/

AUSTRALIAN ATOMIC ENERGY COMMISSION

ENERGY ACCOUNTING IN NUCLEAR POWER SYSTEMS

by

J.L. SYMONDS
P. ESSAM
K. STOCKS

ABSTRACT

Energy analysis is a systematic way of tracing and accounting for the flows of energy through an industrial system and apportioning a quantity of the primary energy input to each of the goods and services sent out. The application of energy accounting to nuclear power stations and their growth in generating systems is discussed. Misunderstandings arising from discrepancies and weaknesses in some published simple analyses of hypothetical growth situations are outlined. Results of a more complex energy flow analysis are used to demonstrate that current nuclear energy programs are running at an energy profit. Large fossil fuel savings will occur in a real electrical grid system under anticipated nuclear power growth rates. These savings will give a new dimension in planning the use of fossil energy resources which will still be needed for transport and industrial processes, such as steel-making, for some time to come.

National Library of Australia card number and ISBN 0 642 99720 9

The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA–INIS–12 (INIS: Manual for Indexing) and IAEA–INIS–13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

ACCOUNTING; COST; ECONOMICS; ENERGY POLICY; NUCLEAR ENERGY; NUCLEAR POWER PLANTS; QUANTITY RATIO

ENERGY ACCOUNTING IN NUCLEAR POWER SYSTEMS

In the innovations and developments of our technological society, we have learnt to use energy to convert primary materials into something which we can conveniently use - manufactured materials, transportation, goods and services, secondary energy forms derived from primary ones (e.g. coal and oil) and so on. The rapid rise in the price of energy and in the demand for it has made it important that we analyse how energy is used in our society, what energy flows occur through sections of our society, whether energy is being used most effectively and what constraints may be imposed on the primary forms of energy available to us.

Energy Cost of Materials

Energy analysis, as Chapman [1975a] summarises it, is a systematic way of tracing and accounting for the flows of energy through an industrial system so as to apportion a quantity of the primary energy input that goes into the system, to each of the goods and services which are outputs of the system. By analysing the energy requirement for the production of goods it is possible to develop an 'energy cost' in terms of the primary energy input. The final result of an energy analysis is a set of energy costs for all the goods and services in an industrial system so that the quantity of each multiplied by its specific energy cost will equal the primary energy input to the system.

Energy analysts have drawn attention to one result of such studies - the largest energy-consuming sector on this accounting basis in any economy is the energy sector itself. For example, Chapman, Leach & Slesser [1974] have indicated that in the United Kingdom, coal mining, oil refining, and the production of coke, gas and electricity consume more than 30% of the total energy input.

It is apparent that an energy analysis of the energy sector will require a wide variety of data. Information is needed, for example, on the energy cost of producing steel which in turn has primary energy inputs in the form of coal, coke, gas and oil, and secondary energy input in the form of electricity. Cement, bricks and materials for the metallurgical processes are required and these also have energy costs which must be determined. Oil and electricity are provided to mine coal which is sent to the power utility for generating electricity, some of which is used in the oil refinery. We see that the various sectors supplying and demanding energy are interlinked through complex paths which must be traced back until any additions from the component parts become so small that they may be neglected. Figure 1 gives an impression of the interlinking which occurs in the energy sector [Chapman, Leach & Slesser 1974].

Energy cost is expressed as the number of energy units per unit of the commodity e.g. megajoules per kilogram. While it is possible to determine the total energy cost of materials in commodities by analysing the processes used in a plant, it is often difficult to evaluate the indirect energy costs associated, say, with the construction of the plant.

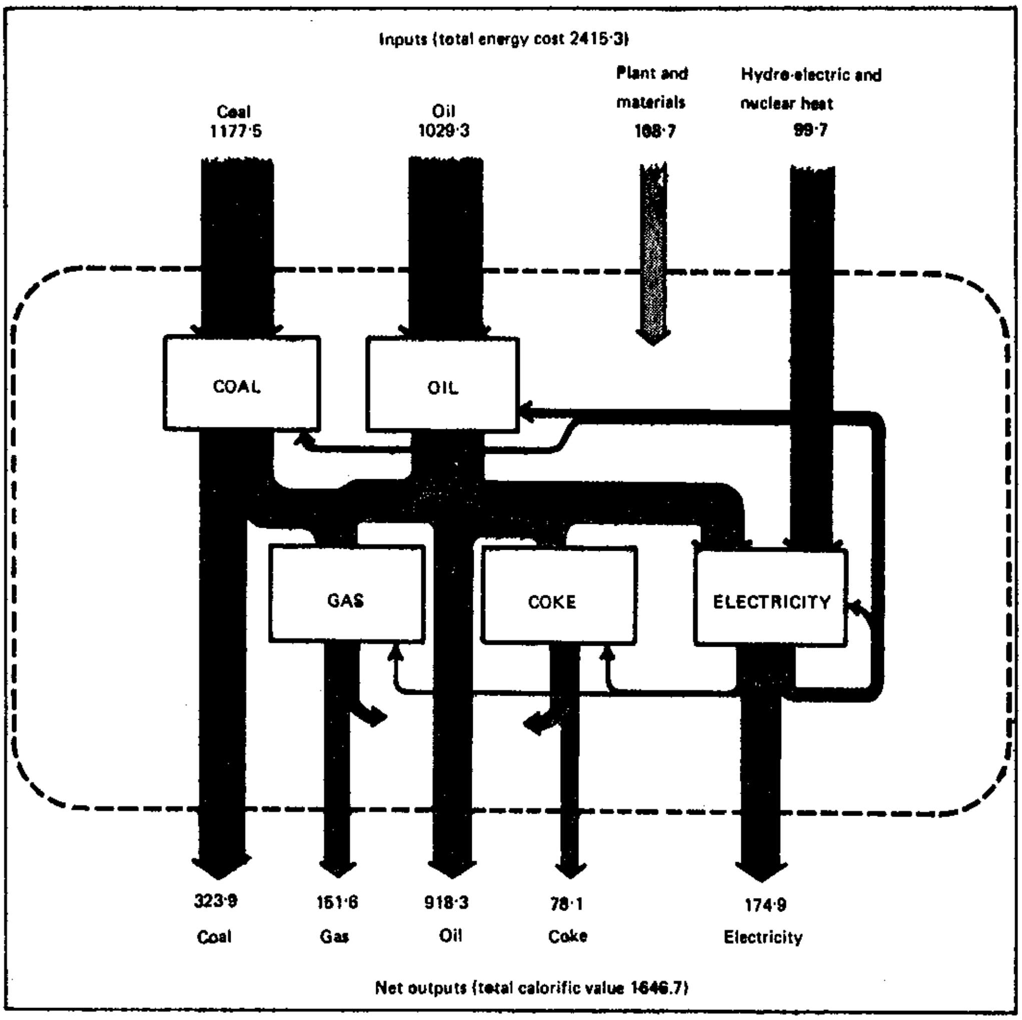


Figure 1 - The Energy Cost of Fuels in the UK
[After Chapman, Leach & Slesser 1974]

Monetary and Energy Costs

To overcome the complex problems of a thorough energy analysis of processes with allowance for indirect energy costs, other approaches have been adopted which will give the energy cost of commodities more readily, though less accurately. The monetary costs of plant, machinery, operations or commodities may be used with statistics of energy usage to develop a relationship between energy cost and monetary cost; the ratio of energy cost to monetary cost is called 'energy intensiveness' (megajoules per dollar).

