Surrey Energy Economics Centre

NUCLEAR POWER, THE GREENHOUSE EFFECT AND SOCIAL COSTS OF ENERGY

Two papers by

P M S Jones

SEEDS 51 May 1990

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NUCLEAR POWER AND THE GREENHOUSE EFFECT

P M S Jones

INTRODUCTION

At first sight nuclear power looks to be a ready made solution to the greenhouse effect. Uranium fission produces no carbon dioxide, no nitrous oxide and no higher oxides of nitrogen which can contribute to tropospheric ozone formation. As an added bonus it produces sulphur dioxide which, together with nitrogen oxides, contributes to acid rain. However, there are major logistic problems which limit the contribution nuclear power can make in the short and medium term.

In the following paragraphs both the potential of nuclear power and the nature of the constraints restricting its penetration of world energy markets will be examined. A view will be taken about the likely rate of nuclear expansion and its contribution to reductions in the greenhouse warming effect will be described, based both on surprise free projections and on an assessment of what might be practicable given a determined effort to substitute nuclear power for fossil fuel combustion. Following this, consideration will be given to some of the arguments that have appeared in the literature concerning the relative attractiveness of nuclear power and renewable energy sources and nuclear power and energy efficiency measures.

THE POTENTIAL

The potential of nuclear power is enormous. At the latest reckoning (1) known low cost uranium resources (recoverable at further costs of $130/kgU or less) amounted to 3.5 million tonnes with another 1.7 million tonnes in the estimated additional resource category, EAR-II, which are inferred to exist but not yet proven (Figure 1). These figures refer to the world outside the centrally planned economies (WOCA) since data for the eastern bloc are hard to come by. In the same region (WOCA) attempts to estimate the level of resources remaining to be discovered, the so called speculative resources, have produced a figure of 9.6 to 12.1 million tonnes of uranium recoverable at $130/kg or less (1). About half of this is believed likely to occur in North America and Australia. Certainly more uranium does exist and will be discovered, although it would be unwise to rely on speculative estimates as a sound quantitative guide.

Additionally, uranium can be recovered as a by-product of phosphoric acid or copper production, and resources with higher recovery costs also exist but have not been well researched.

5 million tonnes of uranium is sufficient to fuel some 1250 GWe of improved light water reactors for their anticipated life time, taken here as 30 years, if the spent fuel is not reprocessed to recover and recycle plutonium and unused uranium-235 (Figure 2, ref 2). Whilst this looks large compared with the 340 GWe of thermal reactors now projected

FIGURE 1

URANIUM RESOURCES IN WOCA

million tonnes U

Category	**Further Recovery Cost** **<$80/kg U**	 **$80-$130/kg U**	 **<$130/kg U**
Known			
Reasonably Assured	1.55	0.68	2.23
Estimated Additional I	0.89	0.43	1.32
Inferred			
Estimated Additional II	0.66*	0.54*	1.68
Guessed			
Speculative	-	-	6.4-16.0 (9.6-12.1)#

* Excludes South African resources

\# Most likely range

Note: One is cautioned not to sum across resource categories

Source: Ref 1

FIGURE 2

INDICATIVE REQUIREMENTS FOR REACTORS AND PLUTONIUM YIELDS

For 30 year operation of 1 GWe plant at 70% load factor

Enrichment tails = 0.25%

Type	**Lifetime U requirement** tonnes	**Fissile Plutonium yield** tonnes
PWR	4588	4.9
Improved PWR	4016	3.8
Candu (Nat. U)	3674	10.0
Magnox (Nat. U)	6990	14.0
AGR	4700	2.9
FBR	664*	35.2

* Depleted uranium

Source: Ref 2

to be in place in WOCA by the year 2000 it is not large compared with the 1800 GWe of electricity generation capacity currently existing in the region, although it is comparable in terms of actual electricity output (~850 GWe year/year). The same uranium resource is capable of fuelling some 60 times as many fast reactors, so that the known low cost uranium resources alone could support all the world's current electricity production for over 1000 years. If they are used in fast reactors the known and estimated additional low cost (<$130/kgU) WOCA uranium resources are equivalent to 6 million million tonnes of coal which is 5 times the proven resources of all fossil fuels combined and 500 times the energy (expressed as primary energy equivalent) used annually for all purposes globally (3).

It is evident that the potential of nuclear power is vast but the logistics are not simple. So far nuclear power has been used largely to produce electricity which provides only 30% of total world energy consumption (on a primary energy equivalent basis). There is potential for electricity to expand into conventional heat markets and into some areas of transportation however. Also nuclear power can provide a source of direct heat for industrial or district heating purposes. Indeed, such applications have already been practiced for many years on a limited scale (4). It would be possible, economics permitting, to use nuclear power to produce hydrogen electrolytically or thermochemically for situations where a transportable fuel was required. Hydrogen production could be one approach to exploiting cheap off-peak electricity production on a daily or seasonal basis.

Leaving aside detailed arguments about odd fractions of a penny, nuclear power produces electricity at about the same cost (Figure 3A) as it can currently be produced by fossil fuels (5). The most recent estimates (6, 7) suggest that electricity from fast reactors (Figure 3B), when these are operating on a commercial scale with commercial scale fuel plants, should cost about the same as electricity from new LWRs. As a source of centralised large-scale heat production (either as dedicated heat sources or in the form of combined heat and power plant) nuclear power costs are comparable to those of fossil fuels.

In principle it would appear that in the long term nuclear power has the potential to provide the bulk of the world's energy in an environmentally benign way and that it should be able to do so at costs that are not significantly differently to those currently being paid for fossil fuels.

However, this idealised view is not achievable overnight.

CONSTRAINTS

(a) Infrastructure

A potential constraint on the deployment of nuclear power is the ability of the construction industry to erect plant. Opponents of nuclear power have frequently quoted estimates for high energy demand scenarios with high nuclear penetration in which a new

FIGURE 3A

COMPARATIVE GENERATION COSTS IN OECD

Region	**Coal/Nuclear**	**Gas/Coal**	**Wind[2]/Coal**
Europe	0.95-1.79	1.18-1.47 (cc)	1.06-1.23
N. America[1]	1.07-1.33	2.60 (GT)	-
Pacific	1.28	1.27 (LNG Th)	-

[1] High cost coal regions

[2] Assumptions for wind plant load factor and lifetime vary

cc = combined cycle

GT = Gas Turbine

LNG Th = Thermal plant using LNG fuel

Source: Ref 5

Based on levelised lifetime costs at 5% discount rate. Coal, nuclear and gas plants with 30 year lives, 73% load factor.

FIGURE 3B

COMPARATIVE GENERATION COSTS IN THE UK

Source	**Ratio to PWR**
Run of river Hydro	0.7
On-shore wind	1.3-1.6
Off-shore wind	2.0-3.5
Geothermal (hot dry rock)	1.5-2.8
Wave	4.3-7.6
Photovoltaic	3.8-30
Fast reactor*	1.0

* For settled down post-2000 design with commercial scale fuel plant

Source: Refs 6, 7, 10

nuclear plant would have to be commissioned at a rate of one every three or four days (8).

By the 1970s, less than 20 years after the first commercial deployment of nuclear power, the global construction capacity was estimated to amount to some 60 GWe per annum with an actual rate of commissioning of 35 GWe per annum being achieved (9). In recent years, due to the reduced rate of energy and electricity demand growth following the economic slow down of the 1970s and 1980s, the number of reactors being ordered has declined significantly, and this will be reflected in the rate of commissioning new plant in the 1990s (Figure 4).

