G. JENKINS COPY

ENERGY ANALYSIS IN THE ASSESSMENT OF THE U.K. WAVE ENERGY PROGRAMME, 1978.

Harrison, R.
Jenkins, G.
Mortimer, N.D.

ENERGY WORKSHOP REPORT NO. 18

Final report on project SRC GR/A50450

Energy analysis in the assessment of the U.K. wave energy programme, 1978

HARRISON, R.
JENKINS, G.
MORTIMER, N.D.

SUNDERLAND POLYTECHNIC

Sunderland Polytechnic

JUNE, 1980

CONTENTS

1. SUMMARY

1.1 In a long term situation of rising energy prices conventional economic appraisal of energy technologies has a number of shortcomings. It is not possible to determine the inflationary effects of energy price rises on costs and also it is a very uncertain guide in R & D planning. By using energy analysis the energy element in costs and the inflationary effects of price rises can be determined directly. Also the net energy requirement is an index of merit which is available during the R & D phase and can be related theoretically to the economics of a technology. It provides a good indicator, during R & D, of economic potential.

1.2 The calculations reported here for wave energy systems are based mainly on information contained in RPT 1978 draft report and hence relate to the reference designs as then conceived.

1.3 The modal net energy requirements (energy input/energy output) for the 1978 Reference Designs on a primary energy basis are as follows

National Engineering Laboratories	(NEL)	2.79 $GJ_{(t)}/GJ_{(e)}$
Wavepower Limited	(WPL)	1.45 $GJ_{(t)}/GJ_{(e)}$
Hydraulics Research Station	(HRS)	3.27 $GJ_{(t)}/GJ_{(e)}$
Sea Energy Associates	(SEA)	2.89 $GJ_{(t)}/GJ_{(e)}$
French Flexible Bag	(FFB)	0.46 $GJ_{(t)}/GJ_{(e)}$

1.4 On the basis of this information only the FFB satisfies the basic criteria of energetic viability. This criteria is that the net energy requirement of a wave energy system should be less than one.

1.5 While it is not possible as yet to establish the precise relationships between energy requirement and economic viability, clearly the 'energy returns' of the FFB are so low as to make it doubtful that this device would ever be economically viable in this form.

1.6 It is possible to model simply the relationship between energy requirements and costs. This indicates that a technology with a high energy requirement will suffer rapid cost inflation as energy prices rise. Depending on estimates of the value of output electricity (compared with the value of firm electricity) it seems that energy prices will have to rise 13 times before the FFB becomes economically viable. This is far beyond the limits of current medium term and even long-term planning horizons.

1.7 It is difficult to imagine any realistic economic circumstances which may develop in the medium and long term which would make wave energy, in this form, economically viable.

1.8 To radically alter this assessment will require a reduction in net energy requirement by factors ranging from 2.3 (FFB) to 16 (HRS). These improvements can only be achieved by substantial reductions in masses of structural and mooring materials per unit output together with improvements in the average load factor of all installed machinery.

1.9 Energy analysis raises serious questions about the wave energy programme. These must be answered convincingly before a rational case for committing major funds to the further development of these designs can be made. In particular the current emphasis on design for production would seem to be premature when basic problems of device size remain unresolved.

1.10 Further work is required constructing models of the net energy requirement of all devices in the programme in terms of major system parameters (structural size, peak/average power ratings etc.). Also energy analysis of new concepts and generic studies of wave energy devices is required. In this way established devices and new concepts will be analysed in a systematic way and it may be possible to identify directions of development which will offer the possibility of wave energy devices with low net energy requirements and with the ultimate potential to be economically viable.

2. ASPECTS OF DECISION-MAKING

The general aim of this work is to provide information that will assist decision makers to obtain rational assessments concerning energy technologies. From the beginning, in order to avoid confusion, it is important to distinguish between the different types of decision which have to be made during the development and implementation of energy technologies. It is the purpose of this introduction to describe the significance of the results presented here in terms of three particular forms of decision.

2.1 Imminent investment decisions

When a technology is fully developed and there is a good understanding of the likely costs of components and construction, then investment decisions can be made. These are frequently based upon comparison between the value of the output, in this case fuel, and the value of resources committed to its production. The value of the resources committed is usually assessed through a conventional cost engineering exercise, and it is normal to compare the unit costs of producing energy (e.g. pence/kWh) for competing technologies. All other factors being equal, it is rational to choose the technology with the lowest unit cost. A more sophisticated approach involves the application of discounted cash flow analysis to different schemes and the system with the highest net present value then becomes the rational choice. Whichever particular technique is used in assessment, a decision-making procedure is followed in a situation of moderate or low uncertainty, where current costs can be evaluated with some precision and subsequent outputs can be forecast.

Figure 2.1 Simple cash flow energy project during a period of constant fuel prices.

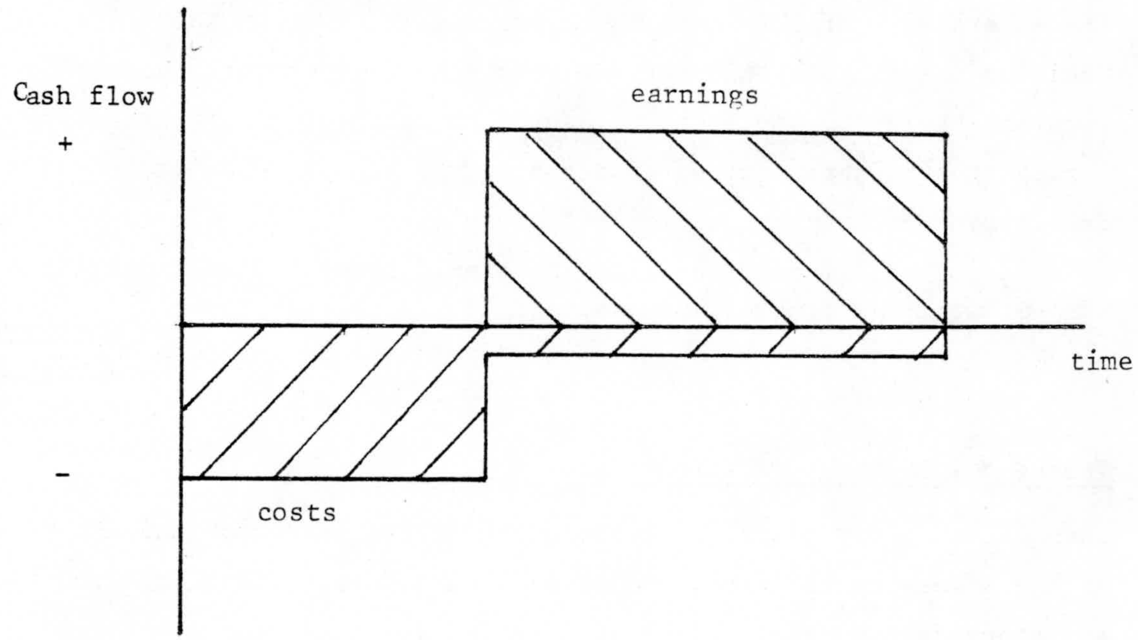
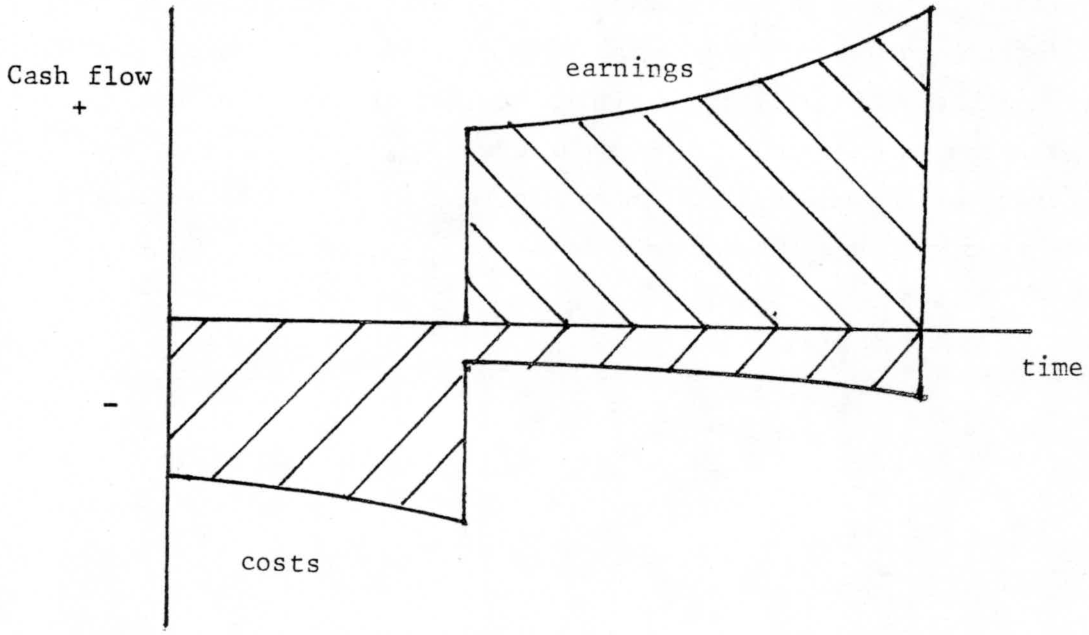


Figure 2.2 Simple cash flow of energy project during a period of rising fuel prices



There are problems, however, in situations where fuel prices are rising during construction and operation. This is illustrated by comparing figures 2.1 and 2.2 which show the actual cash flow during periods of both constant and rising fuel prices. These figures take into account the fact that, for energy technologies, fuel price inflation can influence costs as well as earnings. In general, this offsets the effects of discounting the cash flow. It is a relatively simple matter to assess the impact of such price rises on earnings and the analysis has already been applied to geothermal energy systems (Garnish,1976). However, it is not possible to determine the effect of price rises on costs using a conventional costing data base. Such an assessment must incorporate the results of energy analysis in the method shown later. If the construction period is short then it may be argued that the corrections are minor, but this may not be true in all cases, nor in the case of a project with a long construction time. For the sake of completeness this inflationary effect must be taken into account.

2.2 Medium-term planning decisions

If all energy policy could be based on the aggregate of individual investment decisions then policy formulation would be greatly simplified The approach outlined above, with appropriate corrections to accommodate fuel price rises, would be used in decision making situations. Whenever additional fuel supplies were needed, current unit costs would be computed, an expensive exercise in itself, and a new energy project, such as a new coal mine, oil well or nuclear power station, etc., would be started depending on the results. However, energy policy is clearly not as simple as this. It is concerned rather with industrial strategy; that is, whole industries must consider their commitments to particular technological routes, forecast the likely economic consequences of different options and plan developments accordingly. The electricity supply industry must decide whether or not to commit itself to the wide-scale introduction of nuclear power, the oil industry to exploration and production west of Shetland, for example. It would be naive to suggest that these industries are choosing strategies just on the basis of today's current costs,when it is obviously important to forecast the way in which input costs and the value of output will vary over the lengthy planning time scale being considered. It is conventional reasoning that fuel price rises will have the effect of reducing the economic threshold of new energy developments. In this reasoning it is usually assumed

Figure 2.3 Conventional view of new energy technology development.

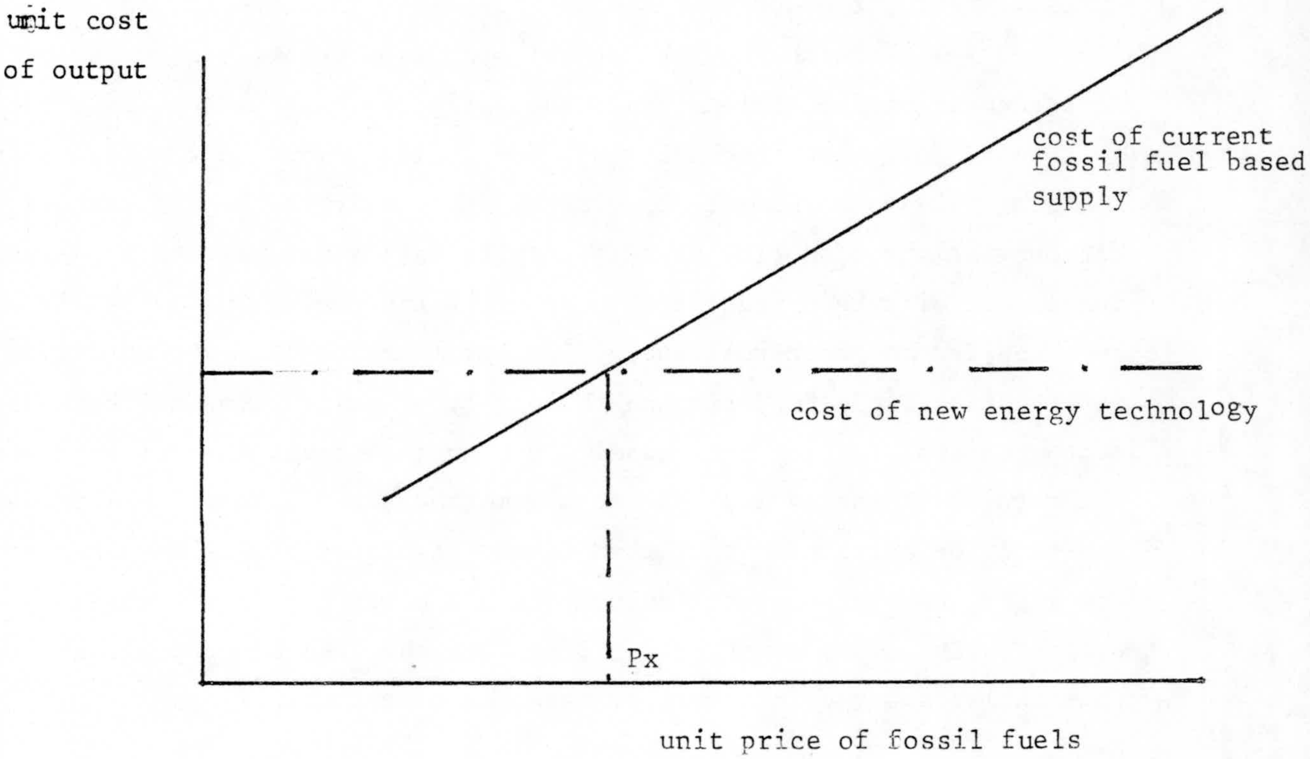
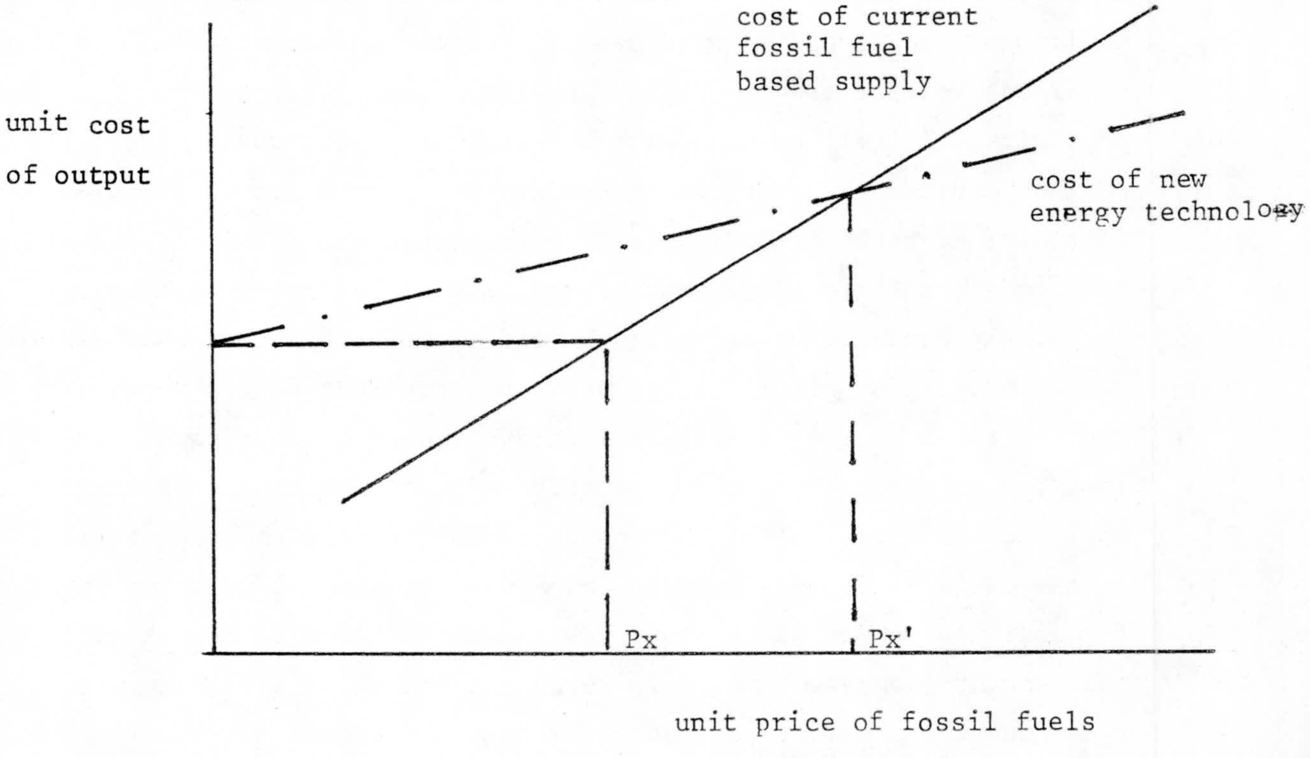


Figure 2.4 View of new energy technology development corrected for fuel price inflation.



that costs remain fixed whilst the output value rises as a result of fuel price increases. This view is fairly widely accepted (e.g. Starr, 1977) and is illustrated in figure 2.3

On this basis a new energy technology becomes economically competitive when fuel prices reach a certain level, Px , that is determined by the point at which the two cost lines intercept. However, this method of reasoning ignores an essential point, namely, that current fuel prices form an element of any current cost assessment. Hence, as fuel prices rise not only will the value of the energy produced increase but also the cost of production will increase in real terms. Figure 2.4 describes this relationship and demonstrates that economic viability is delayed until fuel prices rise beyond Px to a level Px'. Any major energy planning exercise, especially involving a radically new, different technology, which failed to take this into account could result in serious error if the energy element in the costs was large. Unfortunately, there is no simple method of determining this using conventional cost information and cost economics.

As an extension of this argument, fuel price inflation can also affect estimates of total reserves of energy sources. These reserve figures indicate the amount of energy resources available for use below particular maximum cost levels and, as such, these are important factors in medium and long term planning. The conventional view is represented in figure 2.5 which illustrates the variation of cumulative reserves with cost. This shows that, at a prevailing price level of C_1, it becomes economic to exploit resources up to a reserve level of R_1. Normally, as fuel prices increase to the new level of C_2, it is assumed that resources up to the new level of R_2 become economically extractable. However, this again ignores the effect of fuel prices on costs. A more realistic interpretation is depicted in figure 2.6. Here the entire reserve variation curve shifts to the right towards higher costs as fuel prices rise. The extent of this shift depends upon the size of the energy element in the costs. As shown, the actual growth of reserves is now determined by the way in which the reserve variation curve responds to price rises and this is depicted by the line AB. Figure 2.7 indicates that new reserve estimates obtained in this fashion are consistently lower than those previously predicted on constant cost assumptions. The difference between these current and actual reserve variation curves becomes more apparent as larger fuel price increases are contemplated.

Figure 2.5 Conventional view of reserve assessment

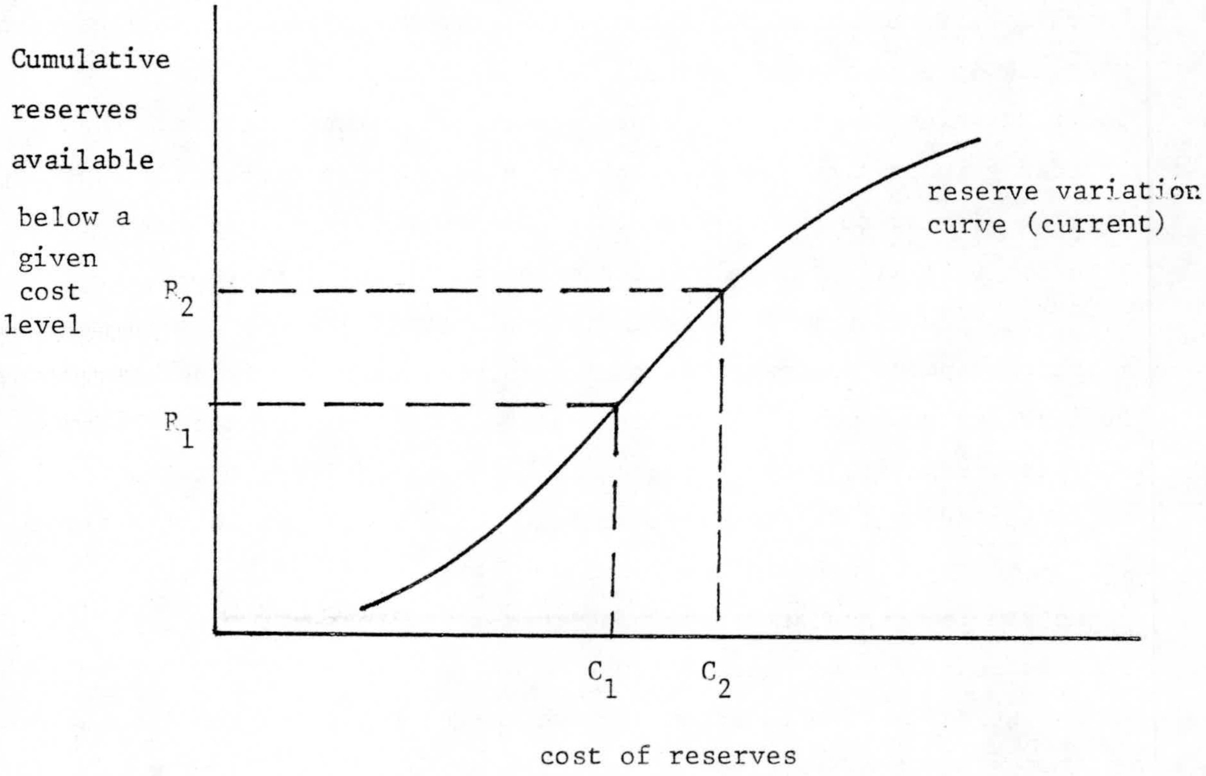


Figure 2.6 View of reserve assessment corrected for fuel price inflation.

