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The Economic Analysis of Wave Energy

H G Tolland
J F Walker

ECONOMIC ANALYSIS OF WAVE ENERGY

H.G. TOLLAND AND J.F. WALKER

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SUMMARY

The economic analysis of the production of electricity on a significant national scale from wave energy reported in ETSU's Strategic Review of the Renewable Energy Technologies showed that in 1982 it was unattractive when compared with competing technologies. Subsequent analysis has refined our understanding of wave energy economics while confirming the findings of the Strategic Review.

The Harwell electricity supply system model has been used to recalculate breakeven costs, net present values and benefit/cost ratios in the same scenarios as used in the Strategic Review. Attention was focused on a 2 GW wave power station with an assumed annual load factor of 25% installed between 2001 and 2010 with a life of 25 years. Much of the analysis was carried out for this first wave power station but the sensitivities to the main assumptions and the economics of subsequent wave power stations were considered.

This more recent economic analysis shows that while wave energy can appear cost-effective under particularly favourable scenarios using optimistic assumptions on costs and productivity, its overall economic prospects are not good. The analysis merely serves to strengthen the conclusion of the Strategic Review of the Renewable Energy Technologies that the economic prospects of wave energy are poor both in comparison with other renewable energy technologies and with conventional thermal plant. This suggests that wave power is only likely to be considered by a UK electricity board as some form of strategic option which could be relied upon if other more economically attractive generation options became unavailable for non-economic reasons. Its deployment would increase costs to the consumer in all scenarios considered.

KEYWORDS

Wave energy; economic analysis; electricity generation.

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H. G. Tolland and J. F. Walker

Energy Technology Division, AERE, Harwell, Oxon.

ABSTRACT

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INTRODUCTION

The economic analysis of wave energy reported in the Strategic Review of the Renewable Energy Technologies (ETSU, 1982) showed that the economics of wave energy are unattractive when compared with competing technologies. This conclusion, which was the basis of the ACORD recommendation to run down the wave energy programme, has subsequently been confirmed by further economic analysis. The main findings of this analysis are presented in the Wave Energy Report (ETSU, in prep.) and the purpose of this note is to provide a more detailed documentation of this work.

The direct costs of wave energy are the engineering costs of construction, operation and maintenance. These costs, while they may be subject to many uncertainties and difficulties of interpretation, are relatively easy to recognise and define. The Wave Energy Report gives detailed consideration to the various elements of costs, how they are estimated and the uncertainties in these estimates. The net benefit of wave energy is the reduction it would bring about in the overall system cost of meeting a given level and pattern of electricity demand with a defined level of security of supply. In addition to these direct costs and benefits there may be indirect costs and benefits arising from the impact wave power stations and their associated infrastructure make on the environment and man's activities (Probert and Mitchell, 1981; ETSU, in prep.). No attempt has been made to quantify these indirect costs and benefits and indeed some are difficult to quantify in financial terms. Nevertheless, these indirect effects are likely to be small in financial terms in comparison with the direct costs and benefits and are unlikely to modify the economic analysis in any significant way. Thus the present analysis is based on direct costs and benefits alone.

The economic analysis of wave energy is based on the use of a total system model of the UK electricity generating system. The justification for this approach is given in the Strategic Review (ETSU, 1982). The Review discusses the main features of how wave energy would interact with the electricity generating system and the use of the system model in assessing economics of wave energy and other renewable energy technologies. The Review demonstrated that the economic prospects of wave energy are poor both in comparison with other renewable energy technologies and with conventional thermal plant.

The economic analysis reported here has refined and extended our understanding of wave power economics while confirming the results of the Strategic Review. The same basic methodology was used in both analyses. This is described in the following paragraphs, together with the structure and operation of the electricity generating system model. The results of the analysis are then presented in terms of breakeven costs, net present values and benefit/cost ratios.

Electricity Supply System Model

The financial value attributed to an electricity producing renewable energy source such as wave energy arises from the contribution it makes to meeting the expected total demand for electricity during its lifetime. It is reasonable to suppose that at the future date when wave power stations might be in operation, most electricity would be provided from proven conventional sources, principally from nuclear and coal-fired steam cycle plant (oil-fired plant being phased out), and from gas turbines operating to meet peaks in demand. Peaks in demand may also be met via storage schemes. In addition there may be other renewable energy sources on the system such as a Severn

Barrage or wind power. It is necessary to take account of these various possibilities.

