Sea Grant Oregon

Program Development Grant Report

Conversion of Wave Characteristics to Actual Electric Energy/Power Potentials

January, 2004

INTRODUCTION

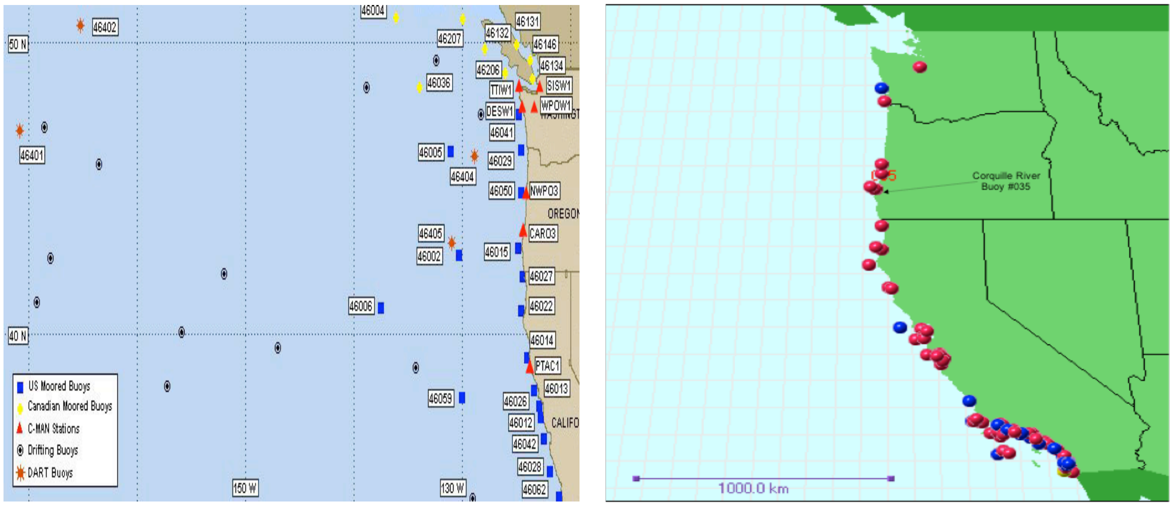
Ocean wave energy is generally considered as a fuel-free, clean, renewable energy with a vast resource potential. With mounting environmental concerns about traditional methods of energy production and the ever increasing demand for energy, research into wave energy extraction technologies has experienced renewed interest in recent times. In order to ascertain how much energy a wave energy device will be able to convert to useful energy, the potential power available to the device at the site it is located must first be determined. Also, the estimation of the incident wave power is an important step in the design of wave energy devices because if the equipment is rated too high it will be under utilized most of the time; on the other hand if it is rated too low it will be unable to capture much of the available energy or may be damaged. The potential power is quantified in the form of the annual average incident wave power.

Previous research has shown that Oregon has one of the coastlines with the richest Ocean energy potentials in North America [14]. However, this potential and the actual electric energy/power that can be extracted from the resource has never been fully studied and documented. With the advancing ocean energy extraction technologies being tested and efficiencies of these technologies being documented, it is now appropriate to correlate the coastal characteristics and energy potentials into actual electric energy that can be obtained from a given amount (actual real estate) of coastline.

This report presents an assessment of the wave power potential of the Oregon coast and how much of that power can actually be converted into useful energy, based on analysis of the conversion efficiency of the two most advanced and probable technologies: oscillating water columns (OWC) and buoys. The actual ocean real estate that would be required for the power output of each device has also been estimated.

SOURCE OF WAVE DATA

The source of the data for this study is the National Data Buoy Center (NDBC) database of wave characteristics collected over a number of years from buoys located along the coastal waters of North America. This data is published hourly on the NDBC website [3]. Also, wave data from the Coastal Data Information Program (CDIP) of the Scripps Institution of Oceanography, available on the web [6] was used. Fig. 1 shows the buoys located along the Oregon coast and Table 1 and 2 show the specific buoys that were used in this study.



(a) NDBC (b) CDIP

Fig. 1 Buoy Allocations

Table 1: NDBC Buoys

Buoy#	Location	Distance from Shore	Water Depth (m)
46002	West of Coos Bay, OR	275NM	3420
46005	West of Aberdeen, WA	315NM	2780
46015	West of Port Orford, OR	16 NM	448
46029	South Southwest of Aberdeen, WA	78NM	128
46050	West of Newport, OR	20NM	130

Table 2: CDIP Buoy

Buoy#	Location	Distance from Shore	Water Depth (m)
#035- Coquille River	Bandon, OR	1 mile	13 approx.