Given the incentive, and bearing in mind the high rates of ordering achieved in countries like France (5-6 GWe per annum in the late 1970s), there would seem to be no reason why, on a pro rata basis, construction rates in excess of 60 GWe per annum could not be achieved in WOCA by 2010; although such a rate of construction would be difficult to achieve in the short term. It has to be born in mind, however, that existing nuclear plant will begin to be phased out from the late 1990s onwards as it reaches the end of its design life. The rate of addition to existing capacity will therefore be somewhat lower than the total rate of plant completions. Certainly it should not be impossible to have nuclear capacity in place equivalent to the whole of today's 1800 GWe of electricity generating capacity by the year 2040 if it were desired and generating significantly more electricity than that now produced.

(b) Finance

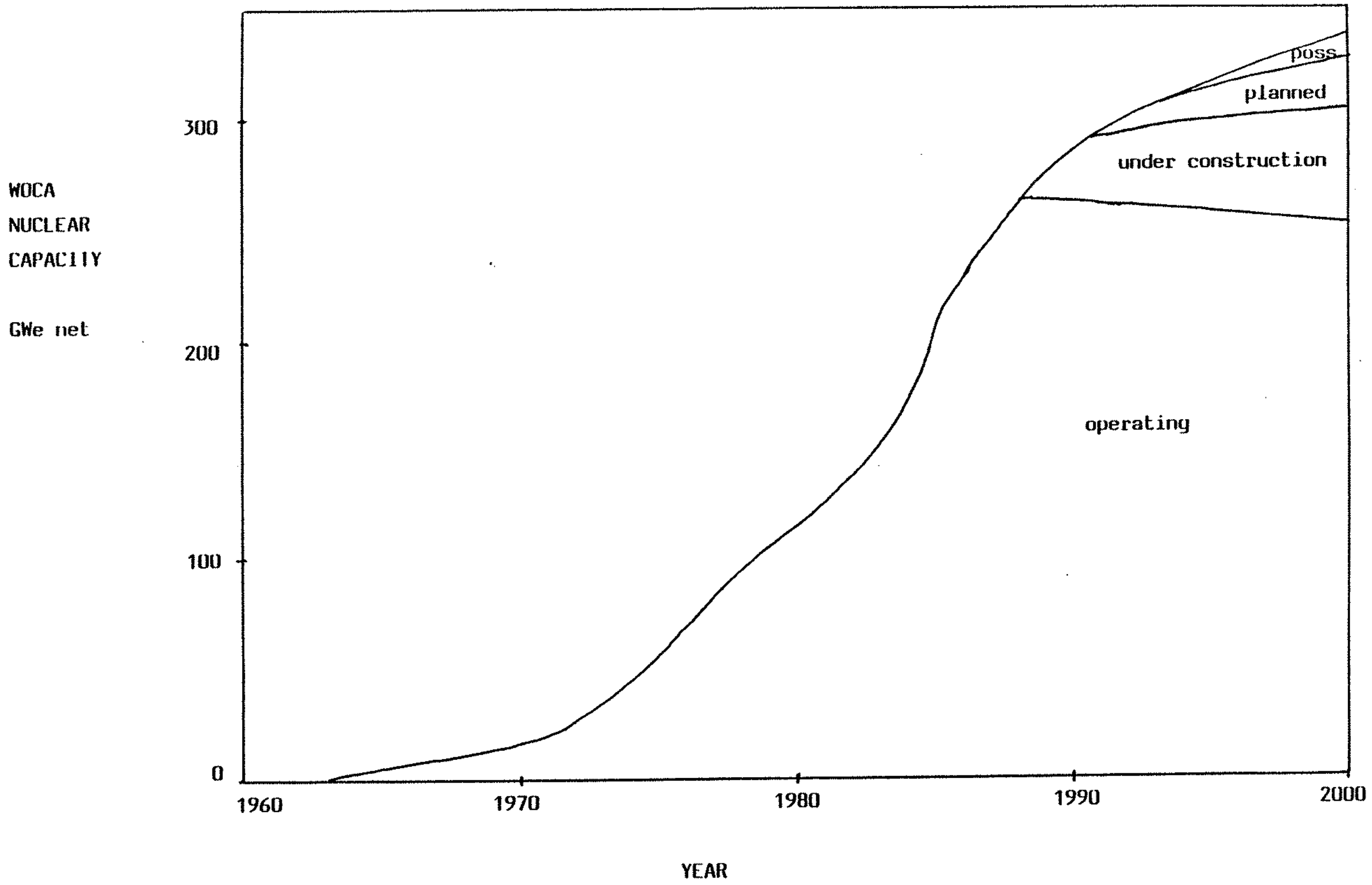
Financing the construction of a nuclear plant can be a problem in countries where access to capital is limited, notably in the developing countries. There may also be problems in some though not all countries where private funding is sought and attitudes to financial risk or the pursuit of quick returns favours less capital intensive investment.

However, since the overall cost of electricity production from fossil-fuelled sources, from nuclear power and from the cheaper renewable resources are, in broad terms, comparable, electricity supply from any one of them will impose much the same strains on national economies. (In practice, with the exception of hydropower, the majority of the renewable sources are more capital intensive and produce electricity at higher costs than nuclear power (Figure 3B) (10)). It may be that capital constraints will pose a barrier to investment in energy supply but this is not something that in the long term should affect nuclear power more than any other source, given pressures to move away from the use of fossil fuels. The question is 'Can we afford energy?', not 'Can we afford nuclear power?'.

The necessary capital investment should be readily achievable. The United Kingdom, with some 60 GWe of generating capacity in place (11), would need to be building some 2 GWe per annum on a pro rata basis, which also corresponds to the rate of new plant construction required to maintain the UK's capacity at about its present

FIGURE 4

NUCLEAR CAPACITY IN WOCA



size. At current costs this would amount to an expenditure of some £3 billion per annum which is about 3% of current levels of gross domestic fixed capital formation (Figure 5) and under 1% of gross domestic product (12). (Some £6.2 billion per annum is currently spent on fixed capital for energy and water supply). The rate of expenditure on new power plant is less as a share of both GDFC and GDP than the UK was spending on power stations in the 1960s. France, with an economy similar in size to that of the UK, has achieved and maintained even higher rates of investment (13) over a significant period (see above). It would therefore seem that a significant proportion of the worlds total electricity production could be produced from nuclear sources by 2030 to 2040 should that become a political or environmental objective.

(c) Uranium Supply

With installation rates of nuclear plant at quite modest levels existing known low cost uranium resources would be fully committed well before 2020 (Figure 6), and significant investment in uranium exploration would be needed to ensure that as yet undiscovered resources are located and brought into production. In the event that estimates of undiscovered resources proved to be unduly optimistic fast reactors would need to take over the dominant role in supply.

This eventuality has been anticipated almost from the birth of the nuclear industry. Only 9 years ago many of us believed that fast reactors would be the preferred commercial choice for introduction from the late 1990s onwards (14). The slow down in the growth of energy and electricity demand coupled with the discovery of additional uranium resources has led to a relaxation of the timescale so that it has become common, even in countries committed to the fast reactor, to talk in terms of 2030 as a potential date for their deployment on a large scale. Leaving aside the question of the precise date of their introduction it is possible to take a broad view on the rate at which such reactors might be deployed and the rate at which their contribution to electricity production could increase in the future.

