W.E.S.C. E/5A/CON/1632/172/099
ENERGY ANALYSIS OF
WAVE ENERGY CONCEPTS
FINAL REPORT   SECTION 1
G. JENKINS & R. HARRISON
DECEMBER 1981

SECTION 1

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ENERGY ANALYSIS OF WAVE ENERGY CONCEPTS

EXECUTIVE SUMMARY

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1. Energy analysis compares the energy input to build and operate wave energy devices with their energy output. It indicates the viability of the system in energy terms.

   The basic test of viability is that:

$$\frac{\text{energy input}}{\text{energy output}} \;(N) < 1$$

   This index, the net energy requirement (N) of the electricity produced by a wave energy system, is calculated in this study. The smaller the value of net energy requirement (N) which is obtained the greater the merit of the system in energy terms.

2. A thorough energy analysis of 1979/80 Reference Designs of wave energy devices has been performed . The results are shown in Table 1. The devices are ranked in order of merit, the device having the lowest net energy requirement (N) being the Lancester Flexible Bag. It can be seen that the Vickers device does not pass the test of basic viability.

3. Through discussions with device teams, information has been obtained for some of the Reference Designs being finalised for 1981. . The net energy requirement (N) of these devices has been calculated and is shown in Table 2.

4. Where possible calculations have been performed for the reference designs which have been developed over the period of the wave energy programme (1977-1981). This has been done by using device team and consultants reports and discussions with device teams. In this way it has been possible to compile a time series of values of net energy requirement (N) relating to different reference designs of the different devices (Figure 1).

This gives an indication of the state of development of the different devices. The pessimistic results obtained for most 1978 Reference Designs reflected the imbalance in input and output at the time. Devices were designed to operate in OWS "India" sea state, and were thus sized to extract the 70 kW/m expected there. The device outputs were assessed however, using the recently (in 1978) available data from South Uist, averaging 42 kW/m available wave power. Also, correction for directionality and reliability were included for the first time, resulting in an overall efficiency of less than 10% for all devices. The Lancaster Flexible Bag, introduced into the programme only in 1977, was at a much earlier stage of development than the other devices assessed in 1978.

The 1979 reference designs of devices were more closely matched to the South Uist sea state, and this is reflected in the much lower values of N. Two distinct groups can be seen, the floating devices such as LFB, Duck, Clam and Bristol Cylinder having substantially lower net energy requirements (N) than the bottom standing NEL OWC and Vickers systems. The latter device appears to be outside the 'feasible' region of net energy requirements.

For the 1981 devices so far studied, (LFB, Clam, Bristol Cylinder and the "Floating Terminator" NEL OWC) there has been a slight improvement in the net energy requirements overall, although the Lancaster Flexible Bag has a higher net energy requirement than in 1979. All these floating devices studied have very similar net energy requirements.

5. If a system produces electricity with a net energy requirement less than one ($N < 1$), this in itself is not a firm indicator of economic viability. Because energy inputs are only one element in costs, and the output energy sold must pay for all costs, the condition of economic viability requires the net energy requirement to be very much less than unity ($N \ll 1$). It is possible to use the results of energy analysis to indicate the economic prospects of

a new energy technology. Table 3 has been compiled which gives the results of calculations of net energy requirement for a range of energy producing systems from a variety of sources. A theoretical argument has also been developed to suggest the level of net energy requirement which may be consistent with economic viability (Appendix D).

6. It is not possible at present to make either the theoretical argument or the process of comparison with other systems absolutely precise. However, these indicate that, in order to have the potential to be economically viable in the context of the general supply of electricity a wave energy systems must produce electricity with a net energy requirement (N) somewhat less than the range 0.2 to 0.1.

7. However, wave energy devices could be used to offload fossil fuel thermal stations resulting in savings in fossil fuel. While it is not possible to estimate precisely the fossil fuel savings which would accrue it is possible that a wave energy system which would generate electricity with a net energy requirement of say X (in GJ_t/GJ_e) could save fossil fuels with a net energy requirement say Y (in GJ_t/GJ_t) where $Y \approx 0.3X$. However, we have no information relating to such a combined system and thus have no economically viable comparative examples to use as a base line. It may be that systems which would produce electricity with a net energy requirement (X) of 0.3 to 0.6 would, when used in this way, save fossil fuels with a net energy requirement (Y) of 0.1 to 0.2. This may be economically viable at these levels in certain special cases.

8. In situations where the value of the fuel produced is very much greater than that of the input fuel, for example solar cells in space or wave powered navigation buoys then the use of energy analysis results as indicators of economic viability is limited. Hence it is possible that wave energy systems which produce electricity with net energy requirements of 1 and above ($N > 1$) could be economically viable in isolated communities where the electricity output has a high value. However, in this situation the electricity supply is not a renewable resource independent of the fossil fuel energy economy.

9. A report has been produced on the energy requirement of the cement which could be used in the construction of wave energy devices (Appendix B). Whilst savings of between 30 and 40% can be made in the cement energy input this is not sufficient to radically affect the levels of net energy requirement calculated or the ranking of devices.

10. A survey was conducted of the energy requirements per unit mass of the concrete structures used in the 1979/80 Reference Designs. Values between 3.95 GJ_t per tonne and 7.1 GJ_t per tonne was observed, the variation being due to the different percentages of steel reinforcement and prestressing used in the structures.

11. Through a study of the steel hulled Cockerell Raft, the effects of automated production using dedicated plant on the energy requirement was investigated. It was found that the energy requirement of the steel hull constructed in this manner would be twice that of the equivalent concrete hull. Thus even under the most favourable conditions, steel cannot compete with concrete in energy terms.

12. A manual has been prepared outlining the methods used in the energy analysis of renewable energy sources based on worked examples taken from the wave energy work. This is being made available to device teams who wish to monitor the progress of their design work using energy analysis. (Appendix A).

APPENDIX A

References

1. Energy analysis of wave energy concepts: Final Report, R. Harrison and G. Jenkins, Sunderland Polytechnic, Energy Workshop Report No. 27, November 1981.

2. Energy analysis and the U.K. Wave Energy Programme:Presentation to the Wave Energy Steering Committee, R. Harrison and G. Jenkins, WESC (81) P 591, June 1981.

3. The energy requirement of cement for use in the construction of wave energy devices, G. Jenkins, Sunderland Polytechnic, Energy Workshop, Report No. 24, May, 1981.

4. Review of energy requirements of wave energy device structures 1979/80, G. Jenkins, Sunderland Polytechnic, December 1981.

5. The Energy Analysis of Rewable Energy Technologies: A Guide to Methods, G. Jenkins, Sunderland Polytechnic, Energy Workshop Report No. 26, September, 1981.