APPROACH

The wave conditions of any location can be described by the statistical wave parameters such as the significant wave height, average wave period, and dominant wave period. The significant wave height is defined as the average of the highest one-third of all of the wave heights during a sampling period (20 minutes). The average wave period is also defined as the average zero crossing period of all waves during the same sampling period (20 minutes). The dominant wave period is the period with the maximum wave energy in a random wave train.

The incident power from a wave can be expressed as [1]:

$$P = \frac{\rho g^2 T H^2}{32\pi}\left\{(1+\frac{2kd}{\sinh(2kd)})\tanh(kd)\right\} \qquad (1)$$

where P = wave power potential (W/m)

d =vertical distance between mean water depth and seabed (m)

ρ = the density of sea water = 1025 kg/m^3

g = acceleration due to gravity = 9.8 m/s^2

T = period of wave (s)
H = wave height (m)
k =wave number $= \frac{2\pi}{\lambda}$, and
λ = wavelength (m), the horizontal distance between successive crests or troughs.

For deep seas where $\frac{d}{\lambda} > 0.5$ the approximation for wavelength from the dispersion relationship $\omega^2 = gk \tanh(kd)$ is given by $\lambda = \frac{gT^2}{2\pi}$ and the expression in brackets in equation (1) is approximately unity. Also for shallow sea, $d < 1/20^{th}$ wavelength, and $\lambda = T\sqrt{gd}$ .Using statistical wave parameters such as the significant wave height H_s and the energy period wave power can be expressed as [4]:

$$P = 0.49 H_s^2 T_e \quad (2)$$

For shallow seas where the dependence on depth is critical, the wave length can be solved from the dispersion relationship and used to compute the average wave power. The average wave power can also be calculated from a typical sea states scatter table shown in Table 3.

WAVE PARAMETERS

The significant wave height and wave period are fundamental parameters for determining the wave energy. The parameters vary and consequently the wave power also varies. Table 3 shows a typical annual variation of sea state for the NDBC buoy #46050 in year 2000, while Fig. 2 graphically shows the joint distribution of wave heights and period. The numbers show how often in a year a combination of significant wave height and period occur. Each combination contributes to the annual average power, proportionally to how often they occur.

Table 3: Scatter table, NDBC Buoy #46050, year 2000

Scatter, NDBC Buoy #46050 2000 H_s and T

Hs\Tp	Dominant Wave Period, s																									
Significant Wave Height, m	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	>25
0-0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5-1	0	0	0	0	17	13	35	41	26	69	0	18	0	0	27	0	72	0	0	4	0	0	0	0	1	0
1-1.5	0	0	0	3	54	98	137	363	279	340	0	66	108	0	65	0	145	0	0	28	0	0	0	0	0	0
1.5-2	0	0	0	0	21	65	157	300	201	549	0	171	175	0	148	0	91	0	0	16	0	0	0	0	4	0
2-2.5	0	0	0	0	2	23	96	164	122	341	0	274	184	0	189	0	130	0	0	45	0	0	0	0	5	0
2.5-3	0	0	0	0	0	6	13	43	60	176	0	157	165	0	171	0	128	0	0	43	0	0	0	0	7	0
3-3.5	0	0	0	0	0	0	10	12	20	73	0	77	130	0	159	0	124	0	0	60	0	0	0	0	2	0
3.5-4	0	0	0	0	0	0	2	18	13	84	0	73	98	0	141	0	95	0	0	29	0	0	0	0	1	0
4-4.5	0	0	0	0	0	0	0	9	17	48	0	46	72	0	112	0	81	0	0	18	0	0	0	0	1	0
4.5-5	0	0	0	0	0	0	0	0	7	23	0	19	46	0	84	0	40	0	0	4	0	0	0	0	0	0
5-5.5	0	0	0	0	0	0	0	1	1	18	0	6	20	0	65	0	17	0	0	4	0	0	0	0	0	0
5.5-6	0	0	0	0	0	0	0	0	0	9	0	2	8	0	23	0	23	0	0	6	0	0	0	0	0	0
6-6.5	0	0	0	0	0	0	0	0	0	8	0	2	5	0	15	0	6	0	0	5	0	0	0	0	0	0
6.5-7	0	0	0	0	0	0	0	0	0	2	0	1	1	0	11	0	11	0	0	0	0	0	0	0	0	0
7-7.5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5	0	5	0	0	0	0	0	0	0	0	0
7.5-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	7	0	0	0	0	0	0	0	0	0
8-8.5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	7	0	0	0	0	0	0	0	0	0
8.5-9	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0
9-9.5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
9.5-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10-10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.5-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
11-11.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
11.5-12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12-12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
12.5-13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