The rate of plutonium accumulation in spent fuel arisings in OECD Countries will be around 60 tonnes total per annum during the 1990s (Figure 7) (15). By the late 1990s reprocessing plant capacity will exist that could recover some 50 tonnes total per annum (15), although in practice quantities will be significantly below this. 50 tonnes of plutonium is sufficient to provide the fuel inventory for some 7-10 GWe of fast reactors per annum when allowance is made for hold-up and losses in the fuel cycle (16, 17). Plutonium produced in WOCA in gas reactor and LWR fuels will exceed 1000 tonnes total by 2000 but it is unlikely that more than one quarter of this will have been separated by this date (15).

Each GWe of fast reactor capacity, once installed, can sustain itself without fresh uranium supplies, making use of the existing large stocks of depleted uranium from enrichment plant or uranium recovered from reprocessing, the uranium-238 content of

FIGURE 5

UK ECONOMIC INDICATORS

£ Billion

	1967 (1963 prices)	1988
GDP (factor cost)	30.5	390
GDFC	6.5	86
Energy and Water industries fixed cap. formation	0.95 (a)	6.3 (b)

(a) excludes oil industry

(b) includes oil industry

FIGURE 6

URANIUM REQUIREMENTS IN WOCA

SURPRISE FREE NEA PROJECTIONS

2030 capacity 604-861 GWe net

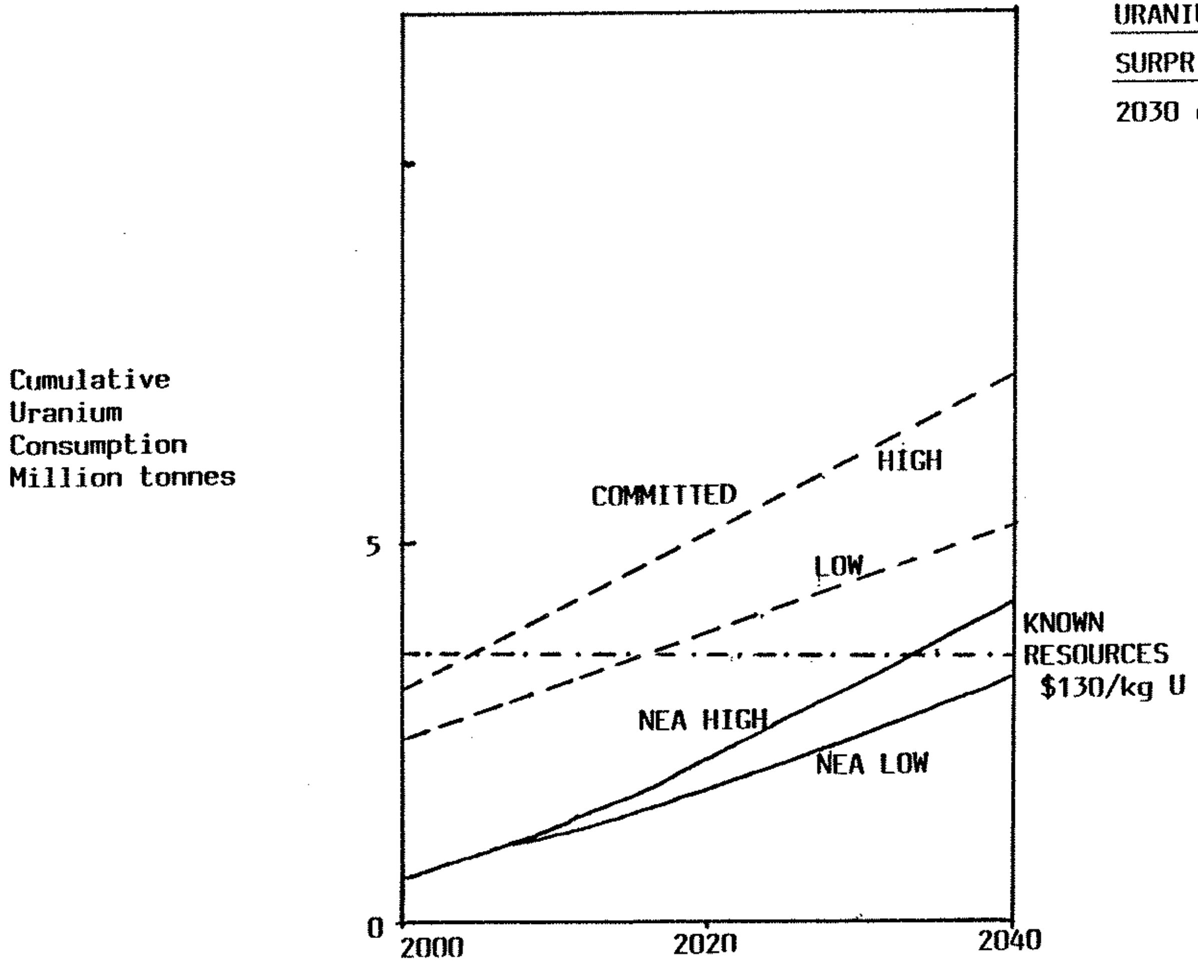


FIGURE 7

PLUTONIUM PRODUCTION AND FUEL SUPPLY IN OECD

Tonnes pa

	1987	1990	1995	2000
Plutonium yield from existing reactors[1]	52	57	59	61
OECD Pu recovery capacity[2]	13	15	42	45
MOX fuel fabrication capacity[3]	51	125	330	460

1. Including non-reprocessing countries
2. Maximum capacity
3. MOX (plutonium uranium oxide) fuels contain about 4% Pu

Source: Ref. 15

which can be converted to fresh plutonium fuel in the reactor. One tonne per year of depleted uranium will provide the feed for a 1 GWe fast reactor. Additionally, depending on the design parameters, the fast reactor will produce a surplus of plutonium which will contribute to the fuel inventory of other fast reactors. For designs described (16, 17) in the literature using oxide fuels the exponential doubling time for plutonium can be in the region of 20 to 30 years, so that by the middle of the next century fast reactors could be being constructed as the dominant reactor type. This would, however, require that fast reactors were deployed fairly early in the next century. It would not be possible if commercialisation of the fast reactor were deferred until 2030. Deferral would lead to the accumulation of a stockpile of plutonium so that a larger number of fast reactors could be fuelled when commissioning eventually begins, but the total numbers would be constrained by the amount of plutonium foregone in the absence of earlier breeder reactors.

An additional factor is the current intention on the part of many OECD Countries (15) to use plutonium recovered from spent thermal reactor fuel to produce mixed uranium plutonium oxide fuels (MOX) for use in LWRs. Whilst this does not preclude the subsequent use of the plutonium recovered from MOX fuels in fast reactors it will marginally reduce the effective stockpile and will lead to the need for additional reprocessing capacity if the plutonium is to be available for incorporation into fast reactor fuels.

Whether or not these constraints on plutonium availability and the ability to deploy fast reactors are significant depends on the rate of growth of demand for electricity, on the adoption or non-adoption of nuclear power as a preferred route to amelioration of carbon dioxide production, and on the investment in and success of future uranium exploration activity.

ELECTRICITY DEMAND

At this juncture it is appropriate to look at the existing projections of electricity demand and current expectations of the rate of penetration of nuclear power.