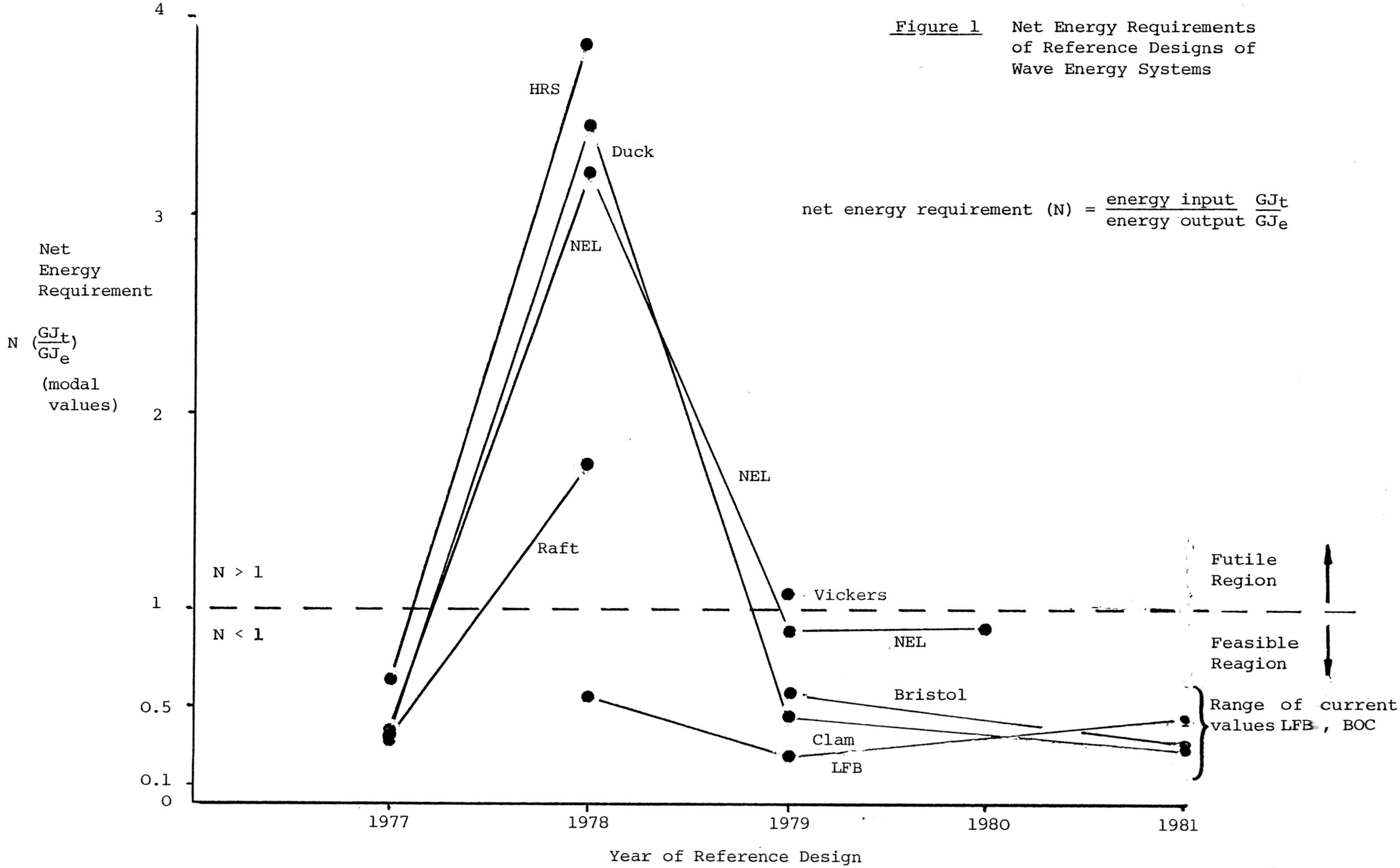

Figure 1 Net Energy Requirements of Reference Designs of Wave Energy Systems

Table 1

Energy Analysis of Wave Energy Systems: 1979/80 Reference Designs

Summary of Results

	System	Type & Dimensions	Date	N Net Energy Requirement $*(\frac{GJ_t}{GJ_e})$			Date of Calculation
				R Energy Ratio $*(\frac{GJ_e}{GJ_t})$			
				Lower Bound	Modal Value	Upper Bound	
1	Lancaster Flexible Bag	'Top Duct' 190 x 10 x 13m	Nov. 1979	N 0.15	0.23	0.39	February 1981
				R *6.70*	*4.38*	*2.56*	
2	Salter Duck	ESL 24 x 10m ϕ	Nov. 1979	N 0.25	0.44	0.79	August 1981
				R *4.05*	*2.29*	*1.26*	
3	S.E.A. Clam	11 x 15 x 270m 'HHM'	June 1980	N 0.25	0.44	0.86	Preliminary Values: July 1981
				R *4.01*	*2.25*	*1.17*	
4	Belfast Buoy	'Tension Leg' 40mϕ x 40m	Nov. 1979	N 0.30	0.48	0.83	August 1981
				R *3.37*	*2.08*	*1.21*	
5	Bristol Oscillating Cylinder	'precast pipeline & piled' 50 x 12m ϕ	March 1980	N 0.32	0.53	0.92	March 1981
				R *3.15*	*1.87*	*1.08*	
6	NEL Oscillating Water Column	'Bottom Standing' 80 x 44 x 32m	Nov. 1979	N 0.55	0.87	1.47	April 1981
				R *1.80*	*1.15*	*0.68*	
7	NEL Oscillating Water Column	'Breakwater' 64 x 24 x 26m	March 1980	N 0.50	0.89	1.91	October 1981
				R *1.98*	*1.12*	*0.52*	
8	Vickers	Original Mk 7 29 m ϕ x 16m	Nov. 1979	N 0.63	1.05	1.91	April 1981
				R *1.59*	*0.95*	*0.52*	

- over -

NOTES

* Above results are expressed on an annual basis
* Net Energy Requirement (N) $= \frac{\text{equivalent annual primary energy input}\ (GJ_t)}{\text{annual energy output at Perth}\ (GJ_e)}$
* *Energy Ratio (R)* $= \frac{\textit{annual energy output at Perth}\ (GJ_e)}{\textit{equivalent annual primary energy input}\ (GJ_t)}$

Lifetime of system used for 'lower bound value' : 30 years
'modal value' : 25 years
'upper bound value' : 20 years

'Modal Value' represents most likely combination of input and output

'Lower' and 'Upper' bound values represent most extreme combinations of input and output.

Table 2 Energy Analysis of Wave Energy Systems: 1981 Reference Designs Based on Device Teams Output From RPT Letter 14.12.81

System	Type and Dimensions	Date	Net Energy Requirement N GJ_t/GJ			Energy Ratio R Modal Value GJ_e/GJ_t	
			Low	Modal	Upper		
Bristol Oscillating Cylinder	75 m x 12 m	November 1981 Ref.	0.19	0.32	0.58	3.16	
Lancaster Flexible Bag	255 x 22m x 15m (1.8MW/device)	November 1981 Ref.	0.26	0.44	0.72	2.30	
NEL Oscillating Water Column	Floating Terminator	November 1981	0.22	0.38	0.70	2.65	incomplete information on moorings
	Floating Attenuator	November 1981					
	Raised Breakwater						
S.E.A. Clam	275 x 15 x 13m	November 1981 Ref. (18.1.82)	0.17	0.28	0.50	3.63	

Table 3 Examples of Energy Analysis Results for Selected Energy Technologies

	Technology	Example	Specification	Average Energy Ratio GJ_e/GJ_t	Average Net Energy Requirement GJ_t/GJ_e	Source	Notes
1.1	Nuclear Fission	Magnox	Current Systems	11.11	0.09	N.D. Mortimer, Energy Analysis of burner reactor power systems: Open University, 1977	All electricity from nuclear power stations
				7.19	0.14		All electricity from current mix of power stations
1.2	Nuclear Fission	A.G.R.	Current Systems	15.38	0.07	N.D. Mortimer, Energy Analysis of burner reactor power systems: Open University, 1977.	All electricity from nuclear power stations
				3.70	0.27		All electricity from current mix of power stations
1.3	Nuclear Fission	P.W.R.	Current Systems	20.80	0.05	N.D. Mortimer, Energy Analysis of burner reactor power systems: Open University, 1977	All electricity from nuclear power stations
				3.65	0.27		All electricity from current mix of power stations
2.1	Nuclear Fusion	Tokamak	Culham Conceptual Tokamak Mk II B	22.2	0.045	N.D. Mortimer, Energy Analysis of Nuclear Fusion Reactors, Sunderland Polytechnic, 1981	No account taken of recirculated energy. Study funded by U.K .A.E.A.

