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THE ECONOMICS OF NUCLEAR pOWER

Thermal nuclear power stations will continue to provide economic electri-city until the cost of uranium rises to several times its present level; fast reactors could then stabilise the cost of electricity. By Hugh Hunt and Gerry Betteridge (Economics and programmes Branch UKAEA)

THE ECONOMIC OF NUCLEAR POWER

Nuclear power stations throughout the world are now providing consumers with substantially the cheapest electricity, except in areas with extensive hydro-power or cheap, clean, local coal. Thermal nuclear power stations will continue to provide economic electricity until the cost of uranium rises to several times the present level; fast reactors have the potential to continue to stabilise the cost of electricity and by moderating demand for other fuels will keep down their cost also. These are conclusions to the study presented here, by Hugh Hunt and Gerry Betteridge*

The historical perspective

Looking back over a hundred years we see a close relationship between useful energy consumption and standards of living. This is not surprising, since it is largely external energy that has enabled man to produce much more during his limited life-span than he could unaided, and rescued him from a short and brutish existence. However, it is not only by using more energy that living standards have been improved but also by

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progressively using sources of energy which require less resources (particularly of labour) for their extraction, transport and processing. Thus, as illustrated in Figure 1 relating to the USA, wood gave way to coal, and coal to oil and gas.

In the world as a whole (excluding the Centrally Planned Economies) between 1945 and 1974, the proportion of energy (measured in terms of primary fuel input) provided by oil fuels increased from 25 to 54 per cent, and that of natural gas from 10 to 18 per cent. During the same period the share of solid fuels fell from 60 to 19 per cent. This means that in a period when overall energy demand has been growing at about 5 per cent p.a., both oil and gas have been rising by 8 per cent p.a.[1]

In this progression, each succeeding fuel has had a higher energy content per unit weight than its predecessor (Table 1). Moreover, liquid and gaseous fossil fuels have largely superseded solid fuels because they are also more easily extracted and transported in bulk and are more efficient in end use. Natural gas is perhaps the ultimate fuel for many purposes in being conveyed from source to consumer with little intermediate handling or processing, and if it was in unlimited supply the story could end here.

Uranium is the latest addition to this sequence. If fully fissioned, natural uranium has a specific energy content some 3.5 million times that of coal. However, uranium ore, as mined, typically contains only about 0.1 per cent uranium. Also, in practice, not more than about 1.0 per cent of the potential energy in natural uranium can be extracted using a moderated (so-called 'thermal neutron' or simply 'thermal') reactor, although up to 60 per cent using unmoderated ('fast neutron' or simpley 'fast') reactor. After making allowance for this we get the scale of specific energies for the various fuels per ton of useful material extracted shown in Table 1.

The step-change from fossil to nuclear fuel is such as is rarely encountered in the evolution of a technology. Although nuclear fuel requires much more processing than other fuels before it is in a usable form, its higher energy content more than offsets this. It can be economically concentrated to an almost pure form near the point of mining, so saving considerable on subsequent transport and storage costs compared with fossil fuels.

Energy costs generally have been further reduced by improving the efficiency of appliances in which fuels are consumed[2], e. g.

(a) by moving from reciprocating steam engines to steam turbines in electricity generation; to internal combustion engines for road transport; and to gas turbines for air transport where power to weight ratio is important.

(b) by increasing the size of generating units: (e.g. in the UK from 1 MW in 1900 to 660 MW by 1974. In the USA, 1000 MW generating sets are in use). This, as well as other interdependent technical factors, has played a big part in reducing unit capital costs and in improving the best attainable thermal efficiency from 20 per cent in 1948 to 35-40 per cent today. Average thermal efficiency in the UK system has increased from 8 per cent in 1900 to about 31 per cent today and will increase towards 40 per cent as new plant takes over (Fig. 2).

(c) The introduction of the distribution grid has reduced the overall generating capacity required to provide a reliable service by a factor of 2 compared with what would be required if separate individual local power stations were used[3]. Increasing the grid voltage has also greatly reduced distribution costs. The combined result of these improvements is that today some 137 power stations in England and Wales produce almost 40 times as much electricity as 438 stations in 1925.

Table 1

	Specific energy content therms per ton
Wood	160-180
Coal	230-300
Oil	420-440
Gas	500
Uranium ore refined and fissioned to 0.6-1 per cent in a thermal reactor	4800-8000
Uranium ore refined and fissioned to 60 per cent in a fast reactor	480 000