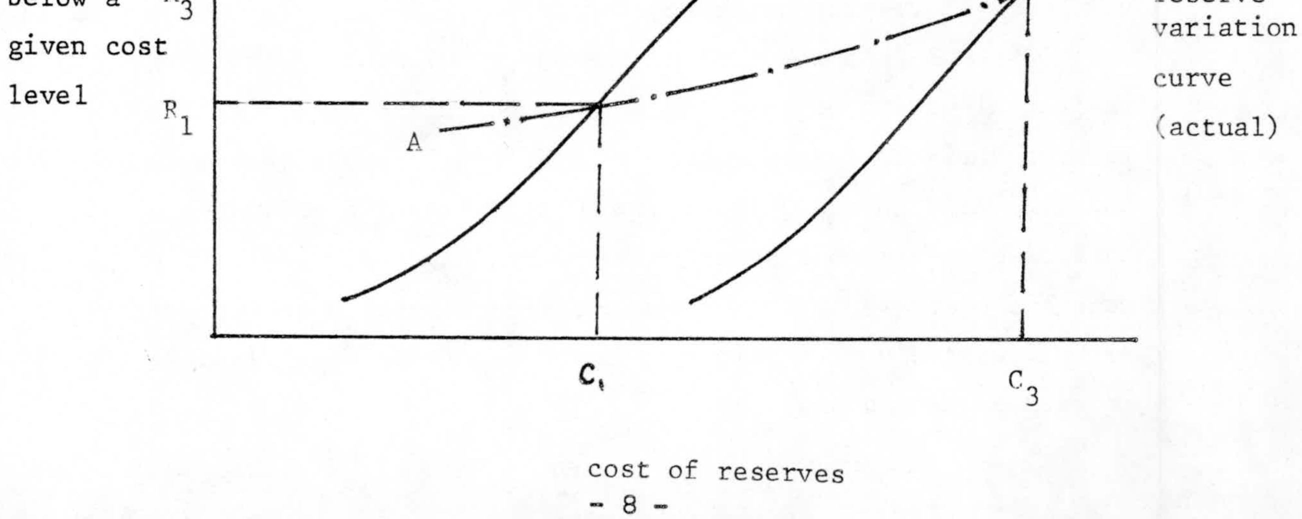
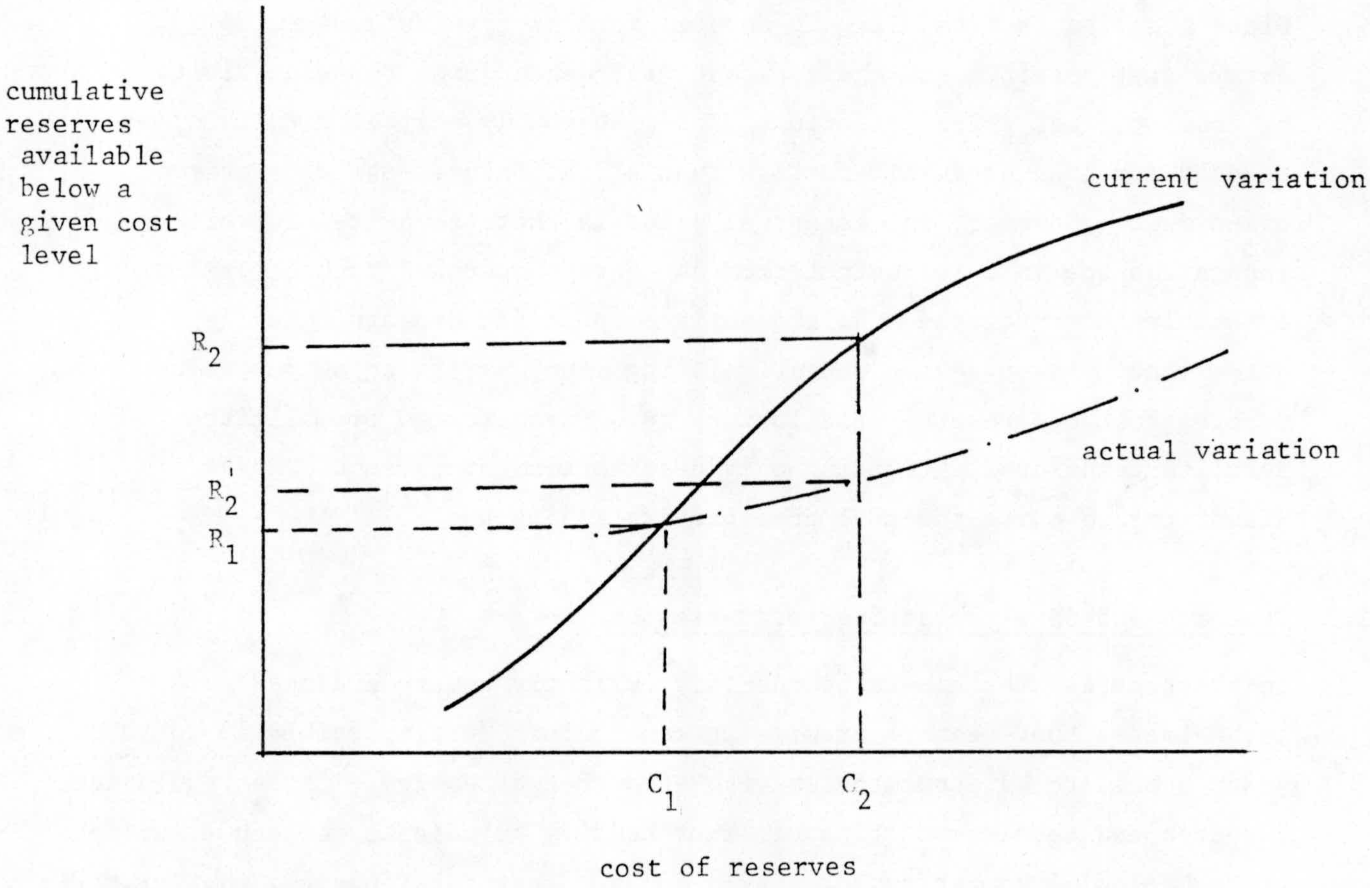


Figure 2.7 Current and actual reserve variation curves



Although there should be no errors in the periodic re-assessment of reserve limits when they are re-calculated to adjust for changes in all factors including fuel price rises, actual reserves will generally tend to be consistently lower than those indicated by earlier forecasts. Since planning is based largely on some form of forecast, planning errors are possible and their extent will depend upon the sensitivity of costs to fuel price inflation. It is obviously very difficult to account for changes in all factors that affect future cost and reserve assessment. However, the essential point is that the price of fuel inputs and the value of output from an energy-producing technology can be highly inter-related. At the extreme these factors are mutually determined. As suggested above, relating input prices to output value enables cost and reserve calculations to be transformed from limited reactive techniques, providing only descriptions of current or past situations, to quite powerful predictive planning tools.

2.3 Research and development funding decisions

In these cases, the aim is to identify currently under-developed technologies that seem to promise at some future date, possibly 10 to 50 years hence, to be economically viable sources of energy. Those regulating research and development finances must usually adjudicate between a number of technologies competing for scarce funds. In this situation, what criteria can be used to identify the most promising designs and allocate funds accordingly? Cost forecasts cannot be used with confidence because this information is precisely what is so uncertain at this stage of development. The ultimate purpose of research and development is, in fact, to reduce technical and costing uncertainties so that sensible investment decisions can be made eventually. Funding decisions may not be so crucial during the fairly inexpensive laboratory stage of research when the performance of models is being investigated, the scale of ultimate devices is being evaluated and the performance of proposed designs is being forecast. However, difficulties do arise in the later stages of small-scale and full-scale prototype testing where the research costs are likely to be high.

Ostensibly decisions are made on the basis of highly uncertain cost estimates. This is hardly satisfactory since the results of the prototype experiments themselves have an enormous bearing on final costs. Additionally, the cost assessment exercise is ambiguous in another interesting sense. While a favourable cost assessment would be interpreted as strong evidence to continue, an unpromising result may generally not be regarded as strong evidence for abandoning further work. It can always be argued that more research and development effort will reduce costs, as will production experience resulting from a trial construction programme. The final justification is, of course, that unit costs will improve as fuel prices rise.

From this discussion it can be seen that conventional current cost assessment, though it may be reasonably adequate in the field of specific investment appraisal, does not present sufficiently complete evaluations when used in more general, increasingly uncertain decision-making contexts. Energy analysis, however, can provide the essential information required to assist conventional assessment techniques in this matter.

2.4 Contributions from energy analysis

The limitations identified previously in the use of current cost assessment in decision making and planning for new energy technologies can only be rectified by incorporating information derived from energy analysis into the normal process of economic evaluation. Energy analysis can account for the effects of fuel price rises because it enables a basic current cost assessment to be written in the following simple form:

$$K = K_o + \sum_{i=1}^{i=n} P_i \cdot E_i \qquad (1)$$

where, K = total cost

K_o = non 'energy' element of cost

P_i = price of the i.th type of fuel

E_i = quantity of the i.th type of fuel consumed directly or indirectly

and $\sum_{i=1}^{i=n} P_i \cdot E_i = P_1 \cdot E_1 + P_2 \cdot E_2 + \ldots\ldots\ldots$

= aggregate cost of all traded fuels consumed

The methods of energy analysis, that generate information on the amount of energy consumed directly or indirectly to provide goods and services, are required to obtain the quantities of fuel, E_i. Although much work is currently in progress, a complete data base that yields the quantities of individual fuels used to provide all common goods and services is not yet available. The existing data base contains information about fuels used aggregated on the basis of calorific value alone. However, a data base has been developed that distinguished between the consumption of electricity and all other types of fuel (Mortimer, 1977). These data can be used to construct a useful hypothetical model in which electricity is substituted for all other fuels.

To proceed realistically, equation (2.1) must be simplified to the following form:

$$K = K_o + P.E_{in} \qquad (2.2)$$

where, depending upon the data base used,

P = an average price for either (a) fossil fuel thermal energy or (b) electrical energy

and, E_{in} = the aggregate of all (a) fossil fuel thermal energy used or of (b) electricity inputs.

Within the context of the current fuel economy the results are not very sensitive to the choice of which form of energy is measured or which data base is used. The fossil fuel thermal energy requirement is typically twice the substituted electricity energy requirement. Conversely the price of electricity is between twice and three times the price of thermal energy from fossil fuels. However, there could be large difference in choice in some future situation where the price of electricity were significantly less than the price of thermal energy from fossil fuels. This could occur in an economy predominantly fuelled by electricity and the "all electric" data base is important here because it enables statements to be made about this particular situation.

To compare technologies it is normal to calculate unit costs, that is costs per unit output, and hence equation (2.2) becomes:

$$c = c_o + p.\frac{E_{in}}{E_{out}} \quad \text{pence/kWh} \qquad (2.3)$$

where, $c = \frac{K}{E_{out}}$ = cost per unit

$c_o = \frac{K_o}{E_{out}}$ = non 'energy' element of costs per unit

$\frac{E_{in}}{E_{out}}$ = net energy requirement (n.e.r.)

(note, $\frac{E_{out}}{E_{in}}$ = energy ratio which is the inverse of the net energy requirement*)

While it is repeatedly claimed that energy analysis has a role to play within economic appraisal , this relationship has only been specifically defined within the context of a definite model occasionally. (e.g. Chapman, 1976; Chapman and Hemming, 1976; Mortimer, 1979) However, using this model of the relationship between costs and energy prices, it is possible to identify the critical range of energy requirement values that determine the practical limitations of energy technologies.

The results of an analysis of this type can be put into two categories as illustrated by the following examples:

The first example concerns technologies producing fuel with a unit value similar to the unit value of the input fuels. In this situation the value of the output will rise in step with the price of input fuels within the supply system. As explained above, unit costs will also inflate in response to these price rises, at a rate determined by the value of the net energy requirement of the specific energy technology under consideration. If the net energy requirement is low then unit costs will increase slowly. Eventually at some prevailing price level the value of the output will exceed costs and the technology will become economic. If, on the other hand, the net energy requirement is high, then costs increase rapidly with fuel price inflation and economic viability is seriously delayed. Figure 2.8 demonstrates these situations where unit costs are plotted against the unit price of input fuels, p.

---

* This is an index which is commonly used in some of the literature.

Figure 2.8 Comparison of costs and value in cases of similar fuels

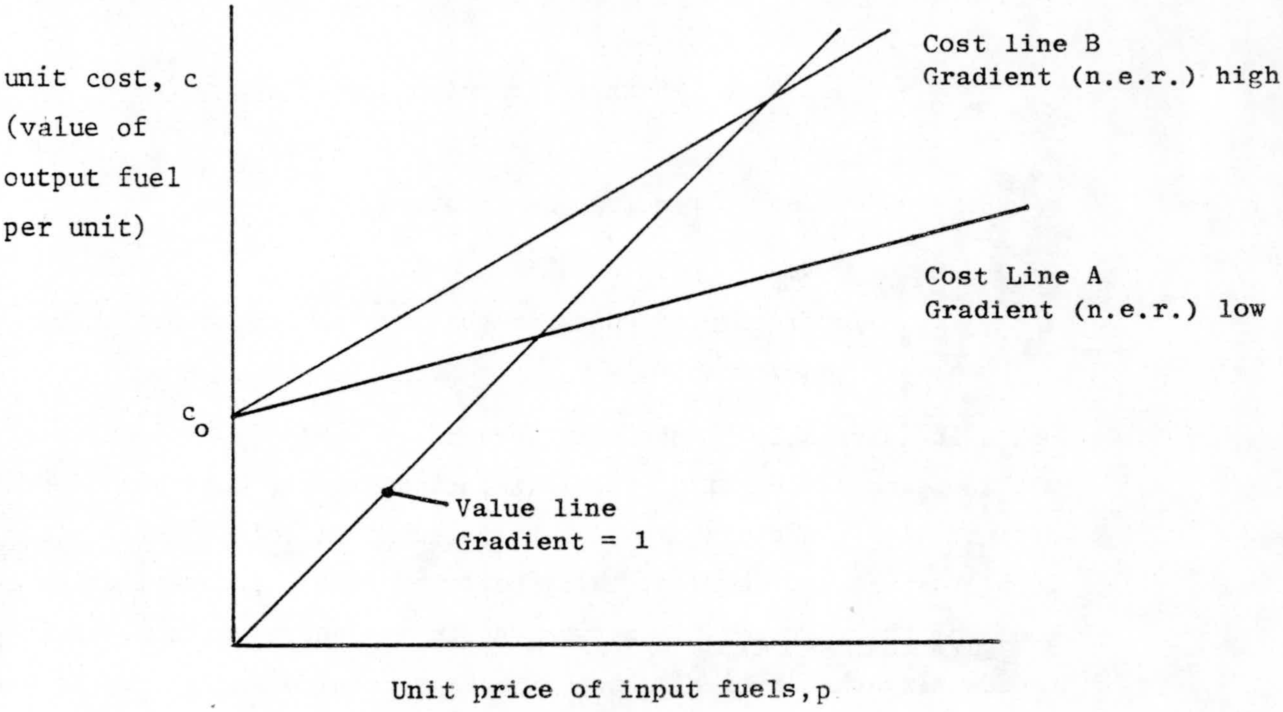
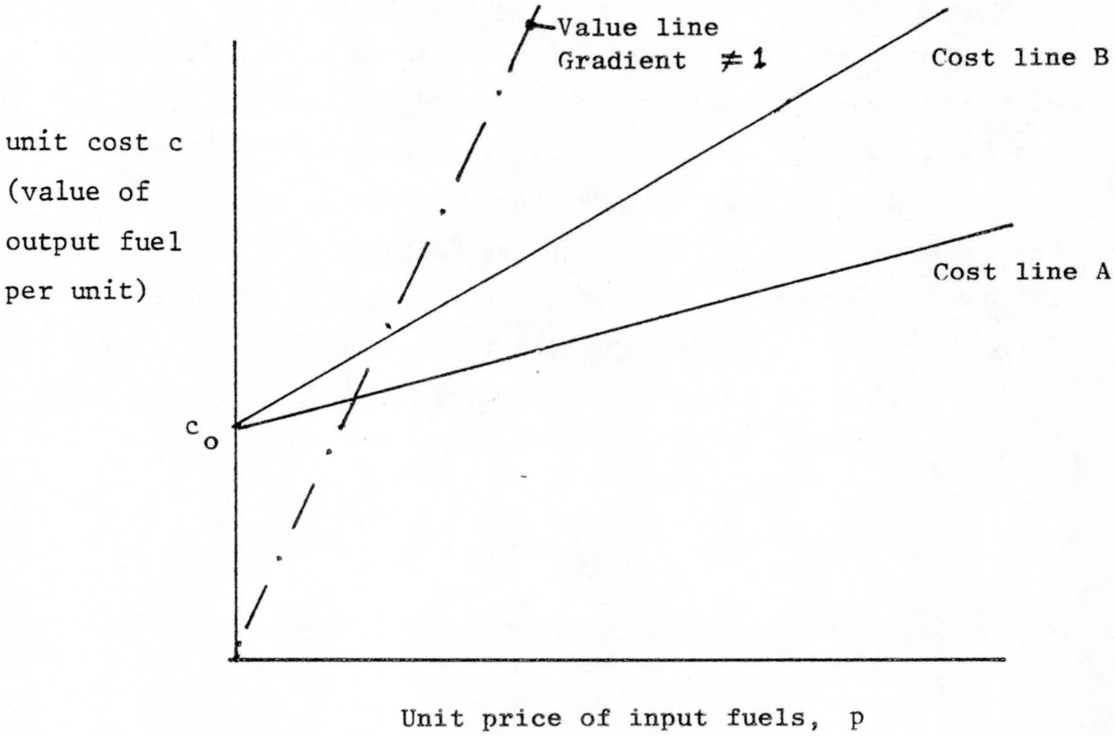


Figure 2.9 Comparison of costs and value in cases of different fuels



Thus the important factor affecting the value of output fuel is the gradient of the cost lines. These gradients are equal to the respective net energy requirements, $\frac{E_{in}}{E_{out}}$

The cost lines in figure 2.8 must cross the given value line at some point in order that the technology may have the potential to be economically viable. In this case, a net energy requirement of less than one is the minimum criterion for a technology to have any potential to achieve eventual economic viability. However, if success is to occur within a reasonable period of time then it can be seen that the net energy requirement must, in fact, be much less than one.

The second example relating to the use of energy analysis concerns technologies producing fuel with a unit value quite different from the unit value of input fuels. As shown in Figure 2.9,and the value of output rises with input fuel price inflation, but at a different rate. The minimum criterion for a technology to display potential for economic viability is that it should have a net energy requirement equal to the gradient of the relevant value line. It is possible to conceive of realistic cases where the slope of the value line can differ from about 0.6, when oil is used for the production of coal (in an opencast mine for example), to about 3.5, when fuel oil is used to produce electricity. Hence an absolute value of the net energy requirement cannot be defined to relate to all cases uniquely. This is not unusual since the relevance of all techniques of assessment depends on the context of the particular issues under investigation.

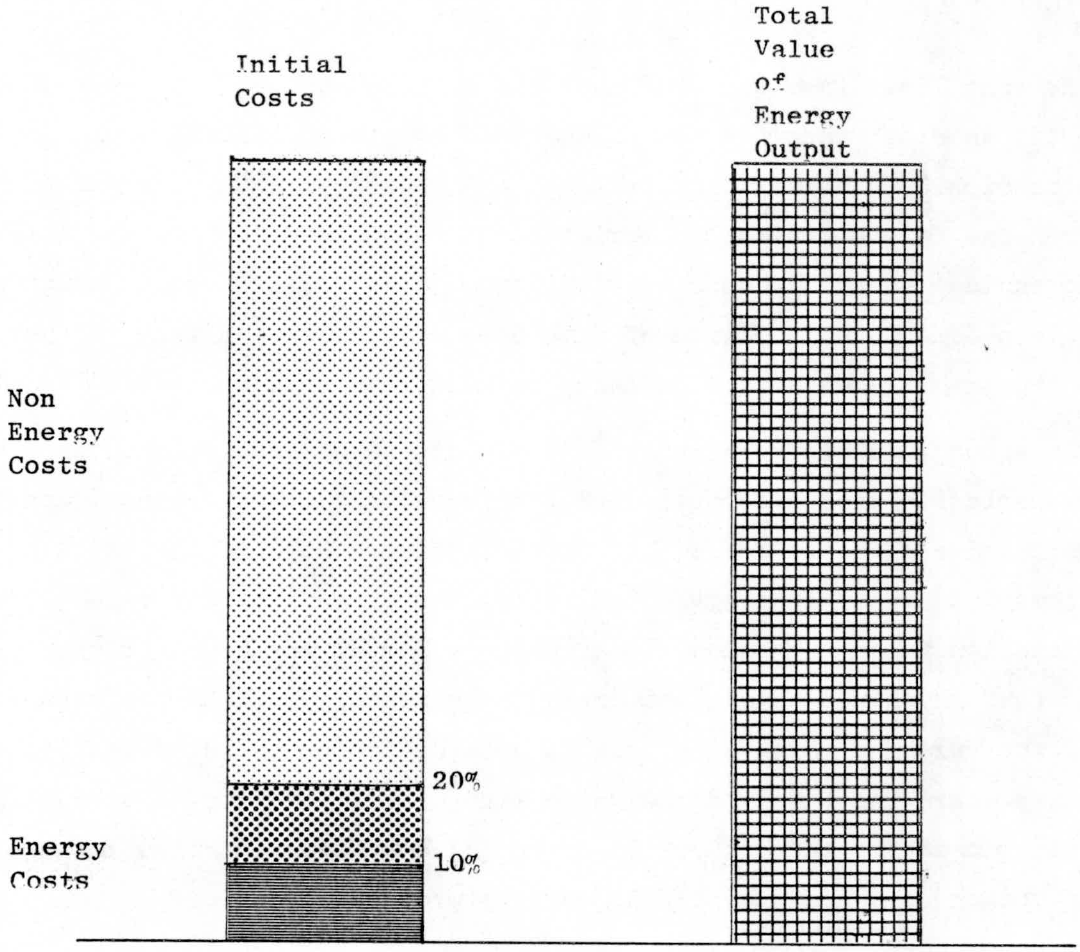
It is not possible to set a rigidly justifiable minimum value of net energy requirement below which a technology shows eventual economic promise. However, it may be reasonable to aim for a net energy requirement that is a factor of ten less than the minimal criteria discussed previously. This implies that the necessary condition is a net energy requirement of below approximately 0.3.

Such a suggestion is supported by the fact that, currently, fuel purchases represent about 10% of basic costs, as defined by net output*.

---

*Studies at the Energy Workshop on the 1974 Census of Production also support this contention.

Fig 2.10 Simple Comparison Between Initial Costs and Total Output For a Primary Energy Production System



<u>For minimum condition of economic viability</u>

Value of output energy $\geqslant$ initial cost of scheme

$\therefore$ Value of output energy $\geqslant$ 5- 10 x initial cost energy

$$\therefore \text{ Ratio of } \frac{\text{cost of initial energy}}{\text{value of output energy}} \leqslant 0.1 - 0.2$$

If output and input energy are of a similar value

$\therefore$ Net energy requirements $\leqslant 0.1 - 0.2$

If fuel prices double in real terms during coming years then this proportion could rise to 20%. Figure 2.10 demonstrates that the energy output from the project would have to be between five and ten times the energy input just to cover basic first costs. This suggests a net energy requirement of between 0.1 and 0.2 as a minimal criterion for realistic future economic promise.

This discussion of the significance of net energy requirement results leads to the application of the concept within the decision-making context outlined in section 2.3, that of research and development planning. The central problem in such a planning situation is that some kind of guide is required to give an indication of commercial potential during the research and development phase when costings are not available or are so uncertain as to be unreliable. Calculation of the energy inputs to construction and manufacture is based upon estimates of quantities of materials, machinery, etc., and this does not require the detailed level of design information that is needed for a useful cost estimate. Cost estimates are very sensitive to the details of prototype experience, production planning and learning curve improvements. All these factors are studied during the relatively expensive prototype and subsequent stages of development. The quantities of materials, etc., however, remain largely unaltered during this phase and this is reflected in fairly constant energy input results. By comparing these energy inputs with performance estimates during the early stages of the life of a new technology, it is possible to deduce the net energy requirement. This result is then available prior to further development and enables future progress to be assessed in the manner described above.