Although there are widely divergent views on the likely global energy demand, depending on their source (18), there is general agreement that electricity, because of its desirable characteristics, will continue to increase its share of energy supply and that it will increase in absolute terms. The driving force behind energy growth continues to be the economic growth in both the developed and developing countries, together with the need to provide additional energy to match the growing population of the latter. Where analysts differ is in their expectations or hopes concerning the rate at which improvements in the efficiency with which energy is used can offset growing demand. Optimistic assessments of what might be achieved in both the developed and developing world lead some authors to conclude that a total world primary energy supply of 11 TWy/y by 2020 might suffice, ie the same as total supply in 1980. However, the achievement of this is recognised, even by its proponents (19, 20), to be an almost impossible goal and in the real world it seems unlikely that energy demand in 2020 could be very much less than 15 TWy/y. Given buoyant economic growth and in the absence of constraints demand could even reach 20 TWy/y by this date (Figure 8).

Regardless of the total energy requirement there seems to be closer agreement that electricity demand in WOCA and the world as a whole is likely to double by 2020 (18-21). On a trends continued basis the Nuclear Energy Agency has projected that some 500 to 700 GWe of nuclear capacity might be installed within WOCA (21), compared with the 340 GWe expected to be in place by the year 2000. Taking a conservative 700 GWe for global nuclear capacity in 2020 corresponds to around 20% of total electricity production. It would only reduce anthropogenic global warming effects by some 6% due to the relatively small contribution of electricity production to total greenhouse gas emissions (Figures 8 and 9) (18).

A vigorous programme of nuclear substitution aiming to achieve 50% nuclear penetration globally by 2020 would require a further 900 GWe capacity (1600 GWe total) which would be equivalent to the construction of some 60 GWe per annum of new nuclear capacity post 2000. Towards the end of the period some 30 GWe pa of replacement capacity for nuclear plants erected in the late 1970s and early 1980s would be required, depending on their technical and economic lives (18). This total of around 90 GWe pa would succeed, if electricity demand does indeed double, in holding greenhouse gas emission from electricity production at about their present 1989 level. The contribution to the reduction of total anthropogenic greenhouse gas emissions would amount to around 15% depending on total energy growth (Figure 8) (18). If energy efficiency improvements or other factors limit the growth of energy demand then the contribution of nuclear power would be proportionately greater. However, since energy use only accounts for some 45% of anthropogenically produced global warming there is an upper limit on what can be achieved by fuel substitution or energy conservation.

Construction of 60 GWe pa of nuclear plant from 2000 rising to 90 GWe pa by 2020 would represent an enormous increase relative to what is currently planned for the second half of the 1990s. Its achievement would require a major industrial effort and firm decisions before the early 1990s, bearing in mind that nuclear plants take at least 5 years (and often much longer) to build and commission. It is probably an upper limit to what might now be achieved.

If large scale fast reactor commissioning were started in the year 2000 on the basis of the separated plutonium stockpile, and if the then existing reprocessing capacity plus adequate fast reactor fuel reprocessing plant were employed, then fast reactors could contribute at best about one third of total nuclear capacity and annual additions by 2020 based on the lower 20% nuclear share of electricity. In practice such an early large scale start is no longer feasible so that smaller contributions are inevitable. Furthermore the doubling time of plutonium oxide fuelled breeder reactors corresponds to only about 3%

FIGURE 8

WORLD ENERGY DEMAND AND ELECTRICITY SUPPLY

	1987	2020 modest		2020 low	
Primary Energy TWy/y	12.0	19[1]		15[2]	
of which Electricity (primary equivalent)	3.5	7		7	
Electricity generation 1000 TWh/y	10.2	20		20	
		Postulated		Postulated	
Nuclear share %	16.2	21	50	21	50
Nuclear capacity GWe	298.0	700	1650	700	1650
Carbon dioxide reduction bn tonnes pa	1.7	4.2	10	4.2	10
Reduction in global warming %	3	6	14	7	16

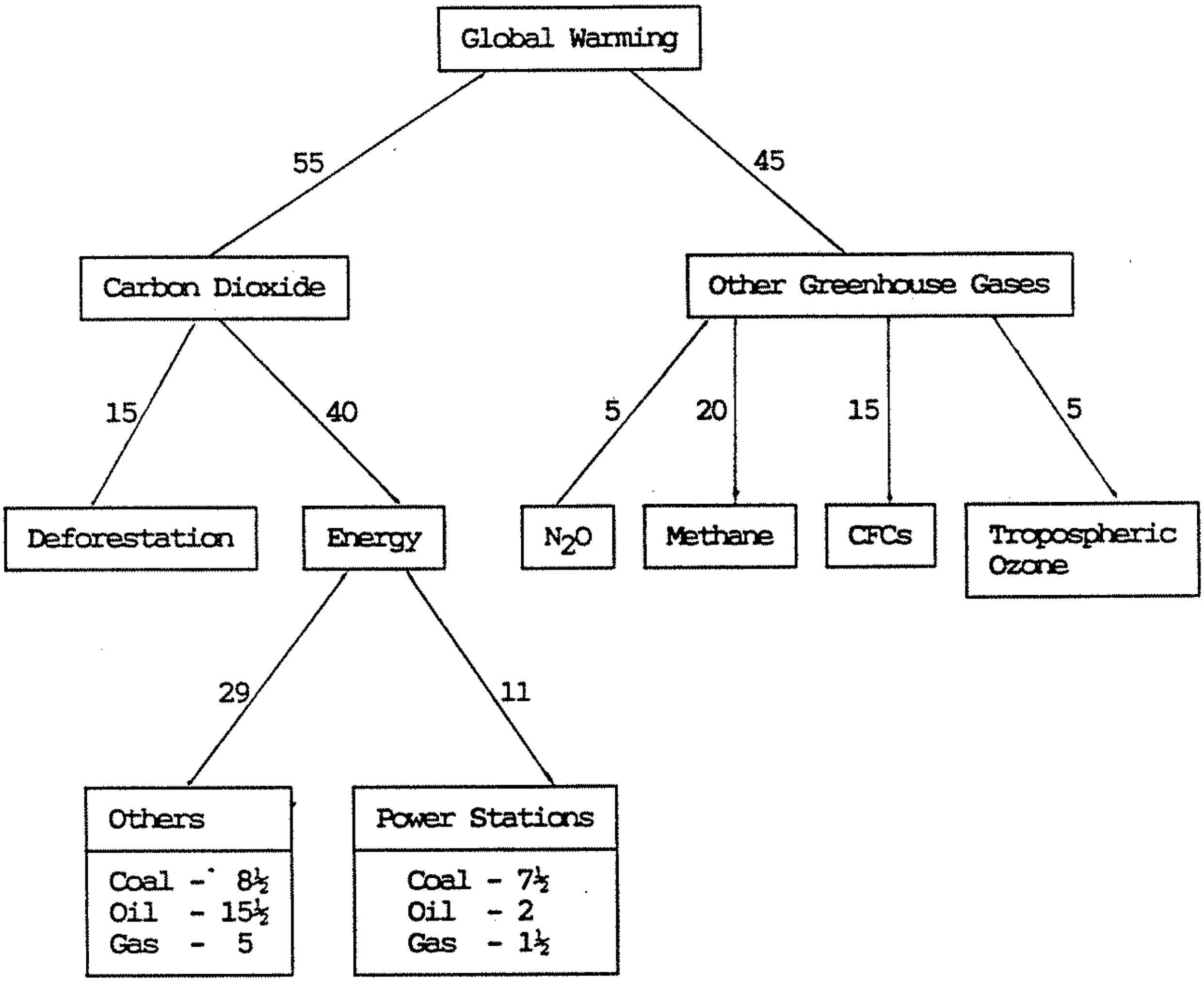
1. Based on World Energy Conference/International Institute for Applied Systems Analysis/IAEA low scenarios

