Appendix D-2.b

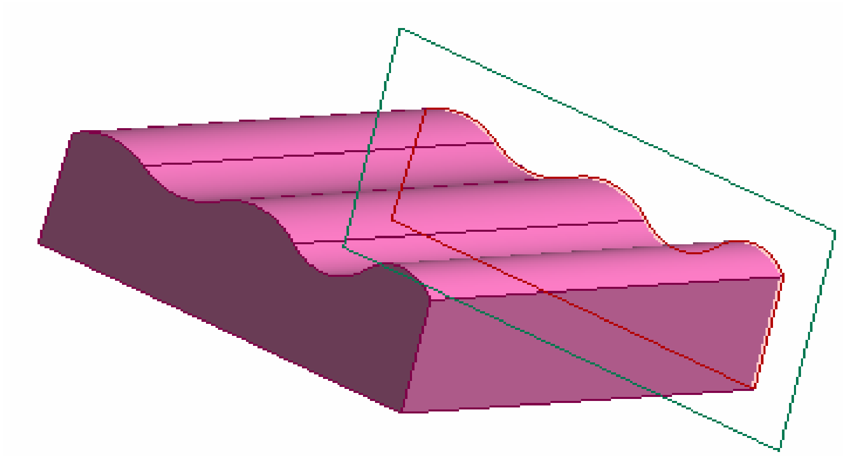
Energy Plan 2004-2013 Follow-up Studies and Reports

Wave Power Feasibility Study

GIANNOTTI ASSOCIATES

Wave Power Generation and Mitigation of Beach Erosion for Long Island

Final Report
Prepared for Long Island Power Authority



CONTENTS

PROJECT OVERVIEW

The purpose of this project was to investigate

- the economic and intangible feasibility of wave power conversion off LI, including benefit-to-cost, beach erosion mitigation, and other environmental considerations;
- wave energy focusing to facilitate power conversion;
- what kind of device could be used;
- whether development of a new device is warranted and, if so, what the new device would entail;
- and also seek Corps of Engineers input, identify co-funding sources, and
- formulate a Phase II proof-of-concept proposal.

To do so it was necessary to

- look at the variety of existing devices in context of their respective installation environments (power in waves, sea depth, shoreline features, etc.),
- assess the characteristics of the installation environment off LI,
- extrapolate the performance of existing devices to the LI application,
- generate ideas for a device which would be better suited for LI than any of the existing devices, and
- make a comparative assessment of the various options with regard to economics and intangible considerations.

The conclusions/milestones reached (superscripts refer to relevant report sections):

- There are a few devices which have made it to commercial deployment, more which have made it to the stage of prototype demonstration, far more in the conceptual stages.[A2] The ones which have made it furthest with regard to these developmental stages are the primitive onshore devices.[C5]
- LI available wave power is about 17 MW/mile.[A1] Some localities in other parts of the world can have availability four times this amount,[A1] but these environments are much more difficult for installation and operation of wave power devices. LI has the advantage of a long shoreline, with numerous possible connection points along the way.
- Beach erosion on LI is a major problem and absorption of wave energy would substantially mitigate this.
- The primitive onshore devices are not suitable for LI for a variety of reasons. Offshore devices, especially those which are best for erosion mitigation, would be of the most interest. Also, high efficiency is necessary for economic feasibility in the context of a low wave power climate. Visual obtrusiveness would be a significant concern even for offshore devices, but it is possible to design a system which would be essentially invisible.
- Corps of Engineers interest was obtained along with interest from several possible sources of co-funding.
- A novel wave-focusing device concept was devised during this project. [B3]
- WOPAC (Proprietary) wave power device was conceived of, which would be cost-effective and have intrinsic functional characteristics optimal for erosion mitigation.
- After this project, OPIOS wave power device was conceptualized with funding from Giannotti Associates.
- The above mentioned devices are being processed for patenting.
- Ideally, the cost effectiveness of an optimized system for LI such as WOPAC or OPIOS could compete favorably with fossil fuel[A3a] (and very favorably with wind power[A3b]) and if beach erosion savings are figured in, electrical costs could be reduced by about 1½ cents/kWh.[App. C]

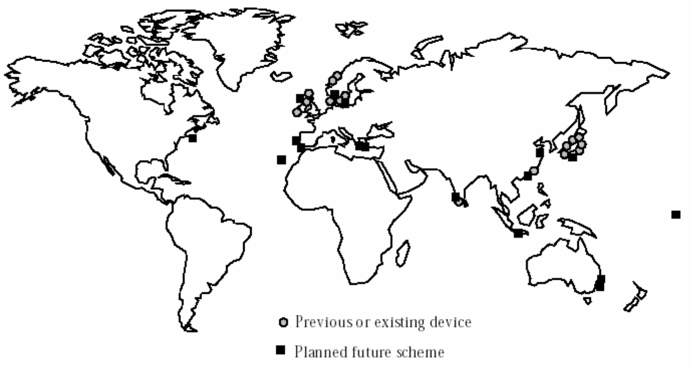
A. INTRODUCTION

A.1. How much power is there in sea waves?

The total power of waves breaking on the world's coastlines is estimated at 2 to 3 million megawatts.[1] In favorable locations, wave energy density can average 65 megawatts per mile of coastline.[2] Long Island wave energy density is estimated at between 17 and 20 MW/mile (11 kW/m).[3]

A.2. Where and how is wave energy being converted?[4]

Devices at the demonstration stage include the Oscillating Water Columns, Pendulor, Tapchan. Demonstration schemes being built include McCabe and OPT. the New modular floating devices require further research and/or demonstration.



A.3. Why study wave power for LI?