Two general parameters can be identified which impose inherent physical limits on the commercial prospects of renewable energy sources now being developed. These are the energy density of the source which determines the scale of devices required by the new technology, and the availability pattern of the source which governs the average load factor and hence, degree of redundancy of machinery, etc. Since energy inputs calculated by energy analysis are closely related to the size of structures and quantities of machinery, comparison of such inputs with the subsequent output provides an index, the net energy requirement, that is sensitive to the basic physical principles of the energy source and its relevant means of use; the particular energy technology.

As explained previously, it is difficult to define a unique ultimate net energy requirement criterion because of unavoidable problems of relating the relative value of input and output energy in isolation from the specific case being examined. However, it can be seen that a net energy requirement in the region of 0.6 to 3.5 is a fairly good indication that a technology is very close to the inherent physical limits of energetic viability. Although energy analysis cannot provide unqualified criteria, this does not invalidate it as a means of assessment. Indeed, all other comparable techniques of evaluation are prone to the same condition that the answers they provide only have meaning in relation to the question being asked. In summary, research and development funds must be concentrated on those new energy technologies which have clear potential for techno-economic viability and not on those which cannot progress from the limits of physical futility. For this, technologies must be sought with net energy requirements less than 0.2 to 0.1

Results and Discussion

3.1 Energy Analysis

This study of the energy analysis of wave energy systems is based upon a series of Reference Designs drawn up by Rendell, Palmer and Tritton (RPT), Consulting Engineers to the Wave Energy Steering Committee of the Department of Energy. Full details of these designs are contained in the 'Consultants' Second Report, 1978' (Rendell, Palmer and Tritton, 1978). Five different devices were studied in depth, as shown in Table 3.1. They were compared on the basis of their deployment in a projected 2000 MW wave energy installation off the coast of Outer Hebrides, near South Uist in Scotland.

Energy analysis of energy conversion systems is concerned with determining the direct and indirect energy inputs used to construct, operate and maintain the system, and also with the energy outputs of the system, taken over a common period.

The energy analysis was, where possible, based on physical quantities derived from the RPT report and from numerous visits and communications with individual device teams and consultants. However, for the Salter's Duck (SEA) system, insufficient data were available for a purely physically-based energy analysis. In this case, the energy intensities ($MJ_{(t)}/£$) derived from statistical data, (Casper, Chapman and Mortimer, 1975), were combined with costs, to perform the energy analysis.

Energy analysis of energy sources can produce various results, of which the gross and net energy inputs are two particularly useful types. The gross energy input to a scheme includes all the energy processed and consumed by the scheme. For example, the energy in the waves, as well as energy used to construct and maintain the devices, is included in the gross energy input. In this study, net energy analysis is used. Net energy analysis does not include the energy of the primary energy souces being processed, which in this case is the energy in the waves. Thus the net energy analysis concentrates on traded fuels, in primary or delivered terms.

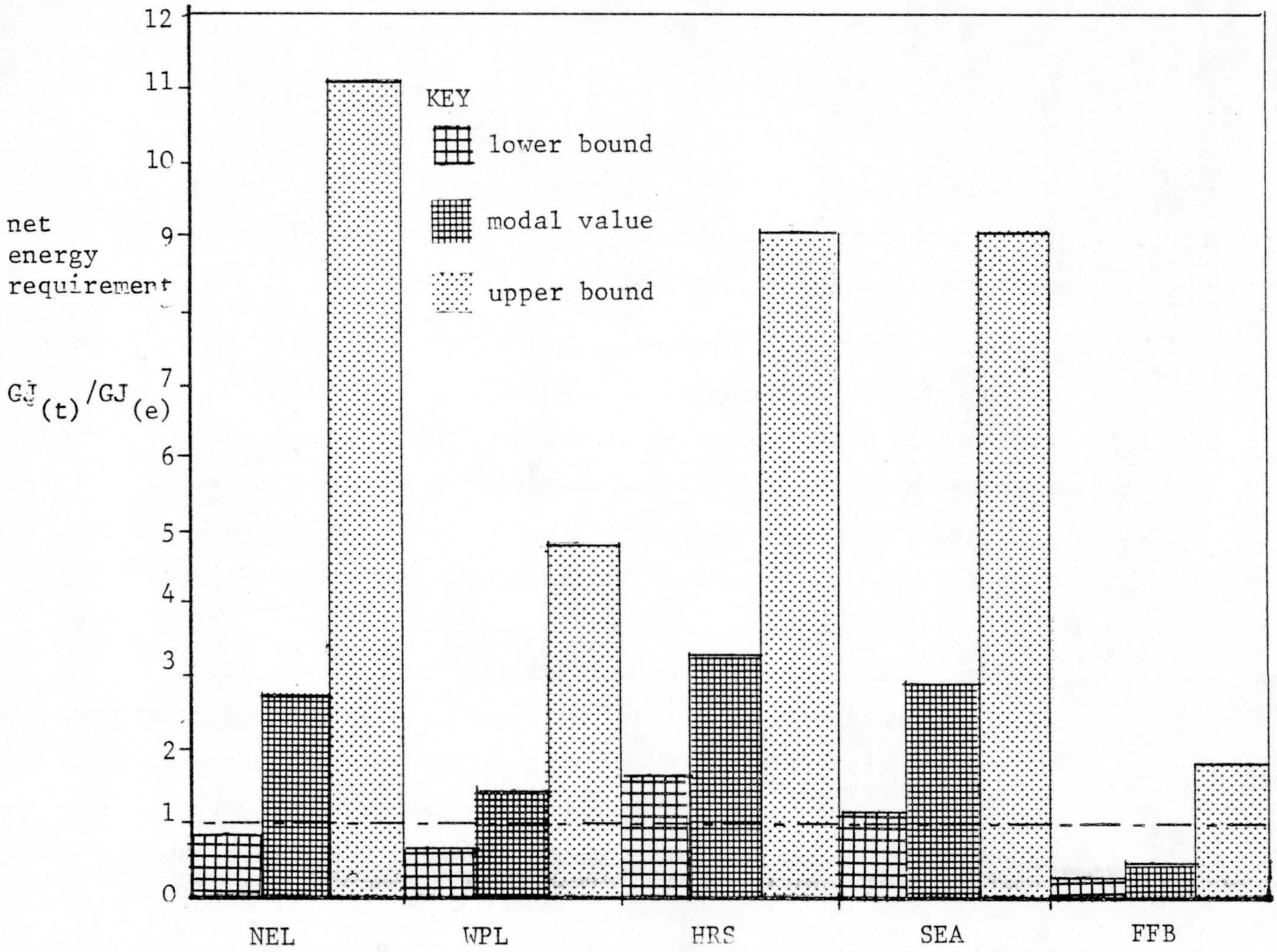
TABLE 3.1 1978 REFERENCE DESIGN DEVICES

GROUPS	DEVICES	ABBREVIATIONS
National Engineering Laboratories	Oscillating Water Column	NEL
Wavepower Limited	Cockrell's Raft	WPL
Hydraulics Research Station	Russell Rectifier	HRS
Sea Energy Associates/ Edinburgh University	Salter's Duck	SEA
Lancaster University	French Flexible Bag	FFB

All the fuel energy input measured here is embodied in the construction, maintenance, repair and replacement of components over the lifetime of the system.

The wave energy schemes studied are composed of various sub-systems: device structure, mechanical, hydraulic and electrical machinery, towing out, moorings, power collection and transmission. A worked example demonstrating how the energy inputs of components, subsystems and schemes are developed is given in Appendix A. This concerns the Wavepower Limited (WPL) raft scheme in the 1978 Reference Design form. In general, the energy input of a single component is determined by multiplying the relevant amount of that component, say in tonnes, by the subsequent energy requirement of the material from which it is made, say in gigajoules per tonne ($GJ_{(t)}/te$). Representative energy requirements for a variety of materials and products are given in Appendix D. These energy requirements indicate the total amount of energy resources, measured in terms of primary energy, required to produce a unit of output. An effective annual energy input can be derived by dividing the initial energy input of each component by the corresponding lifetime. Thus the annual energy input is a weighted figure which takes into account the replacement of components with relatively different lives. Since the individual lifetime of components are used in this study, the results are independent of the 'financial' life of the wave energy scheme. Estimated mean value and ranges of component lifetimes are given in Appendix E. The overall annual energy input to a 2GW scheme can be compared with the energy output from that scheme. A range of annual energy outputs for each wave energy system is given in Chapter 13 of the RPT report. These were determined from the likely performance of devices in the sea state of South Uist in the Outer Hebrides. These sea state data had recently been made available by the use of Waverider buoys that are part of a information collecting scheme instigated for the U.K. wave energy programme. The average power in the sea at the South Uist site is about 47 kW/m, this compares with 70 kW/m at Ocean Station, India in the mid-Atlantic which was used for the 1977 Consultants Preliminary Study (Rendell, Palmer and Tritton, 1977).

FIG.3.1 NET ENERGY REQUIREMENTS OF 1978 WAVE ENERGY REFERENCE DESIGNS



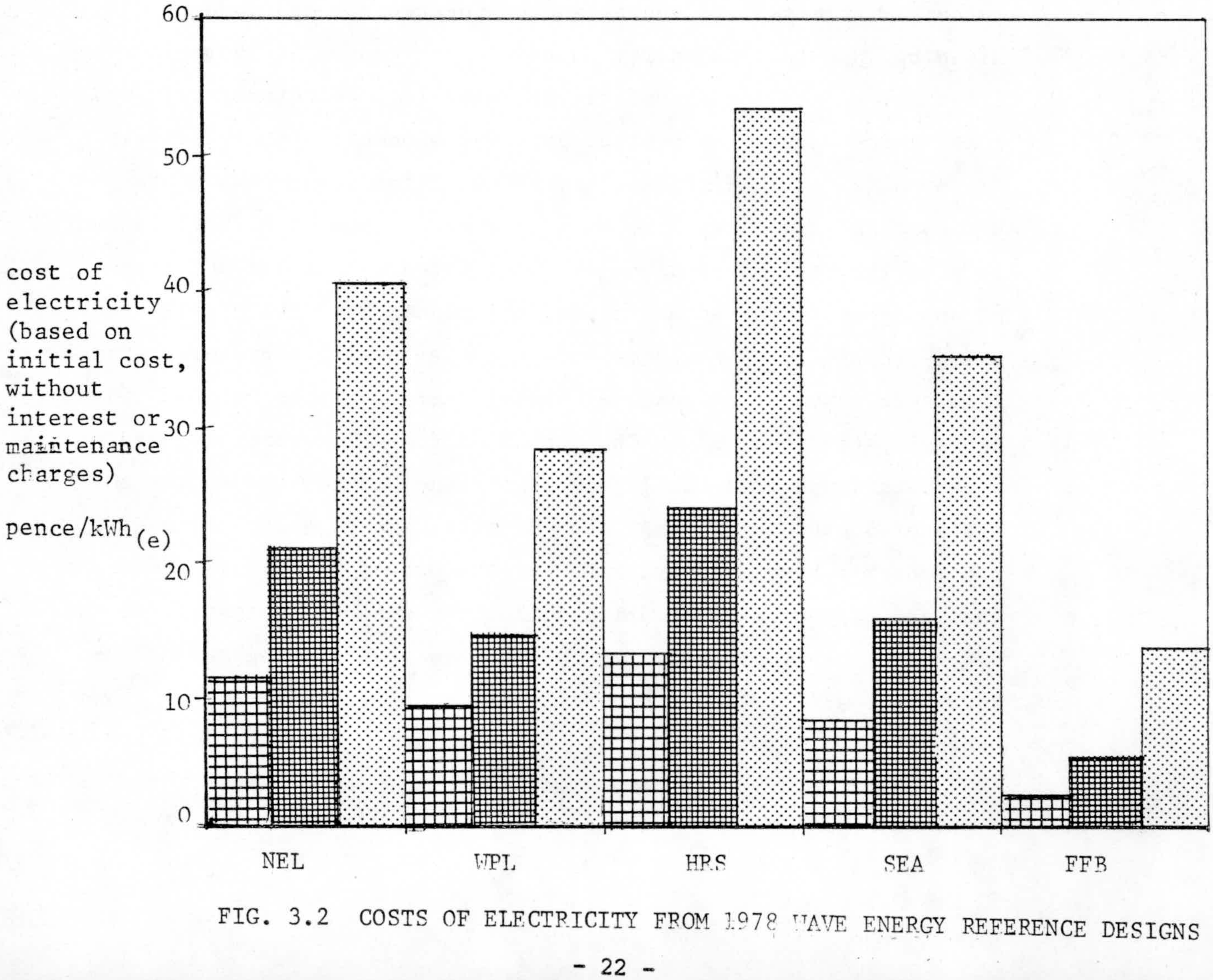


FIG. 3.2 COSTS OF ELECTRICITY FROM 1978 WAVE ENERGY REFERENCE DESIGNS

The output from the devices is given in terms of electricity delivered to the national grid at Perth. In comparing the annual delivered energy with the average energy in the sea, account must taken of directionality, primary and secondary conversion efficiencies and generation and transmission losses. Hence, the average electrical power output of the wave energy scheme, delivered to the national grid is typically estimated between 2.2 and 6.4 kW/m, which is significantly less than the original power in the sea.

3.1 1 Results

Throughout this work, the results are expressed in terms of net energy requirement (n.e.r.) which is the energy input of the fuels consumed by the scheme divided by the energy output of the scheme, as electricity delivered at Perth, both expressed in annual terms. If the energy output is measured in the form of primary energy a scheme should have a net energy requirement of less than unity in order to be a net primary energy producer.

A summary of the results of the energy analysis of 1978 Reference Designs are given in Table 3.2 and Figure 3.1. The wide range of net energy requirements shown in Figure 3.1 result from uncertainties contained within the RPT report, concerning the input quantities of materials and the expected outputs of the schemes. Uncertainties concerning the expected lifetime of components also influence the results. The results have been combined in such a way as to produce a modal (most likely) value of n.e.r. The upper and lower bound values represent the worst and best possible combinations of factors used to calculate the net energy requirement. They therefore represent the most extreme cases possible using the data available for 1978 Reference Designs. The uncertainties of input material and component quantities are also reflected in the cost estimates of the wavepower systems. This variation is cost estimates taken from volume 3 of the RPT report, is shown in Figure 3.2

The modal net energy requirements of the five schemes, categorised into subsystems, are shown in Figure 3.3. This indicates clearly how the schemes differ markedly in their mode of operation, and

TABLE 3.2 SUMMARY OF ENERGY ANALYSIS OF 1978 REFERENCE DESIGNS

	NEL			WPL			HRS			SEA			FFB		
ANNUAL ENERGY INPUTS (x 10^6 $GJ_{(t)}$ per 2GW scheme)	LOWER	MODAL	UPPER	LOWER	MODAL	UPPER	LOWER	MODAL	UPPER	LOWER	MODAL	UPPER	LOWER	MODAL	UPPER
1. Construct concrete units and launch	3.43	6.43	10.32	2.71	4.11	6.29	5.00	6.84	10.30	1.88	5.01	11.28	0.55	0.73	1.10
2. Structural steel components	0.08	0.20	0.37	1.43	1.97	2.84	-	-	-	1.67	2.23	3.09	0.00	0.01	0.01
3. Mechanical components to power take-off	0.30	0.37	0.49	1.78	2.38	3.57	3.29	4.31	6.29	6.17	10.46	19.71	0.21	0.29	0.51
4. Hydraulic and electrical power take-off	1.03	1.24	1.55	3.31	4.38	6.50	2.97	3.70	5.35	0.37	0.62	1.01	0.34	0.44	0.63
5. Tow units to site and place	0.22	0.39	0.59	0.11	0.15	0.23	0.24	0.42	0.78	0.04	0.24	0.63	0.03	0.04	0.06
6. Anchors and mooring	2.73	6.86	20.68	1.23	3.28	14.39	-	-	-	0.40	0.53	0.83	0.16	0.41	1.52
7. Power collection and transmission	0.59	1.44	9.16	0.42	0.69	1.09	0.15	0.21	0.33	0.62	0.93	1.64	0.42	0.68	1.08
TOTAL ANNUAL ENERGY INPUT	8.38	16.93	43.16	10.99	16.96	34.89	11.64	15.48	23.05	11.14	20.03	38.19	1.70	2.60	4.91
TOTAL ANNUAL ENERGY OUTPUT (x 10^6 $GJ_{(e)}$ per 2 GW)	10.10	6.30	4.10	16.08	11.67	7.25	7.25	4.73	2.52	9.77	6.93	4.10	9.13	5.67	2.83
NET ENERGY REQUIREMENT $GJ_{(t)}/GJ_{(e)}$	0.83	2.79	11.11	0.68	1.45	4.81	1.16	3.27	9.09	1.14	2.89	9.09	0.19	0.46	1.72

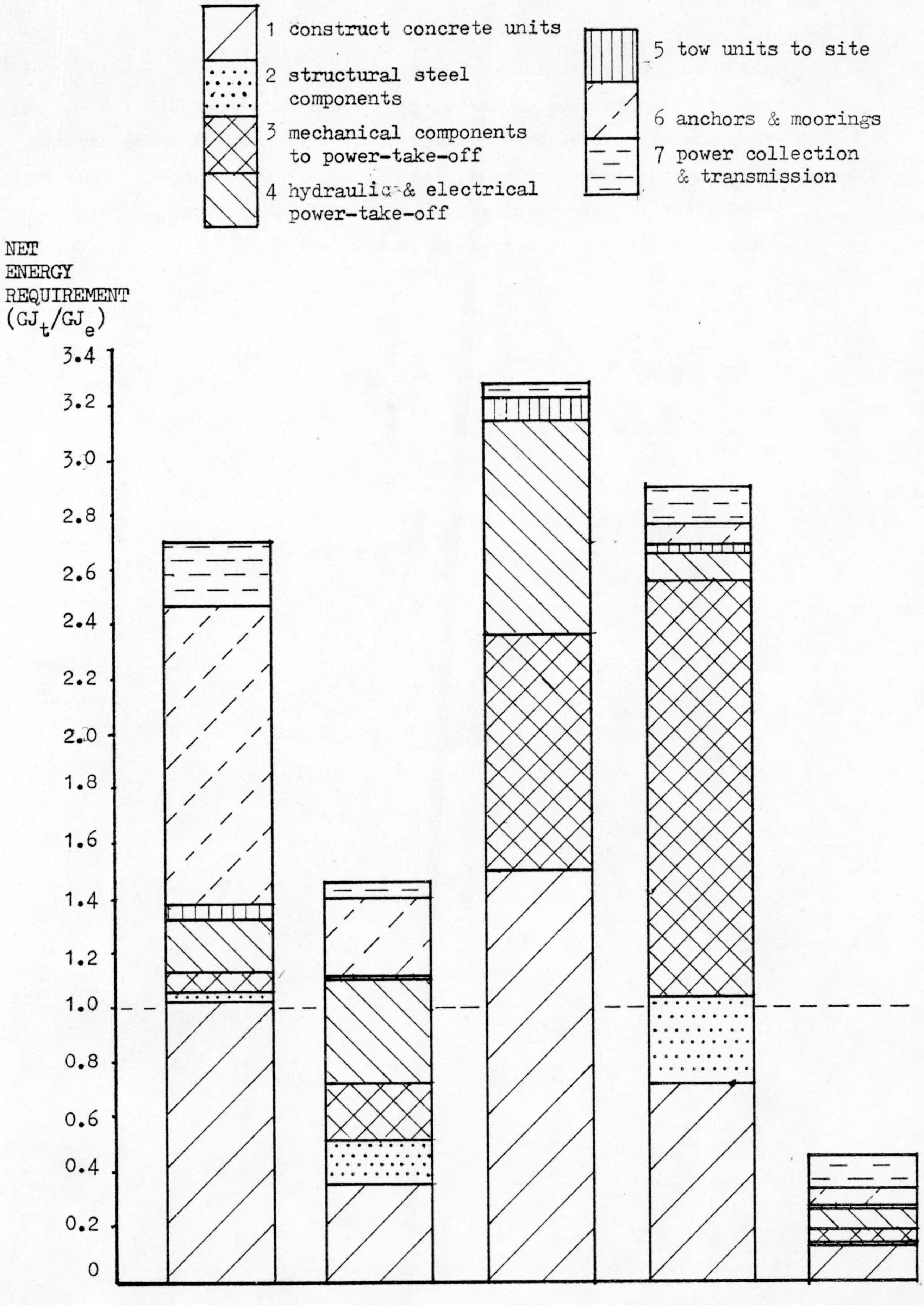


FIG 3.3 NET ENERGY REQUIREMENTS OF WAVEPOWER SYSTEMS

where the 'energy requirement centres' occur for each scheme. For example, a comparison of the energy requirements of NEL and SEA devices shows how the different operating characteristics of these devices influence the amount of energy embodied in the moorings. Thus any improvement in net energy requirement must concentrate on a reduction in these 'energy requirement centres'.

3.1.2 Discussion

The overwhelming conclusion of this energy analysis is that only one device, the Lancaster design (FFB), will be a net primary energy producer in the most likely, or modal case considered. The four other devices (NEL, WPL, SEA and HRS) consume more energy than they will produce over the system lifetime in the modal case. These four devices have been funded from the beginning of the U.K. Wave Energy Programme and can be regarded as the most thoroughly researched devices in existence at the time of writing of the 1978 RPT report. In contrast, the Lancaster device had only recently been taken into the research programme.

