six buoy/pump moorings supply one RO module that delivers 5,700 liters (1,500 gallons) of fresh water per day, in waves 1 m high, having a period of 3-6 seconds. Such waves are typical in the Caribbean Sea and along the arid coastal regions of Africa, where average incident wave power is on the order of 1-10 kW per meter of shoreline.

Breakwater Protection. Since caissons reflect all wave energy that they don't absorb, there is the possibility of a distinct low-energy "shadow" developing behind the plant, depending on how closely the individual caissons are spaced. This maximizes their potential environmental impact on longshore sediment transport. It is this reflective feature of caissons, however, that make them ideal candidates for combining wave energy generation with breakwater protection at coastal harbors. In such cases their visual appearance would probably not be considered intrusive, since local scenery has already been altered by the existing harbor development.

Even in remote coastal areas, an occasional wave energy breakwater might be acceptable for creating a harbor of refuge for small craft in the event of sudden storms, medical emergencies, or engine problems. The co-production of fresh water and electricity would have obvious advantages in such an application.

It should be noted, however, that the potential market for wave energy breakwaters is relatively small. For example, Pacific Gas and Electric Company (PG&E) has an open ocean coast approximately 1,000 km in length. Yet a recent survey identified only two existing harbors that needed additional breakwater protection, and five coves that could be developed into harbors of refuge. The potential wave generating capacity at these seven sites was estimated to be only 12.5 MWe (SEASUN Power Systems, 1991), which is insignificant in terms of PG&E's grid-wide demand. Nevertheless, if even the smallest of these (700 kWe) was developed, it would more than double the world's present wave generating capacity. Therefore, breakwaters are an important stepping stone in the commercialization of wave power.

Offshore Utilization of Ocean Space

Very large floating structures (VLFS) have been proposed for a variety of offshore applications, including airports, space launch facilities, naval bases, living and recreation complexes, and production of energy-intensive materials and fuels. Barge-like VLFS modules are less costly than semisubmersibles, but require protection from wave action (Chow, et al., 1991). Fabricating the perimeter of such a VLFS to accommodate wave energy absorbers such as oscillating water columns, pivoting flaps, or flexible bags should not add significantly to its total construction cost.

The large inertia of the VLFS provides the necessary reaction point for these absorbers, which in turn act to remove energy from the wave before it passes under the platform. It is important to note that much of this energy is ultimately absorbed by the VLFS via structural foundations for power conversion equipment, but these may be less costly than designing the platform to withstand large sagging and hogging loads associated with undampened waves.

As previously noted, reaction structures are the single largest capital cost item for caisson-based wave energy devices and the SEA Clam. If the fabrication cost of the VLFS is supported by revenue derived from its main function, then wave energy costs for power conversion equipment and other balance-of-plant may be half or less than that now projected for systems connected to onshore utility grids (see Figure 12).

The development of VLFS-based offshore wave power plants could lead to the large-scale production of hydrogen for mainland electric power generation and as a heating or transportation fuel. If so, wave energy has the ultimate potential to supply a large portion of global energy demand, as explained below.

A steady wind blowing over water imparts its energy to waves, which grow in size until they become unstable and break. Shorter-period waves reach limiting steepness first, while longer-period waves continue to grow. Longer-period waves also have a higher group velocity (the speed at which wave energy propagates across the ocean surface), and for a given wind speed, waves longer than a certain period travel faster than the wind. Once waves of this period have reached limiting steepness, the sea can absorb no more wind energy and is said to be fully developed. At this point, energy input from the wind is offset by energy losses due to wave breaking.

If energy is absorbed from a fully developed sea by a wave power plant, however, the waves can absorb more energy from the wind than otherwise. Given sufficient fetch downwind of the plant, the waves will again become fully developed, regaining the energy that was absorbed. To use an agricultural analogy, waves re-grow as they are "grazed", and the overall productivity of the sea surface (in terms of rate of energy yield, or power) increases. If such cropping can be achieved economically on a worldwide scale, then the global wave energy resource base exceeds that of ocean thermal energy conversion (OTEC) and is comparable to civilization's present power demand (Isaacs and Schmitt, 1980).