It is also necessary to take account of the important characteristics of wave energy from the point of view of the electricity system. These characteristics are that wave energy is intermittent and unpredictable and that the output is not related to daily variation in demand. In addition there is a seasonal variation in the amount of energy available. This is discussed in Fig. 1.

Whenever possible, plant in the electricity supply system is used in merit order (Fig. 2), that is in order of increasing avoidable operating costs, to meet immediate demand. The electricity producing renewable energy sources, including wave energy, have low avoidable operating costs and so energy from those sources would always be taken up as first choice. The benefit arises mainly in the form of fuel savings from the plant displaced from operation whenever the renewable energy source is in operation. Thus its value depends on the quantity and cost of the fuel which would otherwise have to be used to provide the same electricity from conventional plant. The distribution of these savings among the fuels for the various types of thermal plant depends on the available capacities of each type of thermal generation. In addition there are lesser benefits arising from the contribution the renewable energy source makes to the capacity required to meet demand. The value of these benefits changes from year to year as fuel prices and the pattern of electricity demand changes and as the plant mix on the system is altered due to new plant being commissioned and old plant being retired. The proper evaluation of these benefits therefore requires a model of the electricity supply system together with a set of assumptions concerning future variations in fuel prices and demand.

The system model approach takes account of possible changes in the pattern of investment and system operating costs after a renewable energy source such as wave energy is introduced by calculating the least cost mode of meeting demand with or without the renewable energy source. If we regard such a source as part of a large interactive system (the mainland UK electricity supply industry), the net benefit it confers is measured by the reduction it brings about in the overall system cost of meeting a given level and pattern of electricity demand.

The model used is a refined and developed version of the model used for the initial appraisal of wave energy economics contained in the Strategic Review of the Renewable Energy Technologies (ETSU, 1982). The Review contains a description of the model and its use. The methodology was influenced by the fact that the model could not at that time take a renewable energy source as one of the plant types and include it in the optimisation. The same basic procedure was used for much of the work on wave energy and was as follows:-

- (i) compute the optimum plant mix and cost over time of meeting a defined pattern of demand without renewable energy on the system;
- (ii) subtract from the demand profile used in (i) the power output of any renewable energy source being considered, to give a modified pattern to be met by the rest of the system;
- (iii) use the model to compute the optimum plant mix and cost of meeting the modified demand pattern from (ii);

- (iv) the difference between the total discounted costs in (i) and (iii) is the gross benefit ascribable to the renewable energy source. This may be used in the derivation of a benefit/cost ratio;
- (v) the output from the programme also shows the savings that arise in the capital investment programmes for various categories of plant, and analyses the overall gross benefit into fuel and other cost savings of various types.

An important refinement of the model carried out since the Strategic Review is that it is now able to include up to 3 renewable energy sources in the optimisation process (ETSU, 1983). This means that when operating in this mode it will only call for the renewable source if it is economic to do so. Then it will either build up to the economic maximum or to a limiting constraint supplied to the model, whichever is the lower. This approach enables both the maximum economic penetration of the renewable source into the plant mix and the breakeven cost to be determined.

A limitation of the model as used in this study is that it does not deal directly with any changes to the operating costs of conventional power stations which would arise from the introduction of a renewable energy source. For example the intermittent nature of the output from such a source would cause other stations to be run at part load or to follow load more often. This would be likely to increase both the fuel and other running costs per unit of electricity generated by these stations. However, it is thought that these extra operating costs are likely to be less than 10% of the benefit from an intermittent renewable energy source such as wave energy (ETSU, 1982). Thus, while this limitation is likely to cause the model to overstate the benefits of wave energy slightly, it can do nothing to alter the basic conclusions that the economic prospects of wave energy are poor.

The model was specifically designed for long term planning problems. It is therefore designed to be fairly cheap and quick to run. To achieve this certain aspects of the electricity supply system are treated only in sufficient detail to give valid results, for example only 4 generating plant types (nuclear, coal, oil and gas turbines) are considered at present. This is judged to give adequate results for the present purpose. In considering the importance of these limitations, it is worth noting that the analysis is mainly concerned with evaluating differences in system planning requirements with and without renewable energy. If the errors introduced are approximately equal in the 2 cases, there will presumably be little effect on the conclusions of the economic appraisal.