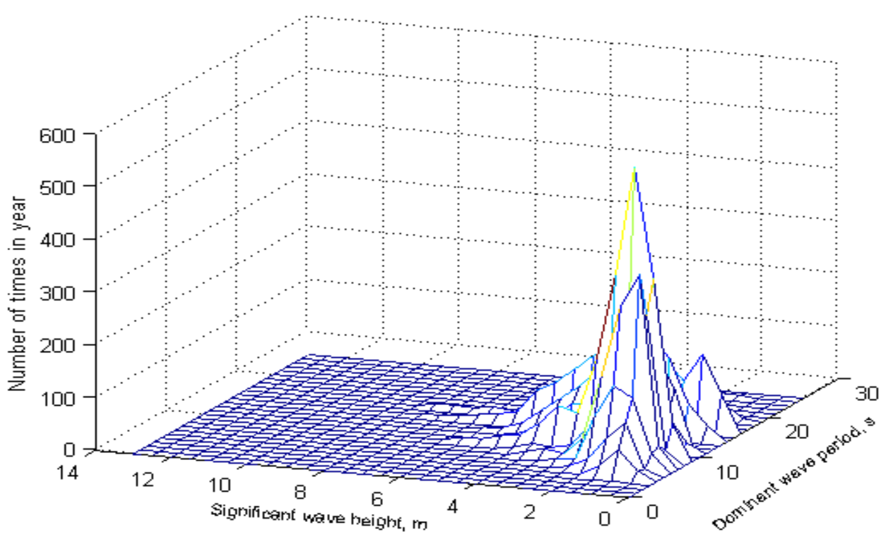


Fig. 2 Joint distribution of wave heights and period NDBC #46050, y2000

The variations in wave conditions can be hourly, daily, monthly, annually or seasonal and these changes could be due to the variations in the winds that cause waves, or due to swells moving from one location to the another. Fig. 3 shows some hourly wave heights measured on given days in 1994 and 1998 for buoys #46005 and #46029. It is evident that the changes in wave heights do not follow any particular pattern; sometimes the buoys located several miles apart seem to have similar wave heights recorded and sometimes the wave heights differ significantly.

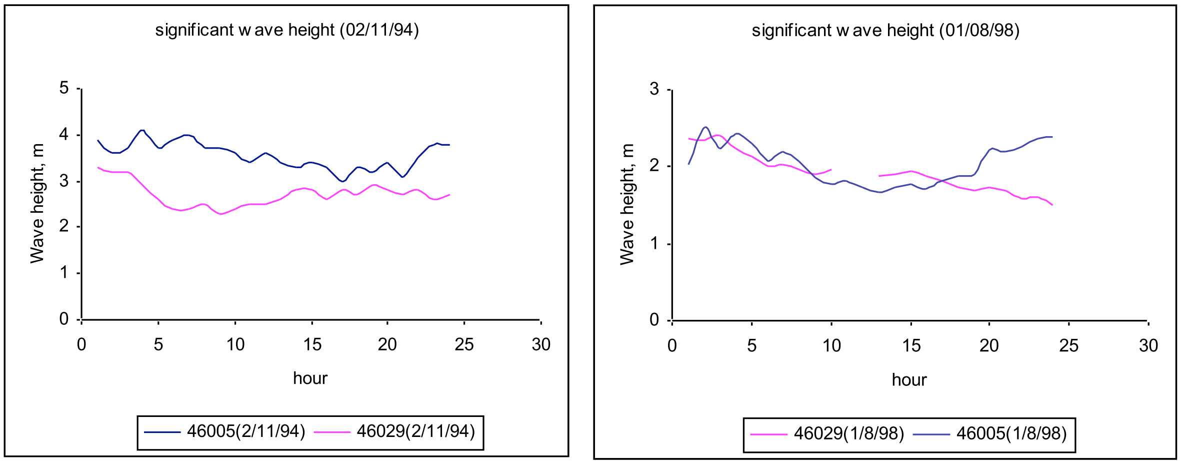


Fig. 3 Significant wave height on a day

The buoys compared in Fig. 3 are more than 270 miles apart and since the waves can travel several miles without losing much of the energy contained, it is possible to predict wave conditions near-shore based on the wave conditions that have taken place several hours earlier off-shore. For instance, it was estimated that waves generated at Buoy# 46050 located 20Nm away will take about 2 hours to arrive at the coast. The ability to forecast the actual power generation from renewable devices hours in advance is of significant importance for the coordination of renewables and the load scheduling of the utility grid.

