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RESEARCH ESTABLISHMENT
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NET FOSSIL ENERGY SAVINGS FOR ALTERNATIVE MIXES IN VARIOUS ELECTRIC SUPPLY SYSTEMS

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ABSTRACT

The actual and projected electric power station building programs of several countries and regions have been examined to determine what effect the introduction of nuclear power has on fossil fuel usage by the electricity system. It was found that (i) nuclear power leads directly to savings in fossil fuel usage, a larger nuclear component leading to larger savings; (ii) individual nuclear stations rapidly wipe out the energy 'debt' incurred during building; and (iii) the relatively short periods of consolidation in the early stages of a nation's building program usually prevent the nuclear component from going into energy 'debt'. Assessments of the energy requirements to build and run various types of power station have been made from the available literature.

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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.

POWER GENERATION; NUCLEAR POWER; ELECTRIC POWER; ENERGY SOURCES; POWER PLANTS; ENERGY POLICY; COMPARATIVE EVALUATIONS; ECONOMICS; FOSSIL-FUEL POWER PLANTS

AUTHORS' NOTE

This analysis was performed in late 1975-early 1976. Although some updating was possible on assessing the energy 'costs', it was generally found that the variations were covered in the sensitivity analysis. Projected building programs have been substantially modified (generally downward) since making the analysis; however, the general trends and conclusions will not be affected.

CONTENTS

1. INTRODUCTION

The data published during the last few years on the amounts of energy required to manufacture goods and materials and perform services have given a basis for examining the energy inputs of various systems. Examples of systems studied are those which examined the energy expended in producing metals [Bravard, Flora & Portal 1972; Chapman 1974a, 1974b], investigated the energy cost of fuels [Chapman, Leach & Slesser 1974], and calculated the energy required in the production of agricultural supplies [Leach & Slesser 1973].

In the field of electricity supply, Chapman & Mortimer [1974] investigated the energy required to build, fuel and run various types of nuclear power station and compared this energy with the electrical energy generated. The investigation covered the case of a single station and various building programs with different growth rates. A major convention that they adopted was to assume that all energy inputs came ultimately from fossil fuel and, since the electricity supply system in the United Kingdom used about four units of fossil fuel to produce one unit of electricity, they multiplied the electricity component of any item by four and added it to the thermal component from fossil fuel to obtain the overall equivalent thermal energy cost of any item. In itself, this convention is reasonable; however, difficulties can arise in interpretation when the electrical outputs from the nuclear stations are compared with the thermal inputs, given the number of alternative situations. Price [1974] extended the work of Chapman & Mortimer along analytical lines but still retained their basic conventions.

Hill & Walford [1975a, 1975b] pointed out that a more detailed and informative picture could be obtained if the energy forms were accounted separately and all types of power plant used in the system were considered. The effect on the various resources could then be found much more accurately, the overall contributions of the different energy forms in a system could be analysed, and sensitivity studies could be made.

Keeping track of the different energy forms is difficult in an analytical approach but is relatively simple when using a digital computer. In addition, the discontinuous nature of system growth can be simulated more readily with a computer. Faulkner & Stocks [1976] have developed a computer program, FURES, which accepts the growth and mix patterns of energy supply systems and calculates the separate electrical (e) and thermal (th) energy requirements together with the electrical output, given the necessary data on individual energy costs.

FURES has been used to examine the energy flows associated with the growth of a number of electrical supply systems in Japan, the United States of America (USA), the United Kingdom (UK), the Organization for Economic Cooperation and Development - Europe (OECD-Europe) and the World (as a whole unit). The starting date was the introduction of the first nuclear power station into the system being investigated and the study extended to the year 2000 AD. Estimates of future growth rates were based on those published figures from authoritative bodies which were available at the time of the study. Sensitivity studies covered the effects of changes in nuclear content, energy costs for specific items, station capacity factor and uranium ore grade.

2. GENERAL SYSTEM

The electrical generating system of any country or region draws on many energy sources such as coal, oil, gas, hydro, nuclear, geothermal, tidal and solar. Most systems essentially rely on three main sources of fuel, namely fossil, hydro and nuclear. These sources and combinations of them provide the primary energy for the systems studied in this investigation.

Figure 1 illustrates the flows of primary energy into the system and the net electrical energy produced, together with the flows of primary and electrical energy within the system. The internal flows provide the energy required to (i) mine, process and transport the fuel to the station, (ii) produce the materials for fabrication, manufacture components, site preparation, construction and erection, and all processes necessary to bring the station on line, and (iii) run the station and produce the required electrical power.

The computer program FURES [Faulkner & Stocks 1976] accepts information on the station mix and growth pattern of an electricity system as input data. It then computes the quantities of electricity and fossil fuel energy required to run the system, and to construct new power stations which are needed both for system growth and to replace old plant. Time delays such as those required to mine and process fuel are incorporated.

A standard data bank has been established for the program providing the user with a choice of up to 13 types of nuclear plant and five types of conventional plant. The data can be overwritten to change the plant

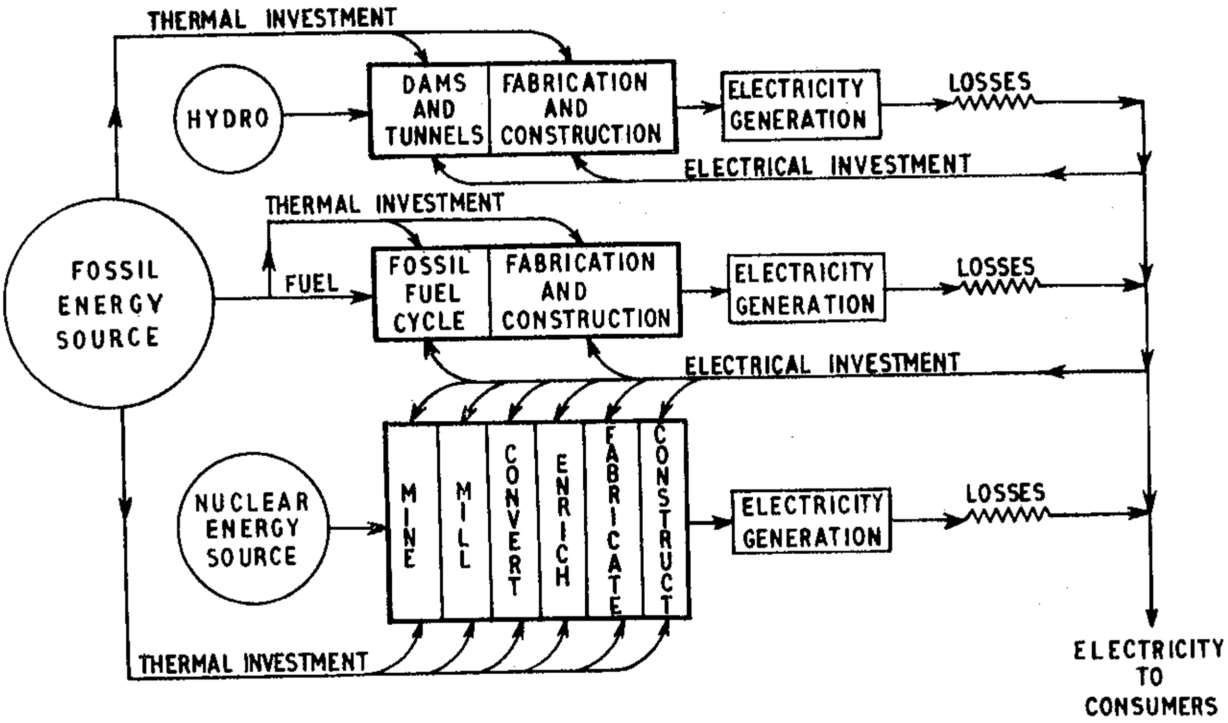

FIGURE 1 ELECTRICITY SUPPLY SYSTEM ILLUSTRATING THE THERMAL AND ELECTRICAL INVESTMENTS AND VARIOUS ENERGY SOURCES [After Symonds, Essam & Stocks 1975: Figure 3(b)]

characteristics and the energy costs for various goods and services when carrying out sensitivity studies. The output from FURES consists of lists by year and also graphs of:

- thermal and electrical energy to manufacture and build the stations,
- thermal and electrical energy to provide fuel,
- thermal energy as fuel for conventional fossil-fired stations,
- gross electricity output from the stations, and
- net electricity (*i.e.* gross less electricity for investments).

3. ENERGY COST DATA

3.1 Background

Energy costs, as used in this report, are not the monetary costs of energy but the energy required to manufacture an item or perform a service. While this concept is simple, its application in assigning an energy value involves many levels of complication. For example, the system used to obtain the energy costs has to be defined. Such a system for, say, a steel bolt may only consider the energy necessary to form the bolt head and then machine the bolt. A much wider system could consider the energy necessary to mine the iron ore, produce pig iron and steel, and then machine the bolt; allocate a proportion of the energy involved in the buildings and capital equipment required to produce the basic material and to manufacture the bolt; and finally, evaluate the manual labour of the people involved. The coverage of the first system is too meagre; the second system is highly complex with a strong likelihood of 'double accounting'.

In practice, a much more pragmatic approach is adopted, each case being considered on its merits. The system boundary for 'high' technology items such as bolts, cars, concrete, power stations, *etc.*, generally includes the energy costs necessary to obtain the raw materials and process them into finished products. Some effort is usually made to include a proportion of the energy which is embodied in capital works. Manual labour energy is generally excluded. 'Low' technology items, such as agriculture with low levels of mechanisation, incorporate the high levels of labour (human and animal) which are a feature of such items. A detailed discussion of types of energy accounting and the extent of suitable system boundaries has been published by the International Federation of Institutes for Advanced Study [1974].

Broadly, three techniques have been used to arrive at energy costs. One technique is to consider the process by which an item is produced and measure or estimate the amount and type of energy involved at each step; all the inputs are then added together [Leach & Slesser 1973]. Another technique is to take the monetary cost for an item and multiply it by an energy/cost ratio to obtain the amount of energy required. The energy/cost ratio may be an overall one for a region, based on the total primary energy consumed by the region in any one year divided by the gross domestic product for that year (Rombough & Koen [1975] quote an energy cost ratio of 69 352 Btu/$ (73.166 MJ/$) for the USA in 1970). Equally, the ratio may also be based on some sector of a nation's economy [Herendeen 1973] or some other factor. The primary energy is broken down into fossil plus electrical energy on the basis of overall statistics.

The third technique is to analyse the input/output tables of a region's economy. The economy is divided into a number of industries and these are listed as the rows and columns of an input/output matrix. Generally, a column lists the economic contributions of all other industries to any one particular industry so that it produces one unit of output. This matrix can be manipulated to obtain all the direct and indirect inputs necessary for one unit of output to attain final consumption. Since the energy industries are included, the direct and indirect energy inputs can be obtained. These inputs are monetary costs, but if the cost of that particular form of energy to the industry is known, then the energy costs can be obtained. Herendeen [1973] presented the basic theory and applied it to the 1963 input/output tables for the USA.

Energy costs obtained by any method vary from region to region because each region tends to favour a particular technology. The energy costs also tend to vary with time, reflecting development in technology. Both these trends are illustrated below in the 'efficiency' of the electricity supply industries in the UK and USA:

Year	1963	1968	1971/72	
UK	22.02%	23.85%	25.2%	Chapman *et al.* [1974]
USA	25.8%	-	-	Herendeen [1973]

where 'efficiency' is the amount of electricity delivered by the system to the customer divided by the amount of fossil fuel burnt. However, since at this stage the variations do not appear to be great, data for an item obtained in one region are frequently applied elsewhere. The rationale generally is that the errors in other parts of an energy analysis tend to swamp relatively minor discrepancies and so allow major trends to be seen.

Some energy cost data are expressed as 'equivalent thermal' energy. This convention reflects a concern by the pioneering energy analysts with the depletion of primary fossil fuel reserves. The convention adopted was that any electrical energy required (say, to drive forges, rolling mills, lathes, cranes, *etc.*) was converted to primary energy input. In some cases, only the thermodynamic efficiency was used (some 30-40 per cent) and electrical to primary energy factors of about three were used. Investigations into the overall energy requirements, summarised above, showed total 'efficiencies' of about 25 per cent. Consequently, a factor of four is used nowadays to convert electrical energy into equivalent fossil thermal energy. The factor of four has been used in this report for translating electrical to equivalent thermal energy and *vice versa*. Thus if the energy input to an item is 1 MJe and 9 MJth, then the equivalent thermal energy is 13 MJth (*i.e.* 1 x 4 + 9).

TABLE 1

SUMMARY OF PUBLISHED ENERGY CAPITAL COSTS FOR 1000 MWe PLANTS

Station Type (units(1): TJ or 10^{12} J)								Source
PWR	BWR	LWR	SGHWR (10)	CANDU (10)	AGR (2)/HTGR (11)	Magnox	Fossil	
973e + 10 710th (≡14 602th)	-	-	1687e + 17 531th (≡24 279th)	2740e + 27 251th (≡38 211th)	1254e + 13 798th (≡18 814th)	1738e + 19 112th (≡26 064th)	-	Chapman(2) [1975]
-	-	-	2050e + 11 880th (≡20 090th)	3240e + 22 320th (≡35 280th)	-	-	1692e + 6840th (≡13 640th)(4)	Hill & Walford(3) [1975b]
- 16 800th (8) (14 460th) -	- 17 060th (8) (14 680th) -	15 830th (5) 14 770th (6) 610th (7)	- - -	- - -	- - -	- - -	- 11 600th (6) (coal) -	Rombough & Koen [1975]
-	-	2680e (≡10 720th)	-	-	-	-	2420e (≡9670th) (coal)	Bald et al. (9) [1975]
738e + 10 110th (≡13 061th)(12) -	719e + 10 035th (≡12 910th)(12) -	805e + 8785th (≡12 007th)(13) -	- -	2616e + 22 426th (≡32 889th)(14) -	1021e + 13 817th (≡17 903th)(12) 995e + 10 546th (≡14 368th)(13)	-	-	Rotty et al. (11) [1975]

NOTES

(1) Breakdown into electrical and thermal units is as presented by the originating authors: bracketed values are equivalent thermal (= 4 x e + th): e = electrical energy, th = thermal energy from fossil fuels for capital items.

(2) Data obtained from 1973 CEGB costs: energy/cost ratio from 1968 UK input/output table adjusted for inflation to 1973: electrical/thermal ratio from 1968 UK Census of Production, HMSO 1971. Omitted from the table are data for HTR (1045e + 11 502th (≡15 682th)).

(3) Basis of data is quantity of material used in construction multiplied by the energy required to produce one unit of the material [Walford, Atherton & Hill 1976]. D_2O costs given as 2.52(e) + 23.04th GJ per tonne (1 GJ = 1 gigajoule = 10^9 joules).

(4) Actually typed as fossil by authors, so presumably refers to coal, oil or gas. Omitted from the table are the data for the FBR (3780e + 14 940th (≡30 060th)).

(5) Based on January 1971 costs [USAEC 1972] and overall USA 1970 energy/cost ratio.

(6) Based on January 1971 costs [USAEC 1972] and 1963 energy/cost ratio of industrial sector - new construction for public utilities indexed from 1963 to 1970 by 16.2 per cent wholesale price increase for the period.

(7) Summation of tonnages of material times the production energy/tonne ratio for a 2240 MWe plant; excludes 'overheads'.