Within its limitations the model provides a straightforward means of examining the economics of wave power under a wide range of conditions and of examining its sensitivity to different assumptions. The results section illustrates how this has been done. No doubt other variations in the basic assumptions could have been investigated, but it is thought that the main areas of sensitivity have been adequately explored to give a good understanding of wave energy economics and to place on a sound footing the fundamental conclusion that the economic prospects of wave energy are poor.

Development of the Electricity Supply System

The first wave power station would be unlikely to be fully operational before about 2010 and might have a life of around 25 years. Thus the timescale over which the economic analysis must be carried out is necessarily long. Because

of the great uncertainties involved in predicting the future it is necessary to take into account a broad range of possibilities in order to reach reasonably robust conclusions.

The economic analysis used the same scenarios as the Strategic Review of the Renewable Energy Technologies (ETSU, 1982). The use of these scenarios has the advantage that much information on the economic performance of other renewable energy technologies is then directly available for comparison with wave energy on the same basis.

The Strategic Review is based on a set of 9 independent scenarios made up of:

- 3 different views of future fuel prices coupled with a consistent view of electricity demand growth. Scenario I has the highest fuel prices and demand growth, Scenario III the lowest;
- 3 separate assumptions on the maximum rate at which nuclear power stations could be installed. These constraints, denoted H, M and L, are taken to be independent of changes in fuel prices and electricity demand: they refer only to the maximum rate at which the number of nuclear power stations can be increased, assuming they are required.

The full range of scenarios is therefore designated IH, IM, IL, IIH etc. Detailed definitions are given in Table 1.

In practice it is unnecessary to consider in detail the full range of scenarios in analysing wave energy. Only a few results are presented for all 9 scenarios, for most work a subset comprising scenarios IM, IIM, IIL and IIIM was used. This is thought to give a representative and adequately wide range of views of the future.

The price base used in the Strategic Review and in the model is mid-1981. All results in this report have been converted to May 1982 money values using a multiplier of 1.09 for consistency with the Wave Energy Report (ETSU, in prep.).

RESULTS

There is a wide variety of wave energy devices each with their own cost and performance characteristics. Also, it is necessary to consider not only the parameters of devices in their present state of development but also how these might be affected by refinement of device design and the influence of possible, though as yet unidentified, technical breakthroughs. Under these circumstances a parametric approach has been adopted which is aimed at giving a firm picture of wave energy economics and how it is influenced by possible variations in the basic parameters and assumptions. This enables breakeven costs, net present values and benefit/cost ratios to be derived for a range of costs and performance covering the likely range for wave energy.

The exploitation of wave energy as part of the bulk supply of electricity in the UK would presumably involve a series of power stations developed in a modular manner. Each of these could be around 2 GW capacity. Much can be learnt about the economics of wave energy simply by considering the first 2 GW station. Additional factors need to be taken into account for larger installed capacities and in general the analysis is more complex. These considerations are set aside until later.

An important characteristic of a wave power system is its annual productivity; i.e. the ratio of the energy actually produced by a system in a year to the quantity of energy it would produce if operated at full installed capacity throughout the year. This definition is equivalent to an annual load factor. In practice, the load factors associated with the various wave power devices are broadly similar, many lying between 20 and 25%. For simplicity of presentation attention is focused on a 25% load factor, which is perhaps slightly optimistic. However, its use facilitates comparison with the Strategic Review and it could be regarded as making some allowance for the possibility that device performance might improve as designs are refined.

The extent to which this 25% load factor is optimistic is illustrated in Table 2. This shows load factors for a number of devices for a nominal capacity of 2 GW and suggests that a typical load factor would be around 20%. The fact that the economic prospects of wave energy are shown to be poor is reinforced by the latest (and lower) load factor information.

A further complication is that the load factors discussed above are for a nominal capacity (2 GW). This nominal value is based on being able to supply 2 GW for at least 5% of the time and implies actual installed capacities are higher, sometimes much higher. This is illustrated in Table 2 where load factors based on actual installed capacities are quoted. Full power output would only occur for a small proportion of the year and the analysis and costings assume that this power could be accepted. This would imply operating the transmission system under overload conditions as part of normal practice. It is unlikely that this would be acceptable to the electricity supply industry so that the potential additional output above the 2 GW would not be available. The effect of this is that the analysis overstates the benefits slightly.