The average significant wave heights and wave periods are shown in the Fig. 4. This is the average (from 1993 to 2002, using data where available) for buoys located along the Oregon coast.

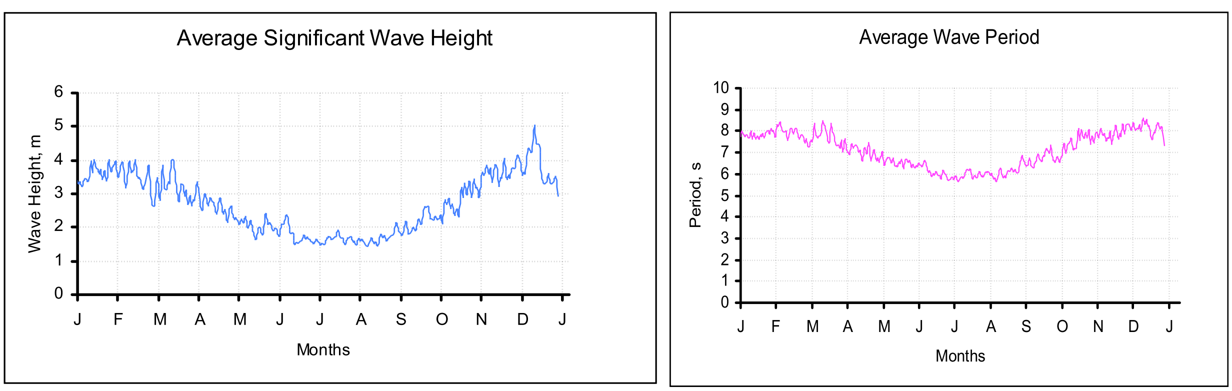


Fig. 4 Seasonal variation in wave height and period

WAVE POWER

The power in ocean waves can vary hourly, daily, seasonally, etc. Fig. 5 shows the variations in power for NDBC buoy #46050 on a given day. The figure shows how variable the wave power can be on a single day, peaking from 15kW/m to nearly 400kW/m in 12 hours.

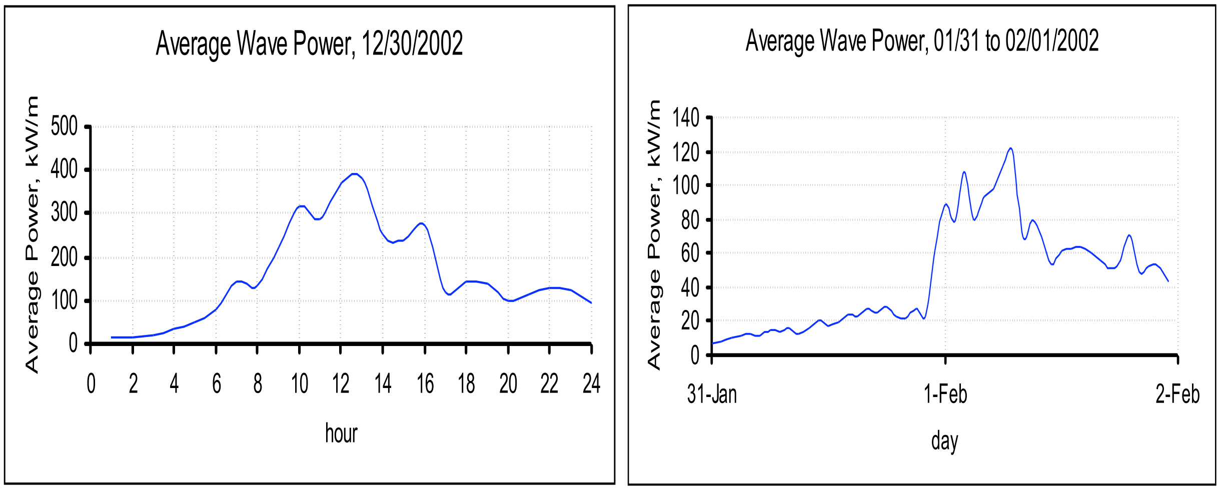


Fig. 5 Typical hourly variation in wave power

The seasonal variations are evident in Fig. 6 which is the long-term average power along the coast averaged from all of the available buoys. The long term seasonal wave power was derived from long term average values of wave power computed from 1993-2002 wave data (when available) near the Oregon coast. In most historical wave data records, there are often missing data or error data that may be due to various reasons such as equipment failure, storms, etc. In this particular case after the data was checked to eliminate errors recorded as "99" (which occurred randomly), the hourly recordings were averaged for a given 24-hour period that contains at least 50% of valid data. Each piece of data was date-tagged serially in such a way that data that was averaged belongs to the same day of the calendar. As shown, there is higher power in winter seasons than the summer seasons, which correlates well with the high winter heating/power demands better than most renewables.

