Feasibility of Developing Wave Power as a Renewable Energy Resource for Hawaii

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Economic Development, and Tourism
P.O. Box 2359
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House Resolution No. 8 (HR 8) - "Requesting the Department of Business, Economic Development, and Tourism (DBEDT) to Study the Feasibility of Developing Wave Power as a Renewable Energy Resource for Hawaii," was adopted by the House of Representatives of the Twenty-First Legislature of the State of Hawaii, Regular Session of 2001. This report is the DBEDT's response to HR 8.

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EXECUTIVE SUMMARY

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The idea of harnessing the tremendous power of the ocean's waves is not new. Hundreds of wave energy conversion techniques have been suggested over the last two centuries. Although many wave energy conversion systems (WECS) have been invented, only a small proportion has been tested and evaluated. Furthermore, only a few have been tested at sea, in ocean waves, rather than in artificial wave tanks.

WECS are in an early stage of development and are not yet commercially viable. Such devices are not expected to be available on a large scale within the near future due to limited research and lack of funding. Nevertheless, significant progress has been made in the development of WECS technology, but more needs to be done.

Many research and development goals remain to be accomplished. These include: (1) cost reduction, (2) efficiency and reliability improvements, (3) identification of suitable sites, (4) interconnection with the utility grid, (5) better understanding of the impacts of the technology on marine life and the shoreline; and (6) demonstration of the ability of the equipment to survive in the marine environment, as well as weather effects, over the life of the facility.

Hawaii may be an ideal site for early commercial development of WECS owing to the following reasons: (1) Hawaii has some of the highest electricity costs in the world; (2) Hawaii has one of the better and more consistent wave regimes; and (3) Hawaii is dependent on imported fossil fuels for more than 90% of its energy needs.

Few reliable cost data were found during this study. The lack of commercial WECS facilities means that cost and performance are difficult to estimate. Furthermore, many current cost estimates appear to be overly optimistic. Some developers are projecting electricity costs as low as 3 cents/kWh (without having any large-scale operational facilities and extended operation times to justify and verify these predictions). Accurate data will only become available as more such facilities are developed.

As a result, the approach taken was to: (1) summarize whatever information was available; (2) update previous cost data using a construction cost index, and (3) determine allowable capital and O&M costs for WECS systems for them to be viable

in Hawaii under the constraints of average avoided energy costs (i.e., for electricity purchased by the utility) and average commercial utility rates (i.e., for wave energy-generated electricity used directly by an end user) for each of Hawaii's utilities.

Case studies were analyzed for Kauai (highest avoided energy cost and commercial retail rates) and Oahu (lowest avoided energy cost and commercial retail rates) to demonstrate the effects of: (1) improvements in system performance (i.e., increased wave-to-electricity capture and conversion efficiency); (2) reduced capital costs; and (3) reduced operation and maintenance (O&M) costs.

In spite of the fact that Hawaii has one of the better, and more consistent wave energy regimes in the world, WECS systems are not cost competitive in Hawaii today on an avoided energy cost basis. Very significant improvements in efficiency, capital cost, and O&M costs will be required to change this situation. On the other hand, there may some direct use applications that are cost-competitive today on a relatively small scale. These applications may provide the best opportunities for WECS technology demonstration and development in Hawaii. If projected costs can be achieved, the potential for WECS in Hawaii will be significant.

The successful further development of this technology requires a committed and consistent research and demonstration effort, which is unlikely to proceed without government support.

The State of Hawaii can do a variety of things to assist WECS developers. Among the ideas suggested are: (1) provide permit assistance, including streamlining/facilitating the permit process; (2) facilitate community interaction/assist in surveying consumer response to proposed developments before they are started; (3) use Hawaii as a test bed for WECS development (e.g., at Makai Pier on Oahu or the Natural Energy Laboratory Authority (NELHA) on the Big Island; (4) provide some cost sharing at a relatively low level, and/or possible loans or special purpose revenue bonds to assist the more viable WECS technologies; and (5) promote purchasing incentives for wave energy and for other renewable energy technologies.

Finally, the State of Hawaii needs to evaluate the relative costs, status of development, and potential applications for each of its many indigenous renewable energy resources. With limited funding and manpower, the amount of effort focused on each of these technologies should be proportional to the potential benefits.

1.0 INTRODUCTION

House Resolution No. 8 (HR 8) - "Requesting the Department of Business, Economic Development, and Tourism to Study the Feasibility of Developing Wave Power as a Renewable Energy Resource for Hawaii," [1] was adopted by the House of Representatives of the Twenty-First Legislature of the State of Hawaii, Regular Session of 2001.

In this Resolution, the Legislature found that: (1) wave energy is an abundant, renewable energy resource with great potential; (2) there are a large number of types wave energy conversion devices; (3) such devices can be located on-shore or off-shore, and can be fixed or floating; (4) wave energy conversion also has a number of disadvantages; and (5) there is a need to study the advantages and disadvantages associated with the development of wave power as a commercially viable renewable energy resource in Hawaii.

As a result, the Legislature requested that the Department of Business, Economic Development, and Tourism, through its personnel having expertise in energy and technology: (1) "update its study regarding the feasibility of developing wave power as a renewable energy resource for Hawaii;" (2) "evaluate the feasibility of constructing a commercial wave power generator in Hawaii, similar to the LIMPET wave power station in the United Kingdom;" (3) "review the feasibility of large versus small scale wave power generators, and to weigh the advantages and disadvantages of implementing wave power technology in Hawaii as a renewable resource;" and (4)" report its findings and recommendations to the Legislature no later than twenty days before the convening of the Regular Session of 2002."

This report is the Department of Business, Economic Development, and Tourism's response to the Legislature's requests as stated in HR 8.

Section 2.0 of this report looks at Hawaii's wave energy resource. This includes a discussion of wave characteristics in Hawaii, average power densities, and an evaluation of the annual wave resource for each island.

Section 3.0 summarizes the types and characteristics of various wave energy conversion systems (WECS).

Section 4.0 provides a brief overview of the history of WECS development. Section 5.0 looks at current WECS development worldwide, and in Hawaii. At least four WECS developers have proposed or are considering WECS developments in Hawaii.

Section 6.0 summarizes the many advantages of wave energy conversion. Section 7.0 discusses challenges that must be overcome before WECS are widely used. Section 8.0 describes the variety of potential WECS applications.

Section 9.0 provides an economic assessment of WECS. The approach taken was to summarize whatever information was available (Section 9.1) and to update previous cost data using a construction cost index and to determine allowable capital and O&M costs for WECS systems for them to be viable in Hawaii under the constraints of average avoided energy costs and average commercial utility rates for each of Hawaii's utilities (Section 9.2).

Section 10.0 briefly identifies WECS research and development goals.

Finally, Section 11.0 provides a summary of general and specific conclusions and recommendations concerning WECS potential in Hawaii, and initiatives necessary to achieve this potential.

2.0 HAWAII'S WAVE ENERGY RESOURCE

In 1992, George Hagerman, of SEASUN Power Systems, conducted a "Wave Energy Resource Assessment for the State of Hawaii [2]" on behalf of the State of Hawaii - Department of Business, Economic Development, and Tourism - Energy Division. It was the first complete assessment of wave power as a potential energy source for the State of Hawaii.

This wave resource assessment began with an overview of wave data resources in Hawaii. Example wave records from four measurement sites were then used to illustrate the effects of coastline orientation and sheltering on island wave regimes. The islands of Kauai, Oahu, Maui, Molokai, and Hawaii were then divided into a total of twenty-four coastal segments (as shown in Figure 1), each having a different orientation and a different degree of sheltering by adjacent coastal features or neighboring islands. Annual average incident wave power was estimated at five water depths for each coastal segment, using a spectral refraction and shoaling analysis. The total wave energy resource for each island was then compared with the island's total electricity demand (in 1990).

Six wave energy technologies that were believed to have near-term potential application in Hawaii were evaluated. These wave energy technologies are:

- Land-based tapered channel (TAPCHAN);
- Land- or caisson-based oscillating water column (OWC);
- Caisson-based pivoting flap;
- Offshore heaving buoy;
- Offshore flexible bag; and
- Offshore submerged buoyant cylinder.

Cost and performance projections were then made. As an example of an offshore device, cost and performance projections were made for a Swedish heaving buoy system, deployed in outer shelf waters off Makapuu Point, Oahu. An overall assessment was made of Hawaii's wave energy resource, and areas requiring further investigation were identified.

According to Hagerman's definitive study, " … recovering only 5 - 10% of the wave energy potential available in outer shelf waters off the northern coastlines of Kauai, Maui, and Hawaii could meet the total electrical demands of these islands. Less than one half of one percent of Molokai's wave energy resource could meet the electricity needs of that island. Except for Oahu, where electricity demand is comparable to two-thirds of the available resource, wave energy can be withdrawn at very low levels and still make a substantial contribution to island energy supply."

Hagerman further stated that "[i]n practice … Hawaii's wave energy development potential will be limited by the following considerations:

- Environmental constraints based on potential negative impacts and local public concerns, particularly with regard to visual appearance;
- Utility constraints based on time variability of the wave resource and the limited capacity of onshore transmission lines; and
- Financial constraints based on the limited number of economically feasible sites for land- or caisson-based systems and risks associated with uncertainties in cost and performance projections for offshore systems"

These constraints are just as applicable today as they were in 1992.

2.1 Wave Characteristics in Hawaii

The three primary sources of wave energy in Hawaii are seas built up by local trade winds, swell generated by storms in the north Pacific Ocean, and swell from similar storms in the southern hemisphere. High waves are also generated by tropical storms and Kona winds, but these are relatively rare wave events, occurring no more than a few times a year. Such waves represent a significant hazard that must be considered in the design of a wave power plant, but their contribution to the islands' wave energy resource is negligible. The day-to-day and seasonal variability of wave energy in Hawaii depends largely on the orientation of a given island coast and the extent to which it is sheltered from the primary wave systems described above [2].

2.2 Resource Assessment Results

In Hawaii, wave power density along the 260-ft (80-m) depth contour typically averages 3.0 to 4.6 kW/ft (10 to 15 kW/m). Because the island shelves are so narrow, even this outer shelf depth contour can be closely sheltered by adjacent headlands or peninsulas, which is the case at Kailua, Oahu, and in the vicinity of Hilo. At these locations, wave power density along the 260-ft (80-m) depth contour ranges from 2.1 to 2.7 kW/ft (7 to 9 kW/m) [2].

Refraction and shoaling significantly reduce wave power densities in shallow water; along the 16-ft (5-m) depth contour, they are roughly 20% lower than along the 260-ft (80-m) contour. Due to the wide variety of coastal orientations and exposures, shallow water wave power has greater longshore variability than it does in deep water and can range anywhere from 1.5 to 3.7 kW/ft (5 to 12 kW/m) [2].

2.3 Total Resource Base

Multiplying the average wave power along a given depth contour by the length of each coastal segment and by the number of hours in a year, and summing the results for all segments, gives the annual wave energy resource for a particular island. This result is plotted for the 260-ft (80-m) and 16-ft (5-m) depth contours in Figure 1. Each island's annual electricity demand in 1990 is also plotted for comparison [2].