The persistent trade winds of the tropics provide a wave climate in which such cropping is a realistic proposition. Mathematical modeling indicates that at a wind speed of 10 m/sec, wave regrowth between power plants spaced 50 km apart along a 600 km fetch increases wave energy yield by 40% (Claeson and Sjostrom, 1991).

The ultimate prospect of large-scale production of wave-generated hydrogen suggests certain criteria for wave energy conversion devices that might be targeted for accelerated research and development during the next five years. One criterion is an absorber configuration that can be easily integrated into VLFS perimeter construction. Another is the use of high-pressure seawater as a working fluid. Efficient electrolyzers require fresh water, and DELBUOY has demonstrated that with a sufficiently large ratio of absorber area to pump cross-section, seawater can be desalinated directly via reverse osmosis, without an electrical intermediary step. Thus, high-pressure seawater systems have both long-term commercial potential for efficient hydrogen production offshore, and near-term commercial potential for cogeneration of fresh water and electricity at remote island and coastal locations.

Market Development

The near-term market for wave power is clearly in the Pacific Ocean, which has an energetic wave climate (despite its name) and a large number of island nations where the need for small-scale electric power and fresh water is great. If electrified at all, these islands are typically served by old diesel units, some dating back to the second world war, operating at the far end of the oil distribution network.

Where coastal land is not at a premium, and where a reservoir can be built without extensive blasting or dam construction, Norwave's Tapered Channel is the most economical wave energy system developed to date, and is expected to capture a fair share of the Pacific market. Japanese caisson-based systems are also expected to enter this market within the next five years.

The commercial export of offshore systems is expected to lag behind that of land- and caisson-based systems. Significant improvement in cost and performance will not occur until a floating device is successfully demonstrated at full scale for a period of years. Commercial sales will not occur without a successful demonstration, and without sales, the developers of such systems will not have the financial resources or operating experience necessary to make significant improvements.

Based on the foregoing text, it would seem that for industrialized nations, commercial development of wave power beyond a few tens or hundreds of megawatts depends on the construction and operation of a demonstration plant for performance and endurance testing of offshore components. To the extent that reinforcement or extension of onshore utility grids is prohibitively expensive or environmentally unacceptable, large-scale wave power development may also depend on the existence of an onshore infrastructure for the handling, storage and distribution of hydrogen.

Without the long-term component testing afforded by a demonstration plant, it is doubtful whether any sort of offshore wave energy system would become economically feasible in the foreseeable future. Under this scenario, wave power development in industrial countries will be largely limited to caisson-based systems deployed as breakwaters at locations where their environmental impact is consistent with the existing level of onshore harbor development. This would probably amount to only tens of megawatts worldwide.

Without the development of an onshore hydrogen infrastructure, utilization of wave power will be limited by the economic and environmental costs of reinforcing or extending the utility grid and wave energy's lack of dispatchability. Under this scenario, it is expected that wave energy would be used primarily for distributed generation, as described previously. This would probably amount to only hundreds of megawatts worldwide.

With both drivers in place, however, it is conceivable that industrial countries could meet a large part of their energy needs from wave power. Under this scenario, tens of megawatts of caisson-based capacity would be deployed over the next decade. These would be demonstration plants designed primarily for harbor protection, but which would incorporate components used in various offshore wave energy systems, for purposes of long-term endurance testing.

By the end of this century, sufficient component sea time would be accumulated to enable confident projections of the cost and performance of offshore wave power plants. These would then be commercially deployed: first in island applications where the competing technology is diesel generation; later, in distributed "mini-utilities" along mainland coasts, where the competing technology is extension of the central grid.

Meanwhile, an onshore hydrogen infrastructure would have been developed, fueled initially by surplus hydroelectric generation. The incentive for this development might come from depletion of fossil methane reserves (the feedstock for existing hydrogen production by steam reformation), coupled with legislation designed to reduce carbon dioxide emissions.

This does not require a full-blown "hydrogen energy economy", where hydrogen is also used for transportation and electric power generation. It does require, however, sufficient infrastructure that hydrogen can be used as a replacement fuel for major heating applications now served by natural gas.