A.3.a. Because it can be cost-competitive with fossil fuel

Cost of power from coal-fired plants[5]

Process	Specific investment ($/kWc)	Cost of electricity (cents/kWh)
Supercritical PF (no CO2 capture)	1020	3.7
Supercritical PF (with CO2 capture)	1860	6.4

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1. http://www.unit-e.co.uk/wavepower.asp
2. http://www.eere.energy.gov/RE/ocean_wave.html
3. http://pirates.wes.army.mil/public_html/pmab2web/htdocs/newyork/westhampton/ny001/ny001_perocc.html

Data source classifies seven years (1994-2000) of hourly omnidirectional wave data points for 0.75 miles off Westhampton Beach into height and period range combinations. Each range combination was assigned a single power value equal to the average of the highest and lowest possible power from it. Each power value was weighted according to the percentage of points falling into its respective range combination to determine the overall average of 17.3 MW/mile. This was assumed along the length of LI. Also, energy loss to the seabed may make the power at this distance from shore lower than that available further out.

4. Thorpe, T. W., 1999. A Brief Review of Wave Energy. Available from http://www.dti.gov.uk/energy/renewables/publications/pubs_wave.shtml
5. Freund, P., 2003. Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy Volume 217 No 1 page 4 Table 2: Cost of coal-fired power plant with CO2 capture from: Making deep reductions in CO2 emissions from coal-fired power plant using capture and storage of CO2. This material has been reproduced with permission of the Institution of Mechanical Engineers.

A.3.b. Because it can be a good alternative energy source for LI

Use of the ample LI offshore space allows for avoidance of real estate consumption and access to highly concentrated offshore energy. Wave power devices can compare well to offshore wind turbines (the other offshore alternative) in cost-of-electricity (3-5 cents/kWh[6] vs. 6-9 cents/kWh[7]) and non-tangible benefits. Wave devices can mitigate beach erosion; wind turbines do not.

Energy Type	Energy Density	Predictability	Availability	Potential Sites
Wave Energy	Low to Moderate	Predictable in most sites	80-90%	Extensive but can become Limited
Combustible Fuels	Very High	Predictable	80-90%	Extensive
Wind	Low	Unpredictable except in limited number of sites	30-45%	Limited
Solar	Low	Unpredictable except in limited number of sites	20-30%	Limited

Table A.3.b.i.

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[6] Based on cost estimate for WOPAC (Proprietary App. C) and corresponding sensitivity analysis (App. D); also based on OPT claim for primary power cost (Table A.3.b.iii.).

[7] AWS Scientific, Inc., April 2002. Long Island’s Offshore Wind Energy Development Potential: A Preliminary Assessment. On page 27: “Current estimates of the cost to install a 100 MW offshore project range from $150 to $180 million, and energy costs range from six to nine cents per kilowatt-hour.”

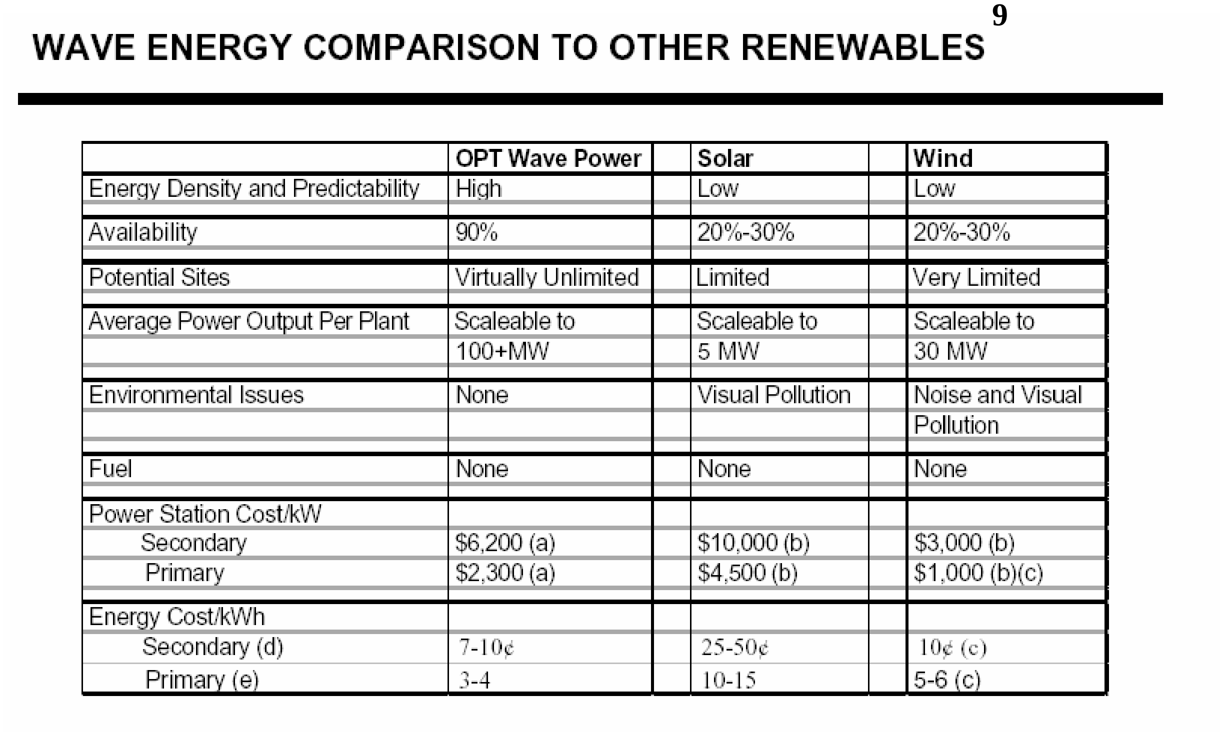
ENVIRONMENTAL IMPACT,
COMPARISON OF ENERGY SOURCES[8]

KEY:
NEG = negative effect
POS = positive effect

IMPACT MODE	**ENERGY SOURCE**						
	Fuel	**Wind**	**Solar**	**Wave, onshore**	**Wave, offshore terminator**	**Wave, offshore point absorber**	**WOPAC**
Air pollution	NEG						
Noise pollution	NEG	NEG					
Visual obtrusiveness	NEG	NEG	NEG	NEG			
Real estate consumption	NEG	NEG	NEG	NEG			
Beach dynamics					POS	POS	POS
Marine life					POS	POS	POS
Navigation					NEG	NEG	SLIGHT NEG

The general trend of improvement in environmental impact corresponding roughly to chronology of commercial deployment.