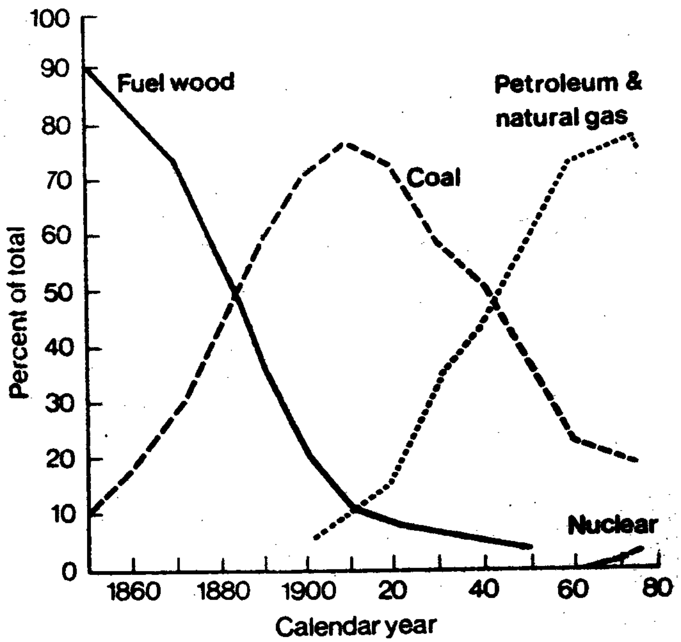

Fig. 1

Source: Historical Statistics of the United States Bureau of the Census; US Bureau of Mines, 1974.

It is by such means as these that, until 1973, the cost of energy has been reduced in real terms despite the considerable increase in the cost of inputs to the energy industries.

Although the price of electricity is several times that of other fuels in terms of simple heat output, it can command this price on the open market in competition with other fuels because it is a high grade energy source of great versatility, cleanliness, convenience and efficiency in end-use. Clearly, these virtues are highly valued by consumers. Moreover, it makes use of low-grade fuels (power station coal, residual oil and uranium) which have at present little other use and could

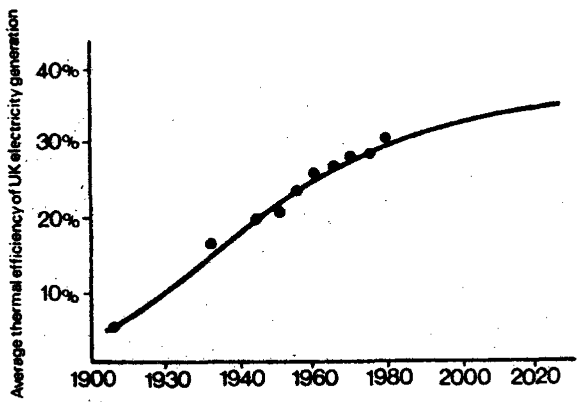

Fig. 2 The average thermal efficiency of generating electricity in the UK. From 1960 excluding nuclear stations. (Source: UK Energy Statistics).

not be burnt as efficiently, if at all, locally. For some applications electricity is the only practicable form of energy.

The five-fold increase in oil prices in 1973, although not completely passed on to consumers, gave us a foretaste of the effect of increasing energy costs. It brought about sudden press pressures for change in economic relativities and accustomed life-styles in oil-consuming countries. Although resisted, these pressures persist and their repercussions are a major cause of current world depression and unemployment. A continuation of rising fossil fuel prices due to the increased cost of exploiting more expensive sources will have a more gradually debilitating but more permanent effect.

In these circumstances conservation measures, to the extent that they are economic, will become more important, but cannot by themselves meet the needs of an expanding world population. The need remains for a large new economic source of energy. Uranium with its much higher energy content and no other large-scale uses is the front runner, particularly when used in fast reactors.

Methods of comparing nuclear and fossil generating costs

In electricity production it is especially complex to allocate costs between one type of station and another in a strictly comparable and consistent manner, since within a large system stations are operated in merit order of variable operating cost to meet a continually fluctuating demand.

The economics of any particular design of power station can be looked at in terms of

(a) its own generating cost in comparison with an alternative design used for the same purpose;

(b) the effect of one station on the total generating cost of the whole system in which it has been or is assumed to be, used;

(c) the effect of a series of stations of one type on the total system cost.

Where load-factors on alternative types of station are not very different, a direct comparison at the same load factor can be made. A more complex method involving analysis of total system cost is necessary if the two stations to be compared will operate at different average load factors over their lives and will affect differently other stations operating in the system. A third even more complex method of systems analysis is needed to calculate the long-term mix of stations which will produce minimum total system generating costs over a period of decades.

Historical comparisons of UK nuclear and fossil generating costs

The development of nuclear power first assumed importance in the early post-war period when coal output was inadequate. The Suez crisis of 1956 added urgency to the task of finding an alternative fuel, but when, with expanding cheap Middle East supplies and an oil import ban by the US, oil became plentiful outside the US, nuclear power seemed less necessary. The subsequent rapidly expanding oil imports of the USA, Japan and Europe changed all that. In the wake of the oil crisis of 1973 the foresight of the nuclear pioneers became apparent, and it is fortunate that in the UK, the original long-term goal of developing nuclear power as a cheaper substitute for imported oil and deep-mined coal was not abandoned simply because, for a while, oil became the cheapest fuel.

