OCEAN ELECTRICAL ENERGY GENERATION

AN OVERVIEW AND POTENTIAL FOR OREGON'S TERRITORIAL SEA

by

Gary Frederick Smith

Special Project

Submitted to:

Marine Resource Management Program
College of Oceanography
Oregon State University

July 1987

In partial fulfillment
of the requirements for
degree of

Master of Science

ACKNOWLEDGEMENTS

I would like to thank my fellow students in the Marine Resource Management Program for their friendship, assistance, and suppport during my stay in the program. Further thanks to Robert Rose for his patience in bringing to accepted standards my somewhat creative spelling.

CONTENTS

INTRODUCTION

This report deals with the current status of four promising sources of electrical energy generation from the oceans. They are, in sequence;

Ocean Thermal Energy Conversion: Where energy is obtained by exploiting the temperature differences between warm surface waters, and much deeper colder waters.

Tidal Energy: Where differences in water height between tidal cycles is contained within enclosures of the sea, and then released through turbines to generate power.

Wind Energy: Where the high velocity of wind over the ocean is harnessed by wind turbines mounted on offshore structures.

Wave Energy: Where the power of ocean swells is captured by devices which turn this energy of height and movement into useful power.

Although many other forms of obtaining energy from the sea have been proposed, the above four have been chosen for presentation due to the fact that each has reached at least the prototype stage or has actually been commercially implemented. Other forms of ocean energy generation, such as current energy, power from salinity gradients, and kelp biomass conversion, are largely still in creative infancy.

Presentation of each of the four energy generating techniques is by three sections; Background and Technology, Environmental

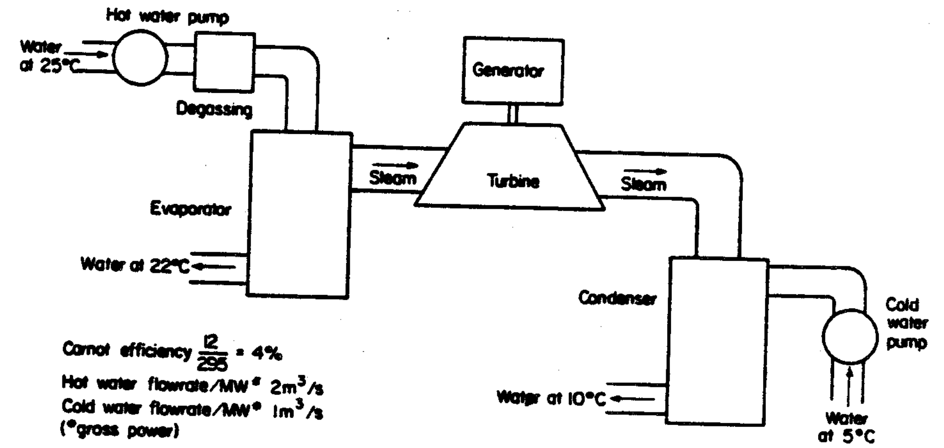
Impacts, and Potential for Oregon's Territorial Sea. A less researched and detailed treatment of Ocean Thermal Energy Conversion is presented than for the other three potential sources of ocean energy. This is for two reasons. First, unlike the other energy sources, Ocean Thermal Energy Conversion has previously received extensive popular publicity. Much better treatments of the subject are available than presented here. Secondly, the technique has absolutely no potential for Oregon's territorial sea, a focus to which this report is geared.

It is unlikely that any of these forms of energy production will provide part of Oregon's near term energy supply. A present over capacity of electrical power, as well as low oil prices now remove the incentive to begin development. High capital costs of construction, and an energy policy which provides indirect subsidies to traditional energy generating techniques, including nuclear power, make ocean energy electrical costs higher than existing rates.

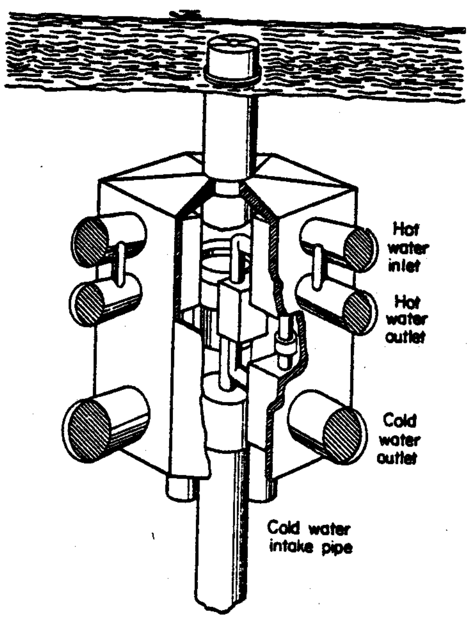
Such a situation may change in the future. Nuclear power may become politically unacceptable. Oil prices will rise. Technology of ocean energy will improve. Advances in design, and standardization of techniques will bring cost down. Long term commitment to ocean energy may be forthcoming. And finally, related developments such as workable, cost effective "super conductors" may allow the intermittent power of the ocean to be stored without loss, resulting in a more dependable ocean energy supply.

OCEAN THERMAL ENERGY CONVERSION

(OTEC)



Operating principle of an open circuit OTEC plant



Floating plants of this type, which are not appreciably affected by the swell would weigh several thousands of tonnes (*after Trimble et al. Ocean Thermal Energy Conservation System Study Report, John Hopkins University, and Lockheed*)

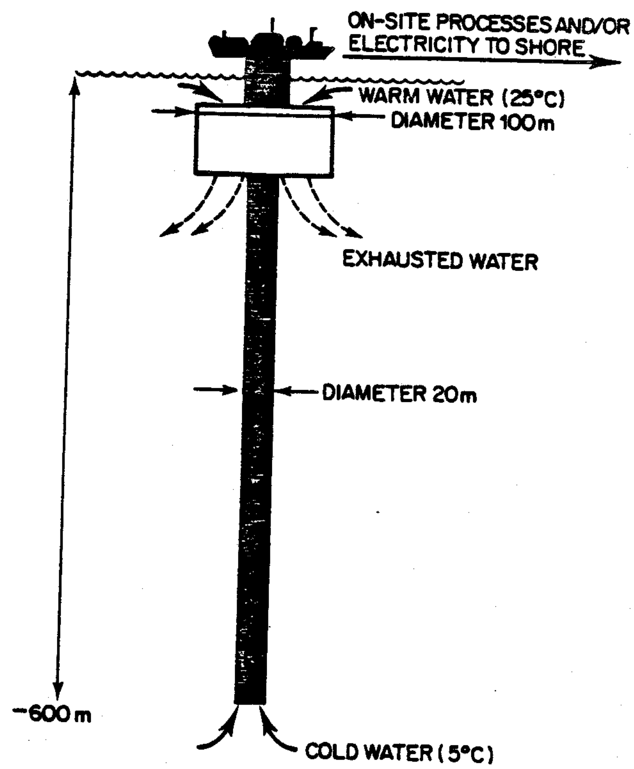


Diagram showing the principle of OTEC.

Background and Technology:

Ocean thermal energy conversion (OTEC) is a method of producing electricity from the temperature difference between the warm surface waters present in tropical and sub-tropical oceans and the much colder water present in the ocean depths. As such, it can be considered a solar energy technology, with the ocean surface serving as the solar collector.

OTEC has several advantages over other methods of ocean energy generation. Ocean wind and wave power, while originally deriving their energy from the sun, are intermittent and variable producers of electricity. OTEC plants can provide power to the existing electrical grid on a continuous basis. In addition, most OTEC designs would be relatively unobtrusive; tall smokestacks, cooling towers, and large ammounts of land would not be required. Electricity need not be the only product of an OTEC operation. Some designs would also produce fresh water. In addition, the could water pumped up from the depths is rich in nutrients and could be used in some aquaculture operations.