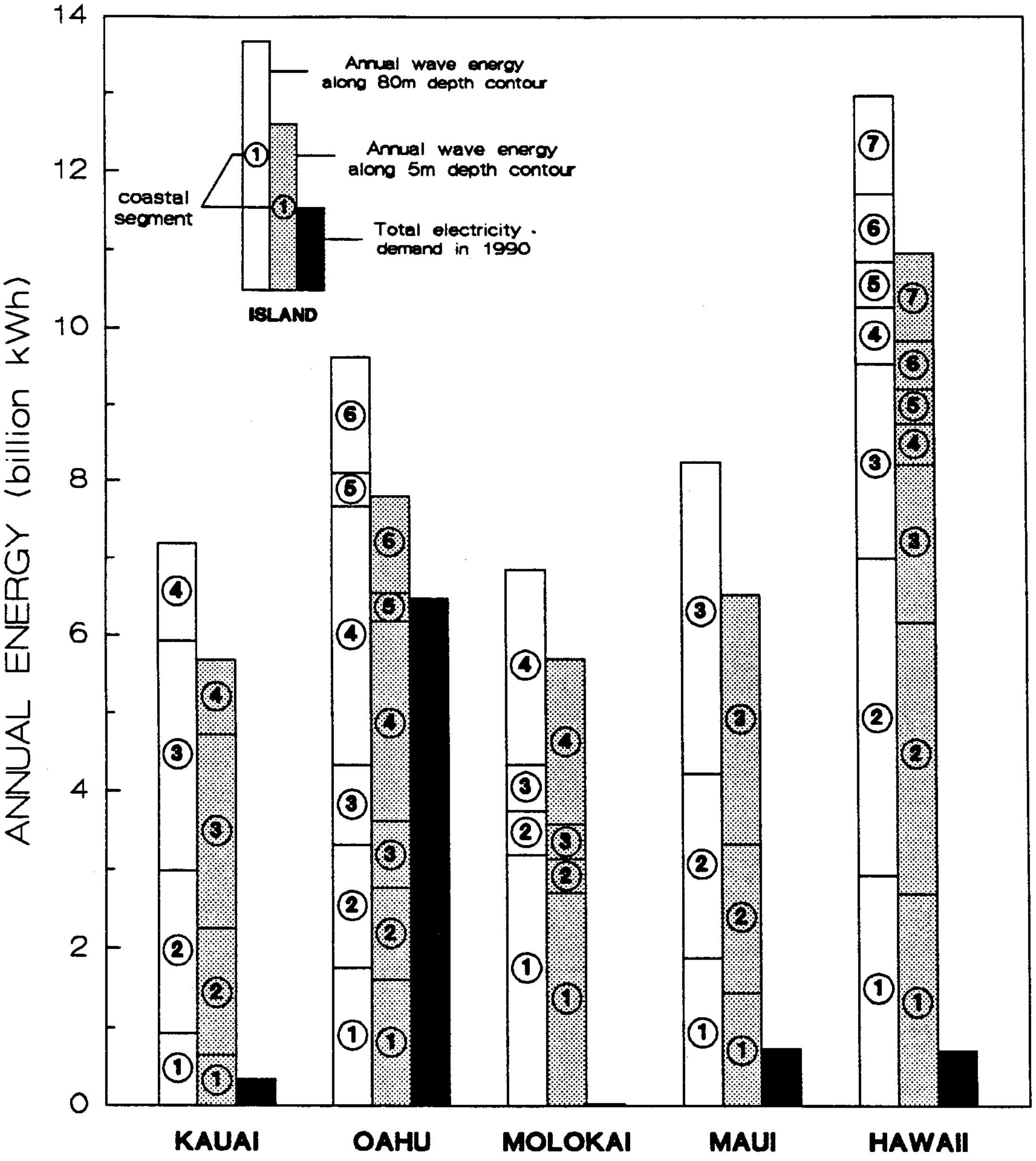

Figure 1 - Annual wave energy resource compared with annual electricity demand in 1990 (Source: [2])

3.0 TYPES OF WAVE ENERGY CONVERSION SYSTEMS

Although many wave energy conversion systems (WECS) have been invented, only a small proportion has been tested and evaluated. Furthermore, only a few have been tested at sea, in ocean waves, rather than in artificial wave tanks [3].

A WECS may be placed in the ocean in various possible situations and locations. It may be floating or submerged completely in the sea offshore or it may be located on the shore or on the sea bed in relatively shallow water. A WECS on the sea bed may be completely submerged, it may extend above the sea surface, or it may be a converter system placed on an offshore platform. Apart from wave-powered navigation buoys, however, most of the prototypes have been placed at or near the shore [3].

Land-based systems include the tapered channel (TAPCHAN) and a variety of fixed oscillating water column (OWC) devices. Caisson-based systems include fixed OWC devices, pivoting flaps, and confined, heaving floats. Offshore devices include floating OWC devices, heaving buoys and other devices [4].

WECS can also be categorized as: (1) oscillating water columns; (2) wave surge or focusing devices; or (3) floats or pitching devices [5].

- Oscillating Water Columns (OWC) - These devices generate electricity from the wave-driven rise and fall of water in a cylindrical shaft. The rising and falling water column drives air into and out of the top of the shaft, powering an air-driven turbine.

- Wave Surge or Focusing Devices - These shoreline devices, also called "tapered channel" or "TAPCHAN" systems, rely on a shore-mounted structure to channel and concentrate the waves, driving them into an elevated reservoir. Water flow out of this reservoir is used to generate electricity, using standard hydropower technologies.

- Floats or Pitching Devices - These devices generate electricity from the bobbing or pitching action of a floating object. The object can be mounted to a floating raft or to a device fixed on the ocean floor.

The following figure shows some of the many wave energy conversion processes that have been proposed.

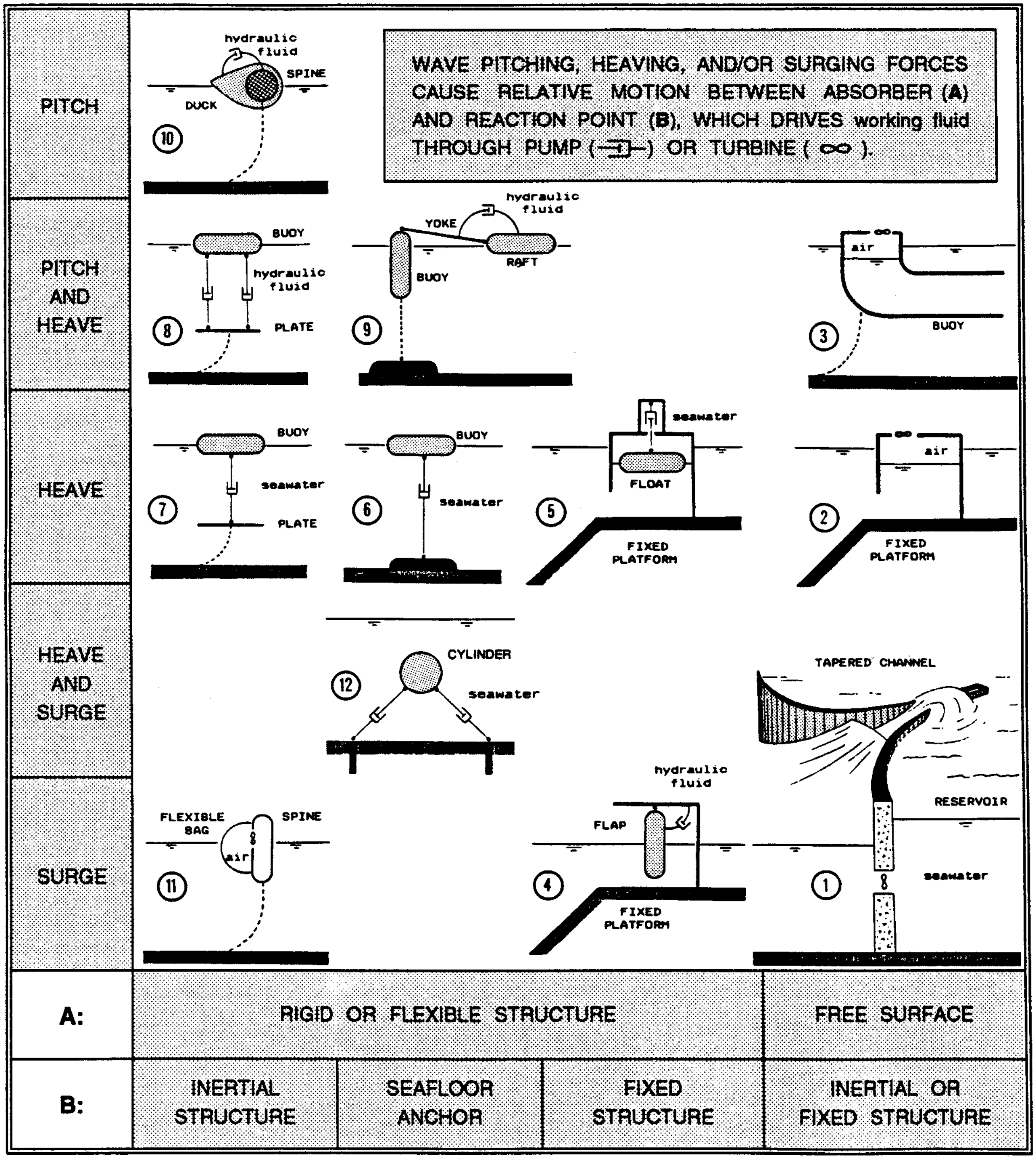

Figure 2 - Wave energy conversion processes (Source: [2])

3.1 Oscillating Water Column

The main device deployed worldwide is the Oscillating Water Column (OWC). This consists of a partially submerged, hollow structure that is open to the sea below the water line. This encloses a column of air on top of a column of water. Waves cause the water column to rise and fall, which alternately compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a Wells turbine, which has the ability to rotate in the same direction regardless of the direction of the airflow. The rotation of the turbine is used to generate electricity [6]. By a comfortable margin, the most money and effort being spent worldwide on wave energy development employs the OWC [7].

The wave energy collectors used in Wavegen's LIMPET and OSPREY modules are in the form of a partially submerged shell into which seawater is free to enter and leave. As the water enters or leaves, the level of water in the chamber rises or falls. A column of air, contained above the water level, is alternately compressed and decompressed by this movement to generate an alternating stream of high velocity air in an exit blowhole. If this air stream is allowed to flow to and from the atmosphere via a pneumatic turbine, energy can be extracted from the system and used to generate electricity [8].

One of the major problems with shoreline-based OWCs is their construction, which must necessarily take place on rocky shores exposed to wind and waves. In the case of the prototype Islay OWC system it was relatively easy to build a temporary dam on the shoreline to protect the unit. However, LIMPET is a much larger system, with a lip 66 ft (20m) wide. It was, therefore, ultimately decided to build the unit back from the coastline and remove an embankment to make the system fully operational [9].

Figure 3 - LIMPET 500 (Source: [8])

To overcome some of these problems, Wavegen [10] has developed new techniques that it claims will:

- Reduce the amount of rock to be removed;
- Reduce the installation period;
- Enable the device to be located nearer the cliff edge - which increases wave energy capture; and
- Significantly reduce the capital cost of the installation.

3.2 Tapered Channel Systems (TAPCHAN)

This is the simplest conversion process, similar in many ways to conventional low-head hydroelectric technology. Where site conditions permit construction of a large coastal reservoir without extensive blasting or dam-building, it is the most economical wave energy device developed to date [2].

The tapered channel (TAPCHAN) consists of a collector that funnels waves into an ever-narrowing channel that increases their height. The kinetic energy of the moving wave is converted into potential energy as the water is stored in the reservoir. The stored water is then fed through a Kaplan turbine. It then spills into a reservoir. Water drains back into the sea through a conventional hydroelectric turbine that generates electricity. [4,11]

TAPCHAN systems are not suitable for all coastal regions. Suitable locations for TAPCHAN systems must have consistent waves, with a good average wave energy and a tidal range of less than 3.3 ft (1m), suitable coastal features including deep water near to shore and a suitable location for a reservoir [11].

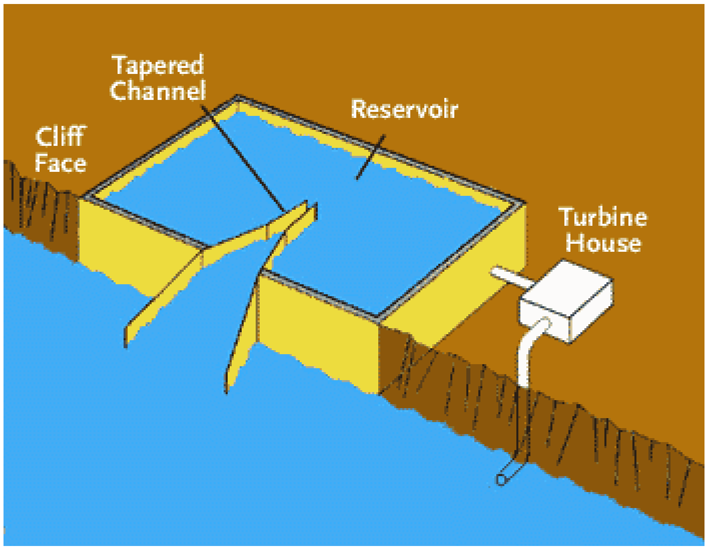

Figure 4 - TAPCHAN wave energy device
(Copyright Boyle, 1996) (Source: [11])

3.3 Floating Devices

One of the advantages of floating devices over fixed devices it that they can be deployed in deeper water, where wave energy is greater (since waves lose energy with decreasing water depth). There is no need for significant earthworks, either, as there is with onshore devices [12].

The Salter Duck, Clam and other floating wave energy devices generate electricity through the harmonic motion of the floating part of the device, as opposed to fixed systems which use a fixed turbine which is powered by the motion of the wave. In these systems, the devices rise and fall according to the motion of the wave and electricity is generated through their motion [11].