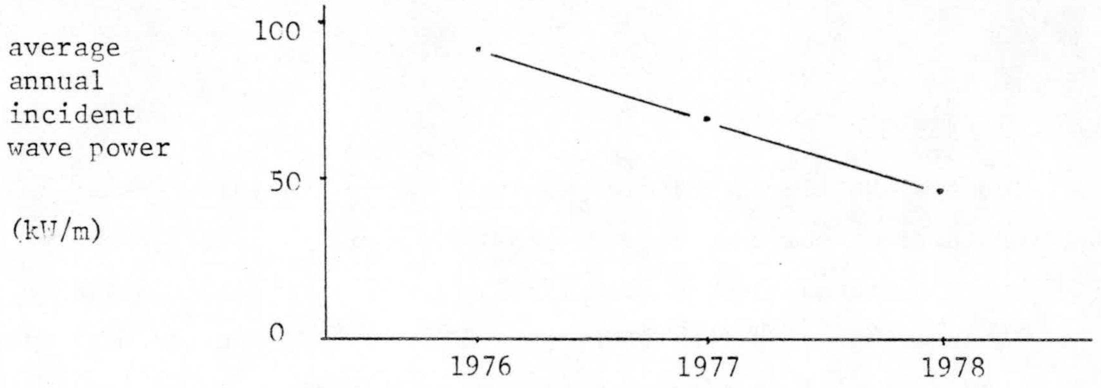
The results of this current study are markedly different from earlier research which showed that all the devices, as then conceived, had net energy requirements less than unity (1 $GJ_{(t)}/GJ_{(e)}$) (Smith, Harrison and Varley, 1977, and Harrison, Jenkins and Roberts, 1978). The reasons for this dramatic change is illustrated in Figure 3.4 a-d which demonstrate the variation in basic data over the period 1976-78 for the SEA device for example. Figure 3.4a shows that the amount of energy available in the sea at proposed sites has been greatly over-estimated for all devices during the early stages of development. Such information on sea wave power rating is obviously crucial to the meaningful development and realistic assessment of devices. More accurate information was only becoming available for the 1978 RPT report and it can be seen that the early rating estimate has now been halved. The overall system efficiency* of the designs has also changed between 1976 and 1978, and Figure 3.4b shows an eventual fall in efficiency to one third of the original estimate. These factors combine in Figure 3.4c to produce a reduction in the unit electricity output of the scheme by a factor of almost eight. During the same period the unit energy input estimated by energy analysis did increase by a factor of about five. However, it can be seen in Figure 3.4c that the dramatic

---

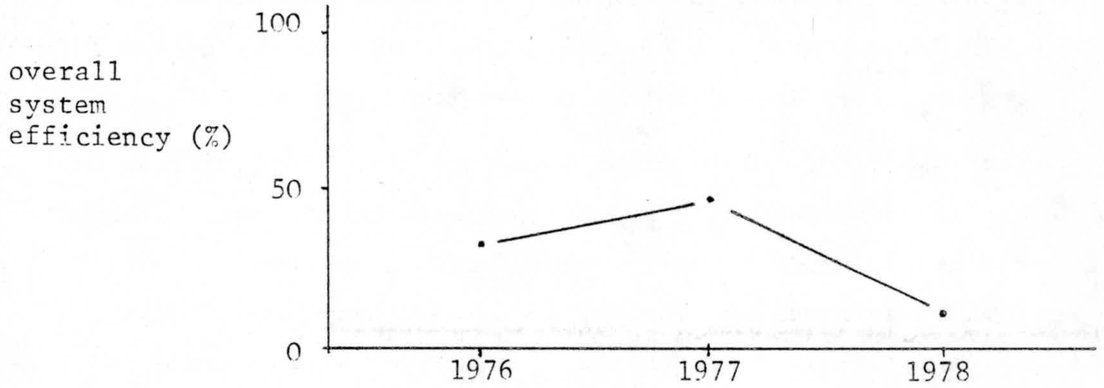
* The overall system efficiency includes the efficiency of device capture as well as the power chain efficiency etc. In other words it equals the total electricity power output at Perth divided by the average power in the sea.

FIG. 3.4 EFFECT OF CHANGES IN DATA ON ENERGY ANALYSIS - SALTER'S DUCK 1976-78

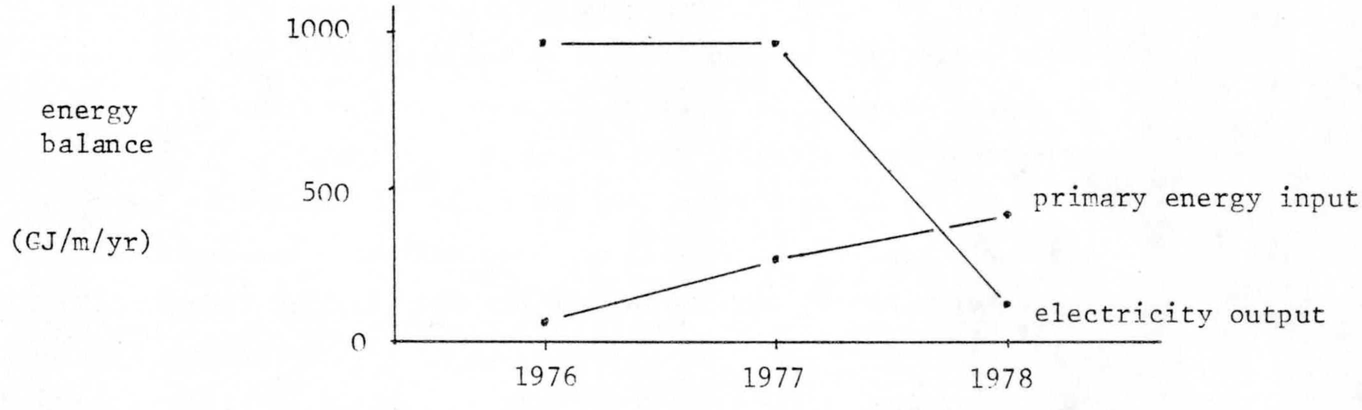
a) average annual incident wave power



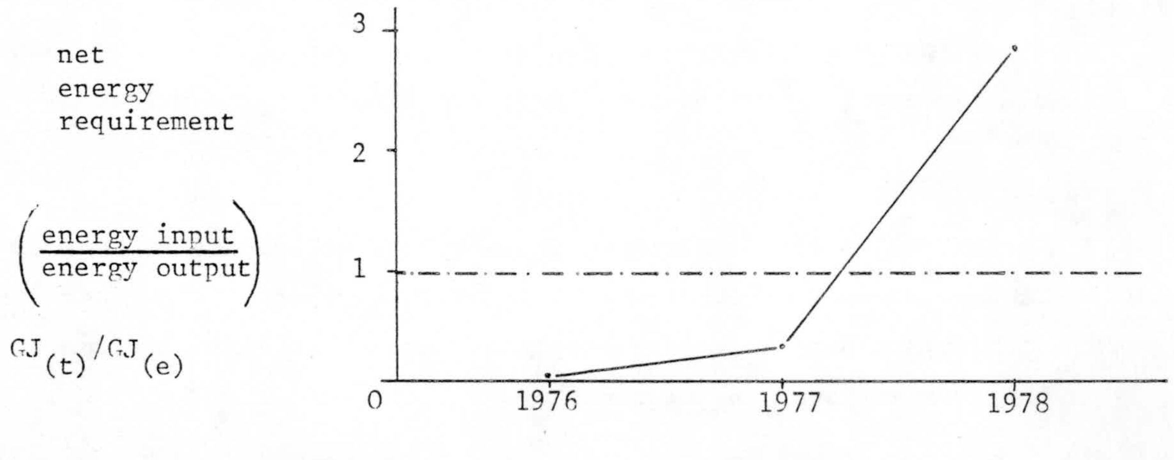
b) overall system efficiency : from energy in the sea to delivered electricity



c) annual energy input and output



d) net energy requirement



drop in output was the fundamental reason for a net energy requirement 1978 of more than 1 $GJ_{(t)}/GJ_{(e)}$ as illustrated in Figure 3.4d. Provision of reliable information on such basic factors as the amount of energy available from the primary source in this case the sea, should be the most important initial feature of any energy R & D programme. This has obviously not been the situation in the U.K. Wave Energy Programme and if early wave data had been correct then the current devices would still be 'energetically' viable.*

Using 1978 data it can be seen that some devices, in their best, or lower bound, value of net energy requirement, can just be net primary energy producers. However, they do not attain the current criterion of economic viability considered in a previous section (section 2.4).

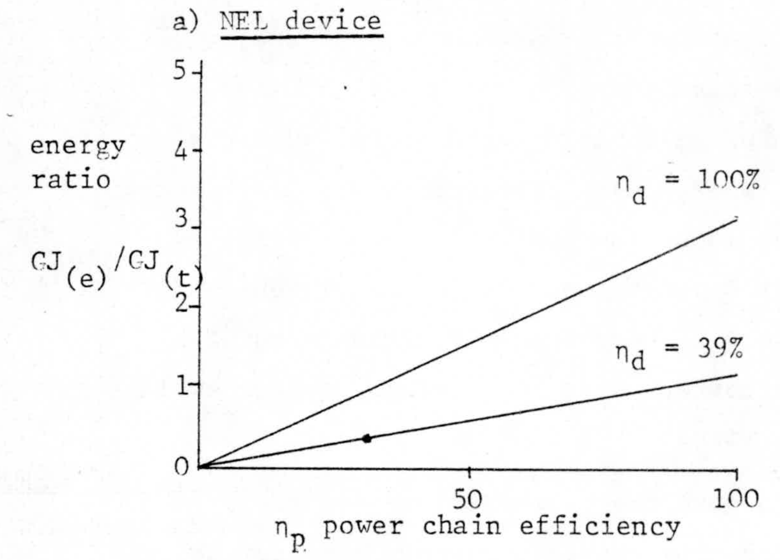
Thus, it is a major conclusion that significantly large and fundamental improvements need to be made in all aspects of the present wave power systems before they can become net suppliers of economically - competitive electricity to the national grid.

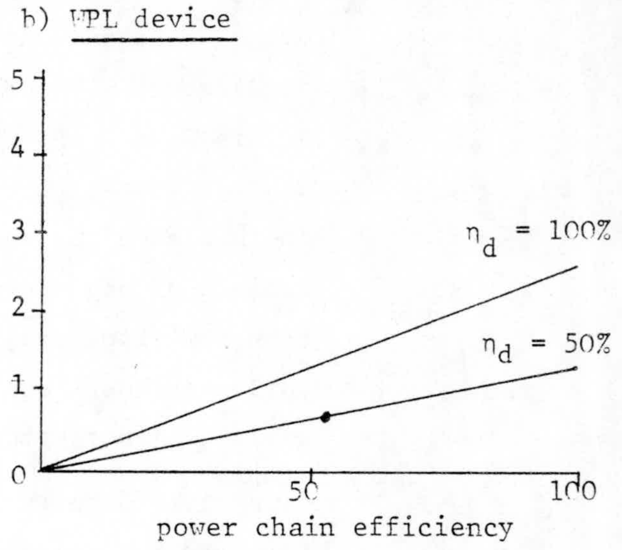
Some such potential improvements are shown in Figure 3.5 a-d which demonstrate the effect on the energy ratio of varying the device capture efficiency, η_d, and the power chain efficiency, η_p for all 1978 wave energy systems.

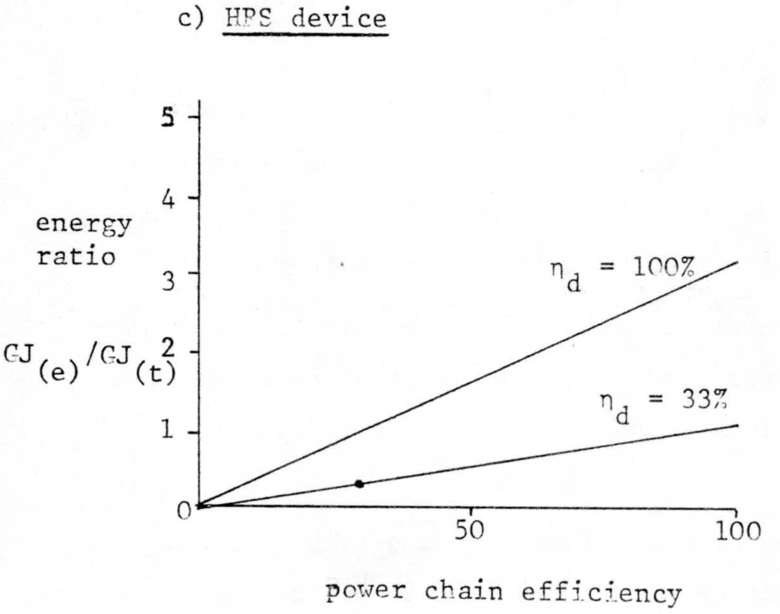
In order to determine the nature and magnitude of improvements that are required for each device to demonstrate basic economic potential, the following simple targeting exercise was performed with each set of design data. First, a plausible target net energy requirement of 0.2 $GJ_{(t)}/GJ_{(e)}$ was postulated. Then, assumptions of possible improvements to both device performance and sub-system equivalent energy requirements were made on the same basis for each scheme in an attempt to achieve this postulated value. Up to this point, most of the obvious improvements were considered apart from major changes in the equivalent structural energy requirement via reductions in the structural mass of devices. Consequently,

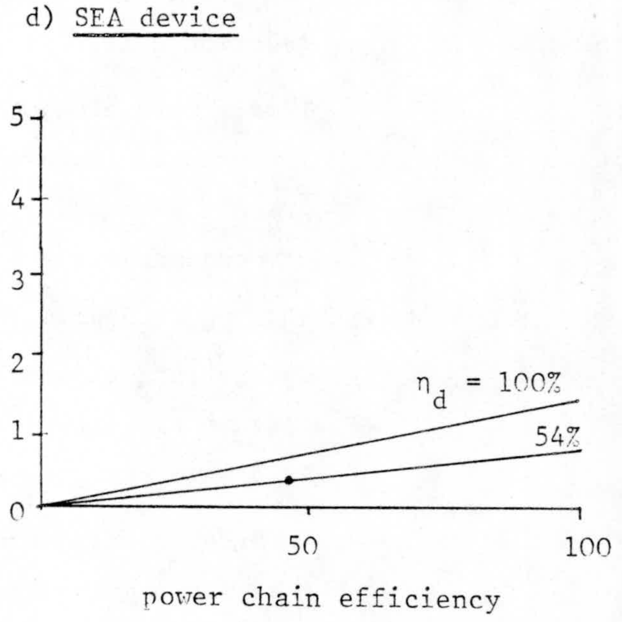
* For example, using 1976 data on output the SEA device would still be a net producer of primary energy, having an energy ratio of 2.73 GJ_e/GJ_t. (A net energy requirement of 0.366 GJ_t/GJ_e).

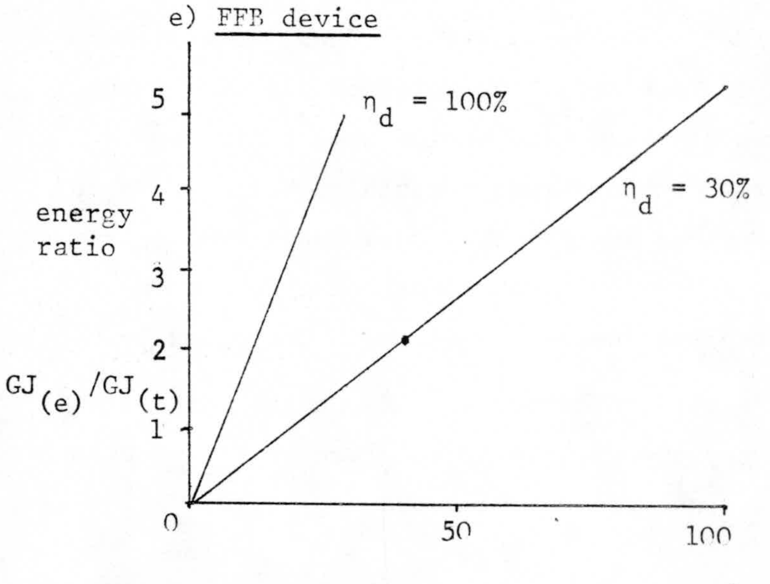
FIG. 3.5 EFFECT OF EFFICIENCIES ON ENERGY RATIOS


a) NEL device


b) WPL device


c) HRS device


d) SEA device


e) FFB device

NOTES

• 1978 Reference Design

η_d device capture efficiency

$= \frac{\text{energy captured by device}}{\text{energy available in sea}}$

η_p power chain efficiency

$= \frac{\text{energy delivered at Perth}}{\text{energy captured by devices}}$

the following initial improvements were applied to each scheme: a factor of three increase in device output or overall system efficiency; a factor of two increase in the load factor of hydraulic and electrical power take-off equipment; a factor of four decrease in the energy inputs of mooring, device tow-out, and power collection and transmission; and a factor of two reduction in the energy inputs of non-structural mechanical components. Improvements in efficiency and load factor were assumed to come from mechanical design progress. Reductions in the energy input of certain components were suggested on the basis of using smaller amounts of material and/or less energy intensive materials.

The results of the initial part of this targeting exercise are shown in figure 3.6. As can be seen, only the FFB device attains the requisite value of net energy requirement. Hence, additional changes are required to reduce the net requirements of the other devices to the target value of 0.2 $GJ_{(t)}/GJ_{(e)}$. It is suggested that these changes must result from decreases in the energy input of device structures by reduction in their mass. Thus, target masses can be defined that comply with the criterion for possible economic viability described here. These targets are shown in Table 3.3 for the NEL, WPL and SEA devices in terms of tonnes of concrete and steel per metre of device frontage* and per KW of power converted. Consequently, to attain the postulated value of n.e.r. the structural mass of the NEL device must be reduced by a factor of about seven, the WPL device by a factor of about two and the SEA device by a factor of about fifteen. This is in addition to the other improvements outlined above. The HRS device is excluded from the preceeding exercise because the non-structural components contribute more than the target value to the net energy requirement. Hence, even if the structural energy input of the HRS device was zero, the target of 0.02 $GJ_{(t)}/GJ_{(e)}$ could not be achieved.

---

* This is the unit length of the device rather than the unit length of total searoom occupied by the device.

FIG. 3.6 Speculative changes to achieve a target net energy requirement of 0.2

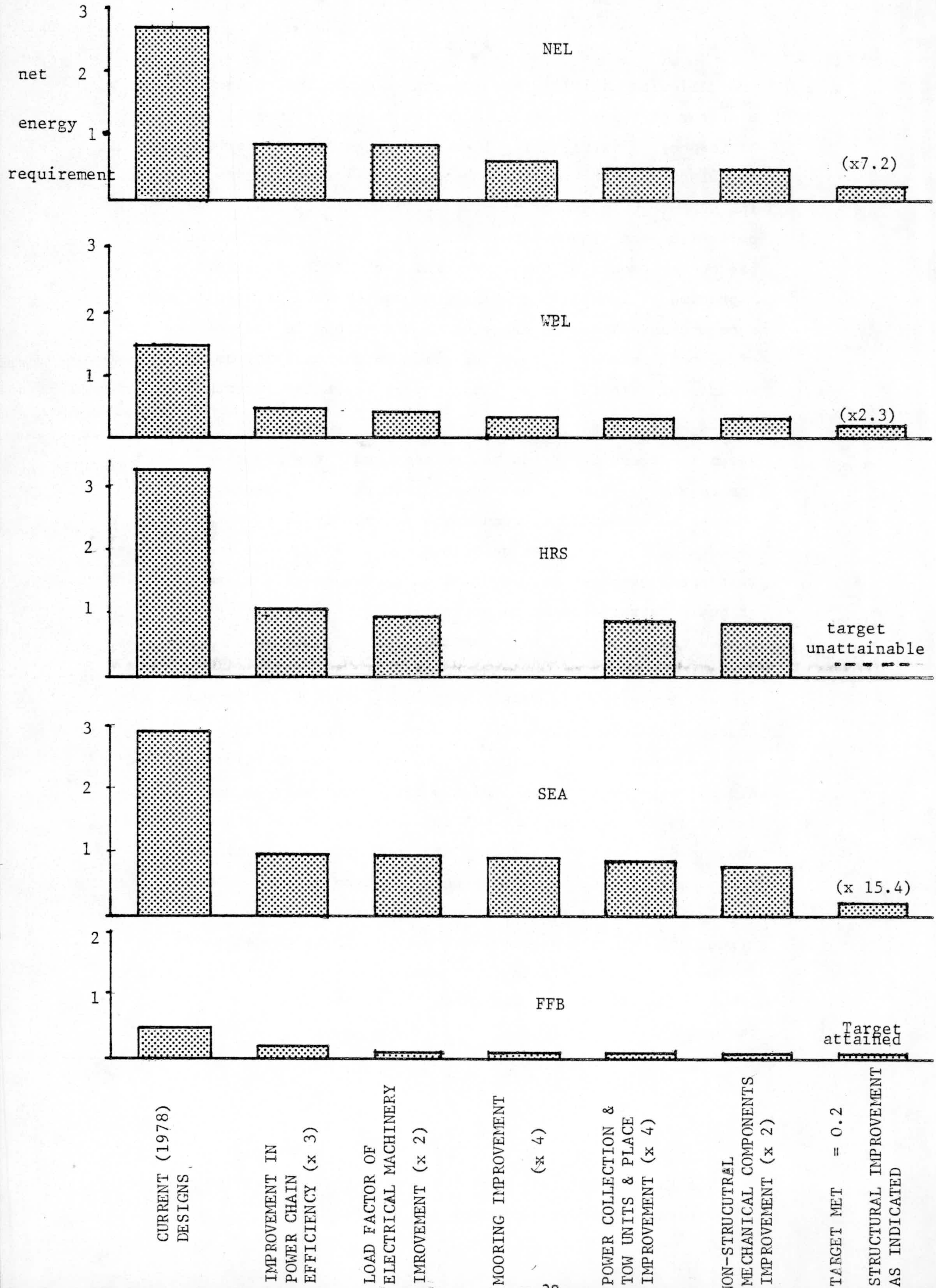


TABLE 3.3 STRUCTURAL TARGETS FOR WAVEPOWER DEVICES

(Note: all other device improvements given on Appendix B must also be made in order to reach a target net energy requirement for systems of 0.2).

		Reinforced concrete units		Structural steelwork	
		tonne/metre	tonne/kW (converted)	tonne/metre	tonne/kW (converted)
NEL	CURRENT	814	49.0	1.5	0.09
	TARGET	114	6.8	0.2	0.01
WPL	CURRENT	300	14.1	15.5	0.73
	TARGET	132	6.2	6.8	0.32
SEA	CURRENT	110	4.8	15	0.70
	TARGET	7.2	0.31	1.0	0.04

3.2 Modelling of device scaling

Modelling of device scaling was carried out to determine whether improvements in energy ratio (the inverse of net energy requirements) could be gained by altering certain parameters of device design. In this case the parameters chosen were: structural scale, given in terms of the characteristic dimension of the device; and the amount of on-board machinery, given in terms of the installed capacity (power limit) of the device. The characteristic dimension of the device is that dimension which controls the performance of a device, in the conversion of incoming wave energy into mechanical motion, mass air movement, or head of water depending on the particular mode of operation of the device. The characteristic dimension of the Salter's Duck (SEA) device is the duck stern diameter. The characteristic dimension of the Oscillating Water Column (NEL) device is the column length (front-to-back). These parameters dictate how well the device is 'tuned' to the incoming wave regime.

Previous work at Sunderland Polytechnic, (Smith, Harrison and Varley, 1979) was concerned with an early version of the Salter's Duck device, operating in the mid-atlantic 'Ocean Station "India" sea state with an earlier estimate of the average annual power level of 90 kW/m. This work showed that valuable non-initiative insights could be gained into the best combinations of parameters to give a maximum energy ratio, or a different combination to give the best use of sea-room. The best energy ratio from these designs, with such an energetic sea, was found to be 13 $GJ_{(e)}/GJ_{(t)}$ (a net energy requirement of 0.08 $GJ_{(t)}/GJ_{(e)}$).

Computer modelling of the 1978 Reference Designs, described fully in Appendix B, used the more thoroughly engineered NEL and SEA designs in the 'South Uist' sea state for which parameterized output data were made available by the device terms. (Jeffrey et al, 1978; Moody, 1978). The total energy inputs for the devices were determined by the use of a simple scaling model based on the Reference Designs. More sophisticated models of how the various device parameters vary with characteristic dimension were not available from the device teams.

