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Appendix A

Benefits of Dispersed Siting of Wind Turbines

If the output of wind turbines located at widely dispersed sites is collected, then the variability of the collected power is less than that at each independent site.

This matter has been studied by a number of analysts, in the U.S. particularly by C. G. Justus and A.S. Mikhail of the Georgia Institute of Technology. (Citation throughout this appendix is to their report: Energy Statistics for Large Wind Turbine Arrays, annual progress report to U.S. Dept. of Energy under contract EY-76-S-06-2439, May 1978).

Justus and Mikhail have studied the variability of the output from an array of wind generators distributed at sites across the contiguous U.S., as shown in Figure A-1.

Spatial cross-correlations* of windspeed for the sites of this continental array are shown in Figure A-2. It is seen that annual average correlation is low beyond 1500 km separation, being roughly zero in winter and between -0.1 and +0.1 in summer.

This low correlation suggests that the combined output of an array of wind generators at these sites should exhibit less variation than the output at each site.

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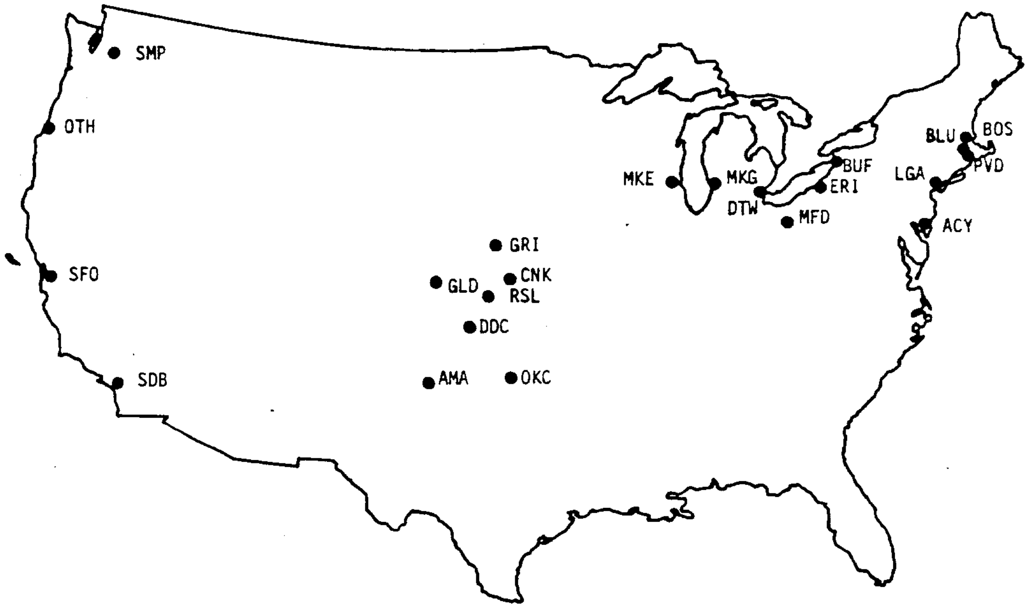
*The cross-correlation between sites i and j is defined as:

$$\chi_{ij} = \frac{\langle v_i - \bar{v}_i \rangle \langle v_j - \bar{v}_j \rangle}{[\langle (v_i - \bar{v}_i)^2 \rangle \langle (v_j - \bar{v}_j)^2 \rangle]^{1/2}}$$

where: v_i is wind-speed at site i
$\bar{v}_i$ is monthly mean wind-speed at site i
angle brackets denote averaging for the month



NORTHEAST	
ACY	Atlantic City, NJ
BOS	Boston, MA
BLU	Bluehill, MA
LGA	New York (Laguardia), NY
PVD	Providence, RI

CENTRAL U. S.	
AMA	Amarillo, TX
CNK	Concordia, KS
DDC	Dodge City, KS
GLD	Goodland, KS
GRI	Grand Island, KS
OKC	Oklahoma City, OK
RSL	Russell, KS

GREAT LAKES	
BUF	Buffalo, NY
DTW	Detroit, MI
ERI	Erie, PA
MFD	Mansfield, OH
MKE	Milwaukee, WI
MKG	Muskegon, MI

PACIFIC COAST	
OTH	North Bend, OR
SDB	Sandberg, CA
SFO	San Francisco, CA
SMP	Stampede Pass, WA

Figure A-1: Continental Array of Wind Turbines used by Justus and Mikhail.