The effect on generating costs of the changing relativities between the costs of alternative fuels is illustrated by the following comparisons[4] of historic generating costs of CEGB nuclear and fossil stations. To increase comparability the comparison is limited each year to stations built during the preceding 12 years. Nevertheless differences in availability of individual stations can affect the comparisons.

Table 2

	Generating cost (p/kWh) of stations constructed during previous 12 years (in current money terms)		
	Nuclear	Coal	Oil
1971/2	0.43	0.43	0.39
1972/3	0.48	0.49	0.40
1973/4	0.52	0.53	0.55
1974/5	0.48	0.74	0.88
1975/6	0.67	0.97	1.09
1976/7	0.69	1.07	1.27
1977/8 (provisional)	0.76	1.23	1.42

N.B. Transmission and distribution costs more than double the cost of electricity to final consumers.

The breakdown between fuel costs, other operating costs, and capital charges of nuclear, coal and oil-fired stations, again up to 12 years old, for the three years 74/5, 75/6 and 76/7 is as shown in Table 3.[5]

The figures for the last few years are not comparable year to year, since the figures for 1974/5 are confined to current costs, while those for later years allow for commitments which will fall to be met in future years. In general, UK generating boards use an 'absorption cost' system, i.e. costs actually borne during the year have been spread over electricity generated during the year. Depreciation has been charged on the cost of construction of the station in equal increments over the life of each station, but interest at the Boards' average borrowing rate for each year is charged on the residual value of the station, which has generally resulted in a falling interest charge year by year. For example, with a life of 25 years and an interest rate of 10 per cent p.a., annual capital charges (depreciation plus interest) fall from 14 per cent to 4 per cent of initial capital cost over the life of the station. Utilities in some other countries, notably the USA, use an annuity or building society amortisation method. This results in a constant capital charge (11 per cent p.a. for the example given above) containing a rising proportion of capital and a falling proportion of interest. Over the life of the station the results are the same, but the UK method gives higher generating costs at the beginning and lower at the end, and direct comparability in any given year is then not possible, at least without correction.

These historic comparisons of UK generating costs are based on standard accounting conventions used generally throughout industry. Such accounting conventions are an entirely adequate way of presenting the actual current costs to utilities and to electricity consumers. Ordinarily the interest rates include an element reflecting the current rate of inflation. In times if rapid inflation this element may not be large enough and this then gives a temporary advantage to borrowers (i.e. utilities utilities). Conversely, in a period of falling inflation, fixed interest rates may over-compensate investors. In the long-term, however, utility average borrowing rates are a reasonable reflection of the market value of money and are the reward necessary to persuade lenders to forgo present consumption. The adoption of Current or Replacement Cost Accounting (in one form or another) is now proposed, to ensure adequate accumulation of funds for replacement of capital assets, stocks, etc. As recently adopted by the generating boards (in the form of a 40 per cent increase in depreciation provisions), Replacement Cost Accounting has apparently narrowed (but not eliminated) the gap between historic costs of nuclear and fossil stations (because of the higher capital cost of nuclear stations) simply by charging current consumers more and future consumers less.

On the basis of actual costs borne by the generating boards, nuclear stations were in 1971/72, generating at the same cost as those burning UK coal. Using cheap (but taxed) oil, generating costs of oil stations were at that time 20 per cent lower than either coal or nuclear stations. Today, with the rise in fossil fuel costs to nearer replacement cost levels, nuclear generating costs are some 38 per cent below those of coal stations, and 46 per cent below those of oil stations.

Those (mainly Magnox) nuclear power stations already operating in the UK, although only 9 per cent of total installed capacity, are generating about 14 per cent of electricity produced and, in comparison with fossil-fuelled stations built over the same period, are currently reducing oil imports by some 250m per annum, of which 100m is a saving to the electricity consumer. When the remaining AGR* nuclear stations now under construction are operating, the nuclear proportion of total output will rise to 20 per cent (from 14 per cent of total capacity). It has been estimated[6] that each AGR station will, when fully commissioned, reduce the generating boards' overall costs by 1½m a week. This will add savings of 375m a year to the savings from existing Magnox stations. Had these additional stations been available sooner, the total savings would of course have been greater, but it is impossble to know the extent to which this could have been achieved using any generating system novel to the UK. Mistakes in the execution of the AGR programme are now self-evident, but this should not be allowed to detract from their competitivity when completed. The high additional cost of providing substitute power at the moment results from the high operating cost of mid-merit fossil plant in current use. As the proportion of nuclear capacity increases, this cost will fall.

It is not only in the UK, that nuclear power is decisively competitive with fossil stations. Utilities throughout the world have testified to the large reductions in consumers'

* AGR ——Advanced Gas-Cooled Reactor.

