AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

PERSPECTIVES IN ENERGY REQUIREMENTS OF MANKIND

by

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ABSTRACT

The growth of energy demand from the nineteenth century to the present and its likely future development are described, for the interested layman, in the context of the changing pattern of resource use. The availability and distribution of the renewable and non-renewable resources of energy, which will provide for the future, show that developed and developing countries will incur supply problems in the decades ahead unless the potential of all energy reserves is tapped. Factors such as the market penetration of new resources and the depletion of resources are outlined. It is pointed out that coal may be used increasingly for some time but that nuclear energy is the only other energy form which is immediately available and which can be utilised commercially. Nuclear energy will be needed even if countries are prepared to cut back to low growth rates in energy use. It is suggested that lower growth rates may well be necessary in the next twenty to thirty years, since it takes this time to bring new alternative technologies into commercial use, and a further similar period will be required to achieve significant resource substitution.

National Library of Australia card number and ISBN 642 99699 7

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COMPARATIVE EVALUATIONS: ENERGY SOURCES: FOSSIL FUELS: GEOLOGIC DEPOSITS: MARKET: NUCLEAR ENERGY: SOLAR ENERGY: URANIUM

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ENERGY IN HISTORICAL TERMS

Throughout the development of man and his society, particularly in the last two centuries, a significant factor in his progress has been his ability to use energy to perform work and to produce materials. He has done so by invention and innovation, by the application of scientific principles and by the development of new technologies.

From the beginning of the industrial revolution in England about 1750, newly invented machines and the large scale manufacture of iron and steel relied on coal for energy production. Mechanical assistance in the mining and transport of coal stimulated further industrial progress. Faraday's discovery of the dynamo principle in 1831 led to the gradual development of the electric generator between 1845 and 1880; steam engines were prime movers and coal was the primary energy source. By the start of the twentieth century, electricity was being used extensively as a secondary energy source for lighting, power, and traction.

Meanwhile, the application of the steam engine to transportation systems opened a new era of rapid movement of people and goods by railway systems on land and by steamships at sea. The later development of the internal combustion engine freed the land transportation systems from fixed railway routes and produced a startling rise in the use of liquid fuels.

Each of these steps relied on techniques which overcame the resource constraints of an earlier age. Each, however, has caused increasing dependence of our society on energy and, more recently, a greater consciousness of the need for dependable and diverse resources of energy upon which we may draw. Two significant problems emerge from the demand for energy. The first is the magnitude of the resources which are capable of economic use, the efficiency with which they are being used, and the rate at which they are being depleted. The second is the impact that our use of energy makes in ecological and environmental terms.

CHANGING PATTERNS OF ENERGY DEMAND

Studies of the resources of the world and assessments of the growth of supply and demand, both in retrospect and prospect, have proliferated as concern has been expressed about limited resources, social and environmental impacts, and the price of energy. The importance of a historical review of energy consumption lies not so much in quantifying it, as in studying the factors which have caused changes in the pattern of energy use and growth.

From the nineteenth century, the growth in the use of energy has been marked by changing total growth rates and by significant alterations in the mixture of resources being employed. Table 1 gives estimates of the world energy consumption and its average growth rate since 1800, followed by a range of forecasts for these factors to the year 2000. The changes in the mixture of resources used are reflected, for example, in the changing rates of growth in Table 2, and later in Table 7.

Energy demand has fluctuated under economic, technical, social and political influences, at times abruptly. Wars and economic depressions produced periods of increased energy demand, decline or stagnation, while steady demand growth can be noted when economic activity and market conditions remained settled. New technical knowledge associated with energy stimulated further demand as efforts were directed towards the more efficient and diverse use of existing forms and towards harnessing energy sources not previously used.

The growth of social concern for conservation of resources and the growing degradation of the environment is now adding a new dimension to the political, economic and technical factors which were the prime influences up to the 1950s. In particular, it is apparent to some economists that normal market forces may not deal with these environmental and special problems effectively enough, so that some other form of control is needed. In some cases, legislation such as the UK Clean Air Act has been extremely successful. On the other hand, imposition of what are in principle entirely reasonable requirements for improvement of environmental factors and of the health and social welfare of workers may have adverse effects on productivity and total output of energy materials (e.g. the US Coal Mine Health & Safety Act of 1969).

TABLE 1

WORLD ANNUAL ENERGY CONSUMPTION ESTIMATES

Years 1800-2000

	Year	Consumption*	Average Growth Rate†
(ACTUAL)	1800	0.006	2
	1850	0.016	1.8
	1900	0.035	1.1
	1925	0.045	2.3
	1950	0.075	5.1
	1960	0.124	5.4
	1965	0.161	4.5
	1970	0.201	4.6
(FORECAST)	1973	0.23	3.9 - 6.2
	1980	0.3 - 0.35	5.4 - 9.5
	1985	0.39- 0.55	2.9 - 6.4
	1990	0.45- 0.75	2.9 - 4.4
	2000	0.6 - 1.15	

Sources: J. Darmstadter - Energy in the World Economy 1925-1968
United Nations

Sources: J. Darmstadter - Energy in the World Economy 1925-1968.
United Nations 'J' Series - World Energy Supplies 1950-1970.
Forecasts to Year 2000 from various sources of US & European origin.

* Energy Consumption in units of Q per year.

† Growth rate is the percentage rate of change per year as mean compound interest over the period.

NOTES ON UNITS: Many different energy units are quoted in the literature. for this paper, the following equivalents are used -

1 Q = 10^{18} British Thermal Units (BTU)
= 1.055×10^{21} joules (J)
= 1.85×10^{14} barrels of oil (bbl)
= 3.66×10^{4} million tonnes of coal equivalent (Mtce)

Growth Rate of Energy Consumption

The annual percentage rate of growth in total energy consumption between 1925-1950 averaged about 2.3% but proceeded at an accelerated pace of more than 5% from 1950 onwards. Allowing for population growth, the figures for the growth rates in energy consumption per person were 1.1 and 3.2%.

Such aggregated figures obscure some of the large variations in certain areas such as the USSR whose rates of growth in energy consumption for the above periods were 10½% and 7½%, reflecting exceptional growth between the two world wars; both figures are higher than the world average. Similar situations are now beginning to show in the developing countries for which 10% average annual energy growth rate has appeared in the period 1961-1970.

The changing role of the various fuels and the interfuel shifts in growth are shown in Table 2. The growth of some energy consuming industries is given in Table 3.

For the purposes of discussion, it is worth remembering that compound interest growth doubles the factor to which it is applied in the following times:

Compound Interest (Per cent per year)	Doubling Time (Years)
2.5	28.0
5	14.2
7.5	9.6
10	7.3
25	3.1

Put another way, about 2.4 times more energy will be needed to the year 2000 than has been used in all previous time to the year 1975, if growth in energy demand continues at about the same average annual rate of 3.5% as in the last fifty years.