Table A.3.b.ii.



WAVE ENERGY COMPARISON TO OTHER RENEWABLES [9]

	OPT Wave Power	Solar	Wind
Energy Density and Predictability	High	Low	Low
Availability	90%	20%-30%	20%-30%
Potential Sites	Virtually Unlimited	Limited	Very Limited
Average Power Output Per Plant	Scaleable to 100+MW	Scaleable to 5 MW	Scaleable to 30 MW
Environmental Issues	None	Visual Pollution	Noise and Visual Pollution
Fuel	None	None	None
Power Station Cost/kW			
Secondary	$6,200 (a)	$10,000 (b)	$3,000 (b)
Primary	$2,300 (a)	$4,500 (b)	$1,000 (b)(c)
Energy Cost/kWh			
Secondary (d)	7-10¢	25-50¢	10¢ (c)
Primary (e)	3-4	10-15	5-6 (c)

Table A.3.b.iii.

8. Giannotti Associates compilation.
9. From Taylor, G.W. Using wave power for energy: issues in design and deployment. http://oceanpowertechnologies.com/pdf/montreaux_energy.pdf

A.3.c. Because waves can theoretically provide a significant part of total LI power

L.I. available wave power is conservatively estimated at 1,700 MW.[10] LI present electric capacity is about 5,000 MW (4,803 MW[11]).

A.3.d. Because it mitigates beach erosion

Wave energy capture means erosion reduction. Proportional sand replenishment savings can figure out to a dramatic reduction in cost-of-electricity for an efficient device.

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[10] Based on the result of the wave power density calculation explained in Footnote 3 (17 MW/mile), applied to an approximately 100 mile long L.I. south shore.

[11] http://www.lipower.org/pdfs/Draft-V1-101702.pdf

B. WAVE THEORY AND MEASUREMENT

B.1. Wave dynamics and parameters

Waves are comprised of water particles behaving in an orbital motion. Key wave parameters are Height (H), Wavelength (L), Period (T) and sea Depth (d). Formula for P, power per unit length of wave crest, is given in terms of these variables. The relations among height, power, period, wavelength, wave speed (C) and energy speed (C_{g}) at a fixed depth are shown graphically in Fig. B.1.c. Wave shoaling is depicted in Fig. B.1.d. and explained beneath it.

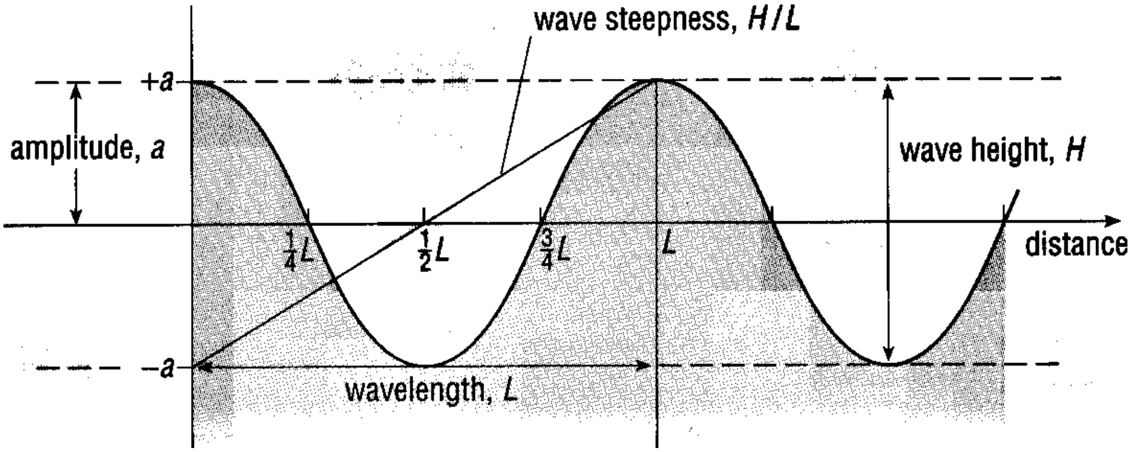


Fig. B.1.a.

$$P := \frac{\rho \cdot g^{2} \cdot T \cdot H^{2}}{32 \cdot \pi} \cdot \left[1 + \frac{4 \cdot \pi \cdot \frac{d}{L}}{\sinh\left(4 \cdot \pi \cdot \frac{d}{L}\right)} \right] \cdot \left(\tanh\left(2 \cdot \pi \cdot \frac{d}{L}\right)\right)$$

Fig. B.1.b.