Economics of the First 2 GW Station

For most of the economic analysis it was assumed that the first 2 GW of capacity are installed from 2001 to 2010. The rate of increase of capacity was assumed to be linear and the life of a new installation 25 years. For example the 0.2 GW of plant installed in 2001 would be retired at the end of 2025. This assumption is identical to that contained in the Strategic Review (ETSU, 1982) and ensures that the results are directly comparable.

Results from the electricity model show that for a given seasonal distribution of energy the system cost savings arising from any wave power station of 2 GW capacity and annual load factor up to 50% are proportional to the annual energy produced. This implies that the benefits are linearly dependent on load factor. This result is true in all 9 scenarios and enables the results presented here to be readily extended to cover other load factors. However, because additional factors become important for larger installed capacities, it is only true provided the total installed capacity of wave energy stations remains of modest size. Also, this analysis implicitly assumes that no other intermittent renewable energy source is present on the system.

The results from the model may be used to derive breakeven costs directly and when taken in conjunction with cost data can give net present values and benefit/cost ratios. Table 3 gives a sample of the model output and ensuing calculations for a 2 GW wave power station at 25% load factor. These give breakeven cost together with the net present value and benefit/cost ratios for a wave power station costing £5,000 M to build and £80 M per year to maintain.

Breakeven Costs

Breakeven costs define the minimum cost target which must be met by wave energy. The total breakeven cost is the sum of the initial capital cost and the capitalised value of fixed operating and maintenance costs for which the benefit/cost ratio is one. Table 4 gives the breakeven costs for a wave power station with 25% load factor expressed as £/kW of installed capacity. Equivalent p/kWh figures are also shown, though these do not depend on load factor.

Only in Scenario I is the lower part of the cost range for wave power of 9-15 p/kWh (RPT, 1983; ETSU, in prep.) reasonably close to the breakeven cost of 7-8 p/kWh. However, this scenario is especially favourable to renewable energy and in the remaining scenarios wave power does not meet breakeven costs and so would not be built.

The gap between wave energy costs and breakeven costs is already significant in Scenario I, particularly bearing in mind the optimistic assumption of a 25% load factor. In other scenarios the gap is much greater. In order to meet breakeven costs one or more technical breakthroughs resulting in significant cost reductions or improvement in performance or both appears to be necessary.

Net Present Values

The net present value (NPV) gives an absolute indication of the worth of an investment. It is simply the difference between the benefits and costs, all discounted, i.e.

$$\text{NPV} = \text{PV (Benefits)} - \text{PV (Costs)}.$$

An investment is economically acceptable if it has a net present value which is greater than or equal to zero. However, there may be more attractive investment options so a positive net present value does not necessarily imply that an investment should go ahead. Indeed, going ahead with some other more attractive investment may decrease the benefits and hence reduce the NPV of wave energy below zero. The results presented here take no account of investment in, for example, wind or tidal power stations, both of which are more attractive economically than wave energy. Thus the results presented for wave energy are the best it is likely to achieve.

Table 5 shows NPVs for a 2 GW station at 25% load factor in Scenarios IM, IIL, IIM and IIIM. The various assumed capital costs span the range covered by the leading wave energy devices and the assumed capitalised maintenance cost of £350 M is typical of wave energy devices.

Only in Scenario IM are there cases where the NPV is positive. In most cases it is strongly negative. The NPV can be used as an indicator of how much it is worth spending on R&D. At best, it seems fair to assume that the chances of a positive NPV being realised are small, i.e. the combination of circumstances for which this is the outcome is rare. This indicates that on present evidence only a modest R&D programme is justified, in line with the decision by the Department of Energy to greatly reduce the scope of the wave power programme.

Benefit/Cost Ratios

The main economic criterion used in the Strategic Review to present the results of the economic appraisal of renewable energy technologies is the benefit/cost ratio. This focuses on the net benefit per unit of investment in capital works and is applicable where money for capital investment is the main constraint. This criterion is consistent with the main principle of minimising the total cost of meeting electricity demand. For presentational purposes it has the advantage over the net present value of reducing the comparison of benefits and costs to a small number rather than a large amount of money. It gives a fair guide to the ranking of investments. Its use in the present analysis also makes the Strategic Review data on other renewable energy sources directly available for comparison with wave energy.

A benefit/cost ratio of one implies that the investment is economically acceptable; however, there may be more attractive investment options. As with the NPV, going ahead with these more attractive options may reduce the benefit/cost ratio. This is a particularly important consideration for wave energy since its economics are markedly less attractive than other renewable and conventional energy sources.