Forecasting the Future

Just over a century ago an English economist, W. S. Jevons, developed an instructive analysis of coal supply and demand in the Britain of the 1860s. Fears were being expressed by 'alarmists' that reserves of coal would be depleted in the mid-1950s if the consumption rate were to continue at its then level. He pointed out that these projections were erroneous because important economic influences had been ignored. Examples were the

TABLE 2

WORLD GROWTH RATES IN ENERGY CONSUMPTION

(Per cent per year)

Type	1938-1950	1950-1960	1960-1970
Solid Fuels	1.8	2.3	1.9
Liquid Fuels	5.6	7.6	8.7
Natural Gas	8.0	9.3	8.7
Electric Power Capacity	6.4	9.3	7.9
Nuclear Electric Output	-	-	26*
World Energy	3.2	4.9	5.3

* Period: 1965-1970

Source: J. Darmstadter - Energy in the World Economy.
United Nations 'J' Series - World Energy Supplies.

TABLE 3

WORLD GROWTH RATES IN ENERGY CONSUMING INDUSTRIES

(Per cent per year)

Industry	1953-1963	1965-1970
Crude Steel	5.1% p.a.	5.2% p.a.
Aluminium	7.8	9.3
Motor Transport	6.8	6.5

Source: United Nations 'J' Series - World Energy Supplies.

increase in the price of coal to manufacturers as coal was hewn from greater depths, the impact of new inventions and their technological applications on energy supply and demand, and the appearance of effective substitutes for coal at competitive prices. As Jevons had opined, substantial changes in the mixture of fuels used were to take place from that time onwards. Nevertheless, it is instructive to observe that Jevons was not optimistic about petroleum as a substitute fuel, yet it has supplanted a large fraction of coal usage in the last two decades to the extent that

oil reserve depletion by 2020 is being predicted!

Some recent estimates of future energy supply and demand have been made on naive 'compound-interest' projections of the immediate past without due consideration being given to influences that will be at work in the future, i.e. to the changing economic, social, technological and political circumstances of the time. Whatever these future influences will be, it is necessary to have some understanding of the restraints imposed by our energy resources, of factors offsetting these restraints, and of the complex interactions which produce the demands for energy.

WORLD ENERGY RESOURCES

Over the last two centuries, man has learnt to draw his energy needs from an ever-changing set of world energy resources. The four principal sources of these energy stores are:

- solar radiation - the main energy income to the Earth, and the source of the water and air circulations.
- nuclear reactions involving the release of energy from fusion of certain atomic nuclei (as already happens in the sun) or from the fission of heavy nuclei.
- subterranean heat from natural radioactive decay within the Earth, from geological rearrangements, and from intrusions of molten rock.
- inertial forces generated by gravitational and rotational action within the solar system.

Through a variety of physical, chemical and nuclear processes and transformations, energy has been stored as heat in the Earth, in fossil fuel deposits, and in a wide variety of atomic nuclei as non-renewable supplies. Forms of energy which can be classed as renewable include water storage, tidal, wind and wave energy, together with solar energy itself which derives from a nuclear source with exceedingly long life.

The development of world industry up to the present time has depended largely on the non-renewable energy supplies from materials with concentrated energy content, progressing from wood and peat to coal, oil, natural gas and nuclear resources.

Defining Energy Resources

Although the total energy resources of the Earth are vast when solar,

geothermal, tidal, gravitational, fossil and nuclear energy are summed and compared with present world consumption, questions arise about the extent to which they may be exploited by man and about the time scale of their use. There is wide disparity in definitions of the quantities of raw materials stored in various forms and their availability for energy supply.

For our purposes, we will use the definitions developed for the World Energy Conference 1974, where a distinction is made between the total stored energy and that actually available for use:

Resources of non-renewable raw materials are the total quantities available in the Earth that may be successfully exploited by man within the foreseeable future.

Reserves are the corresponding fraction of resources that have been carefully measured and assessed as being capable of exploitation in a particular nation or region under present local economic conditions using existing technology.

Recoverable Reserves are that fraction of the reserves-in-place that can be recovered under the above economic and technical limitations.

Additional Resources embrace all other resources not yet discovered but believed to exist from geological evidence.

Renewable Resources such as hydraulic and geothermal, must be treated differently, as they are rate-controlled rather than stock resources. These resources are frequently quoted in terms of an integrated annual energy value derived from a maximum power level (in megawatts).

It is proper to warn that fully acceptable and effective world-wide definitions are difficult to achieve. As we shall see, the percentage of resources which become actual reserves in the future depends on the state of technology and the relationship between the price of the raw material and the cost of obtaining it.

ENERGY RESERVES AND RESOURCES

Estimates of the recoverable energy reserves of the world are listed in Table 4, together with some figures for additional resources as defined. The table also includes those resources which have future potential.

Estimates of available energy resources are a function of the state

of technology at the time of estimation so that projections into the long-term future can only be forecasts subject to wide margins of error. After all, uranium, deuterium and tritium were not listed as energy resources in 1910. Nevertheless, by assuming today's technology and by predicating some future advances in technology from known scientific research, it is possible to indicate also in Table 4 the variety and extent of resources which could be used over the next fifty years.

TABLE 4

WORLD PRIMARY ENERGY RESERVES AND RESOURCES

(Units: Q = 10^{18} BTU = 1.055 x 10^{21} joules)

	Recoverable Reserves	Resources (Estimated)
OPERATING		
Coal	35	325
Oil	6	25
Natural Gas	6	
Fission (Thermal Reactors)	2	10
	49	
Hydro (per year)	0.1	
POTENTIAL		
Fission (Fast Breeder Reactor)	200	4000
Fusion (Deuterium-Tritium)	240*	1000?
Fusion (Deuterium-Deuterium)	10^8?	10^{10}?
Solar (per year)	0.5	1000 (total surface)
Geothermal (per year)	10	1000

*Limited by lithium supplies of recoverable nature.

Sources: M. King Hubbert - Energy Needs and the Environment.
United Nations 'J' Series - World Energy Supplies 1961-1970.

Inequities of Geographic Distribution of Resources

Geographic differences in fossil fuel resources are large and depend on the specific fuel being considered. Almost one-third of world oil production and about half of world oil reserves are in the Middle East where demand is very small, whereas Western Europe and Japan account for 28% of world energy consumption, but have minimal oil resources (Table 5).

TABLE 5

ENERGY CONTENT OF RECOVERABLE RESERVES OF FOSSIL FUELS

BY WORLD REGIONS

(Units: Q = 10^{18} BTU = 1.055 x 10^{21} joules)

Region	Energy Content	Proportions
Northern America*	15.7	US; all fossil fuels 78%
USSR	4.6	USSR; all solid fuels 76%
East Asia	3.4	China; coal 96%
Southwest Asia	2.0	Saudi Arabia & Kuwait; oil and gas 68%
Eastern Europe	1.2	Poland, E. Germany; Coal 77%
Western Europe	1.2	W. Germany; coal 83%
Australia	0.5	Coal 91%
Tropical South America	0.4	Venezuela; oil and gas 69%
Japan	0.03	Coal 98%

*Includes Canada and U.S.A.