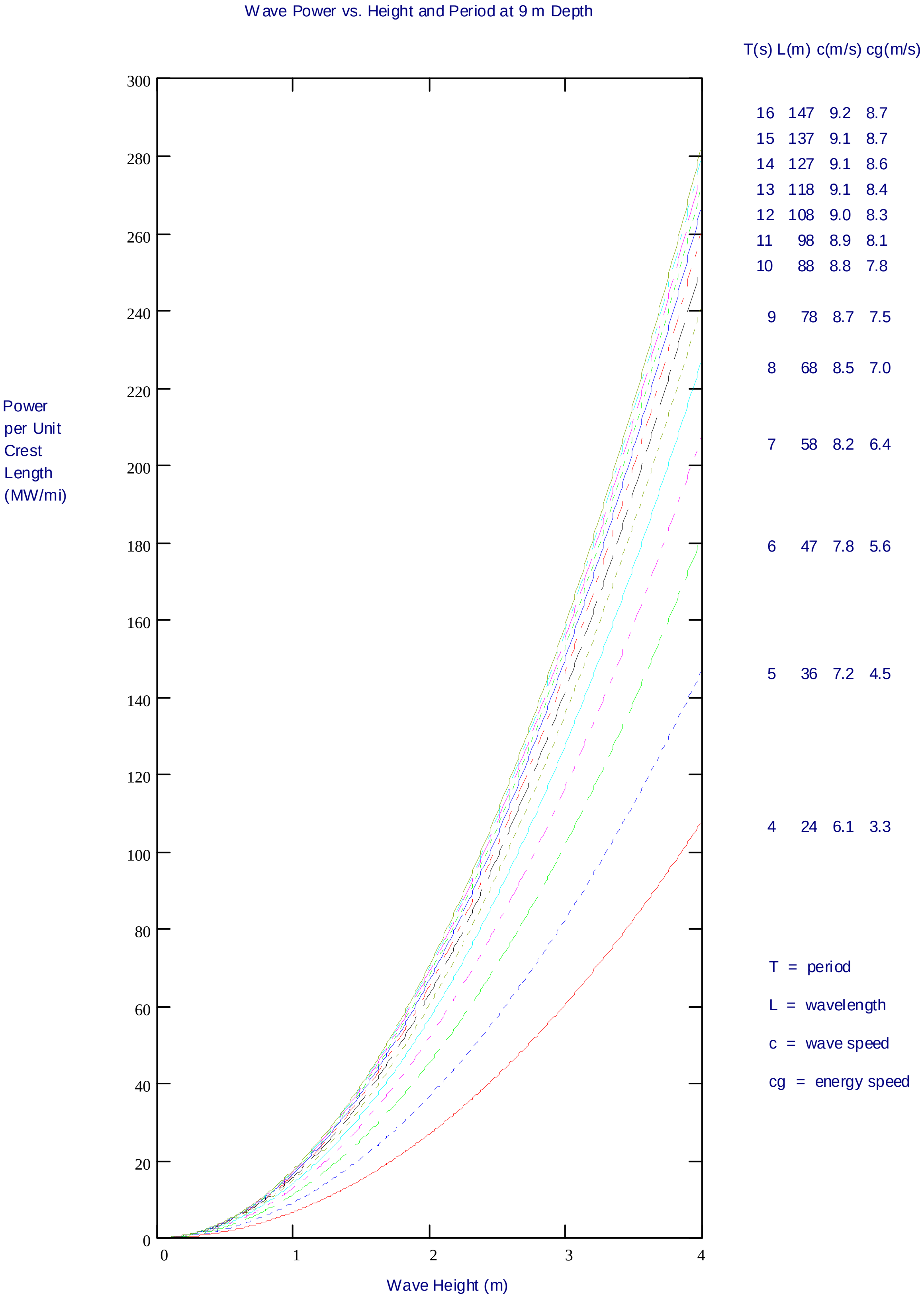

Wave Power vs. Height and Period at 9 m Depth
Power per Unit Crest Length (MW/mi)
Wave Height (m)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
0
1
2
3
4
T(s) L(m) c(m/s) cg(m/s)
16 147 9.2 8.7
15 137 9.1 8.7
14 127 9.1 8.6
13 118 9.1 8.4
12 108 9.0 8.3
11 98 8.9 8.1
10 88 8.8 7.8
9 78 8.7 7.5
8 68 8.5 7.0
7 58 8.2 6.4
6 47 7.8 5.6
5 36 7.2 4.5
4 24 6.1 3.3
T = period
L = wavelength
c = wave speed
cg = energy speed

Fig. B.1.c.

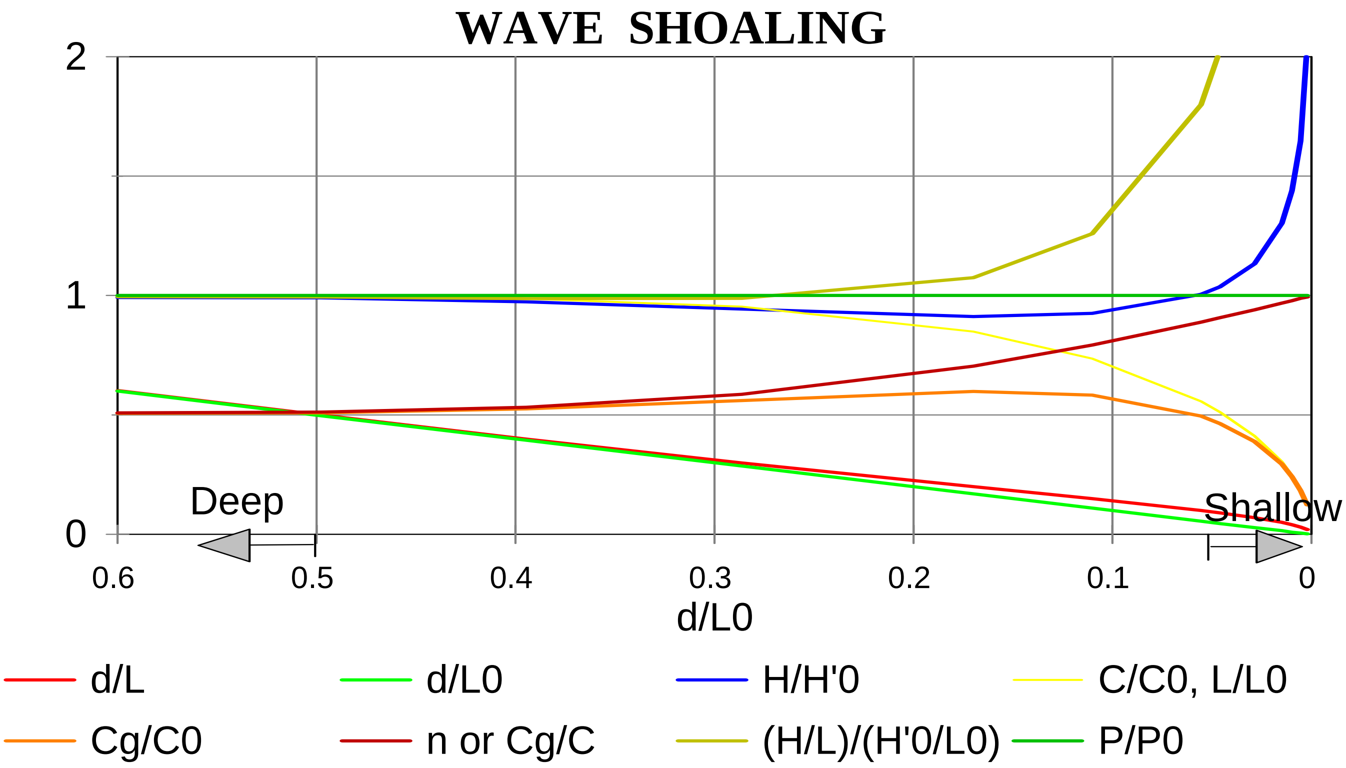


Fig. B.1.d.