2. Based on Ref. 19 but with less optimistic efficiency assumptions

Source: Ref. 18

FIGURE 9

SCHEMATIC MAKE-UP OF PRESENT MAN-MADE GLOBAL WARMING



Note:

All numbers given above are percentages of the total global warming effect of man-made emissions integrated over two decades or so. These emissions enhance the warming due to the Greenhouse gases which occur naturally in the atmosphere. The global warming effect of a gas depends both on its concentration and how effective it is in trapping thermal radiation. It is worth noting that power stations account for about one-quarter of the energy contribution. Moreover, energy-related activities contribute perhaps 5% of global warming via gases other than carbon dioxide (methane, N_2O, ozone).

pa increase in plutonium availability and hence fast reactor capacity. This is well below the projected rates of growth of total nuclear capacity while it is taking over from fossil power so that reliance on thermal rectors would continue to increase. There are technical routes which offer the prospect of higher fast reactor penetration rates; the use of plutonium carbide fuels which would reduce the doubling time, or the use of uranium-235 for initial fast reactor inventories for example (16).

The UK position is better than that of most countries in that it has a sizeable and growing stockpile of plutonium from high yielding Magnox plants. This would allow a rapid initial build-up of fast reactor capacity.

ALTERNATIVES TO NUCLEAR POWER

(a) Supply Options

How does nuclear energy compare with other possible means of reducing greenhouse gas emissions? Clearly there are possibilities in the short term for the substitution of oil or, better, natural gas for coal fuel in electricity production or more general energy use. The hydrocarbons produce significantly less carbon dioxide per unit of electricity produced than coal although the reduction does not compare with that achieved using nuclear power or renewable sources (18). However, neither nuclear power nor the renewables can completely eliminate carbon dioxide production since the construction of plant requires the extraction, processing and transport of materials (as does the nuclear fuel cycle) during the course of which fossil fuels will be consumed.

Extensive studies have been undertaken of fossil fuel use in the course of the extraction and production of materials (21, 22) so that it is possible to make broad estimates of the quantities of fuel and carbon dioxide emission associated with different energy sources. Clearly the subject is not simple and the answers one obtains will depend very much on the assumptions made concerning the specific details of the different energy sources. In the case of nuclear power the energy required will depend on the quantities of cement and steel used in plant construction and on the energy required for mining and extraction of uranium from its ores, its processing, enrichment and fuel fabrication as well as the requirements associated with the storage, processing of spent fuel and the ultimate disposal of radioactive waste. The amount of ore extracted will depend on its uranium content and the energy required for enrichment will depend on the process adopted. The diffusion plants used in the United States and France, for example, consume 20 times the electricity used in the centrifuge plants deployed in the Urenco countries including the UK (23).

Mortimer (24) has recently updated his earlier work on the energy balance of nuclear power plants and adapted it to relate to total carbon dioxide releases. He retains a rather dated lifetime load factor of 62% and uses the odd assumption for a 1000 MWe UK PWR that it gets 90% of its enriched uranium from diffusion plant. On this basis he concludes that the construction and operation of a UK PWR would produce an average of 230,000 tonnes of CO_2 per annum compared with 5.9 million tonnes pa from a 1000 MWe coal fired station.

From a UK standpoint it would be more appropriate to assume that all enrichment was in a centrifuge plant fed with electricity from nuclear sources. The annual average carbon dioxide production then falls to 43,000 tonnes with a 73% load factor. This is less extreme than Mortimer's own calculation (24) which assumes all electricity for mining, milling and plant materials comes from nuclear sources and leads him to a conclusion of 21,000 tonnes pa average emission.

These lower and more appropriate emission levels are below those the same author has estimated for renewable sources (24) which are displayed in Figure 10. The comparative situation will be closer at present to the high bound in countries like the USA and to the lower in the UK and France. The latter, despite using diffusion plant, gets almost all its electricity from nuclear or hydropower sources. In the future, as advanced centrifuges and laser enrichment plants become more widespread, all countries will move towards the lower bound.

Other renewable sources appear to have larger construction material requirements (25) than those considered by Mortimer and would appear to have higher associated carbon dioxide emissions.

It will be evident from Figure 10 that the adoption of either nuclear or renewable sources will reduce the amount of carbon dioxide associated with energy production by a very high percentage and that there is on this score little to choose between them. Even in circumstances where the nuclear fuel is enriched using a diffusion plant and the energy for that plant is provided largely by fossil sources the quantities of carbon dioxide associated with nuclear electricity production remain small in relation to the savings from the avoided direct combustion of coal.

It has been argued that the work involved in mining and extracting uranium from low grade ores can lead to very heavy demands for energy and that in extremis the energy requirement is greater than the energy recoverable from the uranium (24). This in turn would imply that the carbon dioxide production associated with the extraction of low grade uranium could well be as high as or higher than the carbon dioxide produced in the direct combustion fossil fuels. Clearly there is an ore grade below which it will be uneconomic to extract metals whether they be uranium, gold or whatever. However, in the case of uranium it has been demonstrated that there are significant energy gains even in the case of recovery of uranium from shales, sea water or granite, although in the latter case the net benefit is relatively small (Figure 11). If low grade ores are used the benefits in terms of carbon dioxide reduction would be less than those detailed earlier.

As has been pointed out in the past (26) the very low grade ores (<0.01% U) are not likely to be used for environmental and other reasons. Neither are they needed in the foreseeable future since the known low cost resources, together with those that are likely to exist but have so far not been discovered, should be adequate to meet requirements of

FIGURE 10

CARBON DIOXIDE RELEASE v. TECHNOLOGY

Based on production or saving of 5 TWh per year

Plant	Average total carbon dioxide release pa 100,000 tonnes
Supply options	
Coal-fired	59.1
PWR (USA)	2.3
PWR (UK)*	0.43
PWR (self-supplied)	0.21
FBR*	0.23
Hydro-power	0.87
Wind power	0.54
Tidal power	0.52
Efficiency measures	
Loft insulation (10cm glass fibre)	0.24
Polystyrene cavity wall insulation	0.23
Low energy lighting	0.12

* This paper. All other figures from Ref. 24

FIGURE 11

NET ENERGY GAIN RATIO FOR URANIUM SOURCES

Source	**Electricity contribution Recovery energy**
0.18% ores	15.4
Chattanooga shale 0.007%	7.3
Sea water 0.007%	6.4-11.2
Granite 0.002%	2.2

Once through with 0.3% tails assay

Source: Refs. 26, 27

all reasonable nuclear programmes, given the timely deployment of the fast breeder reactor.

The FBR itself requires no fresh uranium and has a small fuel throughput so that its energy costs and associated carbon dioxide emissions are very low (Figure 10).