Compiled June 1981
by G. Jenkins, Energy Workshop, Sunderland Polytechnic.

	Technology	Example	Specification	Average Energy Ratio GJ_e/GJ_t	Average Net Energy Requirement GJ_t/GJ_e	Source	Notes
3.1	Tidal	Severn Barrage	Single basin	13	0.071	F. Roberts, Private Communications 1981	Study for E.T.S.U. Energy Ratio Range 10-16
4.1	Wind	3.7 MW B Ae Basline Design	Concrete Tower, Prime UK Site	12	0.083	F. Roberts, Private Communication 1980	Study for E.T.S.U. Energy Ratio Range 6-13
4.2	Wind	3.7 MW B Ae Baseline Design	Steel Lattice Tower, Prime UK Site	11	0.091	F. Roberts, Private Communication 1980	Study for E.T.S.U. Energy Ratio Range 6-13 GJ_e/GJ_t
4.3	Wind	4 MW US Baseline Design	Compliant steel tower 400 MW array Prime UK Site	25.2 (22.9*)	0.04 (0.04*)	J.C. Dixon & R.J. Lowe Energy Requirements of large wind turbine Systems 3rd BWEA Conference Cranfield 1981	Design similar to Boeing MOD 2 & GE MOD 5A * See below
4.4	Wind (offshore)	4 MW US Baseline Design	Shallow water steel tower on concrete gravity base. 20km off-shore. UK. 100 MW array	18.4 (15.5)*	0.05 (0.06*)		Results have been converted to energy ratios (in GJ_e/GJ_t) by G. Jenkins * See below

	Technology	Example	Specification	Average Energy Ratio GJ_e/GJ_t	Average Net Energy Requirement GJ_t/GJ_e	Source	Notes
4.5	Wind (offshore)	4 MW US Baseline Design	Deep water (50 m) steel tower on tension leg platform 100 km off-shore UK 100 MW array	13.1 (9.7*)	0.08 (0.10*)	J.C. Dixon & R.J. Lowe Energy Requirement of Large wind turbine systems 3rd BWEA Conference Cranfield 1981	*The energy requirement for reinforced concrete used in the paper is 2 GJ/t. Results using the more realistic figure of 5 GJ/t have been added in brackets.
5.1	Solar Photovoltaic	Cadium Sulphide Sputtered thin film cells	AMI Sunlight 18 MJ/m^2/day (e.g. S.W. USA)	10	0.10	G. Jenkins, Energy Analysis of Cds, Cu_2S Sputtered Solar Cells 'Solar Cells' 1 1979/80	Cell only Energy ratio range 6—12
5.2	Solar Photovoltaic	Amorphous Silicon MIS	AMI Sunlight (18 MJ/m^2/day) e.g. S.W. USA	3.4	0.29	F. Riddoch and J. Wilson, The Energy Cost of Amorphous Silicon Solar Cells, Herrior-Watt 1980	Cell only

	Technology	Example	Specification	Average Energy Ratio GJ_e/GJ_t	Average Net Energy Requirement GJ_t/GJ_e	Source	Notes
5.3	Solar Photovoltaic	Silicon single crystal	AMI Sunlight 18 MJ/m^2/day (e.g. SW USA)	1.3	0.77	L.P. Hunt, Total Energy Use in the Production of Silicon solar cells from raw materials to finished product, Baton Rouge 1976 IEEE Conference	Cell Only
6	Solar Satellite Power Station	U.S. Designs	Silicon Single crystal cells Geosynchronous Orbit	2.2	0.45	R. Herendeen, Energy Analysis of two technologies Gaschol and Solar Satellite Power Station IGT Symposium Colorado 1978	Range of Energy Ratios 0.7-3.9
7.1	Solar Thermal	Active Flat plate domestic heating	Electric pump Santa Fe New Mexico	3.0*	0.33*	L. Sherwood, Total Energy Use of Home Heating Systems. IGT Symposium, Energy modelling and net energy analysis Colorado Springs 1978	*Thermal energy delivered
7.2	Solar Thermal	Passive Domestic heating	Various** systems Sante Fe New Mexico	12-26*	0.083 - 0.038*		*Thermal energy delivered **Trombe wall, direct gain and greenhouse systems studied

	Technology	Example	Specification	Average Energy Ratio GJ_e/GJ_t	Average Net Energy Requirement GJ_t/GJ_e	Source	Notes
8.1	Geothermal-electric	Dry steam	Geysers, California Units 9 & 10	13	0.077	R. Herendeen and R. Plant Energy Analysis of Geothermal Electric Systems, Energy Research Group, Univ. of Illinois December 1979	Currently operating system: 500 MW installed
8.2	Geothermal-electric	Hot dry rock	Republic Geothermal 35°C/km to 55°C/km	2.7 - 3.9	0.37 - 0.26		Results dependent on geothermal gradient
8.3	Geothermal-electric	Liquid dominated	Bechtel Study	4.3	0.23		
9	O.T.E.C.	Lockheed system	160 MWe output titanium heat exchangers	6.6	0.15	A. Perry and G. Morland and Zelby, Net Energy Analysis of an OTEC-System, Institute for Energy Analysis, Oak Ridge, 1978	
10	Ethanol (Gasohol)	U.S. Corn Based	10% Ethanol used as Gasoline additive	0.9* - 1.5**	1.11 - 0.67	R. Herendeen, Energy Analysis of two technologies Gasohol and Solar Satellite Power Station IGT Symposium, Colorado Springs, 1978	Corn stalks not burnt in process *Energy value of output as a displacer of gasoline **Allowances for improved m.p.g.

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1. Introduction

Energy analysis is the study of the energy required to provide a product or service. In the case of the wave energy systems being developed in the U.K., the product is electrical energy, delivered to the electricity supply network at Skye.

The energy necessary to supply this electricity comes in two forms. The first is the energy in the sea waves which is converted by the wave energy device to electricity by means of intermediate mechanical, hydraulic or pneumatic mechanisms. This route is studied carefully by the engineers of device teams in order to arrive at an efficiency for the device.

The remainder of the energy necessary to supply the output electricity does not appear in the direct conversion process noted above. It is embodied in the structure and equipment of the wave energy devices, and is also used up in the installation and maintenance of the devices during their operating lifetime.

Every product of the industrialised world uses energy in its production. Most of this energy is supplied by the fossil fuels such as coal, oil and gas, the remainder being supplied as nuclear or hydro-electricity. So every wave energy system will be subsidised to a certain extent by previously supplied, mainly fossil fuels.

The job of the energy analsyst is to find out the quantity of this external energy necessary to build and maintain a wave energy system. This energy input can then be compared with the energy output of the wave energy system, using a measure known as the net energy requirement (N). This expresses the amount of external energy subsidy per unit of energy output. If this number is very small ($N << 1$) the system uses verylittle external subsidy compared to its energy output and the system is energetically viable. If the net energy requirement is larger than unity ($N > 1$) it will mean that the system is a net energy sink, as it has used up more externally supplied energy in its construction than it produces during its lifetime and thus the system is energetically futile. Most of the wave energy system studied here lie somewhere between these two extremes. To calculate the energy input to a wave energy system, a large amount of information is necessary. A detailed weight breakdown of each component of the wave energy system is needed, along with a data base of the energy requirement of all the products and processes which go in to manufacturing a complete wave energy system. This data base has been assembled at Sunderland Polytechnic, and has been greatly enlarged since first started in 1975.