Countries such as the UK and the USA have developed Commodity Input-Output Tables which give the total inputs in money terms to each of a selected group of sectors in the economy, arising from every other sector in the group. The data in these tables can be converted to provide, amongst other information, the monetary worth of primary energy input per monetary unit of commodity output (dollar worth of energy input per dollar worth of commodity output). The works of Heredeen [1973] and Wright [1974] are examples of US and UK studies in this field. Taken together with the prices of the various energy forms and the prices per unit mass of the commodities in the various sectors, the monetary values may be converted to give either energy intensiveness (megajoules per dollar) or energy cost (megajoules per kilogram).

There are limitations to the use of Input-Ouput data because they relate to the economy of a particular country using its existing technologies in the year when the tables were developed. Furthermore, the tables are often out of date since it takes some time to gather and assess data for them. The latest UK tables are for 1968. Nevertheless, the two approaches - one through energy costing and the other through energy intensiveness - do give similar figures for capital items such as industrial plant.

Tables of energy intensiveness for various products, materials, goods and services have been derived from operations within such countries as the USA and the UK [Wright 1974]. By using these data, a form of energy accounting is possible for industrial plants and industrial systems to give, for example, interplant comparisons of energy cost. The energy accounting which we will consider here stems from the recent growth of interest in conservation of natural resources and relates to the use of primary energy resources in the production of the secondary resource, electricity.

The recent nature of such studies is evident from the list of publications at the end of this paper. The application of energy analysis to the development of energy policy is in its infancy but the range of topics under study is interesting. In providing this list, it is timely to add a warning that the results of energy analysis depend very heavily on the purpose for which the analysis was made and on the conventions used in the analysis. Readers are referred particularly to the comments of Chapman & Mortimer [1974] and of Hill & Walford [1975].

Power Station Energy Accounting

In monetary accounting parlance, it is possible to develop a balance sheet of all the energy inputs, outputs and losses involved in the construction and operation of a power station. Such a balance sheet will list how much energy is invested in the plant and equipment in the station, how much went into the construction of buildings, the transport of materials, the introduction of power lines and so on. It will show how much energy is developed from the coal as well as how much went into the mining and transport of the coal. Finally, it will indicate the electrical energy produced at the generators, the losses incurred in running the plant and services and in the transmission lines and the amount delivered to consumers.

In this balance sheet accounting, no variations with time enter the calculation directly. An example of such a balance sheet is given for the UK electricity supply industry in Appendix A and is taken from studies by Chapman [1974a]. It should be noted that the 'efficiency' derived from the analysis is not the usual engineering definition of thermodynamic efficiency related to the ratio of the electrical energy output from the generators to the heat input from the fuel; this ratio for a modern coal-fired power station is close to 0.4. The Chapman figure of about 0.25 is the electrical energy delivered to the consumers, divided by the thermal energy from fossil fuel required to construct and operate the plant. As Leach [1975] puts it, the energy cost of the service is the amount of fossil fuel energy 'in the ground' that is needed directly and indirectly to deliver the service to the final customer.

One problem area causing diagreements in energy analysis arises from the need to combine energy inputs from both primary and secondary sources (e.g. fossil fuels and electricity). The energy cost of electricity is about 4 kilowatt-hours (thermal) for each kilowatt-hour of delivered electricity. By convention, energy analysts who are interested in resource depletion relate all their energy costs back to fossil fuel energy, and electrical energy used in a process is converted back to fossil fuel energy using the above factor of four. For example, the construction and fuelling of the first nuclear power station will require fossil fuel input during construction although, once operating, stations provide electrical output which makes them more independent of fossil fuel electricity generation.

This convention is used to determine the fossil fuel energy input to nuclear power stations during the early stages of system development. However, when the nuclear section of the grid system has expanded to become an appreciable proportion of the total system in terms of electrical output, the convention raises some difficult problems in the proper derivation of an energy cost for electrical output owing to the variety of sources of electricity. A similar problem arises where, as in Japan, the electrical grid system has an appreciable contribution from hydro-electric generation.

Nuclear Power Station Energy Accounting

The energy analysis of nuclear power stations has been studied by Chapman & Mortimer [1974] who have developed estimates of the fossil fuel energy required for the mining, processing, enrichment and fabrication stages of the preparation of nuclear fuel, as well as that required for capital investments involved in the stations. A balance sheet for a steam-generating heavy water reactor system is shown in Table 1 [Chapman 1974b]. As yet, there has been no attempt made to include disposal of radioactive waste in energy analysis estimates. However, using the criteria laid down recently by the US Energy Research and Development Administration, we have estimated that the energy cost of vitrification and disposal of waste will be less than 0.1 per cent of station output for present day concepts and less than 1 per cent for space disposal (Appendix C).

TABLE 1

ENERGY BALANCE SHEET

1000 MWe STEAM GENERATING HEAVY WATER REACTOR

Inputs (in 10^6 kWh thermal)		'Thermal' Energy Input	
		0.3% ore (3 kg U_3O_8/t)	0.007% ore (0.07 kg U_3O_8/t)
UK purchase of plant, equipment & building requires			
1. Electrical equipment (£52M at an energy intensiveness of 33 kWh/(£))		1 716	1 716
2. Buildings and services (£31M at 28 kWh/(£))		868	868
3. Nuclear steam system (£67M at 30 kWh/(£))		2 010	2 010
4. Heavy water (250 tonnes) at an energy cost of 8600 kWh/kg		2 150	2 150
These total		6 744	6 744
Initial fuel (160 tonnes at 2.1% enrichment) requires			
5. Mining 657 tonnes natural uranium		252	12 319
6. Enrichment 320 tonnes SWU (0.25% tails assay)		3 130	3 130
7. Fabrication		36	36
8. Giving total energy inputs (10^6 kWh)		10 162	22 229
Output and Losses (in MWe)		**Electrical Energy Output**	
The nuclear power station provides			
9. Nominal net power (MWe)		1 000	1 000
From this subtract			
10. Load factor correction (62%)		-380	-380
11. To give electricity generated (MWe)		620	620
Subtract			
12. Loss in distribution	46.5		
13. Use by electricity industry	23.3		
14. Use to replace heavy water loss	3.4	-73.2	-73.2
The total is		546.8	546.8
Which is further reduced by			
15. Energy used to refuel reactor (31.4 tonnes at 2.1% enrichment)		-23.4	-291
16. Giving net power available (MWe)		523.4	255.8
17. Total energy out in 25 years (from 16 above) (10^6 kWh)		114 625	56 020
18. 'Thermal' energy inputs (from 8 above)		10 162	22 229
19. Energy Ratio E_R = (17) ÷ (18)		11.3	2.52