Floating WECS are normally tethered to a fixture on the seabed. Various devices have been developed which include the generation of electricity from waves through the inflation of a bag to trap and release air (as above) or mechanically driving a motor/ pumping fluids by the differential motion of the waves. As some devices could be tethered to the seabed, this would not cause any unnecessary lateral loading on the installation and, therefore, could appear to be a viable WECS. The offshore installation would be in this case an ideal substation/ maintenance platform [13].

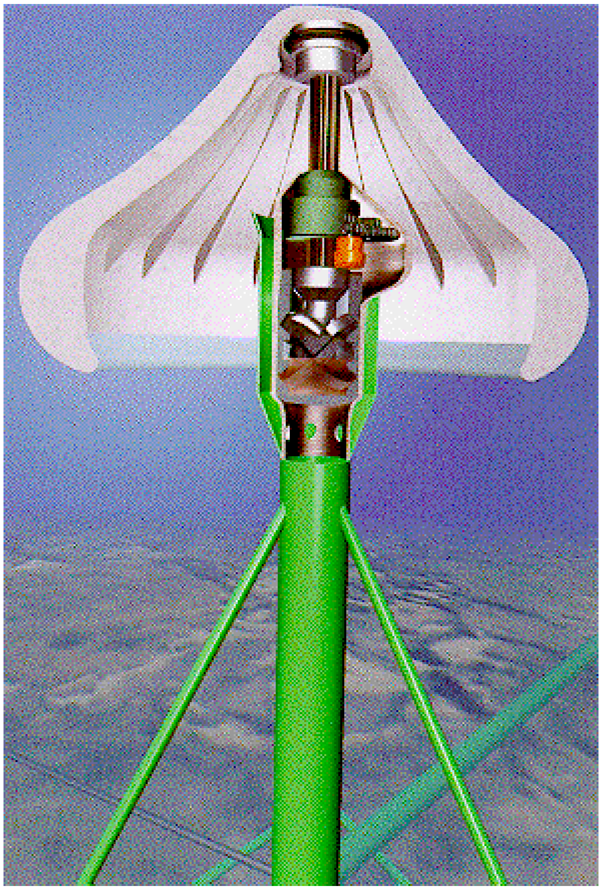

Figure 5 - The Archimedes Wave Swing (Source: [14])

Heaving buoys and pivoting flaps use the up and down motion imparted by passing waves to pump fluids, create oscillatory movements which are translated to rotary movements, or use oscillatory movements directly in a variety of devices to generate electricity [4].

Among the large variety of floating devices are the: (1) Salter Duck; (2) Lanchester Sea Clam; (3) Bending Spline WPT-375; (4) Ocean Power Technologies (OPT) PowerBuoy; (5) IPS Buoy; (6) Wave Energy Module; (7) Multi-Wave Plane; (8) HYDRA; (9) Pelamis

Wave Energy Converter; (10) Mighty Whale; (11) Pneumatically Stabilized Platform (PSP), (12) McCabe Wave Pump, (13) Point Absorber, and (14) Wave Rider.

The OSPREY and WOSP are gravity-based devices that are floated for transport to site [10]. The Archimedes wave swing is now not a floating device, but a near-shore bottom standing. It has changed a great deal from Figure 5 [15].

3.4 Off-Shore vs. On-Shore Devices

Although wave energy applications are still in the early phase of development, a variety of conversion devices have been constructed and tested. These devices can be classified in two groups:

- On-shore systems including a variety of fixed oscillating water column (OWC) devices, and
- Off-shore systems such as oscillating water column (OWC) devices, heaving buoys and rafts

Large-scale on-shore wave power generating stations could face similar problems to those encountered by some wind farms, where opposition has focused on the aesthetic and noise impact of the machinery on the environment. Noise impacts can be reduced by enclosure of the turbine and other sound attenuation methods [10]. Many wave power supporters say that the answer lies not in huge plants but in a combination of on-shore generation and near-shore generation focused on meeting local or regional needs. On-shore or near-shore plants, they argue, could also be designed as part of harbor walls or breakwaters, performing a dual role [16].

3.4.1 On-Shore Devices

Where the shoreline has suitable topography, cliff-mounted OWC generators can be installed. On-shore systems have a number of advantages over off-shore systems, not the least of which is the fact that generators and all power transmission are shore-based, making maintenance much cheaper [9].

Currently, being onshore is an advantage. The relative simplicity of onshore plants, compared with WECS meant for deep water, is helping researchers and builders get the LIMPET and the Azores plants up and running. However, such shoreline plants also face an insurmountable obstacle (i.e., wave energy dissipation in shallow water) that may soon end their dominance [17].

The economic viability of such a shoreline device depends greatly on local rock and soil conditions, as well as the shape and size of the gully (channel) and the presence of wave dissipating rock formations. Civil works, which account for more than half the capital cost, must be tailored to each project site, and even mechanical and electrical components may have to be differently-sized for the variable capture chamber geometry expected among natural channels along a given section of coast [18]. The current LIMPET device used a man-made channel not a natural channel. Only the pilot 75kW device built on Islay in 1990 used a natural channel. Energetech is reducing the requirement for a channel [10].

3.4.2 Off-Shore Devices

Despite their less-advanced development status, offshore systems have much wider deployment potential, since they don’t involve shoreline modification or breakwater construction. Floating devices have been developed that use air or seawater as working fluids, eliminating the risk of chemical pollution. High-pressure seawater is particularly attractive as a working fluid, since it can produce both electricity and fresh water [2]. The trend is now towards offshore devices [15].

An offshore wave energy project can be composed of identical structural modules, each housing a standardized mechanical and electrical plant that can be fitted into the module when it is built. This maximizes the benefits of mass production and makes large projects easier to finance, since a block of ten or twenty modules can be brought on-line in a relatively short period of time. Increasing generating capacity in such an incremental manner also reduces the risk of utility commitment to excess supply [18].

However, offshore wave-power plants operate in a very hostile environment. There are problems of getting electricity to land and also of anchoring. In stormy weather, there are very large forces. Powerful waves and storms can damage WECS. And, there is the problem of maintenance if the WECS is very far from the coast, especially in winter. There's also the tendency of seawater to short-circuit and corrode equipment. There is also concern that one of the new offshore devices might pull loose of its moorings and drift into a ship's path or wash up on a beach [17,19].

Fortunately, there are many solutions to these problems thanks to the offshore oil and gas industry. The offshore oil and gas industry has developed better ways to anchor equipment, more durable and corrosion-resistant materials, and improved cables for carrying electric current underwater. For example, electrical connectors that are easily mated and unmated underwater are proving vital to modular wave-energy designs [17]. Improved design tools have also been provided by the offshore oil and gas industry [10].

The optimal location for harvesting wave energy is in water about 164 to 328 ft (50 to 100 m) deep. There, waves retain nearly all the power they've gathered while crossing the ocean, but the sea bottom is near enough that anchoring wave-power equipment is easier and cheaper than in deeper waters [17]. Energetech's HYDRA device is designed for use in water about 98 to 328 ft (30 to 100 m) deep [10].

3.5 Hybrid Systems

Hybrid systems combine the available power for more than one source. These include the: (1) Monitor (hybrid wind, tide, and wave) and (2) Wind and Ocean Swell Power (WOSP). Combining two, or more, sources of renewable energy into one systems may improve the cost effectiveness and available power from these systems.

4.0 WECS DEVELOPMENT

The idea of harnessing the tremendous power of the ocean's waves is not new. In the middle ages (1200-1500 AD) farmers used to trap sea water in mill ponds and use it to power water mills as the tide dropped [9,20].

Hundreds of wave energy conversion techniques have been suggested over the last two centuries. One of the first patents was granted to Girard Messers in 1799. It was a constructed raft that acts like a buoy. On the raft he attached a rope that pulled some mechanism [21].

More recently, engineers have begun to look at wave power on a larger, industrial scale. However, until the last few years, particularly in Europe, wave power was seen as uneconomic. Although some pilot projects showed that energy could be generated, they also showed that, even if cost of the energy generated was not considered, there was a real problem making equipment that could withstand the extremely harsh marine environment [9]. Nevertheless, significant progress has been made in the development of WECS technology.

As stated previously there is a large number of different WECS technologies under various states of development. One measure of the degree of development is the current or relatively recent presence of operating prototypes (or the presence of developers who are actively pursuing relatively large-scale demonstrations). These are the WECS technologies that will be focussed on in this analysis.

Two heaving buoy systems were 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. The Swedish prototype was deployed intermittently during the two-year period. Incident wave power at the test site averaged 1.5 kW/m, and generator output averaged 3 to 5 kWe. Very good agreement was obtained between measured energy production and that predicted by a numerical model of the system. The prototype also survived extreme storm waves (16 ft [5 m] high) without significant damage. The Swedish heaving buoy/hose pump WECS was used as the basis for Hagerman's analysis of WECS systems in Hawaii [2].

5.0 CURRENT DEVELOPMENTS

5.1 Worldwide

The LIMPET was specifically identified in HCR 8 as one WECS technology that may have promise in Hawaii and should be investigated further. LIMPET (Land-Installed Marine-Powered Energy Transformer) offers modular construction and simple operation, and company officials predict its applications will fill a growing need in coastal communities around the world that are trying to replace diesel generation [22]. LIMPETs can be developed at the shoreline or in the nearshore environment. The actual location would make a significant difference to the captured power [10].

The LIMPET uses an OWC in an inclined concrete tube that has its opening below the water level. Wave action causes the water level in the collector to oscillate, and this variation alternately compresses and decompresses the trapped air in the column. The air flows back and forth through a pair of generating turbines that are driven in the same direction at all times, regardless of the direction of the airflow [22].

The world's first commercial wave power station has been connected to the national grid in Britain. Wavegen and Queen's University Belfast jointly developed the LIMPET WECS with financial support from the European Union. The LIMPET is operating on the Island of Islay, off the West Coast of Scotland. This first site will generate 500 kW of renewable energy. That capacity is sufficient for 400 local homes [22]. It is the direct successor of an experimental 75 kW turbine (built by researchers from the Queen's University of Belfast) which operated on the island between 1991 and 1999 [9].

The LIMPET device was designed as a commercial test bed and research facility, to enable Wavegen and Queen's University Belfast to run experiments, measure environmental load data and evaluate systems to gain an improved understanding of design. The device achieved maximum power output shortly after commissioning was completed. Because the plant is so mechanically simple, the availability for the LIMPET has been very high. The device can be run remotely from Wavegen's office in Inverness, Scotland [10].

Wavegen is currently developing a new generation of LIMPET shoreline devices. With United Kingdom labor rates and 25kW/m seas, Wavegen is anticipating installed costs of around $720/kW. Wavegen has also received around $10 million for the development of a new offshore device called HYDRA. They have been working on this new floating device for around two years. It has a nominal rating of 2 MW. They have plans to build one towards the end of 2002. At this stage technical information regarding this device will not be in the public domain until they have completed insurance approvals [10].

Energetech Australia Pty. Ltd. has demonstrated a 1/25 model of a novel wave energy system that incorporates two important and unique features: (1) a parabolic wall to focus the power of incoming waves, and (2) a turbine developed in Australia that is claimed to be four to five times more efficient than the competing technology, the Wells Turbine [23].

There are conflicting opinions regarding the relative efficiencies of the Wells and Denniss-Auld turbines. Many of these differences result from various assumptions regarding: (1) current and future levels of development, (2) turbine design, and (3) operational modes and characteristics for each of these turbines.

More recently, Energetech stated that the "estimated efficiency of the Denniss-Auld turbine is, in fact, about two times that of the Wells due to a different operation [24]." And, Previsic [25], maintains that the Wells turbine efficiency is, "depending on the design, between 30% - 40%." At this relatively low efficiency level, Energetech's claimed efficiency level for the Denniss-Auld turbine (i.e., twice that of the Wells) is theoretically possible.

However, Wavegen states that the peak efficiency for the Wells turbine on the LIMPET is 72%, and average efficiency is 42%, with a non-optimized control strategy. Wavegen anticipates raising the average efficiency to around 60% and the peak efficiency to 80% [10]. Salter [15] maintains that "[a]t its best steady air flow and with good diffusers a full size Wells turbine should be just over 80% efficient." He further states that "[I]n random seas of the best amplitude this falls to just over 50%, some of which can be regained by use of variable pitch." At these higher average and peak efficiencies, Energetech's claimed efficiency level for the Denniss-Auld turbine would not be possible.