Source: World Energy Conference - Survey of Resources 1974.

The other immediately available fossil fuel resource is coal, the world reserves of which contain as much as fifteen times more energy than those of oil. Again, a disparity in geographic terms exists, this time in favour of North America, the USSR and the Comecon countries, but against some of the other large energy users such as Japan.

The consequences of inequitable distribution are exemplified by the lack of coal reserves in Japan and the short time span that the Western European coal reserves may cover (some 36 years). These countries must

consider alternative fossil and non-fossil sources of energy at prices competitive with the new oil prices. The only extensive energy options currently available to them directly are imported coal and nuclear energy, together with limited quantities of imported oil.

Looking at the Australian energy resource scene, we see the world's inequitable distribution in microcosm. The east coast region has the bulk of the solid fuels; the centre, south and northwest regions have the oil and gas; uranium principally occurs in the north, south and west regions. Although for the time being Australia is fortunate that the bulk of the energy demand is in the eastern region where the energy supply is greater, problems will arise in the next 15-20 years in the southern and western regions if further fossil fuel reserves are not found and used.

CHANGING CONCEPTS OF RESOURCES : URANIUM

A snapshot view of energy resources as a fixed stock with unchanging intrinsic value ignores the processes of change that define a resource. Of more recent times nowhere is this better illustrated than in the application of the nuclear fission process. Thirty-five years ago, uranium was still considered a relatively exotic material, it was known to be radioactive and had just been found capable of undergoing fission. Today, nuclear energy systems are the only commercially viable source of energy other than those using fossil fuels.

Within the present commercially-available range of nuclear reactor systems, uranium is the important fuel, with the energy being derived from the fission by low energy neutrons of the fissile isotope uranium-235 (0.7% of natural uranium) and, to a degree, from the fissile plutonium-239 created by the capture of neutrons by the fertile uranium-238 isotope. Present day commercial reactor systems use either natural uranium (in the Canadian CANDU and British Magnox reactors) or uranium enriched to around 3% in the fissile isotope U-235 (in Pressurised Water Reactors, Boiling Water Reactors, Steam Generating Heavy Water Reactors). The fission energy resource figure in Table 4, listed as 'Thermal Reactors', is based on average fuel requirements for such systems. Later, this resource level would provide some sixty times the energy output when used in fast breeder reactor systems.

Uranium is the first energy resource to have been listed regularly in groupings according to relative costs of recovery. This becomes important when considering reserves in relation to the operation of fast breeder reactor systems which have very low fuel costs.

Uranium is widely distributed throughout the world and has an average crustal abundance in continental rocks of around 2 grams per tonne (2 ppm). Most uraniferous ores contain less than one per cent uranium but unusually high concentrations do occur in some places, making extraction costs relatively low. The largest known reserves of low cost uranium occur in Australia, Canada, France, Gabon, Niger, South Africa and the USA (Table 6). Although it is known that the Communist nations in Europe and Asia have extensive resources, inadequate data makes it difficult to present a reliable entry in Table 6.

TABLE 6

ESTIMATED WORLD RESOURCES OF URANIUM

TONNES (URANIUM)

COUNTRY	Cost Range <$US26 per kg U		Cost Range $US26-39 per kg U	
	Reasonably Assured Resources	Estimated Additional Resources	Reasonably Assured Resources	Estimated Additional Resources
Australia	184,000	32,000	60,000	46,000
Canada	185,000	190,000	122,000	219,000
France	37,000	24,000	20,000	25,000
Gabon	20,000	5,000	Nil	5,000
Niger	40,000	20,000	10,000	10,000
South Africa	202,000	8,000	62,000	26,000
Sweden	Nil	Nil	270,000	40,000
U.S.A.	242,000	738,000	81,000	438,000
Other Countries	53,000	52,000	26,000	47,000
TOTAL	963,000	1,069,000	651,000	856,000

World reserves of uranium are currently estimated at about 3.5 million tonnes of uranium metal. By our earlier definition, these reserves will supply fuel for nuclear reactors using existing thermal fission technology primarily for electricity generation.

FUTURE POTENTIAL IN NON-RENEWABLE RESOURCES

Table 4 demonstrates the apparent relevance of the potential resources available through scientific discoveries within the last four decades, leading to possible development of new energy conversion technologies. In this context, however, it is important to point out that, following technical and then commercial proof of feasibility of a new method of energy production, some 20-30 years must be allowed before application achieves significance in the total world energy scheme.

Process Heat

In most developed countries, over one third of the energy consumed goes into the industrial sector to provide process heat in the chemical and metallurgical industries, the former requiring temperatures up to about 350°C and the latter around and above 1000°C. Both rely on fossil fuels at present. Substitution of other energy resources will become essential in view of the decreasing reserves of oil and natural gas. Thermal fission reactor systems are capable of supplying process heat to the chemical industry which is now programming construction of such plants.

The primary energy demand using the higher temperatures around 1000°C provides an incentive for further development of the High Temperature Gas-Cooled Reactor (HTR) systems which have operated at around 950°C outlet temperature. Apart from their potential use in the metallurgical industry, their high temperature gas may be employed to provide energy to heat-absorbing chemical processes such as hydrogen production and the splitting of methane. Such secondary liquid and gaseous energy sources may be used as substitutes for natural gas and petroleum products capable of mobile or pipeline transport throughout wide areas and over any distance.

Thorium and the High Temperature Gas-Cooled Reactor

The nuclear properties of High Temperature Gas-Cooled Reactor (HTR) systems are such that it is practicable and even preferable to use

thorium as a fertile material within the reactor core to produce another fissile isotope, uranium-233. The effectiveness of the thorium-uranium-233 cycle has been demonstrated, particularly in the USA and West Germany, so another potential future energy resource is to be found in thorium.

Thorium is somewhat more plentiful in nature than uranium and has an average crustal abundance in continental rocks of about 8 grams per tonne (8 ppm). The principal commercial source of thorium is the dense hard mineral monazite usually containing 3 to 9% thorium. Very large beach deposits of monazite occur along the south-west coast of India with other important deposits in Brazil, Australia, Egypt, Sri Lanka, Korea and the USA. Sedimentary and vein deposits of monazite are known in the USA and South Africa while thorium bearing minerals are also present with uranium deposits in Canada and the USA. The estimated energy resource is in the region of 150 Q (compare with Table 4).

Breeding of Nuclear Fuels

The use of uranium in present day thermal fission reactors allows only 1-2% of the potential energy of natural uranium to be withdrawn; of this 1-2%, about 50% is provided by plutonium. The so-called spent fuel from these reactors contains plutonium, in addition to uranium containing a reduced percentage of uranium-235, both of which may be recycled to obtain further energy output.