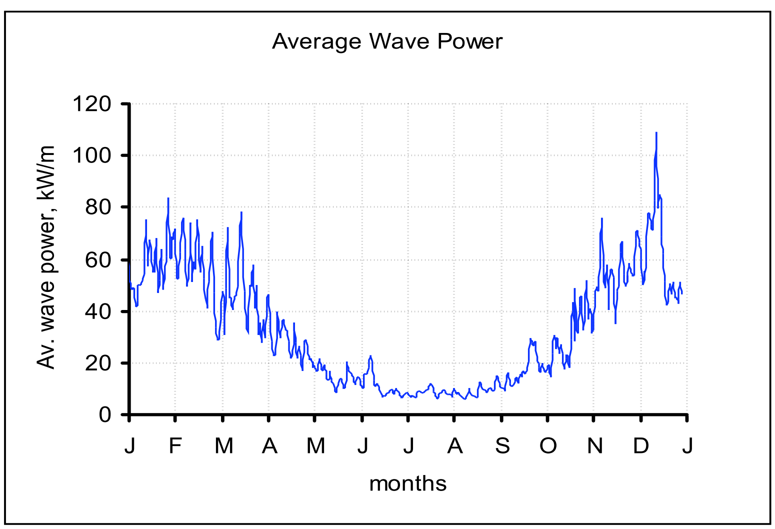


Fig. 6 Seasonal variation in wave power

Off-shore wave energy resource

Fig.7 shows the annual incident wave power of some buoy locations along the Oregon Coast. The locations offshore as expected show higher values of wave power than the locations near shore. Also there are variations of average annual flux from year to year in the same locations.

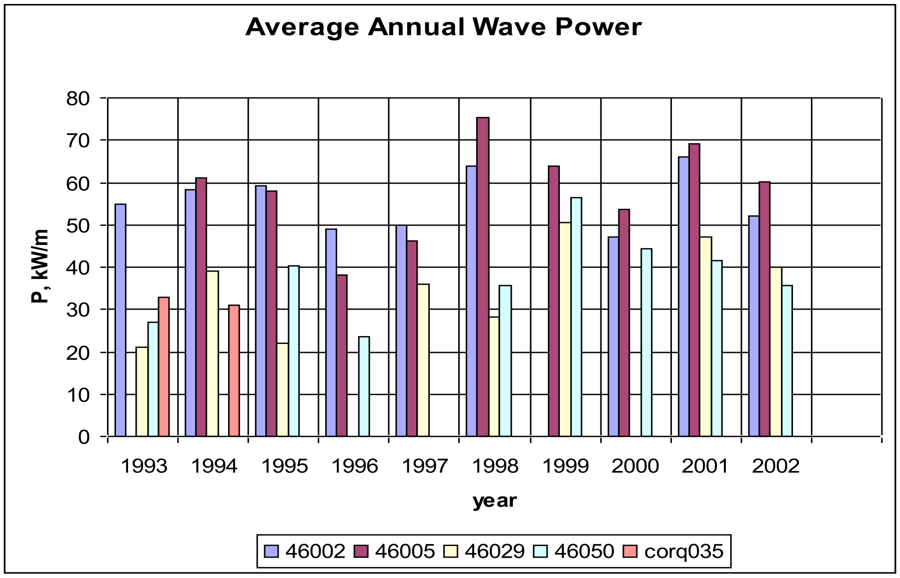


Fig. 7 Annual average wave power

Average annual incident wave power of about 60 kW/m was recorded in the deep sea off-shore locations. These buoy (#46002 and #46005) locations as shown in Table 1 are several miles offshore and the water depths could pose practical challenges for wave devices that use solid bedrock foundations as reaction forces for the floats. However, they may be suitable for floating devices such as the Pelamis. In addition, the sea states in these locations can be used to predict wave conditions near shore. The buoy (#46029 and #46050) incident power levels give indications of what will probably exist up to within 1 to 2 miles off the coast. These locations averaged about 37 kW/m. By comparison with wave energy resources around the world [9,14], this resource is among the richest.