Several different location and construction scenarios have been proposed for OTEC plants. A plant could be land based, mounted on a tower on the continental shelf, moored near the shelf, or be designed as a self-propelled, open ocean plantship. A land based plant would have a warm water intake, cold water intake, and water discharge pipes extending offshore to desired depth and conditions. A tower-mounted plant would be built on a platform much like an offshore oil rig. The cold water intake would run down the tower to the bottom, and then continue offshore to the desired depth. A moored plant would consist of a floating platform which would be anchored in water deep enough for the cold water intake pipe to extend down to the desired depth beneath the plant. All of these designs would be connected by cables to the existing electrical power grid. Open ocean plantships, on the other hand would be large ships on which energy intensive industrial processes such as aluminum refining, ammonia production, or hydrogen production would be carried out. The energy for these processes would be supplied by an onboard OTEC plant.

The first prototype OTEC plant was constructed in Cuba in 1926. Although it showed the potential of the design, it consumed more power in operation than the 22 KW it produced. Interest in OTEC surfaced again in the 1970's during the so called energy crisis. During this period, the United States operated two test OTEC plants. The first, "Mini-OTEC", operated from the island of Hawaii for a period of four months. It produced 50 KW gross power. 15 KW of this was net power, or power in excess of that consumed in operation.

The "OTEC-1" project followed. This design was installed in a converted U.S. Navy tanker. It established the validity of a roving plantship design. The last fully operational OTEC plant was operated by the Japanese during 1981 and 1982. Sited on a tropical Pacific island, it produced 35 KW net power.

The only OTEC facility in operation today is located at the National Energy Laboratory on the island of Hawaii. While not a fully operational system, its 1.5 km cold water intake pipe provides water for testing of system components. A side benefit is that this cold nutrient rich water is used by an adjacent aquaculture firm (Penny and Bharathan, 1987).

In terms of actual operation, an OTEC power plant requires a heat source and a heat sink. In the process of transferring heat energy from the source to the sink, some of this heat energy can be converted to other forms of energy; in this case mechanical, and then electrical energy. The warm surface water serves as the heat source, while the much colder water present at great depths serves as the heat sink. Heat energy from the surface water is used to vaporize a working fluid, while the cold water is used to condense that same fluid. Although a number of different power system processes have been proposed, the two systems most commonly employed are the closed-cycle and open-cycle systems.

In the closed-cycle system, a working fluid such as ammonia or Freon is pumped through a heat exchanger. Although heat exchanger design varies, it can be thought of as similar to that of an automobile radiator, with the working fluid passing around the tubes and the warm surface water being pumped through the tubes. Some of this working fluid evaporates as a result of the heat which is transferred to it. The vapor passes through a turbine, which generates power; and then on to another heat exchanger, where the working fluid is again condensed. The fluid is then pumped back to the vaporizing heat exchanger.

Development on the open-cycle system is not as advanced as that of the closed-cycle system, yet it offers several advantages. In the open-cycle system, the warm water itself serves as the working fluid. This eliminates the need for chemical working fluids and allows for less complex heat exchangers. The warm water is pumped into a chamber where, under reduced pressure, it is flash evaporated. The water vapor then passes through a turbine and on to a condenser. The condenser can take one of two forms. A heat exchanger such as used in the closed-cycle system can be used; in this instance the condensed working fluid consists of fresh water. Alternatively, the vapor could be condensed with a mist of cold water, thus saving the cost of a heat exchanger.

Environmental Impacts:

There are sizable environmental impacts associated with OTEC plants due to their need for tremendous ammounts of water. In a typical proposed open-cycle design, only .5% of the warm water circulated through the system would be converted to steam. Thus, from 32,000 to 63,000 gallons of surface water would be required per minute (Penny and Bharathan, 1987). Depending upon condenser design, a large portion of the plankton passing through the system would be killed. Considering that fish eggs and larvae are concentrated in the upper warm surface waters, this presents great problems. Models estimate that .05% of the benthic invertabrate egg and larvae population of the Hawaiian Islands would be entrained daily by the operation of a 400 MW plant operated off the island of Hawaii (NOAA, 1981; Myers et al., 1985).

Organisms sucked into the cold water intake would have a mortality rate of 100%. However, at the depths where the cold water intake is located, planktonic organisms would be at a minimum. Additionally, accidental release of Freon or ammonia from heat exchangers could act as a biocide to local fish and plankton population. As a small balance to these problems, the cold water discharge of nutrient rich waters would increase surface water productivity.

These observations make it clear that OTEC plants need be situated in areas of low ocean productivity. As much of the tropical or subtropical locations where OTEC plants could successfully operate are such areas, the magnitude of this problem can be minimized.

Potential for Oregon's Territorial Sea:

For an OTEC plant to be economically feasible, an annual average temperature difference between the warm and cold water intakes of approximately 20 degrees C is needed. This requirement is dictated by the constraints on the OTEC design; particularly the design and construction of the heat exchangers, and the financial rate of return need to offset the high capital costs of plant construction. A temperature difference of this magnitude is available between the surface water and waters at a depth of 1000 meters at most sites within 20 degrees latitude of the equator (NOAA, 1981; Myers et al., 1985). Unfortunately a temperature difference of this magnitude is not present off the Oregon coast.

Data collected seasonally off Newport, Oregon clearly indicates this (Huyer, 1977). At a bottom depth of 50 meters, (which roughly corresponds to the territorial sea limit 3 miles offshore), temperature variation between surface and bottom waters averages 4 degrees C. During winter months there is almost no temperature difference. At depths of 130 meters, (which can be found close to 12 miles offshore), summmer differences average 7 degrees C, and winter differences average 2 degrees C. Such differences are typical of the entire Oregon nearshore shelf.

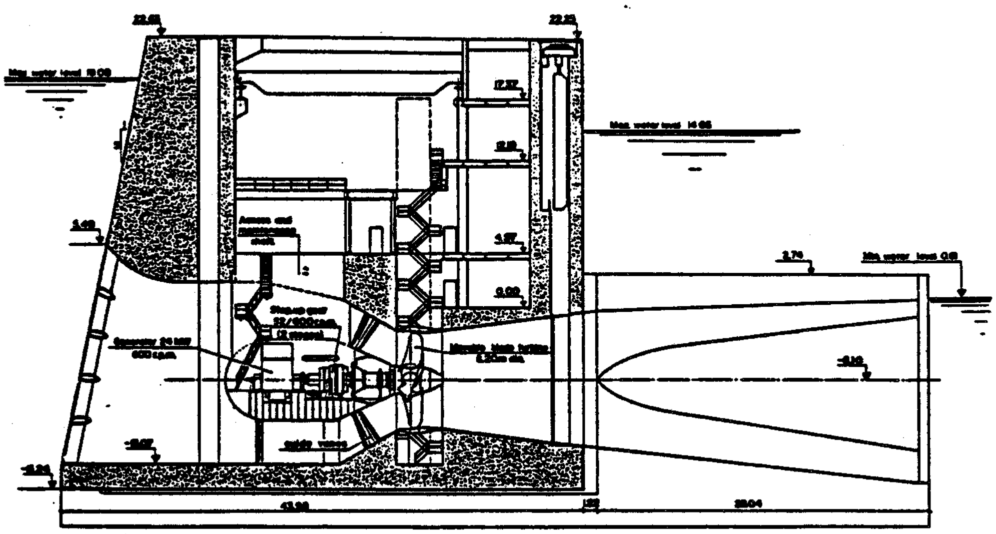
Even assuming that an OTEC plant could be placed far offshore, the critical 20 degree C difference could never be had, even if the cold water intake pipe was placed deep enough to reach near 0 degree C water. Thus OTEC generated electricity is impractical for waters off Oregon.