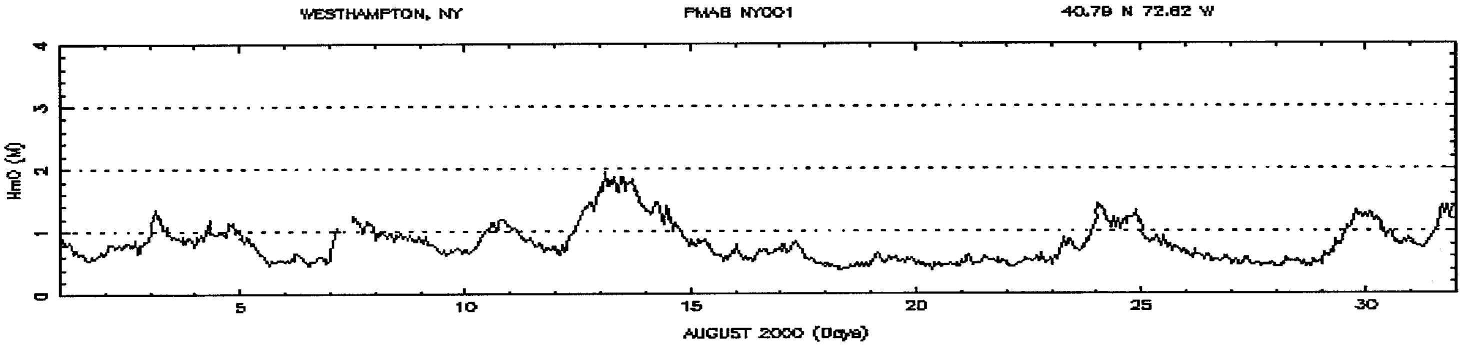
d = sea depth
L = wavelength
d/L = relative depth
L_0 = wavelength in deepwater
C = wave speed (phase speed)
C_0 = wave speed in deep water
C_g = wave group speed (energy speed)

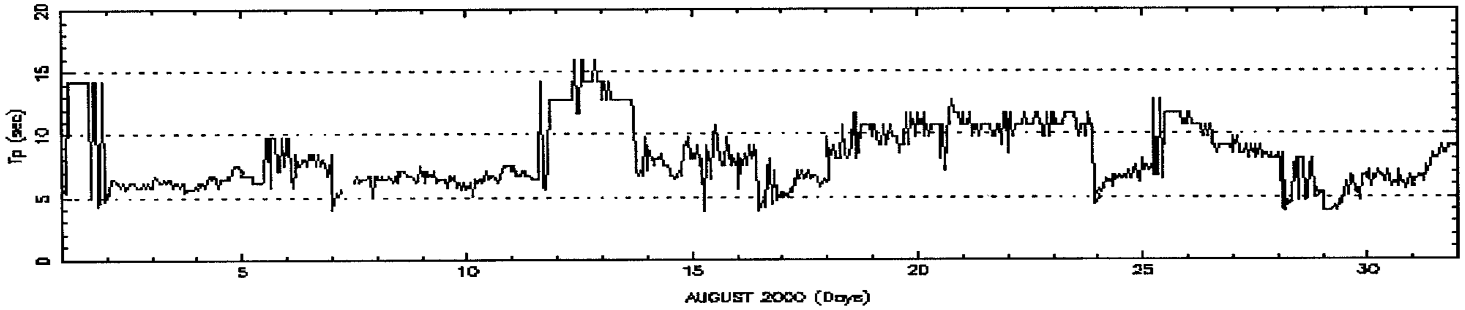
H = wave height
H'_0 = wave height in deep water
n = Cg/C
P = wave power
P_0 = wave power in deep water

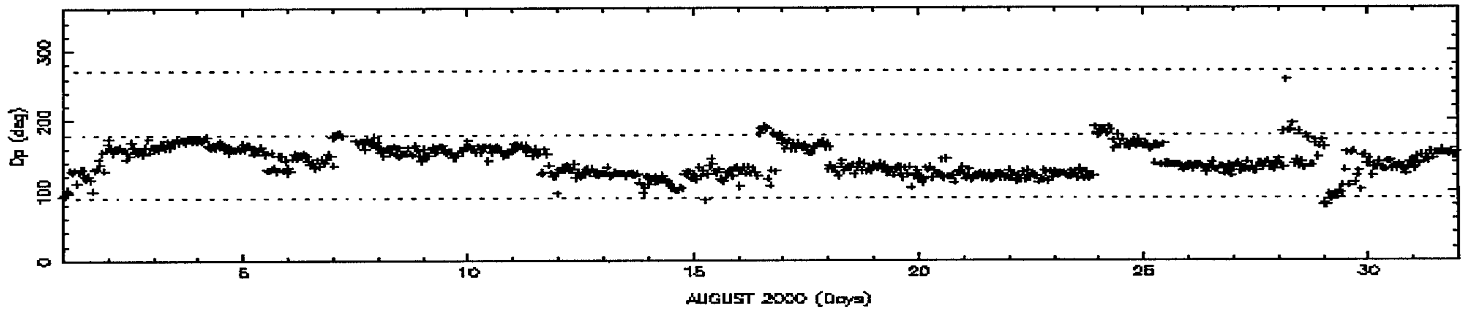
The above diagram shows what happens to a wave's characteristics as it shoals (changes height with changing sea depth) into shore. As the wave 'moves' from the left of the diagram to the right, it is assumed that there is no loss of energy to the seabed (notice that wave power remains constant). Deep water is where relative depth (d/L) is more than (to the left of) 0.5; shallow water is where it is less than (to the right of) 0.05. Notice that the wave parameters remain constant in deep water, where orbital motion does not extend all the way down to the seabed; there is no interaction with the seabed and hence the seabed has no effect on the wave. When the wave is in intermediate and shallow water, orbital motion exists all the way down to the seabed and its geometry changes with changing d/L. This is the reason for the continually changing wave characteristics.