Should an onshore infrastructure develop to receive hydrogen, wave energy has several advantages over competing technologies to provide it. Unlike steam reformation of methane or coal gasification, hydrogen production via electrolysis produces no carbon dioxide. Water supply would not be a problem for wave-powered electrolysis but could be a limiting factor in those inland areas having good solar or wind resources. While these renewables could gain access to water by moving them offshore, wave energy makes much more efficient use of sea space (SEASUN Power Systems, 1991).

Cost-of-Energy Comparison with Other Energy Options

In the above market development scenario, wave power must be commercially successful in distributed generation before it can be seriously considered for central station use. The likelihood of this development depends a great deal on the cost of wave-generated electricity relative to that generated by other technologies.

This section examines wave energy's present state of economic competitiveness. As before, EPRI financial parameters were used to compute levelized energy costs in constant 1990 U.S. dollars (see Appendix for details).

Looking first at the export market, Table 4 compares the projected cost of energy for various projects in the South Pacific Ocean. The Stewart Island examples are from a study of central electricity supply options for the island's 500 inhabitants (Royds Garden Limited and Worley Consultants, 1985). Although New Zealand and eastern Australia are not considered viable candidate sites for land-based OTEC plants, many nearby island nations are, including Fiji, Tonga, and Samoa (Vega, 1992).

The projected cost of wave energy in such small-island applications is 4 to 5 ¢/kWh lower than hydro or diesel, and less than half the cost of a land-based OTEC plant. It should be noted that King Island is located south of the Australian mainland, where it is fully exposed to high-energy Southern Ocean swell. As this swell travels north, it becomes more widely dispersed and its energy density decreases. In the same direction, however, trade wind wave energy levels increase. Overall, incident wave power in the region framed by Vanuatu, Tongatapu, Rarotonga, and Tuvalu is expected to average 15-20 kW/m annually (Barstow, Soras, and Selanger, 1991). As indicated by Norwave's Java project (Table 1) and the heaving buoy design for Makapuu Point (Table 3), this is still an adequate resource for competitive wave energy costs.

While the comparisons of Table 4 are applicable to smaller projects, on the order of a few megawatts, there are many Pacific islands with a well-established utility grid and large demand growth, such that projects on the order of tens to hundreds of megawatts are warranted. Representing this market, Table 5 presents cost-of-energy comparisons for the densely populated island of Oahu, Hawaii. Although wave power is still competitive with OTEC there, it is more costly than coal by 2 to 3 ¢/kWh.

It should be noted that the coal-fired plant at Barbers Point was commissioned early in 1992, so that cost and performance projections for this project are quite reliable. Less certain are the wave power plant data. Although based on vendor estimates and existing technology, the original design was for deployment off northern California, later adapted to Hawaii, as described previously. Even less certain are the OTEC data, which include cost reductions associated with engineering developments beyond the present state of the art, particularly in cold water pipe design (Vega, 1992). There is also a wide range in sub-system cost estimates among different OTEC design studies (Zangrando, 1992), which adds further uncertainty to cost projections based on engineering development of any particular sub-system.

TABLE 4. Wave, OTEC, small hydro, and diesel comparison in the southwest Pacific Ocean. [a]

Option:	WAVE	OTEC	HYDRO	DIESEL
Technology:	Tapered Channel	open-cycle, w/ 2nd stage condenser [b]	10 m dam height, 80 m dam length, 8 km^2 reservoir	water-cooled w/ heat rate of 11,400 BTU/kWh
Location:	King Island (Australia)	unspecified	Stewart Island (New Zealand)	Stewart Island (New Zealand)
Energy resource:	Southern Ocean swell at 30-32 kW/m	surface water at 26°C, deep water at 4°C	mean river flow of 4.2 m^3/sec, hydraulic head of 34.5 m	bulk diesel fuel w/ 37,000 BTU/liter heat content
Plant capacity:	1.5 MWe	1.256 MWe (net)	1.2 MWe (2 x 600 kWe)	0.9 MWe (3 x 300 kWe)
Annual output:	9 GWh	8.8 GWh	5 GWh [c]	5 GWh [c]
Capacity factor:	68%	80%	48%	64%
Initial investment:	$3,290-3,840/kWe	$23,000/kWe	$4,290/kWe [d]	$600/kWe
Re-investment:	none	none	none	$268/kWe at 10 yr
Annual O&M cost: (non-fuel)	$33/kWe	$391/kWe	$25/kWe	$71/kWe incl. variable
Annual fuel cost:	none	none	none	9.7 ¢/kWh [e]
Plant service life:	40 yr	30 yr	40 yr	20 yr
Cost of energy:	6.2-7.2 ¢/kWh	14.9 ¢/kWh [b]	11.3 ¢/kWh	12.6 ¢/kWh