Therefore, the significantly higher efficiency claimed for the Denniss-Auld turbine is difficult to verify at this time, and should be verified by a side-by-side evaluation, or an evaluation under similar conditions, of these various turbine types.

The Energetech wave generator is designed to be anchored on shore in areas where there is fairly deep water right up to the coast such as on harbor breakwaters or rocky cliffs. The parabolic shield focuses waves into the bottom of a chamber filled with air, the shield increasing the amplitude of the waves at the focal point by about a factor of three. The rising and falling column of water in the chamber pushes air back and forth through an aperture in which a turbine is placed [23].

Energetech is currently finalizing designs for a wave energy device to be installed at Port Kembla. This is a 350-kW device that will be built in 2002. Funding has been provided by a grant from the Australian Greenhouse Office and through private funding arrangements. Energetech is also currently in the early stages of project development in Canada, Spain and on the U.S. East Coast [24].

A New Jersey company (Ocean Power Technologies, Inc. [OPT]) plans to launch a series of its PowerBuoys in the Southern Ocean more than a mile (1.6 kilometers) off the coast of Victoria, Australia, to harness the power of the ocean's waves. The system can be scaled up to generate up to 10 megawatts of electricity. The current proposed Australia project could have up to 20 buoys, each about 15 ft (4.5 m) in diameter and each capable of generating 50 kilowatts of electricity (for a total of up to one megawatt). The buoys are submerged more than three feet (one meter) below the water's surface. Inside, a cylinder moves around a piston-like structure as the buoy bobs with the rise and fall of the waves. That movement drives a generator on the ocean floor, producing electricity, which is sent to the shore along an underwater cable [20,26].

Ocean Power Technologies also has a contract with the U.S. Navy to investigate the installation of a system for Kaneohe Marine Corps Base Hawaii [20,26]. This project is discussed in more detail in Section 5.2.

Sea Power & Associates has developed the Wave Rider technology that consists of a series of lightweight concrete floats that would sit one to two miles off shore. Floats are connected to a hydraulic pump that extends about 60 ft (18 m) down to the ocean floor. The up-and-down motion of the waves creates pressure that drives the hydraulic pump, which then drives turbines to generate electric power [27].

Sea Power's first target market is Hawaii and the islands of the Pacific Ocean, where the relatively high costs of generating electricity from imported fossil fuels provide an opportunity for immediate profitable operations and positive cash flow. Additionally, demand in the Pacific for electrical energy – especially from renewable, non-polluting sources – will increase substantially in the years ahead [28]. They claim their system could be cost-competitive with diesel, which now costs 18 to 25 cents/kWh [27].

According to Sea Power, their product is also scaleable to various commercial and industrial applications, such as remote resort and research facilities, desalination plants, and hydrogen production facilities. Ultimately, Sea Power plans to offer its OWEC products and technology worldwide [28].

The Archimedes Wave Swing is another concept for converting wave energy into electricity. It was invented by Fred Gardner and has been investigated at the Energy Centre of the Netherlands (ECN). It consists of a number of inter-connected, air-filled chambers situated below the sea's surface. These are topped with movable floats, like hoods on the air chambers, and waves cause them to oscillate vertically. As a wave crest moves over a hood, the pressure on it rises, the trapped air is pushed into another chamber, and the hood starts to sink. The process is reversed in a wave trough. Each wave repeats this process [29]. There is considerable interest in this WECS by at least one State of Hawaii legislator.

BC Hydro, a major power corporation in Canada, and the government of the province of British Columbia, have established a program to demonstrate 20 MW of renewable energy on Vancouver Island, with a possible expansion to several hundred megawatts. BC Hydro recently issued a global request for proposals for WECS developers to demonstrate 2 MW of wave power on the island. This will be the first commercial-scale WECS development in North America. The installation is proposed for 2003 [24].

At present the worldwide installed WECS capacity is about 1 MW, mainly from demonstration projects. In addition, several commercial power plants may be deployed over the next couple of years (2002-2005). SROI-3, the Scottish renewable energy obligation awarded three projects with a 15 year power purchase contract. The first power plant developed by Wavegen went online last year, and two more are planned to follow [25].

A non-profit corporation dedicated to the development of wave energy has been formed. Pacific Ocean Wave Energy Research (POWER) will educate the public about wave energy, provide grants for WECS development through full scale prototypes, and work on the generic issues surrounding the use of wave energy [30].

A consortium was formed to install a demonstration project to generate electricity from wave energy. Leading the consortium is AquaEnergy Group Ltd. of Mercer Island, Wash. The Makah Nation and Clallam County PUD are project participants, as is the Northwest Energy Innovation Center, made up of the Bonneville Power Administration, Energy Northwest, Pacific Northwest National Laboratory and Washington State University. The consortium plans to invest seed money for initial permitting and development of the demonstration project. AquaEnergy expects to pay for construction through a combination of power sales, venture capital investments and grants. The immediate goal is to install a 1 megawatt offshore wave energy power plant in the vicinity of Neah Bay, Washington [31].

5.2 Hawaii

Ocean Power Technologies (OPT) has a contract with the U.S. Navy to investigate the installation of a system for Kaneohe Marine Corps Base Hawaii (KMCBH). The overall program is split into three phases with the following objectives [32]:

- Develop and validate the technology base required to design and reliably operate an Ocean Wave Energy Conversion (WEC) System, and
- Demonstrate the technical and economic feasibility of using Ocean Wave Power to:
  - Reduce the total cost of facility ownership.
  - Reduce the Navy's dependence on fossil fuels for power.

In Phase I, OPT plans to deploy and test a full-scale wave PowerBuoy to gather important information about system performance and reliability in a full-scale real ocean environment and connect into the electrical grid. The primary site for this test currently is the KMCBH. Due to the time necessary to conduct all environmental assessment work and obtain the appropriate permits as required by NEPA, the deployment will most likely occur early in 2003.

In Phase II, OPT plans to fabricate, deploy and test one more buoy to achieve a multiple (in this case two) PowerBuoy System in Hawaii and test it for a total of six months.

The Phase III program will allow OPT to extend the test period beyond six months and add at least one more PowerBuoy. The detailed program plan for this phase is not yet complete.

Energetech has also submitted a proposal to develop a wave energy station at KMCBH. The demonstration project will supply power and act as a research facility. The Hawaii Natural Energy Institute (HNEI) of the University of the Hawaii is involved as a research participant. The proposal has been reviewed and approval has been granted to proceed with preliminary work. Energetech has secured venture capital funding to support the preliminary work (site survey, environmental assessment, etc) and will be proceeding with this in the near term, using Hawaii-based consultants. The HNEI will take part in the project by conducting optimization research once the facility is built. The major capital funding for the project may be provided by further venture capital or through Special Purpose Revenue Bonds (SPRBs). This project aims to provide direct benefit to the economy, visibility, education and research in the state [24].

Sea Power & Associates proposed setting up a test and demonstration WECS in Hawaii and provided a presentation on their technology here earlier this year. However, funding for this project never materialized [33].

Neptune Sciences Inc. (NSI) has submitted a proposal abstract to the National Defense Center of Excellence in Ocean Sciences (CEROS), to do a demonstration of wave energy powering a desalination plant. They partnered with the Hawaiian Electric Company (HECO), the Honolulu Board of Water Supply (HBWS), Parsons Brinckerhoff Water, and Proton Energy Systems Inc. They have not yet been contacted to see if they want a full proposal, but NSI expects to hear soon [34].

NSI expects to provide a scientific report on their findings, and to include a detailed wave resource analysis of Oahu, which will provide a detailed plan and methodology for future WECS site selection. NSI claims that this methodology can also be applied to any coastal region, for pre-installation analysis and selection of proper WECS technologies. Finally, a proposed permit process for future WECS manufacturers to follow will also be delivered [34].

There appears to have been a number of technological advances in WECS technology since 1992. Unfortunately, few reliable cost data were found during the literature search for this study, and via communications with WECS developers and researchers. The lack of commercial WECS facilities means that the cost and performance of WECS are difficult to estimate. Accurate data will only become available as more such facilities are developed.

As a result, the approach taken was to summarize whatever information was available and to update previous cost data using a construction cost index [35] and to determine allowable capital and O&M costs for WECS systems for them to be viable in Hawaii under the constraints of average avoided energy costs and average commercial utility rates for each of Hawaii's utilities. This analysis is summarized in the "Economic Assessment" section of this report (Section 9.0).

6.0 ADVANTAGES OF WAVE ENERGY CONVERSION

Wave energy systems have many advantages. Among these are:

- Renewable and sustainable resource;
- The resource is relatively well-characterized;
- Abundant;
- Indigenous;
- Reduces dependence on fossil fuels;
- Pollution-free;
- Relatively consistent;
- Relatively predictable;
- More concentrated;
- Modular;
- Siting flexibility;
- Dissipates wave energy/protects shoreline;
- Present no difficulty to migrating aquatic animals;
- Local economic development; and
- Multiple applications

Renewable and Sustainable Resource - Wave energy is a renewable and sustainable energy resource. Waves are generated by the wind, which is in turn generated by the uneven heating of the atmosphere by the sun. As such, wave energy is a virtually inexhaustible resource. The energy is free (although the cost of conversion is not).

The Resource is Relatively Well-characterized - There is a ready supply of wave energy data collected from wave monitoring buoys. These data are very thorough and go back many years. These data are important as a guide to the likely economics and the best locations for siting wave plants [36]. Estimating the potential resource is much easier than with wind, an important factor in attracting project lenders [37]. Hawaii has a long-term database of wave data.

Abundant - Wave energy is abundant. Although variable from place-to-place and season-to-season, some estimates show that wave energy could amount to nearly 16 percent of the world's current total electricity output. That would be nearly 2,000 terawatt-hours (TWh) annually, or as much as the world's large-scale hydroelectric plants produce [17]. Hawaii has one of the better, and more consistent wave energy regimes in the world.

Indigenous - Wave energy is an indigenous resource. Conversion of this resource can take place locally, reducing the need to import fossil fuels.

Reduces Dependence on Fossil Fuels - As is true with all renewable energy resources, use of wave energy has the potential to significantly reduce the use of fossil fuels for electricity production and other applications. Wave energy consumes no fossil fuels during operation, and will displace their use. Hawaii currently depends on imported fossil fuels for more than 90% of its energy requirements.

Pollution-Free - No serious environmental impacts have been attributed to WECS, except of course during construction. Construction impacts occur with all energy conversion systems construction. And, construction impacts can be minimized by various mitigation measures. Wave energy generates little or no pollution. On the other hand, non-renewable energy resources such as fossil fuels produce air pollution, water pollution and thermal pollution and nuclear energy produces thermal pollution and highly radioactive nuclear waste. This is particularly important for Hawaii, which depends on its relatively pristine environment to attract tourists and to benefit its residents.

Relatively Consistent - Wave energy is the most consistent of the "intermittent" renewable energy sources. Wind does not blow constantly, and the absolute amount of wind in any one area is highly variable and dependent on topography and obstructions. Solar availability varies with location, time of day and season. Waves, however, remain throughout the day even though wave swells do change in power and size [36].

The average availability of the wave energy resource, expressed as a capacity factor, is generally greater than that of solar or wind. Typical capacity factors for solar and wind are 20 to 25% and 25 to 30%, respectively. Wave energy can have a capacity factor approaching 50%. It may be possible for the capacity factor to be as high as 90% if the system is in a region of high wave energy – as is the case in certain parts of Hawaii. Also by using a modular offshore WECS, further improvements in the capacity factor are possible because there will be less downtime for maintenance.

Relatively Predictable - Because waves originate from storms far out to sea and can travel long distances without significant energy loss, power produced from them is much steadier and more predictable, both day-to-day and season-to-season. This helps to reduce project risk [37]. Waves can be accurately forecast several days in advance. This allows the ability to plan your energy mix with other power plants [15].

More Concentrated - Wave energy contains roughly 1,000 times the kinetic energy of wind, allowing much smaller and less conspicuous devices to produce the same amount of power in a fraction of the space. Wave energy varies as the square of wave height, whereas wind energy varies with the cube of air speed. This results in much higher average power production from waves per unit of time [37].

Modular - A number of these modular devices can be connected together to create a larger WECS. The electricity generated can then be transmitted to the utility grid [4]. System sizes can range from kilowatts to multi-megawatts. Additional modules can be added as needed, with relatively short lead times and at a relatively low incremental cost. These qualities are vital for matching the electrical product to changing end use demands and to improving cost effectiveness.

There are a lot of opportunities for increasing WECS efficiency and bringing down the cost of manufacturing. WECS are generally built in modular units, which provides for opportunities in mass production and standardization. Further innovation and progress will likely come from technology transfers from the related industry sectors, the wind and offshore oil and gas industries [25].