The most effective use of uranium will be in the Fast Breeder Reactors (FBR) whose nuclear properties are such that they will produce more plutonium from uranium-238 than they need to sustain them in normal operation. By reprocessing the fuel on a regular basis, it is then possible to incorporate this excess plutonium in the reactor fuel for recycling and to extract about 60% of the potential energy inherent in uranium. Since the cost of producing electricity with FBRs is much less sensitive to the price of uranium, more expensive uranium may be used so that the levels of recoverable reserves and of estimated resources for FBRs will be correspondingly higher.

By judicious design of the reactor core with thorium elements in suitable positions, uranium-233 can be manufactured as well as plutonium. It is possible to devise a fuel breeding cycle, such as is outlined in Figure 1, making efficient use not only of the energy resource materials but also of the temperature characteristics of each reactor system. It

is with this in mind, that it is possible to estimate the potential world energy resources available with these potential technologies as shown in Table 4.

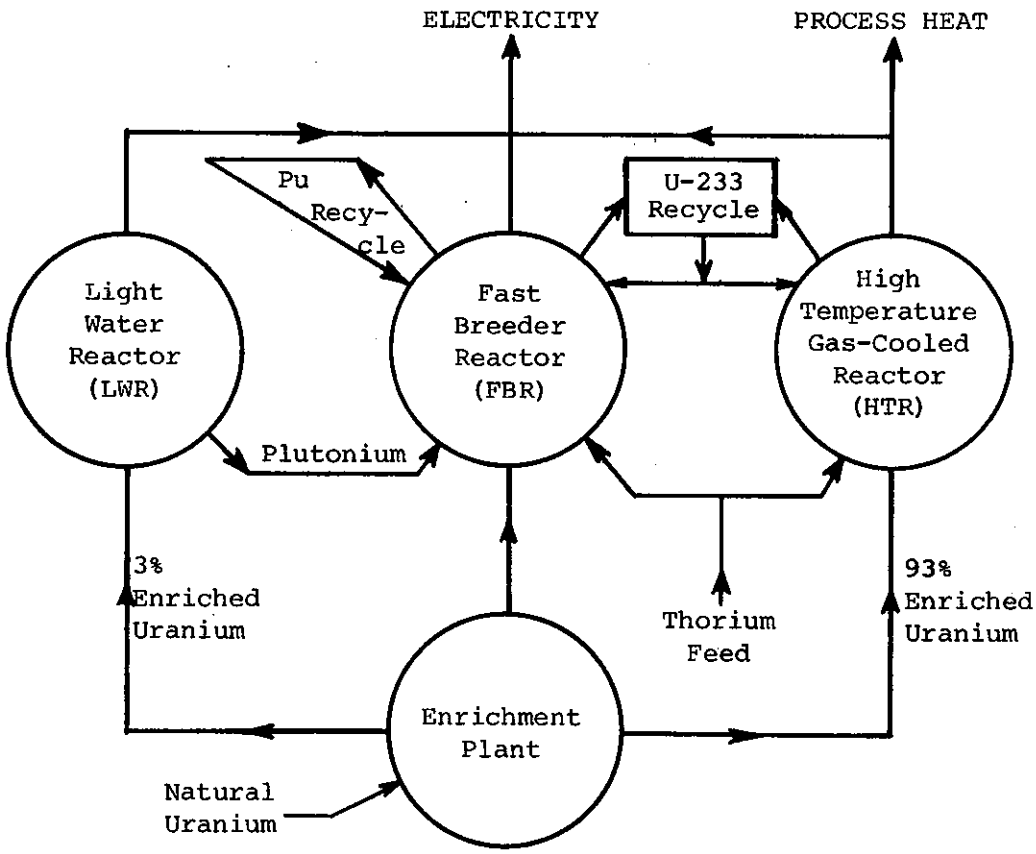

FIGURE 1

A potential fuel breeding cycle employing the most useful characteristics of each reactor type and using the resource potential of both uranium and thorium.

Nuclear Fusion of Light Elements

One of the future energy resource options of non-fossil origin as yet untapped is the nuclear fusion breeder system, based on nuclear reactions at about 100 million ^{o}C between two isotopes of hydrogen; deuterium (D), which is very abundant in sea water, and tritium (T), which is bred from lithium with neutrons from the D-T fusion reaction. This is a somewhat uncertain resource since technical feasibility of the system has not yet been proved.

Contrary to widespread belief, there is no qualitative difference in total energy resources between the fast breeder reactor and the D-T fusion

breeder systems except that the fast breeder reactor is already technically feasible. The limitation on the D-T fusion breeder system is the total resource of lithium.

If at some later time a higher temperature (around 1000 million °C) is practicable, it would not be necessary to rely on the breeding of tritium, as direct reactions between deuterium atoms (D-D reaction) can be employed. The energy resources are then related only to the availability of deuterium (Table 4).

Although fusion is one of the most attractive future energy alternatives, it could not contribute as a significant energy resource before the year 2000. Scientific and technical feasibility may be achieved in the mid-1980s but it will require concentrated engineering effort, particularly in choice of materials, for some 20 or so years after this time to allow optimisation for minimum power costs with minimum hazards.

RENEWABLE RESOURCES

Pioneering uses of all renewable resources are evident in practice but competition from fossil fuels at lower cost has caused their use to decline except in the case of hydraulic resources whose potential is limited by available land forms and by competing uses for water, and is a small fraction of total world energy resources.

Solar Energy

The sun provides most of the world's energy income and influences most of the material circulations of the Earth. Solar energy is important in agriculture and is already providing low grade heating and cooling for housing and commercial buildings.

The total radiation intercepted per year by the Earth's diametral disc is about 5.5×10^{24} joules per annum (5500 Q per year). Some 70% of the radiant energy reaches the Earth's surface. When reduced by the fraction of daylight hours, the total annual energy potentially available is about 1000 Q. Nevertheless, its areal density is low and some good ideas are required to put it in the class of significant energy resources Existing programs indicate that, by the decade 1990-2000, it may be possible to provide from it 1-2% of heating and cooling and 1% of other power needs.

Considerable attention should be given to minimising the energy

which must be invested from existing sources to make the materials and to construct the energy conversion plants and associated equipment. Ecological analyst, H. T. Odum, has warned that 'just as agriculturists of a decade ago forgot the fossil fuel basis of their green revolution, many now advocate solar technologies but fail to examine the energy subsidies. It certainly remains to be proved that solar technology can compete with agriculture in amplifying solar energy with small amounts of fossil fuels.'

Wind and Tidal Power

Solar energy provides another subsidiary energy resource, wind power, which has been used to a small degree for a long period. It is only of recent times that electric generators driven by wind power have been tested to outputs of about one megawatt. Some local areas of the world could use this resource effectively and new systems are being studied to get efficient transfer of wind power to rotational drive systems.

The technology for the use of potential energy from the rise and fall of tides is well developed but suitable areas for its use are few. Only about 2% of the world's total tidal energy of around 64,000 megawatts is potentially usable and actual recovery of energy is only a fraction of this 2%.