[a] A construction time of one year was used for all projects. Costs are in 1990 constant dollars. See Appendix for financial parameters and currency exchange rates. (Data from MEHLUM, 1990; VEGA, 1992; ROYDS GARDEN LIMITED AND WORLEY CONSULTANTS, 1985.)

[b] Co-production of fresh water at an average rate of 4,000 m^3/day. Cost of energy includes credit of 26.5 ¢/kWh, based on an assumed water selling price of $1.6/m^3 ($6/kgal).

[c] Forecast demand ten years after hydro or diesel plant comes on line.

[d] Does not include cost of transmission (21 km overhead, 7 km submarine), access road, or 0.6 MWe (2 x 300 kWe) standby diesel plant in Oban.

[e] Equivalent to a bulk diesel fuel price of 31.4 ¢/liter ($50 per 42-gal barrel).

TABLE 5. Wave, OTEC, and coal comparison on Oahu, Hawaii. [a]

Option:	WAVE	OTEC	COAL
Technology:	Swedish heaving buoy	Land-based, hybrid cycle [b]	Atmospheric fluidized bed w/ heat rate of 10,300-10,800 BTU/kWh
Location:	10 km offshore Makapuu Point, 80 m depth	unspecified	Barbers Point
Energy resource:	north Pacific swell and trade wind waves at 15 kW/m	warm water at 26°C, deep water at 4°C	Indonesian coal
Plant capacity:	30 MWe	40 MWe (net)	180 MWe
Annual output:	111 GWh	280 GWh	1,420 GWh
Capacity factor:	42%	80%	90%
Initial investment:	$1,970/kWe	$8,700/kWe	$2,130/kWe
Re-investment:	$173/kWe every 6 yr	none	unknown
Annual O&M cost: (non-fuel)	$79/kWe	$131/kWe	0.8-1.2 ¢/kWh incl. fixed
Annual fuel cost:	none	none	1.8-2.4 ¢/kWh [c]
Plant service life:	30 yr	30 yr	40 yr
Construction time:	1 yr	2 yr	unspecified [d]
Cost of energy:	8.6 ¢/kWh	9.3 ¢/kWh [b]	5.4-6.4 ¢/kWh

[a] Costs are in 1990 constant dollars. See Appendix for financial parameters. (Data from SEASUN POWER SYSTEMS, 1992; VEGA, 1992; HEMPHILL, 1992.)

[b] Closed-cycle ammonia loop for electric power generation; open-cycle 2nd stage with surface condenser for production of fresh water at an average rate of 62,000 m^3/day. Cost of energy includes credit of 6.5 ¢/kWh, based on an assumed water selling price of $0.8/$m^3$ ($3/kgal).

[c] Based on a projected coal cost of $1.70-$2.20/million BTU.

[d] Initial investment includes interest during construction and other pre-commissioning costs.

Moving from island to mainland markets (Table 6), it is clear that levelized energy costs must drop by a factor of two before wave power will be competitive with wind power or coal-fired generation. As explained previously, capacity factor is lower for the Swedish heaving buoy design in northern California than in Hawaii. Even though wave energy levels are greater off Half Moon Bay, the energy is contained in longer-period waves and is not absorbed as efficiently as the shorter-period trade wind wave energy off Makapuu Point.