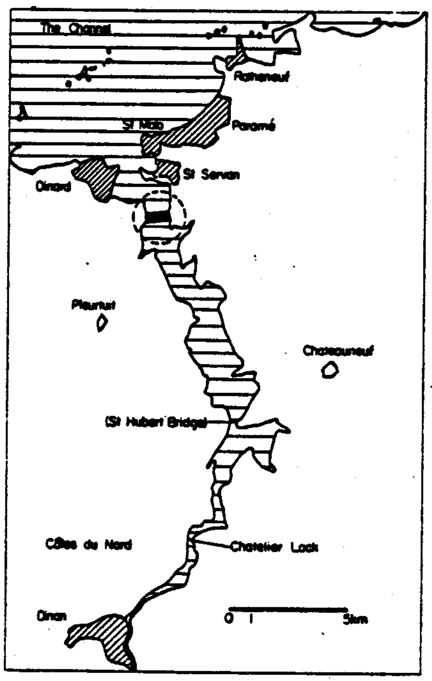
In terms of other ocean areas, the lack of present commercial OTEC development can be attributed to the great cost of OTEC plant construction. It is estimated that a 50 MW plant would cost 200 to 550 million dollars to construct. To finance such a plant, the electricity would have to sell for between 5 to 14 cents per

KW/hr (Penny and Bharathan, 1987). An oil fired steam plant burning fuel at 20 dollars per barrel can presently produce electricity at 5.6 cents per KW/hr. Thus future OTEC plants will probably be most practical in locations where fresh water or aquaculture development coincide with a need for electricity.

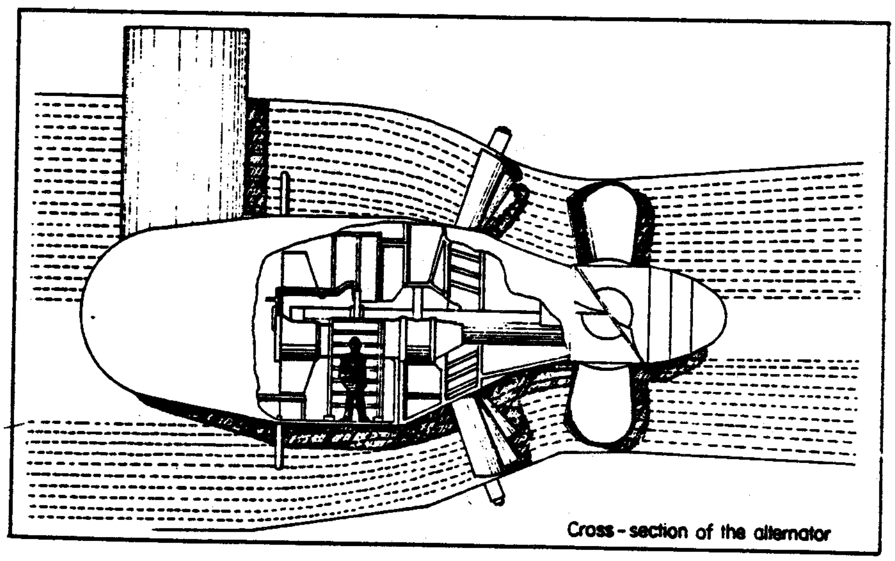
TIDAL ENERGY

LOW-HEAD PLANT EQUIPPED WITH STEP-UP GEAR





La Rance estuary. The length of the dyke needed to form a bar across the estuary is unusually short in relation to the surface area of the basin, and the site at La Rance is the best in France of this size for the production of tidal energy (*EDF document*)



The immersed power unit used at La Rance plant (*after Gibrat, Energie des marées, Presses Universitaires de France*)

Background and Technology:

The tides have been used to produce mechanical energy since at least the 11th century. Water wheel devices and or floating platforms were commonly placed along coastal locations in Europe. With the industrial revolution and the resulting abundance of cheap energy and transmission systems, tidal energy use declined to the point of vertual extinction.

The basic principals utilized in these early applications are still the basis of today's tidal power technology. Water on a rising tide is allowed to fill a diked enclosure of the sea. As the tide recedes, the enclosed water is drained back to the sea through some form of energy producing turbine. Consequently there is great similarity between the familiar hydro-electric power and tidal power.

One major difference between hydro-electric power and a basic tidal power system is that tidal power is only available during given periods of the tide. Such variable production is not necessarily in phase with human needs. As such, tidal power is generally viewed as a supplement to an existing electrical producing grid (Grey and Gashus, 1972).

To extend the electrical production period, variations of this simple basin operation have been used. One solution is to use reversing turbines which operate both on inflowing and outflowing water. Additionally the turbines may be used as pumps to maintain desired water levels (Grey and Gashus, 1972). Such a system is used at La Rance, France, where one of the world's two large scale tidal power stations is located (Brin, 1979). (The other is located in the Soviet Union, and little information is available on it).

Construction on the LaRance plant begun in 1960, at a time when the competitiveness of nuclear power had not yet been confirmed. A 750 m long dike housing 24 submerged turbo-generators was constructed to isolate 22 km^2 of estuary. The location was ideal because tidal amplitude reached a maximum of 13.5 m (Brin, 1979).

At LaRance, 560 GWh (1973) of electrical power is produced, 62 GWh of this being reutilized by the facility for pumping. At an approximate construction cost of 120 million dollars (1970), this equates to 3.5 cents per KWh (Grey and Gashus 1972).

These costs are directly related to the efficiency of the conventional turbines utilized and to the tidal amplitude. At water heads of 7-9 m they are 90% efficient. As the head shrinks to 3 m, their efficiency is reduced to 55% (Brin, 1979). Thus water heads of between 8-10 m in height are considered necessary for conventional tidal power stations to be efficient (Brin, 1979).

The maximum energy available from tidal power (E) is related to surface area in km^2 (S), and amplitude of tidal coeficent (H) as such; $E=0.2SH^2$ (Brin,1979). It is clear that tidal amplitude is a critical variable in power generation.

The basic requirements of tidal power - high tidal amplitude, and an enclosable area of the sea, greatly limit possible development sites. Two such possible sites have been extensively studied for use; Chausey Island in Britanny, and the Bay of Fundy in Canada. At the Chausey Island site maximum tidal amplitude is 14.1 m (Grey and Gashus,1979). However, despite the location's excellent potential, the high cost of constructing the dikes in violent seas has made nuclear energy the desired alternative (Brin, 1979).

The Bay of Fundy, with an average tide of 11 m, has many locations where tidal power could be harnessed. Two such areas are the Cumberland Basin and Cobequid Bay. At the latter site net available power is estimated to be 3800 MW, with an annual production of 12650 GWh. Cost of construction is estimated to be 9.3 billion (1979) Canadian dollars over a eleven year construction period. The period before profitability is estimated to be 30-35 years, at a cost per KW of 2.5-3.0 cents (Brin, 1979).

Although a pilot project of 20 MW capacity is underway, further development is being held back by a problem characteristic to large scale tidal power projects: With current construction techniques the expected life of the facility does not provide an adaquate amortization period. In addition, current high interest rates, acting over the lengthy amortization period necessary for such capital-intensive projects, can raise the cost of the project to unfeasible levels (Brin, 1979).

Many other sites around the world have been considered for possible development. In the U.S. only Cook Inlet, near Anchorage Alaska, is deemed to have the necessary tidal amplitude (Brin,1979).