An index of performance is derived in the form of an 'Energy Ratio' defined as:

$$E_R = \frac{\text{electrical output - running costs}}{\text{capital input}}$$

where inputs and outputs are summed for a period of 25 years. This is a form of return on investment. Some of the E_R values produced by Chapman & Mortimer [1974] are given in Table 2.

TABLE 2

ENERGY RATIOS FOR DIFFERENT REACTORS

Reactor Type	0.3% ore (3 kg U_3O_8/t)	0.007% ore (0.07 kg U_3O_8/t)
MAGNOX	15.1 ± 3	1.28 ± 0.2
SGHWR	11.2 ± 2	2.56 ± 0.4
PWR	16.5 ± 3	4.23 ± 0.8
AGR	10.5 ± 2	1.56 ± 0.3
CANDU	11.1 ± 2	6.24 ± 1.2
HTR	15.8 ± 3	3.56 ± 0.6

Fossil fuel stations have $E_R = 0.25$

Comments on the Derivation of E_R

The analysis assumes that nuclear power stations are built entirely via fossil fuels. When deriving the energy cost for refuelling (Item 15 : Table 1), Chapman & Mortimer have taken the sum of thermal and electrical energy directly as a running cost and subtracted it from the electrical output (Item 16). On their convention, the thermal component of the running costs would be divided by four unless that energy is used directly as heat in ore processing. Study of the mining and milling processes indicates that the main origin of this thermal component is in the extraction and crushing of the ore. Such operations are carried out by either diesel or diesel-electric equipment, so the Chapman & Mortimer convention requires that the thermal component be converted to an equivalent electrical component by dividing by four. This they have not done.

In the case of high grade ore, the effect on E_R is small. However, for the low grade ore, the thermal component dominates the energy cost of refuelling so that Item 15 is reduced from 291 MWe by a factor of nearly four to 86 MWe. The total energy out (Item 17) is thereby increased by a factor of almost two so E_R becomes 4.5 instead of 2.52. Hill & Walford [1975] have derived the set of corrected figures given in Table 3.

TABLE 3

MODIFIED ENERGY RATIOS

[After Hill & Walford 1975]

Reactor	0.3% ore (3 kg U_3O_8/t)		0.007% ore (0.07 kg U_3O_8/t)	
	Chapman & Mortimer	Corrected	Chapman & Mortimer	Corrected
MAGNOX	15.1	15.3	1.28	3.83
SGHWR	11.2	11.6	2.56	4.6
AGR	10.5	10.7	1.56	3.6
CANDU	11.1	11.1	6.24	7.9

Problems in Energy Ratio Methods

The technique of relating all energy inputs back to fossil fuel energy costs gives an oversimplified analysis which is in many respects unsatisfactory, although the concept has been valuable in highlighting the more significant parts of the energy investment problem.

An example of the difficulties which arise can be outlined as follows: an important energy input to the overall operation of nuclear power stations is the electricity used to carry out uranium enrichment by the diffusion process. Chapman & Mortimer adopt the convention of charging the electrical energy required for the preparation of the initial core of the reactor as a 'capital' charge against the fossil fuel investment at 25% efficiency for production from fossil fuels, i.e. an amount equal to four times the electrical investment is added to the fossil fuel investment in the denominator of E_R. The equivalent 'thermal' component is seen in Item 6 of Table 1. Based on this convention, a relatively heavy 'thermal' component appears as capital input in the denominator and not directly as an electrical running cost at a quarter of the 'thermal' value in the numerator of E_R. The difference in E_R is marked, being a larger E_R value in the latter case; moreover it will change with time as the source of electrical energy changes.

In a balance sheet approach where comparisons are made between various types of stations, little difficulty arises as long as the convention is understood. However, in a nuclear station installation program, especially under rapid growth conditions, this convention produces the curious situation that the electricity used for the enrichment of the initial reactor core fuel must be charged as fossil fuel and not, for example, either totally or proportionately against electricity from nuclear or hydro-electric stations.

This is particularly evident in the specific example of the Oak Ridge and Paducah enrichment plants which draw a great deal of their electrical energy from the Tennessee Valley Authority and provide the bulk of enriched uranium to the Western World. In 1974, over 20% of TVA generation was hydro-electric and the total generated by this means was greater than the system delivered to Oak Ridge and Paducah for enrichment purposes. If nuclear power stations were installed with the prime task of providing power for the enrichment process, as has been suggested in the planning in some countries, the convention would be hard to sustain.

An Energy 'Current Account'

Where there is rapid growth in an industry, it is necessary to treat the energy investments and energy flows as varying with time. In monetary accounting terms, this may be likened to the level and flow of money in a current account - money must be available on account such as from an overdraft before it can be invested and the initial level of the overdraft must be adequate to cover the outflow before monetary returns on investment produce an inflow to the account. There is an obvious time delay before the account 'gets into the black'; this will apply whether the units of account are money or energy.

Taking a growing program of electrical power generation, time-dependent or dynamic energy analysis will indicate how much energy subsidy is required for the establishment and operation of the power stations introduced into the grid system before that subsidy is recovered as electrical output. This form of study has been given particular attention where rapid growth of nuclear power stations is projected for various countries of the world.

Chapman & Mortimer [1974] have extended their static analysis to a study of the energy flows encountered during the growth of a nuclear power program. To illustrate the energy demand posed by a rapidly increasing program of nuclear power installation, they have demonstrated how energy analysis may be used to derive useful data about energy consumption and energy investment that must necessarily precede any electrical output. The growth rates they assumed have been characteristic of the early stages of the substitution of nuclear plant for fossil plant in a number of countries but in their examples they have assumed also that the rapid growth rates are indefinitely sustained, (although they recognised that this is not true in practice). Price [1974] has extended their work analytically to very rapid 'compound interest' or exponential rates of growth, again indefinitely sustained. With the conventions for allocating energy investment for the initial core mentioned earlier and with a very rapid and continuous installation of nuclear stations, the Chapman-Price analysis would indicate that nuclear stations represent an ever increasing fossil fuel energy sink. A particular example would be a program which had reactors with E_R equal to five and a doubling time of five years. Reference to Figure 2b indicates that 25% more energy than the total station output would be needed to cover the required energy investment.