(b) Energy efficiency measures

These, if they involve new investment as opposed to simple changes in management practices, also require materials and will result in carbon dioxide emissions. Calculations submitted to the Hinkley inquiry (24) give data on some energy efficiency measures. The use of 100mm thick glass fibre for loft insulation is claimed to save 1000 kW hours per year in a typical semi-detached house, and its manufacture would involve the production of amounts of carbon dioxide that were about the same as those associated with the construction and operation in the UK of a nuclear plant producing this same amount of energy. At a cost of approximately £300 per house the capital investment for loft insulation is also equivalent to that required for the construction of a new nuclear plant. Whether nuclear power or glass fibre insulation is the better in terms of investment and carbon dioxide reduction depends on the period over which the glass fibre conserves energy and the lifetime of the nuclear plant. If both periods are the same as assumed by Mortimer (24) then the two are for all intents and purposes equivalent. If on the other hand the life of the insulation is double that of the nuclear plant then it is the better investment.

The advantage of energy efficiency measures in terms of carbon dioxide reduction and cost is a complex subject which is not helped by lack of data. Undoubtedly conservation measures are likely to prove easier and quicker to introduce than major fuel substitution programmes, although both the ease and the phasing of conservation are likely to be considerably worse in practice than their most enthusiastic proponents would like (20).

The share of electricity consumed by domestic appliances is quite small; nevertheless this is one area which has been selected for use as an example of the potential gains to be achieved through energy efficiency measures. A favoured item is the domestic refrigerator/freezer where there are claims that modern equipment is significantly more energy efficient than the existing stock and that prototypes exist which offer still further improvements (8). However, when one analyses the costs and improvements achievable it is far from evident that premature replacement of the inefficient stock of domestic fridge/freezers with new efficient equipment is more cost effective than the provision of electricity from a new nuclear plant if both the courses of action are considered on an equal kWh footing.

Thus the substitution of an existing fossil fuel plant by a nuclear plant is more cost effective and will save more carbon dioxide per £ spent than the substitution of an existing fridge/freezer by a new more efficient one, and the replacement at end of useful life of coal plant or a fridge/freezer with new equipment similarly shows an advantage to the nuclear plant (Figure 12) (28). The one circumstance in which the fridge/freezer replacement has an advantage is that in which the more efficient unit is introduced as part of a natural replacement cycle and substitutes for an expansion of the electricity supply network. However, the fridge/freezer choice will always appear attractive to the knowledgeable consumer and will quickly pay for itself at current electricity prices.

There are, of course, other energy efficiency measures which are more attractive than fridge/freezers in economic terms, wuch as high efficiency fluorescent light bulbs. The point being made however is that the case of the nuclear reactor is significantly stronger on economic and carbon dioxide substitution grounds than has been implied in a number of recent publications.

CONCLUSIONS

Neither nuclear power nor improved energy efficiency are of themselves solutions to the greenhouse gas problem. Nuclear power will take time to deploy and, on its own, would be able in principle to stabilise carbon dioxide emissions associated with electricity production at their 1989 levels during the early decades of the next century, as electricity demand grows. After 2020 there is no reason why nuclear power could not gradually displace a major part of fossil fuel use. This would require the early deployment of fast reactors.

Switching from coal to hydrocarbon fuels and energy conservation measures will offer a quicker response route if reductions are deemed necessary in the 1990s. However, these approaches are also limited in what they can achieve. In combination with nuclear power they offer the opportunity of considerably ameliorating carbon dioxide emissions although, even so, it is doubtful whether the extremely difficult targets set by the Toronto Conference are achievable, ie a reduction of anthropogenic carbon dioxide releases to 20% below current levels by 2005. As a target this would be difficult enough if all parts of the world were in a position to reduce its production on an equal footing. In practice the task is far harder for the developing nations than it is for the industrial nations, and a large part of projected future growth in energy demand is in these developing countries.

FIGURE 12

FRIDGE/FREEZER SUBSTITUTION

Case	Levelised incremental[#] investment cost per coal unit saved US c/kWh	Levelised total cost per coal unit saved* US c/kWh
Fridge/freezer		
(a) Normal cycle	2.7	2.7
(b) Immediate sub	6.9	6.0
Nuclear		
(a) Normal cycle	0.8	2.4
(b) Immediate sub	1.5	3.1

[#] Net of corresponding coal plant investment costs on continuing system basis

* Includes 1.6 c/kWh for levelised nuclear fuel and operations costs plus incremental investment cost on continuing system basis.

Source: Ref. 28

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SOCIAL COSTS OF ENERGY

P M S Jones

1. INTRODUCTION

There have been many studies over the past 20 years which have looked at the environmental and other impacts of energy production, conversion and use. A number of these have attempted to put a monetary value to the external costs which are not reflected in the prices charged for energy.

The topic has received increased attention recently as a direct result of the recognition of the potentially large social costs that might arise from the depletion of the ozone layer, the consequences of global warming and the continued releases of acid gases from fossil fuel combustion.

One officially sponsored academic study which has received some media attention and government commendation (1) has called for the internalisation of external costs (ie the quantification of damage and social costs and their inclusion in the price charged for fuels or electricity) as a means of bringing about an adjustment in the total use of energy and the mix of energy sources. If this were realisable, and if all other goods and services similarly reflected full social costs, the fuel mix and total economic welfare would be maximised. The present author is sceptical about the feasibility of even approximating this ideal (2) and considers that, at the present state of knowledge, we can do no better than form a balanced judgement on the desirability of modifying fuel use. Pricing mechanisms can be used to encourage changes in use and improved efficiency, but the goal of social optimisation remains a long way off. Pearce and his coworkers (3) recognise the problems and have presented a more pragmatic view in their later publications.

The determination of external costs was attempted in the report for the European Economic Community, EUR11519, "Social Costs of Energy Consumption", authored by O Hohmeyer (4). Due to its official sponsorship, this report has been afforded greater respect than it deserves and is being used in some quarters to claim that the external costs of nuclear power are high relative to those of fossil fuels. The remainder of this note looks at some of the serious deficiencies of the document and why its conclusions offer no meaningful guidance to policy makers. So far as the present author is aware no serious criticism of the Hohmeyer study has previously appeared.

2. THE EVALUATION OF ENVIRONMENTAL IMPACTS

Surprisingly, Hohmeyer claims that his study is the first systematic attempt to evaluate the external effects of energy systems. This is very far from the truth. Even the present author's study, the 'Technical and Economic Assessment of Air Pollution in the United

Kingdom' (5), had been anticipated considerably by the work of the Beaver Committee (6) amongst others.

Important contributions on the topic have come from Ramsey in "The Unpaid Costs of Electricity" (7), from the UK Health and Safety Executive (8), Cohen (9) and Herbert Inhaber (10).

The latter author's studies, because they drew attention to the environmental detriment associated with renewable sources and showed nuclear power in a good light, were subjected to frenzied attack. Whether or not the numerical analysis by Inhaber was correct, he identified the need to take all stages of energy production into account, including, importantly, for the renewable sources, the extraction and fabrication of materials of construction. Ignorance of Inhaber's work and neglect of this important factor is one of the major weaknesses of Hoymeyer's analysis.

In his introduction, Hoymeyer refers to his underlying hypothesis that the external costs of renewable energy sources are less than those of conventional sources. If the principal contribution the renewable sources make to environmental damage is excluded, it is scarcely surprising that the results support the hypothesis!

3. EXCLUSIONS

3.1 General

The study properly recognises the crudity of its figures and the inevitability that many identifiable external effects can not be quantified or have a meaningful monetary value attached to them. This is unavoidable and one reason why great caution is needed in drawing conclusions (2). Unfortunately, whilst those conducting analyses are well aware of the limitations these tend to get suppressed by those seeking to use the studies once a numerical output has been set down.