TABLE 6. Wave, wind, and coal comparison in northern California. [a]

Option:	WAVE	WIND	COAL
Technology:	Swedish heaving buoy	two-hundred 200 kWe turbines	pulverized coal w/ heat rate of 10,000 BTU/kWh
Location:	24 km offshore Half Moon Bay	Altamont Pass	Montezuma
Energy resource:	north Pacific swell at 25 kW/m	unspecified	unspecified
Plant capacity:	30 MWe	40 MWe	460 MWe
Annual output:	76.3 GWh	87.6 GWh	2,820 GWh
Capacity factor:	29%	25%	70%
Initial investment:	$2,100/kWe	$910/kWe	$2,500/kWe
Re-investment:	$143/kWe every 6 yr	none	none
Annual O&M cost: (non-fuel)	$84/kWe	$1.2/kWe and 1.2 ¢/kWh	$55/kWe and 0.5 ¢/kWh
Annual fuel cost:	none	none	1.9 ¢/kWh [b]
Plant service life:	30 yr	25 yr	30 yr
Construction time:	1 yr	1 yr	5 yr
Cost of energy:	13 ¢/kWh	6.0 ¢/kWh	7.9 ¢/kWh

[a] Costs are in 1990 constant dollars. See Appendix for financial parameters. (Data from SEASUN POWER SYSTEMS, 1991; DOYLE, EYER, AND HAY, 1988.)

[b] Based on a projected coal cost of $1.94/million BTU.

None of the regions examined thus far are subject to large tides. Comparison of wave and tidal power is possible in the United Kingdom, however, where good resources exist for both technologies. As shown in Table 7, an important factor in this comparison is size. While the 12.5 MWe circular SEA Clam is competitive with tidal power on the order of a few tens of megawatts or less, it is clearly not competitive with a several-thousand megawatt plant such as that proposed for the Severn Estuary.

TABLE 7. Wave and tidal power comparison in the United Kingdom. [a]

Option:	WAVE	TIDE	TIDE	TIDE
Technology:	Circular SEA Clam	Salford Transverse Oscillator	single-effect, ebb generation	single-effect, ebb generation, w/ flood pumping
Location:	5 km offshore Lewis	Callanish, Lewis	Langstone Harbor	Severn Estuary
Energy resource:	north Atlantic swell at 52 kW/m	2.9 m tidal range	3.1 m tidal range	11 m tidal range
Barrage length:	not applicable	340 m	550 m	15.9 km
Reservoir area:	not applicable	2.7 km^2	19 km^2	480 km^2
Plant capacity:	12.5 MWe	3.13 MWe	24.3 MWe	8,640 MWe
Annual output:	27.9 GWh	4.5 GWh	53.2 GWh	17,000 GWh
Capacity factor:	25%	16%	25%	22%
Initial investment:	$2,210/kWe	$2,060/kWe	$3,480/kWe	$1,640/kWe
Re-investment:	none	none	$1,200/kWe every 40 yr	$178/kWe every 30 yr
Annual O&M cost:	$88/kWe	$43/kWe	$41/kWe	$14/kWe
Plant service life:	25 yr	25 yr	120 yr	120 yr
Construction time:	1 yr	1 yr	5 yr	8 yr [b]
Cost of energy:	15 ¢/kWh	19 ¢/kWh	21 ¢/kWh	11 ¢/kWh

[a] Costs are in 1990 constant dollars. See Appendix for financial parameters and currency exchange rates. (Data from BELLAMY, 1992; CARNIE, 1989; YARD LTD, 1989; DEPARTMENT OF ENERGY, CENTRAL ELECTRICITY GENERATING BOARD, AND SEVERN TIDAL POWER GROUP, 1989.)

[b] Seven years to barrage closure and first commercial power generation, with a further two years to completion and full output.

For electric power generation, then, it appears that wave power is highly competitive with other renewables and with fossil fuels in island markets where capacity additions on the order of a few megawatts are contemplated. On the industrialized mainland and large islands where high demand growth warrants capacity additions of a few hundred megawatts, wave power is not competitive with coal. Among ocean energy options, however, only the largest tidal power stations have lower energy costs.

Regarding fresh water production, there is little economic data available for wave power. While DELBUOY is close to being a commercial product, its output is relatively low, approximately 5.7 m^3/day (1,500 gal/day) for a six-buoy system in a trade wind wave climate. As shown in Table 8, such a system is not well matched to the levels of demand on developed islands. In developing countries, however, even a few cubic meters of fresh water per day would significantly improve basic living conditions in communities now without a reliable water supply.