(8) Based on January 1971 costs [USAEC 1972] subdivided into 62 industrial classifications for which 1963 energy cost ratios are also available. On checking, it would appear that the costs have not been corrected for price changes from 1963 to 1970. The bracketed values include the factor of 1.162 of note (6).

(9) No details of derivation are given; values given as electrical energy only, with no thermal component. Authors state that values are the larger of those obtained by energy/mass ratio and energy/cost ratio methods.

(10) Includes energy required for D_2O production. Chapman [1975] gives 585e + 5400th - SGHWR (250 tonnes) and 1638e + 15 120th - CANDU (700 tonnes) as D_2O energy requirements. Rotty et al. [1975] give 1749e + 10 547th for CANDU (704 tonnes D_2O): capital costs were assumed to be 1.175 × PWR costs.

(11) Basically, this uses the electrical and fossil fuel energy required per $ output from a particular industrial sector; detailed monetary costs for particular reactors are assigned to various sectors; the energy is then obtained by multiplying sector costs by energy/$ ratio.

(12) Basic monetary costs were obtained from USAEC [1972].

(13) Monetary costs from Bechtel Corp. [1975].

(14) Monetary costs from Haywood & Aikin [1967].

PWR - pressured water reactor; BWR - boiling water reactor; FBR - fast breeder reactor; LWR - light water reactor; SGHWR - steam generating heavy water reactor; CANDU - Canadian deuterium, natural uranium reactor; AGR - advanced gas-cooled reactor; HTGR - high temperature gas-cooled reactor; Magnox - UK gas-cooled reactor with Magnox cladding for fuel; Fossil - oil- or coal-fired.

Since this investigation was concerned with the forms of energy usage, as much data as possible were obtained in the separate forms of the electrical and thermal energies. Equivalent thermal energies have generally been used for comparison; the exceptions were when equivalent thermal energy data were solely available or when the process obviously used only fossil fuel.

3.2 Energy 'Capital' Costs

Data on the energy required to manufacture the components and build power stations have been published by a number of authors. Table 1 summarises the recently published data of Chapman [1975], Hill & Walford [1975b], Rombough & Koen [1975], Bald, Harris & Voss [1975] and Rotty, Perry & Reister [1975] for various types of nuclear and fossil-fired stations. In terms of the light water reactor (LWR) types, *i.e.* the pressurised water reactor (PWR) and the boiling water reactor (BWR), which are the predominant types in the world, there is excellent agreement between Chapman [1975] and Rombough & Koen [1975] that the total equivalent thermal energy for a 1000 MWe station is about 14.6 PJth*, using energy / cost ratios. Chapman has also claimed that a Westinghouse study gave the same energy requirement for plant as his study; studies still in progress in Sweden and France have produced very similar estimates of the energy input to the plant based on disaggregated input/output studies.

Rotty *et al.* [1975] carefully broke down the detailed monetary cost estimates for PWRs, BWRs and LWRs into a number of industrial sectors. Analyses of the input/output tables of the USA for 1967 were used to generate energy/monetary cost ratios for each sector and these were applied to the reactor cost breakdown. The resultant total equivalent thermal energy required to manufacture and build the reactors was in the range 12.0 to 13.1 PJth. The values are some 80-90 per cent of those estimated by Chapman [1975] and Rombough & Koen [1975] and so lie within the error band of 20 per cent which appears to be currently applicable to estimates of the energy cost to build a nuclear power reactor [Chapman 1976:293].

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* 1 PJ = 1 petajoule = 10^{15} joules.

Rombough & Koen estimated an equivalent thermal input of 0.61 PJth for a 1000 MWe station using estimates of material quantities and energy/mass ratios. Bald *et al.* [1975] estimates gave an equivalent thermal input of 10.7 PJth/1000 MWe station (although their stated value was 2.68 PJe - *i.e.* in equivalent electrical energy) and it was claimed that this was the larger of estimates *via* energy/cost ratios and energy/mass ratios. Davis [1975], who is not included in Table 1, estimated the energy to construct an 1100 MWe station at 0.74 x 10^9 kWhe; this is equivalent to 7.3 PJth for a 1000 MWe station when using his factor of 0.33 to convert thermal energy to electrical equivalent. He remarked "... the numbers could be wrong by a factor of 2..." and this is the factor between his value for plant and those estimated by Chapman [1975] and Rombough & Koen [1975] when comparing the equivalent thermal energy.

Since there is excellent to good agreement on the value of 14.6 PJth for the plant using energy/cost ratios, it was decided to base the plant data on this value. Since this value was the same as Chapman's, and since Chapman gave a breakdown into electrical and thermal, it was decided to adopt the Chapman data *in toto*. One advantage of using his data was that it would provide a way to check results of the present investigation with the work by Price [1974], which was also founded on the Chapman data (the only form of equivalent thermal energy data then available).

One major omission from Chapman's data was information on fossil fuel-burning stations. Hill & Walford [1975b] had data on an unspecified type of station (13.6 PJth), Rombough & Koen [1975] had equivalent thermal energy for a coal station (11.6 PJth) and Bald *et al.* [1975] gave the equivalent electrical energy for a coal station (which converted to 9.67 PJth). This posed a problem in judgement since recent estimates of nuclear/coal (monetary) cost ratios have been reduced under the effect of more stringent clean air requirements and so would not represent the situation up to the late 1970s. In addition, oil-fired stations have been assuming a higher proportion of the load. Costs of the various types of station in 1970 [USAEC 1972] were

PWR	BWR	Coal	Oil
211.5	213.0	174.1	157.6 (10^6 \$US)

It was decided to derive a ratio for the energy requirements for the fossil plant from the above values of BWR and oil, since they represented probable extremes, and apply the resulting factor of 1.35 to Chapman's value for the LWR to obtain the capital energy costs for a fossil-fired station.

The energy required to build hydro-electric plants is highly variable, depending on terrain, accessibility, type of dam (concrete, rock fill), amount of tunnelling, head of water available, *etc.* Sexton [1974] presented a study of hydro-electric schemes proposed for British Columbia in 1972. Costs varied from 40$/kWe for extensions to existing plants to a general spread of 300-500 $/kWe (excluding transmission costs) for new schemes. The National Petroleum Council [NPC 1973a] gave nuclear plant costs of $400/kWe (1970 constant dollars). Calculations on the Snowy Mountains scheme in Australia indicated that hydro plant costs would be slightly lower than the NPC value by approximately four per cent. A value four per cent lower than Chapman's data for the PWR was adopted for hydro-power. (No significance should be attached to this minor variation.) No provision has been made for the higher transmission costs usually associated with hydro-electric schemes.

Table 2 summarises the capital energy costs which were used as a basis for the present study.

TABLE 2

BASIC CAPITAL ENERGY COSTS USED FOR THE PRESENT STUDY

Station Type	Energy Costs:PJ/MWe Installed
PWR	0.973e + 10.71th
BWR	0.973e + 10.71th
SGHWR[(a)]	1.687e + 17.531th
AGR	1.254e + 13.798th
Magnox	1.738e + 19.112th
All fossil	0.714e + 7.854th
Hydro	0.935e + 10.29th

Note: *The energy required to manufacture, build, install and erect the capital plant items (such as reactor, electrical equipment, buildings, etc.) was spread uniformly over five years.*

(a) Includes heavy water energy costs for the core.

3.3 Energy Costs to Produce Fuel

3.3.1 Nuclear fuel cycle

A number of reports have been published which detail the energy required for the various parts of the fuel cycle. These usually refer to the areas of mining, milling, conversion of U_3O_8 to UF_6 for enrichment (when required) and subsequent reconversion to UO_2, fuel fabrication, fuel reprocessing (after discharge from the reactor), and waste management. Of the published reports, only WASH-1248 [USAEC 1974b] gave energy costs in electrical units and in units of equivalent coal mass. The Council on Environmental Quality [CEQ 1973] gave energy costs only in electrical units; Chapman & Mortimer [1974] gave detailed costs in a mixture of equivalent thermal energy units and electrical plus thermal units; Chapman [1975] updated the Chapman & Mortimer results with a full allocation into electrical plus thermal units, however, all thermal equivalents were the same. The USAEC [1974a] and Rotty *et al.* [1975] investigated the nuclear fuel cycle in detail and also divided energies into electrical and thermal components. Table 3 summarises the data from these sources.

A comparison of the values given in Table 3 points out a number of areas of agreement and disagreement between the various sources. It is difficult to see how the USAEC [1974a] report could imply that no thermal energy is used in mining since, for example, a fair proportion of uranium mines are surface mines and would use fuel oil for powering machines. Equally, a second USAEC [1974b] report allocates only electrical energy to reprocessing. The estimates by Rotty *et al.* were higher than for any other source for all parts of the fuel cycle. They were based on a careful examination of direct energy used in a particular process; finding the quantities of process materials required and multiplying them by the energy content of the material; and dividing the lifetime production from a plant into the capital energy cost of the plant. All processes were carefully investigated and special attention was paid to sensitive items. For example, the energy necessary to mine the sulphur required for sulphuric acid in milling was obtained from actual industry statistics since the input/output tables did not allow disaggregation to individual products. There is good agreement between the sources on the amount of energy required for enrichment - the dominant energy cost in the fuel cycle.

Since it was intended to check our approach with the results obtained by Price [1974] (who used the thermal equivalent data of

TABLE 3

ENERGY COSTS OF NUCLEAR FUEL - LWR

Mining (GJ/t U)			Milling	Mining & Milling	Conversion	Enrichment	Fabrication	Transport	Reprocessing	Waste Management	Source
Direct Energy	Process Materials	'Plant' Costs	(GJ/t U)	(GJ/t U)	(GJ/t U)	(GJ/t SWU)*	(GJ/t U fuel)		(GJ/t)	(GJ/reactor year)	
-	-	-	-	38.9e + 801.1th	57.6e + 194.4th	8710e +350th	173e + 115th	-	-	-	Chapman(1) [1975]
	27.4e + 0th		50e + 475th	77.4e + 475th	39.6e + 132th	9110e + 0th	360e + 3.2th	-	296e + 1470th	-	USAEC [1974a]
43.7e + 271.1th	20.3e + 168th	5.7e +119th	79.5e + 553.9th	144.2e + 1112th	52.6e + 1425th	10 165e + 842th	1084e + 2707th(3) 1210e + 3252th(4)	8.53e + 344th	71.6e + 376th	601e + 6442th(5)	Rotty et al. [1975] (2)
-	-	-	-	-	-	-	-	-	51e + 0th	-	USAEC [1974b]

Notes:

(1) Assumes ore at 0.31 per cent and 24:1 stripping ratio. The base reference gives total for mining + milling + conversion, however, Chapman & Mortimer [1974] give the conversion values as shown. These were subtracted from the total energies to give the mining and milling.

(2) Assumes ore at 0.208 per cent and average for US underground and surface mines. Large amounts of energy are assigned to process materials used in the conversion of U_3O_8 to UF_6, in fabrication, and in reprocessing.

(3) Without Pu recycle.

(4) With Pu recycle.

(5) Assumes operation at 75 per cent capacity factor.

* *SWU = separative work unit.*

TABLE 4

ENERGY COSTS OF FOSSIL FUELS

Underground Mined Coal (MJ/t)	Surface Mined Coal (MJ/t)	Oil (MJ/t)	Oil Desulphurised (MJ/t)	Gas (MJ/1000 m^3)	Gas Desulphurised (MJ/1000 m^3)	Source
0e + 741th	0e + 610th	0e + 5640th(2)	-	0e + 2800th	-	CEQ [1973](1)
16e + 370th	12e + 300th	31.3e + 690th	196e + 890th	24e + 500th	320e + 520th	USAEC [1974a]

(1) References in CEQ 1973: Coal - Figure A-1 plus Table A-1 note 9; oil - Figure A-2 plus Table A-4 note 9; gas - Figure A-3 plus Table A-7 note 5.

(2) For oil extracted, refined and transported to the USA. The value for transporting refined oil to the USA and internal distribution is 819 MJ/t.

Chapman & Mortimer [1974]), and since Chapman's [1975] data were exact thermal equivalents, it was decided to use Chapman's data for all runs and use the USAEC [1974a] data to check for sensitivity. Unfortunately, the data by Rotty *et al.* were not available when the computer runs were made, otherwise they would have been used for the sensitivity analysis. However, the variations considered (for example, in enrichment energy) effectively covered the Rotty *et al.* data.

3.3.2 Energy costs for fossil fuels

Before fossil fuels can be burnt in power stations, energy is needed to extract the fuel from the ground, process it and transport it to the stations. In the case of coal, this involves underground or surface (open cut) mining, wet and dry cleaning and (usually) unit transportation by diesel trains. In the USA, oil and gas have sometimes to be pumped to the well-head, refined, and transported to the refinery and then to the power station.

Table 4 gives the energy costs involved in bringing fossil fuels to the power plant. The difference in energy costs to supply deep and surface mined coal is surprisingly small. The Council on Environmental Quality [CEQ 1973] gave a breakdown of the energy required for the various stages which can be summarised as follows:

Stage	Deep mined coal	Surface mined coal
Mining	454	323
Cleaning *(a)*	40.5	40.5
Transport *(b)*	247	247
	741	610

Units are MJ/t coal delivered to power station.

(a) *Cleaning includes a loss of 23 per cent (rubbish and coal fines, etc.) of the coal sent for cleaning (66 per cent of the total amount of coal extracted).*

(b) *There is a 1 per cent loss unless the coal is wetted during transportation.*

Although there is a major difference in the energy requirements for mining deep and surface coal, the percentage differences in the totals are greatly reduced owing to the high amount of energy required for transportation (about 40 per cent of the total).

There is a very large difference between the CEQ [1973] and USAEC [1974a] estimates of energy costs for supplying oil and gas. The USAEC ignored the energy cost of refining oil, whereas the CEQ allocated the refinery energy costs in proportion to the energy values of the end products. The USAEC apparently ignored the energy cost of processing the gas after extraction, although costs for 'desulfurization' [sic] were estimated. On the other hand, the CEQ claimed that about 3 per cent of gas processed is used in the processing plants [CEQ *op. cit.* Table A-7, note 8].

The data obtained from CEQ were adopted as the base data for the present study since it seemed more reasonable to allocate energy costs to the refinery stage in producing fuel oil from crude (although such fuel is normally termed 'residual fuel oil', denoting material of little value), and the use of data from a single source seemed desirable. A run with the USAEC [1974a] data was made to check the sensitivity.

3.4 Power Station Operating Characteristics

The reactor characteristics used were based on the OECD/NEA [1973] values listed in Table 5. The inventories and net consumptions given in the table were independently calculated from the reactor characteristics. They differ only slightly from the corresponding values given in the OECD/NEA report. An exception is the enrichment work requirement for the steam generating heavy water reactor (SGHWR) and advanced gas-cooled reactor (AGR) initial cores, and the SGHWR reload which is about 5 per cent less than the OECD/NEA values.

Table 6 lists the heat content of fossil fuels used in the study. Corresponding values from the World Energy Conference [1974] are also given for comparison. The thermal efficiency for all conventional plant was taken as 35 per cent.

4. COMPARISON WITH OTHER RESULTS

To date, most attention in the energy analysis of electricity systems has focused on the work carried out by Chapman [1975], Chapman & Mortimer [1974], Price [1974] and others who studied the transient energy debts associated with assumed exponential growth of nuclear power systems. Chapman was concerned about the depletion of fossil fuel reserves and his earlier work expressed energy costs in terms of equivalent thermal energy units.