Need for Energy Storage

Direct solar, and wind and tidal energy are intermittent or periodic in availability and there is definite advantage in providing energy-storage systems. However, their cost often exceeds the cost of the energy conversion system itself, making development of suitable energy storage systems imperative. On a small scale, the use of electrochemical batteries is still worthwhile but is limited by total storage capacity per cell. Other important methods being explored are pumped storage of water, compression of air and generation of hydrogen and oxygen by electrolysis. None of these has yet reached a stage which could prove significant in the total energy scene before the year 2000.

Ocean Thermal Gradients

Within certain areas of the oceans, solar radiation produces thermal gradients between the surface water and water at depth. For example, in

the Gulf Stream the vertical temperature gradient can be around 20°C over about 1000 metres. By using thermodynamic heat engines it is possible to drive electric generators. This resource is feasible in only a few offshore areas of the world and it is unlikely that more than about 1% of the resource could ever be used effectively.

Geothermal Energy Resources

The slow decay of naturally occurring radioactive elements (uranium, thorium, potassium) in all rocks has generated very large quantities of heat energy within the earth. Geothermal energy may be tapped by using naturally heated water, as in New Zealand, USA, Mexico, Japan, Iceland, Italy and the USSR where geothermal power plants now operate. Plans are in hand to attempt the extraction of energy from hot dry rock reserves to a depth of about 10 kilometres.

As a whole, these renewable resources constitute an enormous energy base, compared with foreseeable energy requirements, but none of them is likely to have been sufficiently developed and put to commercial use to have any significant impact until early in the 21st century. Nevertheless, as with all resources, they can make important contributions in localised regions, as geothermal energy has done. Where renewable resources are available but non-renewable ones are not, as in some developing countries, their rapid development could be of great local benefit while not significantly influencing the aggregate world energy situation.

ENERGY SUPPLY AND DEMAND

Coal and the Growth of Crude Oil Use

During the 19th century, the most usual fuel was wood (and, in some countries, peat). By 1850, coal represented 10% of the total energy usage and, by 1910, it provided over 75% of total energy requirements. Oil began to penetrate the energy market about this time in spite of the size of coal reserves still available. Its greater convenience, relatively low price and an increasingly open market, and the difficult working conditions for winning coal have caused crude oil and its products to take over an increasing share of the expanding primary energy market since about 1950 (Table 7).

TABLE 7

WORLD ENERGY PRODUCTION

1950-1970

(Units: Mtce = million tonnes of coal equivalent)

Year Units	Coal & Lignite	Crude Oil	Natural Gas	Primary Electricity - (Hydro & Nuclear)	TOTAL
1950 Mtce	1605	701	261	41	2607
%	61.6	26.9	10.0	1.5	100
1960 Mtce	2193	1396	622	86	4296
%	51.0	32.5	14.5	2.0	100
1970 Mtce	2408	3002	1434	156	7000
%	34.4	42.9	20.5	2.2	100

Source: U.N. Statistical Year Books.

More extreme situations developed in Western Europe where Belgium and the Netherlands effectively closed their coal mines on economic grounds and West Germany reduced its dependence on coal in favour of oil and gas (Table 8).

TABLE 8

ENERGY REQUIREMENTS OF WEST GERMANY

1957-1972

(Expressed as percentage of the total)

	1957	1967	1972
Coal & Lignite	84.7%	46.4%	32.3%
Oil	11.0	47.7	55.4
Gas	0.3	2.1	8.6
Nuclear	-	0.2	0.9
Other	4.0	3.6	2.8
Total Requirements	0.0053 Q	0.0074 Q	0.0099 Q

Market Penetration of Other Resources

It should be noted that natural gas began to penetrate the market around 1950 and its use is increasing, while crude oil appears to have now reached its maximum usage. Convenience, cleanliness, and economics are possible causes, but studies by General Electric indicate that curves of a special shape may be fitted well to existing data on market penetration. This style of study has been extended to other fuel substitutions. While such projections may be suspect because there is no sound understanding of their causal background, they emphasise the time required for market penetration by a successful, but new, technology.

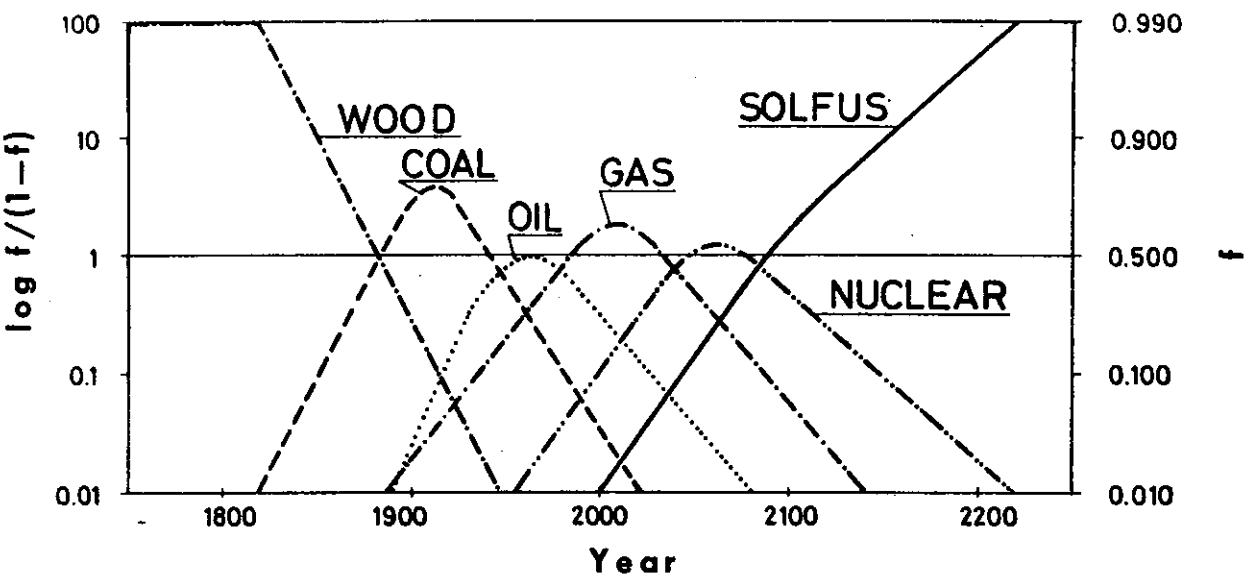

FIGURE 2

MARKET PENETRATION OF FUELS IN THE UNITED STATES

Plotted as a function of the fraction, f, of the market penetrated (right hand ordinate) or of the logarithm of f/(1-f). After Marchetti - as reported to the 1974 World Power Conference by Haefele.

*SOLFUS = some combination of solar and fusion energy.

Thermal fission energy at present supplies about 2.5% of the world annual energy consumption. Various projections suggest that it could supply over 10% of total energy consumption by the year 2000, i.e. it is then reaching a market penetration comparable with that of oil about the second decade of this century.