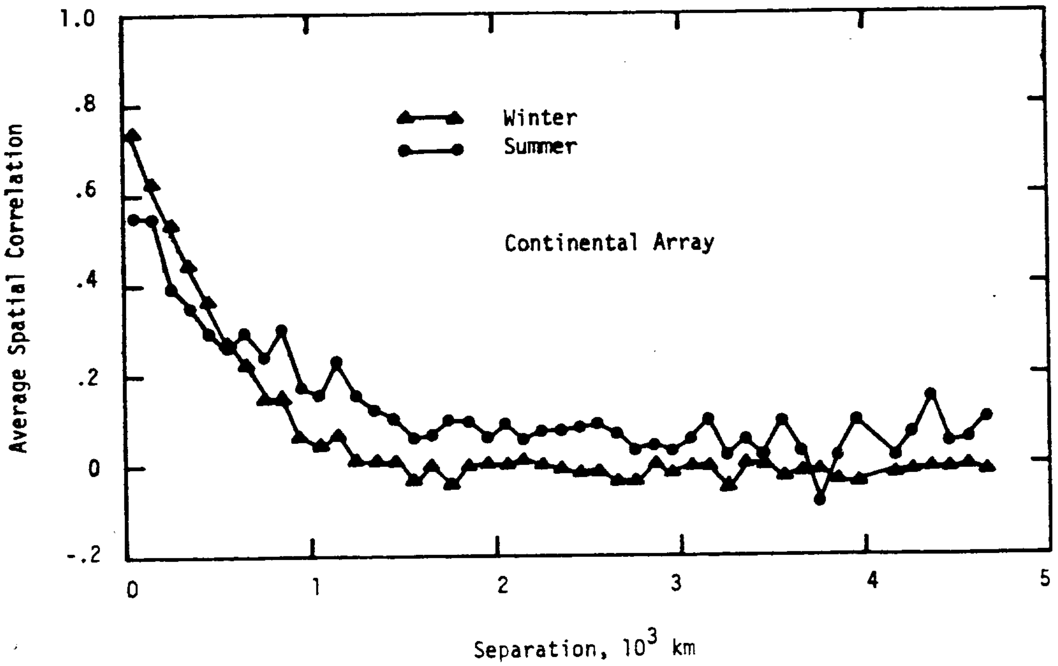


Figure A-2: 1971 Spatial Cross-Correlation for the Continental Array Including Data from All Inter-Site Separations: from Justus and Mikhail.

The respective performances of generators in the combined continental array or at an average independent site are shown in Figure A-3 for the winter season. It can be seen that, during this season, the array output never reaches its full capacity but that there is a relatively high probability of its capacity factor being around 50%.

Table A-1 shows, for all seasons and times of day, the availability (the probability that output power exceeds a given level) of output at 10% and 25% capacity factors for both the continental array and an average independent site. One sees that the array attains almost perfect (99.8%) annual availability at 10% capacity factor, whereas the generator at an average independent site attains only 72.5% annual availability at 10% capacity factor. This table also shows that availability tends to be higher during the middle of the day, which is useful because electrical demand follows a similar trend. However, availability also tends to be lower during the summer season, which is unfortunate in the USA since electrical demand follows a converse trend (see Table 8 in the body of this report).

Average annual availability is shown in Table A-2, for the full range of capacity factors. It is clear that the continental array has excellent availability at low capacity factors (up to 25%) but very poor availability at higher capacity factors.

This analysis deserves extension to include the role of storage. It is likely that addition of storage would lead to an improvement in availability at higher capacity factors (see Figure 14, for a single site, in the body of this report). Also, the array used by Justus and Mikhail (with equal weighting per site) is not an ideal representation of a continental power-producing array.