Shoreline and near-shore wave energy resource

Most of the NDBC operated buoys along the Oregon coast are within 18 miles from the shore. For wave energy devices that would be located near the shore, the incident power was estimated using data from a buoy located at about one mile from the shore. This buoy is one of several buoys operated by the Coastal Data Information Program of the Scripps Institution of Oceanography, that has since been decommissioned (see Fig 1b). The two most recent years (1993 and 1994) of operational data were used for computations. The data for the Coquille River buoy #035 is available on the website [6] and recorded at three-hour intervals most of the time. There were some instances where there were two-hour interval readings and sometimes one hour readings. The processing was done based on the assumption of three hour interval readings and missing data was treated in a manner that is consistent with the processing method for the NDBC buoys, described previously. As shown in Fig. 8, it is interesting to see that data sets recorded by two different methods by NDBC and CDIP have similar patterns of change in the significant wave height and average wave period.

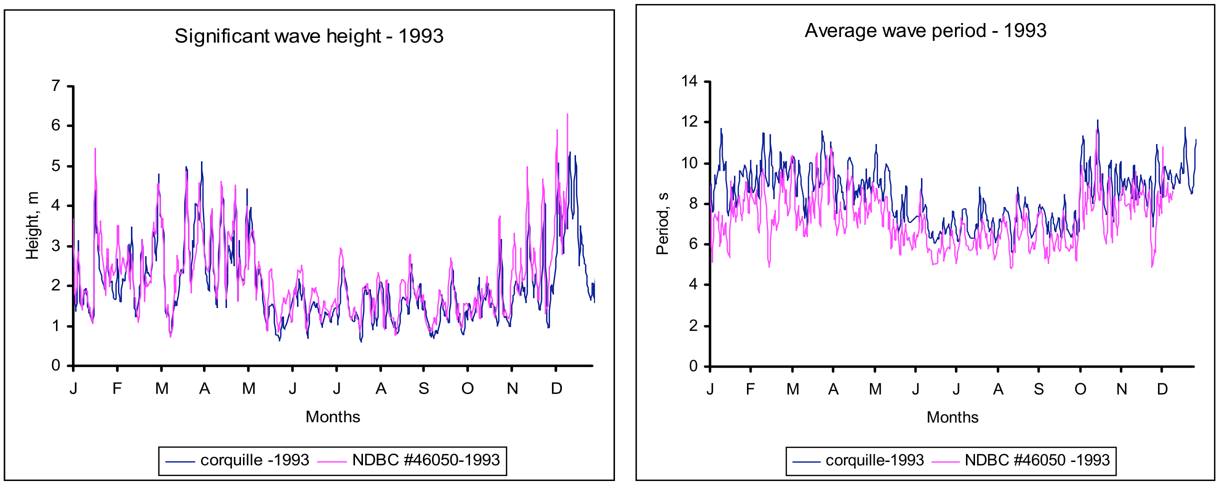
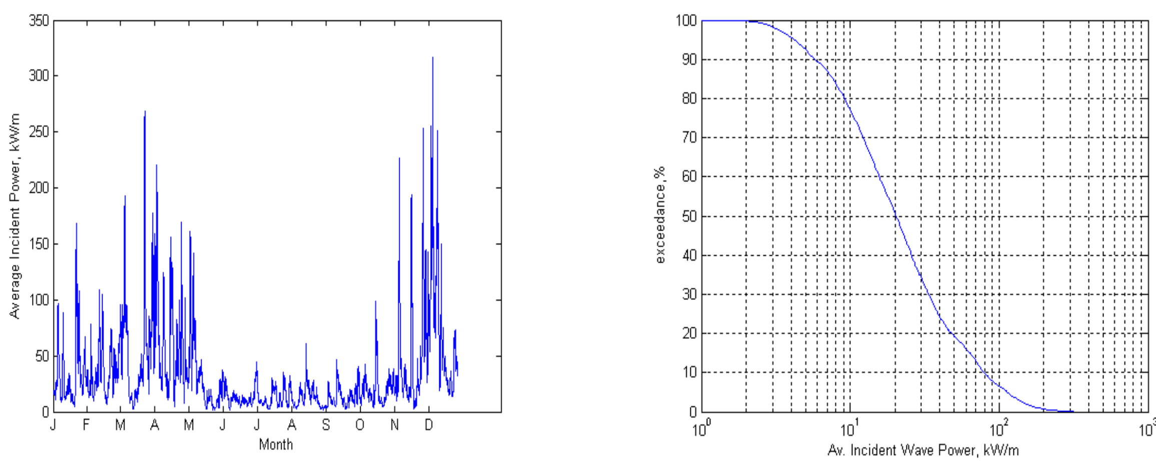


Fig. 8 Comparison of wave heights and period buoy #035

The seasonal variation of wave power in 1993 from this site is shown in Fig 9(a). Fig 9(b) shows the number of times in the year (expressed as percentage) that the wave power has exceeded various levels in the year 1993. The annual mean for this location is about 33kW/m.