Price used Chapman's data to make an analytical study of the nuclear component of an electrical supply system. To handle the problem he assumed (i) a constant exponential growth rate (expressed in terms of the doubling time of the system (T_D), and (ii) a 'power ratio' (P_o/P_i)

TABLE 5

POWER REACTOR CHARACTERISTICS

[After OECD/NEA 1973]

	PWR	BWR	Magnox	AGR	SGHWR
Thermal Efficiency (%)	33	34	30	42	32
Average specific power in fuel (kW/kg heavy metal)	41	24	3.7	12.5	19.7
Fuel inventory (kg/MWe)	74	122.5	9.01	190.5	158.6
Initial Core					
Irradiation level (MWd/kg heavy metal)	24.4	21	*4(1)*	*18(1)*	*21(1)*
Fresh fuel enrich. (% ^{235}U)	2.63	2.2	Nat.	1.63	2.13
Spent fuel enrich. (% ^{235}U)	0.84(1)	0.75(1)	0.4(1)	0.81(1)	0.63(1)
Inventory kg nat. U/MWe	383	519	901	572	648
kg SWU/MWe (0.25% tails assay)	229	280	-	242	342
Pu(eq) produced(2) (g/MWe y)	346	296	595	181(1)	259(1)
Replacement Loadings					
Irradiation level (MWd/kg heavy metal)	33	27.5	4	18	21
Fresh fuel enrich. (% ^{235}U)	3.19	2.56	Nat.	2.23	2.11
Spent fuel enrich. (% ^{235}U)	0.84	0.75	0.4	0.81	0.63
Net consumption kg nat. U/MWe y	175	156	304	152	176
kg SWU/MWe y (0.25% tails assay)	138	114	-	109	118
Pu(eq) produced(2) (g/MWe y)	269	248	595	181	259
Operation time to reach equilibrium (y)	3	4	3	4	5

Notes:

(1) Put equal to equilibrium value.

(2) Allows for reprocessing losses and, where appropriate, for the decay of ^{241}*Pu. All plutonium figures are expressed in equivalent grams* ^{239}*Pu, i.e. in Pu(eq) for use in fast breeder reactors, applying the following 'worth factors': 239 x 1.00; 240 x 0.18; 241 x 1.53; 242 x 0.08.*

SWU = Separative work unit.

TABLE 6

HEAT OUTPUT (CALORIFIC VALUE) OF FOSSIL FUELS

(a) Data used in the present study

Fuel	Heat Output
Coal	27.1 GJ/t
Fuel Oil	44.0 GJ/t
Gas	38.7 GJ/1000 m^3

Source: *CEQ* [*1973*]: *Coal - Table A-1 note 9; fuel oil - Table A-4 notes 9 and 12; gas - Table A-7 note 5.*

(b) Data from World Energy Conference [1974]

Fuel	Heat Output
Coal	29.3 GJ/t
Crude (not fuel) oil	43.2 GJ/t
Gas	37.3 GJ/1000 m^3

Source: *World Energy Conference* [*1974*]: *Table IX-2.*

which was the ratio of the average annual energy output (P_o) of a power plant to the average energy investment per year (P_i) for a plant during construction. The components of the power ratio were defined as:

P_o = [Annual electricity output (at a capacity factor of 62 per cent)] - [electricity losses in distribution and use of electricity by the generation body] - [the sum of equivalent thermal energy for the replacement fuel (excepting enrichment)] - [electricity necessary to enrich replacement fuel],

and

P_i = [Equivalent thermal energy to build the reactor (including the initial core)] ÷ [building time (years)].

Two graphs by Price (Figures 2 and 3) typify the results of his analysis. Figure 2 shows the investment energy required per year as a function of the system doubling time for various power ratios and assuming an infinite plant lifetime. Figure 3 shows the time required for the

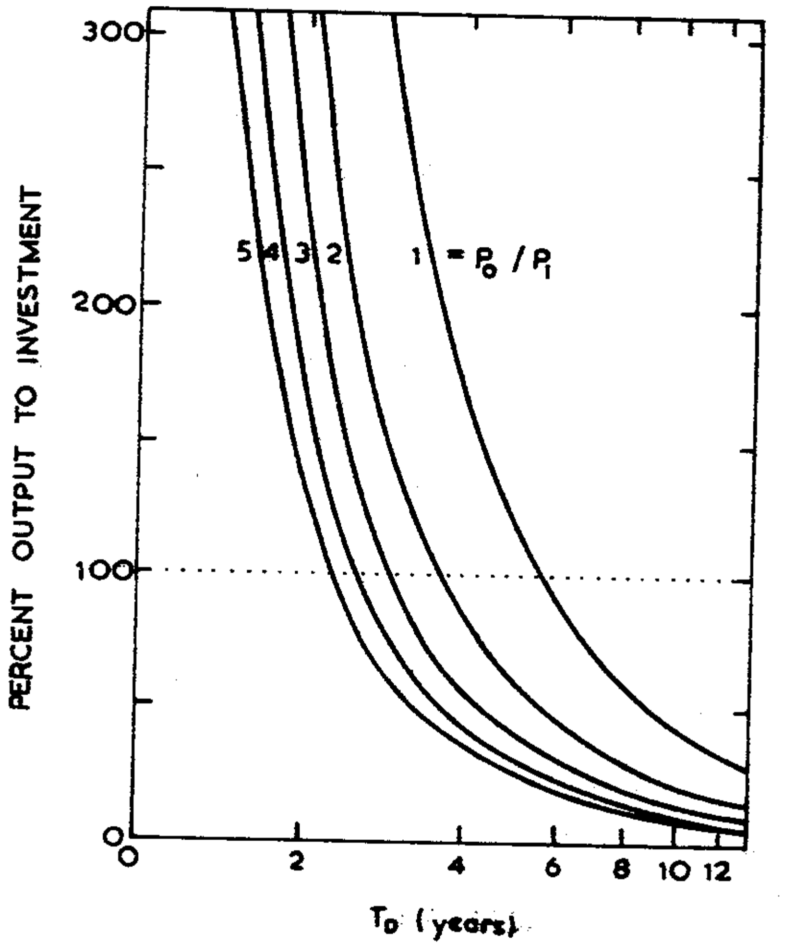

FIGURE 2 ENERGY/YEAR REQUIRED FOR INVESTMENT (AS A PERCENTAGE OF OUTPUT/YEAR) *vs* EXPONENTIAL DOUBLING TIME T_D, FOR VARIOUS VALUES OF P_o/P_i (AND INFINITE PLANT LIFETIME).

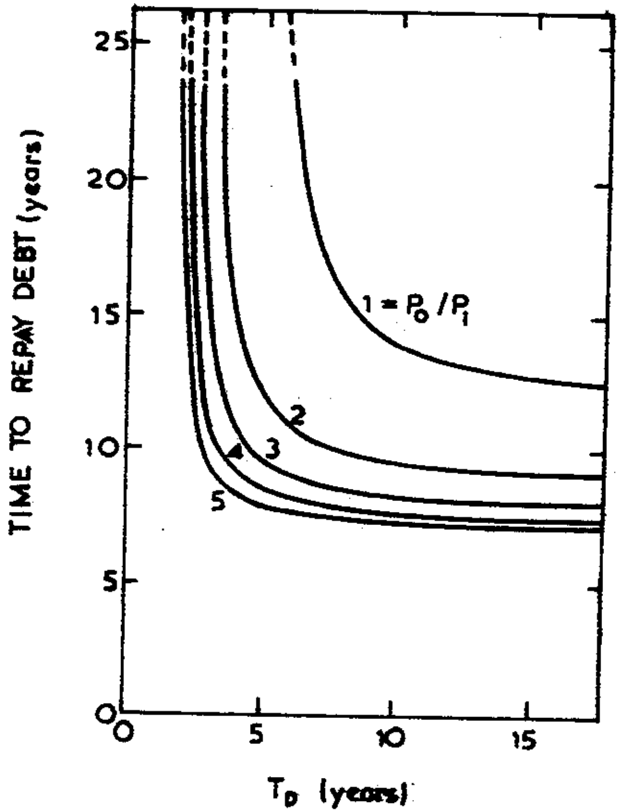

FIGURE 3 TIME BEFORE CUMULATIVE ENERGY DEBT IS REPAID, WITH ASSUMPTIONS AS IN FIGURE 1.

[After Price 1974: Figures 13 & 14]

system to repay the cumulative energy debt, also as a function of doubling time for various power ratios. *It should be noted that the time to repay the debt includes the time to build the first station (generally assumed to be five years plus about one year for testing and commissioning). It is not the time from the start of operation of the first station.*

It will be seen from Figure 2, that if the system installed capacity doubles every three years and $P_o/P_i = 2$, then the energy investment in building new stations is always more than the energy produced by the stations in operation. However, if the doubling time is six years and $P_o/P_i = 4$, there is a substantial surplus of power produced over that required for building. From Figure 3, it is clear that for the first case the system will always be in debt, whereas for the second case the system repays the debt some eight to nine years after starting work on the first station (or two to three years after commercial operation of the first station).

Price calculated that $P_o/P_i = 3.30$ for a PWR which implied that if the doubling time for a system made up of PWRs was 2.8 years or less, then the system would always be in an energy debt.

Although a number of criticisms have been made of Price's work on conceptual grounds [see Hill & Walford 1975a, 1975b; Wright & Syrett 1975; Brookes 1975], his analytical results could be used to check the numerical output from FURES. As a check, FURES was used to consider a nuclear system having doubling times of two to six years inclusive, with a capacity factor of 62 per cent.

The PWR in this investigation had a P_o/P_i of 4.0; however, this did not include an allowance for transmission losses, *etc*. The FURES ratio of 4.0 reduced to 3.5 when this factor was taken into account. In addition, information in the FURES databank was based on OECD reactor characteristics which slightly reduced the energy for the first core. Price assumed that the electricity utilised to provide the plant and initial core for a nuclear reactor originated entirely from fossil sources, hence the electrical component was added to the thermal component by applying a conversion ratio of 4:1 [see Price 1974]. On the other hand, the electricity *and* thermal energy needed to provide reload fuel were subtracted from the electrical output of the nuclear plant.

Chapman [1975] and Price [1974], when calculating the energy requirement for the initial capital investment for a nuclear plant, converted all construction and initial core electrical and thermal energies into equivalent thermal, and spread it evenly over the construction period of five years. Thus the inputs per year were 2.92 x 10^{12} J/MWe (plant construction) and 1.73 x 10^{12} J/MWe (initial core) making a total of 4.65 x 10^{12} J/MWe. The plant and initial core energies were combined into an equivalent thermal component for one run in FURES so that a comparison could be made with the Price results. Generally in FURES, the energy requirements for the initial core were placed in the year of occurrence. Thus the mining, milling and conversion services (5.34 x 10^{11} Jth/MWe), were placed in year four of construction whereas enrichment and fabrication services (8.12 x 10^{12} Jth/MWe), were placed in the last year of construction. The different schedules for energy investment are shown in Figure 4.

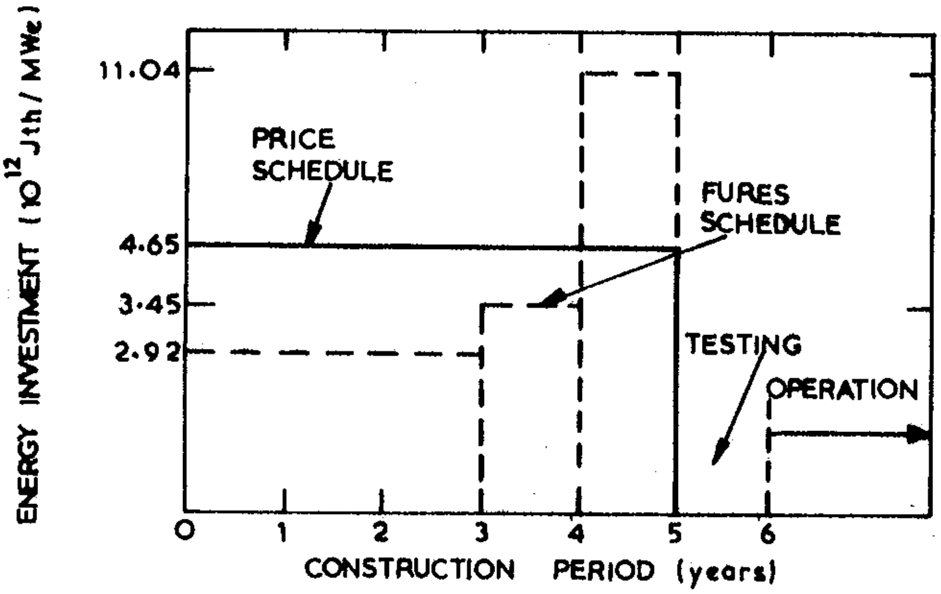

FIGURE 4 ENERGY INVESTMENT OVER CONSTRUCTION PERIOD

There are two other points at variance. In the Chapman/Price approach, the energy requirement for reload fuel was subtracted from the station electrical output without allowing for the necessary time delays, whereas FURES allows for the necessary delays. Further, the actual system expansion follows a step-function as used in the numerical analysis but is approximated by a continuous curve in Price's work. However, the variation in the comparative results caused by these factors would be minor.

To illustrate the effectiveness of a particular program, Price adopted the criterion of time taken for the program to become energy profitable (see Figure 3). Accordingly, a payback period was defined as the time taken for the cumulative electrical output to equal the cumulative electrical plus thermal input from the start of the construction period. Table 7 lists the payback period for systems having doubling times between two and six years for four cases. The first two rows give a comparison between the Price results and those from FURES based on the same assumptions, and it can be seen that the results for the payback period are in close agreement.

TABLE 7

PAYBACK PERIOD (YEARS)

	Doubling Time (years)				
	2	3	4	5	6
Price ($P_o/P_i = 4.0$)	∞	11.00	9.04	8.44	8.14
Plant/initial core thermal	>>30	11.4	9.2	8.6	8.3
All investments thermal	>>30	11.4	9.4	8.8	8.5
Electrical and thermal treated separately	13.2	8.2	7.6	7.4	7.2

Two other methods of handling the energy inputs are given to illustrate their effect on the results for these exponential systems. The first method assumed all inputs to be thermal (including such items as electricity for enriching reloads, which were not converted by Price) and a 4:1 conversion ratio was used to convert the electrical component to equivalent thermal energy (the third row of Table 7). The second treated all electrical and thermal components of the energy investments separately. The payback period in this case assumed that electrical and thermal requirements were met from an electricity 'bank' (*i.e.* no 4:1 ratio was involved). Generation from the system was then paid into the bank (no interest was charged) and set against the debt (the last row in Table 7).

A main criticism of nuclear programs by Price was that a large proportion of the electrical output needs to be reinvested in plant construction and provision of fuel (see Figure 1). He illustrated this by calculating the fraction of annual energy output (net of process inputs) which is required for reinvestment in the building program.

Table 8 shows this percentage for both the Price calculation and the various methods used to assign energy inputs in FURES. Some differences might be expected in the first two rows of the table, as the FURES calculation included time delays in the nuclear fuel cycle. Bearing this fact in mind, the results show good agreement.

TABLE 8

ANNUAL THERMAL ENERGY INVESTMENT AS PERCENTAGE OF ELECTRICAL OUTPUT

	Doubling Time (years)				
	2	3	4	5	6
Price (P_o/P_i = 4.0)	164.6	68.5	41.0	28.7	21.9
Plant/initial core thermal	172.2	71.6	43.0	30.3	23.3
All investments thermal	147.7	76.0	53.7	43.3	37.3
Electrical and thermal components treated separately	91.3	35.6	21.1	14.8	11.4

The above method of calculating the reinvestment percentage unduly penalises the electrical component, because a significant portion of the thermal investment is, in fact, electrical energy (*e.g.* electricity for enriching the initial core) which has been converted to thermal energy using the ratio 4:1. This energy could be accounted for directly from the electrical output.