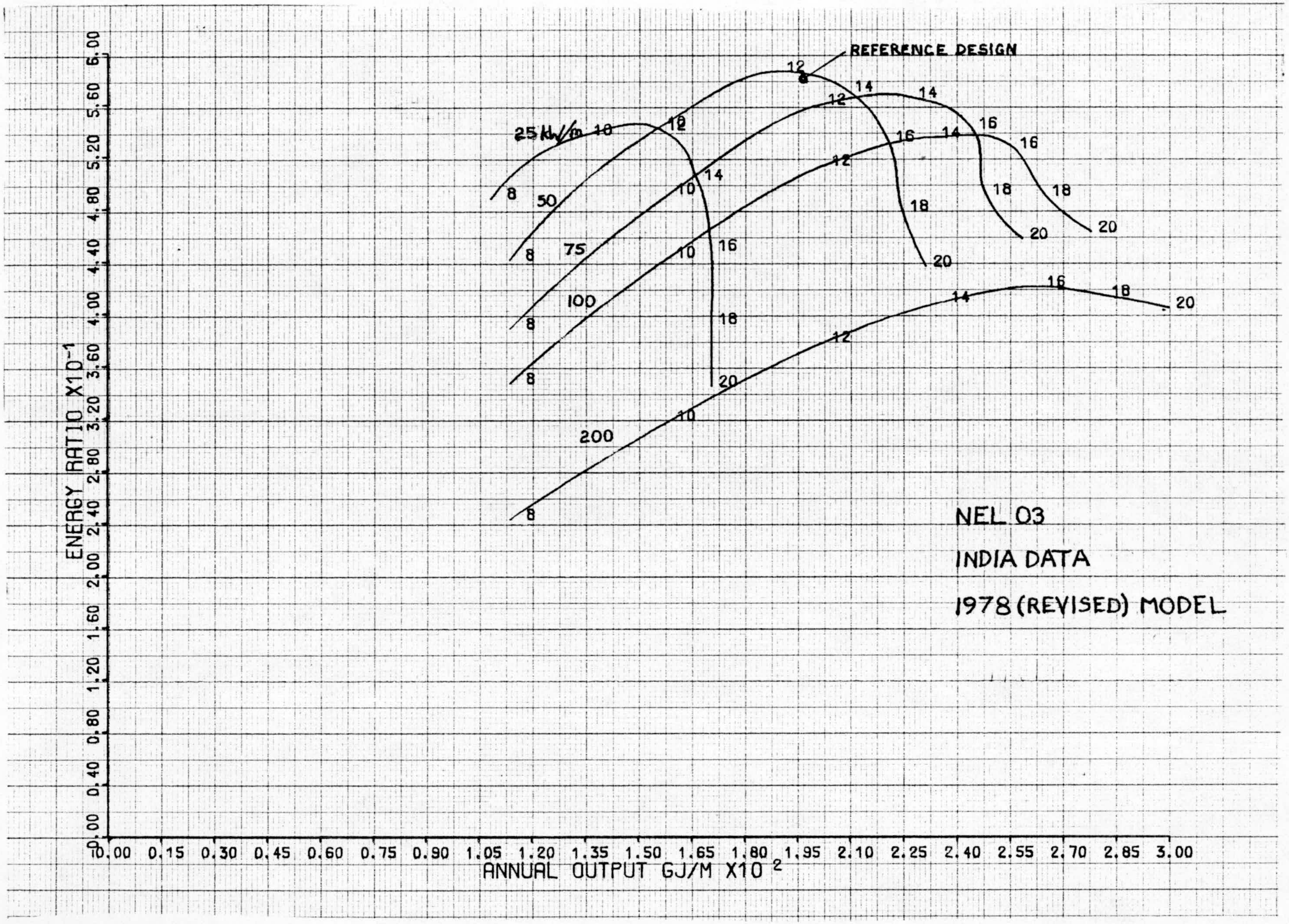


Fig. 3.7 Energy Ratio V Annual Output for NEL Device in OWS India Sea State.

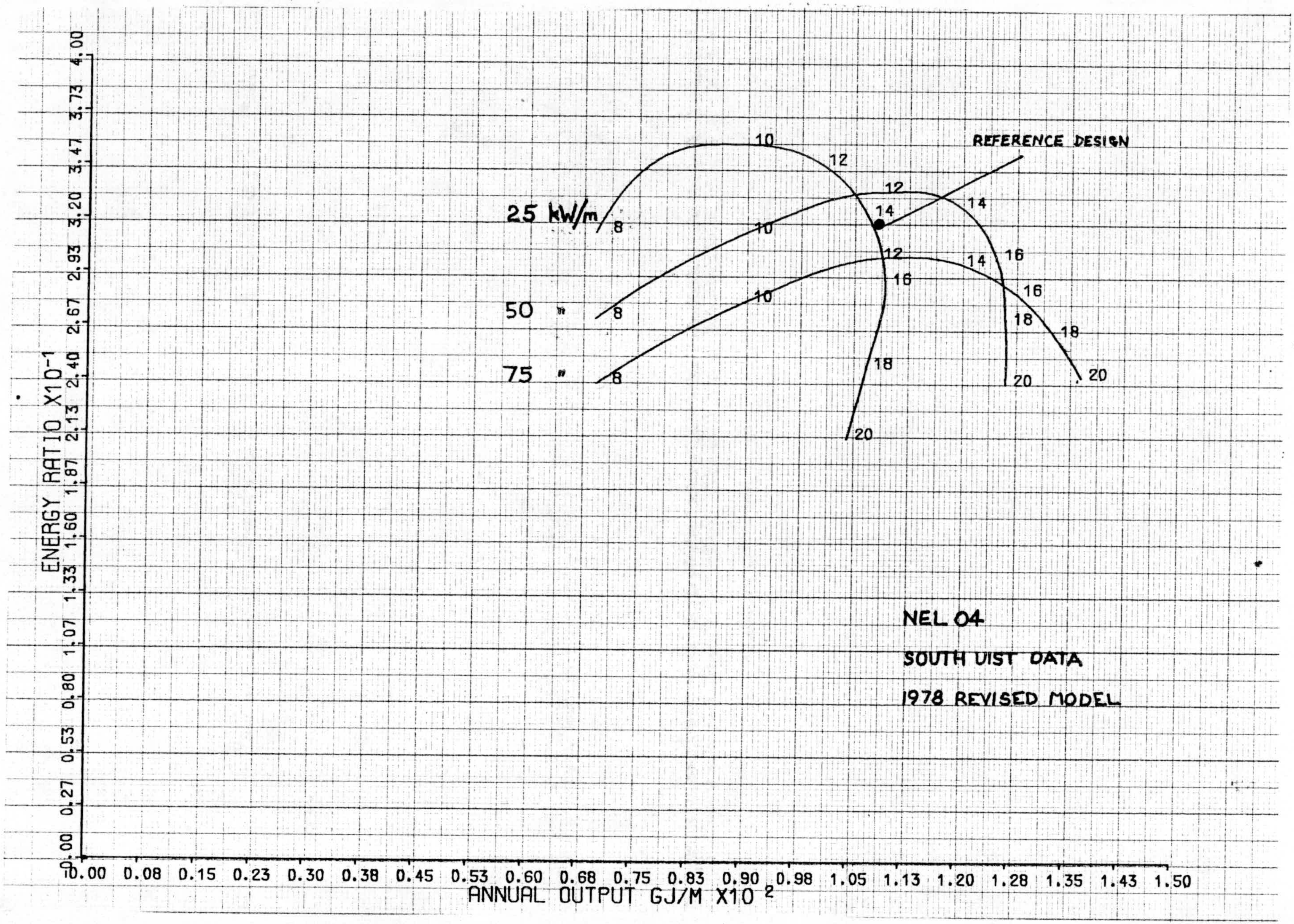


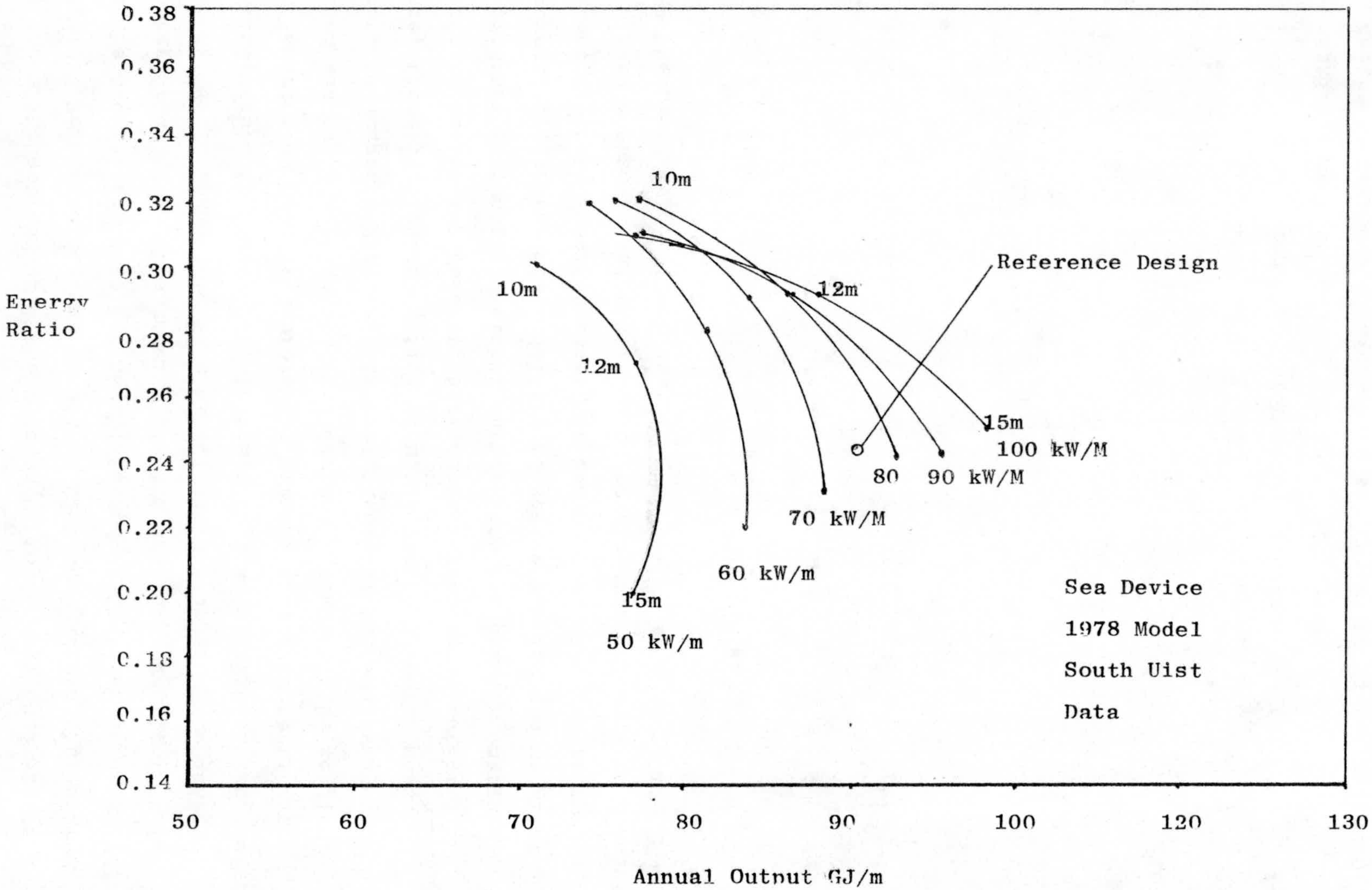
Fig. 3.8 Energy Ratio V Annual Output for NEL Device in South Uist Sea State

As shown in Section 3.1.1 the results of the energy analysis of the 1978 Reference Designs (modal values) demonstrate that neither of the two devices modelled here (NEL and SEA) are net primary energy producers. The results of this scaling investigation for the NEL device, shown in Figures 3.7 and 3.8 and for the SEA device, shown in Figure 3.9, indicate that some definite improvements in 'energetics' can be achieved by varying the characteristics dimension and power limit of the devices. Indeed, the scaling exercise suggests that, within the context of the analysis used here, these particular designs do not correspond to the most optimal device.* However, such optimisation would not be sufficient to transform either device into net primary energy sources. Although the modelling of device scaling has marginal effect in these specific cases, it can be seen that the technique can make a fundamental contribution to the study of generic concepts and the development of new devices.

---

* It should be noted that information of output was not available to enable clear maxima to be obtained for the SEA device in Figure 3.9 which shows the variation of energy ratio with annual output.

FIG 3.9 ENERGY RATIO V ANNUAL OUPUT - 1978 SALTER'S DUCK DEVICE, SOUTH UIST DATA



3.3 Device assessment and fuel price rises

Assessing the effect of fuel price inflation on the economics of new energy technologies is important for two basic reasons. First, such rises are typical features in the present economy and are now officially expected to be common place in the future. Second, the development of new technologies is frequently evaluated in terms of high levels of fuel prices. In other words, although fuel from a new source may currently be expensive, rising prices are expected to make such a source economically competitive in the future. By concentrating on the inflating value of fuels which determines the price of output, the conventional approach overlooks the impact of this same inflation on the costs of the new technology.

The detailed principles underlying the use of energy analysis in predicting the effect of fuel price inflation on the cost of electricity from new sources such as wave energy has been explained in Section 2.4. Basically, for the purpose of this analysis, the cost of electricity can be separated into two elements which are the fuel-related and non-fuel-related costs. These cost elements can be determined using information on total financial costing and net energy requirements as described in Appendix C. From this linear equations can be obtained which show the variation of the cost of electricity from wave energy devices with the price of fuels used during the construction of the wave energy system. The resulting cost-price equations can be expressed in terms of either the price of primary fuels or the price of electricity in an idealised electrical equivalent case.

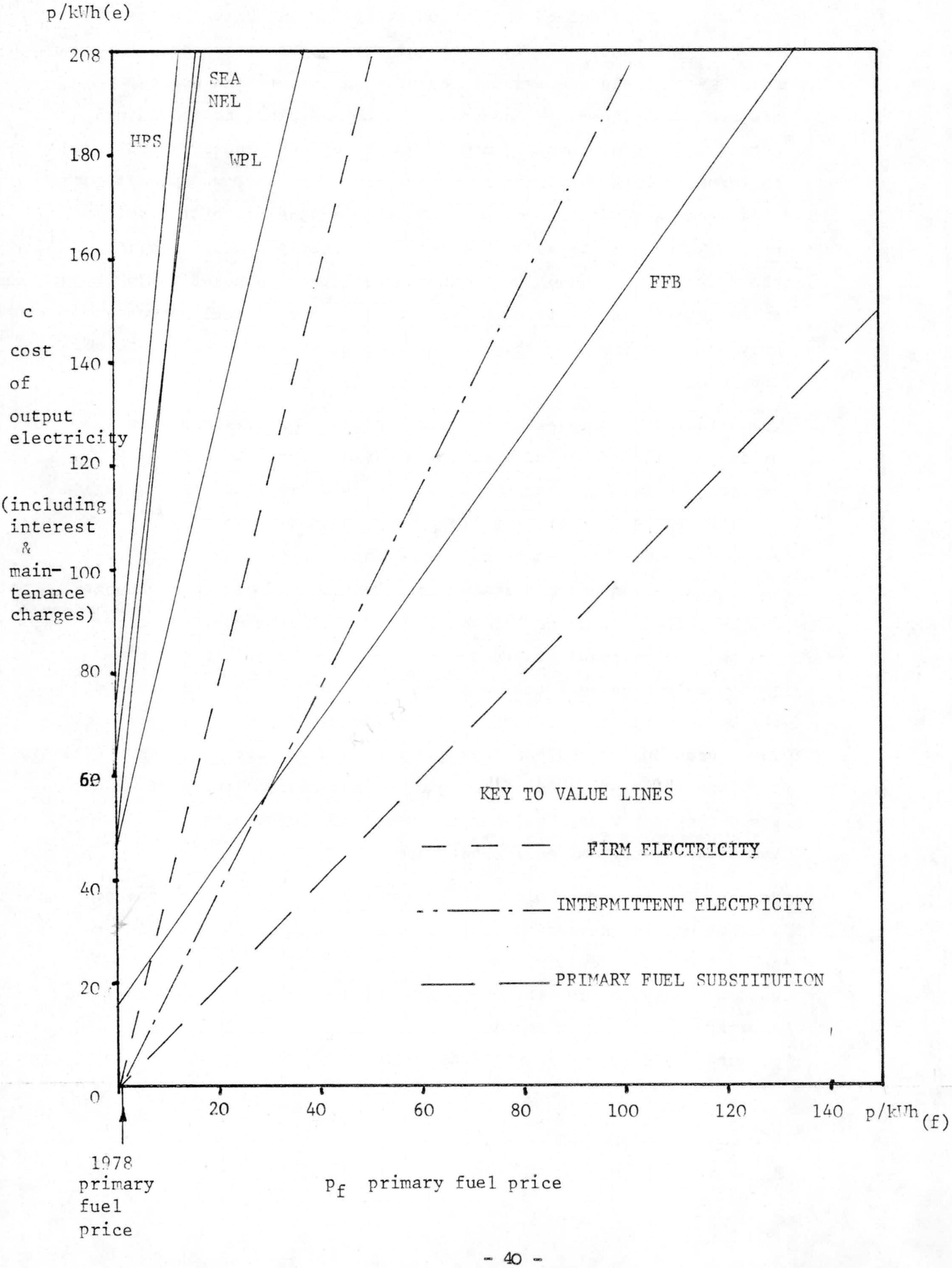
Primary fuels* are those used to provide heat for direct use or further energy conversion (e.g. to electricity). Such fuels are coal, fuel oil, heat from nuclear fission, etc. These can be used directly, or for the production of secondary fuels such as electricity, coke and smokeless solid fuel. A full definition of primary fuels can be found in Appendix C.

---

* measured in energy units of $GJ_{(f)}$ or $KWh_{(f)}$.

Fig. 3.10 COST-PRICE GRAPH FOR WAVEPOWER SYSTEMS

PRIMARY FUEL BASIS



The variation in the cost of electricity from wave energy systems with the price of primary fuels is shown in Figure 3.10. The cost includes interest charged on capital, (at 10% p.a.) and a nominal 10% annual charge for maintenance. Three value lines are shown in Figure 3.10;-

firm electricity value - the premium value of firm electricity, based on the current electrical generating system.

intermittent electricity value - some nominal value reflecting the intermittent nature of the electricity produced by wave energy systems.

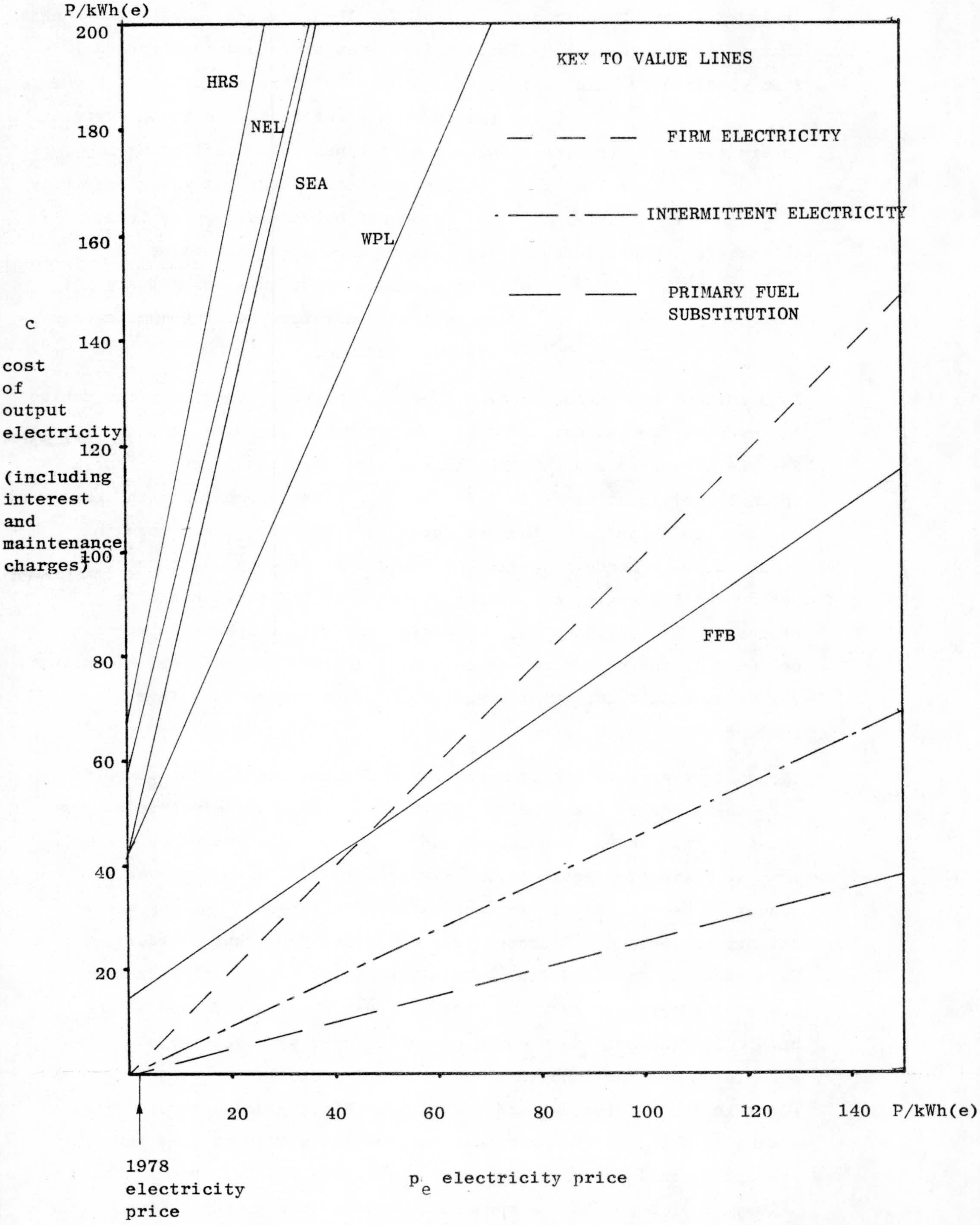
primary fuel substitution value - based on the current value of electricity as a substitute for primary fuels in low-temperature heating applications at the point of use.

This work on the current-fuel mix basis, indicates that only one device can ever become economic if their output can be sold as firm electricity. For the Lancaster device (FFB) this occurs when the price of the thermal fuel input rises to 6.66p/kWh$_{(f)}$. This compares with the current (1978) price of thermal fuels of 0.52p/kWh$_{(f)}$ as shown in Figure 3.10. Hence the price of fuels must rise by a factor of 13 before the FFB device can become economic as a firm electricity producer. Furthermore the FFB device has the prospect of becoming economic if the output can be sold at a nominal intermittent electricity value, so called 'dirty electricity'. This occurs at a thermal fuel price of 28.66 pence/kWh$_{(f)}$.

The cost of electricity from wavepower devices can also be compared with the price of electricity is a hypothetical 'all electric economy case'. This enables the input and output to be compared on the similar basis of electricity. The primary fuel case, however, cannot be used so easily for estimating future energy values where the mix of fuels may be completely different from that of today. To convert to an electrical equivalent basis, substitution factors are used (Mortimer, 1977). These express how the end used of particular thermal fuels could be substituted by electricity. An example of such an industrial application would be the use of electric arc furnaces rather than open hearth furnaces for steel making. Such possible applications are aggregated to give an average overall substitution factor, which is used to convert the primary fuel input to the construction of a wave energy system

Fig. 3.11 COST-PRICE GRAPH FOR WAVEPOWER SYSTEMS

ELELCTRICAL EQUIVALENT BASIS



(in $GJ_{(f)}$) to an electrical equivalent input (in $GJ_{(e)}$).