(a) seasonal variation of wave power 1993 (b) percentage exceedance of wave power -1993

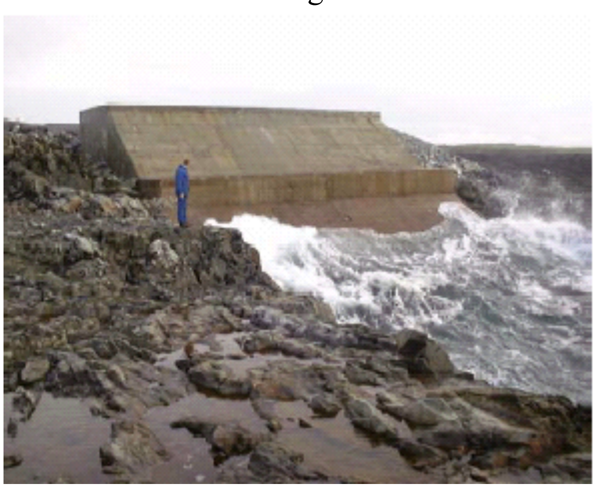
Fig. 9 Average wave power buoy #035

As waves approach the shoreline they generally lose energy due to breaking, frictional losses to the seabed, etc. Waves start to break as their steepness (ratio of significant wave height to wavelength) reaches 0.142 for deep water waves or the wave height to water depth reaches 0.88 for shallow water waves [13]. Generally, wave breaking reduces the energy in a wave. The wave energy resource at the shoreline is site-specific and much more complex to estimate.

Projecting from the mean power of the Coquille River buoy #035 it is possible to find areas at the shoreline with annual mean in the range 20-30kW/m.

ANALYSIS OF DEVICES

The various wave energy extraction technologies at different levels of development have been studied and presented in a previous document (previous OSU development sea-grant report). For the purpose of this study the OWC and heaving buoys are used to evaluate the actual output that can be derived from the available wave resource, based on their advanced state of development and probably employment. The OWC is a shoreline device that has been studied extensively and there are several demonstration plants and a commercial plant in existence. Heaving buoys are made up of a float and a hydraulic system or a direct drive linear generator and have the capacity of harnessing the higher power available from most near shore sites. Typical devices for extracting the shoreline and near shore resources are shown in Fig. 10.



(a) Limpet OWC (b) AquaBouy

Fig.10 Wave energy devices

ASSESSMENT OF ACTUAL POWER DERIVED FROM RESOURCE

The actual output of the wave energy plant is dependent on the conversion efficiency (wave-to-wire efficiency) of the energy conversion process and device limitations. Also, the incident wave power that was calculated by the methods described earlier comes from various directions while most of the wave energy extraction devices would capture only those waves that are incident at their front. The effective annual incident power is thus less than the calculated, and the available wave power is reduced by a directionality factor. This factor was not determined for the Oregon waters but assumed to be 0.9 [4].

The overall conversion efficiency varies depending on the kind of components in the energy conversion chain. The OWC energy conversion chain is shown in Table 4.

Table 4 : OWC Energy Conversion Chain

Energy conversion	Device Component	Indian OWC. Efficiency (%)	Limpet 500 Efficiency (%)
Wave to Pneumatic	Chamber	50	64
Pneumatic to mechanical	Wells turbine	25	40
Mechanical to Electrical	Induction Generator	50 **	#

Not available but typical efficiencies for generator are high 90-96%.
**Generator oversized. Rating changed from 110kW to 55kW

The wave to pneumatic efficiency depends on chamber geometry and wave direction. The induction generator efficiencies are usually high; about 90-96% for the range of application but as shown for the Vizhinjam plant (India), generator over sizing can lead to lower operational efficiency. The Wells turbine efficiency, in the range of 40 to 60%, depends on the air flow coefficient and using pitch control and inverter control can increase the turbine efficiency to about 80%.