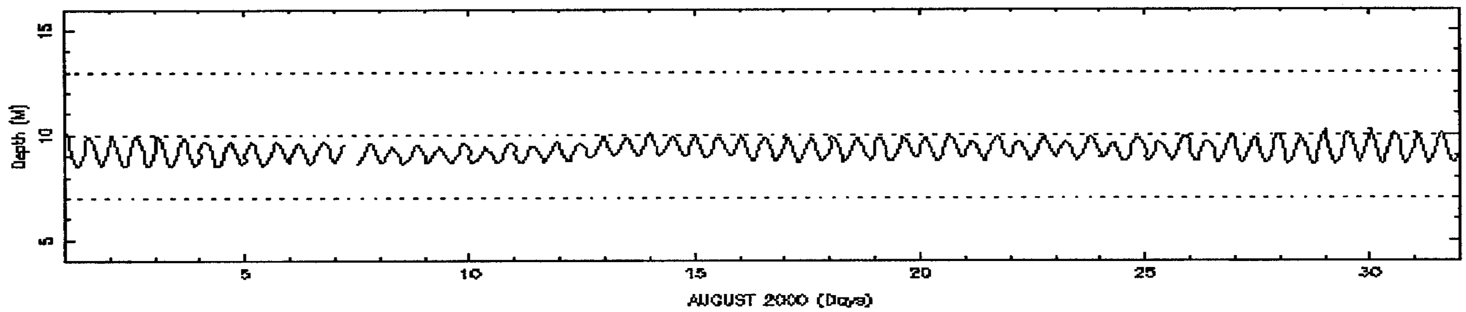
B.2. L.I. Waves

0.75 miles off Westhampton, August 2000.[11] Power at this station averages about 17 MW/mile (see Footnote 3). Shown from top to bottom are height Hm0 (m), period Tp (sec), direction Dp (deg), and Depth (m).









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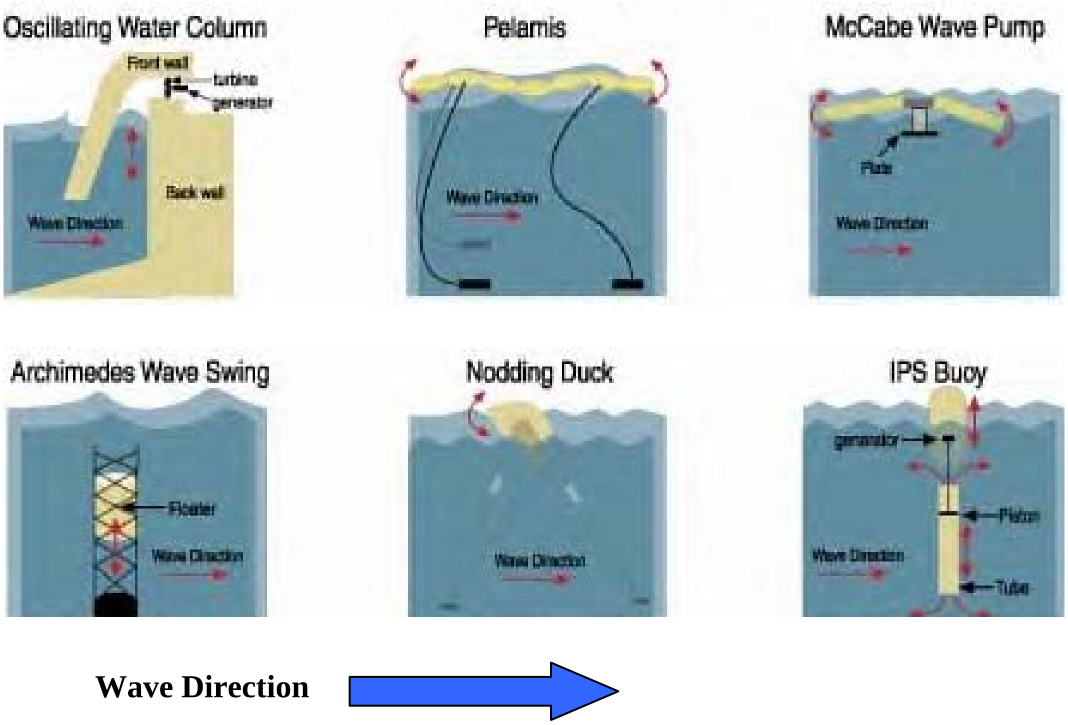
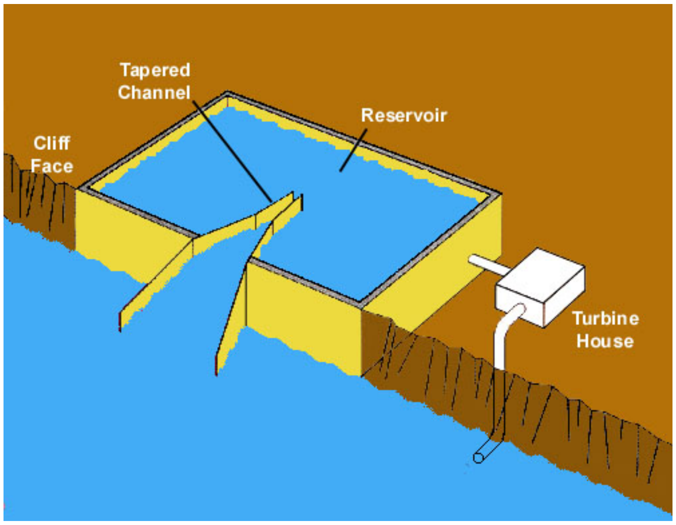
[11] http://pirates.wes.army.mil/public_html/pmab2web/htdocs/newyork/westhampton/ny001/ny001.html