Table 3

p/kWh

	1974/5			1975/6			1976/7		
	Nuclear	Coal	Oil	Nuclear	Coal	Oil	Nuclear	Coal	Oil
Fuel costs	0.13	0.55	0.71	0.25	0.75	0.87	0.34	0.86	1.05
Other operating costs	0.09	0.07	0.05	0.14	0.08	0.07	0.11	0.09	0.08
Capital charges	0.26	0.12	0.12	0.28	0.14	0.15	0.24	0.12	0.14
	0.48	0.74	0.88	0.67	0.97	1.09	0.69	1.07	1.27

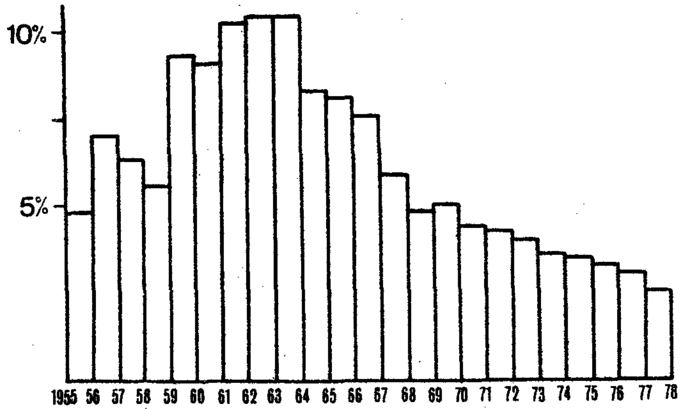

Fig.3. Net UKAEA expenditure on nuclear R & D as a percentage of value of Great Britain electricity sales 1955-1978.

(Sources : Generating Boards and UKAEA Annual Reports).

electricity bills which have already been made possible by the use of nuclear stations. For instance, in survey[7] of US generating costs in 1977, the US Department of Energy recorded average generating costs of nuclear stations as being 15 per cent lower than those of coal-fired stations. Allowing for different coal costs in the USA, this figure is comparable with those for the UK.

The gas-cooled reactors now operated by BNFL benefited from the original small fuel fabrication and reprocessing plants built for military purposes. However, Magnox stations operated by the generating boards have borne their appropriate share of the cost of modernising and adding to these plants, and this cost is charged to current nuclear generating costs. The electricity consumer has therefore benefited to a small extent. But nuclear power is not unique in this respect. Many other civil technologies have been launched on the results of military research. Coal-fired power stations benefit from the huge capital write-offs allowed to the coal industry; from subsidies for burning high-cost coal in Scotland and Wales; and for stockpiling surplus output.

The generating cost comparisons just made include current R & D expenditure of the generating boards and (in the cost of nuclear fuel) the current expenditure of British Nuclear Fuels Ltd. on R & D, and on waste storage and reprocessing. They do not, however, include costs being borne by the Exchequer for national reasons, such as AEA research into atomic energy. As in other countries, such research is carried out as part of national energy strategy, to provide the nation with additional energy sources.

Although it is difficult to attribute particular results of R & D to particular expenditure in view of the inter-dependence of technologies, the annual reports of the UKAEA contain a broad allocation, of R & D expenditure to major reactor systems. The total cost of all energy R & D ought, logically, to be compared with the revenue of all the energy industries. However, at a lower level some perspective on the scale of nuclear power R & D can be obtained by comparing its cost with electricity revenue, as in Figure 3 covering the period 1955-1978.

This shows that the cost of the Authority's nuclear R & D (including underlying basic research) rose to just about 10 per cent of electricity revenue for a brief period 1961-3 and has since declined steadily to the current level of 2.5 per cent (116m on AEA R & D against 4822m in electricity sales). This is a measure of the extra cost to electricity consumers if they had to pay directly for AEA nuclear R & D. In total this is of course much more than has been spent on developing any other new energy source. But this scale of expenditure is justified because it is matched by the enormous quantity of additional energy made available by exploiting nuclear technology, and the consequent large potential saving in generating costs.

Waste storage and decommissioning

Also now included in nuclear generating costs are the future cost of waste storage and decommissioning. In 1977-78 the CEGB's provision for such costs was 0.06 p/kWh generated by nuclear stations. This is much less than the margin of advantage of nuclear over fossil fuels.

Future changes in costs

It cannot be expected that the margins in generating costs between thermal nuclear and fossil-fired stations will remain unchanged. Indeed, it is an economic truism that in a free market the prices of perfect substitutes will tend eventually to converge. In this case the presence of nuclear power will moderate the prices of fossil fuels, particularly those suitable only for electricity generation, and any assessment of the benefits of nuclear power should allow for this.

So far as capital costs are concerned, the past few years are little guide to what may be expected in future. During the recent period of rapid inflation the cost of all large capital projects increased much more rapidly than prices generally. This was mainly because attempts to simultaneously accelerate expansion of several major world economies resulted in an exceptional increase in commodity prices. However, studies of capital costs over a long period show that they increase at about 1 per cent p.a. above the general rate of increase in prices partly because of their high labour content, and such an allowance is currently made in forecasts of generating station capital costs.