To increase the locations where tidal power would be practical, new technologies have been proposed which would reduce the required water heads necessary for efficient energy generation. Such systems it is hoped, will reduce the traditionally high construction costs. An example of such new technology is the "water sail" method, which would utilize a flexible reinforced plastic barrier to dike a basin. Pressure differences between water levels would compress air, which in turn would power turbines. It is predicted that such a system could operate efficiently on mean tidal heights of 2.5 m (Veziroglu, 1981). Other systems have been proposed to operate on ultra low heads of between 0.5 and 3.0 m. Such designs require great water flows. A prototype utilizing an "ossilating paddle" concept is being constructed in 1986 (Twidell et al., 1976).

Diked basins are not the only possible way to obtain tidal power. An example of an alternative means utilizes an expanse of large underground pipes buried within the elevations of the tidal range. A rising tide would fill the system, compressing the trapped air, which in turn would drive a turbine. On the ebbing tide, suction would operate the turbine in the reverse direction (Veziroglu, 1981).

Not all tidal power plants need be large scale. China has at least 100 micro-stations utilizing basins smaller than 1 hectare. Such stations serve rural coastal communities (Brin, 1979). Most, however, require great tidal amplitudes.

Environmental Impacts:

Proponents of tidal power generally stress the positive benefits of such installations. The creation of a closed basin of regulated water level would have many of the same features as lakes created by hydro-electric dams. Calm surface conditions would be a boon to water sports. Increased water depth would aid shipping. Such positive aspects would lead to coastal land reclamation and rejuvenation (Veziroglu, 1981).

Unfortunately, there may be many major adverse environmental effects. These must be adressed in general as impacts will be very site-specific; studies already completed for specific sites have little direct application to a newly proposed site.

A major impact associated with diked basins is the need for locks to transport water craft up and down from sea level to the basins elevation. Such locks would greatly inhibit access to and from enclosed estuaries, and must be large enough to handle required commercial traffic. Tidal power basins could be designed to equal sea level during certain tidal phases, allowing direct access through gates. It is not, however, always practical for commercial or pleasure craft to have to wait hours for this to occur.

Tidal basins may also inhibit river-borne sediment transport to the sea. This may both reduce sediment supply to beaches as well as cause large sediment buildup within the basin itself. Actual hydrologic conditions at a site would determine the scale of this effect.

Marine and estuarine life could also be greatly affected. Devices such as fish ladders could be constructed to aid anadromous species such as salmon in their migrations. Many other species, however, depend upon cyclic or random access to many portions of an estuary during part of their life cycles. Among these are several species which are commercially important in Oregon.

Natural water conditions may also change within a diked enclosure. Wetlands associated with an estuary will no longer be covered and uncovered by the normal tidal cycle. Instead, their plants and animals would be subject to possible longer periods of submergence. Major changes in the abundance of individual species and the composition of the various estuarine communities could be expected. These effects could be even more serious if large ammounts of fresh water were periodically trapped within the enclosure. These changes to the food web of the estuary could also affect estuary-dependent fishes.

A well documented problem with hydro-electric generation may also occur with tidal power stations utilizing turbines. Fish may be sucked through the units, delivering them some degree of damage or mortality.

Finally, while good design may minimize or eliminate many of these problems, the loss of esthetic appeal will be difficult to minimize to those whom find charm in unaltered nature.

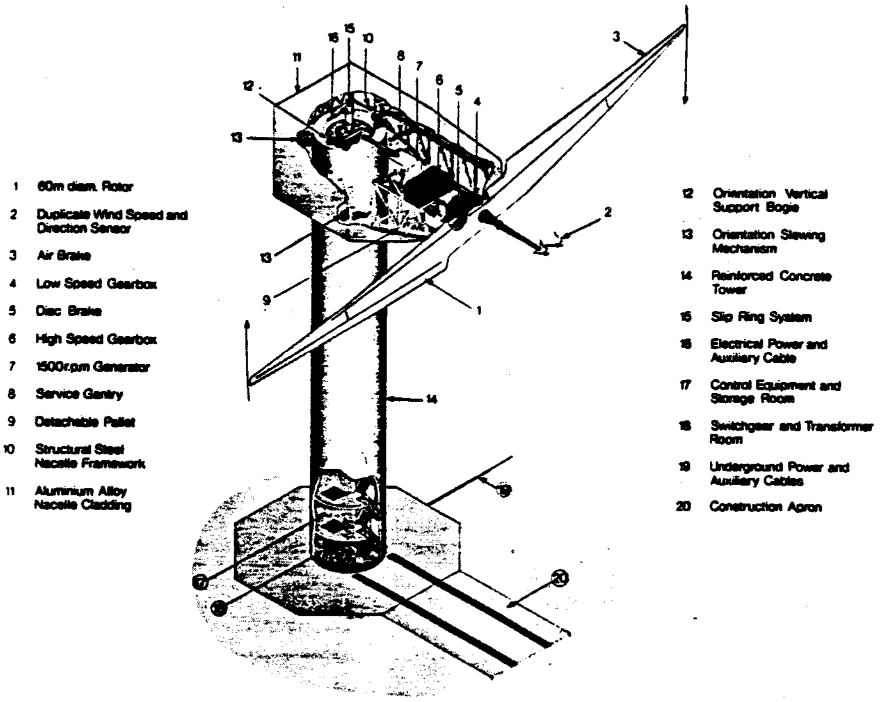
Potential For Oregon's Territorial Sea:

Sea conditions and water depth would probobly make open coast construction of a tidal power station in Oregon totally unfeasible. Oregon estuaries are however of shallow depth and generally have many locations where diking would be feasible. Surface area of the larger Oregon estuaries is on the same order of magnitude as the La Rance, France facility's 5,434 acres. If all Yaquina Bay waters and tidelands were diked, 6,762 acres would be available for electric production (Percy et al., 1974). Tillamook and Coos Bay would have almost twice this area.

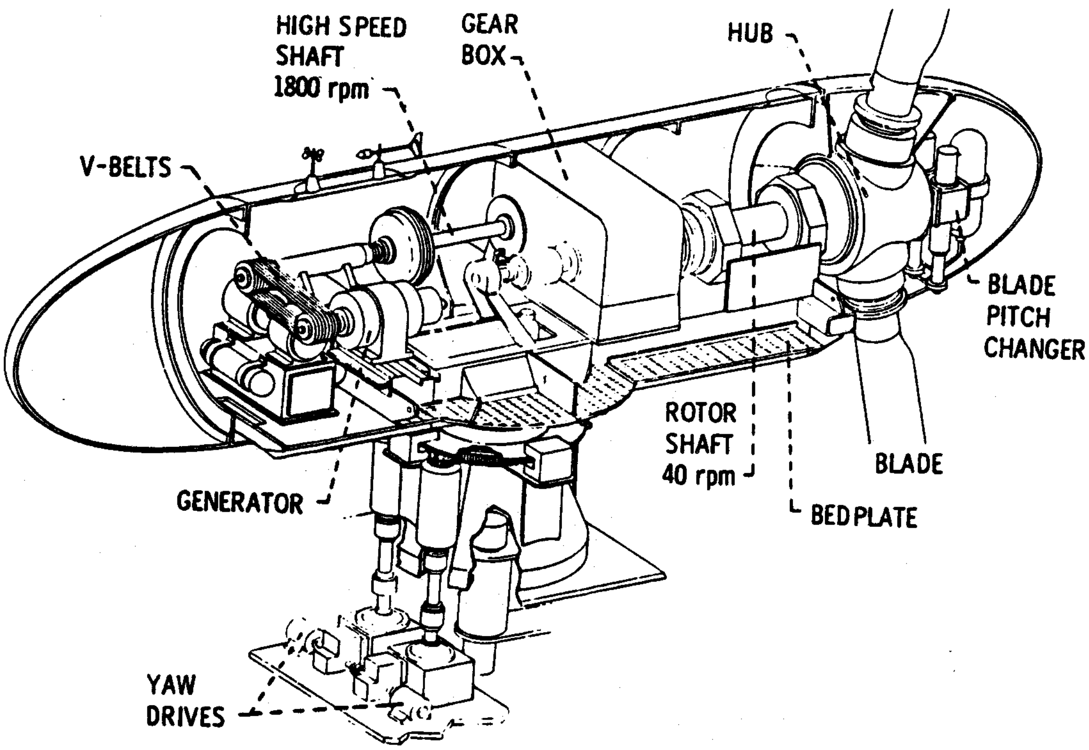
Although adaquate surface area is available for large scale tidal power development, tidal range is not sufficient. Mean tide range at Yaquina Bay is 1.8 m. Maximum tide range is 3.5 m (Percy et al., 1974). Other Oregon estuaries show similar mean tide levels; all being much lower than that required for efficient turbine use. Thus, only new and yet unproven ultra-low head designs could be utilized in energy production.