The cost of electricity output from wave energy systems in a situation of rising electricity prices is shown in Figure 3.11. The costs again include interest on capital borrowed and a nominal 10% annual maintenance charge. The value lines are those described above. It can be seen that, in the 'all electric economy' case considered, again only the Lancaster device (FFB) can ever be economic, and only then if its output can be valued as firm electricity. This occurs when the price of electricity used to construct the devices exceeds $49.7p/kWh_{(e)}$. These results suggest that the prevailing view, that the cost of the electricity output from wave energy systems will remain constant, whilst the price of fuels in the market place is rising, is clearly misleading. To hasten the economic viability of wave energy systems, a combination of capital cost reduction and net energy requirement reduction is necessary as indicated in Section 3.1.2. Unless such cost and input energy requirement improvements are achieved, then four of the devices, NEL, WPL, HRS and SEA, have unit output costs which inflate more rapidly than the prevailing value of electricity. Hence these four devices, as defined in the 1978 Reference Design configuration can never become economic producers of electricity.

The FFB device, although at an earlier stage of developments (in 1978) shows slightly more economic promise. If the output electricity could be sold at a premium value, then primary fuel prices would need to rise by a factor of 13 to make a wave energy system, based on the FFB device, economic. However, the offical view is that fuel prices may only double by the end of the century, thus the general economic prospects for the 1978 Reference Designs of wave energy systems do not seem very promising.

4 CONCLUSIONS AND RECOMMENDATIONS

The overwhelming conclusion of this energy analysis of the 1978 wave energy Reference Designs, is that, with the exception of the Lancaster device, no wave energy system can be considered as a net producer of primary energy. The energy analysis compares the energy input for the construction of the systems, in the form of coal, oil and gas etc. at the point of production, with the energy output, delivered to the National Grid in the form of electricity, over the operating life of the system. The energy of the waves is, of course, excluded from the calculations. This analysis demonstrates that most of the devices consume more primary energy during construction than they produce over their period of useful operation. The Lancaster device is a net producer of primary energy, although it can only generate twice as much primary energy than is consumed in its construction.

Inputs and outputs of energy can be considered on a similar basis by converting the primary energy input to an electrical equivalent input using substitution factors. This enables an assessment to be made independently of the present mix of fuels in the economy. In this case both the Wavepower Limited and Lancaster devices produce more electricity than they would consume, in a hypothetical all-electric economy.

The inability of the 1978 Reference Designs of wave energy systems to demonstrate any clear net energy benefit emphasis further the unpromising results of the corresponding economic evaluation. Detailed costings by the programme's consultants have resulted in costs for electricity from the proposed wave energy schemes at least five times higher than current (1978) electricity costs.

Conventional assumptions envisage wave generated electricity becoming economic as fossil fuel prices rise. These assumptions neglect the influence of the same fossil fuel price rises in the cost of the energy used in the construction and maintenance of wave energy systems. In a situation of fuel price inflation, with the exception of the Lancaster device, the cost of electricity generated by wave energy systems rises faster than the cost of conventional generation of electricity. Even for the Lancaster device, an order of magnitude increase in fuel prices is necessary before the use of wave energy as a marginal producer of electricity can be contemplated in the U.K. If the official estimates that the real price of energy will double by the turn of the century are borne out, then the economic circumstances required to make wave energy viable are very remote indeed. This energy analysis demonstrates that the 1978 Reference Designs wll display no obvious benefits in any realistic future situation of fuel price rises.

The results of this study have shown a drastic change in the energetic viability of wave energy devices, when compared to a similar exercise for the consultants' 1977 designs. This change has been the combined result of a small increase in the energy input to the devices coupled with a substantial decrease in energy output. More detailed cost engineering together with design modifications, have led to the increase in the estimates of resources required to construct the wave energy systems. The decrease in system output is due to two major factors. Firstly, the overall efficiency and reliability of the device and power transmission system have been more thoroughly researched, leading to an estimation of losses and outages which results in a reduced annual yield of electricity delivered to the National Grid. Primarily, however, there has been a massive drop in the estimates of energy which is available for extraction from the sea by devices. This change results from the recent acquisition of reliable sea state data for the South Uist site. Previously, only information on the sea state of Ocean Station India, in the mid-Atlantic had been available. This data had been used by device team as the basis of their 1977 and earlier designs of wave energy systems.

Provision of reliable information on such basic aspects of the primary energy source should be the most important initial feature of any energy research and development strategy. Although, this does not appear to have been the case in the early U.K. wave energy programme, future planning must incorporate a strong element of wave data anaylsis and resource assessment for there to be any realistic chance of developing successful wave energy devices.

Overall, the results suggest that wave energy systems are further from commercial exploitation than was realised early in the U.K. Wave Energy programme. As a consequence it would now seem unfortunate that wave energy development has become so linked to the fortunes of specific designs rather than being based on fundamental principles and broad concepts. It would be rational to change this emphasis in the future.

The results of this study suggest that the technique of energy analysis is required as part of a framework to assess the practical potential of new ideas and improved devices. The field of energy research and development planning can often be one of partial decisions leading to expensive errors. Unfortunately, attaining engineering feasibility in itself is not a guranteed method of avoiding similar mistakes in the future. Instead, a form of economic engineering which concentrates on the relative use of scarce resources in practical applications, is needed by inventors and designers, as a guide to promising areas of future development. A basic example of this type of engineering is suggested by the targeting exercise outlined in this report. This exercise demonstrated the changes necessary in the use of materials and components to achieve economic viability. Another development was the modelling of device scaling as a means of optimising design parameters. These techniques, in addition to others such as the parameterized analysis of generic concepts, form the basis from which wave energy research and development can progress from its current state of impasse. Only through such a committed, comprehensive and rational approach can wave energy become a realistic option for energy supply in the future.

APPENDIX A A worked example of energy analysis

This particular example of the procedures used in this study of energy analysis is based on the Wavepower Limited (WPL) reference design as set out in the Rendell, Palmer and Tritton Consultant's Second Report of 1978 (Rendell, Palmer and Tritton, 1978).

The starting point for an energy analysis of any device or system such as a wave energy scheme, using the basis of physical data, is an inventory of quantities, masses of materials and details of individual and complete components. In this study, inventories were obtained from specifications, engineering drawings and tables given in volume 3 of the 1978 RPT Report. The energy input, or effective contribution, of a specific item is calculated by multiplying the quantity of the item given in the inventory (for example, in tonnes) by its relevant energy requirement (for example, in $GJ_{(t)}$ per tonne). Energy requirements of materials and components used in wave energy systems can be found in the literature* and a short list of energy requirements is given in Appendix D.

An example of energy input results, for the construction of concrete units for one WPL reference design raft is shown in table A1. Inventory data were taken from the RPT Report which gives details of estimated quantities from three independent contractors. Such estimating differences introduce range variations in materials input figures. In order to represent this uncertainty in basic information, three particular types of results were evaluated. These consist of the extreme values of upper and lower bounds, and a most probable result, the modal value. Upper and lower bounds were calculated by multiplying specific energy requirements** by the highest and lowest inventory estimates, respectively. Modal values were obtained by multiplying specific energy requirements by the contractor's inventory estimate that was intermediate between the highest and lowest figures. Where only two inventory estimates were available the modal value was taken to be the arithmetic mean. In cases where only one inventory figure was given, this was taken as the modal value and the bounds were estimated as assumed percentage variations (e.g. ± 15%). It should

*See for example; Chapman, 1975; Gartner and Smith, 1976; Hannon et al, 1976; Varley and Harrison, 1977; Boustead and Hancock, 1979.

** As shown in Appendix D, energy requirement values were taken as typical without 'error bars'. Although uncertainties do occur in practice, these were not accounted for in this study.

Table A1 Energy inputs to construct concrete units (excluding steel centre section) - WPL 1978 Reference Design.

Item	Energy requirement	Material input per device			Energy input per device (GJt)		
		lower	modal	upper	lower	modal	upper
Cement	(a) 7.9 GJt/te	(b) 2206te	(b) 2240te	(b) 2269te	17,429	17,696	17,925
Aggregate	(a) 0.15GJt/te	(b) 8823te	(b) 8960te	(b) 9076te	1,323	1,344	1,361
Formwork framing timber	(c) 2.92GJt/m^3	(d) 94.5 m^3	(d) 120.0 m^3	(d) 125.0m^3	276	350	365
Formwork facing plywood	(c) 0.138GJt/m^2	(d) 3780m^2	(d) 4798m^2	(d) 5000m^2	522	662	690
Steel reinforcement	(e) 39.5GJt/te	(b) 1519te	(b) 1775te	(b) 1800te	50,000	70,113	71,100
Steel prestressing	(e) 43.0 GJt/te	(b) 41.7te	(b) 49te	(b) 56.4te	1,791	2,107	2,423
SUB-TOTAL	-	-	-	-	81,339	92,272	93,907
On-site energy	(f) Sub-total x 15%	-	-	-	12,201	13,841	14,086
Provision of facility	-	-	-	-	(g) 1,300	(g) 1,650	(g) 2,000
GRAND TOTAL	-	-	-	-	94,839	107,763	109.993

Notes.

(a) average value from Chapman, 1975; Gartner and Smith, 1976; and Varley and Harrison, 1977.

(b) from RPT 1978 Report, volume 3, table 8.

(c) average value from Hannon et al, 1976; and Roberts, 1978a.

(d) material consumed in building device from RPT 1978 Report, volume 3, table 28.

(e) from Roberts, 1978b.

(f) from Varley and Harrison, 1977.

(g) based on case studies.

be emphasised that the subsequent range of results produced by this method reflects uncertainties in the basic input information and does not mean that energy analysis, as a technique, is, in any way, unreliable or vague.

The results in table A1 show the energy inputs of various items as one stage of constructing a single WPL device. The energy inputs for cement, aggregate, formwork framing timber, formwork facing plywood, steel reinforcement and steel prestressing is simply all the energy used to manufacture these materials. This includes the energy embodied in the capital equipment used, along with direct process energy requirement. The energy required to construct concrete units from these items is given as the 'on-site energy' and is equal to typically 15% of the energy used to manufacture the materials (Varley and Harrison, 1977). The energy required to provide the facility in which to construct the concrete units was obtained by analysing case studies of North Sea oil platform docks (Hemming, 1975), and proposed wave energy device sites (Rendell, Palmer and Tritton, 1978).

As there are 1144 WPL devices in the 2GW reference power station scheme, the total initial energy input to the complete scheme is simply the energy input to a device multiplied by this number of devices. The total initital energy input for constructing the concrete units of the WPL design is shown in table A2. This can be used to deduce the effective annual energy input by dividing the initial energy input by the corresponding lifetime and results are also given in table A2. In this way, the annual energy input is a weighted figure that takes into account the replacement of components with relatively different lives. Since the individual lifetime of components are used in this study, the results are independent of the 'financial' life of the wave energy scheme. Estimated mean values and ranges of component lifetimes are shown in Appendix E.

The above process was repeated for each subsystem, or classified inventory operation, so that the total initial and annual energy inputs for the entire scheme could be calculated. For the WPL device these subsystems included the concrete units (construction and launch), the structural steel components, mechanical components to power take-off, hydraulic and electrical power take-off, tow out, moorings and anchors and power collection and transmission. The results are summarised in table A3. Also shown here are the expected range and modal values of the annual electrical energy output delivered at Perth in Scotland by the WPL scheme. These values were obtained from chapter 13 of volume 2 of the RPT Report and represent the high, low and most probable estimates, respectively.

Table A2 Initial and annual energy inputs to construct concrete units for a 2GW scheme - WPL 1978 Reference Design.

Item	Initial energy input per 2GW (a) (10^6 GJt)			Inverse lifetime (yrs^{-1})			Annual energy input per 2GW (10^6 GJt/yr)		
	lower	modal	upper	lower	modal	upper	lower	modal	upper
Cement	19.936	20.244	20.506	1/40	1/30	1/20	0.498	0.675	1.025
Aggregate	1.514	1.538	1.557	1/40	1/30	1/20	0.038	0.051	0.078
Formwork framing timber	0.315	0.400	0.418	(b) 1/40	(b) 1/30	(b) 1/20	0.008	0.013	0.021
Formwork facing plywood	0.597	0.757	0.789	(b) 1/40	(b) 1/30	(b) 1/20	0.015	0.025	0.039
Steel reinforcement	68.640	80.209	81.338	(c) 1/40	(c) 1/30	(c) 1/20	1.716	2.674	4.067
Steel prestressing	2.049	2.410	2.772	(c) 1/40	(c) 1/30	(c) 1/20	0.051	0.080	0.139
On-site energy	13,958	15.834	16.114	1/40	1/30	1/20	0.349	0.528	0.806
Provision of facility	1.487	1.888	2.288	(b) 1/40	(b) 1/30	(b) 1/20	0.037	0.063	0.114
TOTAL	108.496	123.280	125.832	-	-	-	2.712	4.109	6.272

Notes

(a) 2 GW scheme consists of 1144 devices.

(b) amortised over structure lifetime.

(c) steel embedded in concrete, hence same lifetime as structure.

Table A3. Initial and annual energy inputs for the complete construction of a 2GW scheme - WPL 1978 Reference Design.

Item No.	Item	Initial energy input per 2GW (10^6 GJt)			Annual energy input per 2GW (10^6 GJt/yr)		
		lower	modal	upper	lower	modal	upper
1	Construct concrete units	(a) 108.5	(a) 123.3	(a) 125.8	(a) 2.712	(a) 4.109	(a) 6.292
2	Structural steel components	(b) 42.8	(b) 49.3	(b) 56.9	1.425	1.972	2.844
3	Mechanical components to power take-off (c)	35.7	35.7	35.7	1.784	2.379	3.568
4	Hydraulic and electrical power take-off (d)	38.3	38.3	38.3	3.307	4.380	6.501
5	Tow out (e)	4.4	4.5	4.6	0.109	0.151	0.231
6	Anchors and moorings	30.7	69.4	249.8	1.234	3.281	14.390
7	Power collection and transmission	10.1	13.1	16.1	0.421	0.689	1.086
	TOTAL INPUT	270.5	333.6	527.2	10.992	16.961	34.870

Notes

(a) from table A2

(b) centre section, hinges and mooring points

(c) gearing, con rods etc.

(d) pumps, pipework, generators, transformers etc.

(e) from analysis based on case studies.

The resulting values of the energy ratio and net energy requirement of the WPL scheme are shown in table A4. The energy ratio is defined as the annual energy output, in terms of electricity (GJ(e)), divided by the total annual energy input, measured as the thermal energy of primary resources (GJ(t))*. The net energy requirement is the inverse of this ratio (GJ(t)/GJ(e)). The results of table A4 are compiled in such a way that the upper and lower bounds of these parameters represent the worst and best combination of input and output figures. For example, the upper bound of the energy ratio was obtained by dividing the lower value of energy input into the upper value of energy output. Modal values are simply combinations of modal input and output.

This type of analysis was repeated for all of the remaining devices except the Salters Duck (SEA)device. Unlike the other devices, no complete data were available on the physical inventory for the SEA device. Consequently, analysis was performed using financial costings given in the RPT Report and energy intensities MJ(t)/£(1978). As a check, the net energy requirements of the other devices were also evaluated with costings and energy intensities, and results are summarised in table A5. It is interesting to note that in each case the net energy requirement based on financial data is considerably more than that based on physical data. This difference suggests that the costs of the devices may have been over-estimated possibly becuase of their novel characteristics.

---

* The method of assessing the input in terms of equivalent substituted electricity is described in Appendix C.

Table A4. Energy ratio and net energy requirement for a 2GW scheme - WPL 1978 Reference Design.

Parameter	Value
Annual energy input (10^6 GJt/2GW/yr)	
- lower =	10.992
- modal =	16.961
- upper =	34.870
Annual energy output (10^6 GJe/2GW/yr)	
- lower =	7.253
- modal =	11.668
- upper =	16.083
Energy ratio (GJe/GJt) (a)	
- lower =	0.21
- modal =	0.69
- upper =	1.46
Net energy requirement (GJt/GJe) (b)	
- lower =	0.68
- modal =	1.45
- upper =	4.81

Notes

(a) $\text{lower energy ratio} = \frac{\text{lower annual energy output}}{\text{upper annual energy input}}$

$\text{upper energy ratio} = \frac{\text{upper annual energy output}}{\text{lower annual energy input}}$

(b) $\text{lower net energy requirement} = \frac{\text{lower annual energy input}}{\text{upper annual energy output}}$

$\text{upper net energy requirement} = \frac{\text{upper annual energy input}}{\text{lower annual energy output}}$

Table A5. Comparison of net energy requirements evaluated using physical and financial data.

Device	Net energy requirement PHYSICAL DATA $GJ_{(t)}/GJ_{(e)}$			Net energy requirement FINANCIAL DATA $GJ_{(t)}/GJ_{(e)}$		
	upper bound	modal value	lower bound	upper bound	modal value	lower bound
NEL	11.11	2.70	0.83	14.29	4.76	1.82
WPL	4.76	1.45	0.68	9.89	3.38	1.48
HRS	9.09	3.27	1.61	20.2	5.56	2.22
SEA	-	-	-	9.09	2.89	1.14
FFB	1.72	0.46	0.19	7.69	1.75	0.50

APPENDIX B: Modelling of the energy analysis with respect to device scale.

The prime function of energy analysis in the assessment of wave energy systems is to check that net primary energy will be produced over the life of those systems. A secondary function is to aid designers and engineers to maximise the potential of the system. This can be carried out either to make the best use of invested energy, or the best use of the natural energy flux available.

The former necessities maximising the energy ratio (energy output/energy input) or, conversely minimising the net energy requirement (energy input/energy output). The energy input is in the form of scarce fossil fuel resources used in the construction and maintenance of the wave energy system.

The maximum utilisation of the natural energy flux available, entails making the best use of sea room. This means maximising system output per unit frontage of scheme. These two conditions may not coincide, as has been shown by earlier work on device scaling (Harrison, Smith and Varley, 1979).

This modelling exercise concentrated on maximising the energy ratio of two devices, in their 1978 Reference Design Form; the National Engineering Laboratories (NEL) Oscillating Water Column device and the SEA/Edinburgh University, Salter's Duck device. The device parameters which were varied were the characteristic dimension of the device, which dictates the structural scale of the device, and the installed capacity (power limit) of the device. The characteristic dimension is that dimension which controls the performance of a device in the conversion of incoming wave energy into mechanical motion or mass air movement. Thus it is this dimension which 'tunes' the device to the sea.

B.1 NEL Model

The characteristic dimension of the NEL Oscillating Water Column device is the 'column length'. This is the front-to-back dimension of the interior of the water column. The information on device outputs with varying column length and power limit, was taken from tank test simulations of device performance in both the South Uist and O.W.S. 'India' sea states by NEL (Moody, 1978).

The energy inputs to build the system were based on the modal values of the results of the energy analysis of the 1978 Reference Design Oscillating Water Column*, converted to a 'per metre of frontage' basis to be compatible with device teams figures.

A model of the variation of energy input with characteristic dimensions D, and power limit P, was created using the following assumptions:

- the structural mass of the device varies with the square of the characteristic dimension. This assumes the need to retain a similar cross section so that the sea-keeping quantities of the device are kept.
- the energy requirement of the steel mooring points remain constant.
- the energy requirement of the mechanical equipment on board varies linearly with the characteristic dimension. This is equipment such as louvre valves, ducting, safety valves, bilge pumps etc.
- the energy requirements of the air turbines, electrical generators and other electrical equipment varies linearly with the power limit set for the electrical generators.
- the energy requirement for tow out and installation, anchors and mooring remains constant for the size of devices envisaged within this exercise (this is the area of greatest uncertainty in this model for the NEL device).
- the energy requirement of the power collection and transmission system varies with the power limit of the devices.

---

* This model was based on a 'mixed-basis' energy analysis. This has since been modified to the 'physical basis' given in Section 3.

TABLE B1 MODELLING OF DEVICE SCALING

National Engineering Laboratories (NEL) Model, based on 1978 Reference Design

ITEM	REF. DESIGN MODAL ANNUAL ENERGY INPUT GJ/m-y	PROPORTIONAL TO:	MODEL VALUES
1. Construct concrete units	108.3	D^2	0.7523
2. Structural steel	3.4	K	3.4
3. Mech. eqpt.	20.5	D	1.713
4. Turbines, hydraulic & Elect. eqpt.	60.6	p	1.01
5. Tow out & installation	6.6	K	6.6
6. Anchors & moorings	115.5	K	115.5
7. Power collection & transmission	24.2	p	0.4033
TOTAL	338.4		

Model energy requirement $N = 0.7523\ D^2 + 1.713D + 1.413P + 125.5$

D - Characteristic dimension (column length)

P - Power limit of machinery

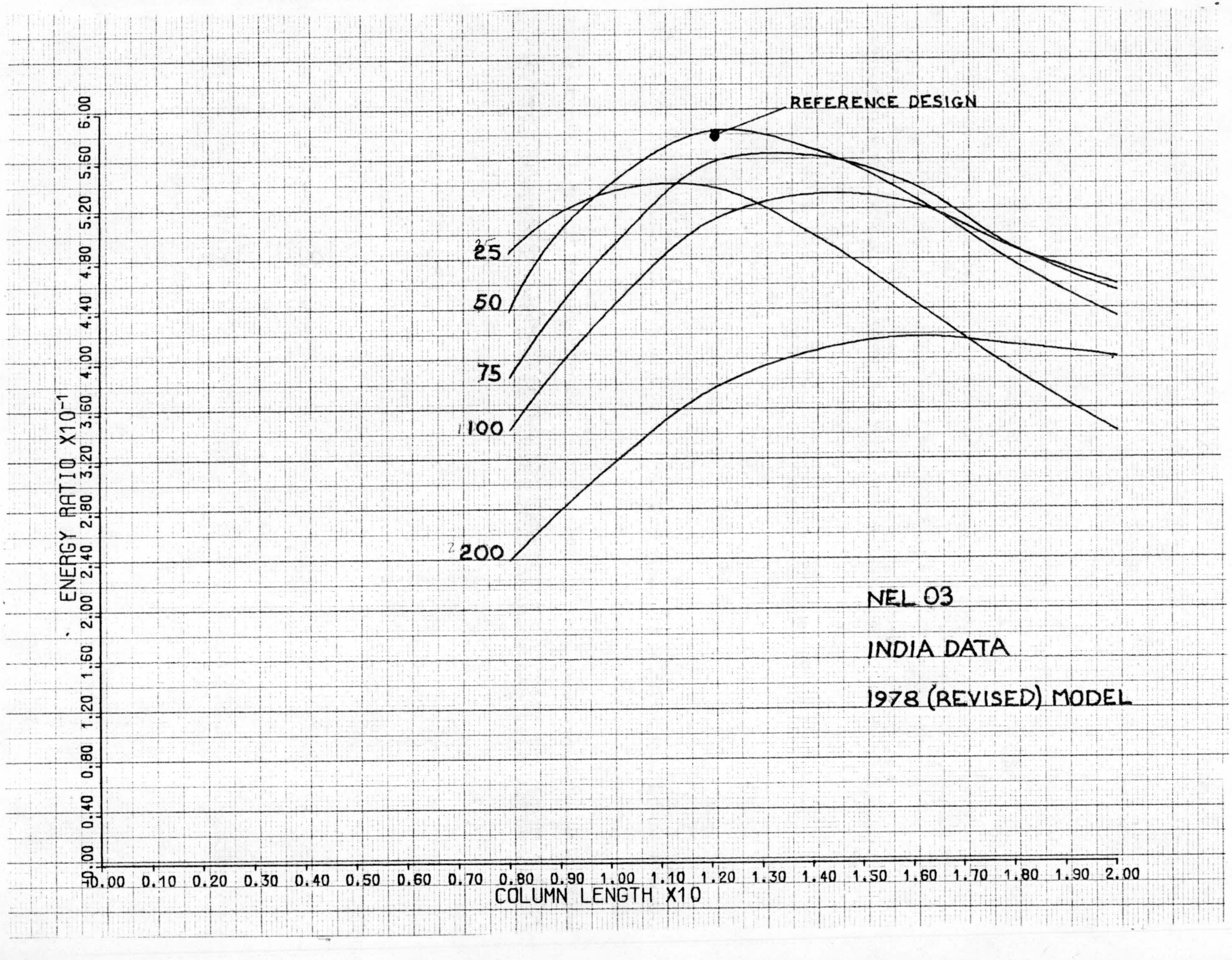
K - Constant

REF. Design

D = 12m

P = 60 kW/m

Fig. B1 Energy Ratio V Column Length for NEL Device in OWS India Sea State.