The dependence of the benefit/cost ratio of a wave power station on both capital and maintenance costs is illustrated in Figs. 3 and 4. These figures have been selected to be reasonably representative of the estimates (RPT, 1983) made for the leading group of wave devices. For example, the capital cost of the leading device is typically $\pounds(3.5-5) \times 10^9$ for a 2 GW station with maintenance costs in the range $\pounds45-130$ M per year. It is worth noting that benefit/cost ratios rise quite rapidly once the breakeven cost is reached but for wave energy costs are generally too high for this to be of much importance.

These figures taken in conjunction with the costs and performance of the leading devices illustrate the extent to which presently predicted wave energy costs result in a discouraging economic appraisal. If the 25% load factor is combined with the lowest costs presently predicted then the benefit/cost ratios are just greater than one in those scenarios (I) particularly favourable to renewable energy sources. In the medium scenarios (II) the benefit/cost ratios all fall below one, even when the nuclear build rate is constrained.

Sensitivity Analysis

Sensitivity tests were carried out for the 2 GW reference case to see if any of the major uncertainties and risks associated with wave energy installation and performance would lead to any significant change in the generally poor economic prospects. For this purpose most of the main assumptions were considered. The overall conclusion is that none of the likely changes in economic performance appears to be large enough to alter the view that the economic prospects of wave power are poor.

Discount rate. The sensitivity of wave power economics to discount rate was tested in Scenario IIM. In general, a lower discount rate would render wave power a more attractive investment while a higher rate would increase its unattractiveness. Table 6 shows how breakeven costs vary with discount rate while Fig. 5 illustrates benefit/cost ratios for 3, 5 and 7% discount rates. The changes shown do not appear sufficiently substantial to suggest that the

economic unattractiveness of wave energy would be overturned merely by changing the discount rate.

Variation in the discount rate would affect the economic attractiveness of other electricity producing renewables and also that of nuclear and hydro power in a similar way. This is because they are all capital intensive investments with the main benefit accruing from a saving in fossil fuels. Thus changing the discount rate would do little to alter the economic attractiveness of wave energy in comparison with these other generating options.

Start of generation. If the deployment of wave energy is delayed then there is in general a higher proportion of nuclear plant on the system during the lifetime of the wave power station. This has the effect of reducing the value of fuel savings - a delay of 10 years lowers the breakeven cost by around 15-25% (Table 7).

Lifetime of plant. The main economic evaluation was carried out assuming a 25 year life. If a 30 year life is assumed with maintenance costing the same per year then the total reduction in system cost would be increased. The effect of this would be modest since savings in the early years of operation, which have a greater fossil fuel component, would have a greater weight in the total discounted value of benefits than those occurring later.

One way of improving the economic attractiveness of wave energy could be to extend the operating life of the plant. This would require replacement of mechanical and electrical plant, moorings and parts of the transmission system but assumes that the civil engineering structure would remain intact. In this way the life of the station might be extended to 50 years at a cost of perhaps 30% of the initial capital cost spent at the end of 25 years. However, the economic benefits accruing in the latter half of the station's life would be heavily discounted and include a relatively high proportion of nuclear fuel savings which are worth less than coal savings.

LARGER WAVE ENERGY INSTALLATIONS

As further wave power stations are installed, additional factors need to be taken into account:

- for larger wave power installations nuclear fuel comprises a greater proportion of fuel savings. This lowers the value of the benefits because nuclear fuel is cheaper than coal;
- also later wave power stations come on stream when the proportion of nuclear plant on the system is greater. This reinforces the last effect;
- the capacity credit for each additional wave power station becomes lower because of the limited extent to which the system can accept output from intermittent sources while still meeting demand with a given level of system security.

The effect of these factors on the gross systems savings of successive wave power stations are illustrated in Fig. 6 for Scenario IIM; for example, the value of increasing the wave power capacity from 15 to 16 GW is about 30% less than the value of the first 1 GW. Capital cost savings decline more rapidly but these always form a small proportion of total benefit.

These factors, together with the increasing transmission costs associated with larger wave energy installations tend to make wave energy rather less attractive than suggested by the results for a single 2 GW station. On current cost estimates they combined to limit the maximum amount of wave energy which the model would build in Scenario I to around 4-8 GW at 25% load factor. Thus even in the most favourable circumstances the maximum economic potential for wave energy is quite modest.