In a real situation, electricity generating systems are generally growing overall at only a few per cent per year so that the faster the initial growth of the nuclear power component, the sooner must that growth rate decrease as the overall growth rate is approached. During this period of decreasing growth rate, the nuclear power part of the system rapidly pays off any energy deficit and becomes a large energy producer [Leach 1975]. The energy flow analysis which we describe later confirms Leach's view.

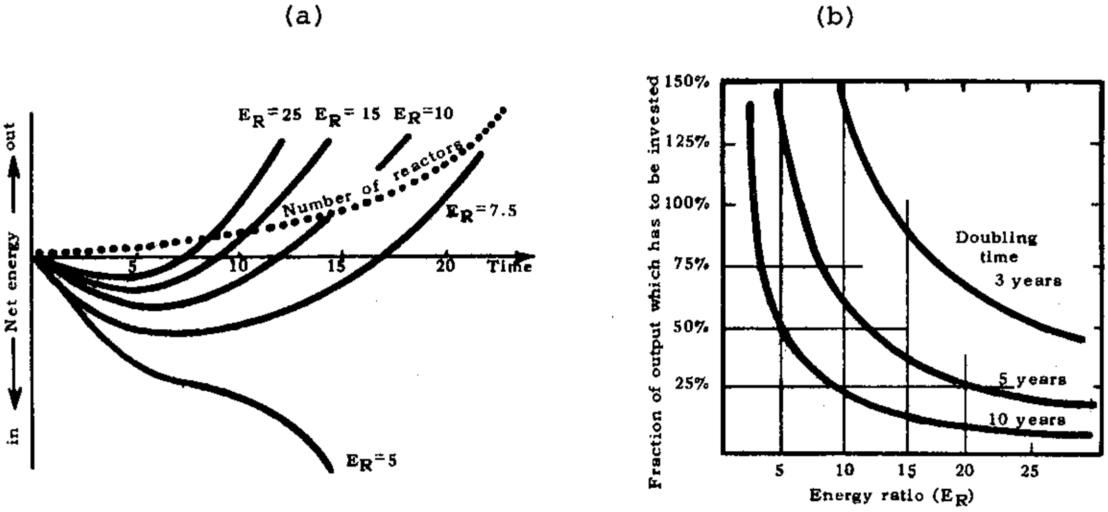


Figure 2 - [After Chapman 1974b]

(a) Net energy curves, corresponding to different energy ratios (E_R), for nuclear building programs with a doubling time of 5 years (14% increase per year).

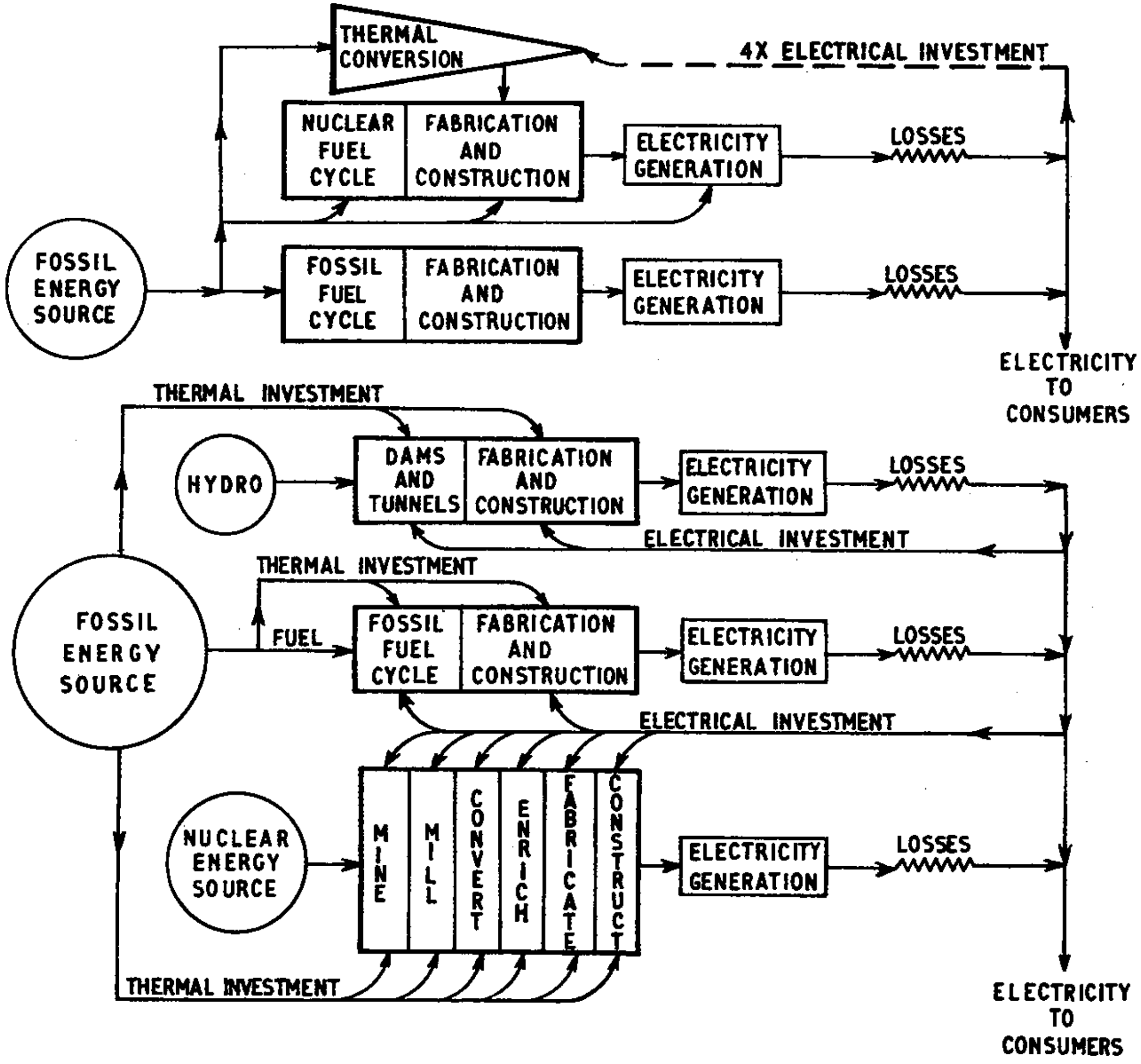
(b) Curves showing the fraction of energy output which is invested for various program doubling times as energy ratio (E_R) is varied.