TABLE 9

ANNUAL ELECTRICAL ENERGY INVESTMENT AS PERCENTAGE OF GROSS ELECTRICAL OUTPUT

	Doubling Time (years)				
	2	3	4	5	6
Electrical and thermal components treated separately	18.2	11.1	8.6	7.4	6.7
Plant/initial core thermal	5.5	4.9	4.6	4.5	4.4

An alternative criterion is the fraction of the electrical output which is reinvested as electricity since this will indicate the amount of nuclear electrical output necessary to support the program. Table 9 illustrates this measure for the two cases of treating all energy investments separately, and taking the plant/initial core as thermal only.

5. SYSTEMS STUDIED (0.3 PER CENT URANIUM ORE)

For the basic study a number of systems were examined, namely those of Japan, USA, UK, OECD-Europe and the World. The various cases considered for these systems are listed in Table 10. The assumptions for growth in these electricity systems are outlined in Appendix A. Essentially, all systems consist of a nuclear, a hydro and a conventional component. The nuclear and hydro portions are given and the conventional steam plant capacity and production (either coal or oil) make up the system total. In general, the plant and production before 1972 were based on United Nations [1972, 1974] statistics, but after this time, simple projections were made in accordance with the assumptions listed in Appendix A. The expansion with time for different plant in the various systems is shown in Figures 5 to 10. For the Japanese and World systems, the nuclear sector was taken to comprise PWRs only. Fast breeder reactors were not included in this study because of the uncertainty regarding their eventual introduction. In addition, their contribution by the year 2000 was expected to be small. The average nuclear capacity factor for all systems after 1972 was assumed to be 70 per cent, except for the World case where a figure of 65 per cent was adopted.

5.1 Nuclear Sector

The first yardstick used to illustrate the performance of the systems was the payback period. This has been defined in Section 4 and is only applied here to the nuclear portion of the systems. The payback period is shown in Table 11 for all systems examined. For just the nuclear portion of the system, Table 12 lists the total energy production and investment to year 2000.

The percentage of nuclear electricity production which must be reinvested to provide nuclear plant and fuel will be high in the initial stages of the nuclear program but gradually decrease as the rate of expansion of this sector diminishes. This must necessarily happen when the nuclear component is the major part of the system. In all cases, there is a net cumulative electrical output in year seven, that is the year that the first nuclear plant comes on line. Table 13 lists the electrical investment in the nuclear program as a percentage of the total nuclear electricity production.