COMPARISON WITH OTHER ENERGY TECHNOLOGIES

Studies reported in the Strategic Review of the Renewable Energy Technologies (ETSU, 1982) showed that even in those scenarios in which wave power is likely to be economically acceptable other technologies including nuclear, tidal, wind and geothermal power offer better benefit/cost ratios on current assumptions. Presumably more economically attractive renewable energy sources would be installed prior to any wave energy. This would tend to reduce its benefits.

CONCLUSIONS

The economic analysis reported above has refined and extended our understanding of wave power economics while confirming the results of the Strategic Review of the Renewable Energy Technologies (ETSU, 1982). The results merely serve to strengthen the conclusion in the Review that the economic prospects of wave energy are poor both in comparison with other renewable energy technologies and with conventional thermal plant. This suggests that wave power is only likely to be considered by a UK electricity board as some form of strategic option which could be relied upon if other more economically attractive generation options became unavailable for non-economic reasons. Its deployment would increase costs to the consumer.

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TABLE 1 Definition of Scenarios

Plant Cost and Characteristics (all scenarios, all years)

	Life years	Capital Costs £/kW	Fixed Costs ¹ £/kW p.a.	Non-Fuel Variable Costs ² p/kWh
Coal	30 or 40 ³	625	10.5	0.137
Nuclear	25	1,310	13.3	0.493
Gas Turbine	30	350	6.7	0.389
Oil	30	540	10.5	0.137

Notes

- ¹ Fixed costs include such items as rents, rates, insurance and regular repairs and maintenance.
- ² Non-fuel variable costs include such items as fuel handling and staff costs.
- ³ New coal stations are taken to have a 40 year life to allow for possible refurbishment after 30 years of operation. This is assumed to cost £6/kW p.a. for each year after 30 years.

Price of Fuel to Power Stations (p/therm)

		1981	2000	2025
<u>Case I</u>	Coal	17.4	55.6	80.6
	Fuel Oil	26.2	82.8	115.5
	Distillate Oil	41.4	111.2	153.7
	Nuclear Fuel (primary energy basis)	5.6	9.7	10.2
<u>Case II</u>	Coal	17.4	37.1	63.2
	Fuel Oil	26.2	66.5	95.9
	Distillate Oil	41.4	90.5	128.6
	Nuclear Fuel (primary energy basis)	5.6	9.7	10.2
<u>Case III</u>	Coal	17.4	25.1	39.2
	Fuel Oil	26.2	40.3	54.5
	Distillate Oil	41.4	53.4	82.8
	Nuclear Fuel (primary energy basis)	5.6	9.7	10.2

Note: The scenario assumptions are given here in May 1982 money values for consistency but they are expressed in the model in mid-1981 money values. The values given here are rounded.

TABLE 1 Definition of Scenarios (continued)Maximum Availability of Power Stations

	Winter	Spring/Autumn	Summer
Coal	88	80	72
Oil	86	80	74
Gas Turbine	90	85	80
Nuclear	85	75	65

Note: The output of some renewable energy sources varies with the seasons. Thus it is important to take into account the effect of regular repair and maintenance on the seasonal availability of conventional power stations. This is done by specifying a maximum availability in each of 3 seasons; a 'winter' of 19 weeks; a 'summer' of 19 weeks; and a 'spring' and 'autumn' of 14 weeks.

Electricity Demand in Great Britain

System Maximum Demand (GW)	1980	1985	1990	1995	2000	2010	2025
Case I	45.0	47.0	53.0	60.0	68.2	88.6	131.5
Case II	45.0	45.2	47.6	50.3	56.7	67.6	90.7
Case III	45.0	45.0	45.6	46.4	47.6	50.8	55.9

Restrictions on Nuclear Power (GW)

Maximum amount of nuclear power (GW) that can be added to the GB electricity supply system during each 5 year period.

	1980-1985	1985-1990	1990-1995	1995-2000	2000-2005	2005-2010	All 5 year periods after 2010
H: High Nuclear	3.1	2.2	4.4	14.3	15.4	15.4	22.0
M: Medium Nuclear	3.1	2.2	4.4	11.0	12.1	12.1	17.6
L: Low Nuclear	3.1	2.2	2.2	6.6	7.7	7.7	11.0

Notes

- 1 The figure for 1980-1985 is the sum of the expected net capabilities of Dungeness B, Hartlepool and Heysham I, excluding auxiliary gas turbines.
- 2 The figure for 1980-1990 is the sum of the expected net capabilities of Heysham II and Torness, excluding auxiliary gas turbines.