Siting Flexibility - Wave power plants can be based on land, on caissons in relatively shallow water (16 to 50 ft [5 to 15 m]) depth, or in deeper (98 to 328 ft [30 to 100 m]), offshore waters.

Dissipates Wave Energy/Protects Shoreline - Wave energy systems can shelter the coast, and are therefore useful in harbor areas or coastal erosion zones [9]. WECS can be incorporated into breakwaters, thus reducing the cost of such systems, and providing for dual use [2]. Construction of large-scale offshore devices results in new areas of sheltered water, attractive for fish, sea birds, seals and seaweed [9].

Offshore wave power plants can be spaced sufficiently far apart that wave energy passing between the plants will diffract into the calmer waters immediately behind the plants. The environmental impact at the coast would be a broad, diffuse lowering of wave energy levels. A 5 to 10% withdrawal of wave energy offshore would correspond roughly to a 3 to 5% reduction in wave heights at the coast [2].

Presents No Difficulty to Migrating Aquatic Animals - While migrating aquatic animals (e.g., fish, whales, and dolphins) may encounter WECS, they can easily avoid them. WECS can be designed to minimize entrapment.

Local Economic Development - Use of wave energy allows the generation of electricity (and other applications) in the local area using a free, indigenous, renewable energy resource. This will reduce the export of scarce local capital that may have been used to purchase imported fossil fuels. Renewable energy systems are also generally more labor intensive than fossil fuel or nuclear energy systems. Increased job creation and retaining capital at home will assist in local economic development. Again, with its more than 90% dependence on fossil fuels, developing wave (and other renewable) energy resources could provide significant economic development opportunities in Hawaii.

Multiple Applications - Wave energy conversion systems can be used in a variety of applications. These include:

- Electricity generation;
- Hydrogen production by electrolysis;
- Seawater desalination through reverse osmosis;
- Potable water production through vapor compression;
- Combined electricity/potable water production;
- Pumping/hydraulic power;
- Refrigeration/air conditioning;

- Navigation aids/environmental data acquisition;
- Shoreline protection;
- Water oxygenation/purification;
- Commercial mariculture/fish farming;
- Enhanced oil recovery; and
- Other downstream applications.

7.0 CHALLENGES FOR WAVE ENERGY CONVERSION

Wave energy systems also face many challenges that must be overcome before they are widely used (it should be noted, however, that many of these do not apply to offshore systems). Among these challenges are:

- Visual impact;
- Noise;
- Disturbance or destruction of marine life;
- Coastal erosion;
- Threat to navigation;
- Interference with commercial and sport fishing;
- Interference with other recreational activities;
- Location-dependent;
- Sited in marine environment;
- Maintenance requirements;
- Power transmission;
- Transmission capacity;
- Variable resource;
- Diffuse resource;
- Power quality;
- Penetration limits;
- Efficiency;
- Economics; and
- Stage of Development

Visual Impact - The visual impact of a wave energy conversion facility depends on the type of device as well as its distance from shore. In general, a floating buoy system or an offshore platform placed many kilometers from land is not likely to have much visual impact (nor will a submerged system) [3]. As an area heavily dependent on tourism, obstruction-free visual planes are critical in Hawaii.

Shoreline and nearshore devices will have a visual impact [6]. Onshore facilities and offshore platforms in shallow water could change the visual landscape from one of natural scenery to an industrial landscape [3]. Onshore overhead electric transmission lines may cause additional adverse visual impacts. However, according to Wavegen, the LIMPET on Islay is not visible from the road or any of the local houses, and offshore devices will generally have a low profile so visual impact will be minimal [10].

To an observer standing near sea level, individual devices within the plant would tend to be obscured by wave action. When viewed from a high elevation, however, they would be more conspicuous and could represent an unacceptable visual intrusion on the offshore seascape [2].

However, onshore wave energy conversion systems have a very low profile compared with your average power station -- they are built into the shoreline [38]. And, many conventional power plants are located on coastlines for easy access to cooling water and also create adverse visual impacts due to overhead electric transmission lines.

Furthermore, wave energy devices are less visually obtrusive than wind devices, which typically run 130 - 200 feet (40 - 60 meters) in height. In contrast, 30 foot (10 meter) high wave energy devices can be integrated into breakwaters in busy port areas, producing power exactly where it is needed [37].

Noise - Wave energy conversion systems will make some noise, although the levels are expected to be below the levels of a normal ship [39]. When fully operational, they are expected to be no noisier than the surrounding wind and waves, and WECS can be built using the best possible sound baffling [36]. Noise may not be an issue with a shore-based WECS, such as the LIMPET, because the turbine is enclosed and includes axial sound attenuation [10].

Any noise that is generated can travel long distances underwater and may have an impact on certain animals such as seals or whales. Research is required to determine if there are any adverse impacts on mammal life due to noise from WECS [25].

Disturbance or Destruction of Marine Life - Wave energy devices may have a variety of effects on the wave climate. This could influence the shore and shallow sub-tidal areas and the communities of plants and animals they support [6]. However, ecological impacts relating to the alteration of waves are not fully understood and need to be studied further [21].

Land-based systems involve significant shoreline modifications and associated environmental impacts. Potential impacts include disturbance or destruction of marine life (including changes in the distribution and types of marine life near the shore).

Installation of the support structures and cable-laying for wave energy devices may temporarily interrupt marine life. However, the ecology of these is likely to recover. Installation of the wave energy device itself will cause a disturbance to local mammals (e.g., seals and dolphins), but, providing the timing of the installation is chosen carefully, there should be little effect and these species are likely to return to the areas after installation [6].

The effects of offshore devices on coastal currents and wave climates are likely to be small (although large devices could have a notable effect). It is expected that there will be a positive benefit to the fish through the creation of artificial reefs as OPT experienced in a one-year trial off the coast of New Jersey. Floating devices could provide shelter to fish/fauna, thereby assisting with the regeneration of depleting fish stocks [14,39].

By absorbing the incoming energy, wave energy conversion devices create calm water in their lee producing a valuable area for other commercial and recreational marine activities. This will also provide a calmer environment for marine life.

Artificial structures in the ocean provide attachment surfaces for a variety of algae and invertebrates, so fouling organisms could colonize WECS. Anti-fouling measures would be necessary where fouling will impact the operations and maintenance of these WECS. There are a number of options to prevent and remove marine fouling. These include: (1) the use of anti-fouling paints, (2) direct injection of biocides, and (3) high pressure jetting for removal of large colonies [25]. However, unless properly applied, these anti-fouling measures may have an adverse impact on marine life.

Coastal Erosion - Some wave energy conversion devices concentrate wave energy into a tapered area before conversion (e.g., TAPCHAN). These focusing surge devices are sizable barriers that channel large waves to increase wave height for redirection into elevated reservoirs. The water then passes through hydroelectric turbines on the way back to sea level thus generating electricity. Continuous arrays of such onshore or shore based wave-energy devices could physically alter coastlines. These array types may result in increased coastal erosion where the waves are concentrated and more sedimentation in adjacent areas [40].

Other types of WECS absorb some of the wave energy contained in the ocean waves. An array of WECS can reduce the wave action coming to shore. This applies especially to large-scale deployments that are close to shore. A reduction of wave action in a shoreline location could result in increased deposition of sediments. This could have effects, such as reduced coastline erosion, or other localized impacts. Any large-scale deployment would require a preliminary study to assess the impacts [25]. Behind a large offshore installation there will be a tendency for growth rather than erosion of beaches but the magnitudes of the effect are not yet known [41].

Threat to Navigation - Once in place, wave energy conversion devices could be a dangerous obstacle to any navigational craft that cannot see or detect them by radar [42], or by direct sighting. For most devices this could be overcome by conventional techniques (e.g., painting, radar reflectors, lights, education regarding location, etc.) [6]. In long arrays of WECS there would be a need for navigational channels between them [25].

Interference with Commercial and Sport Fishing - Also possible is the interference of mooring and anchorage lines with commercial and sport-fishing. Depending on location, such devices could occupy spaces formerly used for fishing.

Interference with Other Recreational Activities - Wave energy systems, if not properly sited, could interfere with other uses of coastal areas such as recreational boating, surfing, and beach use. Scuba diving and jet skiing could potentially benefit from the more sheltered areas behind an array of wave energy conversion devices [25].

Interference with commercial and sport fishing and other recreational activities (especially surfing) is likely to be a significant barrier to WECS development in Hawaii.

Location Dependent - As is true with all forms of renewable energy, the application of wave energy conversion devices is location dependent. Such devices must be sited where the wave resource is greatest. Ideally, they should also be located where the demand for energy is greatest. If they are not sited where demand for electricity is the greatest, electricity (or other product) transmission and distribution costs could be prohibitive.

Sited in Marine Environment - Designing a mechanical device to capture wave energy poses challenging engineering problems. The device must be capable of gathering useful energy from a relatively calm sea with wave heights of a few feet (~1 meter). It must also be able to survive sea conditions where wave heights can exceed 50 feet (15 meters). In this hostile, salt-laden environment, simplicity and reliability become leading design criteria. The rule of thumb has been, the fewer moving parts the better [7]. Components used will have to be "robust" and corrosion resistant.

As stated previously, WECS must be sited where the wave resource is greatest. During severe storms, energy transmitted by breaking waves may be over 10 times average conditions and coastal wave energy plants must be built to withstand these forces [40]. The suitability of the WECS should initially be assessed on the ability to cope with the worst case weather conditions faced in a particular area. Unfortunately, although wave energy conversion devices are subjected to a very harsh environment, they have not been tested on a long-term basis.

Krock [43] urges particular caution in this area. There have been a number of failures (Norway, Japan, etc.) owing to the fact that these things are deliberately located in the worst places with respect to destructive wave forces (i.e., where the best waves, and greatest wave energy, are located). In one example, the OSPREY, planned for installation by Applied Research Technology off Dounreay, was destroyed by heavy waves during installation [41].

Floating devices, by their very nature, need not be fixed to a structure; however, they do require a mooring point by high tensile cable to avoid them floating away. Ideas proposed for floating devices include intentionally "sinking" them until the storm blows over, towing them to shelter or to raise them onto the deck during this period [13].

A big part of the Ocean Power Technology's Hawaii WECS test project is "to see whether the buoys can withstand rough seas. The testing in New Jersey took place when Hurricane Bonnie hit that area in 1998 and the buoys survived without a problem, in part because they are designed with a universal joint on the bottom to allow them to move with the waves [44]."

Maintenance Requirements - The effects of siting in the marine environment (exposure to variable, and sometimes extreme, wave forces; marine corrosion and biofouling; and in some cases, limited accessibility), could significantly increase the amount and cost of maintenance required.

Power Transmission - Power transmission from shore-based WECS should be relatively easy (except, perhaps, where these devices are located in remote areas and/or do not have good access to transmission facilities).

Power transmission from off-shore devices will be more difficult. Wave energy conversion device modules will have to be interconnected, and this combined power will have to be transmitted to shore.

In Hawaii, high-energy coastlines are often remote from island load centers; they also tend to be remote from existing power plants. An early avenue for commercial wave energy development in Hawaii would be the installation of small wave power plants to offset the need for utility grid extension to such remote areas. In addition to meeting coastal load growth, a few megawatts of distributed wave generation capacity could benefit the island transmission network by providing grid stability and voltage support, particularly in the most remote areas that are at the far end of a transmission circuit [2].

Ames [45] has proposed a power transmission method, wherein transmission lines are intrinsic with module linking tubes and carried near the surface. Also, Ames suggests that in situ desalination and hydrogen production may reduce or obviate “umbilical cords."

Transmission Capacity - Another concern is the transmission capacity of Hawaii's island utility grids. An accurate assessment of wave energy’s cost/contribution profile must consider any grid reinforcement that would be necessary for transmitting wave power to load centers that are far removed from the high-energy, north-facing island coastlines. Such an assessment is critical to understanding the true cost of wave energy development in Hawaii [2].

Variable Resource - Wave energy is a variable resource. Waves come in intervals. Wave energy changes with regard to wave lengths, periods and wave heights. Wave energy will not produce electricity at a steady rate and thus not necessarily at times of peak demand.

The variable nature of wave energy can be mitigated to some extent by various energy storage technologies, but at an increased cost. However, being able to provide this energy during peak use periods will increase its value.

Although waves are consistently more energetic than wind or solar resources, supplemental generating plant or battery (or other energy) storage will be required at times when wave energy levels are low and demand is high. This requirement could significantly limit the amount of wave power that can be connected to a given island utility grid [2].