Temporary Return to Coal?

From the pure resource viewpoint, it is possible that coal could again become an important source of energy in some parts of the world. This could apply, for example, in the USA and West Germany because of the large ratio of coal resources to present total energy production level. What is not clear is whether it will be possible to handle the quantity of coal required to meet the target which, in the USA, is to try for double output by 1985.

With a high degree of mechanisation, US productivity per man per shift rose above 12 tonnes in about 1970, while in the restrictive conditions in British and West German deep underground mines it was in the range 2.5-4. It is most unlikely that European production can be raised above the levels of the late 1950s without mining at depths in excess of 1200 metres and perhaps investigating new mining technologies to improve productivity. A serious problem will be to achieve an increase in the labour force.

In the United States, one of the critical problems yet to be faced is a lack of manpower, especially as productivity in underground mining has dropped sharply with the implementation of the Coal Mine Health & Safety Act of 1969. Even more importantly, over half the present US work force will retire in the next few years, indicating a need to train further people in modern mining techniques. Doubts have been expressed whether sufficient national commitment would be possible to double output within ten years but, if it were so, it is relevant to observe that 70% of mines then operating would not exist today; effectively a new industry.

Resource Depletion

From reserves totalling about 50 Q (Table 4), it is estimated that aggregate consumption to the year 2000 (over all previous time) will be at least 11 Q. Let us take the lowest consumption figure for recoverable reserves (0.6 Q per year at the year 2000) and estimate the life of these reserves, unrealistically assuming no energy growth from the year 2000 onwards and no population growth. They would last for (50-11)/0.6 or approximately 65 years. Taking more realistic assumptions of a growth of reserves and growth in both energy demand and world population, it is still quite conceivable that these reserves will have undergone significant depletion by the year 2050.

As further evidence of the factors to be considered, in this case economic ones, it should be noted that oil and natural gas account for about 60% of world energy consumption from a resource base which is only 11% of the total fossil fuel resources. Yet coal is the dominant resource at 80% of the total fossil fuel resources.

Clearly, serious depletion of oil and natural gas reserves has resulted from such a strategy. As an example, we note that the Middle East reserves of oil (about 2 Q) would last the 430 million people of Japan and Western Europe alone for about 23 years if they continued to require an average demand of about 6 kilowatts per person and if oil were to make up two thirds of their energy supply as at present.

It is just this time scale which the Secretary General of the Organisation of Petroleum Exporting Countries (OPEC) observed as being too short for countries of the Middle East who feel they must stretch their natural wealth over a longer period. He concluded that oil prices must go up to a level which would allow other primary energy sources to contribute and to alleviate the oil supply situation.

The importance of finding substitute fuels for oil and gas suggests that some method is necessary for determining how long these resources may be depended upon as major energy sources. Hubbert has provided one answer by extrapolating existing data with special curves to give production rate versus time. The area beneath the curve from the beginning up to any given time will be proportional to the cumulative production up to that time, while the total area cannot represent more than the extractable amount of the resource originally present. Although a variety of curves can be made to fit such resource data, the production curves for different resources resemble each other strongly.

The complete cycle for crude oil is shown in Figure 3 where the growth curve shows what production would have been required if growth had continued at an average rate of 5.86 percent per year over the period 1933-1955. Using such an analysis, Hubbert notes that the time to reach 80% depletion of known oil reserves is only extended from 58 to 64 years when the estimated total reserves are increased by 55%. As Jevons wrote of coal in 1865, '... I attach less importance than might be thought to the exact estimate of the coal existing in Great Britain. ... The absolute amount of coal in the country rather affects the height to which we shall rise rather than the time for which we shall enjoy the happy prosperity of progress.'

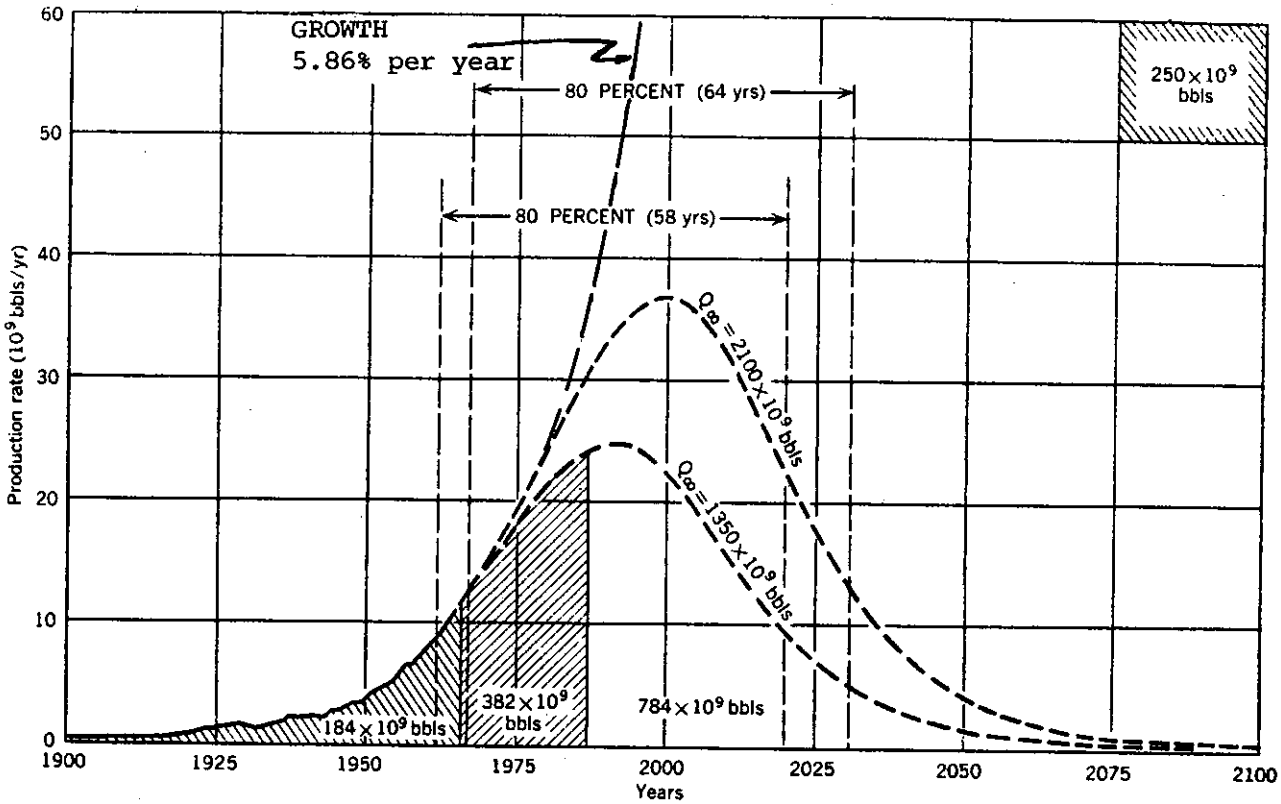

FIGURE 3

COMPLETE CYCLE OF WORLD CRUDE OIL PRODUCTION

Source: Hubbert 1973 - Energy Needs & the Environment

Units: 1 bbl = 1 barrel of oil = 5.7 x 10^6 BTU

Q_∞ = total oil resource represented by the area under the curve.