A buoy point absorber is a float with horizontal dimension smaller than the wavelength and can oscillate in a combination of different modes. Theoretically, it has been determined that a buoy point absorber using one mode of oscillation (for example heaving) can capture the wave incident in a wave front of $\frac{\lambda}{2\pi}$ [1]. The power take off system for buoys depends on the design and is made up of the generator and the hydraulic systems comprising hydraulic cylinders, valves, hydraulic motors, pumps, pistons, accumulators, etc. The internal energy conversion systems of the existing buoy prototypes are different from each other and difficult to characterize due to lack of information on them. Direct drive systems provide prospects for higher overall efficiency and are currently being investigated.

There is little information on overall efficiency of prototype heaving buoys. However, a 30-35% efficiency was reported for the buoys shown in Fig. 11 [5]. The shown buoy technology has since been patented and is now modified into the AquaBuoy and being promoted by Aqua Energy Group of Mercer Island, WA. Also, an overall efficiency of about 20% was obtained in experimental and model tests on buoy point-absorbers developed in Denmark [7]. An overall efficiency of 30% has been used to calculate the actual output.

From the analysis of incident wave power from the NDBC and CDIP data buoys, the actual output of the devices was computed based on an annual average incident wave power of 35kW/m for the buoy and 25kW/m for the OWC. A ratio of 5:1 was used for the OWC ocean real estate requirements to water surface area, similar to existing dimension ratio of actual plants in operation. For the buoy, a 40% increase over the cross sectional area of float was allowed for mooring.

Actual Output: Buoy Point absorber

From distribution of Fig.12, Hs = 2m, T=9s. $\frac{\lambda}{2\pi}$ 20m

λ 126m

Annual Average Power	35kW/m
Device Diameter	3-10m*
Average Power Incident (35x20)	700kW
Directional Factor	0.9
Mean Power Intercepted	630kW
Conversion Efficiency	30%
Average Output	**189kW**
Cross sectional area of float	7-78m^2
Area of Sea required (40% more than float)	10-110m^2

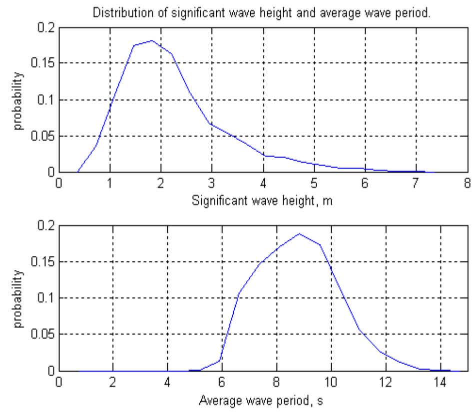


Fig.11 Distribution of Hs and T, 1993-1994
Corquille River #035

Annual Output(100% factor) 1.7GWh

*The individual size of the buoys are designed according to the energy content of the prevailing seas at a particular installation site. Utilization factors are chosen in the plant design (such as 30-40%) indicating the plant capacity relative to the available energy.

Actual Output: OWC

Incident Power in Sea	35 kW/m	30kW/m	25kW/m	20kW/m
Device Width	10m*	10m	10m	10m
Directional Factor	0.9	0.9	0.9	0.9
Mean Power Intercepted	315 kW	270kW	225kW	180kW
Pneumatic Capture Efficiency	64%	64%	64%	64%
Power Captured	202kW	173kW	144kW	115kW
Conversion Efficiency	60%	60%	60%	60%
Electrical Efficiency	95%	95%	95%	95%
Average Power Output	**115kW**	**98kW**	**82kW**	**66kW**
Area of Coastline covered	100 m^2	100 m^2	100 m^2	100 m^2

(Device depth is 0.1 to 0.2 of wavelength, thus ≈10m)

Annual Output (100% Factor)	1.0 GWh	0.9GWh	0.72GWh	0.6GWh

*The individual size of the OWC's are designed according to the energy content of the prevailing seas at a particular installation site. Utilization factors are chosen in the plant design (such as 40-50%) indicating the plant capacity relative to the available energy.

CONCLUSIONS

An assessment of the ocean wave energy potentials of the Oregon Coast has been carried out. The results confirm that the potential wave power off the Oregon coast is among the best in the North America. Annual wave power of about 37kW/m can be obtained along the coast of Oregon. The actual output that can be obtained from wave devices such as buoys and OWCs has been estimated and actual real estate requirements determined. Using a buoy point absorber technology, it is possible to produce about 189kW of power from a device requiring a diameter of 10m, and a total area of about 110m^2 of ocean real estate . This translates into about 0.17GWh of electricity assuming a 10% load factor. With an OWC it is possible to produce at least 80kW from 500m^2 of coastal real estate.

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