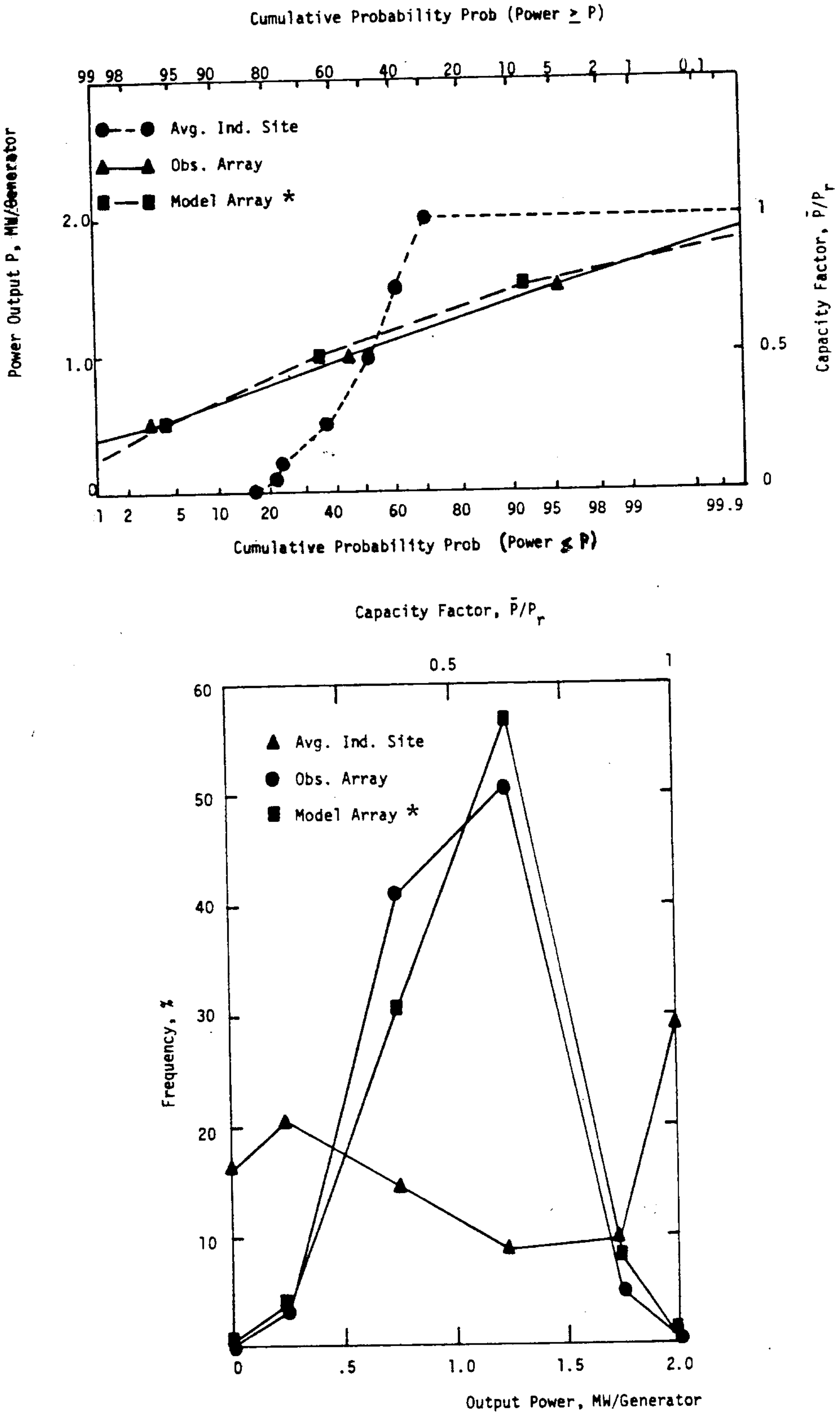


Figure A-3: Performance of 2 MW Wind Generator in Winter for Continental Array and Average Independent Site: From Justus and Mikhail.

(* "Model Array" refers to a mathematical model)

(a) Availability (Percent) of 200 kW per 2 MW Generator
(10% Capacity Factor) in Continental Array
(Individual Site and Whole Array)

	Winter		Spring		Summer		Fall		Annual	
Hour	Ind.	Array	Ind.	Array	Ind.	Array	Ind.	Array	Ind.	Array
1	73.9	100.0	71.1	99.6	58.2	99.6	63.7	99.6	66.7	99.7
4	73.3	100.0	68.9	100.0	53.9	98.9	62.0	99.3	64.5	99.5
7	73.0	100.0	70.9	100.0	55.3	97.1	62.7	99.3	65.4	99.1
10	78.0	100.0	80.0	100.0	68.9	99.6	73.3	100.0	75.0	99.9
13	82.4	100.0	85.8	100.0	79.8	100.0	78.2	100.0	81.6	100.0
16	82.2	99.6	89.1	100.0	84.2	100.0	81.1	100.0	84.2	99.9
19	74.2	100.0	83.4	100.0	76.1	100.0	68.5	100.0	75.6	100.0
22	73.9	100.0	71.6	99.6	58.5	100.0	65.8	100.0	67.4	99.9
All	76.4	100.0	77.6	99.9	66.9	99.4	69.4	99.8	72.5	99.8

(b) As in (a) for 500 kW per 2 MW Generator
(25% Capacity Factor) in Continental Array

	Winter		Spring		Summer		Fall		Annual	
Hour	Ind.	Array	Ind.	Array	Ind.	Array	Ind.	Array	Ind.	Array
1	60.0	95.2	54.4	89.5	40.4	68.8	45.9	82.1	50.1	83.9
4	58.9	94.5	52.6	87.3	37.0	52.9	44.3	72.9	48.1	76.8
7	59.0	94.8	55.4	88.4	37.1	52.9	45.1	74.7	49.0	77.6
10	64.7	97.4	68.4	98.2	53.2	88.0	58.3	91.2	61.1	93.7
13	70.9	98.9	75.0	100.0	66.2	99.3	65.0	98.2	69.3	99.1
16	70.6	98.2	80.4	100.0	71.9	99.3	66.6	97.4	72.4	98.7
19	59.4	97.0	70.2	99.6	60.0	99.3	51.9	90.5	60.4	96.6
22	58.9	97.8	56.2	91.3	42.3	73.2	47.7	82.1	51.2	86.0
All	62.8	96.7	64.1	94.3	51.0	79.2	53.1	86.1	57.7	89.1

Table A-1: Availability* (for 200 kW and 500 kW Output) of 2 MW Wind Generator for Continental Array and Average Independent Site: From Justus and Mikhail.

(* Availability = Probability that output power exceeds stated level)

Table A-2: Average Annual Availability (%) of Wind Generators at Various Capacity Factors for Continental Array and Average Independent Site

Capacity Factor	Independent	Array
0.10(a)	73	100
0.25(a)	58	89
0.50(b)	41	40
0.75(b)	31	3
1.0(b)	23	0

Notes

(a) From Table A-1

(b) Average summer-winter numbers; from figures C-9 and C-11 of Justus and Mikhail.