TABLE 8. Electricity and fresh water demand on four Hawaiian islands. [a]

Island:	Molokai	Kauai	Maui	Oahu
Resident population:	6,700	47,600	81,100	830,600
Total annual electricity demand:	25.4 GWh	270 GWh	620 GWh	5,804 GWh
Average per capita electricity demand				
• all uses:	10.4 kWh/day	15.5 kWh/day	20.9 kWh/day	19.1 kWh/day
• residential:	4.3	5.6	6.8	5.0
Total annual fresh water demand [b]:	$17.6x10^6$ m^3	$314x10^6$ m^3	$646x10^6$ m^3	$555x10^6$ m^3
Average per capita fresh water demand				
• all uses [b]:	7.2 m^3/day	18.1 m^3/day	15.8 m^3/day	1.8 m^3/day
• domestic:	0.8	0.9	0.7	0.6
• agricultural:	6.4	16.5	15.0	0.9
Fresh water demand per unit electricity demand (all uses):	0.7 m^3/kWh	1.2 m^3/kWh	0.8 m^3/kWh	0.1 m^3/kWh

[a] Population estimate is as of 1 July 1987, electricity demand is for 1987, fresh water demand is for 1985. (Data from STATE OF HAWAII, 1988).

[b] Does not include water diverted for hydroelectric power generation (which is significant on Kauai), since this does not represent a potential market for desalinated seawater.

The development of large wave-powered desalination systems has been little explored, yet the potential energy benefits of such a technology are great. Conventional reverse osmosis (RO) plants consume 5.8 kWh per m^3 of product (22 kWh/kgal), even when fitted with energy recovery systems (Block, 1991). Using conventional RO to supply only 10% of the fresh water demand on Molokai would increase total electricity consumption on that island by 40%; the impact would be even greater on Maui (60%) and Kauai (67%). In arid coastal regions and small islands, where fresh water supplies are inherently limited, a growing population's need for water could well create a worse energy crisis than its demand for electric power.

Assuming that competitive prices for fresh water and electricity are $.80/$m^3$ ($3/kgal) and $.08/kWh, respectively, then the market for fresh water is at least comparable in dollar value to that for electricity on an urbanized island such as Oahu, and many times greater on islands with extensive ranching and farming. It is difficult to escape the conclusion that wave power may be commercialized sooner if fresh water, rather than electricity, is viewed as the primary product. Such a development, if realized, will owe much to the pioneering work of Hicks, Pleass, and Mitcheson (1988).

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Appendix

The energy costing method used in this chapter computes the levelized annual revenue requirement over the book life of a power plant, and divides this by the plant's annual output. If all electricity generated by the plant were sold for this amount, the total collected revenue would have the same present value as the sum of all fixed charges and expenses paid out during the life of the plant. Levelization thus makes it possible to compare investment alternatives in terms of a single cost.

It should be noted that depreciation of the plant and periodic reinvestment in new equipment will cause the actual revenue requirement to change from year to year, whereas the levelized revenue requirement represents a constant annual payment and does not indicate the effect that a particular investment will have on actual cash flow.

Energy costs can be computed in both constant dollars and current dollars. Constant dollars were used, because they have a purchasing power more akin to the reader's recent experience. Current dollars represent what the energy would actually cost at the time payments are made.

Revenue requirements accounted for by this method are listed below. A more detailed description, including an explanation of levelization, can be found in Volume 3 of the EPRI Technical Assessment Guide (Electric Power Research Institute, 1987).

The annual revenue that must be collected to pay for the construction and operation of a power plant consists of fixed charges and expenses. Fixed charges are long-term financial obligations associated with building the plant and periodically replacing equipment that may wear out during the plant's life. They are "fixed" in the sense that they must be paid, regardless of how much electricity the plant generates. The following fixed charges were applied to the computation of energy costs presented in this chapter:

- Return on capital investment, in the form of debt return to creditors and equity return to shareholders.
- Book depreciation.
- Property taxes and insurance.
- Income taxes. Depreciation, property taxes, insurance, and interest on debt are assumed to be tax-deductible.

Expenses are annual payments associated with operating and maintaining the plant, and include fuel costs for diesel and coal generation. Note that the sale of co-products, such as fresh water, is credited towards expenses. If co-product sales exceed expenses, then the difference (which represents profit) is subject to income tax. For this chapter, it was assumed that fuel and other annual expenses would not be subject to real price escalation over the life of the plant.