Even given future development in this field, estuarine area capable of being diked would most likely be limited to portions or arms of Oregons bays. Unobstructed sea access would need be given to main boating and shipping channels. These undiked areas would further reduce electrical generation potential.

Finally, any proposed tidal power project would likely be inconsistant with Oregon's statewide planning goal 16 (OAR 660). Although it appears that a structure such as a dike would be allowable in a designated Development Management Unit, it would probably have great impact on associated Natural and Conservation areas, where such impacts would not be allowed.



60 m diameter horizontal axis wind turbine generator—Taywood 3.7 MW machine (1980 design). (Picture courtesy Taylor Woodrow Ltd.)



Mod-0 drive train system

Background and Technology:

Wind power has been a major source of energy, particularly in rural areas, for much of this country's history. Since the 1850's more than 6 million small windmills were built; mainly for the pumping of water. The great demise of the windmill came in the 1930's with the impact of the Rural Electrification Administration's power construction programs (Corps of Engineers, 1979).

While several large experimental electrical generating wind machines were built in the ensuing years, it was not until the early 1970's and the energy shock that new interest was rekindled. Many new prototype machines which applied aviation technology in their design were constructed around the country.

Wind Conversion Devices (WCD's) can generally be divided into three catagories, based on power generating capability. Small WCD's produce up to 9 KW. Applications are generally for farms or homes requiring remote equipment. Intermediate sized WCD's produce 10-99 KW. Such units are now becoming the growth area of the industry. Large WCD's produce greater than 100 KW. It is such units in which government involvement has been greatest (Hewson, 1977).

All WCD's share the same basic components.

(1) Airfoils or blades to convert wind velocity into mechanical energy. A single long horizontal blade looking like an airplane propeller is now the most common design. Such units rotate to

continually face into the wind.

(2) A generator which converts mechanical energy to electrical energy. This is generally a geared systems to increase the blade rotation speed to that speed best utilized by generators. Converters may be used to turn DC current into AC current.

(3) A support structure to raise the unit to a height where wind velocity is greater.

(4) A transmission facility or energy storage unit. In addition to direct links to electrical power grids, forms of electrical storage may be considered. Among these are batteries, flywheels, pumped water, hydrogen gas or compressed air production (LCDC, 1978).

Determination of actual energy available from the wind is difficult. Wind power is proportional to the cube of the wind speed. Thus WCD's are much more efficient in strong winds. Wind power is also proportional to the square of the blades diameter. This means that two small WCD's will not be as efficient as one somewhat larger one (Corps of Engineers, 1978).

Obviously wind speed is highly inconsistant from hour to hour, day to day, and month to month. This situation makes wind power more of a suppliment to an existing electrical grid, than a permanent dependable source. Its introduction into a power grid can alleviate the demand on other conservable energy sources such as hydro-electric and fossil fuels.

Wind power is highly variable from location to location. Critical evaluation of the wind at a site is vital in determining the cost effectiveness of WCD placement. Local topography is a major component in creating high wind locations. Extensive studies have been conducted in Oregon to to identify a large body of sites suitible for wind development (BPA, 1985). The realization that particular areas have significant wind potential has led to the concept of wind farms. This describes the placement of large numbers of WCD's on a given site, reducing construction and mainteinance costs.

Wind energy is a large business in California. 95% of the United States' and 75% of the world's wind energy output is generated within this state. A total of 8,469 turbines generated 195 million KWh of electricity there in 1984 (Gipe, 1985). The energy produced was equivalent to saving 340,000 barrels of oil.

The average sized WCD now operating in California is rated at 78 KW, and has a rotor span of 15 to 17 meters (Gipe, 1985). Although this average increases yearly, the trend is away from the very large experimental WCD's constructed during the 1970's. Westinghouse Corporation is the only U.S. firm still committed to the large devices, as cost of construction and operation outweigh their increased power production (Gipe, 1985).

The efficiency of new WCD designs now make wind energy competitive with nuclear energy, i.e., capital costs are approximately 3-5 billion dollars per 1,000 MW of generating capacity. By 1990 it is estimated that advances in equipment efficiency will reduce wind power costs to 6-10 cents per KWh. This would make wind power costs approximately equal to coal fired plants in terms of KWh (Gipe, 1978). Nuclear power costs are expected to rise to 14-16 cents per KWh, exclusive of the costs of decomissioning these facilities.

Given the strong and steady wind characteristics of the nearshore ocean, it would seem a logical region for wind farm construction. In 1977 it was estimated that one-third of Great Britain's electrical power requirements could be generated by WCD's located in the North Sea. At that time a capital cost of 750 dollars per KW was estimated. This appears greatly optomistic considering the high cost of marine support structures (Corps of Engineers, 1978). The British are, however, actively involved in promoting the concept (Nath pers. comm., 1986).

An estimation of the cost involved in constructing an offshore structure can be seen in a proposal for constructing a research tower 15 miles off the Oregon coast in 150 feet of water. While forty feet of tower would project above the sea surface, (hardly sufficient for even the smallest WCD), total construction cost of the basic structure would be approximately 200,000 dollars (Nath, et al., 1973). Additionally, the tower was only designed for a short (two year) life span. These costs reflect only those for a support structure, excluding other requirements of a WCD such as blades, generator, and transmission lines to shore.

It can properly be argued that if large scale development of offshore wind farms were initiated, construction costs could be greatly reduced due to economy of scale and integration of many WCD's into a single massive structure. However, considering that many suitable land based locations for wind farms have not yet been tapped for their potential, immediate offshore development seems remote.

Environmental Impacts:

Since wind is a dispersed resource, WCD's must be widely spaced to effectively capture wind energy. As horizontal axis units must rotate with the wind, a spacing equal to ten rotor diameters is considered conservative. Estimates of actual power generation per acre can not be provided due to site and equipment variability, but siting equations indicate that many hundreds of acres are required for a typical wind farm (WTF, 1980). On land, unforested terrain is required due to the rotating blades of WCD's. Once wind farm construction has been completed, farming or grazing of a site may continue unaffected by the presence of WCD's. The only land area lost to previous use will be due to base structures and access roads to individual WCD's. Electrical transmission lines may be integrated into roadways.

At sea, wind farm area would be lost to other ocean uses except, perhaps, for recreational fishing and small commercial fishing vessels. For larger vessels, height would preclude their safe passage beneath the blades of a WCD. In addition, the possibility of vessel collision with supporting towers would exist. This fear alone may make it reasonable to exclude vessels from the vacinity of an ocean wind farm.