Wind-power varies from year to year, and it is of interest to know if the combined output of an array is less variable than that for a turbine at an independent site. Table A-3 shows that there is indeed such an effect, for an array in the SW of the USA, in terms of annual wind energy intercepted by wind turbines. The nature of these variations as reflected in wind turbine output deserves further study.

Site	Annual Wind Energy (GJ/m^2)													sd as % of av
	Year										10-yr average (av)	Standard deviation (sd)	
	1	2	3	4	5	6	7	8	9	10			
Corpus Christi (TX)	5.42	4.80	6.95	4.46	5.18	5.42	7.98	5.34	3.65	4.82	5.40	1.17	21.7
Albuquerque (NM)	3.39	3.20	2.04	2.68	3.50	2.96	3.23	2.42	3.49	2.62	2.95	0.47	15.9
Dodge City (KS)	7.36	6.60	6.97	5.46	7.27	7.40	6.68	5.45	6.99	9.76	7.00	1.14	16.3
Lubbock (TX)	7.17	6.82	6.38	4.74	5.69	5.80	6.67	6.33	5.45	6.53	6.16	0.69	11.2
Oklahoma City (OK)	7.09	5.96	5.14	6.33	6.99	4.77	5.75	6.62	5.14	5.61	5.94	0.76	12.8
TOTAL	30.43	27.38	27.48	23.67	28.63	26.35	30.31	26.16	24.72	29.34	27.45	2.16	7.9

Table A-3

Annual Wind Energy (GJ/m^2) Intercepted by a Vertical Surface at 10m height, at 5 locations in USA, over the 10 year period 1955-64 (incl.)

Notes

a) Data from J.W. Reed, Some Variability Statistics of Available Wind Power, Sandia Labs Report SAND 78-1735, March 1979.

b) Bearings (from North) and distances of sites from Lubbock are:

Corpus Christi: 145°, 760 km
Albuquerque: 292°, 460 km
Dodge City: 18°, 490 km
Oklahoma City: 61°, 435 km

Appendix B

Offshore Wind Power Potential

Harnessing of the offshore wind resource has been frequently discussed. A recent study*, performed for the U.S. Department of Energy, appears to provide the best available information concerning the U.S. offshore potential. This appendix draws entirely upon that study.

Figure B-1 shows that the annual mean wind speed (10 m height), offshore of the U.S., typically ranges from 5 to 7 m/s (10-14 knots). At 50 m height, therefore, annual average wind-power density typically ranges from 300 to 800 W/m^2. Comparison with Figure 1, in the body of this report, shows that the offshore wind resource is quite rich.

Some characteristics of a possible offshore wind energy system are shown in Table B-1. In this case, 55 turbines would generate up to 550 MW of electricity, delivering about 500 MW at the shore terminal. The turbine would be mounted on tension-moor (floating) platforms. A variety of other concepts are analyzed in the DOE study.

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* Design Study and Economic Assessment of Multi-Unit Offshore Wind Energy Conversion Systems Application, U.S. Department of Energy Report WASH-2330-78/4 (4 Vols), June 1979.