Information concerning device design has been obtained from device teams, their consultants, published and other sources.

Energy outputs for each system are based on the productivities agreed by the programmes assessors, Rendel, Palmer and Tritton.

2. Description of Research Programme

This study of the energy analysis of wave energy concepts was carried out during the period July 1980 to November 1981.

The first phase of the work entailed the performance of a detailed energy analysis of the November 1979 Reference Designs which were the subject of the Maidenhead Conference. Some device designs for 1980 were included where available, making a total of eight devices studied in the first phase. The results of this phase are reported in Section 3.

The second phase of the work was a detailed energy analysis of devices being developed for the November 1981 Reference Design deadline. Close liason with device teams has been necessary in this phase, since no published design details were available at this early stage. In many cases dimensions and quantities were taken straight from the drawing board by the device team. At this intense stage of design activity device designs were changing frequently. The results of the energy analysis of the 1981 Reference Designs, given in Section 4, should be taken as indicative only of the final energy balance.

Parallel studies were carried out on particular aspects of the energy analysis which were relevant to the above designs wave energy systems.

A manual has been prepared for device teams who wish to perform their own energy analysis on their wave energy device, or on particular items of that design. This manual contains a guide to the methodology of energy analysis, worked examples on a relevant device, and a comprehensive data-base of energy requirements of materials and products relevant to the manufacture of wave energy devices. This report is attached as Appendix A.

A detailed study of the energy needed to manufacture and supply cement for wave energy device construction was carried out at the request of device teams. The energy embodied in the cement is one of the largest single energy inputs to the whole wave energy system. This is particularly relevant in the case of devices which rely on large reinforced concrete structures for their operation. The report studies the energy required to manufacture and transport of many different cements, ranging from ordinary Portland cement to blended cements using a large proportion of industrial by products such as blastfurnace slag and pulverised fuel ash.

This report is attached as Appendix B.

Results for a typical energy analysis of a wave energy device, using the example of the 1979 Lancaster Flexible Bag, is attached as Appendix C.

The presentation given to the Wave Energy Steering Committee on the use of energy analysis as an assessment technique for renewable energy systems is attached as Appendix D.

Further work on the subject of the design criteria for wave energy systems is attached as Appendix C.

3. Results of Energy Analysis of 1979/80 Wave Energy Devices

The basic information for this study was gleaned from device team reports, Consultants Interim Reports, Consultants Working Papers and generic reports relevant to each device. The main sources of information for each device are shown in Table 1. Additional information on the device design was obtained during meetings with the device teams.

To perform an energy analysis in such a rapidly changing field as wave energy, it is necessary to have a 'snapshot' of a device at a particular stage in its development, for which corresponding input and output information is available. Thus Reference Designs for 1979 have been studied where possible, although some later designs have also been included (NEL OWC 'Breakwater' Device, SEA Clam Device).

Summary sheets of the energy analysis results are shown for each of the eight devices in Table 2 to 9. Here the annual energy input is broken down into suitable categories, for example: "Construct Devices". The modal value represents the most likely value, whereas the terms 'lower' and 'upper' represent the expected bounds of value. The column giving the percentage of the total modal input in each category clearly points to the 'energy input centres' of the device. These can be thought of as similar in concept to 'cost centres' but expressed in energy terms.

The indicator of merit used in our analysis is the net energy requirement (N) where:

$$\text{net energy requirement} = \frac{\text{annual energy input } (GJ_t)}{\text{annual energy output } (GJ_e)}$$

Thus to be viable in energy terms, net energy requirement must be less than 1. The net energy requirement is similar to the concept of cost in financial evaluation. The energy ration (R) is simply the inverse of the net energy requirement (N), thus:

$$\text{energy ratio} = \frac{\text{annual energy output } GJ_e}{\text{annual energy input } GJ_t}$$

The net energy requirement can be used to rank devices in an order of merit. The device which uses the least primary energy (mostly fossil fuels) to produce a unit of output electricity will rank highest. i.e. the device with the lowest net energy requirement will be at the top of the table.

This summary table has been produced using results for all of the 1979/80 devices studied. This is shown in Table 10 and Fig.1.

It can be seen that the device with the lowest net energy requirement is the Lancaster Flexible Bag with a net energy requirement of 0.23 GJ_t/GJ_e.

The next four devices (Duck, Clam, Belfast and Bristol Cylinder) form a group with an average net energy requirement of 0.57 $\frac{GJ_t}{GJ_e}$ These devices are all floating or have tethered buoyant elements (BOC).

The two NEL OWC's and the Vickers device form a third group which are clustered around the point of futility ($N = 1$). These are all bottom mounted devices.

The conclusions which can be drawn from this exercise appear to show that floating or tethered deep-water devices show better energetic prospects than bottom mounted, shallow water devices.

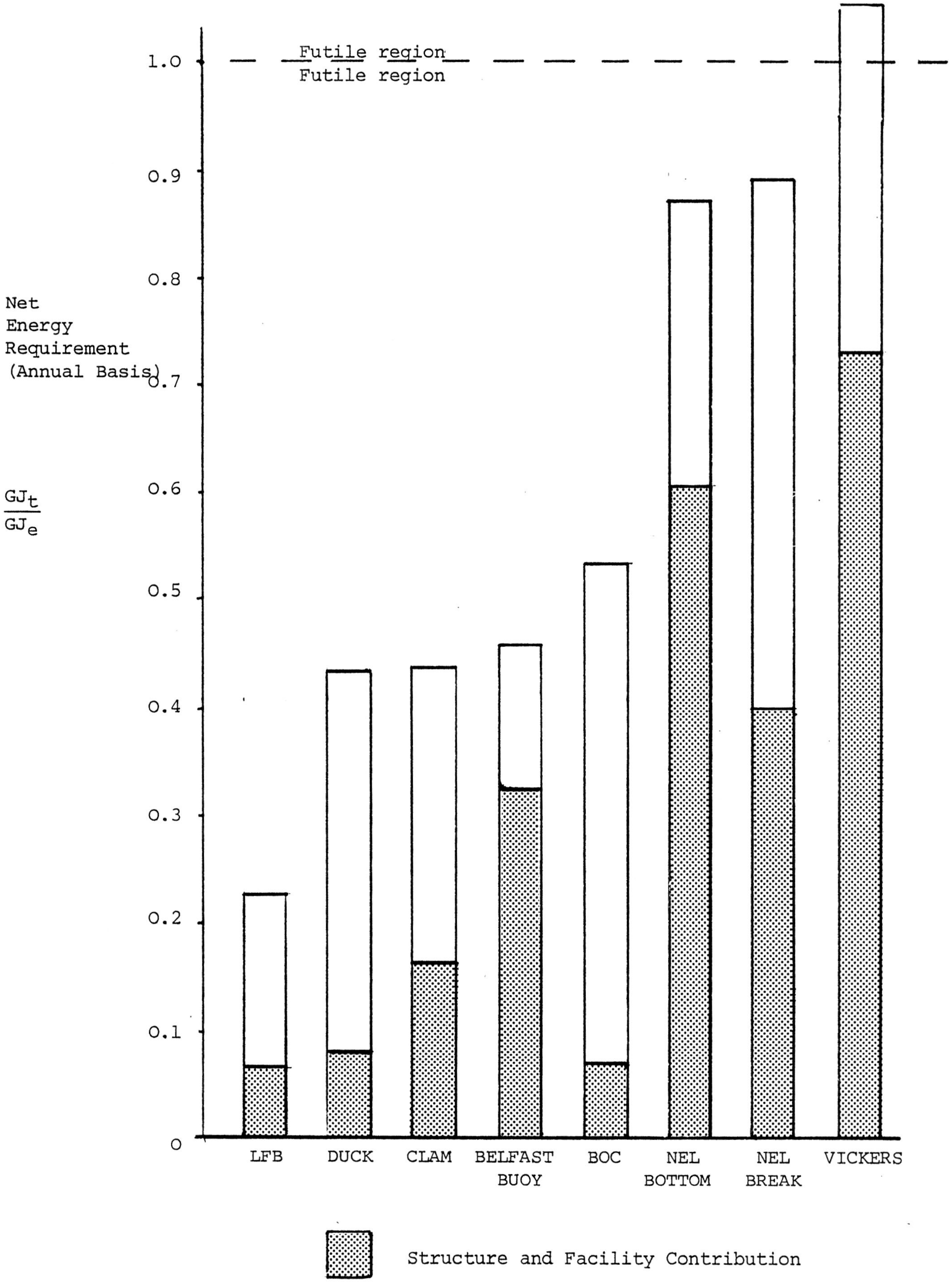
The general viability of devices in energy terms for 1979/80 would appear to be:

a. Lancaster Flexible Bag: this device is viable in energy terms and is in the region where energy analysis is no longer the prime indicator of viability.

b. Duck, Clam, Belfast Buoy and Bristol Oscillating Cylinder Devices: these devices produce approximately twice the amount of energy (as electricity) that they consume (as fossil fuels). Thus they are viable in primary energy terms ($N < 1$) but are unlikely to be economic in terms of bulk supply of electricity to the U.K. grid. It is possible that they could be more economically competitive in isolated communities where electricity supplies would otherwise be generated by using diesels generating sets.

c. NEL Bottom Mounted Device, NEL Breakwater Device and Vickers 'Original' Mk 7 Device. These are all bottom mounted devices sited in shallow water (23m). They are all close to the point of futility in primary energy terms (N = 1). i.e. in other words they only produce as much energy as electricity as has been consumed in primary energy in their construction. Although it is possible they could be used in a fuel-saving role, their capital cost would probably preclude this.

Figure 1 Net Energy Requirements of 1979/80 Wave Energy Devices (2 GW Systems) - Annual Basis



4. Results of Energy Analysis of 1981 Wave Energy Devices

The basic information for this study was mainly acquired through personal visits to the device teams to glean information on device designs directly.

The designs were being produced for assessment by Rendel, Palmer and Tritton in November 1981 and were changing very rapidly at the stage when this energy analysis was performed. The energy outputs was taken from figures agreed between the device teams and Rendel Palmer and Tritton set out in a letter to this group dated 14th December 1981.

Unfortunately, at the time of writing, sufficient information was only available to perform energy analysis on the devices shown in Table 15. Information on other devices at a Reference Design stage is awaited. However, there are a number of conclusions which can be reached on the results so far:

a) Bristol Oscillating Cylinder (Table 11)

The design of this device for 1979/80 was very elementary, and much of the output information was based on two dimensional model tank tests. (See Table 3). A thorough testing of this device in the Cadnam 3-D wide tank has enabled notable strides to take place on the efficiency of the device. The overall energy output per device has been increased by 78%, but the annual energy input per device has only increased by 6%. The increased rating of the power system has enabled the number of devices in a 2GW scheme to fall from 930 to 420, although there has only been a drop in the overall scheme energy output of around 20%. The result is that the scheme has improved considerably, the net energy requirement of the scheme falling from 0.53 GJ_t/GJ_e to in 1979/80 to 0.316 GJ_t/GJ_e in 1981. The system has gone from producing 1.87 times its input energy in 1979 to producing 3.16 times its input energy in 1981. Thus the Bristol Oscillating Cylinder system has improved from an energy analysis point of view. However, more improvement is needed if the device is to become economically viable, since all the output electricity sold must not only pay off the cost of the input energy but also all the labour, materials and capital charges needed to build the system.

Interestingly, the percentage of the total energy input embodied in the power take off and mooring system has remained constant at around 67% of the total even though the design of the power take off system has changed considerably, being based in 1979 on a chain linked system and in 1981 on a steel tubular leg system, weighing 300 tonnes per leg. Reducing this weight would make a significant contribution to improving the energetic viability of the device. A speculative study on 'Tube Pumps' was also performed and this showed some promise in energy terms.

b) Lancaster Flexible Bag (Table 12)

This device is being developed both by Wavepower Ltd., in Southampton and Lancaster University. The Wavepower Limited design was studied in detail, both for an early design in August 1981 and for the more detailed November 1981 Reference Design illustrated here. Extensive tank testing and computer modelling between 1979 and 1981 have shown that the 1979 Top Duct design was not sized correctly. The 1981 device is a much larger structure being 257m x 27m x 15m, although it was also expected to have a much larger output. The annual energy output between 1979 and 1981 has increased per device from 1.1 MW (continuous) to 1.8 MW (continuous) and per scheme from 15,100 GJ_e to 19,082 GJ_e, the latter being a 26% improvement. However, the energy input per scheme has risen 141% in the same period, mainly due to the larger size of the devices and the much improved information on operations at sea.

Thus the net energy requirement has changed from a 1979 value of 0.23 GJ_t/GJ_e to a November 1981 value of 0.44 GJ_t/GJ_e. Before tank tests were carried out in August 1981, it was expected that the output per device would be 3.3 MW (continuous) and that the value of the net energy requirement would be

0.22 GJ. However, this was not to be the case because of dissapointing results on the energy outputs from the models tested in the Cadnam tank. The November 1981 Lancaster Flexible Bag device has not, so far, fulfilled its earlier promises of being a significant breakthrough for wave energy devices. It is now very similar in energy analysis terms to other 1981 wave energy devices studied.

c) NEL Oscillating Water Column - Floating Terminator (Table 13)

This is one of three Oscillating Water Column designs for 1981, the other two being a Floating Attenuator and a Raised Breakwater Device. The latter is the device most favoured by the team, but insufficient detail is available at present for an energy analysis.

An energy analysis has been performed on the Floating Terminator Device, although much of the information on moorings, electrical equipment, power collection transmission and maintenance are very preliminary. This device is similar to the NEL device proposed in 1978 but cannot be compared with the NEL 1979 Bottom Mounted and 1980 Breakwater Devices because it is a floating device with very difference characteristics.

Although the construction programme for this device necessitates a large number of facilities, this only accounts for 5% of the input energy embodied in the whole scheme. Overall the structure accounts for 39.7% of the input to the scheme. The net energy requirement of this system has been calculated as 0.38 GJ_t/GJ_e, in other words the system will produce 2.7 times the amount of primary energy involved in its construction and maintenance.

d) SEA Clam (Table 14)

This device has changed somewhat since 1979/80. The front steel plate and bag system has been replaced by a large air bag with air ducting from the top corners. The overall dimensions of the device are virtually unchanged, since 1980, although there are now 320 devices per scheme, rather than 220 devices in 1980.

The annual energy input to the scheme had dropped by only about 15% since 1980, but the energy output per scheme has improved by 40% giving an overall improvement of 61% in the 'energetics' of the Clam wave energy scheme. The modal net energy requirement is 0.28 GJ_t/GJ_e which gives an energy ratio of 3.6 GJ_e/GJ_t. The equivalent result for the 1980 Clam was a net energy requirement of 0.44 GJ_t/GJ_e. Thus the November 1981 Reference Design Clam would appear to be a reasonable net producer of primary energy.