Increases in nuclear fuel fabrication, reprocessing and waste treatment costs will occur, to accommodate the cost of new plants. However, these factors at present account for about 15 per cent of total costs, and the increase in costs would have to be very large to affect generating costs decisively

As for fuel costs, power station coal prices in the UK now average about 25 per ton. A 20 per cent increase in coal price to 30 a ton by 1985 (in 1978 money) does not appear unlikely in view of greatly-increased levels of investment and the trend in wages.

Uranium bought under existing contracts costs about $20/lb. New contracts for uranium are being let at around $40/lb, so that by 1985 this may represent (in 1978 money) the cost of most supplies. The price of uranium, too, will continue to rise. Lower grade, less accessible deposits will have to be exploited, and there may be difficulty in expanding production by a factor of 10 by the end of the century to match the desired rate of world growth in nuclear power capacity. Unless major deposits are discovered elsewhere, this appears to mean that Europe and Japan will be heavily dependent on N. America, Australia and Africa for a share of limited low-cost uranium supplies. All this implies an increasing cost of uranium and uncertainties of supply. Although this factor is at present a much smaller proportion of nuclear generating cost than that represented by the fuel cost of a fossil-fired station, there will be an increasing incentive to take advantage of the large reduction in uranium requirements possible through the use of fast reactors. It is for this reason that it is important for the development of fast reactor technology to proceed to the point where the UK has a practicable option to use fast reactors

Criteria for future investment in nuclear power

It is clear that historic costs give no direct guide to future investment, although they do provide a base from which updated estimates can be made.*

The overall criterion is total generating costs. To obtain these for the future, a method is required for adding capitalised costs (of construction including interest and initial fuel) to running costs (mainly of fuel) which occur over the life of the station. This can be done either by calculating the' annual capital charges' arising from the construction cost, on a conventional accounting basis in terms of depreciation and interest, or amortisation, and adding them to the annual costs; or alternatively by converting the life-time fuel costs into a

* A potential source of confusion in comparing estimates is the treatment of inflation. The UK practice is to quote costs in constant money values related to one stated date with no allowance for inflation, but making allowance over the life-time of the station for any real changes in particular elements of costs, compared with the general inflation rate.

Some other countries (notably the USA) make an allowance for expected inflation and quote costs in current money terms for each year.

Both methods yield valid comparisons, from which the same conclusions would be drawn, but direct comparison between estimates on the one basis with those on the other are not valid without correction for inflation.

'present worth' using a discount rate. A recent Government White Paper[8] recommended the use of 5 per cent (net of inflation) as the rate for use in future to compare alternative investments in the nationalised industries. Using this rate, the 'present-worth' life-time total generating costs due to both capital and operating costs of new nuclear and fossil stations can be calculated, for any given load factor.

The latest estimates of the cost of constructing nuclear stations in the UK (for commissioning in 1985) and their likely fuel costs are contained in the report of the National Nuclear Corporation submitted to and published by the Secretary of State for Energy[9].

Combining these NNC estimates and a CEGB estimate of coal station capital costs[10] gives a basis for deriving a comparison of the generating costs of a new nuclear (AGR) and new coal station.

Differences between the nuclear generating costs quoted above and those given by NNC are accounted for mainly by the use of the new lower 5 per cent p.a. recommended discount rate instead of the previous public sector discount rate of 10 per cent p.a. used by NNC. The above figures are also not comparable with the historic costs given earlier because they are computed using a constant capital charge method and higher real fuel cost assumptions.

Table 4 presents the situation of both a nuclear and a coal-fired station operating at a 70 per cent base-load factor over the whole of its life. Figure 4 then shows total generating cost over a range of load factors, and the effect of higher capital costs and higher real fuel costs over the life of the stations. In the latter case, the load factor represented is the discounted average life-time load factor. (N.B. The effect of rising uranium costs on nuclear generating costs is reduced -- and at low load factors is more than offset --- by the discounted credit for the final fuel charge). By far the most influential cost in the comparison is that of coal; the second being the capital cost of the nuclear station.

These comparisons show that on the stated assumptions nuclear stations based on AGRs would, when operating at a 70 per cent load-factor, generate electricity some 30 per cent cheaper than coal-fired power stations, and that this cost advantage would not be eliminated until the load factor was only about 40 per cent.

To minimise total system generating costs, the UK generating system is operated on a merit-order basis in which the stations with lowest operating costs are operated in preference to those with higher operating costs. The expected pattern (for CEGB only) in 1982 is shown in Fig. 5.