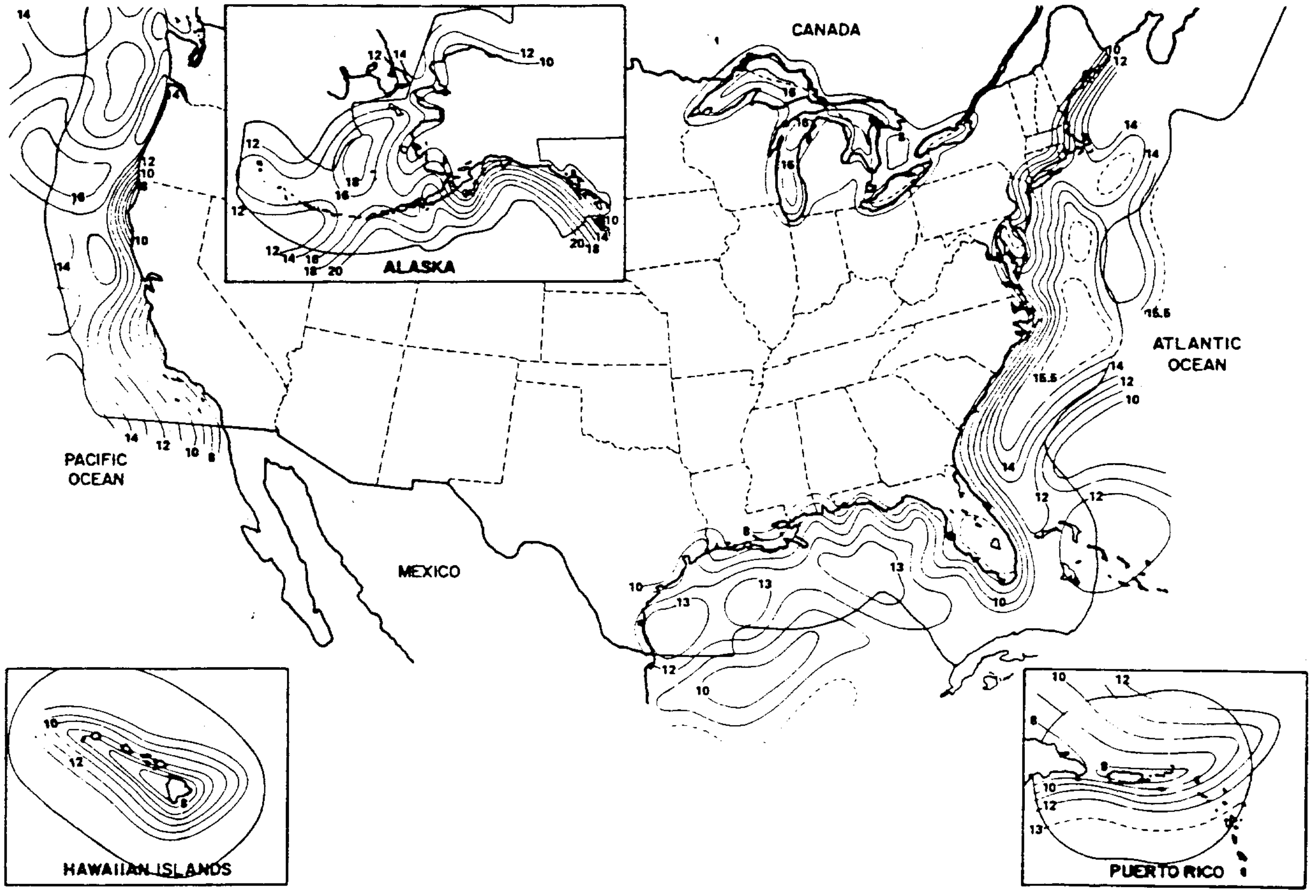


Figure B-1

US Offshore Distribution of Annual Mean Wind Speed (10m height), Indicated in Knots.

Notes

(a) This figure from Design Study and Economic Assessment of Multi-Unit Offshore Wind Energy Conversion Systems Application, U.S. Department of Energy Report WASH-2330-78/4 (4 Vols), June 1979.

(b) 1 Knot = 0.515 m/s.

Table B-1

Characteristics of Baseline Site and Wind Energy System for the US Department of Energy's 1979 Study on Offshore Wind Energy Systems (a)

Site (b)

Mean Wind Speed (10m height):	7.7 m/s
Maximum Sustained Wind Speed (10m height):	41.2 m/s
Water Depth:	153 m
Maximum Wave Height:	30.5 m
Maximum Surface Current:	1.83 m/s
Distance from Shore:	161 km

Wind Energy System

(i) System Elements

Item	Quantity
Horizontal-axis Wind Turbines: (107m rotor diameter, 10 MW rating)	55
Tension Moor Platforms for Turbines:	55
DC Cable Circuit (plus 1 spare cable):	1
Substations:	2
Offshore Power Collection Network:	1

(ii) Performance

Annual Energy Production at Shore Terminal:	1.41×10^9 kWhr

(iii) Costs (c) (1978 $)

Wind Turbines:	\$ 387×10^6
Platforms:	\$ 221×10^6
Cable:	\$ 93×10^6
Substations:	\$ 22×10^6
Total Capital Costs:	\$ 723×10^6
Annual Operating and Maintenance Costs:	\$ 15×10^6

Notes

(a) Design Study and Economic Assessment of Multi-Unit Offshore Wind Energy Conversion Systems Application, U.S. Department of Energy Report WASH-2330-78/4 (4 vols.), June 1979.

(b) Assumed to be off the Atlantic coast of the U.S.

(c) Costs (1977$) in the DOE report adjusted to 1978$ by the ratio (1.05) of The U.S.-averaged Handy-Whitman indices for July 1978 and July 1977 (source: Statistical Year Book, Edison Electric Institute, 1978). Capital cost estimates are based on production of 100 turbine/platform units.

Table B-2 provides an estimate of the cost of energy from the system characterized in Table B-1. It will be seen that electricity might be delivered at the shore terminal at a cost of 65 mills/kWhr (1978 $). This compares unfavorably with a possible cost of 20 mills/kWhr for electricity from a MOD-2 turbine on land (see Table 6, in the body of this report). The unfavorable comparison arises even though the assumed mean wind speed (10 m height) is 6.7 m/s for the land site and 7.7 m/s for the offshore site. Note, however, that costs such as land rental and insurance are not included in either case.

Table B-2

Estimated Cost of Energy, at Shore Terminal, from the Baseline Site and Offshore Wind Energy System

Costs of Electrical Output (1978 mills per KWhr)	
Capital Costs [(a,b)]	54.4
Operating and Maintenance Costs [(a)]	10.6
Total Cost	65.0

Notes

(a) Data on costs and annual energy production taken from Table B-1.

(b) Assuming annual capital charge rate of 0.106 (for 30 year life: see Table 10, note (d), in the body of this report).

Over different coastal regions, there would be a significant variation in the cost of energy from offshore turbines. Table B-3 shows that, for a favorable region such as the Pacific NW, the energy cost might be 70% of the baseline cost (as estimated in Table B-2). For an unfavorable region, such as Puerto Rico, Table B-3 shows that the energy cost might be almost four times the baseline cost.