Conclusions of the Energy Analysis of 1981 Wave Energy Systems

From the devices studied above, and the results shown in Table 10, it can be seen that the modal value of net energy requirement varies between 0.28 and 0.44 GJ_t/GJ_e, with an average value of 0.34 GJ_t/GJ_e. The range of modal values around this average is 22%, which considering the diversity of the wave energy systems involved, is quite remarkable. This seems to confirm the suspicion felt by many within the programme that the devices are becoming more similar as the research progresses. It must be remembered that no bottom mounted devices have yet been analysed and these may affect the above conclusions.

The average value of net energy requirement for the floating devices in 1979/80 (LFB, DUCK, CLAM, BUOY and CYLINDER) was 0.39 GJ_t/GJ_e. Thus there seems to have been very little change from an energy analysis point of view between floating 1979/80 and some floating 1981 Reference Designs of wave energy systems. However, the effect of bottom mounted devices, and whether they are generically difference from floating devices, hs yet to be determined conclusively.

Table 1 Wave Energy Devices Studied (1979/80)

Device	Type or Description	Date of Design	Input Source	Output Source	Date of Calculation
Lancaster Flexible Bag	'Top Duct' 190 x 10 x 13m	Nov. 1979 (Reference)	Wavepower Ltd., Interim Report WP 119 Dec. 1979	RPT* Nov. 1978	Feb. 1981
Bristol Oscillating Cylinder	'Precast pipeline piled'	Oct. 1979 & March 1980	Final Report on Submerged Cylinder Wave Energy Device, Oct. 1979 Supplementary Report on the Feasibility Study, March 1980	RPT* Nov. 1979	March 1981
NEL Oscillating Water Column	'Bottom Standing 80 x 44 x 32m	Nov. 1979 (Reference)	NEL Updated Interim Study PR18: Y5/DEY/2 Nov. 1979	RPT* Nov. 1979	April 1981
Vickers	'Original Mark 7 290 x 16m	Nov. 1979 (Reference)	Feasibility Study on Submerged Oscillating Water Column Wave Energy Devices, June 1980	RPT* Nov. 1979	April 1981
SEA Clam	Sir Herbert Humphries & McDonald	June 1980	The Clam Wave Energy Converter Report for July 1979 to December 1980 February 1981	RPT* Nov. 1979	July 1981 (preliminary report)
Salter Duck	Edinburgh-Scopa-Laing 100 x 24m	Nov. 1979 (Reference)	Edinburgh-Scopa-Laing Fifth year report Nov. 1979	RPT* Nov. 1979	Aug. 1981

Contd.

Table 1 Contd.

Device	Type or Description	Date of Design	Input Source	Output Source	Date of Calculation
Belfast Buoy	Tension Leg 400 x 40m	Nov. 1979 (Reference)	Feasibility Study of Queen's University Wave Energy Device Nov. 1979	RPT* Nov. 1979	Aug. 1981
NEL Oscillating Water Column	Breakwater Device 64 x 24 x 26m	March 1980	Breakwater Device, 2GW Power Station Reference Design 1980 PR22	Device Team (as 'Input')	Oct. 1981

* RPT 'Rendel Palmer & Tritton' Consultants Interim Report ' — — — — Device' November 1979.

1979/80

Energy Analysis

Sumary Sheet: 1

Table 2

Lancaster Flexible Bag

Top Duct Design 1979

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	435	435	435	
	Scheme lifetime (yr)	-	30	25	20	
1.1	Construct Devices	53,972	783	939	1174	27.3
1.2	Construction Facility	2,400	35	42	52	1.2
1.3	Tow Out & Place	3,450	100	120	150	3.5
2.1	B.H.C. Bag	8,946	373	497	746	14.4
2.2	Valves & Other Mechanical Equipment	12,879	199	243	311	7.0
3	Turbine	5,013	72	87	109	2.5
4	Generator & Electrical Equipment on Board	16,866	245	294	367	8.5
5	Moorings & Piles	13,617	286	343	429	10.0
6	Power Collection & Transmission	50,449	732	878	1098	25.5
I	Energy Input	167,592	2,825	3,443	4,436	100%
Ø	Energy Output (x 10^3 GJe)	-	18,924	15,100	11,354	438%
I/Ø	Net Energy Requirement	-	0.15	0.23	0.38	-
Ø/I	Energy Ratio	-	6.70	4.38	2.56	-

1979/80

Energy Analysis

Sumary Sheet: 2

Table 3

Bristol Oscillating Cylinder

Precast, Piled & Pipeline Design 1979/80

Item		Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	930	930	930	
	Scheme lifetime (yr)	-	30	25	20	
1.1	Construct Devices	21,445	625	798	1057	11.5
1.2	Construction Facility	2,400	77	89	123	1.3
1.3	Tow-Out	4,595	128	171	235	2.5
3	Power Take Off Pumps	51,500	1,722	2,300	3,158	33.3
4	Pipework	9,132	255	340	467	4.9
5	Moorings & Piles	45,956	1,640	2,322	3,333	33.6
6.2	Turbo-Generator & Platform	15,853	442	590	811	8.5
6.9	Power Collection & Transmission (Electrical)	8,016	224	299	410	4.3
I	Energy Input	158,992	5,113	6,908	9,594	100%
Ø	Energy Output ($x10^3$ GJ_e)	-	16,085	12,931	10,408	187%
I/Ø	Net Energy Requirement	-	0.32	0.53	0.92	-
Ø/I	Energy Ratio	-	3.15	1.87	1.08	-

1979/80

Energy Analysis

Sumary Sheet: 3

Table 4

NEL Oscillating Water Column

Bottom Standing Device Nov. 1979

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	1382	1382	1382	
	Scheme lifetime (yr)	-	30	25	20	
1.1	Construct Devices	214,700	8,900	11,870	16,320	69.8
1.2	Construction Facility	1,300	50	70	100	0.4
1.3	Prepare Seabed	9,450	390	520	780	3.1
1.4	Tow Out	22,650	940	1,250	1,870	7.3
2.1	Air Valves	2,000	160	220	300	1.3
2.2	Air Ducting	9,500	400	530	730	3.1
2.3	Equipment Housings	5,100	210	280	390	1.6
3	Air Turbines	4,600	380	510	700	3.0
4	Generators & On Board Electrical Equipment	4,300	180	240	330	1.4
5	Rock Anchors	12,600	530	700	960	4.1
6	Power Collection & Transmission	14,800	610	820	1,120	4.8
I	Energy Input	301,000	12,760	17,010	23,600	100%
Ø	Energy Output (x 10^3 GJ_e)	-	23,020	19,550	16,080	115%
I/Ø	Net Energy Requirement	-	0.55	0.87	1.47	
Ø/I	Energy Ratio	-	1.80	1.15	0.68	

1979/80

Table 5

Energy Analysis

Sumary Sheet: 4

NEL Oscillating Water Column Breakwater Device March 1980

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($\times 10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	782	782	782	
	Scheme lifetime (yr)	-	30	25	20	
1.1	Construct Devices	134,870	3,164	4,219	5,800	44.3
1.2	Construction Facility	1,300	30	41	56	0.4
1.3.1	Bed Preparation	14,320	336	448	616	4.7
1.3.2	Tow Out & Emplace	39,620	929	1,239	1,704	13.0
2	Mechnical Equipment (Valves, Ducting Etc.).	17,400	408	544	749	5.7
3	Turbines	11,650	248	364	538	3.8
4	Electrical Equipment on Board	9,000	211	282	387	3.0
5	Anchors	18,000	423	563	774	5.9
6	Power Collection & Transmission	26,160	613	818	1,125	8.6
7	Maintenance *	31,780	746	994	1,367	10.4
I	Energy Input	304,100	7,108	9,512	13,116	100%
Ø	Energy Output ($\times 10^3$ GJ_e)		14,098	10,660	6,876	112%
I/Ø	Net Energy Requirement	-	0.50	0.80	1.91	
Ø/I	Energy Ratio	-	1.98	1.12	0.52	
*	Maintenance included separately for this device. Totals are consistent with other devices.					