Diffuse Resource - Although a much more concentrated source of energy than either wind or solar, waves are still a relatively diffuse energy source. The diffuse nature of waves requires a number of modules to generate large amounts of electricity. However, the fact that wave energy is more concentrated than either wind or solar results in smaller structural requirements, which results in less space requirements than these renewable energy sources [25].

Power Quality - As stated earlier, waves are a variable resource. The fluctuating nature of wave energy may lead to power quality (frequency and voltage fluctuations) issues. These power quality issues can be overcome, to a large degree, by incorporating advanced power monitoring and control systems and by incorporating energy storage.

Penetration Limits - Hawaii's utilities may, and often do, limit the amount of intermittent, non-dispatchable generation capacity that can be installed in their service territories. The two main areas of concern are the time-dependent variability of wave energy and the transmission capacity of island utility grids [2].

Efficiency - While the projected conversion efficiencies of WECS under certain circumstances (e.g., design wave height) are greater than those for wind, solar, or even conventional fossil fuel or nuclear power plants, the output of such devices is significantly less under off-design conditions (small waves). And, wave energy devices will not be able to utilize all of the energy available under storm conditions. In this regard, wave energy conversion devices are similar to wind turbines.

Economics - Construction of strong, inexpensive and efficient WECS may be problematic [21]. System costs and performance are uncertain. Furthermore, many current cost estimates appear to be overly optimistic. Some developers are projecting electricity costs as low as $0.03/kWh (without having any large-scale operational facilities and extended operation times to justify and verify these predictions).

Stage of Development - Wave energy conversion devices are in an early stage of development and are not yet commercially viable. Such devices are not expected to be available on a large scale within the near future due to limited research and lack of funding.

Other Impediments to Development - There are a number of other impediments to wave energy development. These include:

- Funding - Wave energy has received little attention in comparison to other renewable sources of energy. The United States has provided relatively little funding. Most of the development work has occurred in Europe and Japan. And, the UK has significantly increased its funding for wave energy research and development.

- Reliability - Owing to a lack of operating facilities, little is known about the long-term reliability of wave energy conversion devices.

8.0 APPLICATIONS

Wave energy conversion systems can be used in a variety of applications, and in some cases they also provide supplementary advantages. These applications include:

- Electricity generation;
- Hydrogen production by electrolysis;
- Pumping/hydraulic power;
- Seawater desalination through reverse osmosis;
- Potable water production through vapor compression;
- Combined electricity/potable water production;
- Refrigeration/air conditioning;
- Navigation aids/environmental data acquisition;
- Shoreline protection;
- Water oxygenation/purification;
- Commercial mariculture/fish farming; and
- Enhanced oil recovery.

Electricity Production - The primary application for WECS will likely be to provide electrical power to large or remote island grids. In addition, wave energy conversion can be a supplemental source of electric power.

Hydrogen Production by Electrolysis - The electricity produced by WECS can be used to produce hydrogen by electrolysis. Any excess electrical energy produced by wave energy conversion facilities can be stored as hydrogen. This will help to overcome some of the difficulties created by the variable nature of wave energy.

Pumping/Hydraulic Power - The mechanical power produced by a WECS can be used to drive a pump (rather than an electricity generator) to produce fluid (water or hydraulic fluids) at a high pressure.

Seawater Desalination through Reverse Osmosis - Shortage of drinking water is a cause of much suffering and a major limitation to agricultural development in many parts of the world. This application is of particular value in dry coastal areas having good wave resources. Many of these locations currently rely on diesel generators to provide electricity to power their desalination plants [8].

Wave energy can be used to produce potable water from seawater by high pressure reverse osmosis. In such a facility, the electricity generator is replaced with a water pump to produce high-pressure water for direct use in reverse-osmosis desalination plant. Reverse osmosis has also been considered as a possible future potable water source on Oahu.

Potable Water Production through Vapor Compression - According to Salter [15], you may also be able to produce fresh water by vapor compression driven directly from

Duck motion (or from other similar WECS). Such a process can take very dirty feeds but produces medical-grade water.

Electricity/Potable Water Production - A hybrid wave energy system could be designed to produce both electricity and potable water.

Refrigeration/Air Conditioning - Wave energy can be used for the pumping and compression of the working fluid in a refrigeration or air conditioning plant.

Navigation Aids/Environmental Data Acquisition Systems - Among the simplest types of WECS are navigational buoys where waves entering the anchored buoy compress air in a vertical pipe. The compressed air is used to blow a whistle or drive a turbine generator producing electricity for light. Since 1965, Japan has installed hundreds of OWC-powered navigational buoys. Environmental monitoring data acquisition instrumentation is another application requiring in situ electrical power supply that can be readily supplied by wave energy [27].

Shoreline Protection - WECS can be incorporated into breakwaters or harbor wall construction. They can also be retrofitted to existing harbor walls. This dual use can greatly improve the public acceptability and cost effectiveness of such devices. Wave energy breakwaters are likely to be acceptable only at existing ports, or where construction of a new small-craft harbor has already been approved [2].

Water Oxygenation/Purification - A WECS can also be used as a device for oxygenation. This re-oxygenation can protect or re-establish biological life on the seabed (or lakebed) where pollution has caused areas with oxygen depletion [46].

Commercial Mariculture/Fish Farm - Artificial reefs substantially improve the local marine bio-density, attracting schools of fish and providing habitats for the colonization of commercially valuable species. WECS can act as these artificial reefs and also have the potential to improve the local inshore marine harvest. The annual demand for fish already exceeds the sustainable yield by millions of tons, thus promoting a significant increase in fish farm production. The use of artificial reefs will therefore be an important factor. The ability to produce power from a reef will considerably increase the value of any project [8].

Enhanced Oil Recovery - High pressure water or gas from a WECS can be pumped into partially-depleted oil- or gas-bearing strata to increase recovery [47].

9.0 ECONOMIC ASSESSMENT

As stated previously, few reliable cost data were found during the literature search for this study, and through communications with WECS developers and researchers. The lack of commercial WECS facilities means that the cost and performance of WECS are difficult to estimate.

As a result, the approach taken was to summarize whatever information was available (Section 9.1) and to update previous cost data using a construction cost index [35] and to determine allowable capital and O&M costs for WECS systems for them to be viable in Hawaii under the constraints of average avoided energy costs and average commercial utility rates for each of Hawaii's utilities (Section 9.2).

9.1 Cost Data Provided by WECS Developers

According to Wavegen, the 500-kW Islay LIMPET plant cost around $1.44 million to build. Although it is a commercial plant, it is used for ongoing research and development and as a result it is equipped with additional costly features, which would not be required on a production plant. The capture chamber is the major capital item which used around 1,570 cubic yards (1,200 m^3) of reinforced concrete. Future devices will use less than 780 cubic yards (600m^3) of reinforced concrete [10].

Ocean Motion International has been developing its Ocean Motion Project for 15 years. They estimate that their mono-pump design will produce 600 kW, and will cost $3 million each (or $5,000/kW). Their projected costs of production plants are approximately $2,000/kW [48]. No estimates were provided for the corresponding O&M cost/kWh. They are looking for $10 million for a 500 kW demonstration plant.

Energetech Australia Pty., Ltd. states that its unit capital cost is $1,500/kW for a single-device with unit costs of about 10 cents/kWh. For multiple devices the cost is 5 cents/kWh. The cost of multi-device installations projected for 2005 is about 3 cents/kWh. They further maintain that, "while units costs as low as 4 cents/kWh are optimistic in the near term, these costs are fully realizable in second-generation devices [24]."

George Taylor, of Ocean Power Technologies, claims that OPT's proposed Hawaii test WECS will produce electricity at a cost of between 7 and 10 cents/kWh. He further claims that Ocean Power wants to use the test to improve efficiency ratios so it can lower its production costs to about 3 to 4 cents/kWh [44].

No information was provided regarding assumed discount rate, methods of financing, wave energy regime, energy capture efficiency, operation and maintenance costs, or system capacity factor for any of the above projects or WECS.

WavePlane [49] has projected a cost of ~$1,250/kW for a 400-kW WECS. Based on a 15 year amortization, an interest rate of 7%, and maintenance costs of 5%/year, the projected electricity cost is 14.3 cents/kWh. Performance improvements through optimization of the turbine are expected to reduce this cost to 10.7 cents/kWh. All of these estimates are based on theoretical calculations.

A study by the Danish Energy Agency [50] indicates that the cost of electricity based on the use of a 100-MW Point Absorber WECS (the RAMBOLL) placed in the Danish part of the North Sea in a wave regime similar to that in Hawaii (5 to 7 kW/ft [16 to 24 kW/m]), would produce electricity at a cost of 30.3 to 48.5 cents/kWh. Depending on location and with further development, these costs might decrease to 9.7 to 14.5 cents/kWh. The calculated energy price is based on an annual interest rate of 5% over 20 years. Maintenance costs are not included. Collection and transmission costs amount to about 50% of the total cost in the present design. Cost decreases may be achieved through the use of large generators at a higher voltage. The study provides a detailed accounting of component, construction and deployment costs and details on system design.

Current projected capital costs are $6,400/kW in 2001, with a target of $1,820/kW. The calculated capacity factor in a wave regime of 5 to 7 kW/ft (16 to 24 kW/m) in 2001, is 10.8 to 18.5% at these wave power densities, respectively. The target is for a 17 to 26% improvement in this capacity factor.

The Danish Wave Energy Programme [51] has been testing a variety (~40) of WECS for at least two years. All WECS have been tested in one of the two commercial test facilities in Denmark. Test results are based on models tests in a scale from 1:50 up to 1:10. Meyer and Nielsen [51], caution that "[t]he data produced including the results concerning annual energy production and calculated construction costs should only be regarded as status results in relation to the state of development of the different systems."

Twelve WECS were included in the status assessment. The assessment showed a large variation in results. The most expensive system was the Mighty Whale, a research project in Japan not intended to be economic at the present time. The least expensive system is the OWC system Swan DK3. Excluding the most and least expensive systems, the majority of the devices are assessed at between $1.21 to $2.42/kWh in an average wave power level of 5 kW/ft (16 kW/m).

Thus, there is a very wide range of projected costs from a variety of WECS developers and researchers. And, most of these are based on theoretical calculations or small scale tests. Only a few are based on working, larger-scale prototypes or small commercial facilities.

Since there is very little operational experience with wave energy conversion technologies, most of the costing assessments have been done using projected cost figures. These projected cost figures have shown a significant improvement over the last 20 years [25]. Figure 6 shows projected cost development over time. WECS' costs appear to be following a trend similar to other renewable technologies -- i.e., significant cost decreases over time.

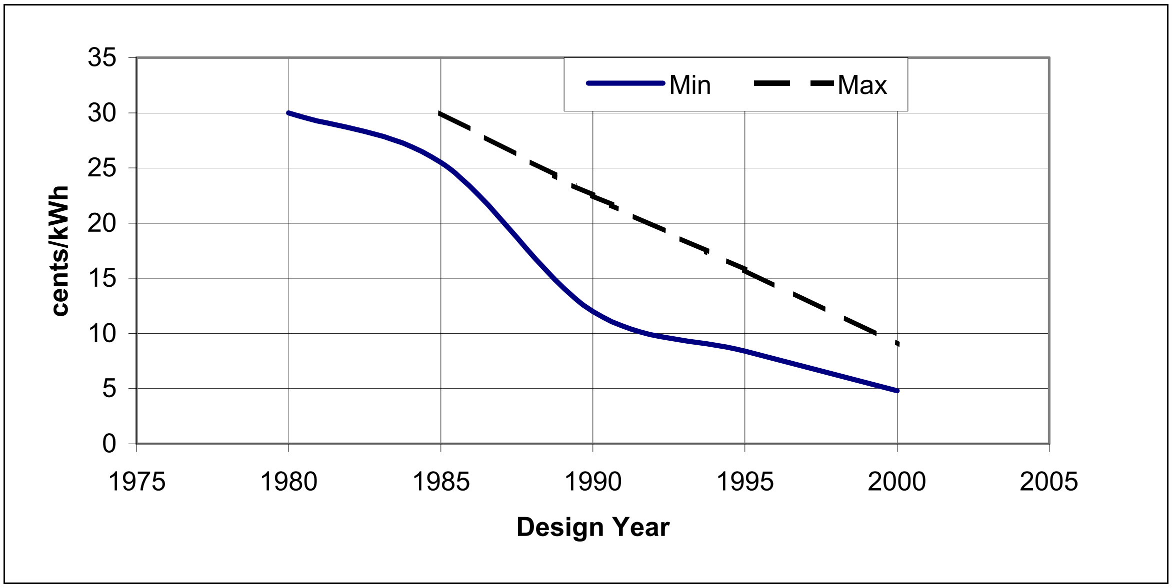

Figure 6 - WECS cost development over time at 8% discount rate (Source: [25])

WECS economics have improved quite a bit over the last 10 years. Advances in the offshore oil and gas industry and advances in improved and more sophisticated remote monitoring technology have led to significant improvement in cost competitiveness. Further cost improvements will come from other successful technology transfers from the offshore oil and gas industry. The WECS industry also has the potential to adapt economies of scale through mass production by modularization of the subsystems [25].