TABLE 2 Electrical Output and Load Factors for 2 GW Wave
Power Stations of Various Types

Station (Device Type)	Performance		
	Mean Annual Output MW	Load Factor 1* %	Load Factor 2** %
Bristol Oscillating Cylinder	410	16	20.5
Lancaster Flexible Bag	282	9	14
NEL Breakwater	370	12	18.5
Vickers Terminator	430	20	21.5
Vickers Attenuator	430	19	21.5
Belfast Point Absorber	350	12	17.5
NEL Floating Terminator	400	15	20
Salter Duck	-	-	-
SEA Clam	430	17	21.5

* Load factor 1 is calculated on the basis of the actual total installed capacity used to achieve 2000 MW output for 5% of the time. In some cases this capacity is significantly more than 2 GW, approaching 3 GW.

** Load factor 2 is based on 2 GW nominal capacity and corresponds to the load factor used in presentation of the economic analysis.

TABLE 3 Model Output and Sample Calculations for a 2 GW
Wave Power Station at 25% Load Factor in Scenario IIM

Model Output

	Total Discounted System Costs in £M		
	Unmodified System (no wave energy)	Residual System	Savings
<u>Cost Savings</u>			
Capital	48,059	47,905	154
Fixed	16,529	16,486	43
Fuel	114,633	113,889	744
Operating	18,317	18,268	49
Total	197,538	196,548	990
Savings for 1 TWh/year	-	-	226

	Capacity in 2030 in GW		
	Unmodified System	Modified System	Savings
<u>Capacity Credit</u>			
Nuclear	82.5	82.5	-
Coal	30.006	29.338	0.708
Oil	0	0	-
Gas Turbine	13.410	13.234	0.176
Total	125.956	125.072	0.884

	Energies in 2030 in TWh		
	Unmodified System	Modified System	Savings
<u>Energy</u>			
Nuclear	500.65	498.83	1.82
Coal	58.45	55.90	2.55
Oil	0	0	0
Gas Turbine	0.57	0.57	0
Total	559.67	555.30	4.37

TABLE 3 (continued)

Sample Calculations

Capital costs (C_{cap}) + capitalised fixed operating costs (C_{op}) were expressed in terms of the costs applying to 1 TWh/year of energy output. At 25% load factor a 2 GW station has an annual energy output of 4.38 TWh/year. Hence the discounted costs are given by:

$$C_{cap} = 4.38 \times 0.04566 (3.2536 K_1 + 3.1752 K_2) \times 10^6$$

where K_1 = initial capital cost expressed as £/kW

K_2 = capitalised value of annual operating cost in £/kW/year.

The breakeven cost occurs when $C_{cap} + C_{op} = B$, the gross benefit and for the 25% load factor case is £3,040 M.

The information and formulae presented above are used in the calculation of net present values and benefit/cost ratios. For example take a 2 GW station costing £5,000 M to build and £80 M per year to operate.

C_{cap}	= £1,626.7 M
K_2	= £(40/0.07095) M (capitalised at 5% for 25 year life)
C_{op}	= £358 M
$C_{cap} + C_{op}$	= £1,984.7 M
Benefit	= £990 M
Net present value	= -£994.7 M
Benefit/cost ratio	= 0.5.

Notes

- 1 All discounting is to January 1981 using a 5% test discount rate. Thus the net present value is that in 1981.
- 2 Costs in the model are in mid 1981 money values but for consistency with the rest of the report they are expressed above in May 1982 money values. The figures above are rounded.

TABLE 4 Breakeven Costs for a 2 GW Wave Energy Station
at 25% Load Factor

Scenario	Breakeven Costs in Terms of:	
	£M	p/kWh
IL	4,720	7.9
IM	4,680	7.8
IH	4,400	7.4
IIL	3,650	6.1
IIM	3,040	5.1
IIH	2,460	4.1
IIIL	2,330	3.9
IIIM, IIH	2,060	3.4

Notes

- 1 Breakeven costs are proportional to load factor for the first 2 GW station though this simple relationship will not hold true for significantly larger installed capacities.
- 2 The above p/kWh figures are independent of load factor for the 2 GW station because the benefits are linearly dependent on load factor, i.e. on energy output. Also, they are insensitive to the proportion of the breakeven cost which is made up from capitalised fixed operating costs.
- 3 All figures are rounded.