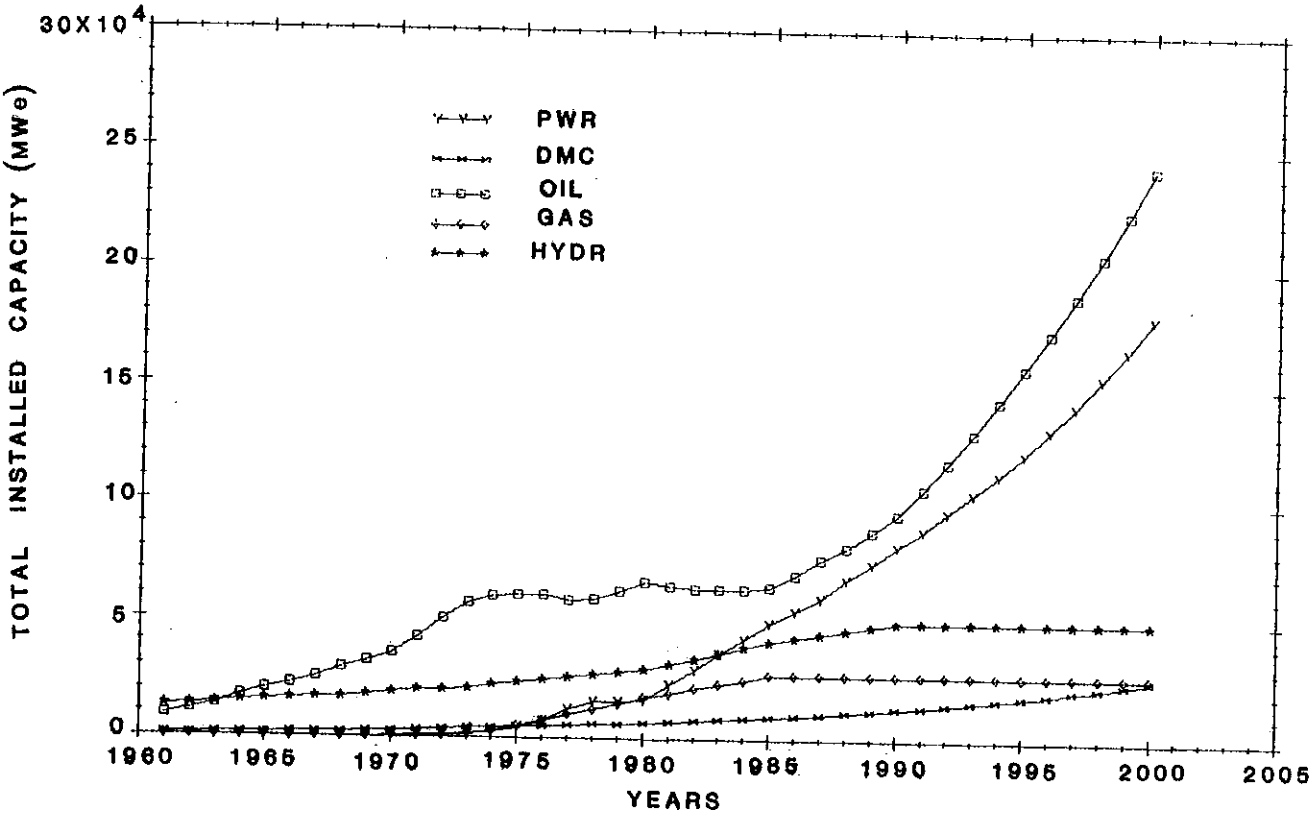

FIGURE 5 INSTALLED CAPACITIES FOR JAPAN

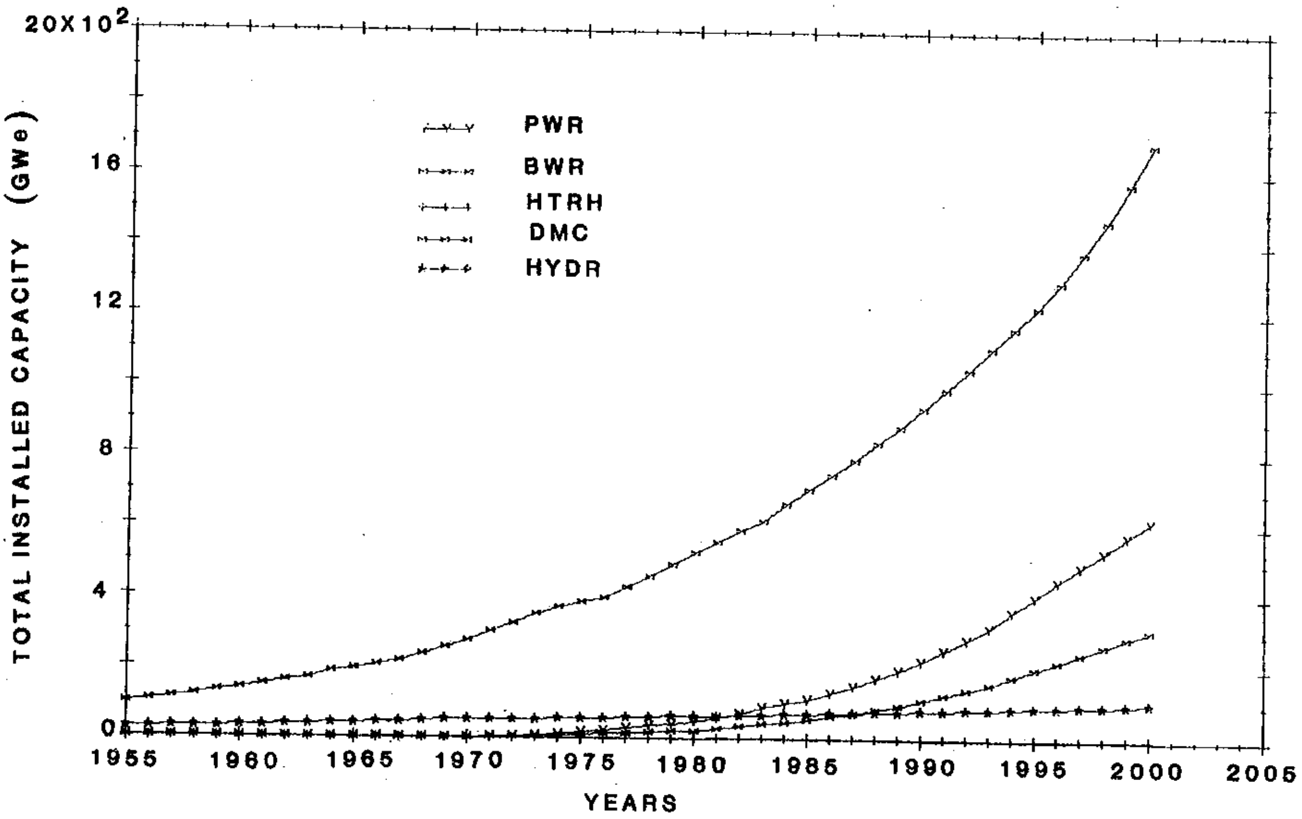

FIGURE 6 INSTALLED CAPACITIES FOR UNITED STATES

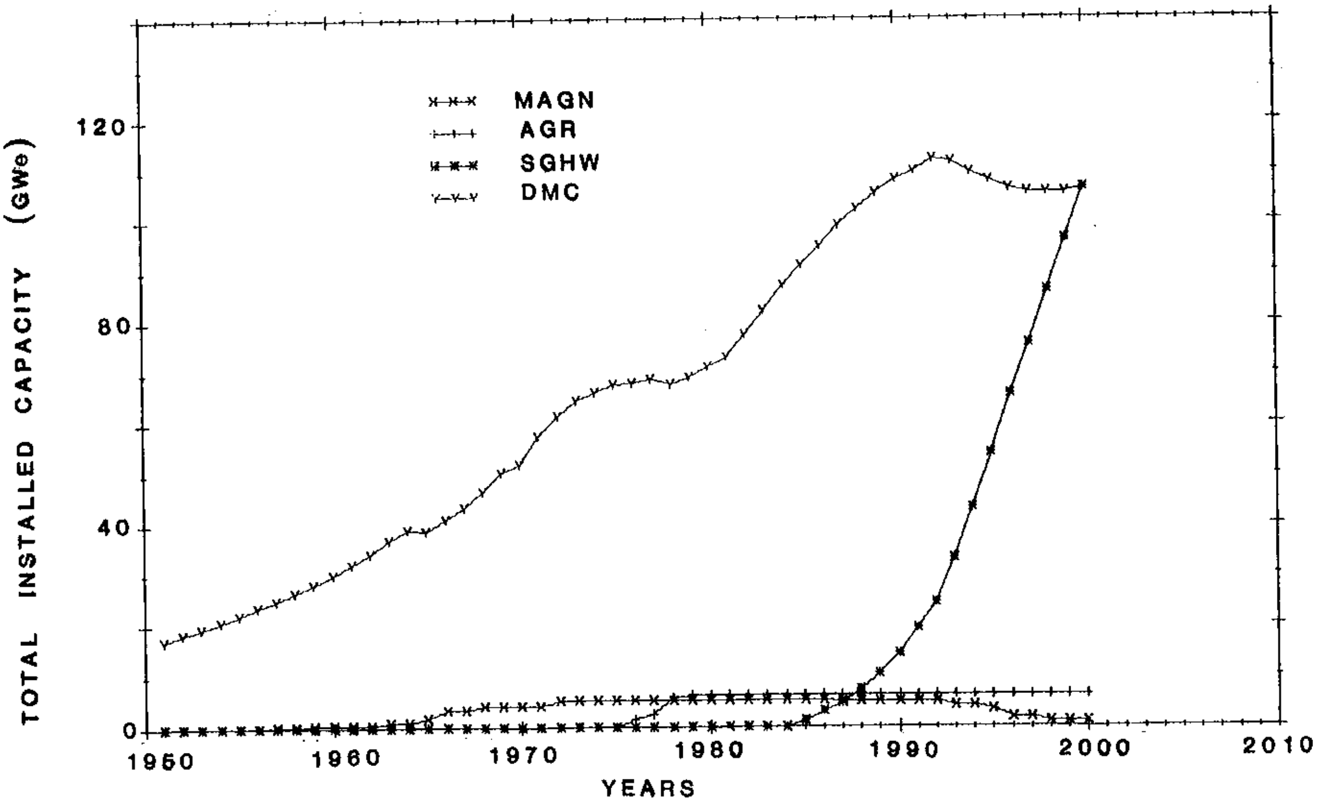

FIGURE 7 INSTALLED CAPACITIES FOR UNITED KINGDOM

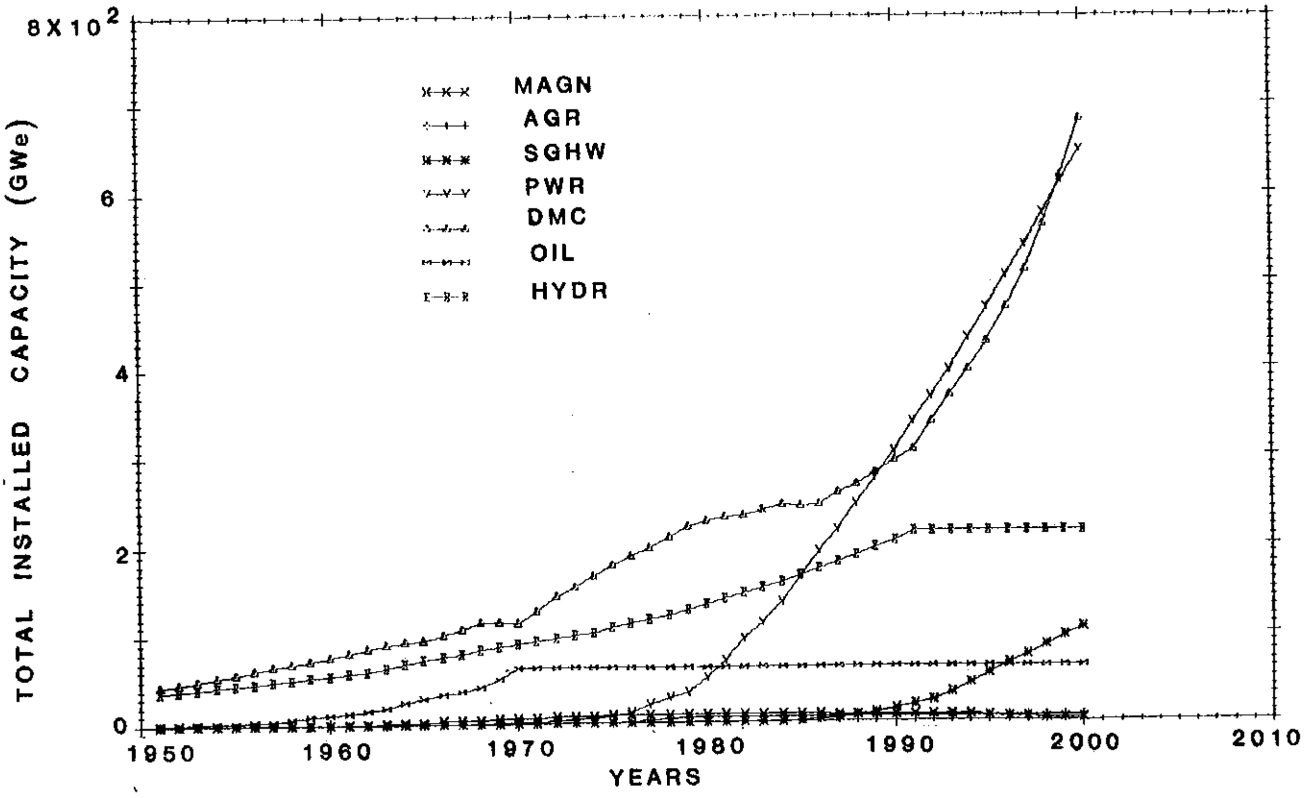

FIGURE 8 INSTALLED CAPACITIES FOR OECD-EUROPE

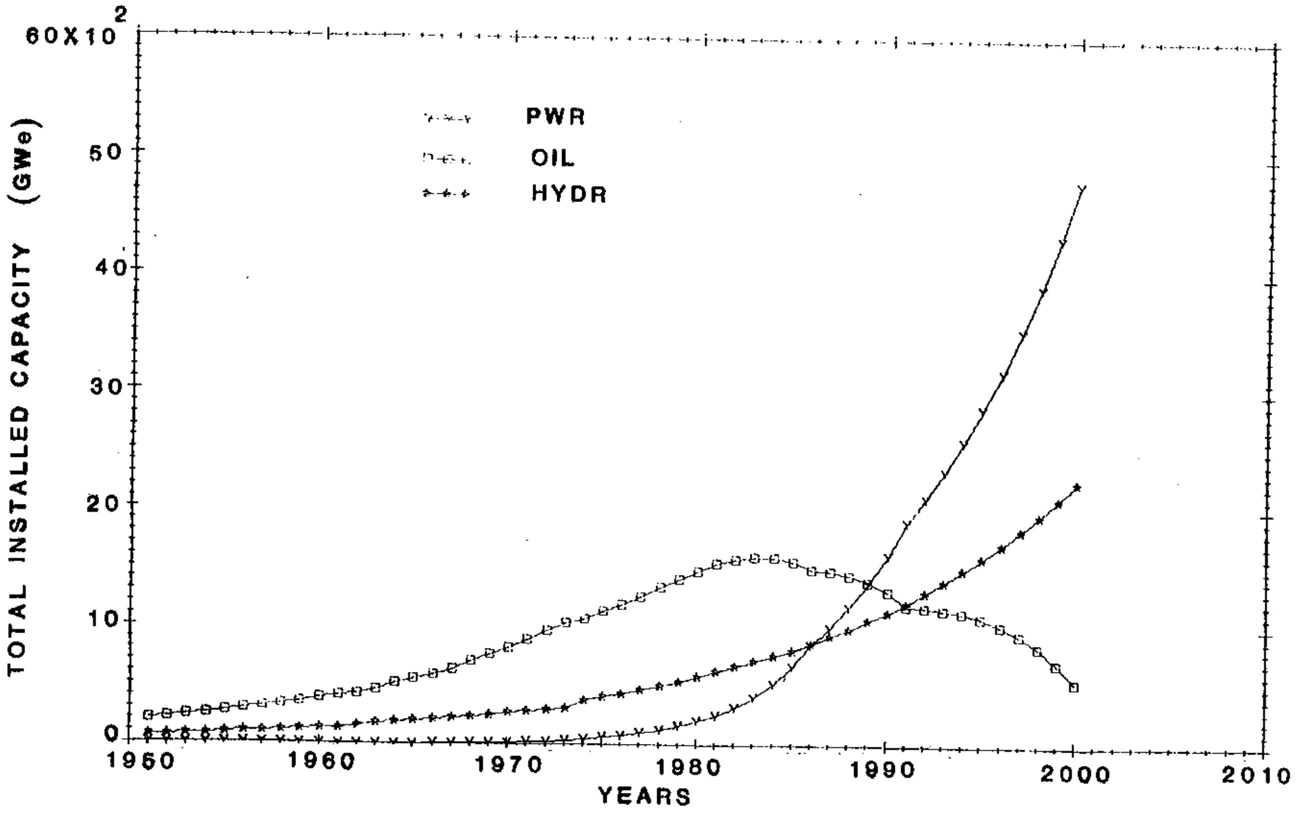

FIGURE 9 INSTALLED CAPACITIES FOR WORLD - NUCLEAR HIGH

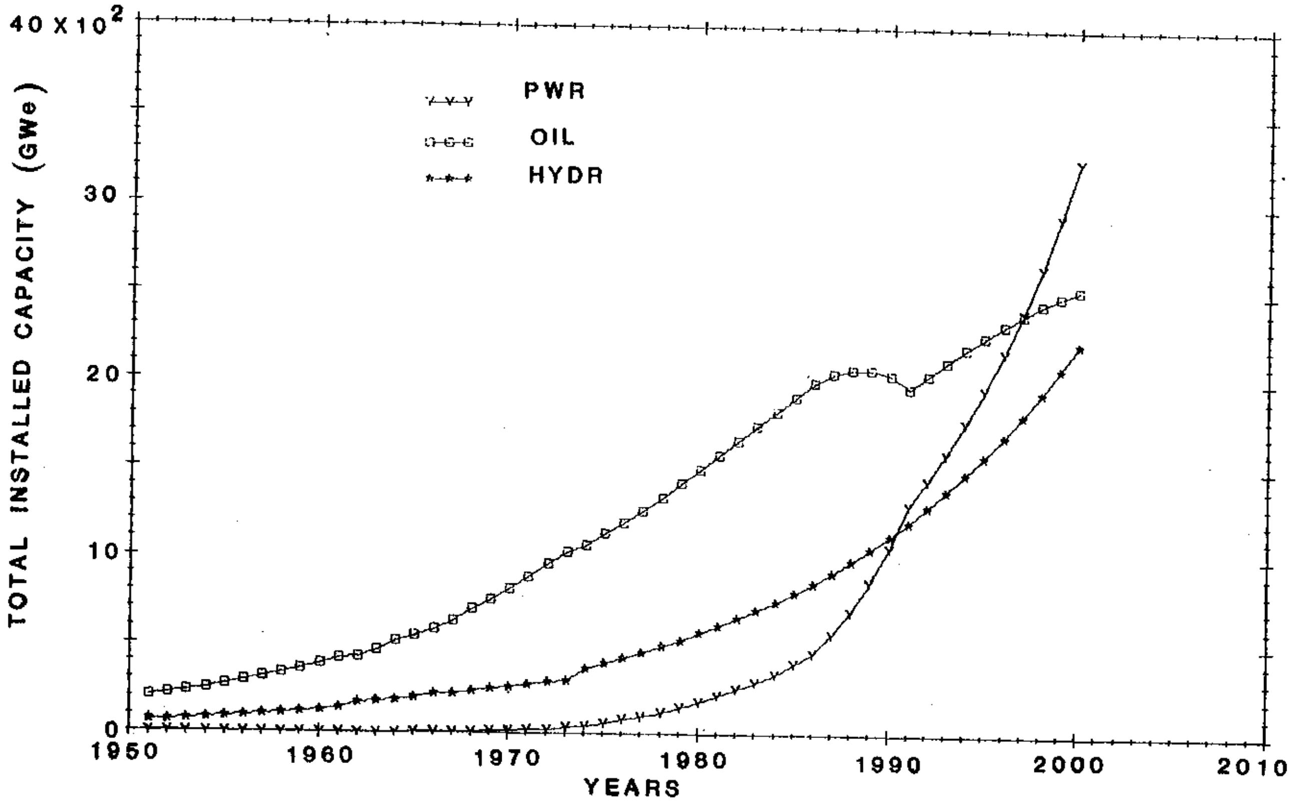

FIGURE 10 INSTALLED CAPACITIES FOR WORLD - NUCLEAR LOW

TABLE 10

CASES EXAMINED

System	Ore Grade (%)		Station Mix
Japan	0.3 and 0.007	1	Nuclear only (PWR)
		2	Coal, oil and hydro
		3	Nuclear, coal, oil and hydro
USA	0.3	1	Nuclear only (PWR, BWR)
		2	Coal and hydro
		3	Nuclear, coal and hydro
UK	0.3	1	Nuclear only (Magnox, AGR, SGHWR)
		2	Coal only
		3	Nuclear and coal
OECD-Europe	0.3	1	Nuclear only (PWR, Magnox, AGR,SGHWR)
		2	Coal, oil and hydro
		3	Nuclear, coal, oil and hydro
World	0.3	1	Nuclear (low) only (PWR)
		2	Oil and hydro
		3	Nuclear (low), oil and hydro
		4	Coal and hydro
		5	Nuclear (low), coal and hydro
		6	Nuclear (high) only (PWR)
		7	Nuclear (high), oil and hydro
		8	Nuclear (high), coal and hydro

TABLE 11

PAYBACK PERIOD FOR NUCLEAR PORTION (YEARS)

System	Years to Repay Debt from Start of Construction
Japan	12.4
United States*	17.3
United Kingdom	13.2
OECD-Europe	13.8
World	13.6

** The US program first showed a net energy output after 8.5 years. However, it went into debit in year 13, before becoming a permanent net producer after 17.3 years.*

TABLE 12

CUMULATIVE PRODUCTION AND INVESTMENT TO YEAR 2000 FOR NUCLEAR PORTION

(EJ: 10^{18} J)

	Thermal Investment	Electrical Investment	Electrical Production
Japan	2.8	2.4	40
United States	14.7	11.5	196
United Kingdom	3.0	1.3	21
OECD-Europe	13.0	10.1	175
World (low)	54.3	37.1	563
World (high)	79.9	54.1	832

TABLE 13

ELECTRICAL INVESTMENT IN THE NUCLEAR SYSTEM AS PERCENTAGE OF TOTAL NUCLEAR ELECTRICITY PRODUCTION

Year	Japan	USA	UK	OECD-Europe	World (low nuclear)	World (high nuclear)
7	11.0	20.6	7.3	8.7	25.5	25.5
10	14.5	9.2	12.5	13.2	22.2	22.2
15	11.6	27.0	0.7	2.0	13.2	13.2
20	10.5	12.7	1.3	4.8	14.3	14.3
30	5.9	7.2	2.2	9.6	7.9	11.2
40	5.1	5.8	8.7	5.8	6.9	6.6
50	-	-	5.5	4.9	5.7	5.7

The extra investment in year 40 for the British program corresponds to the initial stages of a proposed large SGHWR program. (This program has now been abandoned.)

5.2 Total System

A comparison can be made for each system assuming that firstly each consists solely of conventional plants and then a combination of nuclear plus conventional plants. Table 14 lists the total production and investment to year 2000 for both cases as well as the cumulative thermal savings made by substituting the conventional plus nuclear system for the conventional only system. As the required electrical investment increases when this substitution is made, the final column allows for this by subtracting four times the extra electrical investment from the thermal savings. It should be noted that the thermal investment includes the fuel burnt in conventional stations.

The conventional portion of most systems is generally a mixture of oil- and coal-fired plant. Because of the difficulty in allocating the proportion of production to each fuel, arbitrary assumptions concerning the fossil fuel used for each system were made. For the World system, oil was taken as the sole fossil fuel and these results are shown in Table 14. However, a secondary study was made with coal substituting for oil to determine if this had any appreciable effect on the results. The plant energy investment for the coal- and oil-fired plants was taken to be the same so the only difference was in supplying the fuel. For oil, 0.128 joules of thermal energy is required to provide 1 joule of fuel, whereas for coal the corresponding figure is 0.0274 joules. Thus, in the World (low nuclear) case the total thermal investment decreased from 5104 EJ* to 4656 EJ, that is 8.8 per cent, in going from oil to coal. However, the adjusted thermal savings for the conventional plus nuclear system decreased from 1661 to 1498 EJ, that is 9.9 per cent; hence, the percentage savings in the two cases were virtually the same at 32.6 per cent for oil and 32.2 per cent for coal.

Finally, Table 15 shows a comparison of the electrical investment in each system as a percentage of the gross electricity produced when the system consists of conventional plant only, and then the assumed conventional and nuclear mix.

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* 1 EJ = 1 exajoule = 10^{18} J.

TABLE 14

CUMULATIVE PRODUCTION, INVESTMENT, SAVINGS

(EJ = 10^{18} J)

	Japan		USA		UK		OECD-Europe		World (low nuclear)		World (high nuclear)	
	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear
Total electrical investment	0.512	2.71	1.88	12.54	0.23	1.46	1.73	11.13	8.7	42.6	8.7	58.7
Total thermal investment	323	207	1524	955	188	128	989	480	5104	3307	5104	2450
Total electricity produced	119		556		63		400		2068		2068	
Thermal savings	116		569		60		509		1797		2654	
Adjusted* thermal savings	107 (33.3%)		526 (34.5%)		55 (29.3%)		471 (47.6%)		1661 (32.6%)		2454 (48.1%)	

* *Figure in brackets is net savings as a percentage of total thermal investment for conventional only case.*

Adjusted thermal saving = thermal saving - 4.0 x (Electrical investment for case considered - electrical investment for conventional only)

TABLE 15

ELECTRICAL INVESTMENT AS PERCENTAGE OF PRODUCTION

Year	Japan		USA		UK		OECD-Europe		World (low nuclear)		World (high nuclear)	
	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear	Conv. only	Conv. plus nuclear
7	0.67	0.70	0.39	0.43	0.52	0.58	0.53	0.55	0.52	0.52	0.52	0.52
10	0.47	0.59	0.42	0.44	0.47	0.62	0.55	0.58	0.51	0.53	0.51	0.53
15	0.36	0.92	0.40	0.58	0.47	0.52	0.45	0.49	0.46	0.54	0.46	0.54
20	0.40	1.71	0.33	0.99	0.27	0.37	0.39	0.53	0.48	0.65	0.48	0.65
30	0.46	2.64	0.42	2.10	0.40	0.83	0.42	2.09	0.43	1.14	0.43	1.44
40	0.35	2.72	0.34	3.04	0.39	2.57	0.45	3.46	0.43	2.34	0.43	3.22
50	-	-	-	-	0.28	4.27	0.34	3.45	0.33	2.83	0.33	4.02

By comparing Tables 13 and 15, it can be seen that in the initial stages of the nuclear program, the electrical production from nuclear plants was largely reinvested in the nuclear program. This had little effect on the system as a whole as the nuclear sector comprised only a small part of the overall system. It is only when the nuclear capacity becomes significant that the reinvestment percentage has substantially increased but, by this time, the system has a considerable thermal saving.

Figures 11 to 16 illustrate the energy production and investment for the Japanese system. All systems studied behaved in the same way. They showed that although more energy is required for investment in the conventional and nuclear case than in the conventional only case (Figures 11, 12, 14), the total fossil fuel requirement is much higher in the latter case (Figure 13).

6. SENSITIVITY ANALYSIS

6.1 Range of Variables

There are many factors in an energy accounting study which are uncertain, basically for two reasons. The first is the obvious difficulty in predicting far into the future such things as growth rates, capacity factors, and the share of each fuel in the system. Even after 'fixing' a system of nuclear plus conventional plants, there would be considerable disagreement concerning the likely capacity factor at which the base load nuclear plant will operate.