WCD's are capable of reflecting radio and television signals due to blade rotation. Affected frequencies lie in the upper VHF and lower UHF bands. Interference has been documented up to three miles distant from a WCD site. Thus an oceanic wind farm could disrupt local vessel communications and navigation to some degree. Constructing blades of non metallic material greatly reduces this effect. Electronic counter measures can also mitigate this problem to a large degree (WTF, 1980).

Different models of WCD's have highly different noise characteristics. Smaller WCD's generally produce more noise due to their higher rotation speeds. All produced noise frequencies are of a low enough volume that they are localized to the immediate vicinity of a wind farm (WTF, 1980).

Since it takes many WCD's to equal the output of a conventional utility plant, visual impact is a problem for land siting. For an oceanic location, distance from shore and size of the facility would be a major factor in determining impact. Variable human response would also play a factor, i.e., is a line of WCD towers (as opposed to oil rigs) an enhancement or detriment to one's enjoyment of a coastal vista.

Potential For Oregon's Coastal Waters:

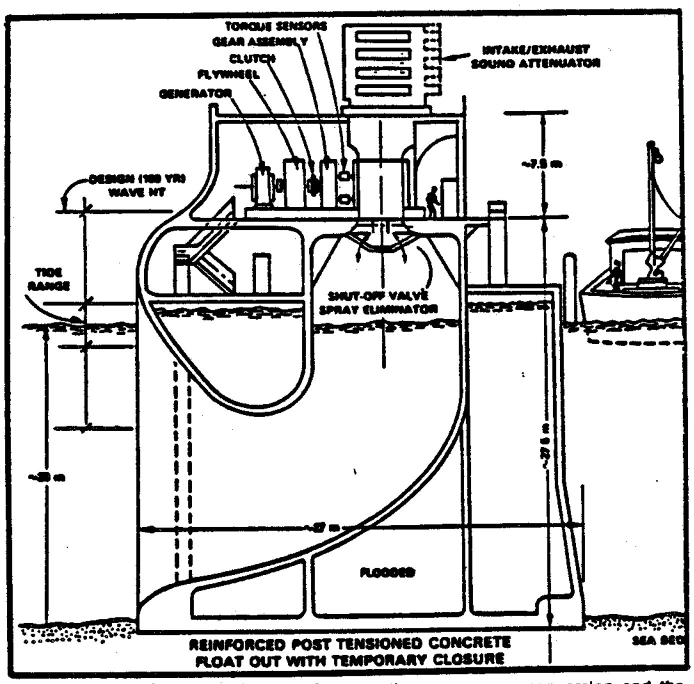
In general, Oregon's coastal waters have higher wind speeds than coastal or interior land areas (Corps of Engineers, 1978). Wind measurements made at the Columbia Lightship indicate that wind strength and duration are adaquate for efficient WCD operation. Present cable technology is such that power generated a few miles offshore could be transmitted to land without serious power loss (Hewson, 1977). WCD technology is reaching a point, "where if expected technical and cost breakthroughs are achieved, wind energy could undoubtably play an important role in the energy future of Oregon's Coastal Zone" (LCDC, 1978).

The major obstacle to wind farms in coastal waters is the cost of the required support structures. "There is the distinct possibility, if not probability, that the supporting tower or mooring mechanism may be inordinately costly if it is to withstand the pounding of wind and waves of mid-lattitude winter storms" (Hewson, 1977).

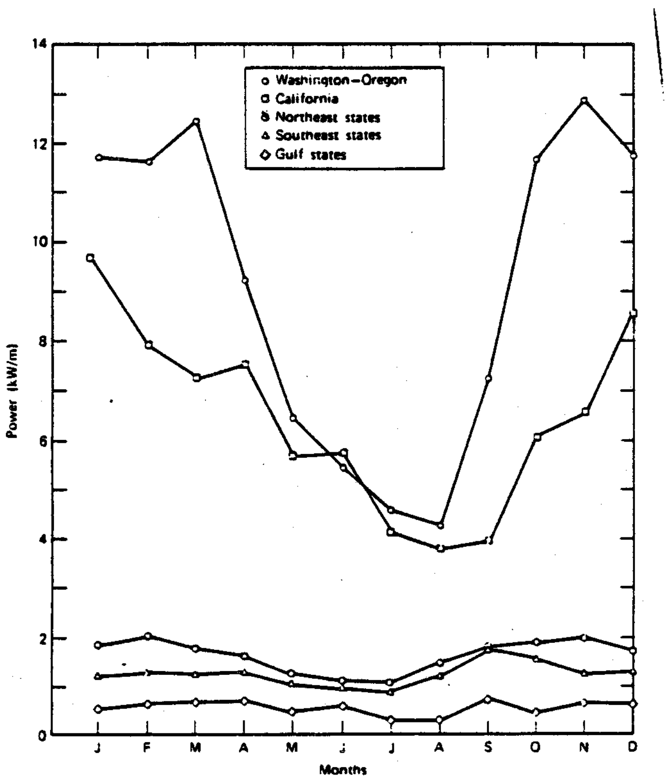
Many factors contribute to the high construction costs noted. To be cost effective an oceanic wind farm might be expected to operate over a period of thirty years. Corrosion and the battery of wind and waves would have to be designed against. Five miles off the Oregon coast ocean depths are approximately 180 feet. At such depths it would be impractical to place individual WCD's. An alternative would be the placement of multiple WCD's on a single large support structure. Such platforms might need be produced and installed in large numbers to keep costs low, thus requiring a strong national and regional commitment. Such has not been the case.

An alternative scenario for support structures may lie in future wave energy developments. If wave energy conversion structures were incorporated into future energy production, they might prove ideal as the base for WCD installation. In this case, a single structure could be utilized to generate two forms of electrical energy.

WAVE ENERGY



The end result of the combination of pneumatic wave energy conversion and the McCormick turbine yields an efficient energy source.



Wave power variations over 1 year. Data from coastal waters, but calculations based on deep water assumptions. After McCormick (1976).

Background and Technology:

Interest in extracting energy from waves is not new. To date, over 1,000 patents are registered in the Western world on ways to harness this power (McCormick, 1981). Previous to the recent renewed interest in wave energy, at least 20 major structures were built to commercially recover this energy. None exist today. This is most likely due to the destructive capacity of storm waves (Hydrotechnology, Ltd., 1982). Since the late 1970's several large commercial prototype Wave Energy Conversion Devices (WECD'S) have been under study throughout the world. Small scale units are now being manufactured to provide electricity to isolated locations as well as remote equipment such as navigation bouys.

Wave energy is originally derived from the effect of wind on the sea surface. Within a wave there are two distinct forms of energy; kinetic energy (energy of motion) is present in a wave due to its forward motion. Potential energy (stored energy), is available due to the difference in height between the crest (or top) of a wave, and its trough (or bottom). Generally, it is the potential energy of a wave which is largely harnessed in WECD designs.

The supply of wave energy is characteristically intermittent and seasonally dependent. Furthermore, a large proportion of the total energy generated occurs during relatively brief periods of intense wave activity (Hydrotechnology, Ltd., 1982). As such, wave energy is best viewed as a supplement to the existing power grid, unless storage of this variable power is called for.

Because waves characteristically vary in period (distance between crests), and amplitude (height), designing WECD'S for optimum efficiency is difficult. As an example, Salter's Nodding Duck, described later, has a 90% conversion efficiency from wave energy to mechanical energy in waves of a 9.5 second period. As wave period increases to 15 seconds or decreases to 7 seconds, efficiency is reduced to 45% (Baird and Mogridge, 1976). Irregular or confused seas further reduce conversion efficiency, as does variation in the angle at which waves strike the WECD. All these factors make actual predictions of true generating power difficult.

Of the many proposed WECD designs, most are variations on a few basic approaches:

"Heaving Body" types utilize the potential energy in passing wave crests and troughs to alternately lift and drop a float or series of floats. This up and down motion can be mechanically harnessed and converted to electrical or other forms of power.