Table B-3

Comparison of Cost of Energy from Offshore Wind Turbines, at Shore Terminal, for Baseline Site versus Typical Sites in Various US Coastal Regions

Coastal Region	Ratio of Energy Cost to Cost for Baseline Site
Northeast (North of 35° N Lat.)	1.2
Southeast (South of 35° N Lat.)	2.0
Gulf	1.5
Southwest (South of 38° N Lat.)	1.8
West (North of 38° N Lat.)	0.73
South Alaska (130° W - 165° W Long.)	0. 78
Aleutian Islands	0.83
Hawaiian Islands	1.7
Puerto Rico and Virgin Islands	3.7

Notes

(a) Data from DOE report cited in Table B-1, note (a).

(b) For each site, a wind energy system similar to the baseline system (see Table B-1) is assumed.

Appendix C

Status of Wave-Power Technology

Many devices have been proposed for the harnessing of wave energy. The overall concepts, together with the research programs of various nations, have been discussed by Shelpuk and Davidoff(1).

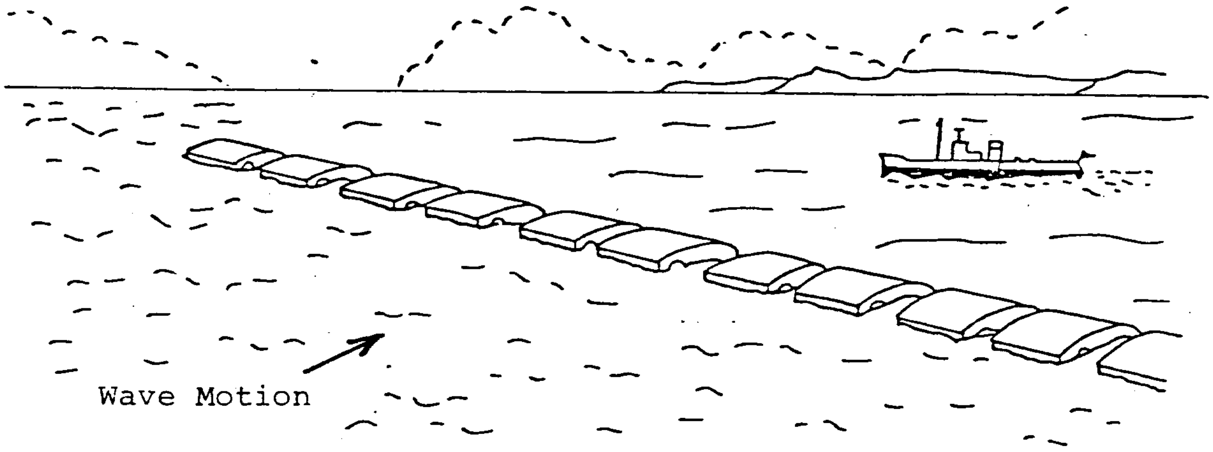
Two of the three principal concepts are shown in Figure C-1. The "terminator" concept places a continuous line of wave-power devices across the path of the waves. In this illustration, a line of "Salter Ducks" is shown; other devices could be employed in the same manner. The "attenuator" concept aims to extract part of the incident wave energy in each of a number of lines of wave-power devices. This concept is illustrated using the "Lancaster University Air Bag"; again, other devices could be employed.

The third principal concept is to focus waves, thereby increasing power density at the point of power extraction. Focussing can be achieved by arranging that the wave front passes over underwater surfaces of appropriately varying depth. Once focussing has been achieved, wave-power can be extracted in various ways. For example, the focussed waves could be channeled upward into an elevated shore-based reservoir, which would feed conventional hydrulic turbines.

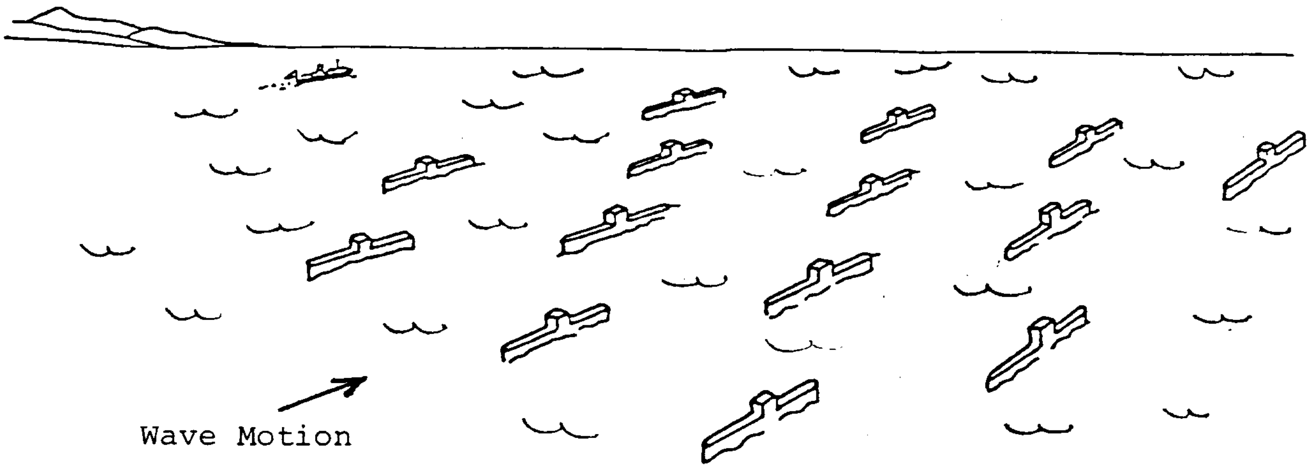
Perhaps the most advanced study of wave-power devices has been made within the UK wave program. Figures C-2 and C-3 show two of these devices in their currently most advanced stage of design.