Table 4

/kW present worth at 70 per cent load factor (1/1/77 prices)

	AGR		COAL	
Construction cost	470		290	
Interest during construction	70		44	
Total station cost	540		334	
Initial fuel or working stock	68		7	
Final fuel	4		—	
Fixed operating costs	76		55	
Total fixed cost		688		396
Replacement fuel	361		1183	
Variable operating costs	38		27	
Total running cost		399		1210
Generating cost /kW(rounded)		1100		1600
Generating cost p/kWh		1.23		1.70

N.B. Other assumptions as stated on Fig. 4

From this has been derived Fig. 6 which shows the relationship between load factor, proportion of generating capacity and proportion of electricity generated. 'Base-load' stations operating at 70 per cent load factor will then comprise some 50 per cent of total capacity and generate about two-thirds of total output. Stations operating down to 40 per cent load factor will comprise 70 per cent of total capacity and generate 90 per cent of total output.

Nuclear stations operating or under construction in the UK comprise about 14 per cent of the total capacity expected in 1981; they will have an output of 10 GW (e); and they are expected on completion to generate about 20 per cent of total output at that time. The proportion of nuclear capacity could be increased by a factor of 4 before all base-load output was from nuclear stations, and by a factor of 7 before the break-even load factor was reached and minimum system generating cost achieved. At this point the generating costs of the dearest nuclear station would equal those of the cheapest coal station (oil stations being assumed by then to be more expensive than either). Optimisation of the system would in practice be unlikely to be taken quite this far, so as to preserve adequate

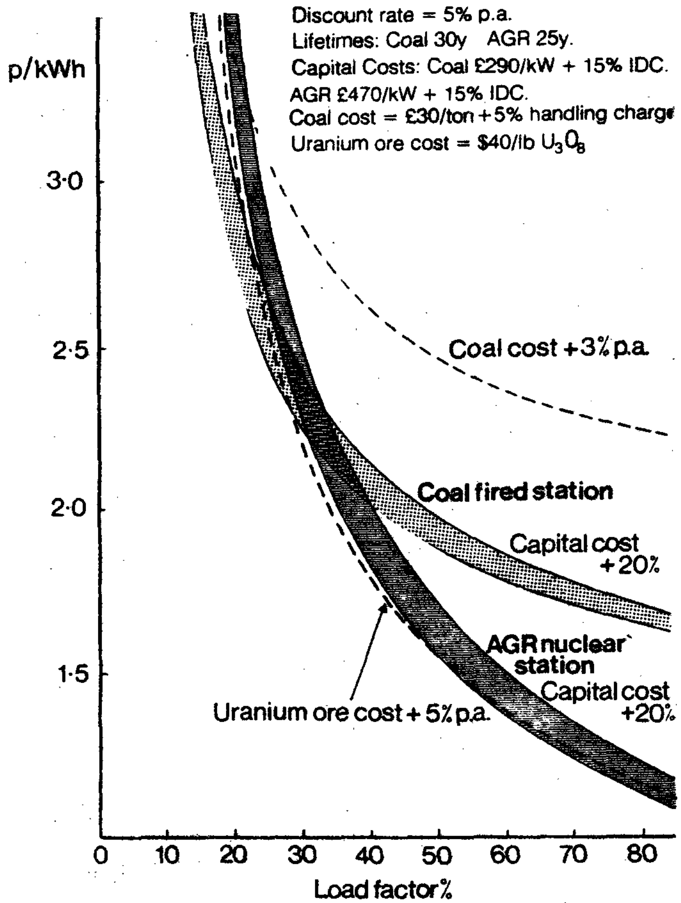

Fig. 4 Comparative generating costs for coal and nuclear stations in 1985.