The model of annual energy inputs to the NEL device, with varying characteristic dimensions D, and power limit p, is shown in Table B1.

The model was run on the Polytechnic computer using graph plotting facilities. The results of energy ratio versus annual output for OWS India performance data is shown in Figure 3.7, and for the South Uist data is Figure 3.8.

The results of energy ratio versus column length, is shown for OWS India in Figure B1 , and for South Uist data is Figure B2.

These results clearly show that the reference design is very well suited to OWS India sea state conditions, but is oversized and over-rated for the sea state at South Uist. It also shows that although a reduction in scale and power limit would improve the energy ratio for a device at South Uist, this would not be sufficient to make the device a net primary energy producer.

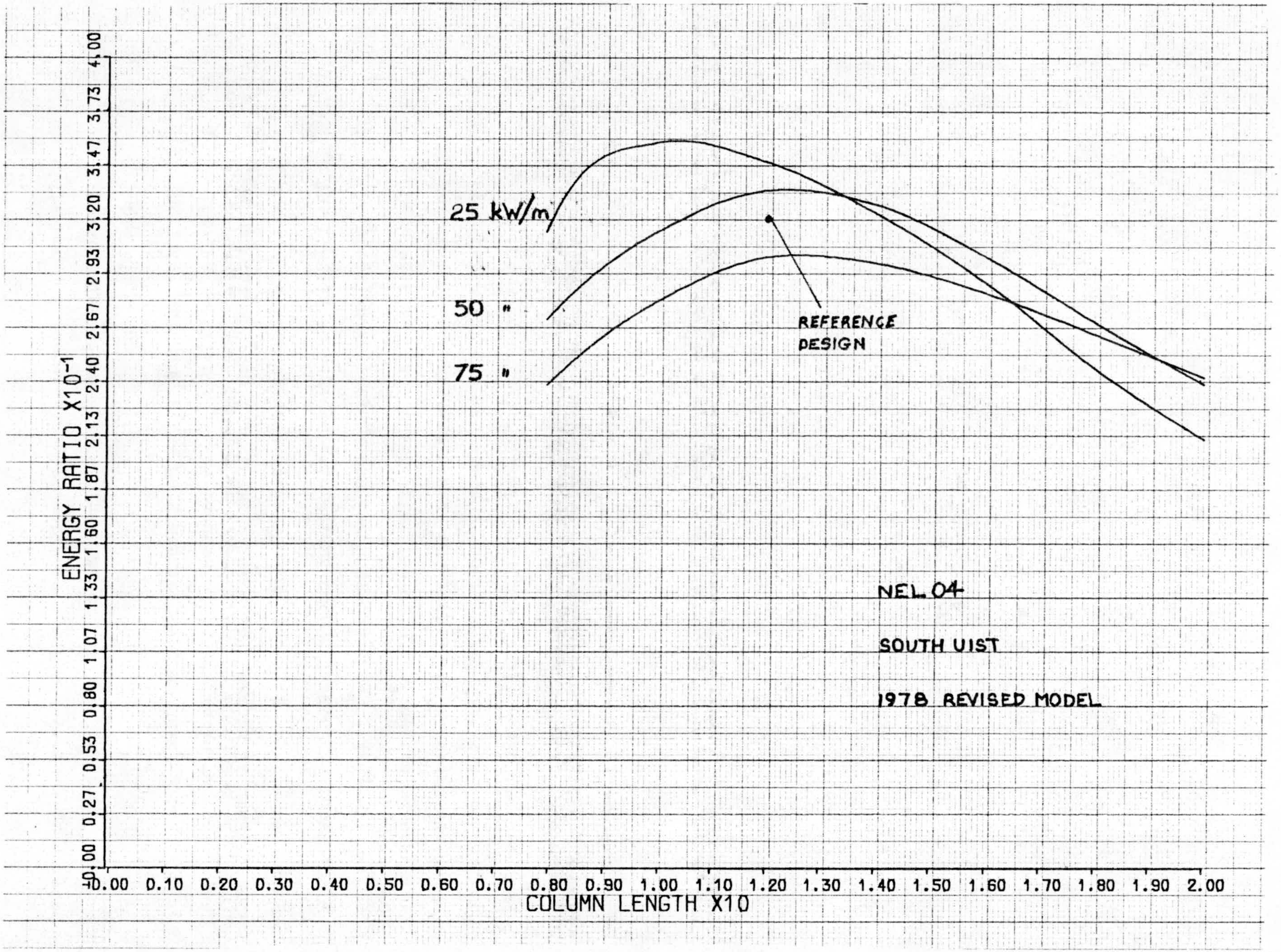


Fig. B2 Energy Ratio V Column Length for NEL Device in South Uist Sea State.

B2 Salter's Duck model

The model used for the 1978 References Design of Salter's Duck is similar to models used in previous studies (Smith, Harrison and Varley, 1979).

Information on system output in the South Uist sea state was taken from the Edinburgh Wave Power Project Fourth Year Report (Jeffrey et al, 1978)

The characteristic dimension of the Salter's Duck device is the duck stern diameter. Output data is parameterised in terms of this dimension (D) and the power limit (P) of electrical machinery. The model of annual energy requirements based on the energy analysis of 1978 Reference Designs, was created using the following assumptions:

- the structural energy requirement varies as the square of the duck stern diameter (The beak/spine structure can be crudely envisaged as having a square cross section)
- the energy requirement of the mechanical power take off equipment varies linearly with duck stern diameter. This equipment is deployed around the spine and will vary with the circumference
- the energy requirement of the hydraulic and electrical power take off equipment varies with the power limit of electrical machinery
- tow out, installation, anchors and mooring energy requirements are constant for the range of diameters considered
- the energy requirement of power collection and transmission equipment vary with the power limit of electrical machinery.

The model derived from the modal value annual energy input for the 1978 Reference Design is shown in Table B2.

The results of the modelling exercise for the Salter's Duck device in the South Uist sea state is shown in Figure 3.9 in the form of a graph of energy ratio versus annual output. Unfortunately only three data points were available for each constant power limit curve.

These results show that large improvements could be made by a decrease in device scale and power limit, although no clear maxima occur with the data provided. This indicates that Salter's Duck devices smaller than 10m diameter should be investigated for use in the South Uist sea state.

TABEL B2 MODELLING OF DEVICE SCALING

SALTER'S DUCK 1978 MODEL

Annual Energy Requirement (Modal)

ITEM	REF DESIGN ANNUAL G.E.R. (GJ/m-y)	PROPORTIONAL TO:	MODEL VALUES
1. Construct concrete units	89.5	D^2	0.457
2. Structural steel	39.9	D^2	0.204
3. Mechanical Equipment	186.6	D	13.346
4. Turbines, hydraulics & Electrical equipment	11.1	P	0.149
5. Tow out & installation	4.3	K	4.304
6. Anchors and moorings	9.4	K	9.375
7. Power collection & transmission	16.6	P	0.221
	357.7		

MODEL ENERGY REQUIREMENT = $0.6603\ D^2 + 0.3696\ P + 13.679$

D - Characteristic dimension (duck diameter)

P - Power limit of machinery

K - Constant

REF DESIGN
D = 14m
P = 75kW/m

APPENDIX C: Assessing the effect of fuel price rises.

In any energy conversion system, some energy is needed to construct and maintain the infrastructure of the system. A new technology, such as wave energy, although not using fuel directly to produce electricity, is no exception. Energy is embodied within the devices and the power collection and transmission systems. Thus any change in the price of fuels initially used in construction and maintenance will inevitably change the final price of output electricity. The importance of this effect depends on the amount of fuel consumed by the system which can be determined by energy analysis. In this way a technique can be developed to determine the sensitivity of the cost of output from an energy system to fuel price inflation.

When discussing the role of energy analysis and the effects of fuel price rises on energy producing systems, it is necessary to be very clear how energy measurement terms are defined. There are many such definitions and each has its appropriate use.

Three particular definitions are used in this study, dealing as it does with fuel price rises.

The first definition is that of energy measured in terms of primary energy. This refers to the energy extracted from a source of a particular energy type. It is the energy supplied to a consumer as delivered fuel, measured in terms of its calorific value, plus the energy required from other fuels, measured in a similar manner, to produce and deliver that fuel from the point of extraction to the point of sale. This term, primary energy, has been used previously in energy analysis, either explicitly or implicitly, elsewhere (Chapman, 1973 et seq; Mortimer, 1977; Boustead and Hancock, 1979; Harrison, Smith and Varley, 1979). This definition takes into account all the energy consumed, released or otherwise appropriated in any given activity. It incorporates not only the heat content of a fuel, but also the energy required from fuels in processing, to produce, for example, marketable coal, coke and coal products from coal at the coal face; marketable oil products from crude oil at bottom of the well; marketable gas from natural gas at the bottom of the well; electricity from nuclear heat in a fission reactor; and electricity from the electrical output of a hydroelectric scheme. The inclusion in this defintion of nuclear heat in a fission reactor, rather than uranium at the mine face, may seem inappropriate. However, this convention was adapted for consistency with earlier work in this field (Chapman, 1973). Energy in the form of primary energy is measured interms of megajoules (thermal) (MJ(t))

The second definition concerns energy measured in terms of primary fuels. This refers to the energy supplied to final consumers and/or to secondary fuel producers as a delivered fuel, measured by its calorific value alone. In this particular case, fuels produced by primary energy processes are considered as delivered fuel. This defintion covers the calorific value, or heat content, of coal, oil and gas sold to final consumers; coal, oil and gas bought by secondary producers such as the coke and electricity industries, nuclear heat from fission reactors used for electricity generation, and the electrical output of hydroelectric schemes. The difference between energy in the form of primary energy and energy in the form of primary fuel is simply the energy used in the extraction and production processes. Energy in the form of primary fuel is measured in terms of megajoules(fuel)(MJ(f)).

The third definition concerns energy measured in terms of the electrical equivalent energy. This is based on the substitution of electricity for all end uses of delivered fuel. All energy used by final consumers is envisaged on the common basis of electrical equivalent energy. Because the wave energy systems studied produce energy in the form of electricity, converting the primary energy input, to construct and maintain the system, into its electrical equivalent enables an appropriate comparison to be made between input and output. This comparison is achieved by converting from the energy used, as delivered fuel for final usage, into the electrical equivalent energy, by means of substitution factors developed elsewhere (Mortimer, 1977). Examples of such realistic substitutions are: steelmaking by electric arc furnace rather than open hearth furnace; rail freight transport using electric rather than diesel locomotives; water heating by electric immersion heaters rather than gas-fired systems; and space heating by electricity rather than coal; oil or gas-fired installations. Electrical equivalent energy is measured in terms of megajoules (electrical)(MJ(e)).

The effect of fuel price rises on the costs of output from alternative energy systems can be discussed on a primary fuel basis or on an electrical equivalent basis. It is not possible to describe this effect on a primary energy basis, because, by definition, no prices or costs can be directly allocated to primary energy.

The costs of output electricity for wave energy schemes on a primary fuel basis is shown in table C3. On the basis of primary fuels, the total scheme cost K of an energy system with no fuel operating costs, for example a wave energy system, is the sum of the total scheme non-fuel cost K_o and total fuel cost K_f necessary to build this system.

$$K = K_o + K_f \quad £ \quad (1.1)$$

This can be expressed, on an annual basis, by dividing equation (1.1) by the system lifetime n (years) to obtain annual costs k, k_o, and k_f.

$$k = K/n \quad (1.2)$$

$$k = k_o + k_f \quad £/yr \quad (1.3)$$

The annual fuel cost K_f can be described as the product of the primary fuel price P_f (£/GJ(f)) and the annual primary fuel energy input E_f ($GJ_{(f)}$). The latter is derived from the primary energy input E_p ($GJ_{(t)}$) by the use of a primary energy to primary fuel conversion factor g ($GJ_{(f)}/GJ_{(t)}$) derived in Table C2

$$E_f = g\ Ep \quad GJ_{(f)} \quad (1.4)$$

thus

$$k = k_o + P_f E_f \quad £/yr \quad (1.5)$$

The electricity output cost per unit C (£/$GJ_{(e)}$) is obtained by dividing equation (1.5) throughout by the electricity output E_o ($GJ_{(e)}$) from the energy system studied.

$$C = C_o + P_f \frac{E_f}{E_o} \quad £/GJ_{(t)} \quad (1.6)$$

The term E_f/E_o is known as the net energy requirement (primary fuel basis); R_f ($GJ_{(f)}/GJ_{(e)}$). Hence

$$C = C_o + P_f . R_f \quad £/GJ_{(e)} \quad (1.7)$$

The output cost per unit can be described in pence per kWh terms by multiplying throughout by 0.36 (pence per kWh/£ per GJ). This gives the output cost per unit c in terms of the non-fuel cost per unit c_o and the primary fuel price p_f.

$$c = c_o + p_f . R_f \quad p/kWh_{(e)} \quad (1.8)$$

This equation describes in a simple way how the cost of the output electricity from a wave energy system varies with the cost of the primary fuel input to its construction. This equation does not take account of interest charges on money borrowed, or maintenance charges.

Interest repayments on the capital borrowed can be taken into account, by assuming that all money is borrowed for construction in a single sum K(£). This is paid back in equal annual sums, or annuities of k'(£/yr) over the payback period which is assumed to be the project lifetime n (yrs). If the annual rate of interest over this period is r, a capital recovery factor a can be defined (Institution of Civil Engineers 1969) such that;

$$a = \frac{r}{1 - (1 + r)^{-n}} \qquad (1.8)$$

The annuity is given by the formula

$$k' = a.K \quad £/yr \qquad (1.9)$$

substituting from equation (1.2)

$$k' = a.n.k \quad £/yr \qquad (1.10)$$

from equation (1.5), this becomes

$$k' = a\ n\ (k_o + P_f E_f) \quad £/yr \qquad (1.11)$$

hence on a cost per unit basis, the cost of output electricity c' (p/kWh(e)) is given by:

$$\underline{c' = a.n\ (c_o + p_f R_f)} \quad p/kWh(e) \qquad (1.12)$$

To adopt an even more realistic cost model, an allowance must be made for continuous maintenance. This will take the form of both money and energy. Thus if the proportion of the non-fuel cost, c_o, which is allowed for maintenance is m_c, and the proportion of the net energy requirement R_f allowed for is m_e, this gives a maintenance charge per unit output, c_m

$$c_m = m_c.c_o + m_e.P_f.R_f \quad p/kWh(e) \qquad (1.13)$$

Thus the cost of electricity, c'_m, allowing for both maintenance and interest charged on initial capital is

$$c'_m = c_m + c' \qquad (1.13)$$

$$c'_m = m_c \cdot c_o + m_e \cdot p_f \cdot R_f + a.n\,(c_o + p_f R_f) \qquad (1.15)$$

$$c'_m = (an + m_c)\, c_o + (an + m_e)\, p_f\, R_f \qquad (1.16)$$

If an assumption is made that the cost and energy maintenance factors are equivalent

$$m_c = m_e = m \qquad (1.17)$$

Then the cost of electricity per unit, with allowance for interest charges and maintenance becomes

$$\underline{c'_m = (an + m)\, (c_o + p_f\, R_f)}\ \ p/kWh_{(e)} \qquad (1.18)$$

This is shown graphically for the five schemes studied figure 3.10 and tabular form in table C7.

The above equation combines the net energy requirement of a system, determined by energy analysis, and the non-fuel cost, determined by a cost engineering exercise. The cost of the electricity output from the scheme can be found for any particular primary fuel price at the time of building the scheme. The other factors in the equation relate to current values of various parameters used for project appraisal within the energy industries. In this case the project lifetime n is taken as 30 years, the annual rate of interest is taken as 10%, giving a capital recovery factor $a = 0.10608$.

A similar process can be carried out to determine the cost of output electricity with the variation in the price of energy on an electrical equivalent basis, as shown in table C4.

Firstly, the initial annual energy input, in primary energy terms Ep $(GJ_{(t)})$, must be separated into the proportion of primary energy which has been used for electricity generation, and the proportion of primary energy which has been used for the production of other fuels used to construct the energy system. Unfortunately the energy analysis data base, at present, is not categorized by fuel type. Hence general industrial statistics of energy consumption are utilised for these normalized primary energy conversion factors, x_e and x_f respectively, as shown in table C1. This primary energy used for electricity generation must then be converted, to actual electricity used as a fuel, by means of the primary energy to electricity conversion factor of the electricity industry y_e. Similarly, the primary energy used to provide other fuels used in the construction, is converted by means of the factor of efficiency of primary energy conversion to primary fuels; y_f. The fuel factors f_e and f_f, expressing fuel use in terms of primary energy input are therefore for the electricity consumed:

$$f_e = x_e . y_e \quad GJ_{(e)}/GJ_{(t)} \tag{2.1}$$

and for the primary fuel consumed:

$$f_f = x_f . y_f \quad GJ_{(f)}/GJ_{(t)} \tag{2.2}$$

The above fuel factors, shown in table C2, give the current mix of fuels used to construct the wave energy system. To express this energy input purely in electrical equivalent terms, a further conversion is necessary. This necessitates the use of a substitution factor S ($GJ_{(e)}/GJ_{(f)}$) which expresses how electricity could be substituted for primary fuels at the point of use (Mortimer, 1977). Thus the annual electrical equivalent input energy E_e to construct the wave energy system is given by

$$E_e = (f_e + Sf_f)Ep \quad GJ(e) \tag{2.3}$$

In similarity with equation (1.2), the annual cost of electricity produced by the system k, on an electrical equivalent basis, is

$$k = k_n + k_e \quad £/yr \tag{2.4}$$

where k_n is the annual non-fuel cost and k_e is the annual fuel cost in electrical equivalent terms. The latter can be expressed in terms of the electricity price P_e ($£/GJ_{(e)}$) and the annual electrical equivalent input energy E_e ($GJ_{(e)}/yr$)

$$k = k_n + P_e E_e \quad £/yr \tag{2.5}$$

this can be expressed on a cost per unit basis, where C is the cost per unit of electricity output, and C_n is the non fuel cost per unit:

$$C = C_n + P_e R_e \quad £/GJ(e) \tag{2.6}$$

Where R_e is the electrical equivalent net energy requirement;

$$Re = \frac{E_e}{E_o} \quad GJ_{(e)}/GJ_{(e)} \tag{2.7}$$

this can be expressed as cost of electricity output per unit c (p/kWh(e)) where c_n is the non fuel cost per unit, and p_e is the electricity price (p/kWh(e))

$$\underline{c = c_n + p_e Re} \quad p/kWh(e) \tag{2.8}$$

Allowing for interest on capital, with a capital recovery factor a, and the system lifetime n, the cost of electricity output, on an electrical equivalent basis is given by c', where

$$\underline{c' = a.n.\ (c_n + p_e\ Re)} \quad p/kWh_{(e)} \tag{2.9}$$

and, in a similar fashion to equation (1.18), the cost of electricity output, with allowance for interest on capital, and maintenance, becomes

$$\underline{c'_m = (an + m)\ (c_n + p_e\ R_e)} \quad p/kWh_{(e)} \tag{2.10}$$

This equation is shown graphically for the wave energy systems studied in fig. 3.11, and in tabular form in table C8.

To determine the break-even cost of electricity from an alternative energy system, firstly on the basis of primary fuels, it is necessary to define the equation of the particular value line required, for example, a line with gradient V such that the cost relates to a price p;

$$c = V.p \quad p/kWh_{(e)} \tag{3.1}$$

At the point of intersection (p_x, c_x), equation (3.1) becomes

$$c_x = V.p_x \tag{3.2}$$

and equation (1.7) becomes

$$c_x = c_o + p_x\ R_f \tag{3.3}$$

combining to eliminate p_x,

$$c_x = c_o + \frac{c_x\ R_f}{V} \tag{3.4}$$

thus the breakeven cost c_x ($p/kWh_{(e)}$)is

$$\underline{c_x = \frac{c_o}{1 - \frac{R_f}{V}}} \tag{3.5}$$

and similarly, the break even price p_x ($p/kWh_{(f)}$)

$$p_x = \frac{c_o}{V - R_f} \tag{3.6}$$

Similarly, allowing for interest on capital, and maintenance charges, using equation (1.18), at break-even, the cost of output electricity c_x(p/kWh) becomes

$$c_x = \frac{(an + m)\, c_o}{1 - (an + m)\,\frac{R_f}{V}} \qquad (3.7)$$

Similar equations can be derived for the break-even cost of output electricity on an electrical equivalent basis, although different value line gradients are used, reflecting the changed basis of assessment.

These break-even costs are shown, on a primary fuel basis in table C5, and on an electrical equivalent basis in table C6.

The value lines are taken from the ratio of relative prices of firm electricity (table C2), intermittent electricity (nominally off peak, night-rate prices), and primary fuel prices, (table C2).

TABLE C1 FUELS USED FOR ELECTRICITY GENERATION - 1978

		COAL (inc. coke breeze)	OIL	NATURAL GAS	NUCLEAR	HYDRO	TOTAL	NOTES
1. FUEL INPUT (units)		81.0 (m.te)	11.5 (m.te)	338 (m.therms)	37.22 TWh(e)	4.04 TWh(e)		(a) table 65
2. FUEL INPUT	$x10^6 GJ_{(f)}$	1914.0	495.0	35.7	134.0(e)	14.54(e)		(a) table 133
3. PRIMARY FUEL INPUT	$x10^6 GJ_{(f)}$	1914.0	495.0	35.7	515.4	14.54	2974.6	(a) table 78 includes nuclear h
4. PRIMARY ENERGY CONVERSION FACTORS	$GJ_{(f)}/GJ_{(t)}$	0.960	0.896	0.875	-	-		Chapman, 1973
5. PRIMARY ENERGY INPUT	$x10^6 GJ_{(t)}$	1993.8	552.4	40.8	515.4	14.5	3116.9	
6. ELECTRICITY SUPPLIED	$x10^6 GJ_{(e)}$	-	-	-	-	-	909.5	(a) table 65

PRIMARY ENERGY TO PRIMARY FUEL
CONVERSION FACTOR (electricity generation) = 0.9542 $GJ_{(f)}/GJ_{(t)}$

PRIMARY FUEL TO ELECTRICITY
CONVERSION FACTOR (electricity generation) = 0.3058 $GJ_{(e)}/GJ_{(f)}$

PRIMARY ENERGY TO ELECTRICITY
CONVERSION FACTOR y_e = 0.2918 $GJ_{(e)}/GJ_{(t)}$

(a) Digest of Energy Statistics, Dept. of Energy, H.M.S.O. 1979

(e) denotes electrical energy.