"Pressure Devices" are another approach. As such, they don't depend on the surface motion of waves, but rather on the increase and decrease in water pressure under passing crests and troughs. These differences are used to expand and contract bellows-like devices which, in turn, may drive a piston or turbine.

"Contouring Raft" designs utilize wave motion to undulate several interconnected, hinged, floating slabs. Mechanical energy is extracted from the hinge points. (Salter's Nodding Duck is a specially shaped variation of such a design).

The "Oscillating Water Column" is a highly developed WECD. This design utilizes the up and down wave motion to alternately raise and drop the water level in a chamber which is sealed at the top. With each wave cycle, rising water compresses air within the chamber. This air forces itself through a top mounted turbine. When the water level in the chamber falls, air is sucked back into the chamber, again spinning the turbine. Turbines capable of operating in this reversible manner are labled "self rectifying".

No matter which design is utilized to harness wave energy, it must collect this power source over a large frontal area to produce appreciable ammounts of electricity. Wave energy is diffuse, having an average total power per meter length of wave crest of between .25 and 13 KW for coastal locations of the United States (McCormick, 1981). At locations off the west coast of Canada, average wave power rises to 35.1 KW/m (Baird and Mogridge, 1976). Thus a WECD with a frontal area of 10 meters, having a conversion efficiency of 72% (McCormick, 1986), and rated for 10KW/m waves, could generate 72 KW at peak. This conversion efficiency is possible today, and technological and structural design improvements may make efficiency increases possible (McCormick, 1986).

Two commercially sized designs utilizing Oscillating Water

Columns are in operation in the world today. In Japan, the experimental "Kaimei", an 80 m long moored barge-like structure has a rated capacity of 1 MW (Morgridge, 1980). Thus it is able to provide power (at peak demand) for 1,250 persons. Norway's first wave power station, at Tostestallen, generates 850 KW, and provides power for a community of 1,000 people (Portland Oregonian, Feb. 19, 1987).

These designs clearly exhibit the immediate potential of wave power to satisfy the electrical needs of small isolated coastal and island communities, where the cost of alternative electrical power is inordinately high. The Norwegian experiment indicates that electricity can be provided for between 2 and 5 cents per KW-hr (Bonke and Ambli, 1985). However, these figures were based on the installation of Oscillation Water Column designs in sea cliffs. Cost of supporting structure was thus minimized. "Optimistic" calculations made prior to these experiments indicated wave energy costs would be within a range of 3.8-4.6 cents per KW-hr (Nath and Williams, 1976).

Given the rated power levels of McCormick's design (7.2 KW/m), it can be seen that the size of a structure capable of generating commercial quantities of power must be immense. Actual calculations to this effect are difficult and must be based on specific wave regimes. For example, assume an average wave power of 12 KW/m for 6 months of the year at Pacific Northwest locations. Further assume that improved technology can provide conversion efficiencies of 85% (McCormick, 1986). Such figures would provide for 10.2 KW of electrical power per meter of frontal area, or 10,200 KW per kilometer.

Although these figures may be highly optimistic in terms of real applications (Slotta, 1987, pers. comm.), they do provide insight into the extreme structural requirements of large scale electrical power production. Based on the above figures and the "Kaimei" experiment, one might hopefully expect a winter generating capacity off the coast of Oregon of 10 MW per kilometer of structure. This could provide peak power demands for about 10,000 persons.

Great variation in structural design concepts also complicate the analysis. In general, structures designed for housing or supporting WECD's may be of two main forms, moored structures or gravity structures. Moored structures, such as the "Kaimei" design are free floating, relying on hugh chain and anchor systems to maintain their position. Gravity structures rest firmly on the seabed. Whatever their design, these structures will constitute a major proportion of the total cost of a WECD (Hydrotechnology, Ltd., 1982). While gravity structures are probably more effective at wave conversion than moored devices, they would be cost prohibitive in deeper water, requiring them to be located nearer the coast.

Not all WECD structural designs call for direct interception of incoming waves. "Lens" or "focusing" designs utilize shaped underwater structures which do not extract wave energy themselves, but instead turn or focus a long length of wave front onto a shorter length of WECD point collectors. As such, they are concentrators, providing increased energy per area on a fewer number of WECD's.

A major question to be addressed in WECD structural requirements is how well they will hold up to many years of waves, and in particular storm impacts. Virtually all existing marine structures are designed to deflect wave energy striking them. WECD's by necessity must absorb it. If, for example, the return on investment from a deployed array of WECD's is expected to be 30 years, it might be necessary to design the units for at least a statistical 100 year storm. This would be no small requirement. Such storms can, and do, demolish seawalls, jetties, breakwaters, and other similar coastal structures.

Given the costs involved in constructing such structures, it might not be unfeasible to consider their multiple use for energy extraction. Offshore wind power has shown potential. Perhaps such devices could be incorporated into the design of WECD structures.

Environmental Impacts:

Due to the dispersed nature of wave energy, large scale power generation would require a lengthy section of seafront (up to several kilometers) to be harnessed. Unless planning called for lens type energy focusing designs, such a large structure would effectively eliminate all ocean swell on its rear side. Such a profound effect may have great consequences on coastal processes within the shadow of the structure.

Littoral drift, the process where beach sands are transported along the coast, may be greatly altered. The direction of net sand movement in the intertidal and shallow subtidal regions is related to the angle at which waves strike the beach. This net movement may be constant throughout the year, or may vary with season, depending upon the wave regime.

Depending upon a WECD structure's size and distance from shore, as well as local littoral drift patterns, a WECD may cause increased sand deposition in some areas, or depletion in others. Such effects could result in impacts to coastal properties and structures, alteration of recreational areas, and changing sedimentation patterns into or out of estuarine mouths. In addition, lack of large waves within the "shadowed" section of coastline could result in a less steep (summer) profile on affected beaches (Dawson, 1979). This could lead to increased offshore shoaling and growth of beaches within the shadowed area.

Wave patterns and or currents in the vicinity of a WECD may also be altered. Directly in front of such a unit, reflected wave energy may cause very steep and confused seas. Waves and currents moving around the ends of a large structure may cause a similar situation (Dawson, 1979).

In the case of "lens" or focusing WECD designs, the above effects would be different. The seawall effect would be minimal.

Depending upon the design, placement, and number of units, some ammount of regular ocean swell would reach the shore. Focused wave energy would, however, create paths of extremely high and powerful seas directed at collector locations. These regions could conceivably be very hazardous to craft traversing them.

The construction of a long connected series of WECD's would also result in several benefits. The sea shoreward of these structures would be subject to only local wave conditions, making it an excellent water recreation area and a possible harbor of refuge for coastal craft. Properly placed, a WECD system could eliminate large waves at harbor mouths, making entrance and exit of craft safer. The area of calm water could also benefit local industry, particularly aquaculture. The structure itself could be used as an operational base for businesses using the area of protected water.

It is conceivable that the local fishery could be enhanced by the presence of a large WECD structure, particularly if it were bottom mounted rather than a free floating structure. As such it would double as an artificial reef. Concern has been expressed in Great Britain that an extremely long WECD might be a barrier to fish migration, particularly by salmon and herring. If this proves to be a problem, it could be alleviated by providing channels or gaps along the structure (Dawson, 1979).

The possibility of ship collisions is also present. Modern navigation equipment, warning lights, and radar reflectors, could minimize this hazard; but danger would nevertheless exist, particularly during periods of adverse weather or poor visibility. The presence of a WECD may actually cause watercraft to be drawn to its vicinity for fishing or recreational purposes, thus increasing the hazard.