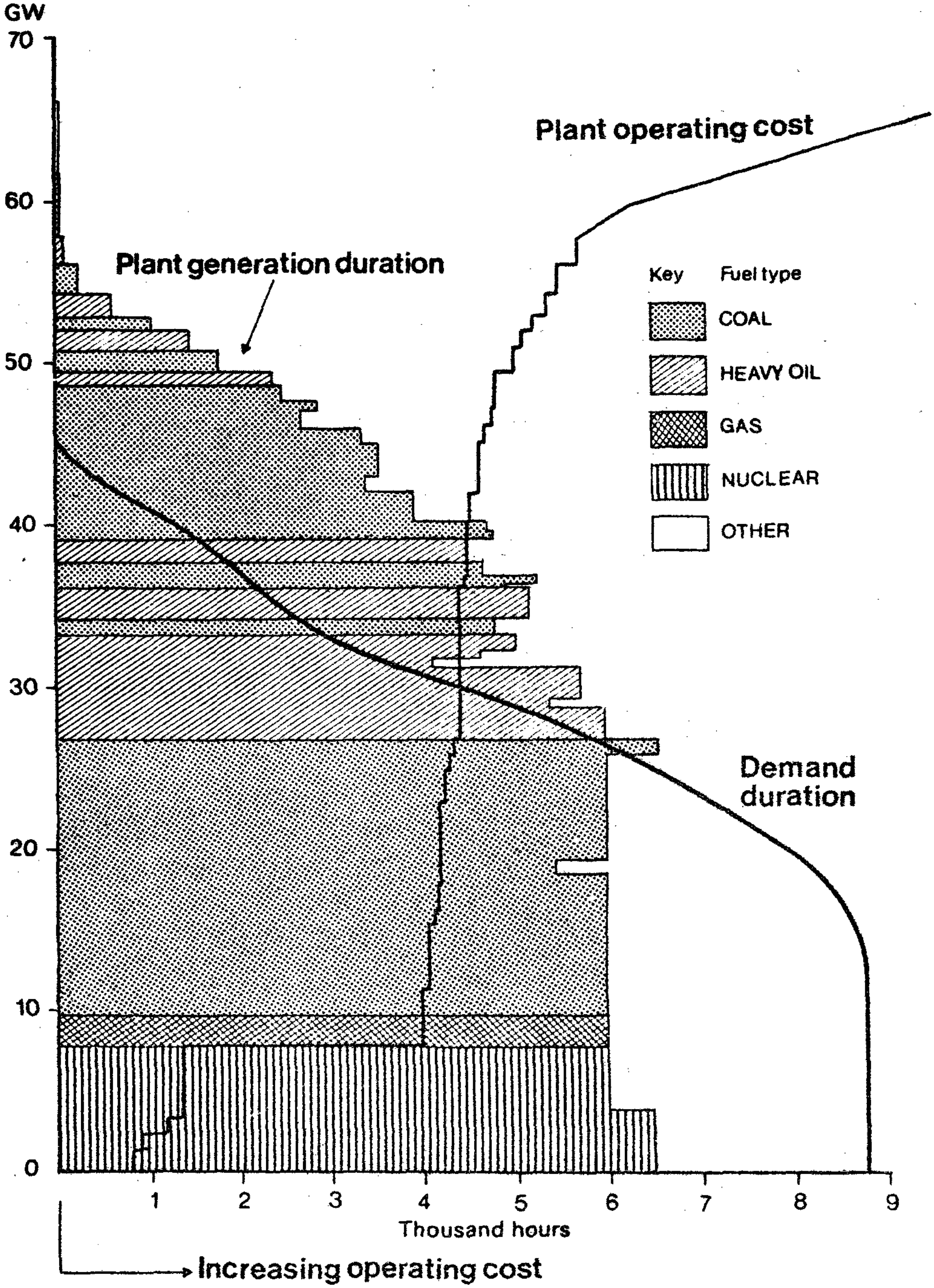

Fig. 5 Estimated mean system characteristics in 1982/83
(Source: S. Catchpole (CEGB), IAEA Salzburg Conference, May, 1977).

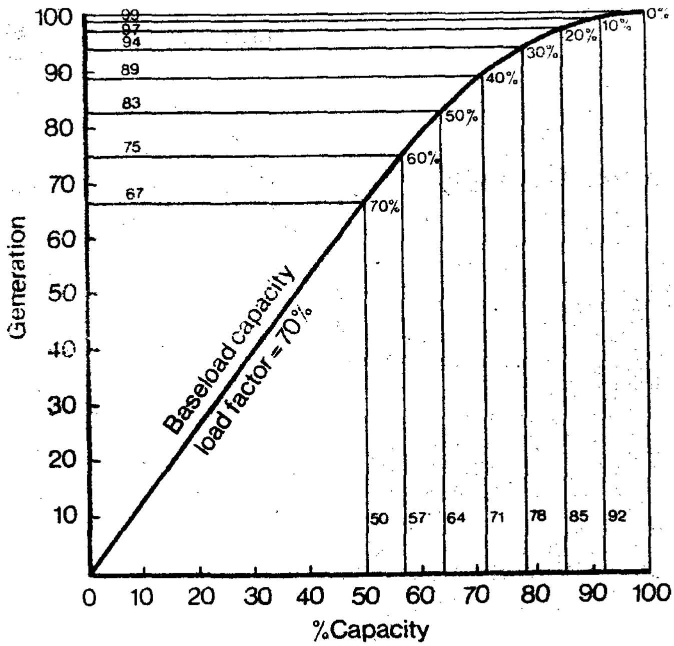

Fig. 6 Annual electricity generation from CEGB power plant.

diversity between fuels and flexibility to cater for unforeseeable changes in relative costs.

Alternative methods of comparison

Marginal analysis

The comparison between nuclear and coal stations can be investigated in a number of other ways. For instance, usng the same basic cost estimates, both the Department of Energy[10] and the CEGB[11] have evaluated the marginal difference in lifetime system costs between using one nuclear station or one coal-fired fired station as the next station in a system expanding by the addition of a predominantly nuclear 'mix'. This is the so-called Standardised System Cost method, described in these and other references. The results can be expressed in various ways as shown in Table 5.

Table 5

Index of comparison	System cost advantage of a nuclear station[2] over a coal station
Net effective cost[1]	£50/kW p.a.
Difference in economic worth on a 2 GW station	£100/m.p.a.
Return on extra capital cost of a nuclear station	>20% p.a.
Payback time on extra capital cost	4 years

[1]The 'present worth' extra system cost expressed as an annuity per kW of capacity — see Ref. 11.