The source of the cost data may also have some bearing on its accuracy and usefulness. According to Salter [15], [I]t is now Edinburgh policy never to make any claim about electricity costs but rather to refer to independent official ones. Designers, especially commercial ones do not have enough detachment to assess their own work." He further states, however, that " … many official wave cost predictions are below the actual costs of wind in California at the start of the wind boom."

As stated previously, system costs and performance are still uncertain, and the values of various economic analysis parameters are generally not provided. What is available tends to be projected costs, not actual costs from operating facilities. Furthermore, many current cost estimates appear to be overly optimistic. Some developers are projecting electricity costs as low as 3 cents/kWh (without having any large-scale operational facilities and extended operation times to verify these predictions).

As is indicated by the following economic assessment, such low costs may be very difficult to achieve. However, if projected costs can be achieved, the potential for WECS in Hawaii will be significant.

9.2 Updated Economic Analyses of WECS for Hawaii

According to Hagerman's 1992 study [2], and based on developers' designs for locations outside Hawaii, it appears that commercial deployment of these systems will be limited not only by environmental concerns, but also by site-specific economic feasibility. At sites where existing shoreline topography minimizes the required amount of excavation and concrete placement, TAPCHAN WECS and land-based OWCs might be able to realize energy costs less than 11 cents/kWh. Breakwater-based wave power plants, however, will be economically feasible only if fabrication of the concrete caissons can be financed for some other purpose, such as harbor improvement, shore protection, or perimeter construction for a very large floating platform.

Krock [43] has also concluded that wave energy would be most easily justified if the devices were incorporated into a breakwater. However, he adds that "there is a low tolerance presently for any extensive altering of the coastline and that the amount of energy that can be extracted from areas such as breakwaters and other hardened coastal areas may not be sufficient."

To assess the economic feasibility of offshore wave power plants, levelized revenue requirements were estimated by Hagerman [2] for a Swedish heaving buoy system, hypothetically located offshore Makapuu Point, Oahu. The updated projected cost of energy is 9.8 cents/kWh for a 60 MWe plant. These projections, however, are sensitive to several cost and performance uncertainties.

For example, there is a large amount of scatter in the absorption efficiency data, and this uncertainty alone governs the economic feasibility of a 60 MWe reference design at Makapuu Point; the upper and lower bounds of the efficiency data are associated with energy costs ranging from 8.0 to 19.2 cents per kWh. Other project development risks cited by Hagerman as having a significant impact on the cost of energy are uncertainties in buoy fabrication cost, operating and maintenance costs, and plant availability. He concluded that although these uncertainties individually have a much lower impact than the uncertainty in absorption efficiency, the combined risk is equally great. Other offshore technologies have similar cost and performance uncertainties, and commercial financing is not likely to be available for offshore wave power projects without construction and operation of a small demonstration plant [2].

Compared to land- or caisson-based wave energy devices, local site conditions have much less impact on the economic feasibility of offshore systems. For a device such as the Swedish heaving buoy, however, whose absorption efficiency is strongly dependent on incident wave period, economic feasibility may depend on the degree to which a particular outer shelf location is dominated by long-period north Pacific swell or short-period trade wind waves [2].

9.2.1 A Comparison of Wind Energy and WECS

A WECS will probably not have much more than three times the output of a single wind turbine, but the construction costs are likely to be far higher due to mooring problems, the bulkiness and comparative complexity of the whole structure and the water-based location. Wave energy systems generally have greater capacity factors than wind or solar systems. Another comparative advantage they may have over other renewable energy systems may be land use. Higher capacity factors, combined with relatively high cost land, may provide a competitive advantage in some instances [53].

This comparison is illustrated in Table 1 using an example for Hawaii utilizing data obtained from the from the Hawaii Renewable Energy Resource Assessment and Development Program Report (HRERADP). This economic analysis assumes: (1) utility financing (45% debt ratio, 55% equity ratio, 7.5% debt interest rate, 12.3% equity return rate); (2) constant dollars; (3) 5.8% discount rate; (4) 5-year tax life; (5) property tax & insurance - 2% of annual expenses; (6) 4.58% state income tax; (7) 35.00% federal income tax; and (8) 30 year system life [54].

A wind energy conversion system is compared to a wave energy system. Both systems are rated at 50 MW and are sited in the Kahuku Point area. Costs have been updated from this 1995 study using a construction cost index [35]. Using this index, construction costs have increased 13.7% over the period from 1995-2000.

Table 1 - A Comparison of Wind Energy and WECS at Kahuku Point, Oahu

Parameter	Units	System Type		Wave/Wind Ratio
		Wave	Wind	
Rated Output	MW	50	50	1.00:1
Capacity Factor (Delivered Electricity)	-	0.402	0.173	2.32:1
Annual Output	MWh/yr	175,998	75,918	2.32:1
Capital Cost	$/kW	2,716	1,306	2.07:1
O&M Cost	cents/kWh	3.34	2.31	1.45:1
Capital Recovery Cost	cents/kWh	7.28	5.69	1.28:1
Total Electricity Cost	cents/kWh	10.62	8.00	1.33:1

Unfortunately, the projected costs for both WECS and wind energy conversion systems are higher than the avoided energy cost the utilities pay for purchases of intermittent renewable resources. Avoided energy costs, average commercial electricity rates, and gross system peaks are shown in Table 2.

The data in Table 2 are presented to show cost production targets that wave (and wind) energy system developers will have to meet if they want to sell electricity directly to the utilities (at avoided energy costs), or to a dedicated commercial end user (at commercial retail rates). The sale price amounts and differences should be factored into market assessments and development approaches.

Table 2 - Hawaii Utility Parameters (Avoided Energy Cost [AEC], Average Commercial Electricity Rates [ACER], and Gross System Peaks)

Parameter	Units	Utility				Ref.
		Kauai Electric	HECO	MECO	HELCO	
Avoided Energy Cost (AEC) (1980-2000) Maximum	cents/ kWh	8.5	7.0	6.8	6.3	55, 56
Average	cents/ kWh	5.7	4.2	4.8	4.4	55, 56
Minimum	cents/ kWh	3.3	2.4	2.8	2.5	55, 56
Avoided Energy Cost (AEC) (2000)	cents/ kWh	7.5	5.5	6.4	5.8	55, 56
Average Commercial Electricity Rates (ACER)	cents/ kWh	21.9	11.4	16.9	19.2	57
ACER/AEC Ratio (2000)	-	2.9:1	2.1:1	2.6:1	3.3:1	-
Gross System Peak	MW	71.8	1,203	196.5	170.8	57

Potential wave energy conversion systems in Hawaii were also identified for each of the major Hawaiian islands. Associated cost data were similarly updated to 2000 costs using the ENR Construction Cost Index [35]. These data are presented in Table 3. In all cases, the delivered cost of energy for WECS is greater than the avoided energy cost. But, for most cases, the delivered cost is less than the average commercial electricity rate.

9.2.2 Hawaii Case Studies

Several case studies are presented to demonstrate the effects of: (1) improvements in system performance (i.e., increased wave-to-electricity capture and conversion efficiency); (2) reduced capital costs; and (3) reduced O&M costs. These case studies clearly show that significant gains will have to be made in each of these areas to reach avoided energy cost levels.

Table 3 - Potential Wave Energy Conversion Systems in Hawaii

Island	Location	Life (Yrs)	Capacity (MW)	Capital Cost Per kW	Capacity Factor	Production (MWh/yr)	Cost of Energy (cents/ kWh)
Kauai	Anahola	30	30	$2,828	0.377	98,947	11.7
	Barking Sands	30	30	$2,992	0.197	51,793	23.6
Oahu	Makapuu	30	60	$2,663	0.427	224,378	9.8
	Kahuku Point	30	60	$2,669	0.402	211,197	10.4
	NE Coast 2A	30	30	$2,776	0.395	103,704	11.0
	NE Coast 2C	30	30	$2,752	0.388	101,831	11.2
	Mokapu Point	30	30	$2,790	0.373	97,966	11.8
	Waimanalo Bay	30	30	$2,760	0.339	88,957	12.8
Maui	Opana Point	30	60	$2,690	0.403	211,984	10.5
	Lower Paia	30	60	$2,690	0.388	203,974	10.9
	Waiehu Point	30	30	$2,886	0.385	101,256	11.6
Hawaii	North Kohala	30	30	$2,895	0.354	93,084	12.6
	Honokaa 2A	30	10	$3,144	0.384	33,612	12.8
	Pepeekeo 2E	30	10	$3,154	0.370	32,389	13.3

Source: [2,35]

Table 3 shows the projected costs of various WECS ranging in size from 10 to 60 MW on each of the main islands. The lowest cost location is Makapuu. Even here the projected cost of 9.8 cents/kWh is 2.3 times the average avoided energy cost for HECO as shown in Table 2 (i.e., 1980-2000 = 4.2 cents/kWh).

All of the above WECS are in the range of 10 to 60 MW. Unfortunately, WECS plant size may have to be limited owing to penetration limits for each utility based on the utility demand. As a variable resource, it may be necessary to limit the maximum size of any WECS and output may be further curtailed during off-peak periods. As an initial estimate, a penetration limit of 10% of the peak utility demand was used. Therefore, based on this limitation and the gross system peak data in Table 2, the largest individual WECS system on each island may be as follows: Kauai (7.2 MW); Oahu (120.3 MW); Maui (19.7 MW); and Hawaii (17.8 MW). These figures are approximate and are for illustrative and analysis purposes only.

Another factor that was considered is that specific capital cost ($/kW) and O&M cost ($/kWh) decrease as the system size (rated capacity) increases owing to economies of scale. An analysis of the data contained in the HRERADP report for WECS show that this cost sensitivity factor is -0.096 for specific capital costs and -0.082 for specific O&M costs. For example, if the size of the facility increases by a factor of 10, specific capital costs decrease by ~20% and specific O&M costs by ~17%.

A number of case studies were analyzed to determine the effects on cost of smaller WECS systems and the associated cost and performance increases required to make such WECS plants cost-competitive in Hawaii.

Kauai Case 1 - WECS Electricity Sales to Utility at Avoided Energy Cost

In the first case we will consider a WECS on Kauai. Kauai has the smallest gross system peak (and consequently the smallest allowable utility-scale WECS) and the highest average avoided energy cost. Based on Kauai's gross system peak of 71.8 MW, and the assumed penetration limit of 10% of this amount, the maximum WECS on Kauai would be about 7.2 MW.

The projected cost of electricity from a 7.2-MW WECS at Anahola is 13.4 cents/kWh (vs. 11.7 cents/kWh for the larger, base-case 30-MW WECS in Table 3). The average avoided energy cost for the period 1980 - 2000 was 5.7 cents/kWh. Therefore, some very significant improvements in efficiency, capital cost, and/or O&M costs are required to meet this goal.

For example, if there is no change in WECS efficiency or O&M costs, an 83% reduction in capital costs would be required (i.e., from $3,243/kW to $551/kW). The latter figure is unlikely to be achieved. Even a 50% reduction in O&M costs and a 20% increase in efficiency would still require a 49% reduction in capital costs. It may be possible to achieve this.

Kauai Case 2 - Direct Use of WECS Electricity by End User at, or Near, Commercial Retail Rates

A second case study for Kauai involves the installation and operation of a smaller WECS (i.e., 2 MW) that might be suitable for a direct end user (e.g., a hotel or other shore-based commercial facility). Such a WECS would only need to produce electricity at a cost somewhat less that the current commercial electricity rate. A cost savings of say 20-30% would likely be necessary to interest a potential customer in this somewhat-risky alternative to utility power.

A 2-MW WECS at Anahola on Kauai might be able to produce electricity at 15.0 cents/kWh. This is 68% of the average commercial utility rate for Kauai in 2000 (i.e., 21.9 cents/kWh). This might represent a good opportunity for prospective WECS developers to demonstrate and develop their technology on a relatively large scale in a cost-effective manner.