Energy Flow Analysis

The problems encountered in deciding how to allocate the various energy investments in the Chapman-Price method of analysis, can be avoided in great measure if the whole system is analysed with all the various energy forms kept separate. In one such approach, electrical and thermal contributions to the energy system are treated as components of the investment in each part of the process. Enrichment investment in the diffusion process is then treated as having a large electrical component derived from an electrical grid system supplied by various types of station, together with a smaller thermal component made up of all the fossil fuels used in construction, transportation and so on.

Chapman & Mortimer have this separation initially in their derivation of energy cost for enrichment but merge the electrical and thermal investment by means of their convention. The difficulties of interpretation with the energy ratio method increase even further if nuclear energy is used to any degree in the future for chemical and metallurgical processing as well as electricity production.

The difference in approach is depicted in Figure 3 where the simple approach adopted by Chapman & Mortimer puts everything in terms of fossil fuel energy whereas the energy flow analysis allows flexibility in directing energy flow from different energy forms.



(a) CHAPMAN-MORTIMER SIMPLIFIED FOSSIL ENERGY ACCOUNTING

(b) ENERGY FLOW ANALYSIS WITH THERMAL AND ELECTRICAL INVESTMENTS AND VARIOUS ENERGY SOURCES

FIGURE 3

Energy flow analysis is exemplified by the work of Hill & Walford [1975] and by our own studies outlined in Appendix B. Hill & Walford have investigated energy flows in the UK electricity industry using seven station types, including fast breeder reactors, under several different installation programs.

Our studies have focused on energy demands made as a result of rapid growth of nuclear installations in a generating system which already has a large investment in fossil fired stations. For this purpose, we have adopted basic energy costs which are mostly derived from the work of Chapman & Mortimer. Figure 4 shows an assumed nuclear installation program together with an equivalent oil-fired program which adds to an already existing grid system, closely resembling published data for electric power development in Japan. Cases with different ore

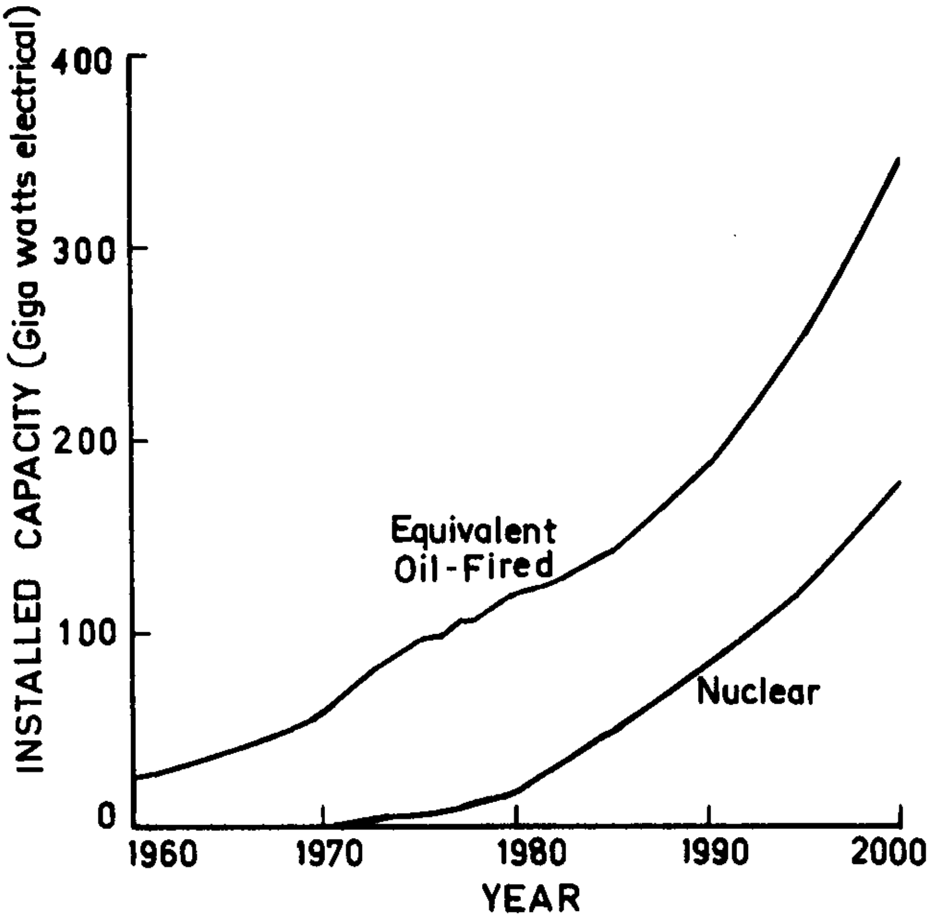


Figure 4 - The growth of installed capacity of nuclear and equivalent oil-fired stations as an example of an electrical grid system

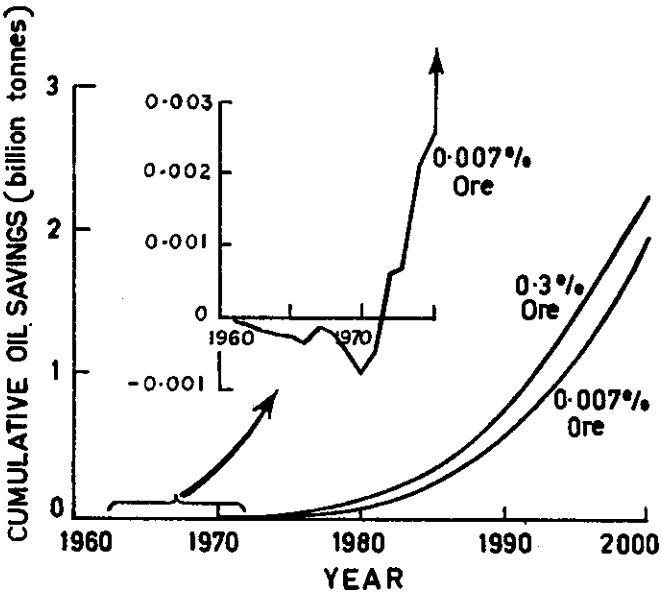


Figure 5 - Thermal energy savings as equivalent oil fuel for the oil and nuclear installation program in Figure 4, for initial ore grades of 0.007 and 0.3% U_3O_8. For simplicity, only the 0.007% ore curve is shown in the enlarged scale insert showing early expenditure of energy.

grades have been studied, one using medium grade uranium ore (0.3% U_3O_8) and the other a low grade ore (0.007% U_3O_8).