C. DEVICE TYPES AND COMPARISONS

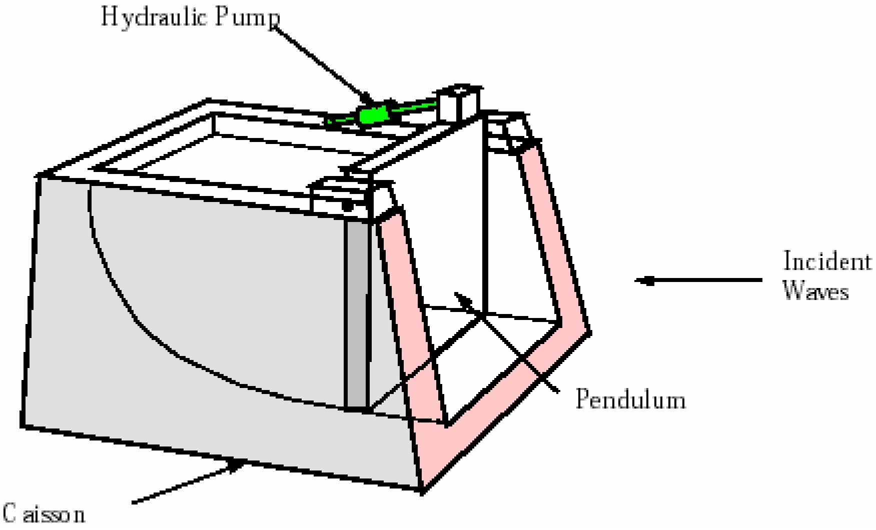
C.1. Some wave power devices



TAPCHAN

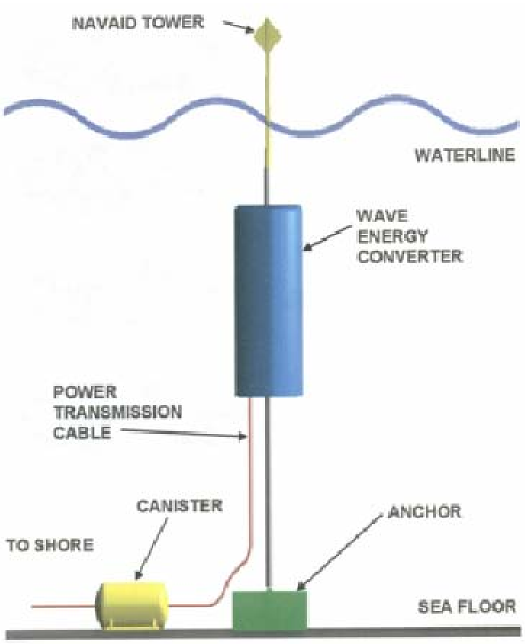


PENDULOR

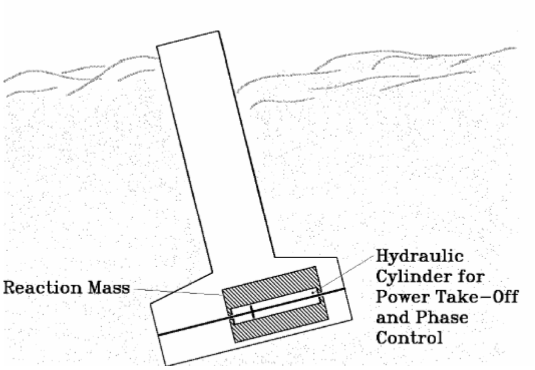


Aquabuoy

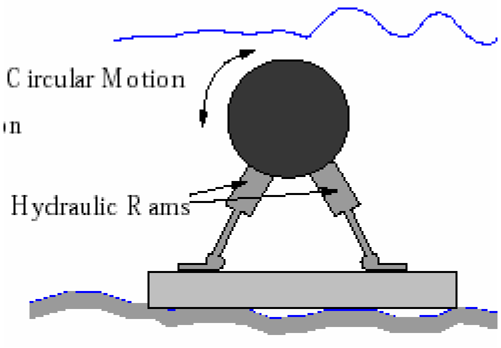
OPT Powerbuoy



PS Frog device concept



Bristol Cylinder



C.2. Sensor types and their motions

The sensor is the object or substance which is in contact with the water and moves in response the water's motion as the first step in the sequence of energy transformations leading ultimately to the production of electrical energy. The following sensor types and their motions are shown in this report:

- Above-surface air; flows in response to water elevation
- Surface float; follows moving surface contour
- Submerged compressible gas compartment; vertical only
- Floating cam; pivots in response to moving surface contour
- Submerged buoy; vertical only
- Hydroturbine; rotational in response to water flow
- Pitching plate; pitches in response to surface level
- Submerged horizontal cylinder; orbits with water particles
- Inverted keel; pitches and surges (tilts and moves forward and backward)

C.3. Frames of reference

The frame of reference is the object which is stationary or moves relative to the sensor providing a means for the controlled relative motion necessary to convert energy from the wave motion into a usable form. The frame of reference is what ultimately provides inertia relative to the motion of the sensor. The following frames of reference are shown in this report:

<u>Stationary</u>

- earth (seabed or seashore)
- massive floating structure

<u>Non-stationary</u>

- adjacent sensor
    - horizontally adjacent
    - vertically adjacent
- gyroscope
- reaction plate
- internal reaction mass
- combinations:
    - adjacent sensor/reaction plate
    - adjacent sensor/gyroscope

C.4. Power chains

The power chain is the sequence of energy transfer steps necessary to convert from wave energy to electric energy. The following power chains are shown in this report:

- air turbine ⎝ rotary generator
- hydraulics ⎝ rotary generator
- linear generator
- hose pump ⎝ water turbine ⎝ rotary generator

C.5. Intangible comparison of wave power devices

NOTE: Yellow-shaded cells indicate most desirable features

Trade name>>>	**Edinburg Duck**	**PS Frog**	**WOPAC**	**Pelamis**	**McCabe Wave Pump**	**Bristol Cylinder**	**Wavegen Limpet**	**Mighty Whale**	**IPS buoy**	**Archimedes Waveswing**	**OPT Powerbuoy**
Device type	Floating cam	Pitch/surge device with internal mass	Submerged horiz. cyl. (non-stationary reference)	Serpent	Hinged raft	Submerged horiz. cyl. (stationary reference)	OWC	OWC	Reaction plate buoy	Buoyancy modulator	Submerged buoy
Stage of develop-ment	proto- type	detailed designs and lab models	preliminary design	demo	demo	detailed designs and lab models	commercialized at 1/2 MW	prototype		demo at 2 MW	demo on small scale
Modularity	pseudo-modular	modular	modular	modular	modular	modular	monolithic	monolithic	modular	modular	modular
Siting	offshore	offshore	offshore	offshore	offshore	offshore	onshore	offshore	offshore	offshore	offshore
Sensor type	floating cam	inverted keel	submerged horizontal cylinder	surface float	surface float	submerged horizontal cylinder	above surface air	above surface air	surface buoy	submerged gas compartment	near-surface buoy
Sensor motion	cam pivots with moving surface contour	pitch and surge (tilt and move forward and backward)	orbits with water particles	follows moving surface contour	follows moving surface contour	orbits with water particles	follows wave elevation	follows wave elevation	vertical only	vertical only	vertical only
Extraction mode(s)	both	both	both	both	both	both	both	both	vertical	vertical	vertical
Width	term	term/point	term/point	point	point	term/point	term	term	point	point	point

Trade name>>>	**Edinburg Duck**	**PS Frog**	**WOPAC**	**Pelamis**	**McCabe Wave Pump**	**Bristol Cylinder**	**Wavegen Limpet**	**Mighty Whale**	**IPS buoy**	**Archimedes Waveswing**	**OPT Powerbuoy**
Device type	Floating cam	Pitch/surge device with internal mass	Submerged horiz. cyl. (non-stationary reference)	Serpent	Hinged raft	Submerged horiz. cyl. (stationary reference)	OWC	OWC	Reaction plate buoy	Buoyancy modulator	Submerged buoy
Frame of reference	adjacent sensors/ gyro-scope	internal reaction mass	vertically adjacent sensor or reaction plate or equivalent	adjacent sensors	reaction plate/ adjacent sensor	earth	earth	massive floating structure	reaction plate	earth	earth
Civil works	extensive	extensive	moderate	moderate	extensive	extensive	extensive	extensive	moderate	extensive	moderate
Moorings compliance	compliant	compliant	compliant	compliant	compliant	non-compliant	N/A	compliant	compliant	non-compliant	non-compliant
Depth restrictions	no	no	no	no	no	yes	N/A	no	no	yes	yes
Power chain type	hydraul to gen	hydraul to gen	hydraul to gen	hydraul to gen	hydraul to gen	hydraul to gen	air turbine to generator	air turbine to generator	hydraul to gen	linear generator	hydraul to gen
Scales to	wave height	wave height	wave height	wave length	wave length	height/depth	wave height	wave height	wave height	sea depth	sea depth
Navigation	not best	not best	best	not best	best	best	not best	not best	not best	not best	not best
Stays near surface?	yes	yes	yes	yes	yes	no	yes	yes	yes	no	no
Submerged?	no	no	yes	no	no	yes	no	no	no	yes	yes

C.6. Tangible comparison of wave power devices

Cost-effectiveness comparison of wave power devices (per meter of device broadside to wave) [12]

	power in waves (kW)	direc-tion factor	inter-cepted power (kW)	over-all effi-ciency	electric power output (kW)	availa-bility	annual elec energy kWh/yr	capex ($)	inte-rest rate	term (yrs)	annual cap repay ($/yr)	O&M rate ($/yr)	total annual cost ($/yr)	cost of elec. (cents/ kWh)
98 Duck	72	0.90	65	0.46	29.72	0.98	255,182	185,436	0.08	35	15,911	5,718	21,629	8.5
PS Frog	52	0.94	49	0.54	26.42	0.93	215,199	83,810	0.08	20	8,536	3,352	11,889	5.5
McCabe	53	1.00	53	1.34	71.05	0.90	560,189	406,000	0.08	20	41,352	12,000	53,352	9.5
Limpet	32	1.00	32	0.49	15.70	0.80	109,524	106,667	0.08	35	9,152	2,210	11,362	10.4
Sloped IPS	53	0.94	50	0.66	32.68	0.90	257,645	187,787	0.08	20	19,126	2,453	21,580	8.4
WOPAC	10.8	0.90	10	0.45	4.39	0.68	26,333	7,434	0.08	20	757	44	801	3.0

Table C.6.a.

Above table normalized to WOPAC

	power in waves (kW)	direc-tion factor	inter-cepted power (kW)	over-all effi-ciency	electric power output (kW)	availa-bility	annual elec energy kWh/yr	capex ($)	inte-rest rate	term (yrs)	annual cap repay ($/yr)	O&M rate ($/yr)	total annual cost ($/yr)	cost of elec. (cents/ kWh)
98 Duck	7	1	7	1	7	1	10	25	1	2	21	130	27	3
PS Frog	5	1	5	1	6	1	8	11	1	1	11	76	15	2
McCabe	5	1	5	3	16	1	21	55	1	1	55	274	67	3
Limpet	3	1	3	1	4	1	4	14	1	2	12	50	14	3
Sloped IPS	5	1	5	1	7	1	10	25	1	1	25	56	27	3
WOPAC	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table C.6.b.

12. Numbers derived from data found in Thorpe, 1999 (see Footnote 4).