A comparable 2-MW WECS on the other islands would provide electricity at proportionately higher fractions of their 2000 commercial electricity rates. The respective fractions are as follows: Oahu (118%); Maui (85%); and Hawaii (90%). At these costs, such a WECS facility is very unlikely on Oahu and marginally cost-effective on Maui and Hawaii. Future improvements in efficiency, capital cost, and O&M cost will likely improve this situation.

Oahu Case 1 - WECS Electricity Sales to Utility at Avoided Energy Cost

Oahu has the lowest avoided energy costs and commercial electricity rate and the largest gross system peak. Allowable plant size based on assumed penetration limits would be 120 MW (or twice as large as the largest WECS considered).

The projected cost of electricity from a 60-MW WECS at Makapuu is 9.8 cents/kWh. The average avoided energy cost for the period 1980 - 2000 was 4.2 cents/kWh. Therefore, some significant improvements in efficiency, capital cost, and/or O&M costs are required to meet this goal.

For example, if there is no change in WECS efficiency or O&M costs, an 84% reduction in capital costs would be required (i.e., from $2,663/kW to $426/kW). Again, the latter figure is unlikely to be achieved. Even a 50% reduction in O&M costs and a 20% increase in efficiency would still require a 48% reduction in capital costs. It may be possible to achieve this. (By coincidence, these required percentage reduction amounts are very close to those for Kauai.)

Oahu Case 2 - Direct Use of WECS Electricity by End User at, or Near, Commercial Retail Rates

At least two WECS developers have proposed demonstration WECS at Kaneohe Marine Corps Base Hawaii (KMCBH). KMCBH might be able to accommodate a WECS of up to 10 MW size. Assuming that the wave regime there is similar to Makapuu, a 10-MW WECS might be able to provide electricity at 11.6 cents/kWh. As a larger facility (electricity user), KMCBH has negotiated a favorable commercial electricity rate of ~10 cents/kWh. They may expect a rate of 7 cents/kWh in order to purchase power from a higher-risk supplier.

If there is no change in efficiency or O&M costs, a 48% reduction in capital costs would be required. A 26% reduction in capital and O&M costs and a 20% increase in efficiency would also provide electricity at 7 cents/kWh. These goals may be readily achievable.

Finally, a 2-MW WECS at Kahuku Point on Oahu (perhaps for the Turtle Bay Resort) might be able to produce electricity at 14.3 cents/kWh. The 2000 average commercial electricity rate for Oahu was 11.4 cents/kWh. If there is no change in efficiency or O&M costs, a 64% reduction in capital costs would be required. A 33% reduction in capital and O&M costs and a 20% increase in efficiency would also provide electricity at 8.0 cents/kWh (i.e., 70% of 11.4 cents/kWh). Again, these goals may be readily achievable.

Thus, WECS systems are not cost competitive in Hawaii today, on an avoided energy cost basis, with current utility generated electricity. Very significant improvements in efficiency, capital cost, and O&M costs will be required to change this situation. On the other hand, there may some direct use applications that are cost-competitive today and on a relatively small scale. These applications may provide the best opportunities for WECS technology demonstration and development in Hawaii.

10.0 RESEARCH AND DEVELOPMENT GOALS

According to Wavegen, "the cost of wave power will reduce. As the wave industry moves from individual demonstration devices to farms there will be an opportunity to reduce costs through technology improvements and economies of scale. Many of the component costs, for example, submarine cables and mooring costs are likely to reduce. The ability to increase grid penetration with intermittent renewables such as wave power will be improved as power storage technology improves [10]."

However, many research and development goals remain to be accomplished. These include: (1) cost reduction, (2) efficiency and reliability improvements, (3) identification of suitable sites, (4) interconnection with the utility grid, (5) better understanding of the impacts of the technology on marine life and the shoreline; and (6) demonstration of the ability of the equipment to survive in the marine environment, as well as weather effects, over the life of the facility [3].

11.0 CONCLUSIONS AND RECOMMENDATIONS

11.1 Overall Conclusions and Recommendations

- Wave energy conversion devices are in an early stage of development and are not yet commercially viable.
- Such devices not expected to be available on a large scale within the near future due to limited research and lack of funding.
- Many research and development goals remain to be accomplished.
- Hawaii may be an ideal site for early commercial development of WECS.
- However, WECS systems are not cost competitive in Hawaii today on an avoided energy cost basis.
- On the other hand, there may some direct use applications that are cost-competitive today on a relatively small scale.
- If projected costs can be achieved, the potential for WECS in Hawaii will be significant.
- The successful further development of this technology requires committed and consistent government support.
- The State of Hawaii can do a variety of things to assist WECS developers.
- Finally, the State of Hawaii needs to evaluate the relative costs, status of development, and potential applications for each of its many indigenous renewable energy resources.

11.2 Specific Conclusions and Recommendations

There is a wide variety of conversion schemes. Although many wave energy devices have been invented, only a small proportion has been tested and evaluated. Furthermore, only a few have been tested at sea, in ocean waves, rather than in artificial wave tanks [3].

Little prospect for commercial development of wave power is envisaged in most short- to medium-term forecasts. Costs are still too high, and the technology remains uncertain. In order for this industry to be successful, there is a need for standardization of subsystems and components, which will allow for modularization and ultimately make this industry competitive to other forms of renewable power generation [25].

Hawaii may be an ideal site for early commercial development of WECS owing to the following reasons: (1) Hawaii has some of the highest electricity costs in the world; (2) Hawaii has one of the best and most consistent wave regimes; and (3) Hawaii is dependent on imported fossil fuels for more than 90% of its energy needs.

Based on the best wave resource data available for the 1992 study, the most promising coasts for wave energy development in Hawaii are those that face northeast and are partly sheltered from north Pacific swell by adjacent coastal features or neighboring islands to the northwest. They are thus fully exposed to persistent trade wind waves, yet protected from extreme winter swell associated with storms in the northwest Pacific Ocean. The output from a wave power plant along such coasts will be more consistent from day to day and from season to season than it would be along a west- or northwest-facing coast [2].

Despite their less-advanced development status, offshore systems have much wider deployment potential in Hawaii, since they don’t involve shoreline modification or breakwater construction. Heaving buoy systems that use high-pressure seawater as a working fluid are particularly attractive, since they can produce both electricity and fresh water. Also, the buoys’ relatively small diameter, and low freeboard minimize their visual impact on the offshore seascape [2].

However, Hawaii’s wave energy development potential will be limited by the following considerations [2]:

- Environmental constraints based on potential negative impacts and local public concerns, particularly with regard to visual appearance;
- Utility constraints based on time variability of the wave resource and the limited capacity of onshore transmission lines; and
- Financial constraints based on the limited number of economically feasible sites for land-or caisson-based systems and risks associated with uncertainties in cost and performance projections for offshore systems

These issues must be resolved before any significant development of Hawaii’s wave energy resource can take place.

At least two developers believe that the wave power densities cited for Hawaii in Section 2.2, above, may be low. If higher, this could significantly change the economics of wave energy in Hawaii [10,15]. These power densities are low relative to the North Atlantic wave climate [15] and may account for the more favorable cost data given for this area. An updated and more detailed analysis of the wave energy resource in Hawaii may therefore be warranted. Also, environmentally suitable sites and their development potential (in terms of energy cost and installed capacity) have yet to be catalogued.

With the recent advances in wave modeling, Wakeham [34] suggests "doing a more thorough analysis of the wave resource, with some of the nearshore wave models. This might show better sheltering and wave propagation and help to find the best places for different types of WECs. Wave modeling can also be used to predict sediment transport beach erosion."

An accurate assessment of wave energy economics must include any reinforcement of onshore utility grids that would be necessary for transmitting wave power to load centers that are far removed from the best wave resources. Depending on the cost of such grid reinforcement, this could severely limit the amount of wave energy development that would be economically competitive with other island energy sources [2].

Site-specific, technology-specific evaluations are required to determine the limits that environmental and utility constraints will place on wave power development in Hawaii. Construction and operation of a demonstration plant would reduce uncertainties in cost and performance projections, making it easier for developers to obtain financing for commercial projects [2].

Wave energy costs less than 10 cents/kWh appear to be feasible for offshore heaving buoy systems sited along coasts dominated by trade wind waves. Where shoreline topography exists that minimizes excavation and concrete placement, TAPCHAN WECS and land-based OWC WECS might be able to realize similarly low energy costs. Caisson-based devices, however, appear to be economical only if the cost of caisson fabrication can be assigned to some other function such as harbor improvement, shore protection, or perimeter construction for large floating platforms [2].

WECS are not cost competitive in Hawaii today, on an avoided energy cost basis, with current utility generated electricity. Very significant improvements in efficiency, capital cost, and O&M costs will be required to change this situation.

Commercial electric rates in Hawaii are typically about 2-3 times higher than utility avoided energy costs. On the other hand, there may some direct use applications that are cost-competitive today on a relatively small scale. Thus, it may be more cost effective to focus initial development efforts on smaller WECS that provide electricity directly to a dedicated end user (e.g., a shore-based hotel or other commercial facility) rather than for sale to a utility. These applications may provide the best opportunities for WECS technology demonstration and development in Hawaii.

Hagerman, in his 1992 study, recommended a four-phase program leading to construction of a fully operational demonstration project. Each phase of the program would have depended on the success of the previous phase before being initiated and would have involved an increased share of private-sector funding by commercial developers. Additional details of this proposed program are provided in reference [2]. The program was projected to last eight years and was to be funded to a large degree by public moneys. However, based on this current review of WECS technology and costs, such a costly and large-scale WECS program does not appear be warranted at this time. This conclusion may change if there are significant developments in WECS technology and cost-effectiveness.

Hagerman has estimated that if the State of Hawaii was sufficiently interested in a more detailed analysis of wave energy technology for Hawaii, such a study could be conducted for approximately $50,000 [60].

The successful further development of this technology requires a committed, and consistent research, development, demonstration, and commercialization effort which is unlikely to proceed without government support [58].

According to Leary [30], "[the above] conclusion is critical to the commercialization of this resource, particularly as it relates to a demonstration effort. Accurate costs and the methods for reducing them will only be obtained from *in situ* demonstrations. The funds needed for such demonstrations will, in all likelihood, not be available from the venture capital sector. These are not the type of investments that will provide the 30%, or greater, return required by venture capital. Without government and/or foundation support, those charged with making economic evaluations will be forced to use assumptions and best estimates. These could be in error by an order of magnitude."

The State of Hawaii can do a variety of things to assist WECS developers. Among the ideas suggested are: (1) provide permit assistance, including streamlining/facilitating the permit process; (2) facilitate community interaction/assist in surveying consumer response to proposed developments before they are started; (3) use Hawaii as a test bed for WECS development (e.g., at Makai Pier on Oahu or the Natural Energy Laboratory Authority (NELHA) on the Big Island [34,59]. According to Wakeham, "[t]here needs to be systematic testing of ideas including computer simulations, wave tank simulation, and finally sea trials [34]." The University of Hawaii, Department of Ocean Resources Engineering may be able to assist in many of these activities.

The State should also encourage private sector developers to continue to pursue WECS demonstration and development programs in Hawaii. Some cost sharing at a relatively low level, and possible loans or special purpose revenue bonds could be provided to assist the more viable WECS technologies.

Alternatively, the State might consider passing legislation to support the development of wave power systems. Given the advantages of wave power to the Hawaiian economy it might be appropriate for Hawaiian utilities to be obligated to enter into power purchase agreements to buy wave generated power at, for example, 90% of the retail sale price, rather than at the avoided energy cost. Similar policies are being adopted in Europe and Australia given the great potential environmental and economic advantages of wave energy [32]. Similar incentives could be considered for other renewable energy technologies.

Finally, the State of Hawaii should continue to evaluate the relative costs, status of development, and potential applications for each of its many indigenous renewable energy resources. With limited funding and manpower, the amount of effort focused on each of these technologies should be proportional to the potential benefits.

(Note: An on-going program entitled the "Renewable Energy Research, Development, Commercialization, and Export Promotion Plan for Hawaii," will identify and prioritize and analyze sustainable resources and technologies having the most maturity and promise for immediate and future (within 5-10 years) commercial application in Hawaii. Those technologies having the greatest potential for commercial export, especially to the markets of the Asia/Pacific Region, will also be identified. This analysis will evaluate a variety of renewable energy resources including ocean energy [wave, OTEC, and seawater air conditioning]; solar [thermal and photovoltaic]; biomass; wind; geothermal; and alternative fuels. This study will be completed by June 30, 2002.)

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