It has been estimated(2) that the Salter Duck and Lancaster University Air Bag, together with other promising devices under examination in the UK, might deliver power at a shore terminal in the cost range 100-300 mills/kWhr. Further design refinements may reduce these estimates.

If the wave-power devices were to intercept waves with an annual average power of 50 kW/m, it has been estimated(3) that they might deliver an average power of 3 to 10 kW/m at the shore terminal.



(a) Terminator Concept [using Salter Ducks]



(b) Attenuator Concept [using Lancaster University Air Bags]

Figure C-1: Concepts for Harnessing Wave-Power

Source: F.J.P. Clarke, Wave Energy Technology, paper to UNITAR Conference, Montreal, 1980.

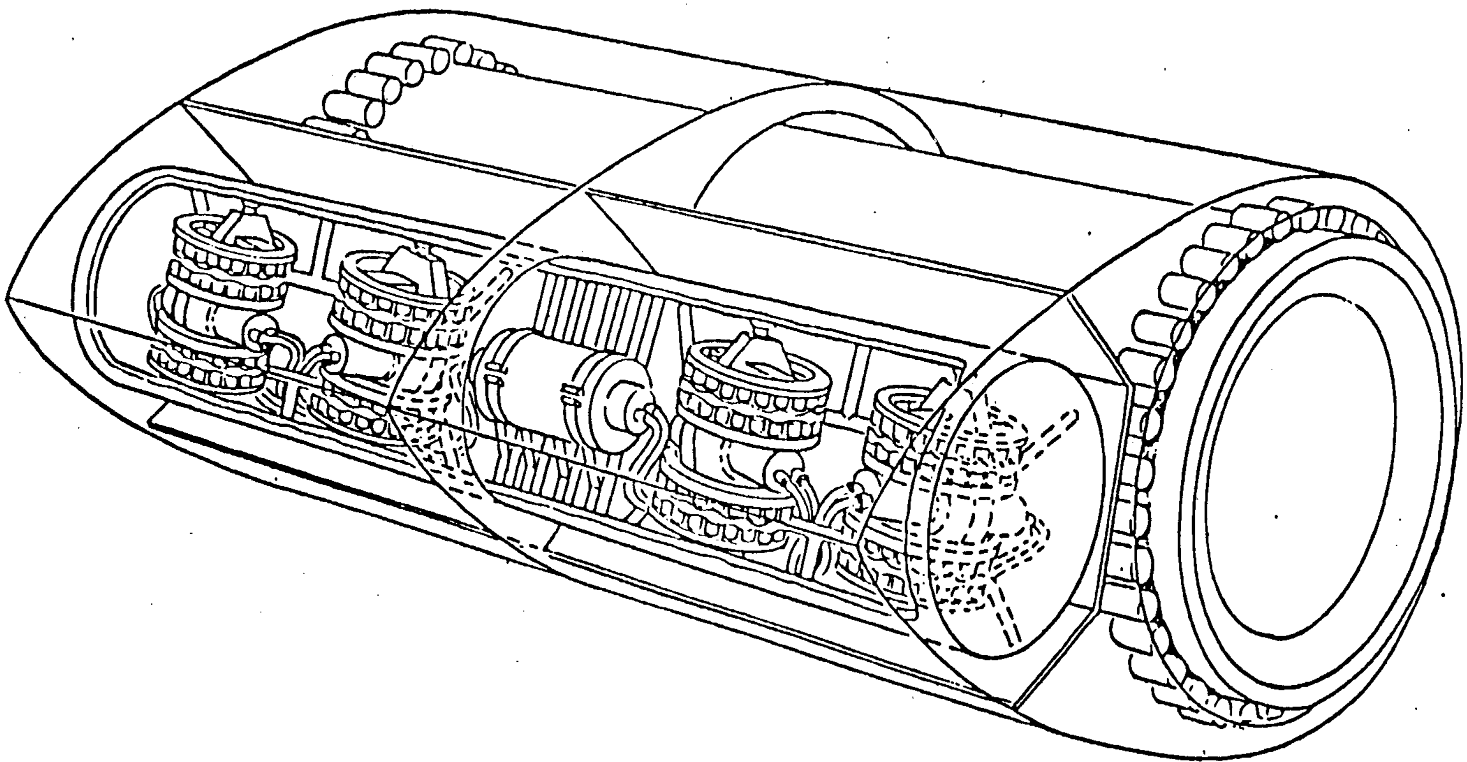


Figure C-2: Typical Wave-Power Device: The Salter Duck

Notes:

(a) The device as illustrated is the latest development of the concept suggested by S. Salter of Edinburgh University. This design consists of a mobile "duck" which is oscillated by wave action about the spine. Four gyroscopes are housed in a pod mounted in the nose of the duck and as the duck oscillates the gyros precess. This rotary motion causes multiple cylinders to interact with a cam ring and generate high pressure hydraulic fluid. This fluid drives the swashplate motor and electrical generator mounted between the gyros. If there is excess wave energy available, the surplus is fed back through the hydraulic system to increase the gyro speed. In periods of lower energy input, this stored energy is recovered.