3.2 Renewables

The omission of the external impacts (mostly from fossil fuel burning) associated with mining, extraction and fabrication of the materials needed to construct aerogenerators and photovoltaic arrays leads to serious bias in the study. Limited reference is made to the toxic hazards associated with the active materials needed in solar cells but this is only part of the picture.

The renewable sources are characterised by the need to convert diffuse low density energy forms into the concentrated forms needed for practical application. By their nature they tend to be demanding of structural materials such as steel and concrete when compared with the high density energy sources like fossil fuels and nuclear power.

Added to this is the fact that most renewable sources are variable (wind, sun, tides, waves) and, in the absence of large scale electricity storage technologies, they need back-up from firm fuel based generation plant. The extent of the back-up required depends on the contribution renewables are making to an energy sytem. For small contributions the major conventional part of the system may provide sufficient back-up to provide the necessary assurance of supply at times of peak demand (11), but as the renewable share increases the specific back-up capacity needed increases. In the CEGB case, for 1GWe average output from aerogenerators the back-up was 1% whereas for 5.5 GWe average output the back-up rose to 11%.

For this reason, renewable sources should carry the extra economic and external costs associated with back-up from, say, gas turbine plants, both in terms of constructional materials and construction and operation. These costs would increase as the share of renewable electrical capacity on the system grew. It is misleading to omit this backup completely as Hohmeyer has done and equally misleading to assume that each unit of variable renewable capacity should carry 100% capacity backup. The solution is to review the external costs of the overall electricity system with different mixes of plant selected to give the desired overall system reliability.

3.3 Fossil Fuels

Hoymeyer recognises the above in the section on fossil fuels where it is noted that, in addition to fuel extraction and processing (refineries), the production of the energy system is excluded. Another important omission is the potential wider impact of carbon dioxide emission, for which costs have been confined to flood defence systems alone.

Lesser exlusions quantitatively are noise, dirt and thermal pollution effects.

3.4 Nuclear

The same exclusions are noted for nuclear power with regard to fuel extraction and processing and construction of the energy system itself. Indeed, for nuclear, all routine operations are excluded because of the author's conviction that they are dwarfed by the external costs associated with potential accidents.

4. METHODOLOGICAL AND NUMERICAL DEFICIENCIES

4.1 Fossil Fuels

As in the case of other energy systems the methodological approach is idiosyncratic and flawed.

One of the main errors in the fossil fuel section is the method adopted to allocate the gross national (FRG) damage costs, calculated by others, to electricity production. A method is used which weights total emissions by their "toxicity" and allocates the total costs by weighted contributions of different sources to computed total toxicity. One may have doubts about the relevance of the "toxicity" measure, not least because of the known synergisitic behaviour of pollutants, but the major flaw is the failure to recognise that emissions can have very different impacts depending on the degree of dispersion achieved before they produce their effects. Low level, low temperature, emissions from car exhausts and domestic chimneys can have a far bigger impact on health and the built environment than the high level, high temperature, flue gases released from large power stations. In terms of distant effects arising from acid rain or greenhouse gases the distinction would be smaller or non-existent. Nevertheless this weakness almost certainly leads to a serious overstatement of external costs arising from fossil fuel use for central electricity production, in the study's own terms. (Whether or not the total damage costs for FRG taken from other studies are reliable or whether the 'toxicity' weighting is meaningful are not examined here).

On the toxicity weighting method, power production is allocated some 34% of the total damage costs. Using Scorer's technical weightings (5, 13) this would be reduced by an order of magnitude to around 3%.

It may be remarked, however, that the treatment of the health impacts of coal burning seem highly arbitary with 20% to 50% of total respiratory disease being attributed to air pollution which is then equated to the products of fossil fuel combustion. The more easily quantified effects of mining, drilling and fuel transport accidents and occupational health impairment are completely omitted (8).

4.2 Nuclear Power

Hohmeyer's general approach of taking overall impacts from the studies of other authors and then allocating them to energy sources leads him to some peculiar statements. Thus, he says the attribution of damage to radioactivity stemming from the civil nuclear power industry is made difficult by the existence of other radioactive sources including weapons' test debris, coal combustion products, medical and natural radiation!

He goes on to claim that it is "obvious that there are no very reliable results on the cause-effect relationship of nuclear energy and probable damages". Yet radiation is one of the best researched hazards in terms of its biological consequences.

The report includes a lengthy discussion based once more on the claims of others concerning overall levels of impact which lead him to conclude that the consequences of accidents so outweigh the routine emissions of nuclear plants that the latter can be neglected. He bases much of his analysis on the effects, estimated by others, of Chernobyl in the Soviet Union and Germany. He blithely dismisses one German study which pointed to the low level of radioactivity relative to variations in natural background in the Federal Republic and says again that "it is obvious that in addition to the material damage to food, there has been considerable health damage as indicated by the higher number of cancer patients and the genetic damage to embryos". No source is quoted for this wild assertion which reads strangely after his recognition a few paragraphs earlier of the fact that cancer resulting from radiation exposure occurs after "very long time lags which make it impossible to trace damages back to specific sources of radioactivity".

In "analysing" the health consequences of nuclear accidents Hohmeyer provides a confused and confusing mixture of effects factored from Chernobyl allowing for population density differences in FRG and more fundamental calculations based on the statistical risks of radiation exposure and the estimated probabilities of accidents.

Specifically his cancer risk review embraces both authoritative official studies and the figures published by anti-nuclear sources. He uses a range of risk from $2x10^{-2}$ per Man Sv to $37x10^{-2}$ per Man Sv with his main calculations based on 10^{-1} per Man Sv, well above the most recent judgements of the International Commission on Radiological Protection and the UK's National Radiological Protection Board.

He compounds this overstatement by taking the risk of major accidents leading to release of 1% to 50% of the core inventory as $5x10^{-4}$ to $5x10^{-5}$. The treatment is again undiscriminating in its use of sources and ignores major differences between the Chernobyl RBMK with no outer containment system and modern LWRs in Western countries which have computed risks of 10^{-5} or lower (Sizewell B PWR nearer 10^{-6}). Furthermore, even with the Chernobyl fire, the fraction of the fissile inventory released lay to the bottom of the range so that it seems highly unlikely that much greater releases could be expected to occur.

For these reasons it seems clear that expert opinion would put the best judgement of overall risk close to or even below Hohmeyer's lowest estimate.

The conversion of postulated cancer incidence to costs uses a figure for the value of life equated to gross income foregone, in common with many other studies (5) (12).

The method selected, however, assumes that the average age of consequential death is 40 and this neglects the acknowledged latent period of perhaps 15 or 20 years after radiation exposure before the disease becomes apparent (12). Again, on the basis used by Hohmeyer, the inclusion of an allowance for this delay would about halve his valuation of the detriment per cancer and, as a consequence, halve calculated detriment cost per unit of electricity produced from nuclear sources.

5. EXTERNAL EFFECTS ON THE ECONOMY

The method adopted examines the impact of adding some 10 GW_e gross of wind as photovoltaic capacity to the national supplies (for FRG) without reducing the investment in conventional plant.

Not surprisingly, this leads to an increase in employment and an overall increase in GNP. By assuming that the real price of electricity (for own use or for sale to the grid) more than doubles by 2030 during a period when wind generator capital and operation costs halve, they are able to calculate that the overall cost of electricity supply will be considerably reduced.