[2]In this case a PWR.

Source, Reference[12]

The sensitivity analyses included in these studies again emphasise the dominant influence of coal costs. On the nuclear side, capital costs and availability are important, but less influential on total generating costs than coal costs.

It is evident from this that the return on the extra capital cost of nuclear stations is higher than for much other investment in the public sector and justifies preference for this form of energy investment.

All the comparisons so far have been in terms of discounted life-time costs. However the electricity consumer will be more interested to know something about cash flows. For a generating station of 1000 MW electrical output these are:-

Extra capital investment in nuclear station (including interest during construction and initial fuel)	270m total over 7-8 years
Annual saving in operating cost.	50m p.a.
Life-time saving in operating cost.	1250m over 25 years
Period of pay-back of investment.	5-6 years

N.B. This comparison takes no account of the substantially higher investment required to produce the annual fuel requirements of a coal station compared with a nuclear station.

Total system cost analysis

To investigate the effect of introducing different proportions of nuclear stations (both thermal and fast reactors), the discounted total generating costs of the system for the various mixes has to be calculated (allowing for changes in load factor) and compared. From these comparisons the 'mix' with the minimum system cost can be selected. However, because many assumptions have to be made about relative changes in future capital and fuel costs over a long period, this method often produces a wide range of answers. These are valuable for strategic purposes (e.g. for R & D and long-term generating system planning) rather than tactical purposes (e.g. for deciding what stations to add to the system in the short term). Such exercises, if regularly updated, ensure that tactics and strategy remain broadly compatible.

The economics of fast reactors

Liquid metal-cooled fast reactor power stations will cost more to build than thermal reactor power stations, because of their greater complexity. To offset this, their fuelling cost per unit of output will be lower, despite the higher unit cost of fabricating and reprocessing plutonium-bearing fuel. This is because they avoid the cost of buying and enriching natural uranium and, as a higher fuel burn-up is achieved, a smaller quantity of fuel has to be processed per unit of electricity sent out compared to current thermal reactors.

The break-down of thermal and fast reactor generating costs given in Table 6 shows their approximate sensitivity to changes in each major component.

These figures illustrate the importance of nuclear capital costs, particularly for fast reactors. Because thermal reactors will over their life-time have to bear increasing prices for uranium and enrichment adequate to encourage expansion of supply, fast reactors could cost more than thermal reactors and still be competitive. Early fast reactors are likely to exceed the economic level of capital costs, but further development based on manufacturing and operating experience of commercial-scale reactors should enable construction costs to be brought within the required margin.

A complete economic analysis of the effect of the introduction of fast reactors would have to allow for their effect on the world price of uranium ore. A large fast reactor component in the world (or even the prospect of it) with an anticipation of a reduced demand for ore compared with allthermal systems will help stabilise the price of ore and with it thermal reactor generating costs. With large numbers of thermal reactors still operating at the end of the century, this would create a powerful economic incentive for fast reactors which is not reflected in the comparison between single station generating costs, or even in a study of the generating system of a single country.

The ultimate role of fast reactors

Fast reactors will be introduced into the electricity generating system before they are currently competitive with thermal reactors or fossil-fired stations. Electrical utilities will develop a preference for fast reactors as soon as they perceive a like-lihood of high uranium prices during the life-time of stations being ordered. The rate of their introduction will depend on requirements for new generating plant and on plutonium availability. Once introduced their low operating costs will put them naturally at the top of the merit order, meeting the base-load. The proportion of fast reactors which it is eventually economic to employ will then be determined by their capital and operating costs compared with those of

Table 6

Illustrative break-down of thermal and fast reactor generating costs.

	Thermal		Fast	
	(Commissioning date 1998)			
	%		%	
Construction Costs		55		67
Fuel Cycle Costs				
Uranium	13		-	
Enrichment	7		-	
Fuel fabrication and reprocessing (incl. Pu value)	15	35	22	22
Other operating costs		10		11
		100		100

Source : Reference 13.

thermal reactors, and it is quite possible that the most economic course will be to operate fast and thermal reactors together indefinitely.

Conclusion

Mankind has progressed by using increasingly efficient fuels in increasingly efficient appliances. Uranium is the latest of these fuels used in nuclear power stations. Nuclear power stations are, throughout the world, now providing consumers with substantially the cheapest electricity, except in areas with extensive hydro-power or cheap, clean, local coal. Thermal nuclear power stations will continue to provide economic electricity until the cost of uranium rises to several times the present level. Fast reactors, if fully developed by then, have the potential to continue to stabilise the cost of electricity and, by moderating demand for other fuels, will keep down their cost also.

Acknowledgment

The authors of this article are grateful for helpful comments received during its preparation. Responsibility for the views expressed is, however, theirs alone.

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