1979/80

Table 6

Energy Analysis

Sumary Sheet: 5

Vickers O.W.C.

'Original Mark 7' November 1979

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme $(x10^3\ GJ_t)$			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	8620	8620	8620	
	Scheme lifetime (yr)	-	30	25	20	
1.1	Construct Devices	48,310	12,490	16,660	22,900	69.4
1.2	Construction Facility	380	20	130	300	0.5
1.3	Tow Out	760	200	260	360	1.1
1.4	Bed preparation & fixing	1,900	490	660	900	2.7
3	Turbines	1,660	860	1,140	1,570	4.7
4	Generators & Other M. & E. Plant	6,630	1,710	2,280	3,140	9.5
5	Rock Anchors	5,050	1,310	1,740	2,390	7.2
6	Power Collection & Transmission	3,320	860	1,140	1,570	4.7
I	Energy Input	68,010	17,940	24,010	33,130	100%
Ø	Energy Output $(x10^3\ GJ_e)$	-	28,390	22,870	17,350	95%
I/Ø	Net Energy Requirement	-	0.63	1.05	1.91	-
Ø/I	Energy Ratio	-	1.58	0.95	0.52	-

1979/80

Energy Analysis

Sumary Sheet: 6

Table 7

S.E.A. Clam

HHM (11m x 15m x 270m) June 1980

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	220	220	220	
	Scheme lifetime (yr)	-	30	25	20	
1.1	Construct Spines	264,560	1,746	2,328	3,200	36.8
1.2	Construction Facility	870	6	8	10	0.1
1.3	Tow Out	19,000	125	167	230	2.6
2.1	Flap	106,080	700	930	1,280	14.8
2.2	Hinge	5,830	165	257	471	4.1
2.3	Bag	7,430	211	328	600	5.2
2.4	Ducts	1,840	12	16	22	0.3
3	Turbines	65,700	434	578	795	9.2
	Generators & Electrical Equipment	27,250	180	240	330	3.8
5	Moorings & Piles	37,910	436	582	685	9.2
6	Power Collection & Transmission	100,000	660	880	1,210	13.9
I	Energy Input	636,460	4,675	6,314	8,833	100%
Ø	Energy Output ($x10^3$ GJ_e)	-	18,730	14,237	10,300	225%
I/Ø	Net Energy Requirement	-	0.25	0.44	0.86	-
Ø/I	Energy Ratio	-	4.01	2.25	1.17	-

1979/80

Energy Analysis

Sumary Sheet: 7

Table 8

Salters Duck

Edinburgh Scopa Laing November 1979

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	1418*	1523	1628*	
	Scheme lifetime (yr)	-	30	25	20	
1.1	Construct Devices	17,302	736	1,053	1,548	16.3
1.2	Construction Facility	1,880	80	114	168	1.8
1.3	Tow Out	2,405	102	147	215	2.3
2	Spine Eqpt., Bearings & Ballast Syst.	16,314	694	994	1,480	15.4
3	Gyro & Power Module	29,638	1,261	1,805	2,654	27.9
4	Generators & Electrical Equipment on Board	2,185	93	133	196	2.1
5	Moorings & Anchors	3,817	162	233	342	3.6
6	Power Collection & Transmission	13,969	594	851	1,250	13.2
7	Maintenance**	18,675	794	1,138	1,672	17.6
	Energy Input	106,185	4,517	6,468	9,508	100%
	Energy Output	-	18,293	14,824	11,985	229%
	Net Energy Requirement	-	0.25	0.44	0.79	-
	Energy Ratio	-	4.05	2.29	1.26	-

* RPT recommended number of devices

** Maintenance included separately for this device, totals are consistent with other devices

1979/80

Energy Analysis

Sumary Sheet: 8

Table 9

Belfast Buoy

Tension Leg Design November 1979

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme (x10^3 GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	2566	2566	2566	
	Scheme lifetime (yr)		30	25	20	
1.1	Construct Devices	49,753	3,830	5,107	7,022	67.1
1.2	Construction Facility	190	15	20	27	0.3
1.3	Tow Out	1,844	142	189	260	2.5
2	Turbine	1,100	85	113	155	1.5
3	Mechanical Equipment	2,220	171	228	313	3.0
4	Electrical Equipment	1,468	113	151	207	2.0
5	Mooring	7,230	557	742	1,020	9.8
6	Power Collection & Transmission	8,400	647	862	1,185	11.3
7	Maintenance*	1,913	147	196	270	2.6
I	Energy Input	74,118	5,707	7,608	10,460	100%
Ø	Energy Output (x10^3 GJ_e)	-	19,239	15,770	12,616	207%
I/Ø	Net Energy Requirement	-	0.30	0.48	0.83	-
Ø/I	Energy Ratio	-	3.37	2.07	1.21	-

* Maintenance included separately for this device. Totals are consistent with other devices.

Table 10

Energy Analysis of Wave Energy Systems: 1979/80 Reference Designs

Summary of Results

	System	Type & Dimensions	Date		N Net Energy Requirement *($\frac{GJ_t}{GJ_e}$) R Energy Ratio *($\frac{GJ_e}{GJ_t}$)			Date of Calculation
					Lower Bound	Modal Value	Upper Bound	
1	Lancaster Flexible Bag	'Top Duct' 190 x 10 x 13m	Nov. 1979	N	0.15	0.23	0.39	February 1981
				R	*6.70*	*4.38*	*2.56*	
2	Salter Duck	ESL 24 x 10m ϕ	Nov. 1979	N	0.25	0.44	0.79	August 1981
				R	*4.05*	*2.29*	*1.26*	
3	S.E.A. Clam	11 x 15 x 270m 'HHM'	June 1980	N	0.25	0.44	0.86	Preliminary Values: July 1981
				R	*4.01*	*2.25*	*1.17*	
4	Belfast Buoy	'Tension Leg' 40mϕ x 40m	Nov. 1979	N	0.30	0.48	0.83	August 1981
				R	*3.37*	*2.08*	*1.21*	
5	Bristol Oscillating Cylinder	'precast pipeline & piled' 50 x 12m ϕ	March 1980	N	0.32	0.53	0.92	March 1981
				R	*3.15*	*1.87*	*1.08*	
6	NEL Oscillating Water Column	'Bottom Standing' 80 x 44 x 32m	Nov. 1979	N	0.55	0.87	1.47	April 1981
				R	*1.80*	*1.15*	*0.68*	
7	NEL Oscillating Water Column	'Breakwater' 64 x 24 x 26m	March 1980	N	0.50	0.89	1.91	October 1981
				R	*1.98*	*1.12*	*0.52*	
8	Vickers	Original Mk 7 29 m ϕ x 16m	Nov. 1979	N	0.63	1.05	1.91	April 1981
				R	*1.59*	*0.95*	*0.52*	

- over -

NOTES

- Above results are expressed on an annual basis
- Net Energy Requirement (N) $= \dfrac{\text{equivalent annual primary energy input } (GJ_t)}{\text{annual energy output at Perth } (GJ_e)}$
- *Energy Ratio (R)* $= \dfrac{\textit{annual energy output at Perth } (GJ_e)}{\textit{equivalent annual primary energy input } (GJ_t)}$

Lifetime of system used for 'lower bound value' : 30 years
'modal value' : 25 years
'upper bound value' : 20 years

'Modal Value' represents most likely combination of input and output

'Lower' and 'Upper' bound values represent most extreme combinations of input and output.