For comparison purposes (Figure 5), an electrical power program with similar overall growth pattern, but with all stations oil fired, was used to give a total thermal energy flow and thermal energy savings or expenditures of the oil-nuclear program.

The thermal energy savings or expenditures are displayed in Figure 5 as the difference between the cumulative thermal energy investment (capital and fuel) for the oil fired program and that for the oil-nuclear program.

Figure 6 presents the net input or output of electrical energy for the nuclear part of the program as the difference between nuclear-electric energy production and the electrical energy investment in the nuclear stations, i.e. the return on electrical investment.

It is important to observe that the thermal and electrical energy deficits which are attributable to the installation of nuclear power stations are recovered within the short time of a year or less for the medium grade ore. The large thermal investment in mining for low grade uranium ore is recovered from oil savings within ten years of the start of construction in the nuclear program.

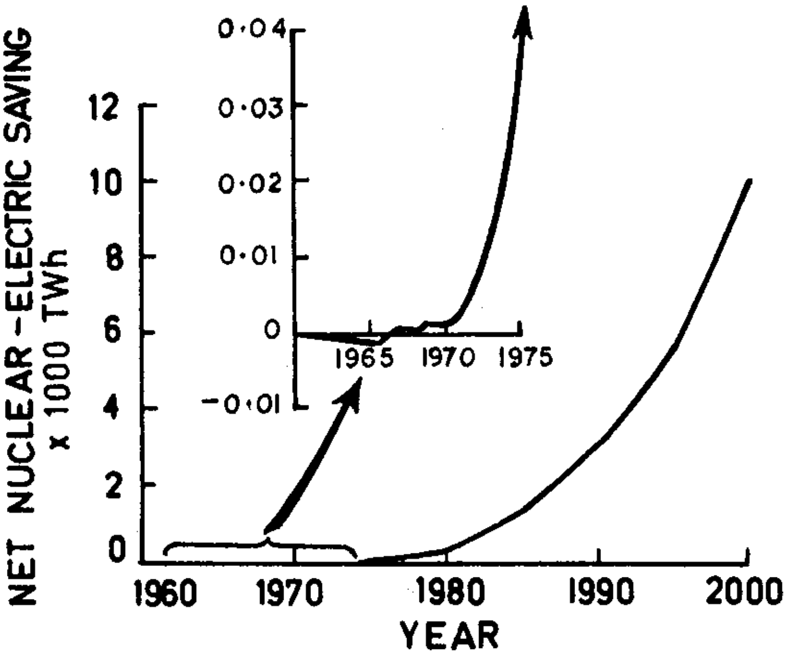


Figure 6 - Net electrical energy production from nuclear stations in the program shown in Figure 4 after allowing for electrical energy investment in the nuclear stations. Units are Terawatt-hours (10^9 kWh)

These results closely resemble data prepared for the Federal Republic of Germany by Bald et al. [1975] using a similar technique. They show that the FRG energy program required 40% of the nuclear electric output in 1972, but that the percentage had dropped to 23% in 1975 and would progressively drop to 7.8% in 1980 and to 1.2% in the year 2000. In both examples, the FRG case and our own, the nuclear electric output recovered the deficit before 1970.

In discussing the Chapman-Price analysis, Leach [1975] pointed out that, in any real grid system, very rapid nuclear growths will inevitably displace conventional power stations and, in consequence, will reduce the direct use of coal, oil and gas. He drew attention to the remarkable fuel saving effect of this substitution. While nuclear reactors have Chapman-Price energy ratios in the range 8 to 19 for present uranium ore grades, and in the range 0.8 to 7.4 for the 'worst case' 0.007% ores (see Table 1) present fossil-electric stations have equivalent ratios of 0.25. On these figures, nuclear systems are some 3 to 80 times better at converting fossil fuels to electricity than are today's conventional power stations. He adds that 'I was forced to the conclusion that in the real world where rapid exponentials do not go on for ever, on fuel saving grounds only, nuclear power is rather a good thing.' Our results bear out this thesis - with an installation program resembling that of Japan, the oil savings are equivalent to about 2.5 billion tonnes by the year 2000, or eighty times the 1973-74 annual consumption of crude oil in Australia.

Conclusion

Although energy analysis is in its infancy, an interesting start has been made to its use as one tool in the study of energy and resource policies. Both the energy ratio and energy flow approaches involve valuable concepts for studying the energy investments required to set up and develop power programs over a period of time. Clearly, much depends on the pattern of development chosen, the energy systems involved, the basic materials providing the feed to the industry and the various energy policies adopted.

In the simplified approach of Chapman & Mortimer, there are significant problems in the development of the energy ratios for nuclear reactors. Leach [1974], in his conclusions, stated 'Perceptive readers will have noticed an awkward incompatibility between the methods used by Chapman & Mortimer, and Price for computing input and output power or energy: a case of comparing apples with oranges, of which all three authors are well aware ..... If these distortions are corrected they are not likely to make any appreciable change to the computed energy and power ratios today. However, as or if nuclear power grows substantially and industries become increasingly electrified, the distortions, if not corrected, could well become serious. There is thus a strong case for re-computing all inputs and outputs with usage of available energy and gross energy requirement recorded separately.' We believe that 'the distortions' are sufficiently marked in the mining of low grade ore and in the enrichment process to warrant the separation of the energy flows today; for this reason, we have adopted energy flow analysis which allows greater flexibility in calculational methods and interpretation of data.

The current studies of nuclear energy accounting are all very preliminary. There is much to be done if the energy cost data are to be refined to cover the truly complex systems which generate electricity in real situations. As new technologies are introduced there will be a marked change in the accounting results presented to date. The discussion of three possibilities should suffice to make the point.

The energy requirements for the present diffusion enrichment process put a heavy electrical investment item in the budget but the introduction of gas centrifuge systems will drop the power requirements for enrichment by a factor of around ten; if laser enrichment is successful, it can be anticipated that a further improvement might occur. The second possibility arises in the mining of low grade ores or the extraction of uranium from seawater which are being examined now only as long term prospects. From our study of these methods of producing uranium, and consideration of the discrepancy which we believe exists in the interpretation of the energy ratio studies, nuclear power stations fuelled from these sources will show an energy profit at projected growth rates; it may well be that these materials may have an unacceptable environmental impact if their extraction is based on present day technology. Thirdly, the introduction of fast breeder technology has been touched on by Hill & Walford [1975]; it appears that there is an appreciable energy advantage in the introduction of fast breeder reactors.