Another source of uncertainty is the estimation of the energy inputs required to provide plant and fuel as well as their division into electrical and thermal components. The variables having the largest effect for nuclear systems are the plant capital investment and the energy for enrichment. The electrical component of the enrichment energy predominates in the calculation of the energy requirements for the nuclear fuel cycle.

The Japanese system was used to examine the sensitivity of the results to changes in these values. Table 16 lists the base values and the variations considered for each factor. It has been suggested that once the high grade uranium ore is exhausted, the need to utilise the lower grade ore will have adverse effects on energy accounting for nuclear systems. To investigate this possibility, an ore grade of 0.007 per cent was investigated. The final variation considered was to regard

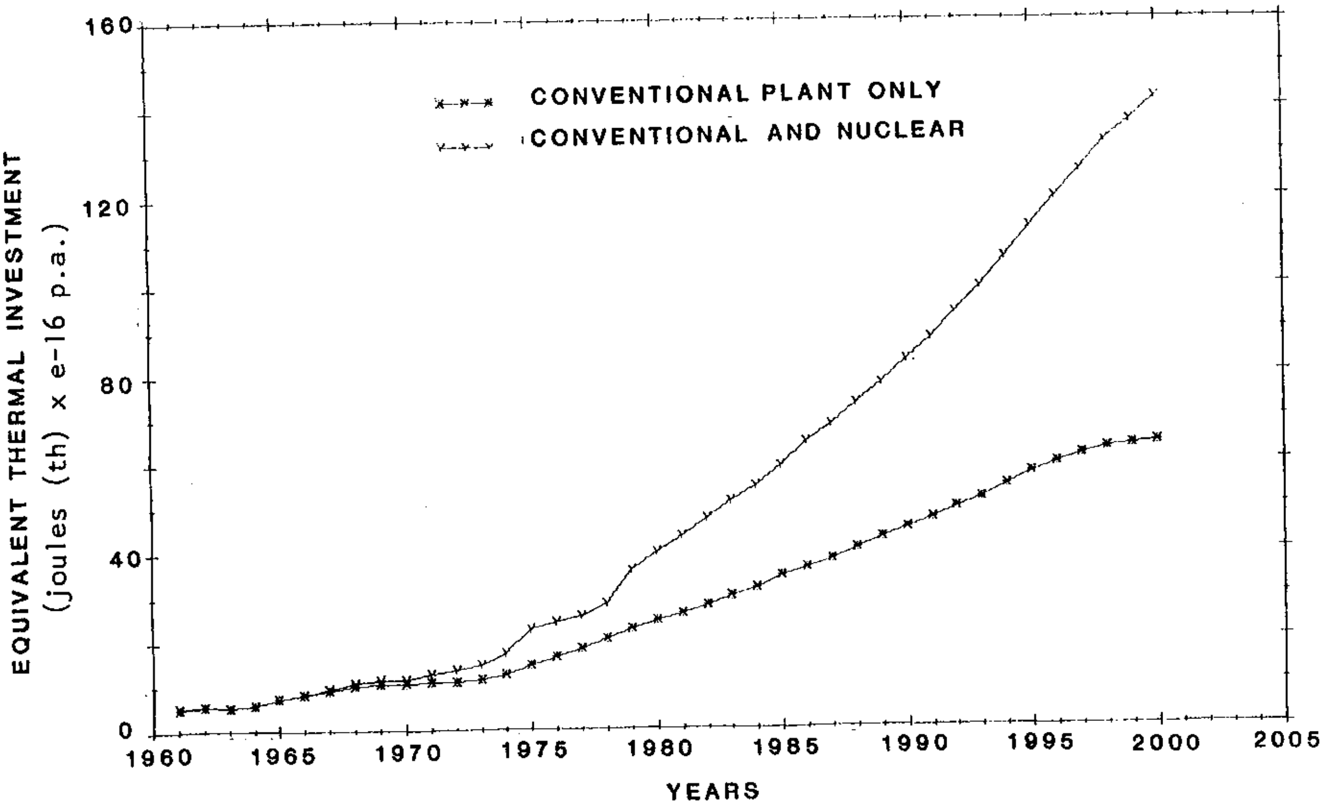

FIGURE 11 EQUIVALENT THERMAL INVESTMENT

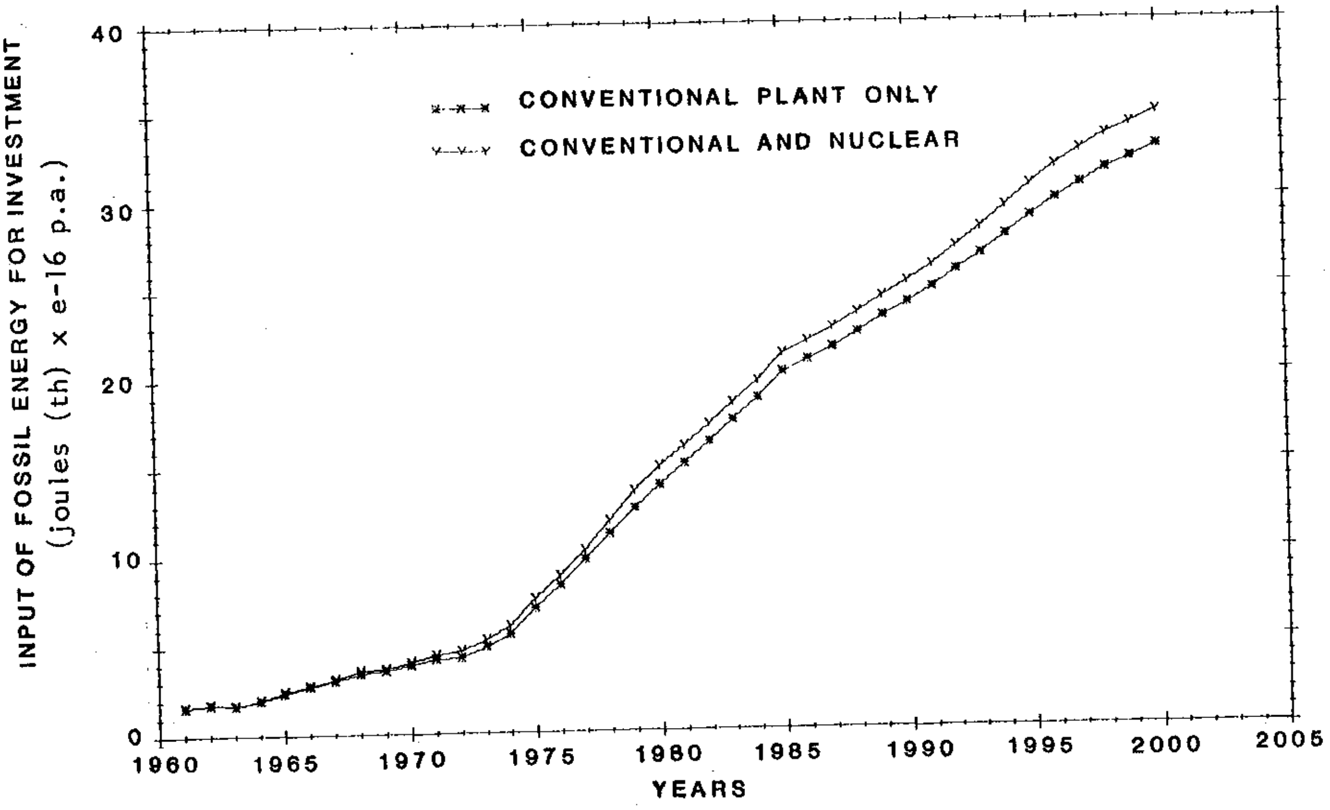

FIGURE 12 ANNUAL FOSSIL REQUIREMENTS FOR INVESTMENT

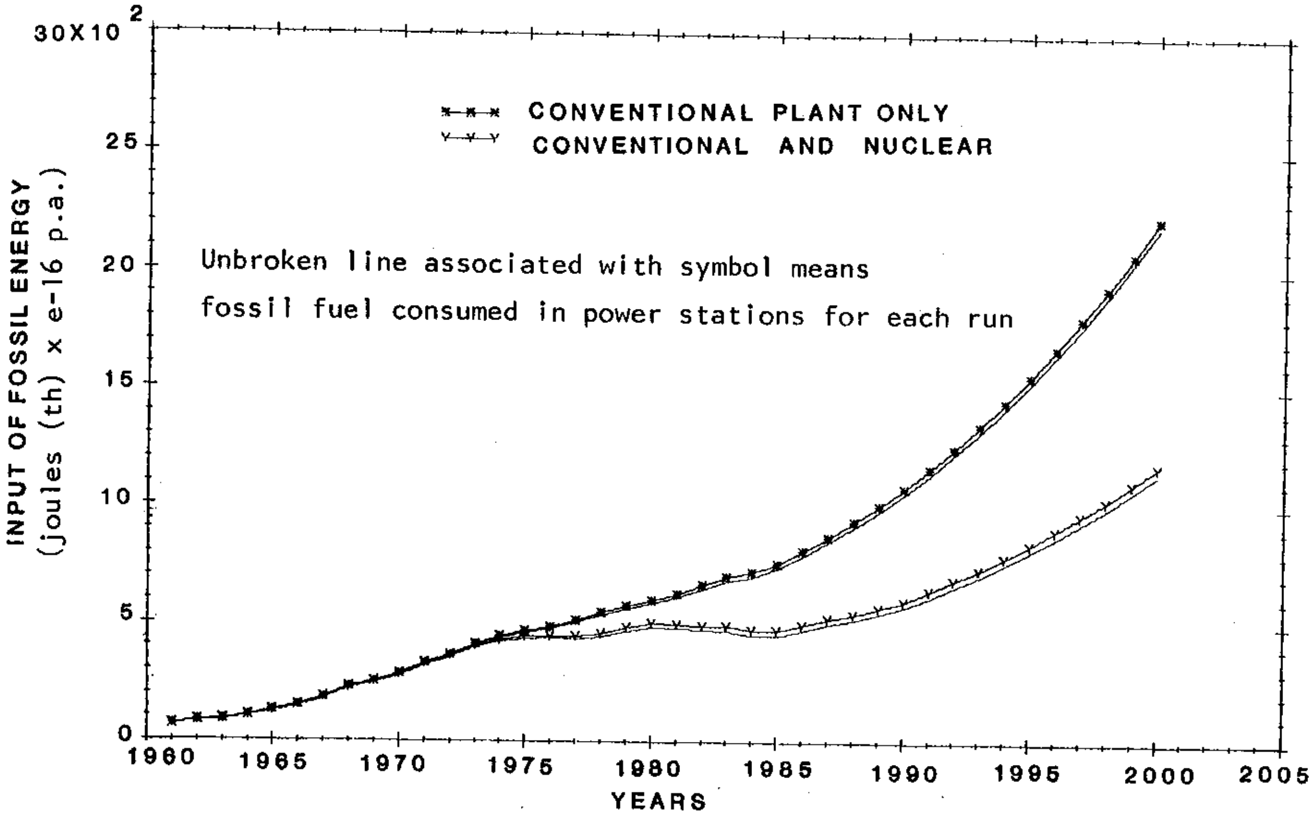

FIGURE 13 ANNUAL FOSSIL FUEL REQUIREMENTS

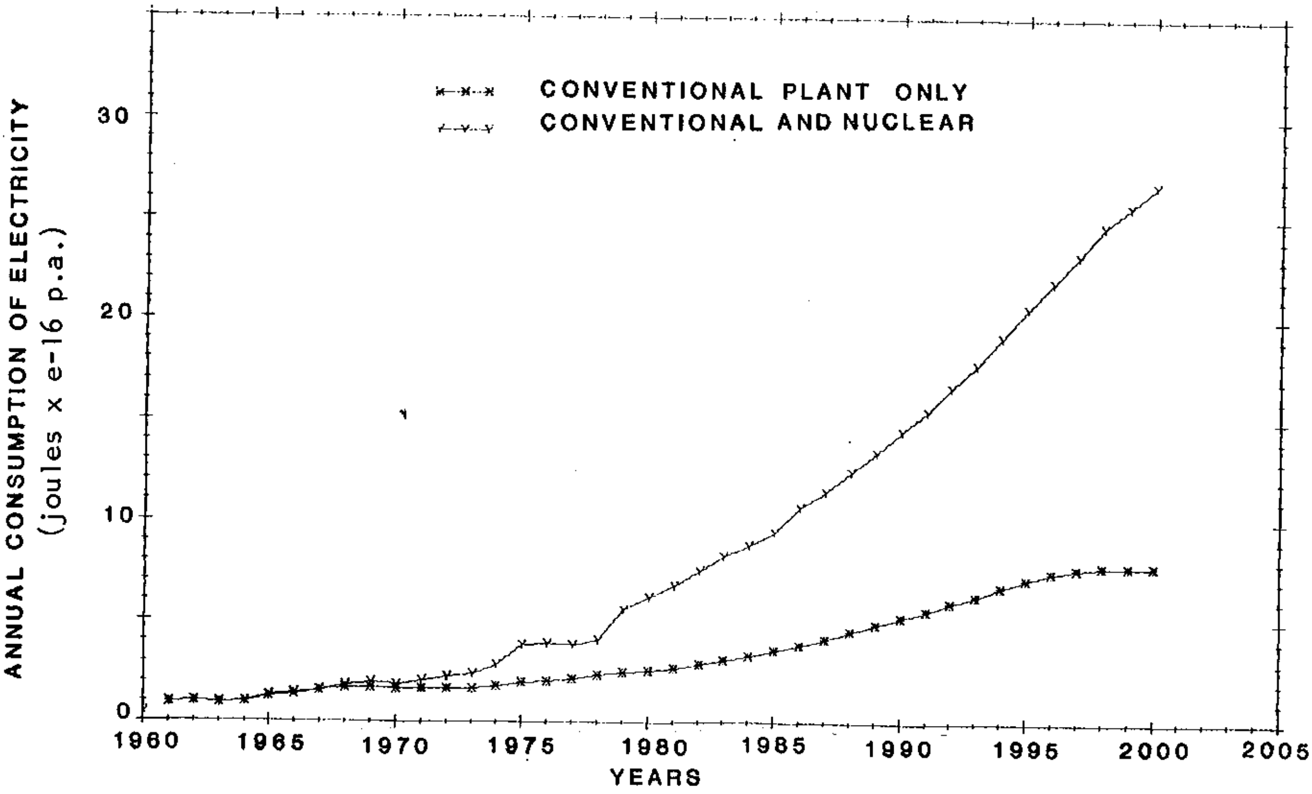

FIGURE 14 ELECTRICAL REQUIREMENTS FOR PROVISION OF CAPITAL AND FUEL

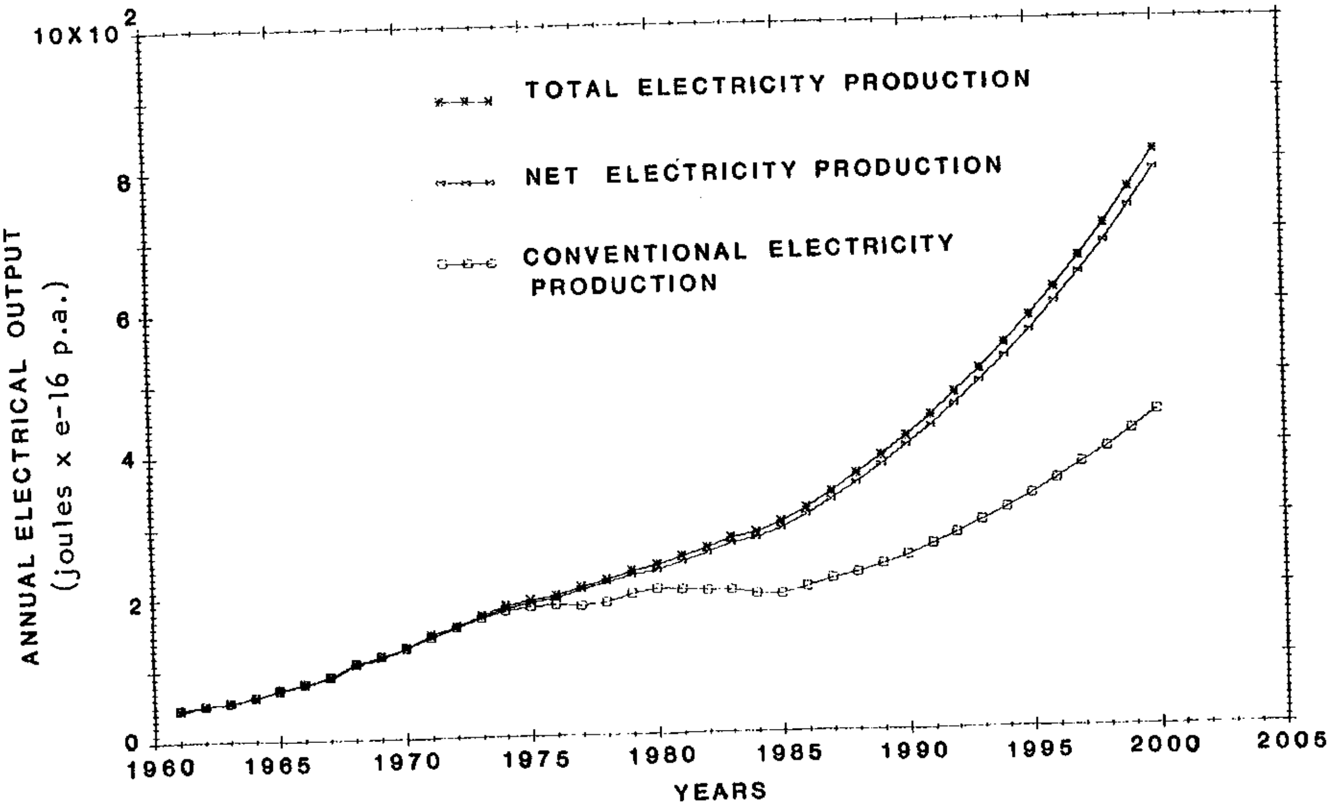

FIGURE 15 ELECTRICAL OUTPUT FOR CONVENTIONAL AND NUCLEAR SYSTEM

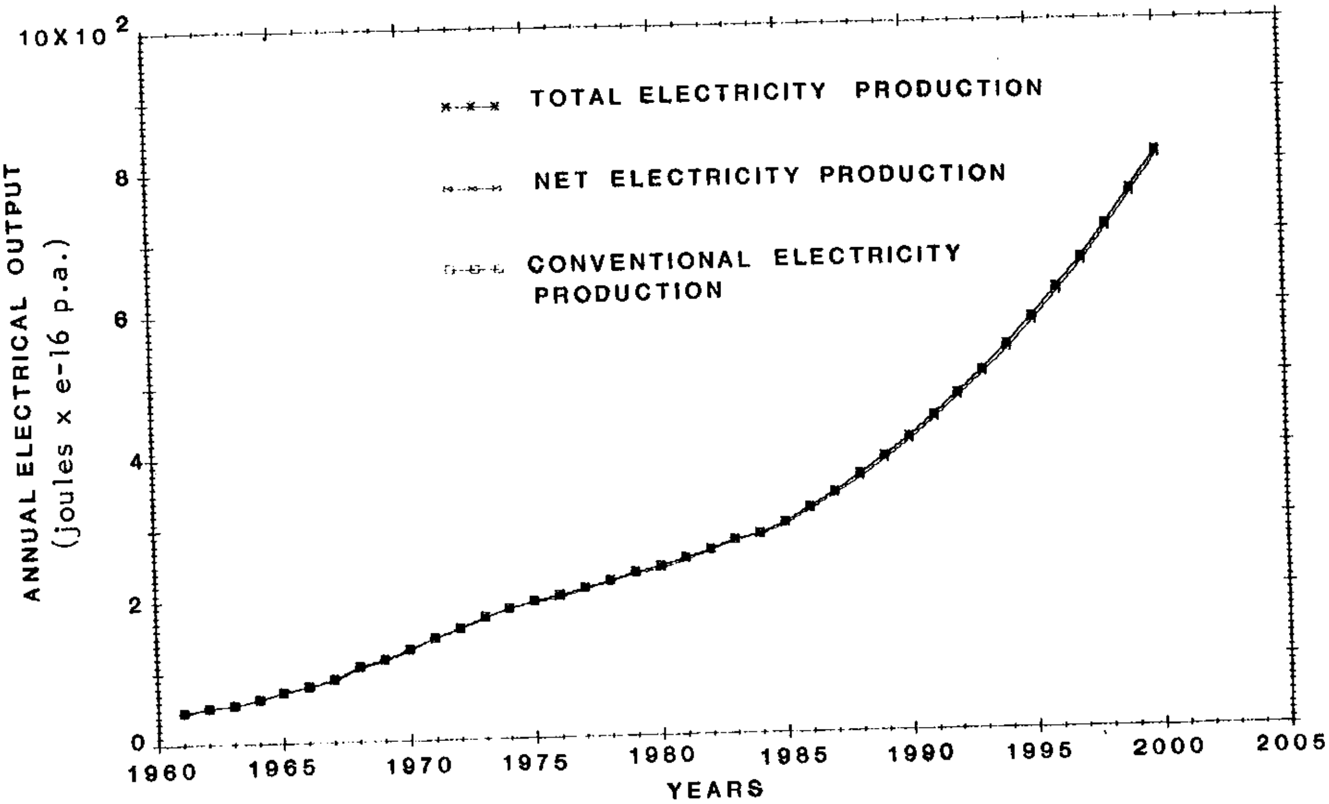

FIGURE 16 ELECTRICAL OUTPUT FOR CONVENTIONAL PLANT ONLY

all energy inputs as thermal by applying a conversion ratio of 4:1 to the electrical component since this maximises the energy inputs.

TABLE 16

FACTORS CONSIDERED IN SENSITIVITY ANALYSIS

Item	Base Value	Variations
Nuclear capacity factor	70%	60%, 80%
Uranium ore grade	0.3%	0.007%
Nuclear plant investment		
Electrical	9.73×10^{11} J $(MWe)^{-1}$	+20%
Thermal	107.1×10^{11} J $(MWe)^{-1}$	
Enrichment energy		
Electrical	8.712×10^{12} J $(tSWU)^{-1}$ *	±20%
Thermal	3.456×10^{11} J $(tSWU)^{-1}$	
Energy inputs	Division into electrical and thermal components - Chapman [1975] fuel cycle energy inputs	All inputs thermal Plant/initial core thermal USAEC [1974a] fuel cycle energy inputs
Nuclear penetration	35%	50%

* *J $(tSWU)^{-1}$ = joules per tonne separative work unit.*

6.2 Capacity Factor

Table 17 shows the variation in the payback period with changing nuclear capacity factor (CF). Two cases with 0.3 per cent ore were considered. Firstly, the electrical and thermal investments were kept separate and then the plant/initial core was taken as thermal. In addition, two further cases, corresponding to the first two but with 0.007 per cent ore, were considered. (In other parts of this report, historical values for production up to 1972 were used. However, the capacity factors listed in this section were assumed to apply throughout the study period.) Varying the capacity factor by ±14 per cent produced variations in the payback period in the range ±4-7 per cent.

TABLE 17

VARIATION IN PAYBACK PERIOD WITH NUCLEAR CAPACITY FACTOR (YEARS)

	Capacity Factor		
	60%	70%	80%
Investment separate (0.3 per cent ore)	14.0	13.1	12.2
Plant/initial core thermal (0.3 per cent ore)	22.9	21.6	20.0
Investment separate (0.007 per cent ore)	17.8	16.9	16.2
Plant/initial core thermal (0.007 per cent ore)	25.4	23.9	22.8

Taking the preservation of fossil fuels as a criterion, the effectiveness of a particular program can be measured by the thermal savings accruing to a nuclear plus conventional system when compared to an all conventional system. For varying nuclear capacity factors, Tables 18a and 18b list these savings for the period to 1985 and 2000 respectively. The percentage savings when compared to the all fossil case are shown in brackets. A similar allowance to that shown in Table 14 is made here to account for the extra electrical investment required in the nuclear plus conventional mix case.

It can be seen from Tables 18 and 19 that changes in the nuclear capacity factor from the base of 70 to 60 and 80 per cent (*i.e.* a variation of approximately ±14 per cent about the base value) causes changes of 1.8 and 4.8 per cent in the adjusted thermal savings to years 1985 and 2000 respectively (*i.e.* variations of approximately ±14 per cent about the base case results).

6.3 Variations in Energy Data

Tables 19a and 19b illustrate the effect on the thermal savings of various assumptions concerning the overall level of energy investment and division of that energy, as stated in Table 16.

It is apparent from Tables 19a and 19b that the cumulative adjusted thermal savings are virtually unaffected by moderate changes in the level of energy investment for the nuclear system. The reason for this is that the extra investment is small compared with the large savings

TABLE 18a

CUMULATIVE THERMAL SAVINGS TO YEAR 1985 FOR VARIOUS NUCLEAR CAPACITY FACTORS (10^{19} J)

Nuclear Capacity Factor	Thermal Investment	Thermal Savings (a)	Net Electrical Output	Adjusted Thermal Savings (b)
Conventional only case	10.142		3.973	
60%	8.494	1.170 (11.5%)	3.945	1.058 (10.4%)
70%	8.285	1.379 (13.6%)	3.937	1.235 (12.2%)