Clearly there will be esthetic and visual impacts. The effect of this will largely be determined by the structures design, size, and distance from shore. Current "Oscillating Water Column" designs also produce much turbine noise. This effect is being greatly reduced in new designs (Portland Oregonian, Feb. 19, 1987). Within the wave shadow of a large WECD the esthetic appeal of large crashing waves will be diminished if not eliminated.

Potential for Oregon's Territorial Sea:

The energy content of waves off the Pacific Northwest coast is greater than at other continental U.S. locations. The average power off Oregon ranges from 12 KW per meter of wave crest during winter months to a low of 4 KW per meter during the month of August. In contrast, winter power levels off California average about 8 KW per meter of wave crest. East and Gulf coast waters all have average monthly power levels of less than 2 KW per meter of wave crest (McCormick, 1981).

Therefore, if wave power were to be harnessed anywhere in the U.S., Oregon would be a logical location. A number of factors, however, combine to make it unlikely that wave energy conversion devices will be installed in Oregon's territorial sea before the turn of the century, if ever.

While the efficiency of wave power conversion has been demonstrated in the last few years, no federal money is being put into wave energy conversion projects at the present time. This is in sharp contrast to the situation in Europe and Japan (Portland Oregonian, Feb. 19, 1987). Risks associated with structural failure have not been carefully looked at, and standardization of equipment and structures has not been accomplished. Structures capable of withstanding the wave climate in the Pacific Northwest have not been specifically designed.

While wave energy conversion does not require an extremely high level of technology, the capital required for large scale implementation would be great. Thus the size and cost of the structures necessary for large scale harnessing of this diffuse source of power has been, and will be, an impediment to commercial application.

Finally, the Pacific Northwest currently has an abundance of electrical generating capacity. Past energy use predictions have greatly overestimated growth in the demand for electrical power. The result is that currently available capacity should prove adequate at least through the end of this century.

In summary, wave energy development in the near future appears likely only in issolated coastal or island areas where the only alternative is the generation of extremely expensive electricity by diesel-powered generating equipment.

REFERENCES CITED

Baird, W.F., and G.R. Mogridge. 1976. Estimates of the power of wind generated water waves at some Canadian coastal locations. National Research Council Canada, Division of Mechanical Engineering, Hydraulics Laboratory. Lab. Tech. Rep. LTR-HY- 53. 30pp. Ottawa, Canada.

Bonke, K., and N. Ambli. 1985. Building of wave energy power stations in Norway. Norwegian Hydrodynamics Laboratories. Trondheim, Norway.

BPA (Bonneville Power Administration). 1985. Pacific Northwest wind regional assessment program. Final Report. Vol. I. U.S. Dept. of Energy, Bonneville Power Administration, Office of Power and Resource Management, Division of Power Resources Planning. Report BPA 85-19. Portland, Ore.

Brin, A. 1979. Energy and the ocean. Ann Arbor Science.

Corps of Engineers. 1978. Pacific Northwest regional wind energy study. U.S. Army Corps of Engineers, North Pacific Division, Walla Walla District. Contract No. DACW68-77-C-0174. 212 p. Walla Walla, Wa.

Dawson, J.K. 1979. Wave Energy: A review paper prepared for the Dept. of Energy by the Energy Technology Support Unit, Harwell. Dept. of Energy, Energy Paper Number 42. Her Majesty's Stationery Office. London, England.

DOE (U.S. Dept. of Energy). 1979. Environmental development plan: Ocean thermal energy conversion. U.S. Dept. of Energy, Assistant Secretary for Energy Technology, Assistant Secretary for Environment. 48 pp. Washington, D.C.

Gipe, P. 1985. Overview of the U.S. wind industry. in Hill, R.F. (ed.), Proceedings of the Twelfth Energy Technology Conf. Government Institutes, Inc. pp. 1709 -1718. Rockville, Md.

Goodwin, C.R., E.W. Emmett, and B. Glenne. 1970. Tidal study of three Oregon estuaries. Oregon State Univ. Engineering Experiment Station. Bulletin No. 45.

Grey, T.J., and O.K. Gashus (eds.) 1972. Tidal power: Proceedings of the International Conference on Utilization of Tidal Power. Plenum Press.

Hewson, E.W. 1977. Electrical energy from the wind. Pages 6: 142-176. in D.M. Considine (ed.), Energy Technology Handbook. McGraw -Hill Book Co., New York.

Huyer, A. 1977. Seasonal variation in temperature, salinity, and density over the continental shelf off Oregon. Limn. and Oceanography. 22(3): 442-453.

Hydrotechnology, Ltd. 1980. An evaluation of the energy of wind generated water waves in the coastal area of Canada. National Research Council Canada, Mechanical Engineering Division, Hydraulics Laboratory. Lab. Tech. Rept. LTR-HY-82. 62 p. Ottawa, Canada.

LCDC (Oregon Land Conservation and Development Commission). 1978. Energy facilities in the Oregon coastal zone. Vol. II: Likelihood of energy facility siting. 85 p. Oregon Land Conservation and Development Commission. Salem, Or.

McCormick, M.E. 1986. Ocean wave energy conversion: Inexpensive energy source yields significant results through simple methods. Sea Technology 27(6): 32-34.

McCormick, M.E. 1981. Ocean Energy Wave Conversion. Wiley-Interscience. 233p. New York.

Mogridge, G.R. 1980. A review of wave power technology. National Research Council Canada, Division of Mechanical Engineering, Hydraulics Laboratory. Lab. Tech. Rept. LTR-HY-74. 109 p. Ottawa, Canada.

Myers, E., D. Hoss, W. Matsumoto, D. Peters, M. Seki, R. Uchida, J. Ditmars and R. Paddock. 1985. The potential impact of ocean thermal energy conversion (OTEC) on fisheries. National Oceanic and Atmospheric Adm., Office of Ocean and Coastal Resource Management, Ocean Minerals and Energy Div. Washington D.C.

Nath, J.H. 1986. Personal communication. Dept. of Civil Engineering, Oregon State Univ. Corvallis, Or.

Nath, J.H., and R.M. Williams. 1976. Preliminary feasibility study for utilization of water wave energy. Pages I-1 - I- 55 in Wave and salinity gradient energy conversion workshop proceedings. U.S. Energy Research and Development Administration, ERDA Rept. No. COO-2946-1. Washington, D.C.

Nath, J.H., J.L. Washburn, R.S. Mesecar, and D.C. Tavolacci. 1973. Offshore research tower: A design report for the National Science Foundation, Engineering Division, Engineering Mechanics Section, Fluid Mechanics Program. School of Oceanography and Dept. of Mechanical Engineering. 69 p. Oregon State Univ. Corvallis, Or.

NOAA. 1971. Environmental impact statement for commercial ocean thermal energy conversion (OTEC) licensing. National Oceanic and Atmospheric Admin. Office of Ocean Minerals and Energy. Washington D.C.

Penny, T.R. and D. Bharathan. 1987. Power from the sea. Scientific American. Jan. 1987. Vol. 256 No. 1.

Percy, K.L., C. Sutterlin, D. Bella, and P.C. Klingeman. 1974. Descriptions and information sources for Oregon estuaries. Sea Grant College Program 294 p. Oregon State Univ. Corvallis, Or.

Slotta, L.S. 1986. Personal communication, March 5, 1987. Slotta Engineering Associates. Corvallis Oregon.

Twidell, J., I. Hounan, and C. Lewis (eds.) 1976. Energy for rural and island communities IV. Pergamon Press.

Veziroglu, T.N. 1981. Alternative energy source II. Vols. 4&5. Hemisphere Publishing Corp.

WTF (Wind Task Force). 1980. Final report to the Oregon Alternative Energy Development Commission.