As Chapman & Mortimer observed, evaluation of a wide range of possible nuclear strategies based on different combinations of energy resources, energy conversion systems (fossil, nuclear and other) and program growth rates will be necessary before anyone can genuinely assess what the final choices should be. We consider that current nuclear energy programs are running at an energy profit but whether they represent optimum solutions remains to be investigated. The use of nuclear power stations will result in large fossil fuel savings in a real electrical grid system with anticipated growth rates. Such savings give a new dimension in planning the use of energy resources since liquid fuels will continue to be necessary in the transport field for some time, and solid fuels will continue to be required for such processes as steel-making.

FURTHER READING

Bald, M., Harig, H. & Voss, A. [1975] - Energy Consumption in the Construction and Operation of Nuclear Power Stations. Atomwirtschaft, 20 (5) 296.

Bravard, J.C., Flora, H.B. & Portel, C. [1972] - Energy Expenditures Associated with the Production and Recycling of Metals. Oak Ridge National Laboratory Report ORNL-NSF-EP-24.

Brookes, L.G. [1975a] - Nuclear Economics. New Scientist, 65 (11 September) 609.

Brookes, L.G. [1975b] - Energy Accounting and Nuclear Power. Atom 227 (September) 164. A recent paper giving a similar outline to the arguments presented in the present paper.

Chapman, P.F. [1973] - The Energy Cost of Delivered Energy, UK 1968. UK Open University Report ERG 003.

Chapman, P.F. [1974a] - Energy Costs : A Review of Methods. Energy Policy, 2 (2) 91. This paper gives an extensive list of references.

Chapman, P.F. [1974b] - The Ins and Outs of Nuclear Power. New Scientist, 64 (19 December) 866.

Chapman, P.F. [1975a] - Conventions, Methods and Implications of Energy Analysis. UK Open University Report.

Chapman, P.F. [1975b] - The Energy Cost of Materials. Energy Policy, 3 (1) 47.

Chapman, P.F. [1975c] - Energy Analysis. New Scientist, 65 (23 January) 230.

Chapman, P.F. [1975d] - The Relation of Energy Analysis to Cost Analysis. SSRC Workshop on Energy, 27 February.

Chapman, P.F., Leach, G. & Slesser, M. [1974] - The Energy Cost of Fuels. Energy Policy, 2 (3) 231.

Chapman, P.F. & Mortimer, N. [1974] - Energy Inputs and Outputs for Nuclear Stations. UK Open University Report ERG 005. This report provides the basis for Chapman [1974b].

Davis, W.K. [1975] - Nuclear Power Net Energy Balances. Chem. Eng. Prog., 71 (4) 12.

Heredeen, R.A. [1973] - The Energy Cost of Goods and Services. Oak Ridge National Laboratory Report ORO-NSF-EP-58.

Hill, K.M. & Walford, F.J. [1975] - Nuclear Aspects of Energy Accounting. Institute of Fuels and the Operational Research Society Conference, 15-16 April, London.

Kenward, M. [1975] - How to Cook the Energy Accounts? New Scientist, 65 (24 April) 205.

Leach, G. [1974] - Nuclear Energy Balances in a World with Ceilings. International Institute for Environment and Development, London.

Leach, G. [1975] - Energy Analysis. New Scientist, 65 (16 January) 160.

Leach, G. & Slesser, M. [1973] - The Energy Equivalents of Network Inputs to Food Producing Processes. University of Strathclyde, Glasgow.

Makhijani, A.B. & Lichtenberg, A.J. [1971] - Assessment of Energy and Materials Utilisation in the USA. University of California Report ERL-M310.

Pigford, T.H. [1974] - Environmental Aspects of Nuclear Energy Production. Annual Reviews of Nuclear Science, 24 : 515.

Price, J. [1974] - Dynamic Energy Analysis and Nuclear Power. Earth Resources Limited, London.

Rombough, C.T. & Koen, B.V. [1975] - Nuclear Technology, 26 (May) 5. Comparison of PWR, BWR and Coal-fired Plant.

Slesser, M. [1975] - Energy Analysis. New Scientist, 65 (9 January) 97.

Train, R.E. [1973] - Energy and the Environment - Electric Power. Council on Environmental Quality, Washington, D.C., USA.

Wilson, R. & Jones, W.J. [1974] - Energy, Ecology and the Environment. Academic Press, New York.

Wright, D.J. [1974] - Goods and Services : An Input-Output Analysis. Energy Policy, 2 (4) 307.

Wright, J. & Syrett, J. [1975] - Energy Analysis of Nuclear Power. New Scientist, 65 (9 January) 66.

USAEC [1972a] - 1000 MWe Central Power Station. Power Plant Investment Cost Study. Volume I : Pressurised Water Reactor Plant. Volume II : Boiling Water Reactor Plant. USAEC Report WASH-1230.

USAEC [1972b] - Environmental Survey of the Nuclear Fuel Cycle. USAEC Report WASH-1237.

APPENDIX A

A BALANCE SHEET FOR ENERGY

An energy balance sheet for the UK electrical industry has been drawn up by Chapman [1974a] and is presented in Table A.1. It summarises an analysis [Chapman 1973] based on the UK Census of Production 1968. The analysis includes purchases of electricity from industry, consumption of materials and equipment, the energy needed to refine oil, mine coal and transport it, the processing of nuclear fuel and so on. Estimates of the energy costs of wastes, including nuclear waste, and the energy costs of nuclear fuel reprocessing are omitted. On this basis, they arrived at an energy cost of 4.19 kWh of thermal energy per kilowatt hour of electrical energy, corresponding to an 'efficiency' of 23.8%.

Chapman, Leach & Slesser [1974] analysed the UK fuel industry, made up of coal mining and the production of coke, gas, oil and electricity. They formulated a set of equations which expressed the energy cost of a particular industry in terms of the cost of its own and other industries. For the electrical industry they derived an 'efficiency' which varied from 22.02% in 1963, through 23.85% in 1968, to 25.2% in 1971-72. Heredeen [1973], using the input-output method for the USA on the 1963 data issued by the US Department of Commerce, obtained a figure of 25.8% for the electric utilities. This compares well with the above values quoted from Chapman, Leach & Slesser [1974].