80%	8.089	1.575 (15.5%)	3.934	1.419 (14.0%)

TABLE 18b

CUMULATIVE THERMAL SAVINGS TO YEAR 2000 FOR VARIOUS NUCLEAR CAPACITY FACTORS (10^{19} J)

Nuclear Capacity Factor	Thermal Investment	Thermal Savings (a)	Net Electrical Output	Adjusted Thermal Savings (b)
Conventional only case	32.31		11.86	
60%	21.54	9.94 (30.8%)	11.67	9.18 (28.4%)
70%	19.85	11.63 (36.0%)	11.64	10.75 (33.3%)
80%	18.19	13.29 (41.1%)	11.61	12.29 (38.0%)

(a) *Percentage savings when compared to all conventional cases in brackets.*

(b) *Thermal saving minus four times extra electrical investment when compared to the all conventional case. Percentage savings in brackets.*

Adjusted thermal saving = Thermal saving -4 x (elec. investment for case considered - elec. investment for conventional only)

= Thermal saving -4 x (net elec. output for conventional only - net elec. output for case considered).

TABLE 19a

CUMULATIVE THERMAL SAVINGS TO YEAR 1985 WITH VARIATIONS IN ENERGY DATA (10^{19} J)(a)

	Thermal Investment	Thermal Savings	Net Electrical Output	Adjusted Thermal Savings
Conventional only	10.142		3.973	
Base nuclear case	8.760	1.382 (13.6%)	3.937	1.238 (12.2%)
Nuclear plant investment increased 20%	8.775	1.367 (13.5%)	3.936	1.219 (12.0%)
Enrichment up 20%	8.760	1.382 (13.6%)	3.931	1.214 (12.0%)
Enrichment down 20%	8.760	1.382 (13.6%)	3.944	1.266 (12.5%)
All inputs thermal	8.972	1.240 (12.1%)(b)	3.990	1.240 (12.1%)
0.007% ore	8.878	1.264 (12.5%)	3.882	0.900 (8.9%)
Nuclear high case	8.763	1.379 (13.6%)	3.935	1.227 (12.1%)
USAEC [1974a](c) coefficients	8.167	1.364 (14.3%)	3.930	1.216 (12.8%)

(a) See footnote Tables 18a and 18b.

(b) Percentage saving compared to the all conventional case with all inputs thermal = 10.212 x 10^{19} J.

(c) Compared to conventional only: Thermal investment = 9.531 x 10^{19} J
Net electrical output = 3.967 x 10^{19} J.

TABLE 19b

CUMULATIVE THERMAL SAVINGS TO YEAR 2000 WITH VARIATIONS IN ENERGY DATA (10^{19} J)(a)

	Thermal Investment	Thermal Savings	Net Electrical Output	Adjusted Thermal Savings
Conventional only	32.31		11.86	
Base nuclear case	20.68	11.63 (36.0%)(b)	11.86	10.75 (33.3%)
Nuclear plant investment increased 20%	20.73	11.58 (35.8%)	11.63	10.66 (33.0%)
Enrichment up 20%	20.69	11.62 (36.0%)	11.60	10.58 (32.7%)
Enrichment down 20%	20.68	11.63 (36.0%)	11.68	10.91 (33.8%)
All inputs thermal	21.77	10.74 (33.0%)(b)	11.91	10.74 (33.0%)
0.007% ore, base case	21.37	10.94 (33.9%)	11.32	8.78 (27.2%)
Nuclear high case	18.00	14.31 (44.3%)	11.57	13.15 (40.7%)
USAEC [1974a](c) cofficients	19.50	11.48 (37.1%)	11.61	10.56 (34.1%)

(a) See footnote Tables 18a and 18b.

(b) Percentage saving compared to the all conventional case with all inputs thermal = 32.51 x 10^{19} J.

(c) Compared to conventional only: Thermal investment = 30.98 x 10^{19} J
Net electrical output = 11.84 x 10^{19} J.

which have already been derived from the substitution of fossil-fired plants by nuclear installations. When the base nuclear case is changed from supply of ore at 0.3 per cent U_3O_8 to supply of ore at 0.007 per cent, the cumulative adjusted saving to the year 1985 falls from 1.238 to 0.900 x 10^{19} J (a drop of 27 per cent). The corresponding fall to the year 2000 is from 10.75 to 8.78 x 10^{19} J (a drop of 18 per cent). The effect of using the lower grade (and more energy intensive) ore is reduced towards the end of the program because the nuclear portion constitutes a large part of the overall system and so gives a large saving in fossil fuel.

7. DISCUSSION

7.1 Input Data

Firstly, some comments should be made on the input data used. The main purpose of the present study was to examine the energy effectiveness of nuclear programs in actual systems, with particular reference to the effect on fossil fuel consumption, as well as to examine the consequences on the different sources of energy such as the fossil and uranium fuels. The results are mainly a comparison between the various energy requirements for the proposed nuclear plus conventional program and an otherwise all conventional program. No attempt was made to optimise the installation pattern in either an economic or an energy sense. Rather, the proposed expansion programs of the various countries were used for the nuclear plus conventional mix, with coal and oil being substituted for nuclear plant in the all conventional program. Arbitrary assumptions were made concerning the division of fossil plant into oil- and coal-fired, but these had virtually no effect on the results — as illustrated for the World system in Section 5. This is because the plant investment energy was assumed to be the same in both cases, so that the only difference in energy consumption was the provision of either the coal or oil for fuel. Since this quantity is a relatively minor part of the total energy consumption, the difference between using coal and oil is negligible. It is recognised that for some systems, other energy forms may be incorporated in the medium- to long-term future, *e.g.* geothermal energy in Japan, but as these could not be accurately estimated, and in any case were thought to be small, they were ignored.