1981

Energy Analysis

Sumary Sheet:

Table 11

Bristol Oscillating Cylinder

November 81 Reference Design

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme (x10^3 GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	420	420	420	-
	Scheme lifetime (yr)	-	30	25	20	-
1.1	Structure (materials)	20,863	262.9	350.5	481.9	10.6
	Construction energy,) Formwork & facility)	8,876	111.8	149.1	205.1	4.5
2 (&4)	Moorings & power Conversion equipment	107,154	1350.1	1800.2	2475.3	54.7
3.1-2	Piled anchors: materials	2,177	27.4	36.6	50.3	1.1
3.3	Piled anchors installation	21,704	273.4	364.6	501.4	11.1
5	Hydraulic transmission	11,637	146.6	195.5	268.4	5.9
6.1	Turbo generator platform	3,617	45.6	60.8	83.6	1.8
6.2	Turbo generator equipment	2,230	28.1	37.5	51.5	1.1
7	Electrical transmission	1,629	20.5	27.4	37.6	0.8
8	Tow out & initial installation	1,627	20.5	27.3	37.6	0.8
9	Maintenance	14,415	181.6	242.2	333.0	7.4
	Energy input	195,929	2468.5	3291.7	4525.7	100
	Energy output (x10^3 GJe)	-	13,010	10,408 (330 MW)	7,806	316
	Net energy requirement		0.190	0.316	0.580	
	Energy ratio		5.27	3.16	1.72	

1981

Energy Analysis

Sumary Sheet:

Table 12
Lancaster Flexible Bag
Nov. 81 Ref. Design

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	336	336	336	
	Scheme lifetime (yr)		30	25	20	
1.1	Structure (Materials)	284,587	2869	3825	5259	46.1
1.2-4	Construction Energy, Formwork & Facility	75,760	764	1018	1400	12.3
2.1	Flexible Bag (2 per life) per bag total	4,600 29,200	93	124	170	1.5
2.2	Valves & Box	13,818	139	186	255	2.2
2.3	Air Ducting	28,562	288	384	528	4.6
2.4	Compartment Lining	7,395	75	99	137	1.2
2.5	Auxiliary Systems	3,492	35	47	65	0.6
3.1-2	Turbines	5,356	54	72	99	0.9
3.3	Diffusers	1,350	14	18	25	0.2
3.4	Power Plant Modules	2,669	27	36	49	0.4
4	Electrical Eqpt. on board	15,050	152	202	278	2.4
5.1-2	Tube Pump Moorings Materials	12,880	130	173	238	2.1
5.3	Pile Materials	5,742	58	77	106	0.9
5.4	Pile Installation	6,541	66	88	121	1.1
5.5	Mooring Installation	7,913	80	106	146	1.3
6	Tow-out	12,451	126	167	230	2.0
7	Power Collection & Transmission	65,476	660	880	1210	10.6
8	Maintenance	59,748	602	803	1104	9.7
	Energy Input	613,390	6,232	8305	10,316	100
	Energy Output (WPL) 1.8 MW	-	23,852	19,082	14,311	
	Net Energy Reqt. (WPL)	-	0.26	0.44	0.72	
	Energy Ratio (WPL)	-	3.83	2.30	1.39	

1981

Table 13

Energy Analysis

Sumary Sheet:

NEL OWC
Floating Terminator
November 1981 Reference Design

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	167	167	167	-
	Scheme lifetime (yr)	-	30	25	20	-
1.1.- 1.3	Structure: Materials	197,135	987.6	1316.9	1810.7	27.6
1.1.- 4.6	Construction Energy, Formwork & Facility	79,318	397.4	529.8	690.6	11.1
1.3	Tow Out	42,155	151.7	281.6	477.0	5.9
2	Mechanical Equipment	6,656	33.3	44.5	61.1	0.9
3	Turbines (cored)	33,324	167.0	222.6	306.1	4.7
4	Electrical Eqpt. on board*	74,100	371.2	495.0	680.6	10.4
5	Moorings & Anchors*	135,908	680.9	907.9	1248.3	19.0
6	Power collection* & tranmission	116,808	585.2	780.3	1072.9	16.3
7	Maintenance*	30,000	150.3	200.4	275.6	4.2
	Energy Input	715,404	3524.6	4779.0	6622.9	100
	Energy Output ($x10^3$ GJ_e)	-	15,809	12646 (401 MW)	9,486	265
	Net Energy Requirement		0.223	0.378	0.698	
	Energy Ratio		4.49	2.65	1.43	

* Full details not available for these categories

1981.

Table 14

Energy Analysis

Sumary Sheet:

SEA Clam
November 1981 Ref. Design

	Item	Initial Input Per Device (GJ_t)	Annual Energy Input Per 2 GW Scheme ($x10^3$ GJ_t)			% of Modal Input
			Lower	Modal	Upper	
	Number of devices	1	320	320	320	-
	Scheme lifetime (yr)	-	30	25	20	-
1.1	Spine Materials	156,886	1477	1970	2708	35.8
	Construction Energy	50,851	488	650	895	11.8
	Formwork and Facility (4 No)					
2	Steelworks	59,646	573	763	1050	13.2
3	Flexible Bag	8,842	85	113	156	2.1
4	Turbogenerator	16,793	161	215	296	3.9
5	Auxiliaries	1,024	10	31	18	0.2
6	Moorings	15,009	144	192	264	3.5
7	Tow Out*	11,005	106	141	194	2.6
8	Electrical Equipment On Board	31,500	302	403	554	7.3
9	Power Collection and Transmission to Skye*	65,781	631	842	1158	15.3
10	Maintenance	15,625	150	200	275	3.6
I	Energy Input	429,962	4127	5502	7568	100
Ø	Energy Output ($x10^3$ GJ_e)	-	24,956	19,962 (633 MW)	14,974	371%
I/Ø	Net Energy Requirement (GJ_t/GJ_e)	-	0.165	0.276	0.505	
Ø/I	Energy Ratio (GJ_e/GJ_t)	-	6.05	3.63	1.98	

Table 15 Energy Analysis of Wave Energy Systems: 1981 Reference Designs Based on Device Teams Output From RPT Letter 14.12.81

System	Type and Dimensions	Date	Net Energy Requirement N GJ_t/GJ			Energy Ratio R Modal Value GJ_e/GJ_t
			Low	Modal	Upper	
Bristol Oscillating Cylinder	75 m x 12 m	November 1981 Ref.	0.19	0.32	0.58	3.16
Lancaster Flexible Bag	255 x 22m x 15m (1.8MW/device)	November 1981 Ref.	0.26	0.44	0.72	2.30
NEL Oscillating Water Column	Floating Terminator 263 x 28 x 19m	November 1981	0.22	0.38	0.70	2.65
	Floating Attenuator	November 1981				
	Raised Breakwater					
S.E.A. Clam	275 x 15 x 13m	November 1981 Ref. (18.1.82)	0.17	0.28	0.50	3.63

incomplete information on moorings