TABLE A.1

THE UK ELECTRICITY SUPPLY INDUSTRY

(Based on UK Census of Production 1968)

Inputs	10^6 kWh(t)
New buildings (£80.08 million)	1 895
Net plant etc. (£462 million)	16 170
Net vehicles (£3.623 million)	178
Vehicle & machine spares	766
Iron & steel (13 500 tons)	134
Wire & cables	1 089
Other materials	985
Nuclear fuels	2 904
Coal (75.54 million tons)	542 015
Coke (314 000 tons)	2 944
Oil products	93 792
Gas	374
Electricity purchased (from industry)	3 479
Heat input (nuclear power stations)	96 113
Electricity (hydro)	3 600
Total Input	766 438
Total electricity generated	215 149
Used in works, offices, etc.	16 195
Loss in distribution	16 182
Sold to final consumers	182 772

Overall Efficiency = 23.84% : Hence 1 kWh electrical = 4.195 kWh thermal

APPENDIX B

ENERGY FLOW ANALYSIS

To overcome the problems associated with the simplified analysis necessary for the Chapman-Price energy ratio methods, it is necessary to keep separate the various energy forms which are used by a complex system in practice. Hill & Walford [1975] suggested that a clearer view should emerge if fossil fuel energy and electrical energy are kept separate when a power program involving both fossil and nuclear energy is being considered. The separation of energy forms more nearly represents the real situation where electricity from the grid system is used to enrich fuel, drive forges and lathes and so on, while fossil fuel (in the form of coal and petroleum products) is used in power station furnaces, in bulldozers and transport vehicles, for making steel, etc.

For our own energy analyses, a computer program FURES has been developed to accept data on a variety of power stations in an electrical system and to generate the quantities of fuels required for running the system. FURES was extended to compute the quantities of electricity and fossil fuel energy required to run the system and to construct new power stations, needed for system growth and as allowance for retirement of old stations. Time delays such as those required to mine and process fuel before use in the power stations had already been incorporated into FURES. Sections were added to handle the energy used during construction (before the station was commissioned) and to present the results in energy units.

In outline, FURES accepts as data the installed capacity of the various power station types which will be present in the period under consideration, together with data on specific energy costs for the various operations and components (allowing for separation of the electrical and thermal energy). It then generates tables of electrical and thermal energy for the various processes (mining, milling, enrichment, etc.) and summarises the results, all on a yearly basis. Graphs of total and net (total less investment) electrical energy, thermal energy (fuel and investment) and construction of electrical and thermal energy are optional outputs.

FURES has been used to study an electrical grid system resembling that for Japan over the period 1961-2000. The data of Chapman & Mortimer [1974] for electrical and thermal inputs have been used. By selecting the period 1961-2000, it has been possible to cover a period when nuclear power was just being introduced, when it was rapidly building up, and when nuclear power might conservatively be expected to generate about 35% of the system capacity. Although the actual electrical installations in Japan include coal, oil, gas and hydro power stations, these have been amalgamated into an equivalent oil-fired system for initial simplicity, with nuclear plant as the other component. The more complex system can be treated in FURES and this is being done, because the program of new installations in Japan also includes a rapidly growing system of hydro-electric power stations which warrants study by energy analysis.

Results given in the main body of the paper show that the fossil fuel savings begin about five years after the first station comes on line, coinciding with the second station coming on line. New capacity is added every year thereafter without a deficit being shown; Figure 5 shows the case for the low grade ore assumed by Chapman & Mortimer. By the year 2000, there are substantial fossil fuel savings for both grades of ore assumed. This is determined by carrying through a similar calculation for a grid system entirely composed of oil fired stations. This system would require an additional 2000 million tonnes of crude oil when compared with the oil plus nuclear system at the year 2000.

APPENDIX C

ENERGY REQUIREMENTS FOR THE DISPOSAL OF RADIOACTIVE WASTE

A preliminary assessment of the energy required to dispose of radioactive waste has been made, based on the prediction of waste from a 1000 MWe nuclear power station operating for 25 years, together with a vitrification plant operating for 20 years. The estimates of energy requirements start from the delivery of high level liquid waste from a reprocessing plant. The energy requirements for solidification are deduced either from the financial cost through the use of energy intensiveness for that type of utility, or from energy costs derived by others.

Estimates for disposal by excavation, seabed and ice sheet methods are based on data provided by Schneider & Platt [1974]; all necessary mining operations, transport costs, handling at the storage area and surveillance are included.

Where there are cooling requirements, the estimate assumes that cooling will be discontinued after 100 years, the maximum time that workers in the USA conceived to be necessary. To achieve this situation without doubt, the containment design and waste content are such that the heat flux from the containers 100 years after disposal will be half that demonstrated as satisfactory, without cooling, in measurements in Kansas salt mine experiments. As cooling becomes redundant owing to the decrease in fission product decay heat, the excess equipment is assumed to be kept on standby.

Space disposal is much more difficult to assess for energy requirements. A great deal depends on the effort put into partitioning the waste into fission products and transuranic waste. A total energy cost of 3.2×10^7 kWh/year or around 8×10^8 kWh over 25 years is estimated. The energy requirements for vitrifying the fuel used by a 1000 MWe station (at 100% load factor) would be 2.3×10^6 kWh per year. Except for ice sheet disposal, this represents the bulk of the energy cost of processes requiring solidification. Table C.1 gives the total energy costs and considers their relation to the energy produced, on the basis that the wastes are derived from 1000 MWe nuclear power output over 25 years and not from a 1000 MWe station operating at some arbitrary load factor; the electrical output in this case is taken as 2.2×10^{11} kWh.

In spite of the very rough estimates, it appears reasonable to expect that the energy requirements for waste disposal will be less than 0.1 per cent of the energy produced, unless space disposal is considered viable and necessary, in which case the energy required may reach one per cent of the energy produced.

Reference

Schneider, K.J. & Platt, A.N. (Eds.) [1974] - High level radioactive waste management alternatives. US Report BNWL-1900.

TABLE C.1

ENERGY REQUIREMENTS FOR WASTE DISPOSAL AS A FRACTION OF ENERGY PRODUCED

	Solidification (kWh)	Disposal (kWh)	Total (kWh)	Fraction of energy produced (2.2×10^{11} kWh)
Excavation methods				
(a) liquid		4.6×10^3 to 4.6×10^5	4.6×10^3 to 4.6×10^5	2×10^{-8} to 2×10^{-6}
(b) solids	6.5×10^6	6.9×10^7	7.2×10^7	3×10^{-4}
Seabed	6.5×10^6	9.2×10^6	7.4×10^7	3×10^{-4}
Ice sheet	6.5×10^7	9.7×10^7	1.7×10^8	7.5×10^{-4}
Space				
(a) actinides	0.5×10^8	7.5×10^8	8×10^8	
(b) remaining fission products	6.5×10^7	6.9×10^6 (excavation method)	7.2×10^7	
Total			8.7×10^8	3.8×10^{-3}