7.2 Total System

The most obvious result from the study is that all the proposed nuclear programs show a large saving in fossil fuel consumption. This is true in the long-term, as evidenced in Table 8 where the cumulative adjusted savings for the nuclear mix programs to year 2000 vary from 30 to 48 per cent compared to the all conventional cases. It is also true in the medium-term; for example, the adjusted thermal savings to the year 1985 were 12 per cent for the Japanese program (Table 18a). On an annual basis, the adjusted savings for the Japanese program were -0.2 per cent in 1965 (the last year of construction of the first plant), 5.5 per cent in 1975, 30.8 per cent in 1985 and 47.3 per cent in 2000. This result is hardly surprising when it is remembered that the nuclear program is not being considered in isolation but as part of an electricity generating system. The nuclear portion substitutes for a fossil fuel program which is a prolific consumer of fossil energy.

The equivalent thermal energy required to build a nuclear station and provide the initial core, 23.25 TJ/MWe (equivalent thermal), is more than twice that for a coal-fired plant, *i.e.* 10.71 TJ/MWe. The equivalent thermal energy required each year to supply the fuel follows a similar pattern, *i.e.* 5.13 TJ/MWe y and 2.47 TJ/MWe y respectively for nuclear and coal plant. However, the coal plant consumes an extra 90.10 TJ/MWe y of thermal energy as fossil fuel each year to produce the electricity. Thus over a 25 year lifetime, the coal plant will consume about 14 times the amount of fossil fuel as a nuclear plant (based on a capacity factor of 70 per cent) as shown below.

EQUIVALENT LIFETIME THERMAL ENERGY REQUIREMENT

TJ per MWe

	Coal	Nuclear (PWR)
Construction	10.71	14.60
Initial core	-	8.65
Refuelling (70% CF, 25 y life)	43.25	89.78
Fossil fuel burnt	1576.75	-
Total	1630.69	113.03

$$\text{Ratio} \quad \frac{\text{Coal}}{\text{Nuclear}} = \frac{1631}{113} = 14.4$$

Price [1974] agrees with this conclusion when he states that "nuclear power can show a fossil-fuel profit when compared to a fossil-fuelled industry which is a prolific net consumer of energy."

A strict energy analysis should, of course, take into account the energy content of the uranium used in nuclear reactors. Energy is not created by man but is converted from potential to usable forms. The major emphasis so far has been placed on fossil fuels for several reasons:

(i) It is the relatively imminent depletion of fossil fuel resources which is of main concern coupled with the fact that our current energy technology is based almost entirely on fossil fuels.

(ii) Nuclear fuels unlike fossil fuels have no apparent use other than as an energy source. Nuclear power unlocks a vast resource of energy (*e.g.* through fast breeder reactors) even though it may be inefficient in a strict energy accounting sense. Fossil fuels are also used as feedstock to the chemical industry.

(iii) The difficulty in assigning a value to the energy consumption in the nuclear fuel. Uranium, which is used today for PWR fuel, may be used again in the future as FBR fuel. This is quite unlike fossil fuels which can only be used once.

Thus in all energy accounting studies of nuclear power published so far, no allowance has been made for the energy content of the uranium. Attention has centred on the consumption of fossil energy and the above discussion has demonstrated that in this sense the nuclear programs are very profitable indeed.

7.3 Nuclear Portion of the Overall System

Until now we have discussed the nuclear program as part of the overall system. Consider the nuclear portion in isolation. As a measure of the performance of a nuclear system, Price [1974] introduced a payback period which is defined as the time taken for the program to repay the cumulative energy investment. This definition does not distinguish between thermal and electrical energy forms and is thus dependent to a large extent on the energy accounting convention used. This is illustrated in Table 17, which shows how the payback period varies for different nuclear capacity factors and different ore grades based on the proposed Japanese nuclear program. For example, it can be seen that the payback period for 0.3 per cent ore and a 70 per cent nuclear capacity factor increases from 13.1 years if the energy investments (*i.e.* electrical and thermal) are kept separate, to 21.6 years if the plant and initial core are expressed in equivalent thermal energy units.

Chapman [1975], Price [1974] and others justify this latter convention by claiming that the electricity requirement for reload fuel can be provided out of the nuclear electricity production. But the electricity for the original plant construction and initial core must be provided from the existing fossil fuel-burning system where a 4:1 conversion ratio for the electrical component applies. This convention can be challenged on several grounds. Firstly, while it is true that the building energy for the first few nuclear stations must come from fossil sources, there is no reason why the electricity required for later plants cannot come from the nuclear program once it is a net producer of electrical energy. In fact, this condition invariably applies during the first year of operation of the first nuclear plant. The second reason is that most national systems have a large hydro component and the ratio of 4:1 applicable to the British system (which has virtually no hydro) cannot be justified on a worldwide scale.

Table 8 illustrates this same dependence on convention for another measure which is frequently used – that of annual thermal energy investment as a percentage of net electrical output. It is seen that a vastly different picture emerges if the electrical and thermal energy components for the plant and initial core are treated separately rather than combined into an equivalent thermal component.

7.4 Energy Investment

It has already been demonstrated that large thermal savings accrue to an electricity system if there is a significant nuclear component. Consider the electrical energy required to build the plant. Table 13 shows that in the early part of most nuclear programs, the fraction of electrical output which has to be reinvested for the program is generally greater than ten per cent. On the other hand, the electrical reinvestment for present conventional programs is less than one per cent (Table 15). Table 15 also illustrates that in the early stages of the conventional plus nuclear program the reinvestment percentage increases, but is still less than one per cent and it is only in later years, when the nuclear portion forms a large part of the electricity system, that the percentage increases to three to four per cent. Of course, by this time, large thermal savings have accrued to the system. It should be noted that this extra electrical investment has been allowed for by subtracting four times the extra electrical investment (when compared to the all conventional program) from the thermal savings to obtain an 'adjusted thermal savings'. At present, the losses in transmission, distribution and use by the generating authority account for about 12 per cent of the power generated (for the UK, see Chapman & Mortimer [1974]), so the increased electrical demand for investment would have only a small effect.

7.5 Payback Period

Finally, reverting to the question of the payback period, the Japanese system with 0.007 per cent ore becomes energy profitable within 25 years of the start of construction of the nuclear program (see Table 17). The average doubling time over this period is 2.25 years which, according to Price [1974], should lead to an infinite payback period. Tabulated below are the average doubling times in five year intervals for the Japanese program:

AVERAGE DOUBLING TIMES FOR JAPANESE SYSTEM

Year	Installed Capacity (MWe - start of year)	Average Doubling Time (years)	
7 (1967)	160		
10	510	1.79	2.25
15	4537	1.59	
20	15 000	2.90	
25	41 000	3.45	
30 (1990)	75 000	5.47	

It is seen that the doubling time is initially very short, but by the 1980s it increases considerably. Once this slowing down occurs, the nuclear program rapidly becomes energy profitable even in the sense of the Price definition. It must be remembered that the energy investment for construction in any year depends on the plants coming on line from two to six years in the future.

From Price's results (Figures 2 and 3) it can be seen that in the range of P_o/P_i values, in which nuclear reactors generally lie (namely two to four), the results are extremely sensitive to the doubling times in the region of two to three years. Although in the period up to 1975 the nuclear installation rate of many national systems had doubling times less than two years, this period corresponded to the introduction of the first few plants into the systems. In fact, the current proposed doubling times for the OECD countries in the period 1975-1990, which will be critical in judging the effectiveness of thermal nuclear programs, vary from 2.8 to 6.4 years with only France (2.8 years), Italy (2.9 years) and Spain (2.9 years) having less than a three year doubling time. Of the major industrialised countries, the US has a proposed doubling time of 4.6 years and Japan 4.3 years. The overall figure for the OECD is 4.1 years.

If a period of four to five years is taken as the reference doubling time, the P_o/P_i ratio can be reduced to about two without any problems of energy profitability arising, in the Price sense. Expressed another way, this means that Price would agree that nuclear programs having doubling times of four to five years and a P_o/P_i ratio of, say, greater than three will be energy profitable. However, it must again be stressed that even programs which are unprofitable (according to the Price definition) will still give a considerable saving in fossil fuel and could be considered to be worthwhile on this basis.

7.6 Changes to Building Programs

In the recent past, many countries have modified their proposed building programs for power stations in response to rapidly changing, and generally worsening, economic conditions. The principal effect has generally been a drastic cut in the programs to reflect perceived lower economic growth rates. Since building times are some 7-12 years, and the firm commitments already entered into were based on high growth expectations, the resultant new building growth rates are below the economic growth rates to compensate for the near-term overshoot.

As a result of these changes, the building programs used in this work overestimate the probable installed capacity. Although these changes lower the cumulative totals, the trends still remain the same for the projected programs.

8. CONCLUSIONS

This analysis of the amount and type of energy used in electrical power systems has covered three main aspects. These involved

(i) assessing the energy used to build and run various types of power station;

(ii) verifying that the results of the numerical analysis reproduced the analytical work by Price [1974]; and

(iii) extending the analysis to actual systems in terms of their historical and projected installation program.

The major conclusion from (i) was that despite some variation in the estimates from different workers, a consensus is emerging on the energy values for building and running power stations. More work is needed to increase the accuracy but the prevailing estimate is that the values given in Table 2 represent capital energy costs within ±20 per cent. There is broad agreement on the energy costs required to supply and process the fuel and dispose of waste (radioactive wastes or fly ash). However, the major component of the nuclear fuel cycle (enrichment) is accurately known.

Agreement was excellent between the results for a nuclear system using the numerical model and Price's analytical study. Minor differences were the result of assigning a different timetable to energy input for the initial reactor core in the numerical model.

Considering only the nuclear component in real electricity systems, all of them moved from an energy deficit to a rapidly rising credit. In most cases, the payback time was about 13 years after construction was started on the first nuclear station.

An examination in detail of the early part of the nuclear component of real systems emphasises the dangers of taking smoothed values of doubling times and using Price's analytical results to determine whether or not a system will be an energy debtor. Short pauses in the program which do not markedly change the doubling time have a major effect on energy debt since reactors produce energy at a massive rate. This situation emphasises Price's remark "Thus the [my] analysis is indicative rather than definitive, and is not a substitute for detailed simulation in any particular case." [Price 1974, section 4, para.28.]

A system of mixed nuclear and fossil-fuelled power stations uses less fossil fuel than the same size system made up only of fossil fuel stations. If the nuclear component is high, then the savings are high. Table 14 shows that for the World low nuclear case a cumulative thermal saving of 1800 EJ is made to the year 2000. This is a significant fraction of the known World recoverable reserves of 4360 EJ of oil and 15 080 EJ of coal [Inst. Eng. Aust., Working Party 1, 1977].

This work demonstrates that nuclear reactors and nuclear power systems are not energy debtors. In fact, after they have paid back their initial construction debt they are strongly positive energy contributors and offer a powerful means of extending the World's fossil fuel reserves.

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APPENDIX A

BASIS OF PROJECTION

Japanese System			
Component	Years	Basis of Projection	Source
Total system capacity	1961-1973	UN statistics	United Nations [1972,1974]
	1974-1985	MITI*	Based on newspaper report *Nikon Keizai* 13 July 1975, p.4.
	Beyond 1985	Annual growth 6.96%	Average of previous five years
Hydro capacity	1961-1973	UN statistics	United Nations [1972,1974]
	1974-1985	Interpolation of MITI values	Based on newspaper report *Nikon Keizai* 13 July 1975, p.4.
	Beyond 1985	Extrapolation to 49.6 GWe in 1990, thereafter constant	All plant operating, under construction or planned - World Energy Conf. [1974]
Natural gas	1974-1985	Interpolation of MITI values	Based on newspaper report *Nikon Keizai* 13 July 1975, p.4.
	Beyond 1985	Held constant at 1985 value	
Nuclear (low) capacity	Up to 1973	Actual from UN statistics	
	1974-1975	Planned installations	*Nuclear News* [1975]
	1976-2000	Pacific region OECD/NEA	OECD-NEA/IAEA [1976]
Nuclear (high)	Beyond 1985	Extrapolation to 50% of total installed capacities in 2000	
Oil plus coal capacity		Evaluated to provide the remainder	
Oil capacity	Before 1972	From percentage production OECD figures	OECD [1972,1974]
	1973-1974	At 1972 level	
	Beyond 1974	Equal to 1970 level - *i.e.* 210 x 10^9 kWh.	

**MITI = Ministry of International Trade & Industry (Japan).*

OECD-Europe System

Component	Years	Basis of Projection	Source
Total system capacity	1961-1973	UN statistics	United Nations [1972,1974]
	Before 1961	Extrapolation of 1961-1973 values	
	After 1973	Interpolation of values from *Nuclear News*	*Nuclear News* [1975]
Hydro capacity	1961-1973	UN statistics	United Nations [1972,1974]
	1974-2000	Extrapolation to 216 GWe then constant	Theoretical hydro capacity for Europe - World Energy Conf. [1974]
Nuclear capacity	Before 1975	Actual installations	*Nuclear News* [1975]
	After 1975	Planned installations	OECD-NEA/IAEA [1976]
Oil plus coal capacity		Evaluated to provide remainder	
Oil capacity	1954-1970	Based on percentage of production by oil	OECD [1972,1974]
	Before 1954	1954 value (4.4%)	
	After 1972	Oil consumption equal to 1970 value	

World System

Component	Years	Basis of Projection	Source
Total system	1951-1961	Extrapolated backwards at 7.7% per annum	Average for next 12 years - United Nations [1972,1974]
	1962-1973	UN statistics	United Nations [1972,1974]
	1974-2000	Interpolation of IAEA values	IAEA [1975]
Hydro capacity	1962-1973	UN statistics	United Nations [1972,1974]
	Other years	27% of the total installed capacity	Average percentage of total 1962-1973
Nuclear capacity	1951-1961	Actual installations	*Nuclear News* [1975]
	1962-1973	UN statistics	United Nations [1972,1974]
	1974-2000	Interpolation of IAEA values	IAEA [1975]

US System

Component	Years	Basis of Projection	Source
Total system capacity	1955-1973	UN statistics	United Nations [1972,1974]
	1974-2000	USAEC projection	USAEC [1974c]
Hydro capacity	1955-1973	UN statistics	United Nations [1972,1974]
	1974-2000	Annual growth 2.5%	NPC [1973b] (pumped storage not included)
Nuclear capacity	Up to 1984	Actual and planned installations	*Nuclear News* [1975]
	1985-2000	OECD/NEA projections with new plant divided PWR/BWR = 2/1	OECD-NEA/IAEA [1976]
Coal capacity		Evaluated to provide remainder (deep mined)	

UK System

Component	Years	Basis of Projection	Source
Total system capacity	1961-1973	UN statistics	United Nations [1972,1974]
	1951-1960	Extrapolation of 1961-73 values	
	1974-1991	Interpolation of values from *Nuclear News*	*Nuclear News* [1975]
	1992-2000	Extrapolation of previous values	
Nuclear capacity			
Magnox		Actual installations (plant retired after 30 years)	*Nuclear News* [1975]
AGR		Actual and planned installations	*Nuclear News* [1975]
SGHWR		OECD/NEA projection minus Magnox and AGR	OECD-NEA/IAEA [1976]
Coal capacity		Evaluated to provide remainder (deep mined)	