(b) Source as for Figure C-1.

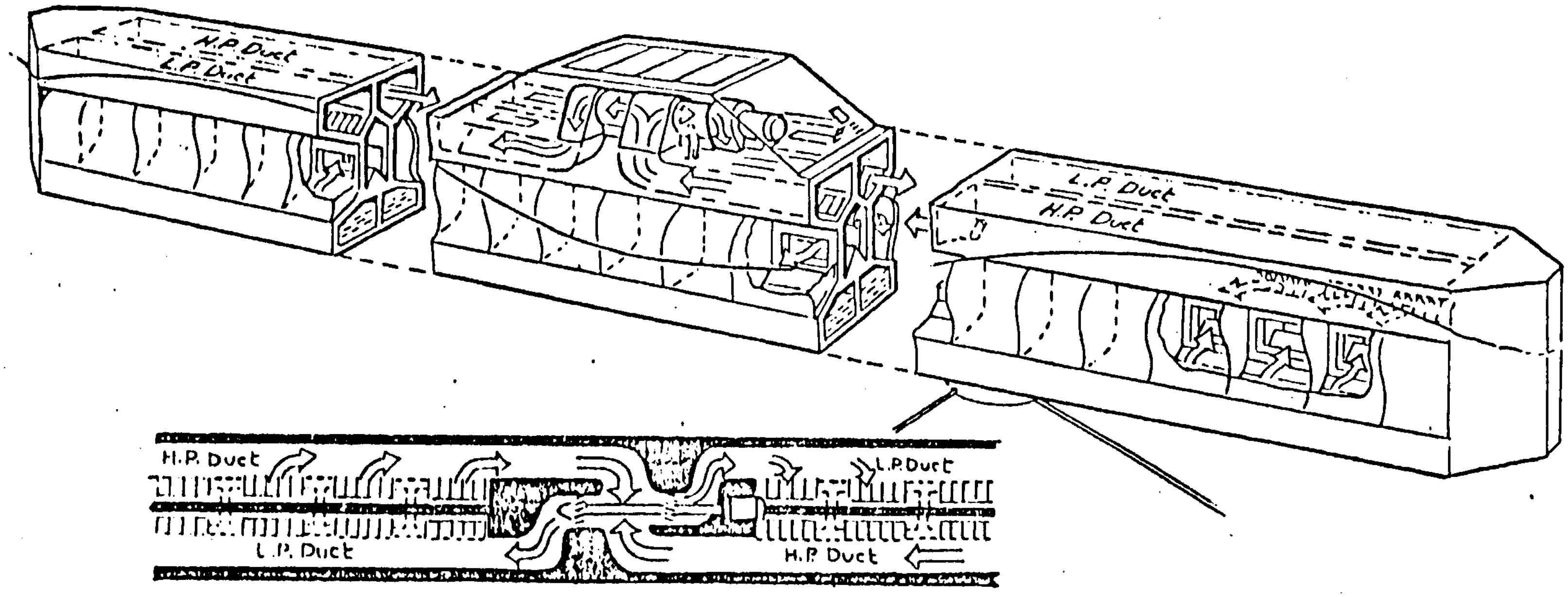


Figure C-3: Typical Wave-Power Device: The Lancaster University Air Bag

Notes:

(a) This illustration shows the latest design concept for the Lancaster Flexible Bag device developed by Prof. M. French at Lancaster University. This device is moored nose on to the waves. The side panels are made of a flexible rubber material and partially collapse under influence of the waves. Air from the chamber behind the flexible bag is forced through ducts to an air turbine coupled to a generator. This air then flows on to re-inflate the bag at positions adjacent to wave troughs.

(b) Source as for Figure C-1.

(1) B. Shelpuk and P. Davidoff, Ocean Wave Energy: Program Overview, Abstract IIA/1, Expanded Abstracts, 7th Ocean Energy Conference, Washington, D.C., June 1980.

(Note: Shelpuk and Davidoff were then involved in the management of the U.S. Department of Energy's wave-power program.)

(2) C.O.J. Grove-Palmer, Development of Wave Energy in the UK: 1976-1980, late submission for Expanded Abstracts cited in note (1).

(Note: Cost estimates presented by Grove-Palmer were converted at the rate 1 UK penny = 2 US cents.)

(3) F.J.P. Clarke, Wave Energy Technology, paper to UNITAR Conference, Montreal, 1980.