TABLE 5 Net Present Value of a 2 GW Wave Power Station
at 25% Load Factor

Scenario	Net Present Value for a Capital Cost (£M) of			
	3,000	4,000	5,000	6,000
IM	+ 197	- 128	- 454	- 779
IIL	- 138	- 463	- 789	- 1,114
IIM	- 336	- 661	- 987	- 1,312
IIIM	- 656	- 981	- 1,307	- 1,632

Notes

- 1 The small variable operating costs of wave power are not included in these totals.
- 2 Annual fixed operating costs are taken as having a capitalised value of £350 M. This corresponds to just under £80 M p.a. and is roughly in the centre of expected maintenance costs.
- 3 All figures are rounded.

TABLE 6 Sensitivity of Breakeven Cost to Discount Rate
(Scenario IIM)

Discount Rate	Breakeven Cost £M
3%	2,380
5%	3,040
7%	3,350

Note: All figures are rounded.

TABLE 7 Sensitivity of Breakeven Cost to Start of Generation

Scenario	Breakeven Cost (£M) for Station Built	
	2001-2010	2011-2020
IM	4,680	3,790
IIL	3,650	3,020
IIM	3,040	2,290
IIIM	2,060	1,620

As the weather changes, so will the amount of wave energy available. When the seas are high, the wave power system will operate at maximum power and so less conventional generating capacity will need to be used, with consequent fuel savings. Conversely, in calm weather there will be no output from the system and conventional plant must operate to make up the deficiency.

In assessing the value of wave energy, we must take account of this variation. The data used are summarised in the table below and are the results of extensive statistical analysis of wave data supplied by the Institute of Oceanographic Sciences and of the conversion characteristics of typical wave energy devices.

The following instances exemplify the variation in wave energy during the year. As shown in the table below, 72% of all the energy would be supplied by the system during October to March and it would operate at full power for 9% of this time. In the calmer summer months of May to August, only 12% of the annual energy is generated. However, there is very little operation at full power during this summer period and for about two thirds of the time there is no output at all.

Seasonal Variation in Resource

Period	Fraction of annual energy produced during period	Mean power as a fraction of peak power (a)	Time at full power		Time at zero power	
			Prop. (b)	Total hours	Prop. (b)	Total hours
October-March	0.72	0.36	0.09	394	0.03	150
April	0.08	0.24	0.02	14	0.14	100
May-August	0.12	0.09	0.01	30	0.68	1,991
September	0.08	0.24	0.02	14	0.14	100
Year	1.00	0.25	0.05	452	0.27	2,341

(a) Equivalent to productivity for period shown.

(b) Proportion of period in extreme left hand column.

Fig. 1. Seasonal and daily variation in wave power.

The demand for electricity varies from hour to hour throughout the year and is met by a mix of types of generating plant, each of which has its special role within the system. Once a certain mix of plant is installed in the system, decisions about how to operate it are based on the avoidable operating costs of the various types of plant. These are the operating costs which can be avoided when the plant is not generating but on standby and for conventional plant they are dominated by fuel costs. To meet demand at a given time, plant will be brought on stream in reverse order of its avoidable operating cost, i.e. in its proper position in the so-called merit order. Plant with low operating costs (e.g. nuclear) is used to meet the base load, while plant which combines low capital cost with high operating costs, such as gas turbines, is used at a rather low annual load factor to meet peaks in demand.

For illustrative purposes the average available capacities of different types of plant have been superimposed on the demand curve of this diagram. In fact, plant availabilities are not constant throughout the year. Also, the level of available capacity for each type of plant will depend on the scenario being considered.

Fig. 2. Schematic annual load duration curve, illustrating plant merit order for a generating system.

Fig. 3. Benefit/cost ratio vs. annual maintenance for capital cost £4,360 M, 25% load factor.

Fig. 4. Benefit/cost ratio vs. initial capital cost, scenario IM, 25% load factor.

Note

The variation of benefit/cost ratio with capital cost is calculated assuming annual operating and maintenance costs of £87 M p.a. and 25% load factor.

Fig. 5. Sensitivity of benefit/cost ratio to discount rate in scenario IIM.

Fig. 6. Effect of increasing the installed capacity of wind or wave power stations (scenario IIM).