NUCLEAR ENERGY - IS IT NEEDED?

More than 30 years of research and development, and construction of demonstration plant have gone into the utilisation of energy from the nuclear fission process. Nuclear plants are being put to use in generating electricity in many power utilities throughout the world. For various reasons, particularly in the context of resource depletion, the question is asked 'Is it necessary to have nuclear energy as an additional resource?'.

Contrary to a widespread belief, resource depletion is not a topic brought into being by the Middle East oil crisis alone. That event highlighted the problem of how to arrange a new and effective balance between resources. West European countries, Japan and the USA saw the shortages of oil-based fuels looming in the 1960s.

As a present day example, we can take the USA where massive consumption is drawn from reserves of fossil fuels showing strong signs of limitations and energy supply is bolstered by heavy oil imports. Table 9 lists the actual energy balance sheet for 1973 in terms of millions of barrels of oil per day (MBPD). Let us assume that a low level energy growth rate of 2.6% per year results from 1.1% growth of population and 1.5% growth of national product by invoking strong conservation measures. Annual energy demand would grow from 37.2 to 50 MBPD from 1973 to 1985. The optimistic estimates for coal production and recovery of oil and gas in 1985 are drawn from a series of estimates made by various US authorities and total 34 MBPD equivalent.

TABLE 9

A US ENERGY BALANCE SHEET

(MBPD = millions of barrels of oil per day)

	1973	1985
Solids	6.8 MBPD	10.0 MBPD
Liquids	10.1	11.0
Gas	11.9	13.0
Nuclear	0.4	8.0
Other	1.4	1.4
	30.6	43.4
Oil Imports	6.6	6.6
TOTAL	37.2	50.0

This domestic fossil fuel supply, taken with the support from hydroelectric and other renewable resources, leaves a 1985 shortfall of 14.6 MBPD. The following points can be made:

. The estimate for coal production is on the high side and is based on an assumption that finance and effort can be found to open more than 200 new mines, to train 100,000 new miners, to provide a very large number of new mining machines costing around $20 billion (1974 dollars). The bottleneck is believed to appear in the construction of huge draglines and other large items of equipment.

- Techniques proposed to improve oil and gas output are quoted as 'promising' but are not yet proven. Even the new Alaska oil pipeline will only deliver 1.2 MBPD in 1977.
- The energy growth rate assumed in deriving the base figure of 50 MBPD is conservatively low.
- The most optimistic projection for the nuclear electrical capacity in 1985 suggests that nuclear stations now in operation, commissioning and construction will total some 200 thousand megawatts electrical capacity which has an oil equivalent of 8 MBPD.

For the USA, even with its relatively large coal and oil reserves, nuclear energy is expected to supply the equivalent of 8 million barrels of oil per day; the alternative is to more than double the present oil import level. The basic US answer to our question is - 'Yes, we need every energy form.'.

West Germany has relatively less reserves than the USA upon which to draw and they are more difficult to extract. Japan has still less reserves and is even more dependent on imports. Domestic production to total consumption percentages for these countries are respectively about 55% and 15%. Nearly 70% of Japan's energy needs is supplied by oil at a rate of about 4 MBPD. The lowest figure for installed nuclear electrical capacity proposed in Japan is in the region of 30-40 thousand megawatts by 1985, representing about one MBPD oil equivalent, a significant level of energy support. Other countries in Europe, such as France and Italy, see a similar need. Bearing in mind the oil reserve situation and OPEC comments (page 21), these countries are forced to seek an independent resource in addition to whatever oil they can get. For them, that resource can only be nuclear energy.

The interdependence of various areas of the world in relation to material resources is of growing importance. The developed world has so depleted its own resources that it is relying increasingly on developing nations to supply, for example, iron ore, bauxite and phosphate. Increased oil and food prices have forced developing nations to redress their balance of payment problems by raising prices of these material resources. Any shortage of oil for developing countries lacking primary resources results in a direct and prompt cut in fertiliser production and industrial output and consequent deficits in food supplies.

If developed countries do cut back on resources substituting for oil, developing countries will almost certainly suffer. The world is no longer made up of groups able to act and live in relative independence. Mesarovic and Pestel present these extraordinarily complex situations in their recent book 'Mankind at the Turning Point' and comment that 'The most outstanding lesson which can be drawn from these events is a realisation of how strong the bonds among nations have become.'

A PERIOD OF TRANSITION

From the previous outline of energy supply and demand, we observe that the industrial activities of our society have been subject to appreciable growth rates for only two centuries. Yet it is apparent that we are approaching various physical, economic, environmental and social limitations to this energy growth, especially if it continues to be compounded at more than 3% annually on a world average, and at more than 5% in some of the constituent energy sectors. Hubbert has commented that 'two realisations of outstanding significance emerge. One is the brevity of the time, compared with the totality of past human history, during which the large scale production of power has grown; the other is that energy resources sufficient to sustain power production of present magnitudes for at least a few millenia have now become available. The limiting factors in power production are, therefore, no longer the scarcity of energy resources, but rather the principles of ecology.' This comment applies whatever energy resources we choose to employ in the near and medium term.

The sheer magnitude of the problems associated with allowing energy demand to grow in developed countries as in the past is only just being appreciated. The dilemma of those countries is that they cannot sustain growths of 5 to 10% annually, and they do not yet know how to slow the growth without appreciable disruption of society and unemployment. Developed countries are aware that they cannot expect to change to new technologies or to upgrade old ones in periods of less than twenty to thirty years. A change to solar or fusion technologies is not made by throwing a switch to change society's energy supplies abruptly, even supposing that technical and commercial feasibility is proven.

Injection of large research funding is always possible but this action does not ensure that the ideas and their development are guaranteed as well. Even supposing that technical success is achieved, the consequent development requires at least ten times the research investment to ensure commercial feasibility, followed by investments larger by several factors of ten to achieve significant and growing penetration of markets.

One example of a subdivision of a US based Research & Development budget to achieve a balance for the near and medium term is shown in Table 10, developed from a US National Academy of Engineering study by

TABLE 10

RESEARCH & DEVELOPMENT PRIORITIES

For the Medium & Long Range Phase

(R & D total funds in the few billion dollar range = 100%)

A. RESOURCE ORIENTED R & D: 40%	
Deployment of an Ecologically Consistent Nuclear Fuel Cycle	13%
Fast Breeder Reactors	15%
Fusion	4%
Solar	6%
Others	2%
B. MODERN SECONDARY FUELS*: 55%	
Synthetic Hydrocarbons, Modern Uses of Coal or Oil Shales	10%
High Temperature Nuclear Process Heat	12%
Energy Transportation	10%
Energy Storage	10%
Hydrogen, Electrolysis	13%
C. SYSTEMS ANALYSIS: 5%	
Ecological, Environmental, Sociological Factors in Energy Use.	