Apart from questions about the validity of the cost and pricing assumptions, the input-output methodology used appears to ignore the opportunity value of the diverted resources should they have been used in other sectors of the economy. The basic assumption is that the manpower will come from the ranks of the unemployed and have no alternative use. This seems an unsound assumption, not least because it should equally apply to the resources employed in the conventional fuel industries if it were valid in the first place.

It is hard to see how the deliberate application of extra resources to produce a given predetermined output of electricity or any other commodity can be beneficial. It has to be done at the expense of increased overall costs, which in a fixed income economy would lead to reduced demand elsewhere and could, through the need to increase prices to recover the fixed costs, make an economy less internationally competitive.

Hohmeyer himself advises that the figures should not be taken at their face value. Certainly, in this author's view, the beneficial social effects calculated for the renewable sources by Hohmeyer appear to be based on extremely dubious assumptions. Recent international studies suggest that wind-based power plants are not yet able to compete with conventional systems when full resource costs are used (14). Proponents of aerogenerator systems might take a more optimistic view but at this time it would be very unwise to attribute a significant beneficial external macro-economic gain to their use.

Resource Depletion

Having calculated high external detriment costs for conventional energy systems and significant external benefits for renewable sources, Hohmeyer executes his coup-de-grace by introducing the concept of a depletion cost.

Conventional economic theory suggests that, with perfect information, a scarce and depleting resource should have a market price that reflects its value to the user and which increases over time at a rate equal to the opportunity cost of capital.

Hohmeyer acknowledges this, but then claims that in the real world, this is not happening and that, due to the high individual discount rates of consumers and producers, the market price of depleting resources is lower than it should be. This is probably true. In a situation where supply potential exceeds demand, producers with the short time horizons encouraged by the operation of the stock market, will be tempted to sell at short run marginal production cost, rather than at long run marginal replacement cost. A net consequence will be overconsumption in the short term, without due attention to the longer term consequences.

The methodology adopted to derive resource depletion premia can itself be questioned. A substitution or replacement cost for electricity based on combustion of hydrogen produced using aerogenerator electricity, together with an estimate of the fraction of the mineral resource consumed, is bound to be contentious. Both coal and uranium resources are extensive and the latter, in particular, offer the prospect of providing for world electricity needs for well over 500 years (15). By this time fusion, improved renewable technologies, or other, as yet unthought of systems may have taken over. The substitution value is therefore almost certainly wrong.

Even if it were not its significance for coal and uranium is overstated. The only uranium resources considered are limited to the published known resources. The best estimates of resources yet to be discovered, suggests that these should triple known resources and, given the deployment of fast reactors, a further 60-fold extension is available. The world's uranium sources far from being 70% consumed by 2060 as suggested by Hohmeyer will have scarcely been touched. On this basis, whatever the very long term substitution cost, the premium to be attached to uranium would be nil.

There is greater justification for applying depletion premia to oil, gas and even coal, but these too seem likely to have been exagerated, though by smaller margins.

Induced Public Expenditure

Hohmeyer introduces this category of costs to cover a mixture of items including infrastructural investment, regulatory and monitoring expenditures, security and emergency services, public countermeasures (such as use of lime in forests and lakes to counter acid rain effects), subsidies and R&D costs.

In so far as these are incremental costs, directly attributable to specific energy sources, over an above those that would otherwise be incurred, they can be properly included. However, the problem of induced public expenditure is far more complex than Hohmeyer suggests.

The question of R&D expenditures is a case in point which is often seized upon by critics of nuclear power. There is no questioning the fact that governments world-wide have spent large sums on nuclear R&D and that these greatly exceed expenditures on renewable sources and fossil energy. In part, this is accounted for by the greater role of private industry in the non-nuclear sector and by the perceived strategic importance of nuclear power.

It is methodologically unsound, however, to take total annual public sector R&D costs, even for thermal reactor systems alone, and relate them to current electricity output from thermal reactors to devise a social cost. For photovoltaic, wind and wave energy this would give near infinite social costs because of their very limited or non-deployment. Hohmeyer ducks this problem by estimating the R&D expenditure for 10 GW_e installed capcity of the renewable sources without, apparently, appreciating the relevance to the conventional sources.

The basic question has to be what extra R&D over and above that which would otherwise be done, is being undertaken in order to back up existing plant. This could properly be included in the social costs if not already captured by direct payments by the supply industry.

Government R & D aimed at the development of new or improved future energy options has a different purpose. Some may be abortive, some imformative, some enabling; but it has to be seen in the context of overall government social and economic policy. This does not mean that the estimated benefits of achieving a viable generating option should not be compared with the estimated costs of its achievement as part of the process of deciding on whether its pursuit is worthwhile or not. However, once the monies have been spent, they are sunk costs, and the concern of society should then be with the ongoing costs of deploying the technology. It would be folly not to exploit a low cost and environmentally benign energy source because it had previously cost a lot to develop.

Such non-exploitation could arise equally from wrongly imposed social premia in the price or from the inclusion of sunk costs in investment decision analysis.

In practice, a relatively small part of nuclear R&D or renewable expenditure is directly concerned with existing plant so that the appropriate social premium is far less than that calculated by Hohmeyer. Even where there is some relationship, as for example with research on waste management, this is linked not just to current plants, but also to future ones, so that the present and future costs should be spread over present and future electricity production.

6. CONCLUSION

From the foregoing it will be evident that little or no confidence can be placed in the numerical conclusions reached by Hohmeyer. For nuclear power his 3p to 7p/kWh external costs are more likely to be around 0.1p/kWh, whereas for fossil fuels his 0.4p to 2p/kWh are more likely to be about 0.3p/kWh.

These figures are derived by rough adjustment of Hohmeyer's errors and do not attempt to re-evaluate the basic input costs, nor to translate them to a UK environment. They should not be taken as even indicative other than as guides to the magnitude of the divergence with Hohmeyer's own findings. Fossil fuel external costs will be very dependent on views on long term climatic effects. The 1972 UK study, which omitted climatic impacts, yielded results eqivalent to 0.1p/kWh (1989 money) for coal-fired electricity (5).

Renewable energy sources can not be similarly adjusted other than to say that the so called socio-economic benefits from their use (as opposed to costs) seem likely to have been seriously overstated by Hohmeyer and may well have the wrong signs. Of greater importance is the omissions of system construction impacts which, on the basis of Inhaber's corrected figures (loc cit), would lie between those of fossil fuels and nuclear power.

A recently located study by Prof. A. Voss (16), seen in a press synopsis only, has reached similar conclusions concerning the magnitude of Hohmeyer's figures. The quoted external costs are 0.3 to 0.4p/kWh for fossil fuels, 0.2p/kWh for nuclear fuel, around 0.1p/kWh for aerogenerators and 0.2 to 0.4p/kWh for solar power. These would be consistent with the present analysis but their basis has not yet been studied.

If the magnitude of the external costs of coal-burning for electricity production are correct then the social cost amounts to around 10% of the generation cost or roughly a 15% surcharge on coal fuel prices. This has to be contrasted with one estimate (17) that surcharges of around 50% would be needed to reduce consumption by 20% and approaching three times this to achieve a 50% reduction, based on short-term price elasticities. This suggests that mere internalisation of external costs, if known, may not be sufficient to achieve the goals for reduction of pollution favoured by some concerned environmental analysts.

Clearly, we remain a very long way from the position conceptualised by Pearce et al (1) in which external costs associated with fuels can be calculated accurately and used as surcharges to encourage welfare-efficient use of energy. We may also find that political goals would not be satisfied by welfare economics based approaches to externalities.

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