TABLE C2 FUELS USED BY INDUSTRY - 1978

		COAL	COKE, BREEZE & OTHER SOLID FUELS	OTHER COAL DERIVED	GAS	PETROLEUM	ELECTRICITY	TOTALS	NOTES
1. TOTAL HEAT SUPPLIED	$\times 10^6$ therms	2,234	2,382	388	6,020	8,557	2,866(e)	22,447	(a) table 14
2. TOTAL HEAT SUPPLIED	$\times 10^6$ GJ	235.7	251.3	40.9	635.1	904.8	302.4(e)	2,370	(b)
3. TOTAL PRIMARY FUELS	$\times 10^7 GJ_{(f)}$	235.7	251.3	40.9	635.1	904.8	988.8	3,057	
4. PRIMARY ENERGY TO PRIMARY FUEL CONVERSION FACTOR	$\frac{GJ_{(f)}}{GJ_{(t)}}$	0.960	0.847	0.847	0.875	0.896	0.954(c)	(d) 0.909	(c) from tabl C1 (d) 'g'
5. TOTAL PRIMARY ENERGY	$\times 10^6 GJ_{(t)}$	245.5	296.7	48.3	725.8	1009.8	1036.3	3362.4	
6. NORMALIZED PRIMARY ENERGY FACTORS		0.073	0.088	0.014	0.216	0.300	0.308(h)	1.00	(h) x_e
7. FUEL FACTOR - PRIMARY FUEL	$\frac{GJ_{(t)}}{GJ_{(f)}}$	0.070	0.075	0.012	0.189	0.269	-	(i) 0.614	(i) 'f_f'
8. FUEL FACTOR - ELECTRICITY	$\frac{GJ_{(t)}}{GJ_{(e)}}$	-	-	-	-	-	0.090(j)	-	(j) 'f_e'
9. TOTAL COST £M		225	570	40	695	1,255	1,670	4,460	

AVERAGE INDUSTRIAL PRIMARY FUEL PRICE = 1,459 £/$GJ_{(f)}$

= 0.525 p/$kWh_{(f)}$

AVERAGE INDUSTRIAL ELECTRICITY PRICE = 5.522 £/$GJ_{(e)}$

= 1.988p/kWh(e)

Continued.

TABLE C2 (continued) FUELS USED BY INDUSTRY - 1978

PRIMARY ENERGY TO PRIMARY FUEL CONVERSION FACTOR		$g = 0.909\ GJ_{(f)}/GJ_{(t)}$
FUEL FACTORS	PRIMARY FUEL	$f_f = 0.614\ GJ_{(f)}/GJ_{(t)}$
	ELECTRICITY	$f_e = 0.090\ GJ_{(e)}/GJ_{(t)}$

(a) Digest of Energy Statistics, Dept. of Energy, H.M.S.O. 1979

(b) 'Iron and Steel' and 'Other Industries' Sections from (a) table 14.

TABLE C3 WAVE ENERGY SYSTEMS - COST OF OUTPUT ELECTRICITY - PRIMARY FUEL BASIS

	UNITS		NEL	WPL	HRS	SEA	FFB
1. Annual primary energy input	$x10^6 GJ_{(t)}$/ yr.	E_p	16.93	16.96	15.48	20.03	2.60
2. " primary fuel input*	$x10^6 GJ_{(t)}$/ yr.	E_f	15.39	15.42	14.07	18.21	2.36
3. " fuel cost**	£M/yr	k_f	22.92	22.96	20.95	27.11	3.51
4. " scheme cost	£M/yr	k	360.7	468.8	313.0	303.9	80.5
5. " non-fuel cost	£M/yr	k_o	337.8	445.8	292.0	276.8	77.0
6. " electricity output	$x10^6 GJ_{(e)}$/ yr.	E_o	6.30	11.67	4.73	6.93	5.67
7. net energy requirement	$\frac{GJ_{(f)}}{GJ_{(e)}}$	R_f	2.44	1.32	2.97	2.63	0.42
8. non fuel cost per unit	$£/GJ_{(e)}$	c_o	53.62	38.20	61.73	39.94	13.58
9. " " "	p/kWh(e)	c_o	19.30	13.75	22.22	14.38	4.89
10. non fuel cost per unit (with interest only)	p/kWh(e)	anc_o	61.42	43.76	70.71	45.76	15.56
11. non fuel cost per unit (with interest + maintenance)	p/kWh(e)	$(an+m)c_o$	63.35	45.13	72.93	47.20	16.05

assumptions: interest = 10% p.a.
lifetime = 30 years
maintenance charge = 10% of capital cost.

* primary energy to primary fuel conversion factor g = 0.909 $GJ_{(f)}/GJ_{(t)}$

** 1978 primary fuel price; P_f = 1.459£/$GJ_{(f)}$

" " " " P_f = 0.525 p/$kWh_{(f)}$

TABLE C4 WAVE ENERGY SYSTEMS - COST OF OUTPUT ELECTRICITY - ELECTRICAL EQUIVALENT BASIS.

			NEL	WPL	HRS	SEA	FFB
1. annual primary energy input	Ep	$x10^6 GJ_{(t)}$	16.93	16.96	15.48	20.03	2.60
2. annual primary input	f_fE_p	$x10^6 GJ_{(f)}$	10.39	10.41	9.50	12.30	1.60
3 " elec. equivalent primary fuel input	sf_fE_p	$x10^6$GJ(e)	6.11	6.12	5.59	7.23	0.94
4. " electrical energy input	$f_e E_p$	$x10^6$GJ(e)	1.52	1.53	1.39	1.80	0.23
5. total electrical equivalent input	E_e	$x10^6$GJ(e)	7.64	7.65	6.98	9.03	1.17
6. annual electrical fuel cost	k_f	£M/yr	42.16	42.24	38.55	49.89	6.48
7. annual scheme cost	k	£M/yr	360.7	468.8	313.0	303.9	80.5
8 " non fuel cost	k_n	£M/yr	318.5	426.6	274.4	254.0	74.0
9. electricity output	E_o	GJ(e)	6.30	11.67	4.73	6.93	5.67
10. electrical equivalent net energy requirement	R_e	$\frac{GJ(e)}{GJ(e)}$	1.21	0.66	1.48	1.30	0.21
11. non fuel cost per unit	C_n c_n	£/GJ(e) p/kWh(e)	50.56 18.20	36.55 13.16	58.02 20.88	36.65 13.19	13.05 4.70
12. non fuel cost per unit (with interest only)	anc_n	p/kWh	57.91	41.88	66.47	41.99	14.96
13. non fuel cost per unit (with interest & maintenance)	$(an+m)c_n$	p/kWh(e)	59.74	43.19	68.56	43.31	15.43

1978 electricity price; P_e = 5.522 £/GJ(e)

p_e = 1.988 p/kWh(e)

s = 0.588 f_f = 0.514 f_e = 0.090

assumptions: interest = 10% p.a.
lifetime = 30 years
maintenance charge = 10% of capital cost.

TABLE C5 BREAKEVEN COSTS - PRIMARY FUEL BASIS
(including interest and maintenance charges)

			NEL	WPL	HRS	SEA	FFB
1. NON FUEL COST	p/kWh	$(an+m)c_o$	63.35	45.13	72.93	47.20	16.05
2. NET ENERGY EQUIPMENT	$\frac{GJ_{(f)}}{GJ_{(e)}}$	R_f	2.44	1.32	2.97	2.63	0.42
		$(an+m)R_f$	8.01	4.33	9.75	8.63	1.38
BREAKEVEN COSTS	p/kWh						
3. FIRM ELECTRICITY VALUE		$V_1 = 3.79$	-	-	-	-	25.24
4. NOMINAL INTERMITTENT ELECTRICITY VALUE		$V_2 = 1.94$	-	-	-	-	55.60
5. PRIMARY FUEL SUBSTITUTION VALUE		$V_3 = 1.00$	-	-	-	-	-
6. PRESENT COST $p_f = 0.525$	p/kWh p/kWh	c_p	67.55	47.40	78.05	51.73	16.77

TABLE C6 BREAKEVEN COSTS - ELECTRICAL EQUIVALENT BASIS
(including interest and maintenance charges)

1. NON FUEL COST	p/kWh	$(an+m)c_n$	59.74	43.19	68.56	43.31	15.43
2. NET ENERGY REQUIREMENT	$\frac{GJ_{(e)}}{GJ_{(e)}}$	R_e	1.21	0.66	1.48	1.30	0.21
		$(an+m)\ R_e$	3.97	2.17	4.86	4.27	0.68
BREAKEVEN COSTS	$p/kWh_{(e)}$						
3. FIRM ELECTRICITY		$V_1 = 1.00$	-	-	-	-	49.66
4. NOMINAL INTERMITTENT ELECTRICITY VALUE		$V_2 = 0.516$	-	-	-	-	-
5. PRIMARY FUEL SUBSTITUTION VALUE		$V_3 = 0.264$	-	-	-	-	-
6. PRESENT COST $p_o = 1.988$	$p/kWh_{(e)}$ $p/kWh_{(e)}$	c_p	67.63	47.50	78.22	51.80	16.78

TABLE C7 EQUATIONS OF COST-PRICE GRAPHS·PRIMARY FUELS BASIS
(including interest and maintenance charges)

NEL $c = 63.35 + 8.01 \; p_f$ p/kWh$_{(e)}$

WPL $c = 45.13 + 4.33 \; p_f$ p/kWh$_{(e)}$

HRS $c = 72.93 + 9.75 \; p_f$ p/kWh$_{(e)}$

SEA $c = 47.20 + 8.63 \; p_f$ p/kWh$_{(e)}$

FFB $c = 16.05 + 1.38 \; p_f$ p/kWh$_{(e)}$

TABLE C8 EQUATIONS OF COST-PRICE GRAPHS·ELECTRICAL EQUIVALENT BASIS
(including interest and maintenance charges)

NEL $c = 58.74 + 3.97 \; p_e$ p/kWh$_{(e)}$

WPL $c = 43.19 + 2.17 \; p_e$ p/kWh$_{(e)}$

HRS $c = 68.56 + 4.86 \; p_e$ p/kWh$_{(e)}$

SEA $c = 43.31 + 4.27 \; p_e$ p/kWh$_{(e)}$

FFB $c = 15.43 + 0.68 \; p_e$ p/kWh$_{(e)}$

in box.

APPENDIX D: Energy requirments of some materials and products

MATERIAL	ENERGY REQUIREMENT	
CONCRETES		
Concrete Grade 30	1.31 GJ/tonne (3.14 GJ/m^3)	Building Research Establishment 1974; Casper et al, 1975; Chapman, 1975; Gartner & Smith, 1976; Varley & Harrison, 1977.
Concrete Grade 40	1.43 GJ/tonne (3.44 GJ/m^3)	
Concrete Grade 50	1.67 GJ/tonne (4.01 GJ/m^3)	
Ordinary Portland Cement	7.9 GJ/tonne	Chapman, 1975
Aggregate (average)	0.15 GJ/tonne	Casper et al, 1975; Gartner & Smith, 1976; Varley & Harrison, 1977.
Reinforced concrete*	4.0 GJ/tonne (10.0 GJ/m^3)	*Grade 40 concrete 7% reinforcing steel by weight.
STEELS (material only)		
Steel - industry average	36.5 GJ/tonne	Roberts 1978 (c)
Steel reinforcing bar	39.5 GJ/tonne	Roberts 1978 (c)
Steel prestressing wire	43.0 GJ/tonne	Roberts 9178 (c)
Steel plate (>4.5mm)	31 GJ/tonne	Roberts 1978 (c)
Steel sheet (<4.5mm)	38 GJ/tonne	Roberts 1978 (c)
Stainless steel	92 GJ/tonne	Berry & Fels, 1973
- plate -	95 " "	Mortimer 1980
Iron castings	44 GJ/tonne	Rose, 1978
NON-FERROUS METALS (material only)		
Aluminium (from ore) 30%	328 GJ/tonne	Chapman, 1973 (a)
" 50%	312 GJ/tonne — typical.	^
Aluminium (UK average)	97.1 GJ/tonne	Chapman, 1973 (b)
Copper (UK average)	45.9 GJ/tonne	Chapman, 1973 (b)
Lead (UK average)	25.2 GJ/tonne	Chapman, 1975
Zinc (UK average)	68.4 GJ/tonne	Chapman, 1975

Cont.

FINISHED PRODUCTS OF ENGINEERING INDUSTRIES		
Steel fabrications	55.6 GJ/tonne	PERA, 1978 Roberts, 1978 (c)
Machined components	60.6 GJ/tonne	PERA, 1978 Roberts, 1978 (c)
Mechanical Equipment	85.5 GJ/tonne	PERA, 1978 Roberts, 1978 (c)
Steel fastners (screws etc.)	~~97.9 GJ/tonne~~ 82.0GJ/tonne	PERA, 1978 Roberts, 1978 (c)
WOOD		
Dressed timber soft wood	2.93 GJ/m^3	Hannon et al, 1976
Plywood, exterior soft wood	5.65 GJ/m^3 (0.052 GJ/m^2)	Hannon et al, 1976
Shuttering* (amount consumed)		*Multiple usage; includes 20% steel by area
Facing only	0.138 GJ/m^2	Hannon et al, 1976
including backing timber	0.172 GJ/m^2	Roberts, 1978 (a) Roberts, 1978 (c)
PLASTICS		
Polythene (high density)	89 GJ/tonne	Roberts 1978 (b)
PVC	96 GJ/tonne	Robert 1978 (b)
Polyester fibre	200 GJ/tonne 170.9 222.14 } av 196.5	NEDO, 1974 BOUSTEAD 1979 }
Epoxy resin	200 GJ/tonne	NEDO, 1974
"Parafil" rope	200 GJ/tonne	NEDO, 1974
GRP (glass reinforced plastic)*	96 GJ/tonne	*50% polyester by volume Long, 1974 NEDO, 1974
RUBBERS		
Natural rubber	6.4 GJ/tonne	Roberts, 1978 (b)
Synthetic rubber	140 GJ/tonne	Roberts, 1978 (b)
Rubber tyres	170 GJ/tonne	Roberts, 1978 (b)
SBR rubber	130.07 GJ/tonne	BOUSTEAD 1979 p 358

PLASTICS

NYLON 66	253.33 GJ/tonne	BOUSTEAD 1979 p 348	} from crude oil
NYLON 66 FIBRE	285.13 GJ/tonne	" "	
ACRYLIC FIBRE	349 GJ/tonne		

ELECTRICAL EQUIPMENT		
A.C. genrators (IMVA)	90.4 GJ/tonne	Electrical Research Association, 1977
D.C. generators	119.0 GJ/tonne	Electrical Research Association, 1977
Transformers (>1.5MVA)	82.5 GJ/tonne	Electrical Research Association, 1977
Turbines	239.1 GJ/tonne	Electrical Research Association, 1977
MISCELLANEOUS		
Glass	24 GJ/tonne	Long, 1976
Hydraulic oil	54 GJ/tonne	Casper, et al, 1975
Water	0.009 GJ/m^3	Casper, et al, 1975

APPENDIX E

Component Lifetimes

Component lifetimes are obviously not known with any accuracy, because the novel operating environment of wavepower systems has no precedent in present day engineering. In considering the energy inputs over the total system lifetime (30 years) obviously some components will suffer rapid wear or fouling, whilst others will have deteriorated very little. Thus a likely range of lifetimes for each component or sub-system has been used in our analysis (APPENDIX A). The modal value of the lifetime is that considered most likely, whilst the lower and upper bound of the lifetimes represent the extremes of the range considered likely by engineers and scientists within the programme.

Unfortunately, no data is yet available on programmes of planned maintenance of wavepower systems. Repair and refurbishment may use much less energy than total replacement of a sub-system.

Obviously as understanding of these systems widens for use in wavepower, better lifetime estimation of smaller components will be possible. This will enable more detailed and accurate energy analysis and cost assessment.

APPENDIX E

Lifetime of components - assumed ranges

Item	Range of Lifetimes (Years)		
	Short	Intermediate	Long
GENERAL			
Structure			
1 Concrete (reinforced or prestressed)	20	30	40
2 Structural steelwork	20	25	30
Hydraulic equipment (Oil)			
1 Hydraulic pumps	5	7.5	10
2 Hydraulic mains and flow regulation equipment	15	20	25
3 Hydraulic oil	2	6	10
4 Hydraulic turbines	10	15	20
Electrical equipment			
1 Alternators	20	25	30
2 Transformers	25	30	35
3 Other electrical equipment on board	20	25	30
Anchors and Moorings			
1. Steel mooring ropes	5	12.5	20
2 Nylon mooring ropes	5	12.5	20
3 Drag anchors	20	25	30
4 Piled anchors	20	25	30
Power collection & transmissions			
1 22 kV Flexible Submarine Cable	5	7.5	10
2 Converter and invertor stations (electrical equipment)	10	15	20
3 Main ± 250 kV D.S. Submarine Cables	15	20	25
4 Terminal substation	20	25	30
5 Overhead transmission lines	20	25	30
6 Communications systems	20	25	30

Item	Range of lifetimes (Years)		
	Short	Intermediate	Long
Special equipment			
HRS			
1 Flap gates - steel components	10	15	20
2 Flap gates - rubber components	10	15	20
3 De-watering gates	20	25	30
4 Kaplan turbines	10	15	20
5 Gearboxes	20	25	30
NEL			
1 Ducting & louvres (g.r.p.)	15	20	25
2 Cranes & crane rails	20	25	30
3 Air turbines & flywheels	20	25	30
WPL			
1 Mechanical components (rack, gears, hinges etc.)	10	15	20
2 Sea water hydraulic equipment	5	7.5	10
S.E.A.			
1 Mechanical components (rack, pinions, bearings etc.)	15	20	25
FFB			
1 Rubber air bags	5	10	15
2 Louvres vales & vanes	10	15	20
3 Air turbines	10	15	20

REFERENCES

Berry, R.S., and Fels, M.F.	1973	The energy cost of automobiles	Science and Public Affairs U.S.A., 1973
Boustead, I., and Hancock, G.F.	1979	Handbook of energy analysis	Ellis Horwood Ltd., Chichester, 1979
Building Research Establishment	1974	Design of normal concrete mixes	Building Research Establishment Watford, 1974
Casper, D.A., Chapman, P.F. and Mortimer, N.D.	1975	Energy analysis of 'Report on the Census of Production 1968	ERG 006 Open University Energy Research Group Milton Keynes 1975
Chapman, P.F.	1973(a)	The energy costs of producing copper and aluminium from primary sources	ERG 001 Open University Energy Research Group Milton Keynes 1973
Chapman, P.F.	1973(b)	The energy costs of producing copper and aluminium from secondary sources	ERG 002 Open University Energy Research Group Milton Keynes 1973
Chapman, P.F.	1973(c)	The energy costs of delivered energy: U.K. 1968	ERG 003 Open University Energy Research Group Milton Keynes 1973
Chapman, P.F.	1975	The energy costs of materials	Energy Policy Vol. 3, No. 1 p47-57 March, 1975
Chapman, P.F.	1976	Are the energy resources guranteed by nuclear power?	International Symposium on the crisis in the nuclear industry, Gottlieb Duttweiler Institute, Zurich 1976
Chapman, P.F., and Hemming, D.F.	1976	Energy requirements of some energy sources	9th International T.N.O. Conference Rotterdam, 1976

Cont..

Department of Energy	1979	Digest of United Kingdom Energy Statistics	H.M.S.O. London 1979
Electrical Research Association	1977	Electrical Engineering Industry	Energy Audit Series Dept. of Industry (in press)
Garnish, J.D.	1976	Geothermal energy - the case for research in the United Kingdom	Energy Paper No. 9 H.M.S.O. London, 1976
Gartner, E.M. and Smith, M.A.	1976	Energy costs of house construction	Energy Policy Vol. 4 No. 2, p144-157 June, 1976
Hannon, B.M, Stein, R.G. Segal, B. Serber, D., and Stein, C.	1976	Energy use in building construction	Energy Research Group, Centre for Advanced Computatio University of Illinois, 1976
Harrison, R., Jenkins, G. and Roberts, F.	1978	Note on the energy analysis of wave power systems	Paper presented at Dept. of Energy, Wave Energy Worksho London, November 197
Harrison, R., Smith, K.G., and Varley, J.S.	1979	Energy analysis of wave and tidal power	Future Energy Concepts Conference IEE London January 1979
Hemming, D.	1975	Energy requirements of North Sea Oil production	ERG 010 Energy Research Group Open Universit Milton Keynes June, 1975
I.F.I.A.S.	1974	Energy analysis Workshop on methodology and conventions	International Federation of Institutes for Advanced Study, Sweden, 1974
Institution of Civil Engineers	1969	An introduction to engineering economics	Institution of Civil Engineers London, 1969

Cont..

Jeffrey, D.C., Keller, G.J., Mollison, D., Richmond. D.J.E., Salter, S.H., Taylor, J.R.M., Young, L.A.	1978	Edinburgh Wave Power Project, Fourth Year Report	University of Edinburgh, July, 197
Long, T.V.	1976	Energy analysis methodology	NATO-CCMS New York, 1976
Moody, G.W.	1978	Private Communication	National Engineering Laboratories, East Kilbride 1978
Mortimer, N.D.	1977	The energy analysis of burner reactor power systems	Ph.D. Thesis Open University Milton Keynes November, 1977
Mortimer, N.D.	1979	Energy analysis applied to uranium production	4th International Symposium of the Uranium Institute London.
N.E.D.O.	1974	Energy Conservation in the United Kingdom	National Economic Development Office H.M.S.O. London 1974
Production Engineering Research Association (P.E.R.A.)	1978	Engineering Industries	Energy Audit Series Dept. of Industry (in press)
Rendel, Palmer and Tritton (R.P.T.)	1977	U.K. Wave Energy Programme Consultants Preliminary Report	Rendel, Palmer & Tritton London, 1977
Rendel, Palmer and Tritton	1978	U.K. Wave Energy Programme - Consultants Second Report	Rendel, Palmer, and Tritton London 1978
Roberts, F.,	1978(a)	Private communication	August, 1978
Roberts, F.,	1978(b)	Private communication	November 1978
Roberts, F.,	1978(c)	Note on energy requirements of finished steel products	unpublished report December, 1978
Rose, K.S.B.	1978	Iron Casting Industry	Energy Audit Series No. 1 Dept. of Industry H.M.S.O. London 1978

Cont..

Smith, H.	1969	The cumulative energy requirements of some final products of the chemical industry	Transactions, World Energy Conference 1969
Smith, K.G. Harrison, R. and Varley, J.S.	1977	Energy analysis of some wave power systems	Energy Workshop Report No. 4 Sunderland Polytechnic, September, 1977
Starr, C.	1979	Current issues in energy	Pergamon Press Oxford, 1979
Thomas, J.A.G.,	1977	Energy analysis	IPC Science and Technology Press Guildford, 1977
Varley, J.S. and Harrison, R.	1977	Energy use in large construction projects	Energy Workshop Report No. 3 Sunderland Polytechnic, 1977