*With the assumption not to opt for an all coal economy.

Haefele. It attempts to achieve a balance between the developmental and research phases of each of the existing and potential technologies, recognising that there is a real need to examine closely how the environment and society respond to new circumstances.

Meanwhile, artificial reduction in the world energy growth rate, whether by restriction of the use of resources or other means, would affect all nations, and could cause severe problems in developing nations wishing to achieve, not necessarily parity, but reasonable relativity to developed nations in standards of living. As has been observed in developing countries, as a result of the recent rise in oil prices energy growth restrictions will impose limits on the growth of agricultural production and on industry on which hopes of improving their gross national product would depend. Already it is apparent that there is a need to find solutions which do not start from some extreme initial conditions such as cutting off the supply of one resource.

A further requirement is that the magnitude of any future crises and their directions should be anticipated, where possible. The inherent societal and political delays in response, as well as the slow reaction to economic and technical developments to input changes, demand deep and systematic analyses, taking account of many factors and their variability as early as practicable. Economists have begun to allow for dynamic conditions in their field while scientists and technologists have long used dynamic analyses in such diverse problems as evolution of stars, energy flows in and out of the 'energy current account', and the behaviour of complex industrial plant. Much less work has been done for inclusion and study of the dynamic responses to sudden changes in our society and in world politics.

As was shown in Meadow's 'Limits to Growth', doomsday scenarios are relatively easy to write if continuous growth is coupled with physical limitations on materials, but the transition to an equilibrium situation is more difficult. Optimum solutions without the collapse of society require cooperation and understanding of a magnitude not previously seen in our society, backed by the means to anticipate not only the changes which are necessary, but also the timing and strength of corrective measures against unwanted changes.

It is unlikely that, in ten years, the pattern of development in quite different parts of the world will allow a drastic change in the mixture of energy resources now in use and in prospect. Nevertheless, as Mesarovic and Pestel have commented, 'Rather, man must initiate on his own, changes of necessary but tolerable magnitude in time to avoid intolerably massive and externally generated change.'.

FURTHER READING

1. Survey of Energy Resources 1974: World Energy Conference.
Published by the US National Committee.
Presents a careful evaluation of world energy resources and contains extensive tabulations of resource data for the world. Descriptive and explanatory material is presented on each fuel type.

2. Darmstadter, J. (Ed): Energy in the World Economy. Resources for the Future, Inc. John Hopkins Press. 1972.
Presents a detailed statistical review of trends in output trade and consumption since 1925.

3. World Energy Supplies, 'J'-Series: United Nations.
Published annually giving world energy production, trade and consumption in that year and over the previous ten years. Complements Item 1 by arrangement with the World Energy Conference.

4. Energy: a special issue of Science, Vol. 184, 19 April 1974; American Association for the Advancement of Science.
An interesting series of articles, chosen 'to present material relevant to important public decisions of the next few years'. Impact of the energy crisis, energy policy, economics, developed and developing technology are discussed. Haefele also writes about energy choices that Europe faces.

5. Status Report - Energy Resources and Technology; Atomic Industrial Forum, Inc. 1975.
Outlines existing and projected capabilities of resources and technology in the energy field with particular reference to fossil-fuel power, nuclear power, hydroelectric and exotic power sources, and energy conservation.

6. Energy and the Environment: US Council on Environmental Quality, August 1973. R. Train (Chairman).
Discusses trends in the demand for energy and the supply systems for meeting this demand. Environmental impacts of fossil-fuel and nuclear electric power systems are outlined. Points out how improved efficiency of energy systems and energy conservation will reduce environmental damage and slow the use of energy resources.

7. Exploring Energy Choices: A preliminary report of the Ford Foundation's Energy Policy Project (S. Freeman, Director).

Explores the whole complex of energy issues facing the USA; the 'energy gap' between supply-consumption; objectives, tools and constraints in relation to energy policy.

8. M. King Hubbert: Energy Needs and the Environment (Seale and Sierke, Eds.), Chapter 2. University of Arizona Press 1973.

Discussion on energy resources and their depletion with projections into the future. The remainder of the book is also relevant - a series of papers on energy generation, air and water quality, pollution control, environmental, engineering and various energy systems.

9. US Energy Prospects - an Engineering Viewpoint: US National Academy of Engineering, 1974.

A discussion of the application of various energy systems, an estimate of economic viability and an attempt to establish priorities in the allocation of research and development funds.

10. Haefele, W.; Future Energy Resources, World Energy Conference September 1974.

A brief look into the medium and long range future of energy resources and a study of research and development priorities in relation to the allocation of funds.

11. Jevons, W. S.: The Coal Question, MacMillan 1865.

An early analysis of depletion of coal reserves and the consequences for Britain.

12. Mesarovic, M. and Pestel, E.: Mankind at the Turning Point; Hutchinson 1975. The Second Report to the Club of Rome.

A more extensive analysis of long term world development which suggests some ways for overcoming the gloomy predictions of 'Limits to Growth', the First Report to the Club of Rome. The effect of delays in taking action to counter 'compound interest' (exponential) rates of growth are very effectively presented.

GLOSSARY

The following definitions are provided for the reader not familiar with some nuclear and other terms used in this paper. The explanations are drawn from standard glossaries.*

breeder	A reactor which produces more *fissile* material than it consumes. *Fertile* material included in the core is transformed into *fissile* material by *neutron capture*.
deuterium	A (heavy) isotope of hydrogen (mass number 2).
fertile (material)	Non-*fissile* isotopes capable of being readily transformed into *fissile* material by the absorption (*capture*) of *neutrons*.
fission	The splitting of a heavy nucleus into two approximately equal fragments. This is accompanied by the emission of neutrons and release of energy; whence *fission products*, the atoms formed in the fission process.
fusion	The process of building up more complex nuclei by the combination, or fusion, of simpler ones. This is usually accompanied by release of energy.
geothermal (power)	Relating to the use of the heat of volcanic regions for electricity production.
isotopes	Varieties of the same element having different masses; whence *isotopic*.
megawatt	The normal practical unit of power station capacity (one million watts). Sometimes megawatts (electrical) and megawatts (thermal) outputs are signified.
neutron	A nuclear particle having no electric charge and the approximate mass of a hydrogen nucleus; whence *neutron absorption, neutron activation, neutron capture*.
thermal neutron	A neutron in thermal equilibrium with its surroundings. At room temperature it has low energy and slow velocity; whence *thermal fission* (caused by thermal or slow neutrons).
tritium	A (heavy) *isotope* of hydrogen (mass number 3).

* Sources:

British Standards Institution : Glossary of terms used in nuclear science and technology, BS 3455:1973

USA Standards Institute : USA standard glossary of terms in nuclear science and technology, USAS N1.1-1967.